

CRANFIELD UNIVERSITY

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EXTENSION OF SKOPINSKI'S APPROACH TO REDUCE
(STRAIN GAUGE) FLIGHT LOAD MEASUREMENT
UNCERTAINTIES

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
PhD in Aerospace

Academic Year: 2017-2018

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requirements for the degree of PhD

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Abstract

Structural Health Monitoring (SHM) is an essential technique for assessment of the integrity of ageing structures or certification of new aircraft. The SHM approach developed by Skopinski, based on conventional strain gauges, is one of the most reliable experimental methods for assessment of the structural loads experienced by lifting surfaces.

This thesis concerns the extension of Skopinski's approach to low aspect ratio wings with multiple spars. This is a challenging problem, as the redundant load paths increase the complexity and difficulty in defining load equations and fitness functions. Similarly, locating, calibrating and selecting relevant strain gauges becomes more difficult.

One of the new developments is a methodology for load measurement based on physical metrics and load data that is independent from the ground calibration used to generate the load equations. The concepts of Influence Coefficient Plots of Strain Gauge and of Loads Equations, were used to identify the predominant loads. The developed fitness function equations are all driven exclusively by these physical quantity parameters. Another key development was reduction of the effort required during the experimental phase achieved using distributed load data, obtained by numerical superposition of individual load cases to develop loads equations. In addition, this approach reduces the risk of damage to the flying test article and increasing the accuracy of the final results as the magnitude of the loads introduced does not need to be limited.

This new framework was coded in Python including a new automated load equation computation technique, Linearised Physical Properties (LPP) and environment Loads Equation Technique Evaluator (LETE). Different search engines, including Exhaustive Search, Strain Gauge Reduction, and Genetic Algorithm, were made available for load assessment.

Code validation (and performance) was performed through root mean square error evaluation in shear, bending and torsion loads using CIRA Test Data for two identical unmanned Space Vehicles, Castore and Polluce. The validation process demonstrated that loads equations developed on Castore can be applied to Polluce, as long as the SHM system design and instrumentations are the same.

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Abbreviations

3AC	Three-Axis of Complexity
AAW	Active Aeroelastic Wing
AF	Air Force
AR	Aspect Ratio
ARWg	Aeroelastic Research Wing
ASIP	Aircraft Structural Integrity Programme
BB	Black Box
CLCC	Check Load Case Condition
CRI	Certification Review Item
D&D	Definition and Design
DAS	Data Acquisition System
DG&A	Data Gathering and Analysis
DLC	Distributed Load Calibration
DLM	Design Loads Measurement
DTFT	Dropped Transonic Flight Test
EQDE	Equation Derivation
ESM	Equation Selection Matrices
ExS	Exhaustive Search
FLM	Flight Loads Measurement
FLSR	Flight Load Specified Range
FT	Flight Test
GA	Genetic Algorithm
GLC	Ground Loads Calibration
IAT	Individual Aircraft Tracking
IEC	International Electrotechnical Commission
ILC	Individual Load Calibration
MoD	Ministry of Defence (UK)

OEM Original Equipment Manufacturer
OLM Operational Loads Measurement
PITS Point In The Sky
RAAF Royal Australian Air Force
RAF Royal Air Force
RC Relevance Coefficient
SDL Sampling Distributed Loads
SgR Strain Gauge Reduction
SM Standard Manoeuvre
SPC Sortie Profile Code
SVD Single Valued Decomposition
TWU Tactical Weapons Unit
USAF United States Air Force
USV Unmanned Space Vehicle
V-n Velocity-Normal Load factor diagram
VGH Velocity - Normal Acceleration - Height
WRBM Wing Root Bending Moment

Chapter 1

Introduction

1.1 Background

To ensure structural integrity and hence maintain safety, in-service health and usage monitoring techniques are employed in many engineering areas. Structural health is directly related to structural performance and in this respect it is one of the major parameters with regard to safety of operation. This aspect of structural health is particularly relevant to transportation systems including various elements of transportation infrastructure. In a similar context structural health monitoring is a safety issue [105].

In fact, the safest and durable structures are those that are well managed. Measurement and monitoring often have essential roles in management activities. The data resulting from a monitoring programme are used to optimise the operation, maintenance, repair and replacing of the structure based on reliable and objective data and but not least the design itself.

In such scenario Structural Health Monitoring (SHM) is a process aimed at providing accurate and real time information concerning structural condition and performance. It consists of continuous, periodic or periodically continuous recording of representative parameters, over short or long timescales. The information obtained from monitoring is generally used to plan and design maintenance activities, increase the safety, verify hypotheses, reduce uncertainty and to widen the knowledge concerning the structure being monitored [34].

Structural health usage and monitoring systems must satisfy realistic performance expectations to meet end-user needs and eventual "Authority" ¹ strict requirements.

The aerospace industry started to fully appreciate the potential of structural health and monitoring usage systems when to face the role of fatigue in serious accidents. Fatigue cracking caused by stress concentrations due to cyclic loads at rivet holes near passenger window openings due to a change of cabin pressurisation upon take-off and landing is the main explanation of the first commercial jet aircraft, Comet, 1950's accident.

¹ Aerospace Authorities: Federal Aviation Authorities (FAA) and EASA Certification Specifications (CS) as Civil Standards, DEF STAN 00-970 (UK documents) and MIL-STD (USAF guidance documents) as Military Standards.

The aerospace Industry had more to learn on fatigue behaviour in another accident involving the Boeing 737-200 aircraft operated by Aloha Airlines on Hawaii in 1988, [105]. The multisite fatigue cracking in the upper crown skin of the fuselage which resulted from the aircraft's age (80 029 flights) combined with operation mainly on runways next to sea and corrosion atmosphere, led to explosive cabin decompression. It was this accident which initiated the major ageing aircraft initiative on the civil aviation side and which is a still ongoing initiative ever since [105].

Military aircraft have also suffered a number of fatigue-accidents. Due to the generally higher age, complex loads environment, compared to the civil aircraft, frequent operation in corrosive environments, consequent increased level of uncertainties and to the shrinking budgets available, the need to control the structural integrity became a main direction of development.

In the mid-1970s the USA Navy started the implementation of the Aircraft Structural Integrity Programme (ASIP). In the same years Royal Air Force (RAF), had to manage operation of a wide range of aircrafts, varying sizes, roles and ages. The use of fatigue monitoring systems based all the efforts on reducing and controlling the lack of understanding of the structural loads experienced by aircraft. So, while in the UK overall assessment of the loads experienced by military aircraft was gained largely from speed V and normal aircraft acceleration g , the **V-g plots**, and Fatigue-Meter, in the US a parallel monitoring activity was underway. In fact, de Forrest 1936 and Simmons 1942 [95], invented the electrical resistance strain gauge that made possible to happen, in 1954, the work of Skopinski et al. [111], recognised as a significant step forward in this field. They published their report on the calibration of strain gauge installations for use in load measurement programmes for techniques in loads monitoring and Skopinski-type calibration methods, approaches are still in use-today [95].

Strain gauge technology, data recording equipments and computing facilities alongside military aircraft becoming far more complex, critical components where loads were uncorrelated with normal acceleration, gave a great impetus for progress of programmes aimed to quantify structural fatigue loading. Direct load measurement, using electrical resistance strain gauge installations on all major components, Figure 1.1, with flight parameters tracking Figure 1.2, proved to be a reliable solution. These programmes were labeled as Operational Loads Measurement (OLM)).

Operational Loads Measurement approach alongside the flight parameters monitoring activity makes possible the task of damage monitoring, essential in any life extension and/or life monitoring campaign, in addition to flight load survey during the development and certification process of a new aircraft, entitled Design Loads Measurement, (DLM).

The following sections of this chapter describe how this research is meant to improve the Skopinski's approach, to reduce the uncertainties associated and limiting the complexity and cost associated with any calibrated strain gauge flight load measurements campaign. More specifically, it will be also described the list of thesis

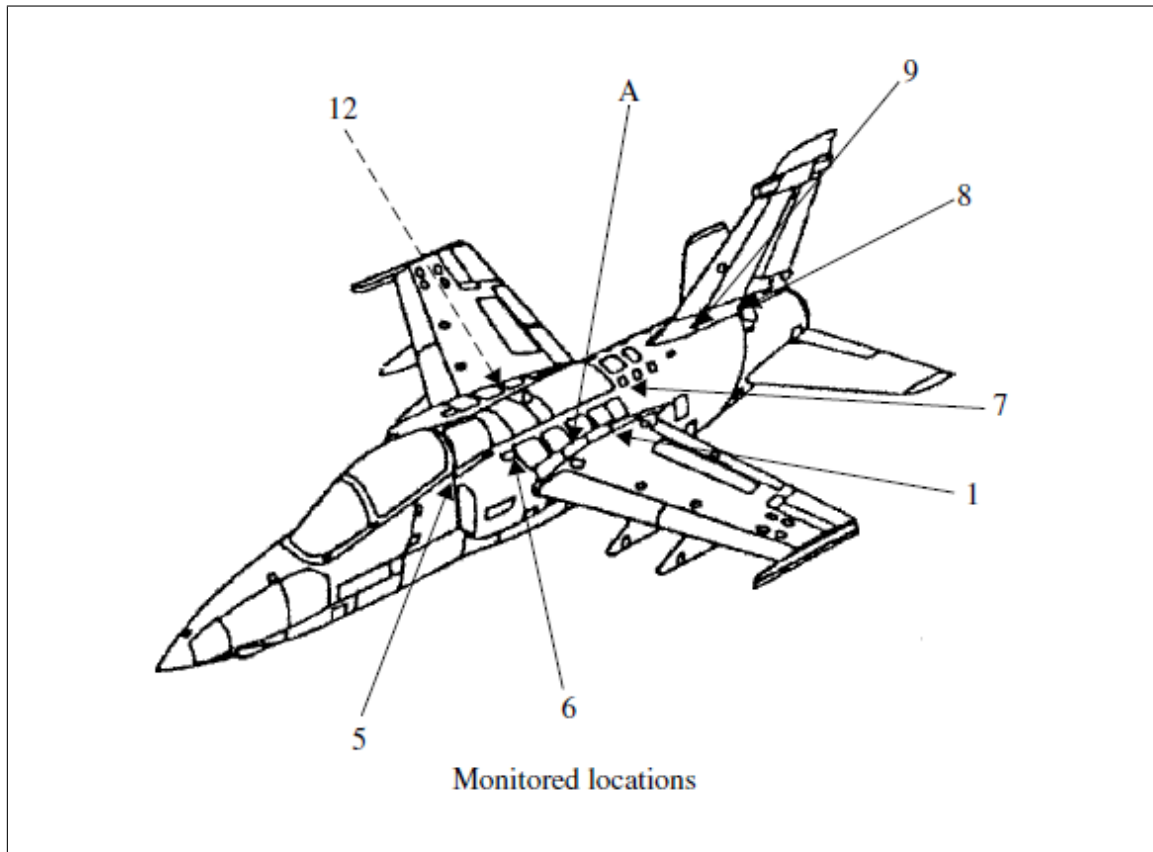


Figure 1.1: Evolution in fatigue monitoring tools, [12].

objectives and the strategy employed to meet them all.

1.2 Need of the Research

The Strain Gauge-Based Loads Monitoring Skopinski-type calibration methods, [111], enable to know the internal loads, Shear, Bending Moment and Torsion span and chord-wise of the component under investigation. This last technique is meant to be explored in this work with the major goal to point out the potential areas of improvement.

The experience gathered with systems based on Design and Operational Loads Monitoring Skopinsky-type philosophy proved over the last 30 years several limitations and areas of improvement. This section focuses on these.

The vast amount of data collected needs a more efficient data management. This issue becomes more specifically relevant when looking at the increasing average age of aircraft, which will significantly increase the amount of ageing aircraft obstacle data to be handled such that fatigue life consumption and possible retirement time of individual aircraft can be better controlled. This procedure can result in significant cost savings (**high data management**). The large amount of data produced in any new certification project, where the prototype understanding and control of load paths, distribution and magnitude coming from the theoretical

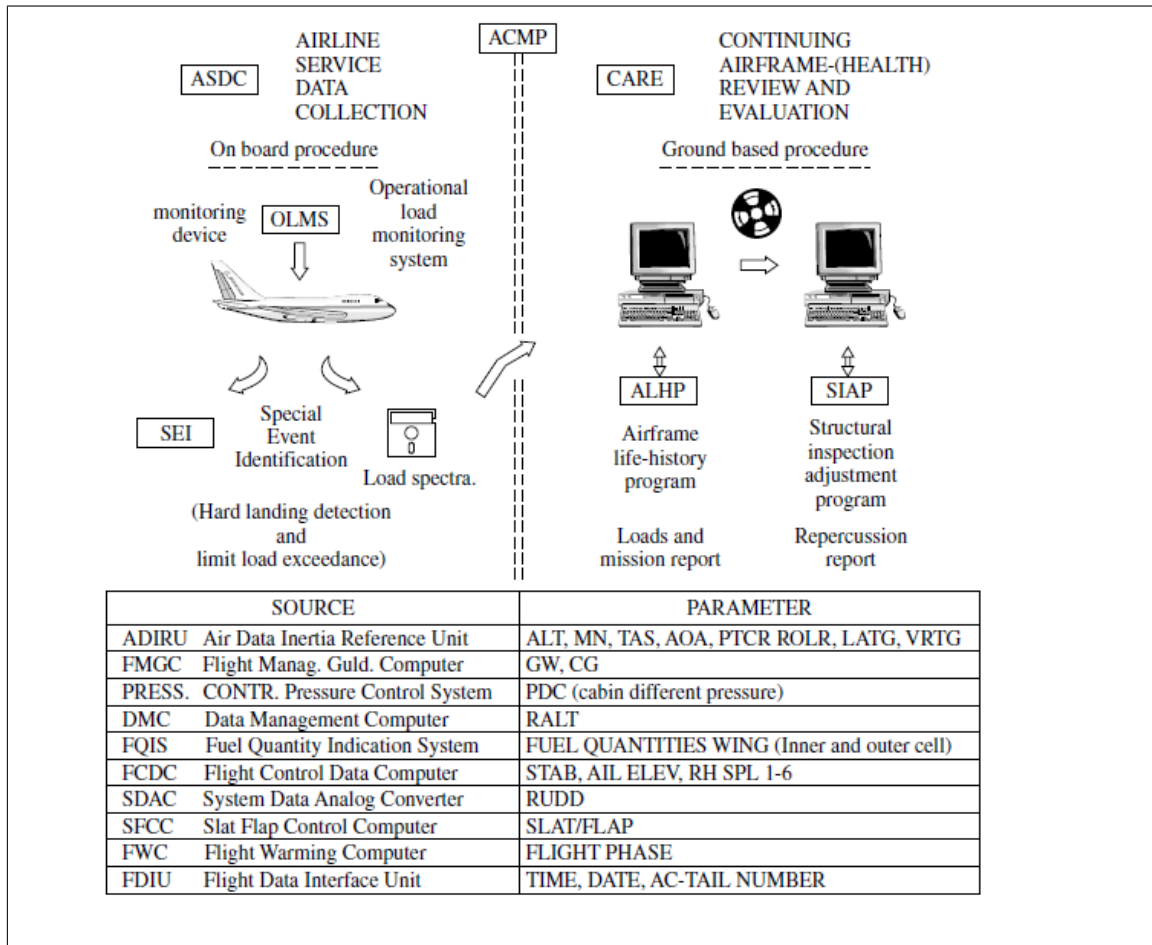


Figure 1.2: On-board life monitoring system (OLMOS) using flight parameters for the AIRBUS A-320, [105].

models becomes a priority for safety and certification reasons.

The OLM systems are not able to directly detect and monitor structural damage. The OLM system can only provide a major input for analytically determining when damage might occur. It is well-known, the experimental and thus real fatigue life can often be two to three times higher than analytically predicted (Boller 1996) [105], which is mainly resulting from scatter in material properties but also due to lack of understanding of the real loads environment. Therefore, it is crucial to characterise ground and flight loads generated over the specific aircraft missions (**reliable loads scenario**).

But aging aircraft is not the only direction for identifying potential improvements. In fact, one of the most current task of Civil Authorities, EASA and FAA [23] and [21], is to present reliable methods to determine load intensities and distribution for high speed/ high altitudes designs and by means of reliable techniques, though, not too intrusive inside the already too cost and time consuming certification process. So, the need to present a procedure structured as such to offer more robust, flexible and reliable outcome than the old fashion means of pressure belts or accelerometers (**certification requirements**).

Since the critical element supporting the whole loads development proposed by

Skopinski's is the "strain gauge", therefore, controlling its inherited uncertainties, not by the physical problem under investigation, but by the applied methodology is another crucial goal. So, instead of developing new types of sensors, such as fibre optics, this research will focus on optimisation tools and robust structured framework to select, through a series of control tasks, the best set of strain gauge capable to produce reliable load equations. The environment and tools proposed will define a flexible environment characterised by offering to employ an automated fast preliminary analysis, or more accurate step by step procedure (**strain gauge health monitoring**).

Gathering all above main emphasised needs and break them down offers a clear status of what is expected to be tackled in this research:

1. The new SG Selection Technique Ranking Criteria of Shear, Bending Moment and Torsion is fully driven by Physical Quantities.
2. The new SG Selection Technique presented robust results for Shear and Bending Moment Loads.
3. The use of two separate test articles, CIRA Data, showed consistent results (Experimental Advantage).
4. The numerical superposed multipoint check load case condition produced consistent results. (Experimental Advantage).
5. The Aircraft Flight Loads Measurement Guidelines reduced uncertainties and produced the best set of load equations.

The approach on how the objectives above will be met is described next.

1.3 The Research Approach

The Flight Loads Measurement process will be investigated with the intention to improve the quality of the final results and present alternatives of execution of some Phases of Figure 2.13 to improve efficiency and reduce the overall effort by referring to past experiences from industries of the field.

For convenience, the whole research has been broken down in four main areas interconnected as described by Figure 1.3.

Figure 1.3 shows the whole concept behind this research. It starts from the Data, that have been requiring a very accurate search as it was necessary to identify as core of the loads to be measured a lifting surface component representative. Therefore, the configuration of the USV Dropped Transonic Flight Test Campaign, [81], multi-spar wing with low aspect ratio, meets the right challenge for such type of swept wing multi-load path lifting surface. Moreover, the strain gauge readings availability during the different experimental test campaigns, made possible investigating the flight loads measurement through its all major phases without exclusion. Equally, having the support for the "Reference Loads", theoretical loads, makes the available CIRA's data an adequate platform. In fact, it defines the right foundation for the development of the research methodologies, representing majority of the

novelties presented and coded with Python and all its available open-source scientific libraries. The results obtained were tested and assessed by means of the same data, different type, used at the beginning. This just described closed loop process enabled to give the continuity to the whole work showing a complete test case applicability from start to the end, though understanding of the real strength and weaknesses should be explored by means of more lifting surface configurations and inside different programmes.

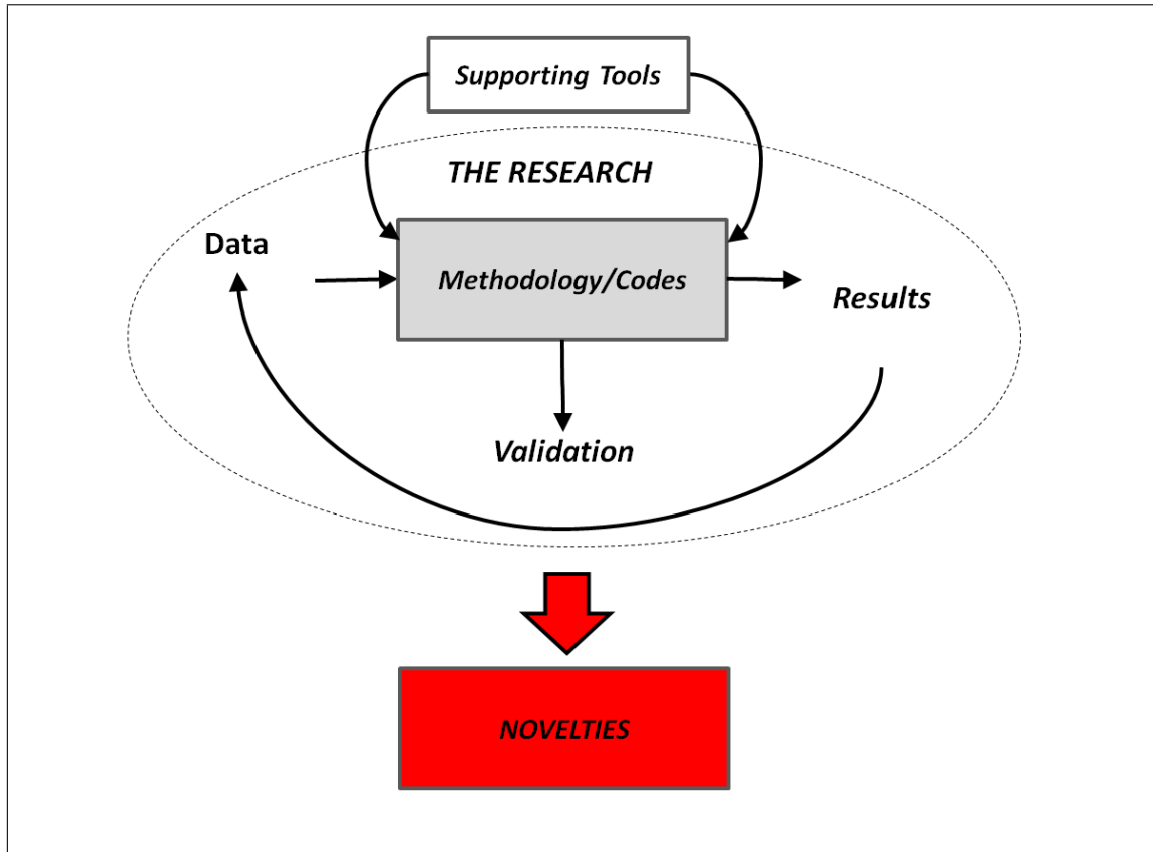


Figure 1.3: Research interconnected areas.

- **Data:** Ground and Flight Test Strain Gauge Readings - The inputs of research, after several unsuccessful attempt with old literature review data, [102], [60], [43] and [103], is coming from a very representative experimental project, the Dropped Transonic Flight Test (DTFT) campaign performed by the Italian Aerospace Research Centre (CIRA), of two different test articles, Unmanned Space Vehicles (USV) [81], Castore and Polluce, but with same type design. GLC and FTC data are not fully available, though are sufficient to generate Loads Equations and Measured Loads. The difficulty of gathering representative data is amplified by the need to distinguish between set of data, dependent and independent of single or multipoint loading, 3.1. Data from the NASA Langley Research Center, [102], [90], [26] and [28], will be added to further contribute to the validation process.
- **Methodologies:** Review the whole FLM of Figure 2.13 introducing differently concepts of Dependent and Independent Data (DD and ID), 3.1, to propose

a new strain gauge selection technique, based on Influence Coefficients (IC) and Influence Coefficient Loads Equations (ICLE), distributed sample data, criteria to be adaptable to different typology of internal forces (Shear, Bending Moment and Torsion), propose a robust environment to deal with any typology capable to generate best possible set of Loads Equations, which will be defined as the "Reference Loads".

- **Codes:** Apply the open source programming language, Python and the associated libraries, suitable to cope with data time histories, statistics, genetic algorithms, required to implement the proposed methodology.
- **Results:** There are different level of results produced. Each software package will be producing outputs necessary to the next step of the whole Flight Loads Measurement process. The major type of results can be identified as best set of Loads Equations obtained by the different coded techniques available and the flight loads measured. These are Codes Results, while the techniques comparisons, made by examining the percent root mean square error, %rms, of the equations found in terms of shear, bending moment and torsion loads, are entitled *Performance Results*.
- **Validation:** It will be validated against the novelties introduced in the thesis. It works with the Data of the CIRA USV and NASA Langley Research Center projects, have been used to assess the two major research elements, *LETE* and *LPP* python coded, which process the experimental data employing the novelties described in section 1.4.
- **Supporting Tools:** In order to develop the novelties by means of methodologies and codes already existing, tools have been employed. The open source Python version 2.7, [67], and its libraries have been used to develop the whole research. Then, an in-house loads software, CIRA's property, based on the Double Lattice Method, Matlab coded has been offered to evaluate theoretical loads. The Weissinger concepts, [117], then became part of the box Methodology/Codes once translated in Python, to generate flight loads as part of *LETE* features.
- **Novelties:** These are supposed to improve the accuracy of the final results of either DLM or OLM measured loads. Equally, these will represent packages, possible to be run by any flight loads measurement professional, capable to select the best set of Loads Equations according to the specific project considered by choosing the techniques most suitable. Additionally, the FLM is reviewed in its own established phases and new directions are explored with the last goal to offer alternatives to the common approach that might make the whole process easier, more flexible and still effective and possible to be engaged not only by big government organisations, Ministry of Defence, or experienced test houses or OEM (original equipment manufacturer).

Notes:

- The dependent and independent **Data** introduced area above requires to be further explained. In fact, the first data type, representing a training data set

used to develop the load coefficients, is labelled in such a way to be consistent with the literature review terminology introduced by the British researchers, Hovel et Al., [43] and [44], to differentiate with the independent calibrated sample employed to assess the quality of the generated loads equations. Basically, the latter data represents a validation set of load and strain gauge responses.

- The scope of this research is to cover the whole spectrum of existing strain gauge selection techniques to compare with the new one proposed. This is why all available search engines, such as strain gauge reduction, exhaustive search, and genetic algorithm, have been translated to Python codes. In fact, the initial research test article structure supposed to be used, to assess the novelties, was highly instrumented with the strain gauges, and the number and selection of gauges used in loads equation could have been problematic, and adopting the genetic algorithm should have been beneficial. Then, a different data set became available with much fewer strain gauges to justify the use of the genetic algorithm. So, as the main scope of this research is to assess the new strain gauge selection technique and the loads equation evaluator framework, the results later on will not be produced other than by strain gauge reduction and exhaustive search engine techniques.

1.4 Novelties

The correct understanding of this research novelties requires the description of its flowchart. Figure 1.4 shows the major areas and their interdependencies. Everything starts from the past works, identified by the label *Literature Review*, responsible to inspire and define the *Tools* and *Concepts* that contribute with the available *Data* to create the novelties of this thesis.

The flowchart uses a top-down approach to justify that a critical review through the years of the science of flight loads measurement enables to locate the thesis project within an existing field of the scientific research indicating the gap, section 1.2, that the *Tools* and the *Concepts* will be filling in.

Furthermore, this study employs the available *Data* in such a way to contribute to the novelties by exploring new directions and also to validate the initial hypothesis of the *Tools* and *Concepts* areas. The area *Concepts* gathers also anything representing methodologies.

The novelties of this research include:

1. **Overview of the Science:** Review through the years the Flight Loads Measurement Science by introducing a critical approach to identify the most significant drivers. (**Literature Review & Data**).
2. **Complete Loads Equations Environment:** Create an environment capable to select the best set of loads equations by employing different techniques based on different search engines and ranking criteria (**Tools & Concepts**).

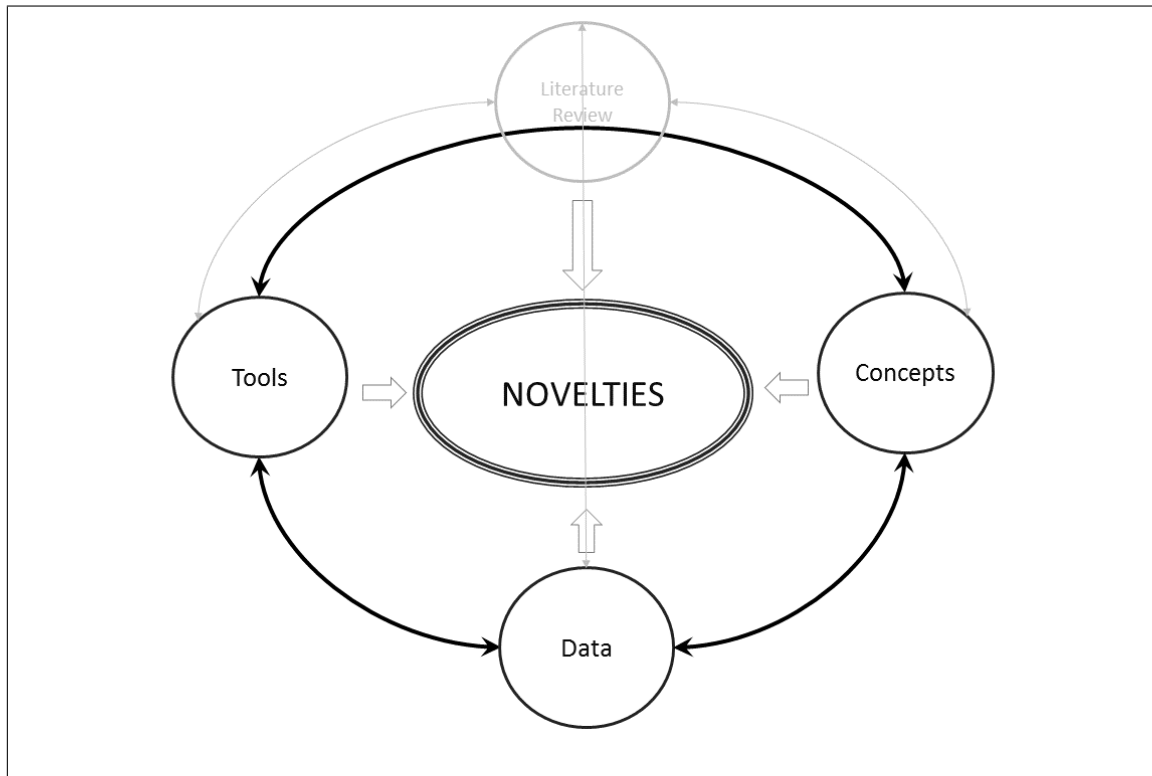


Figure 1.4: Research Novelties Flow Chart.

3. **The Environment Flexibility:** The environment, software package, has to be flexible enough to allow the end user to perform, in addition to loads equation computation, other activities relevant through the whole Strain-Gauge based Flight Loads Measurement. This will have no limitation on the sequence of the features to apply (**Tools & Concepts**).
4. **Ground and Flight Data Framework Adaptability:** The software package is open to receive numerical, ground and flight test data (**Tools**).
5. **New Loads Equations Technique:** A new Loads Equation (LE) Computation technique will be created based on specific Fitness Function equations, fully dependent of physical parameters. The code is supposed to be compiled either automated or semi-automated. (**Tools & Concepts**).
6. **Fitness Function Equations Characteristics:** The new LE specific fitness function equations, different according to the loads, Shear, Bending Moment and Torque, to measure, are based on Influence Coefficient plots of strain gauges and loads equations. (**Tools & Concepts**).
7. **Fitness Functions Development Methodology:** Development of the Methodology to characterise the Fitness Functions equations responsible of the ranking criteria of the new LE computation technique (**Concepts & Tools**).
8. **Data Role:** Development of the different role and typology data combination for the selection of the best set of loads equations (**Data & Concepts**).
9. **Numerical Data Generator:** Distributed Sample of Data, superposed by experimental data, preventing to create a dedicated experimental test case

(Data & Tools).

10. **Loads Equations Expanded Design Space:** Development of techniques to expand the design space of a defined experimental ground load calibration, in terms of strain gauges and load points. Define a methodology behind (**Data & Concepts & Tools**).
11. **Different Ground and Flight Test Articles:** Execution of the Ground Load Calibration on a test article different from the flying prototype (**Data & Concepts**)

All novelties *Tools* listed above will be coded in an open source programming language to enable the research to be continued according to the academic spirit.

1.5 Overview of the Thesis

This thesis covers the Flight Loads Measurement topic in the area of aerospace as valuable mean to support the entire life of an aircraft. Starting from the conception, design and certification, Design Loads Measurement, DLM, through its operation, Operational Loads Measurement, OLM, till the very end of the design service life, including any potential life extension activity, as shown in Figure 2.14.

The chapters focus on the FLM science from different perspectives. First two chapters, chapter 1 and 2, set the context and describe the evolution of the FLM justifying the rationale behind the novelties proposed and the tools employed too. Following two chapters, 4 and 3, introduce the theoretical background before detailing the novelties and their software structure. Chapters 5 and 6 validate and assess the performance of the *Tools* and *Concepts* by using specific test cases *Data*. Last chapter, chapter 7 wraps up the whole study summarising strength and weaknesses and areas of future improvements.

Chapter 2: Once introduced in Chapter 1 the object and objectives of the thesis, this section shows the research niche by introducing a structured approach to review, through the past decades, the Flight Loads Measurement science.

To better capture the areas of improvement and the current status of the art of this science a "Three-Dimensional Complexity Space" is introduced and will be used to classify the flight loads measurement examples.

The identified key drivers will be used as starting point of the next chapters topics.

Chapter 3: The concept of a unique environment, hosting all the strain gauge selection techniques introduced in the next chapter, is presented. The environment is represented by a Python software package. Major characteristics of each coded techniques have been described by showing the *control flow graph*, the major inputs and outputs, description of functions and relevant scripts, all gathered in the Appendix B.

The framework breakdown highlighted the important role of different type of *Data*, and their possible combination.

1.5. OVERVIEW OF THE THESIS

Chapter 4: The theory behind the strain gauge selection process, responsible alongside other parameters of the accuracy of the final loads measured, is described. All the past techniques have been reviewed and their logic flow broken down identifying transfer functions, supporting tools, search engines and different ranking criteria employed.

In such scenario, the new technique has been introduced highlighting the major differences from the past by using the same terminology adopted for the past strain gauge selection methods.

Chapter 5: A three-level assessment process has been shown. The validation phase, *Level 1*, is the core of this section. Specific test cases from past NASA Langley Research Center publications, [102], [90] and [26] have been used as reliable data to assess those codes considered the pillars of the whole framework and new technique of chapter 4. The results have been presented and discussed.

Chapter 6: The performance phase, *Level 2 Comparison* and *Level 3 Assessment*, is the topic of this section. The novelties of the research have been tested by using dedicated test cases, CIRA USV1, [87], and NASA ARWg-2, [28]. A step-by-step approach has been introduced to explain the logic flow behind the execution of specific *Run Cases*. Results, of the codes and of the codes comparisons, have been presented and discussed.

Chapter 7: Summary of the key findings of the work completed. A discussion of the objectives defined at the start of the thesis, section 1.4, will enable to point out the work achievements. Future work will be presented as bulleted list.

Chapter 2

The Flight Loads Measurement Science

2.1 Introduction

This chapter sets the context of the Strain Gauge Based Flight Loads Measurement, FLM, Systems as relevant part of the Structural Health Monitoring, SHM, of the Civil and Military Aerospace world. The Skopinsky strain gauge-based loads monitoring type, considered during the process of development of a new aircraft, DLM, and also through its own operational life, OLM, is described into its main phases. The evolution of the Flight Loads Measurement Science has been interpreted by means of the three axes of complexity concept. In fact, the major drivers of the literature in this field have been pointed out and discussed in a three dimensional space defined by the complexity of the instrumented loads component, analysis and loads typology. This approach allows to assess the current state of the art of this subject and the expected areas of improvements.

2.2 Structural Health and Usage Monitoring

The SHM process consists of permanent, continuous, periodic or periodically continuous recording of parameters that, in the best manner, reflect the performance of the structure at different stage of the life of the object under monitoring. Depending on the type of the structure, its condition and particular requirements related to a monitoring project, SHM can be performed in the short term (typically up to few days), mid-term (few days to few weeks), long term (few months to few years) or during the whole lifespan of the structure.

The representative parameters selected to be monitored depend on several factors, such as the type and the purpose of a structure, expected load, construction material, environmental conditions and expected degradation phenomena. In general, they can be mechanical, physical or chemical. The most frequently monitored parameters are presented in Figure 2.1.

Mechanical	Strain, deformation, displacement, cracks opening, stress, load, acceleration
Physical	Temperature, humidity, pore pressure
Chemical	Chloride penetration, sulfate penetration, pH, carbonation penetration, rebar oxidation, steel oxidation, timber decay

Figure 2.1: The Parameters most frequently monitored, [34].

This research focuses mainly on monitoring mechanical parameters such as strain and loads. In particular, loads are an indirect result of strain readings. The detail of this specific technique, applied on aircraft components, will be further enlightened in the next sections of this chapter.

The core activities of the structural monitoring process are: selection of monitoring strategy, installation of monitoring system, maintenance of monitoring system, data management and closing activities in the case of interruption of monitoring. Each of these activities can be split into sub-activities as described in Figure 2.2.

Monitoring strategy	Installation of monitoring system	Maintenance of monitoring system	Data management	Closing activities
<ul style="list-style-type: none"> Monitoring aim 	<ul style="list-style-type: none"> Installation of sensors 	<ul style="list-style-type: none"> Providing for electrical supply 	<ul style="list-style-type: none"> Execution of measurements (reading of sensors) 	<ul style="list-style-type: none"> Interruption of monitoring
<ul style="list-style-type: none"> Selection of monitored parameters 	<ul style="list-style-type: none"> Installation of accessories (connection boxes, extension cables, etc.) 	<ul style="list-style-type: none"> Providing for communication lines (wired or wireless) 	<ul style="list-style-type: none"> Storage of data (local or remote) 	<ul style="list-style-type: none"> Dismantling of monitoring system
<ul style="list-style-type: none"> Selection of monitoring systems 	<ul style="list-style-type: none"> Installation of reading units 	<ul style="list-style-type: none"> Implementation of maintenance plans for different devices 	<ul style="list-style-type: none"> Providing for access to data 	<ul style="list-style-type: none"> Storage of monitoring components
<ul style="list-style-type: none"> Design of sensor network Schedule of monitoring Data exploitation plan Costs 	<ul style="list-style-type: none"> Installation of software Interfacing with users 	<ul style="list-style-type: none"> Repairs and replacements 	<ul style="list-style-type: none"> Visualization Export of data Interpretation Data analysis The use of data 	

Figure 2.2: Breakdown structure of the core monitoring activities, [34].

Monitoring consists of two aspects: measurement of the magnitude of the monitored parameter and recording the time and value of the measurement. In order to perform a measurement and to register it, one can use different types of apparatus. The set of all the devices destined to carry out a measurement and to register it is called a monitoring system.

The concepts just introduced will be the foundation of the integrity of aircraft structure, paramount to assuring the continuous flourish of aviation inside the technical airworthiness.

2.2.1 Aircraft Fatigue Monitoring Systems

All engineering structures, particularly aircraft, are subject to in service degradation which will limit their future life, and gradually reduce capability to withstand limit load without failure. The processes causing degradation in strength are fatigue, corrosion, wear and random mechanical damage. All of these apart from fatigue are relatively benign in the sense that they have to progress for a considerable time before there is a significant reduction in residual strength. But, when combined with fatigue loading environments, corrosion, mechanical damage and wear can accelerate the nucleation of fatigue cracks which will then rapidly cause failure of the structure[92]. In particular, cycling loads in conjunction with high temperatures results in creep-fatigue, with chemically aggressive environment causes corrosion (pitting, galvanic, intergranular and exfoliation) and with sliding and rolling contact lead to sliding and rolling contact fatigue, respectively. Fretting fatigue is another form of failure due to cyclic stresses and oscillatory frictional motion between components.

So, one of the most relevant activity meant to be encouraged is to reliably identify the initial crack defined, further include fracture mechanics with regard to short and long cracks as well as their phenomena of propagation under static and cyclic loading. A simulation environment for estimating the probability of fracture (PROF), [105], of which a schematic environment is shown in Figure 2.3, relates loads, crack detection (size, propagation, geometry), quality of repair, inspection intervals, probability of damage (POD), and fracture toughness. All these variables are coupled to establish the overall probability of fracture.

Health monitoring of the structure therefore should consist of monitoring of the

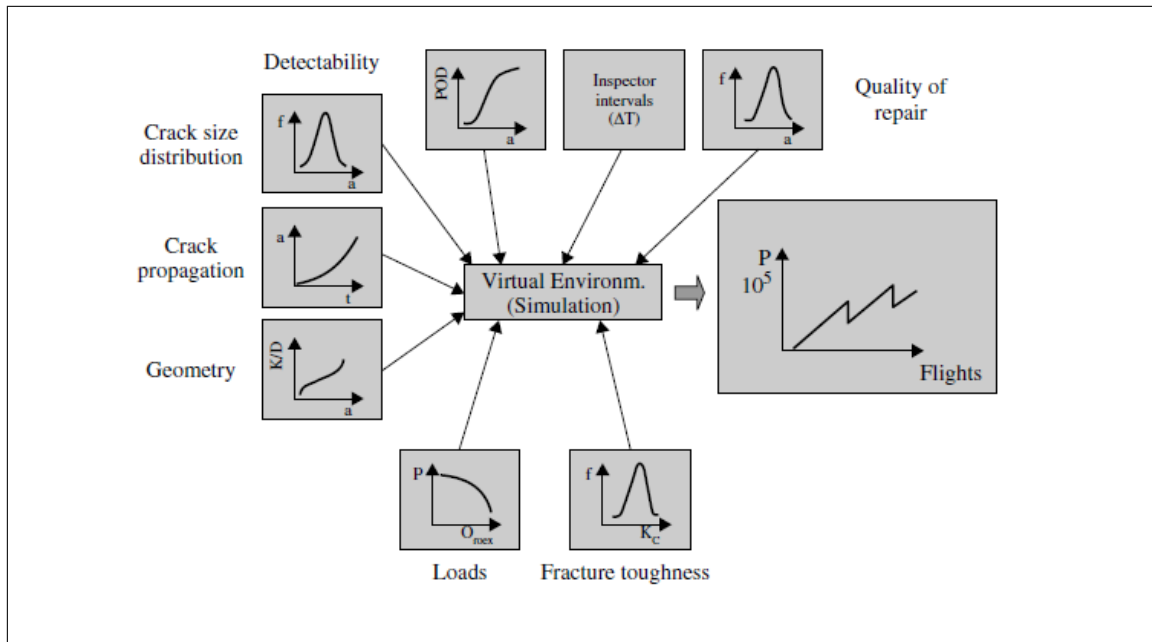


Figure 2.3: Probability of fracture: Schematic diagram of a PROF code, [105].

progress of all failure processes. Mainly, for prognostic capability, it is required the monitoring of the drivers of the failure process, coupled with application of

predictive models that must take into account the following pivotal tasks:

- Design Concepts.
- Load Spectra.
- Fatigue Testing.
- Inspection/Monitoring effort.

In fact, aircraft design procedures have significantly contributed to two major engineering design concepts: the safe-life and damage tolerant design. Both concepts require the cyclic load spectra as an input. Generating the representative spectra loads needs a substantial amount of information, which in the case of an aircraft is related to: flight envelope including runways to be used, loads to be carried, aerodynamics, past experience, statistics and any sort of specific information to be provided by the operator. It is the load spectra used to perform service fatigue life of many critical structural components. As showed by Figure 2.4, fatigue testing includes material or coupon tests, element, subcomponent and component tests and finally full-scale structural tests ending up with Major Airframe Fatigue Testing (MAFT) where the full-scale structure is tested on the ground.

The safe-life concept assumes that all components have no margin for a fatigue

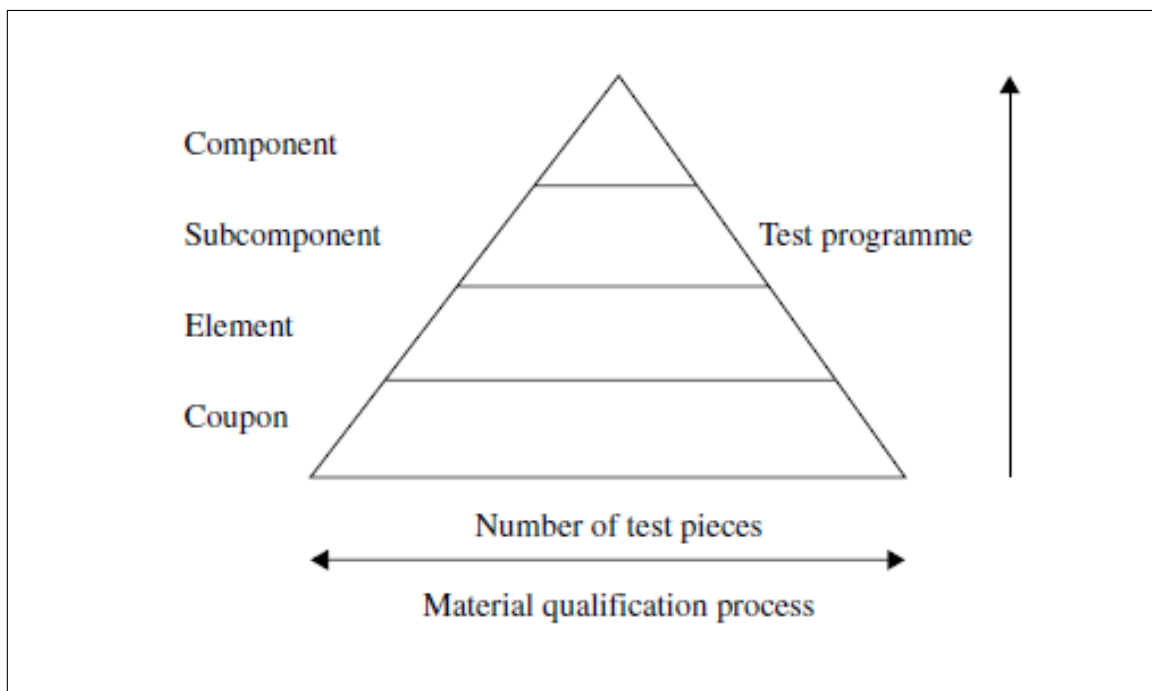


Figure 2.4: Structural Aircraft Fatigue Testings, [105].

failure over a defined fatigue life, usually nominated in flight hours or flight cycles respectively. This safe life is therefore estimated on the basis of experimental results combined with imposed safety factors, which cover any type of uncertainties, such as resulting from scatter in loads, material condition, notch factors, surface

conditions and much more. The lack of knowledge in structural and thus material damaging behaviour has led safe life designed components to be of higher weight. Further information on a material's and thus structure's damaging behaviour can therefore help to make the structure lighter weight designed. This situation has been provided by introducing the damage-tolerant design, which can be achieved by either including redundancy, multiple load path (fail-safe), or by taking advantage of fracture mechanics (slow crack growth). In the case of slow crack growth, crack propagation size and endurance is estimated on the basis of the load sequence assumed and fracture mechanics models as well as crack propagation data. This however assumes additionally that: (a) a location of potential damage is known; (b) damage initiation of a defined length can be reliably detected; and (c) damage propagation until the point of the allowable damage can be tolerated. Thus the damage-tolerant design concept requires by its nature an inspection effort. A big challenge in that context is therefore to use reliable damage detection techniques, which can not only fulfil the above requirements but also reduce related maintenance effort and cost [105]. However, nowadays the Aircraft Structural Integrity (ASI) worldwide air force management incorporates a combination of safe-life and damage tolerance philosophies as described by Figure 2.5, [12].

The final consideration is that irrespective of the design principle, safe-life or

Aircraft	Operator	Safe-life design limit	Damage Tolerance	Year
A-3	United States Navy (USN)	18,000 hrs		'88 [4]
A-7	Portuguese AF		✓	'91 [5]
Alphajet	French AF		✓	'97 [6]
Eurofighter 2000	Partner nations	✓		'97 [7]
F-14	USN	✓		'96 [8]
F-15	United States Air Force (USAF)		✓	'84 [9]
F-16	USAF, Royal Netherlands AF		✓	'96 [10]
F/A-18	USN	6,000 hrs		'97 [11]
F/A-18	RAAF, Canadian Forces, ...	✓		'98 [12]
F-111	RAAF		✓	'96 [13]
Hawk T.Mk.1	RAF, RAAF	6,000 hrs		'93 [14]
Kfir	Israel AF		✓	'88 [15]
MB339 CB	Royal New Zealand AF	✓		'95 [16]
Mirage 2000	French AF		✓	'95 [17]
JAS-37 Viggen	Swedish AF		✓	'93 [18]
JAS-39 Gripen	Swedish AF		✓	'93 [18]
Tornado	German AF & Navy	4,000 hrs		'91 [19]

Figure 2.5: Design philosophies used for fatigue management in use today, [12].

damage-tolerant, the role of inspection dedicated programmes is pivotal alongside embedded damage monitoring systems [10] to monitor any sort of accidental damage and thus overloading.

2.3 Flight Loads Monitoring Systems in Aircraft

Damage monitoring through a system inherent in an aircraft can be principally done in two ways. The former is to integrate systems onto or into the structural component, which mainly works on actuator-sensor basis but can also be reduced to a sensor basis only in the case of acoustic emission. The latter already applied today, which is to monitor loads or better load sequences, which are then used to estimate the accumulated fatigue damage indirectly by means of analytical procedures. This is what commonly also known as Operational Loads Measurement (OLM). The loads monitoring activity, OLM, may be performed by:

- Flight Parameters-Based Loads Monitoring.
- Conventional Strain Gauge-Based Loads Monitoring.
- Skopinski-Type Strain Gauge-Based Loads Monitoring or labelled by a recognised practitioner of the field, Dorothy Holford, Operational Loads Measurement, OLM, Programmes, [10] .

In fact, loads can be monitored through the parameters describing them. This may be either given globally by sensing accelerations or masses or any parameters again influencing accelerations or masses such as flap positions, speed, height, fuel flow or any other. It is what is also considered in the context of aircraft to be a flight parameters-based loads monitoring system. Furthermore, the existing sensors in the aircraft have already proven airworthiness and thus widely accepted. However, the Usage Monitoring systems based on flight-parameters are still very costly and their exactness does often not provide the precision required for analytical fatigue life evaluation, because loads need to be analytically and indirectly determined from the sensor information provided. Further reasons include a coarse differentiation between the different exceedance levels which do not allow differing between different loads in between, the differentiation between and superposition of different loading cases, the lack of transferring loads from the global to the local view or the missing information on the sequence of the loads applied. Statistically only 1% of the flight data recorded is used for monitoring. Figure 1.2 and Figure 2.6 give an overview of the philosophy of the OLM system developed for civil, Airbus A320(Ladda and Meyer 1991), and the military, Panavia TORNADO (Bauer 1987; Krauss 1988), aircraft, respectively [105].

Both systems are designed to perform on-board processing of special events (e.g. hard landing, exceedance) and flight parameter data.

The other OLM approach is more of a global nature through monitoring of strain sequence at discrete locations and then converting this to a more global load sequence of the structure considered. That approach merged with the Skopinski-type, [111], calibration methods enable to know the internal loads, Shear, Bending Moment and Torsion span and chordwise of the component under investigation. The strain gauge-based loads monitoring can be employed at different stages of the life of an aircraft, taking different names such as Design and Operational Loads Measurement accordingly.

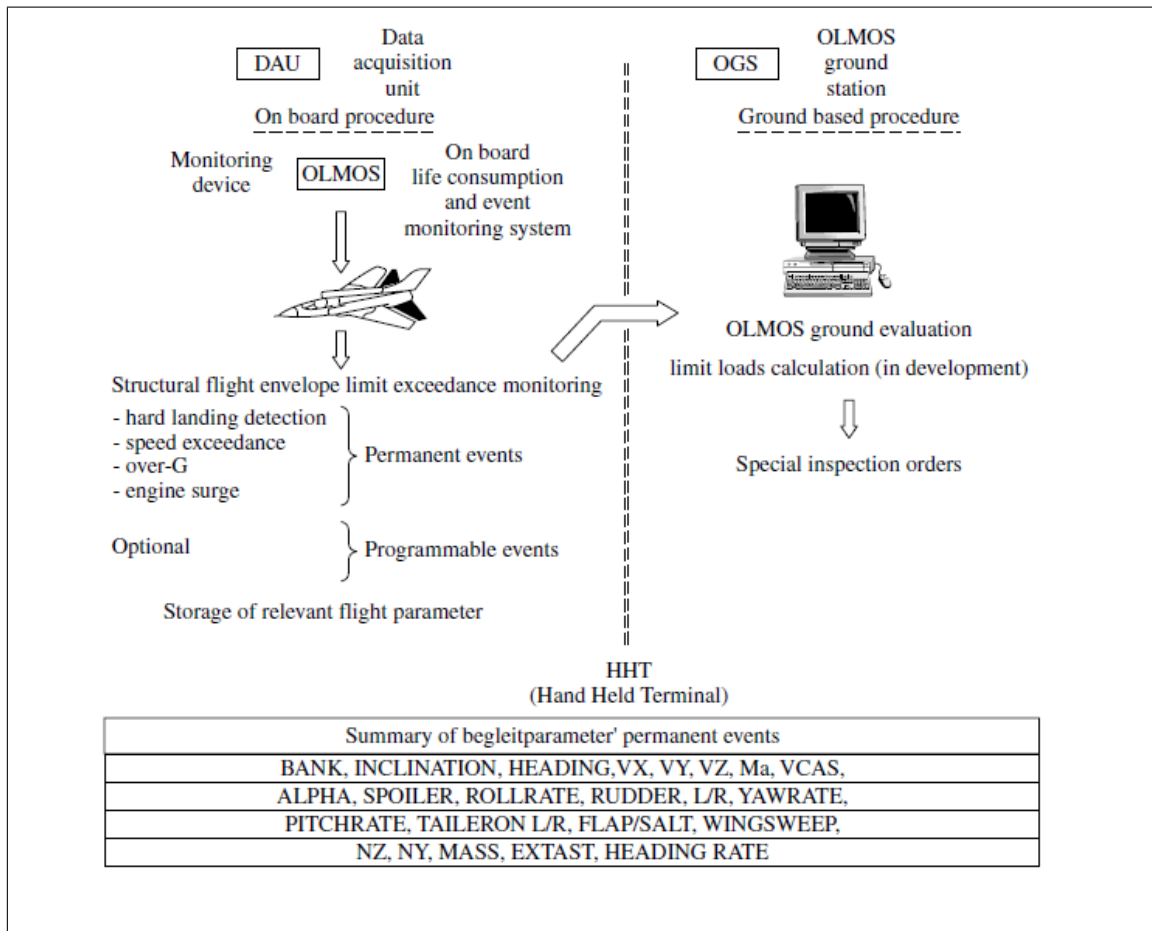


Figure 2.6: On-board life monitoring system (OLMOS) using flight parameters for the TOORNADO Panavia military aircraft, [105].

2.3.1 Flight Parameters-Based Loads Monitoring

The parameter based monitoring, alternative philosophy to the strain gauge method, is the use of flight parameters to estimate the dominant load affecting each critical component, and the subsequent use of transfer functions to relate this to stresses at critical locations. This approach offers the following advantages:

- as there are no strain gauges, the logistical burden of replacing unserviceable gauges is not an issue. The RAAF, with F/A-18 fleet, [12], and the RAF, with Harrier II fleet, [95], have experienced significant numbers of gauge changes due to sensors drift and unexpected non linearity affecting the overall data interpretation. The time lag between when a sensor becomes unserviceable and when remedial action is taken, contributes to reductions in the over-all data recovery rates.
- there is no requirement to calibrate sensors or loads on the fleet aircraft, as the calculated load is normally derived from a calibrated flight test aircraft which demonstrates the "baseline" response for fleet analysis.

However, comprehensive flights trials are required to obtain sufficient loads data to cover all aircraft operations PITS if the aircraft is monitored solely on parameters.

Analyses conducted using multiple parametric equations and Velocity-Normal Acceleration (G) - Height and VGH techniques, produced conservative results within 5% and 1% for these respectively when compared to the results based on (WRBM induced) strain for one particular usage spectrum.

However, the strain based system justifies its existence over parameter based systems as the strain can be related directly to strain measurements on the fatigue test article against which the fleet monitoring is being calibrated. Furthermore, the introduction of OLM programmes, though technically complex, costly and often lasting long, bring a clear snapshot of the load distribution and magnitude of the instrumented components in those requested PITS.

2.4 Strain Gauge Based Loads Monitoring

The partially unsatisfactory precision of loads determined through the flight parameters has justified the development of loads measurement systems based on strain gauges bonded at discrete well selected locations of the aircraft structure.

Military design requirements mandate the incorporation of fatigue monitoring data recorders, however the specifications allow much scope in the implementation of the system and interpretation of the data. Therefore, there exist numerous and varied philosophies for the usage monitoring of aircraft worldwide. As it has been the convention from the past, military aircraft will continue to be procured with incorporated in-service (or fatigue) usage monitoring systems. In fact, this requirement is mandated by the appropriate design regulations such as:

- Def Stan 00-970: "...each aeroplane should be fitted with a compact, robust and reliable recording instrument which monitors the usage of the major structural components. This may record an indirect parameter such as normal acceleration, or a direct parameter such as strain for each component to be monitored. Each parameter should be chosen so that the most damaging loading actions on the component can be determined."
- MIL-A-87221: "...An airborne data acquisition system is required that collects and stores flight data which can be used to determine maintenance and inspection intervals.....The data acquisition system shall be capable of recording operational usage data and shall be compatible with the airframe and all air vehicle systems when installed and used. The system shall interface with the air vehicle systems and record the required data within required accuracies."

Both these typical military requirements specify the need for a data recording system, albeit with differing emphasis, but they allow much scope for the implementation of the systems and interpretation of the data.

At the same time, the civil aviation authorities mainly for their acrobatic category started implementing the gap of their design requirements by means of specific rules, Certification Review Items (CRI). In fact, international civil requirements of CS-23 (for instance European, [22] amendment 3), General Aviation aeroplanes,

such as §23.571, §23.572 and §23.573 are neither clear in terms of fatigue monitoring. Therefore, considering the intended use of the aircraft as a military training certified according to Civil Standards, the Pilatus PC-21 is a significant example [60], the Fatigue Design Spectrum, the Fatigue Analysis, the FSFT and the Fatigue Monitoring System are all complied by an hybrid certification basis military and civil as the end-user is going to be a military air force operator.

2.4.1 Conventional Strain Gauge Based Load Monitoring

The conventional strain based in-flight data recorders, perceived to provide an increase in accuracy over the conventional fatigue g-meter (normal acceleration), utilise strain sensors in conjunctions with multiple flight parameters, allow to monitor the usage of a sample of fleet aircraft or to each aircraft in the fleet, dependent upon fleet size and operator requirements.

The resulting systems required for accurate fatigue damage interpretation are complex, mainly in relation to the gauge placement [75]. Before deciding on the locations of strain gauges, the philosophy to be used to meaningfully relate the strain recordings to fatigue accumulation must be established. The choice of gauge locations is determined from the following considerations:

- **Loads Monitoring.** The placement of the strain gauges can account for aircraft weight and stores effects, and the variation of principal loads, such as Wing Root Bending Moment, WRBM, at various Point In The Sky, PITS, constituting the flight envelope. Thus the location of the strain gauge must be such that its response is predominantly influenced by the principal loading inducing the fatigue damage at the critical locations considered. An example of such philosophy is the F/A-18, [75]. That means the location of the sensor can be calibrated to the damage inducing load, is dominated by the principal load (e.g. WRBM) and insensitive to other loading actions and can be directly related to the stress at critical structural locations.
- **Hot Spot Monitoring.** The alternative philosophy is intended to place strain gauges such that they directly monitor the strain at the critical location. An example of such philosophy is the Royal Australian Air Force, RAAF, F-111. This approach means the sensor may not be dominated by the principal damage inducing load complicating the calibration of the sensor response. If a new hot spot arises, and the gauge does not respond predominantly to the load affecting this new location, then there will be no data available for assessment. Even if the option of placing an additional gauge exists, the problem of "filling-in" for past damage still exists. Moreover, the hot spot may not be readily accessible and thus the sensors are not readily replaceable.

For these reasons the strain based approach as the major fatigue tracking system complimented by parametric flight data measurements to aid in data verification are drastically driven and limited by the strain locations, this is where the Skopinski type loads measurement, though more cost and time demanding, is more flexible.

2.4.2 Skopinski Type Strain Gauge Based Load Monitoring

Aircraft Operational Loads Measurement (OLM) programmes are now firmly mandated in MoD policy (JSP553 and JAP100A-01) and there is general acceptance within the civil and military aviation community that these programmes need to be undertaken. Nevertheless, the potential risks of failing to understand military aircraft usage should not be underestimated. This position is reinforced by the example of the Tornado IDS aircraft where analysis of OLM data identified that the fatigue meter formula was underestimating fatigue damage by a factor of around 3. UK OLM programmes (Holford and Sturgeon 1984, [95]) began in the mid 1970s but progress was initially slow until the fatal loss of a Buccaneer aircraft during a "Red Flag" exercise in 1983. The aircraft had been designed and tested for maritime operations as a naval aircraft. However, it had been operated by the RAF in a terrain-hugging overland role and a failure unpredicted by the fatigue test had occurred. In the aftermath of the subsequent investigation the UK MoD was heavily criticised for failing to exploit available technology in fatigue monitoring systems (Davies 1991). Thereafter, OLM programmes proceeded apace and are now part of the UK Ministry of Defence structural integrity policy for all aircraft, [95].

The objective of these OLM programmes was to validate the fatigue substantiation process in the light of service usage. These programmes aimed to quantify the structural fatigue loading through direct load measurement using electrical resistance strain gauge installations on all major components. In addition, the causes of high fatigue damage rates were identified and the effectiveness of monitoring procedures were assessed.

These smart and thorough Fatigue Monitoring Systems, labelled as OLM programmes, are based on a statistical technique, reported in the NACA report 1178, [111], developed by Skopinski in 1953, for the interpretation of measured flight strains as structural loads. Properly installed and calibrated, such gauges may be used to determine the structural loads on control surfaces, landing gear structures, and relatively complex built-up wing and empennage assemblies. The measured structural loads can, in turn, be converted to aerodynamic loads provided the structural weight distribution is known and the acceleration distribution has been measured.

The use of calibrated strain gauges for flight load determination is a relevant tool not just for the measurement of operational loads but during the design and development of a new aircraft civil aviation authorities requested flight loads survey whose major aim is the measurement of the design loads for direct comparison with those numerically evaluated. The employment of the Skopinski technique as part of this design and certification process is labelled Design Loads Measurement, DLM, campaign.

Next paragraph will focus on the common phases characterising the Skopinski Loads Measurement programme and will highlight major differences and expectations between DLM and OLM campaign.

2.4.3 Existing Strain Gage-Based Load Monitoring

Local stresses, the more relevant inputs for fatigue life assessment, can either be measured directly (by local strain recording) or be derived from flight parameters. The partially unsatisfactory precision of loads determined through the flight parameters has led some aircraft manufacturers to using a loads monitoring system based on conventional strain gauges bonded at discrete well selected locations of the aircraft structure as showed by the British Aerospace Hawk, Figure 2.9 and 2.10 , and the Pilatus PC-21, Figure 2.7, aircraft.

The Pilatus PC-21 instrumentation is part of a fatigue life appraisal by monitoring equipment whose final aim is the calculation of the so-called Fatigue Indices. This specific example shows how the Original Equipment Manufacturer, OEM, is presenting as part of the final certified package a fatigue monitoring system whose usage the future operators will benefit mostly comparing the life consumption against the design life. This allows any operators to have a real monitoring of the fatigue life experienced by the aircraft inside real operational environment that can be more severe than the one used through the design and certification phase.

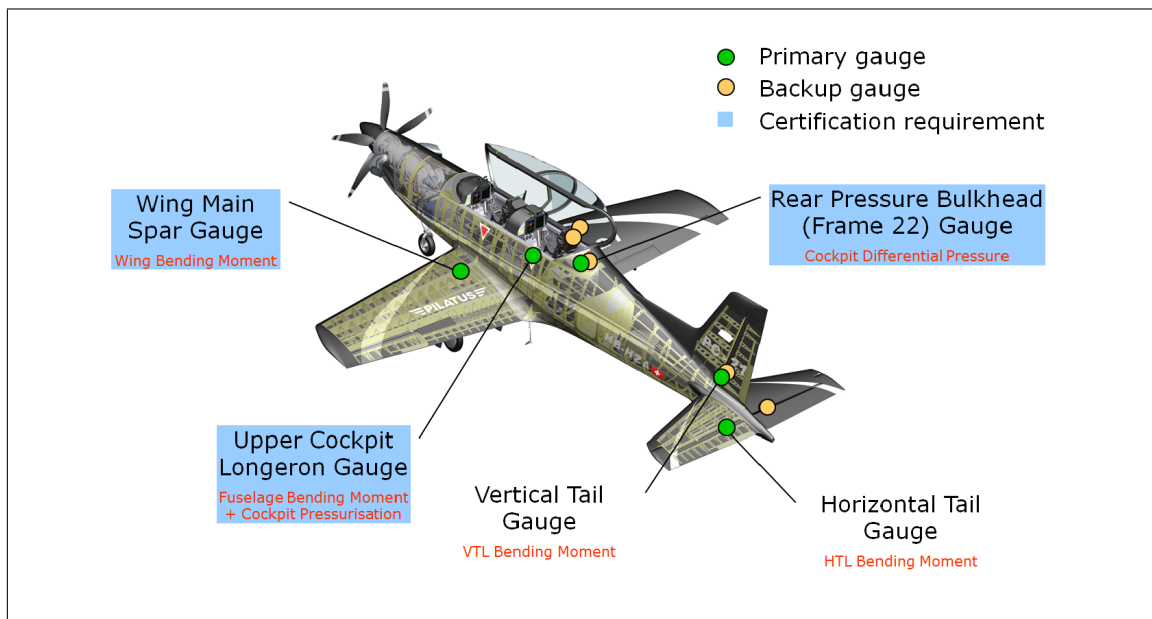


Figure 2.7: PC-21 HUMS, [60].

Strain sequences are monitored for the different strain gauges, stored on-board the aircraft in a data acquisition unit (DAU) and downloaded within specified intervals. Figure 2.8 describes a step by step process of a Pilatus PC-21 trainer aircraft Fatigue Monitoring System (FMS)[60]. The FMS is implemented in a so-called Health and Usage Monitoring System (HUMS). The HUMS consists of an onboard Data Acquisition and Storage Unit (DASU), a laptop computer called Line Test Equipment, and a centralised HUMS Data Analysis System (HDAS), which provides extensive offline data analysis capabilities and network access to the data. The PC-21 fatigue life appraisal process uses measured strain data of principal structural elements of Figure 2.7 to calculate so-called Fatigue Indices, which

Strain Gauge Based Loads Monitoring

express the flight-by-flight severity of the actual usage versus design usage. These locations have been judiciously selected such that their response are predominantly influenced by the principal loading inducing the fatigue damage at the critical locations considered.

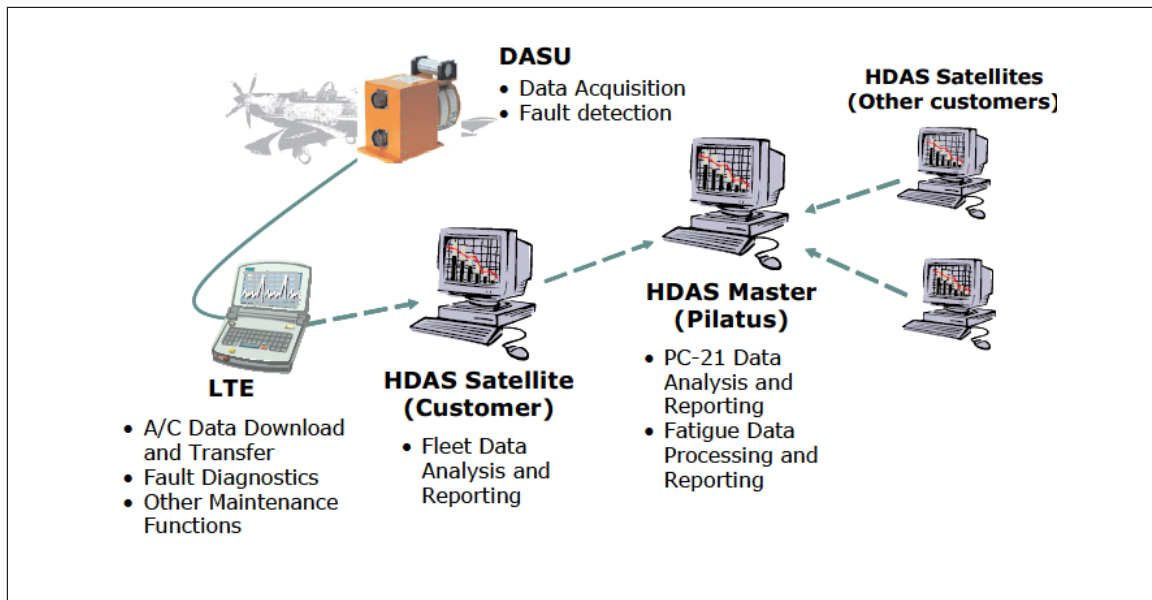


Figure 2.8: Pilatus PC-21 trainer aircraft Health and Usage Monitoring System (HUMS) [60]

On the other hand, the Hawk aircraft represents a more thorough fatigue life monitoring conceived and defined by the operator, instead of the OEM, according to the MoD rules. The aircraft was originally designed for a 6000 hour fatigue life under a Flight Training School load spectrum, [84]. The design was largely substantiated by the Hawk Full Scale Fatigue Test, operated by BAe Kingston between 1979 and 1985, and was subject to a spectrum that was principally based on the RAF's utilisation of the aircraft in its original role as a basic fast jet trainer.

It came evident from the original Hawk OLM programme that the FSFT tailplane and rear fuselage loading was inadequate to provide sufficient structural clearance for the aircraft operated in a tactical weapons role. A phase of dedicated tailplane loading, based on OLM information, was therefore applied to the FSFT. At the time the fuselage was lifed only in flying hours and the OLM had also identified that aircraft operated in the Tactical Weapons Unit, TWU, were accruing fatigue damage at a greater rate than in the fatigue test and in other sensitive locations.

As a result of the additional FSFT tailplane loads increase the FSFT fuselage damage rate rose too. So, the introduction of a TWU role, the Red Arrows, placed significantly differing demands on the airframe and hence affecting the rate of fatigue damage accrual, justified a further investigation of the load mechanisms which are not present during normal in-service usage, such as use of the airbrake as a flying control during the display and close formation flying, Figure 2.11. The tailplane, fin and rear fuselage are subject to additional loading due to the rear flying in this state as a cue for maintaining formation position. Prior to this OLM the structural consequences of this type of flying had not been quantified for the

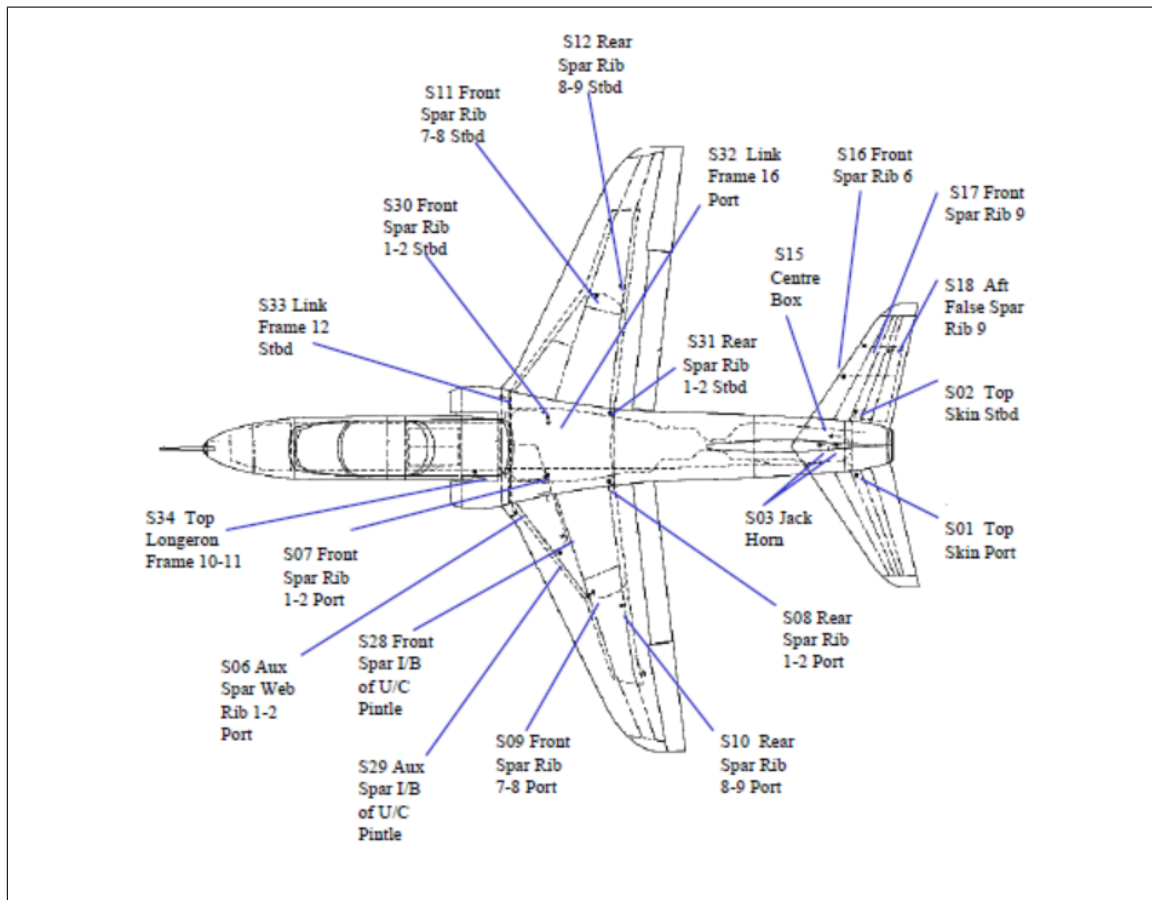


Figure 2.9: Royal Air Force Aerobatic Team Strain Gauge Loads Monitoring Instrumentation, Top View [33].

Hawk Red Arrows fleet aircraft.

The Hawk Red Arrows OLM was based on 36 strain gauges, Figure 2.9 and 2.10, 14 of which duplicated the positions used in the original OLM programme with minor changes to account for a modified wing. The empennage strain gauges were recorded at 2048 sample per second on each channel in order to account for the high frequency vibration that was identified during a dedicated dynamic response flight trial programme in 1988. All other strain gauges were recorded at 256 sample per second per channel. Additionally, 19 flight parameters were recorded to enable aircraft accelerations and control surfaces to be monitored, and to identify aircraft manoeuvres and flight conditions at which significant events occur. The recording system comprised an Aydin Vector Data Acquisition Unit, DAU, for converting the analogue strain gauge and aircraft parameter signals to digital which were transmitted to the on-board NAC video recorder via a Heim PCM encoder.

A total of 194 Red Arrows flights were recorded, following a representative distribution with respect to Sortie Profile Code, SPC, and formation position. The data were processed through cycle counting and fatigue analyses using the "mean S-N" curve approach and the "safe S-N curve method" also, as being the recommended methodology of British Defence Standard 00-970. The analysis of the data was reviewed by component with respect to the corresponding fatigue meter and

Strain Gauge Based Loads Monitoring

furthermore by considering the impact of both sortie type and formation position. The OLM programme demonstrated the adequacy of the wing and fuselage fatigue meter formulae, but highlighted shortcomings of the existing fin fatigue formula which have now been addressed. Significant rear fuselage and tailplane damage rates, particularly for the rear formation aircraft, prompted the proposal for an active Fatigue Monitoring System. The whole campaign pointed out the importance of Red Arrows fleet fatigue management to ensure even lifing across the fleet and this is best achieved through regular aircraft rotation about the formation.

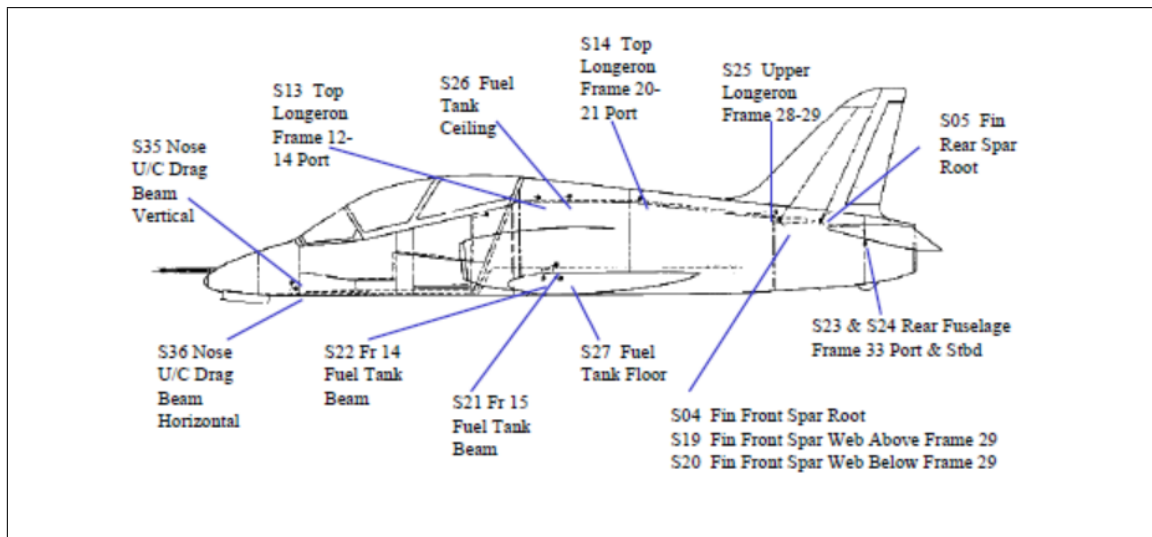


Figure 2.10: Royal Air Force Aerobatic Team Strain Gauge Loads Monitoring Instrumentation, Side View, [33].

Furthermore, Royal Australian Air Force (RAAF) also employed a system which utilised seven strain sensors and multiple flight parameters to monitor the usage of their F/A-18 fleet, Figure 2.11. In common with other F/A-18 operators, RAAF principal tool utilised for managing the life of this multi-role fighter jet, is a system developed by the aircraft's manufacturer, McDonnell Douglas Aerospace (MDA), known as the Maintenance Signal Data Recording System (MSDRS). The MSDRS, performing other functions including engine health monitoring, has been enhanced by Australian Defence Science and Technology Organisation (DSTO) through the development of an alternative method based on Normal Acceleration (Nz) or strain exceedances and simple Miner's Rule known as the Mission Severity Monitoring Program (MSMP). In addition to these two systems the RAAF's F/A-18 fleet is also equipped with a Range-Pair Count (RPC) recording system, manufactured by British Aerospace Australia, known as the Aircraft Fatigue Data Analysis System (AFDAS), which utilises an additional eleven strain sensors [62]. The fatigue life monitoring program implemented for the aircraft, compares the usage of an individual aircraft, possible representative of the fleet, to that of a representative fatigue test article. The test spectrum should be similar to that of operational aircraft spectra. As the aircraft was designed and certified to a safe-life philosophy, when the damage accumulated on a particular aircraft matches that calculated to have been imparted to the test article at the completion of Major Airframe Fatigue Testing, with appropriate scatter factors applied, the aircraft is said to have



Figure 2.11: Royal Air Force Aerobatic Team, The Syncro Pair (Reds 6 and 7) in Close Formation, [33].

consumed its safe life.

Interpretation of the results of MAFT must be supported by a specific Operational Loads Measurement (OLM) campaign, preferably continuous, or repeated every few years capable to point out any differences between actual, in-service structural loads, and the design theoretical spectrum needed to be employed in the MAFT. Thereby suitable corrections are meant to be made to the structural lives cleared by a second full-scale testing or by specific fatigue analysis according to the applicable certification standards [10].

2.5 The Use of Calibrated Strain Gauges for Flight Load Determination

No matters which flight loads measurement is employed, DLM or OLM, the major phases characterising the whole Flight Loads Measurement (FLM) campaign are the same and are listed below:

- Phase 1 Definition and Design, (D&D): It has to be identified the component and the type of loading to be measured. In order to start designing the correct instrumentation and calibration to be executed in the next phase it is worth iterating with the "Reference Loads" to better understand the loads path under investigation. According to the type of FLM, DLM or OLM, these can be either the Loads to be validated, Theoretical Loads, or the Loads to be correlated with, Certified Loads.

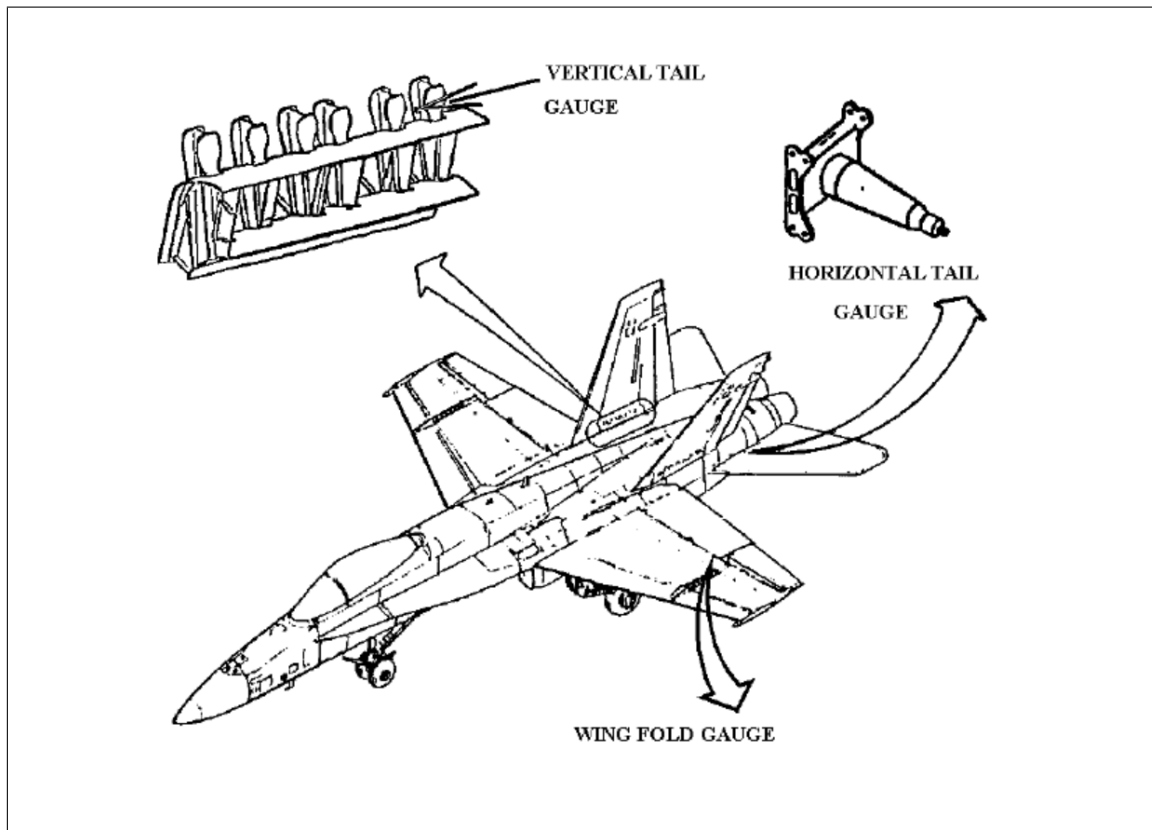


Figure 2.12: A sample of F/A-18 Strain Gauge Locations, [62].

- Phase 2 Ground Load Calibration, (GLC): It represents the one of the two experimental phases, in this case performed on ground, where the whole defined instrumented strain gauges placed along the major loads path, must be calibrated by previously selected magnitude and locations of load cases. The ground test article is the same employed during the flight test campaign for the final loads measurement.
- Phase 3 Data Gathering and Analysis (DG&A): The strain gauge data generated during the Phase 2, GLC, have to be reviewed in order to verify the reliability before being used for loads equations development. Dedicated algorithms, applied on the strain gauges, investigating poor linearity and correlation with loads are part of this phase. Final goal is to identify, with the current available techniques, the best set of "Loads Equations" to be applied to the flight load test strain gauge readings.
- Phase 4 Flight Test, (FT): Dedicated flight test points, Point in the Sky (PITS) are covered in order to measure strain gauge readings and relevant flight parameters.
- Phase 5 Data Gathering and Analysis (DG&A): Flight test data are reviewed, strain gauge and flight parameters, in order to assess their reliability before being coupled with the best set of loads coefficients identified in Phase 3 to produce the "Measured Loads". Before completing this Phase the Measured Loads are compared against the Reference Loads and if necessary the Loads Equations can be reviewed. This is an iteration step that will lead to con-

sider the Measured Loads reliable and so to freeze the selected set of Loads Equations.

A generic flight loads measurement campaign Skopinski type is described in Figure 2.13 linking the five phases described above.

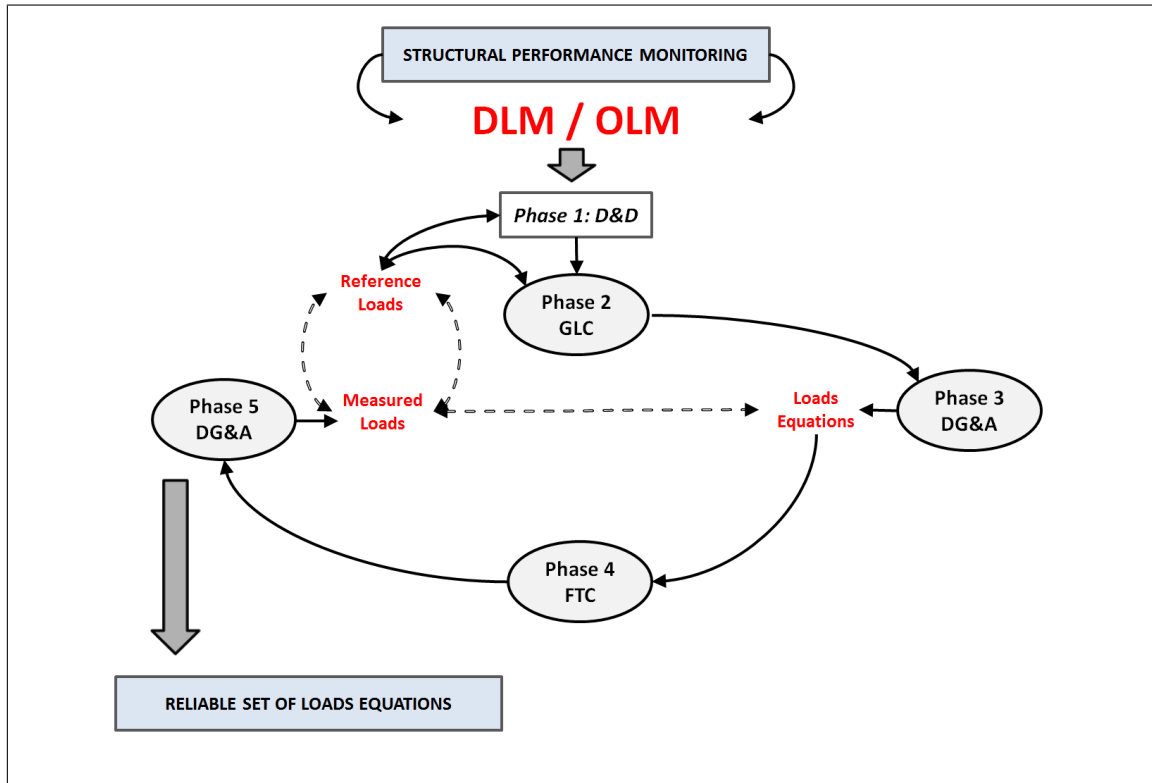


Figure 2.13: Flight Loads Measurement Skopinski type: Major Phases and Flow Process.

A generic flight loads measurement campaign Skopinski type is described in Figure 2.13 linking the five phases described above. In particular, it says that once identified the component and type of loading to measure, (D&D), that allow to design the instrumentation needed, there are two major experimental phases, Ground and Flight testing (GLC and FTC), that generate Data to be analysed, (DG&A's). Each DG&A phase completes all necessary steps to generate the Measured Loads to be compared with the Reference Loads before claiming to have reliable Load Equations. This process requires few iterations, described by the dotted lines of Figure 2.13.

It is worth highlighting that the Reference Loads represent the major difference existing between a DLM and OLM. In fact, the former requires to validate the Theoretical Loads. On the other hand, the latter expects to prove reliable the Measured Loads. This determines different judgements through the whole process. The current research will mainly focus on the Phases 2, Ground Load Calibration, and Phase 3, Data Gathering and Analysis, leading to the definition of the best set of loads equations. These phases will be merged in unique software package

labelled LOME.

A general understanding of the various types of airframe loads, their generation and application during the design process, the transfer processes from "external loads" into "structural loads", loads qualification during ground and flight testing is therefore of equal importance to the process of usage monitoring and derivation of usage factors from the different fatigue tests or the set-up of structural inspection programs. In fact, the flight loads measurement programme is a valuable tool recognised by Military, [83] and [104], and Civil Aviation Authorities, [23], [24] and [2], to be employed during the life of the aircraft, from the design and certification, through the operational and till the very end of the design service life, including any potential life extension. The life evolution of an aircraft combined with the different flight loads measurement programmes, DLM and OLM's, is captured in Figure 2.14.

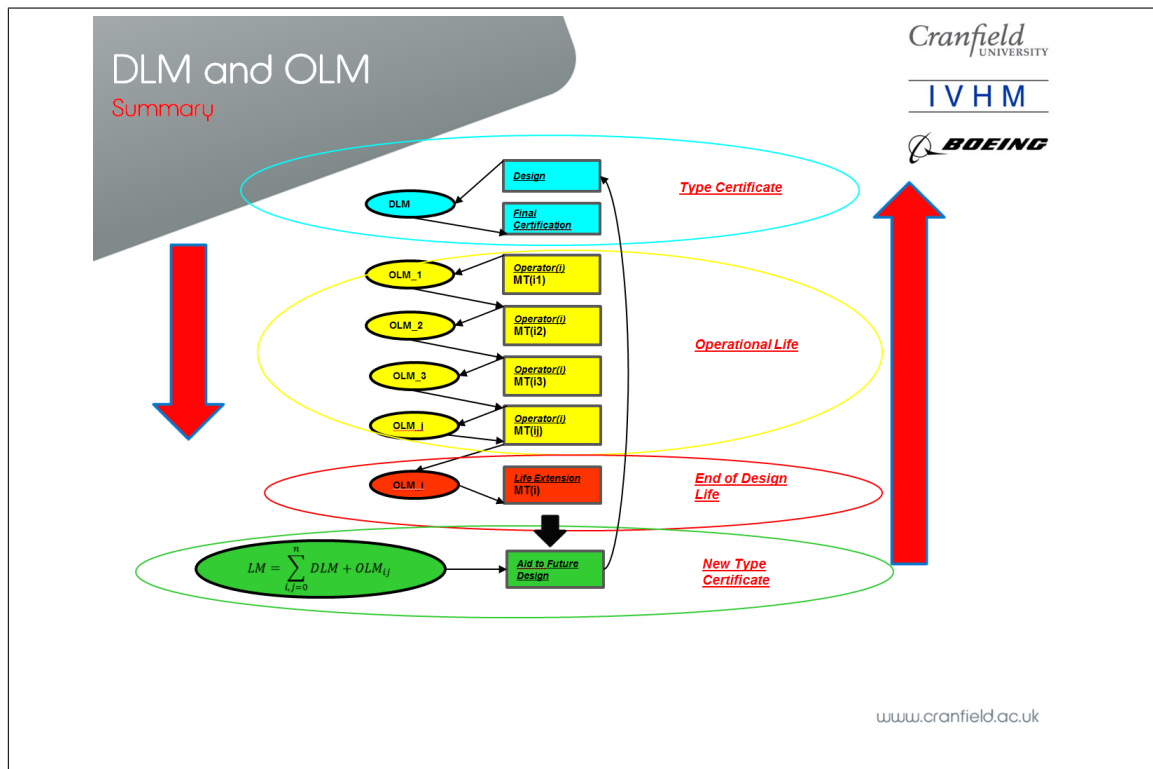


Figure 2.14: Aircraft Life Evolution: DLM and OLM's, [69].

2.5.1 Design Loads Measurement, DLM, Programmes

2.5.1.1 Certification Standards

Structural health and usage monitoring systems based on strain gage loads monitoring do not solve all service problems of aircraft operators and maintenance providers. According to civil standard regulations they are not expressively mandatory. In fact, European and US aviation requirements, the Certification Specifica-

tions (CS) and the Federal Aviation Regulations are mainly structured to focus on fatigue and continued airworthiness of aircraft structures. Nevertheless, the awareness of the high level of uncertainty coming out from a full certification process, also due to the loads environment, convinced the civil aviation authorities to mention in the certification specifications for large aeroplanes (CS and FAR 25) and also for normal, utility, acrobatic and commuter category airplanes (CS and FAR 23), paragraph 25.301(b), that the methods used to determine load intensities and distribution must be validated by flight load measurement unless the methods used for determining those loads conditions are shown to be reliable [23]. To stipulate a number of load conditions, such as flight loads, ground loads, pressurisation loads, inertia loads and engine/APU loads requires methods to be validated by flight load measurements unless proved their effectiveness. The Agency believes some measurements may complement, or sometimes even replace the results from theoretical methods and models. Some flight loads development methods such as those used to develop buffeting loads have very little theoretical foundation, or are methods based directly on flight loads measurements extrapolated to represent limit conditions, [24]. So, the need for and extent of the flight load measurements needs to be discussed and agreed between the Agency and the Applicant on a case by case basis, and the final assessment should be based on [25]:

- a comparison of the design features of the aeroplane under investigation with previously developed (by the Applicant) and approved airplanes. New or significantly different design features should be identified and assessed.
- the Applicant's previous experience in validating load intensities and distributions derived from analytical methods and/or wind tunnel tests. This experience should have been accumulated on previously developed (by the Applicant) and approved types and models of airplanes. The validation should have been by a Flight Load Measurement program that was conducted by the Applicant and found acceptable to the Agency for showing compliance.
- The sensitivity to parametric variation and continued applicability of the analytical methods and/or wind tunnel test data.
- New significant different design features.
- Local loads on elements where loads are typically unreliably predicted such as Loads on high lift devices, Hinge moments on control surfaces, Loads on the empennage due to buffeting and Loads on unusual device.

Basically, products requiring a new civil type certificate will in general require flight-test validation of flight loads methods unless the Applicant can demonstrate to the Agency that this is unnecessary. But in the same time it has been proved the control and measurement of the flight loads is also a precious tool capable to allow the investigation of the flight envelope during flight certification tests, avoiding to explore the most critical flight conditions blindly. The flight load measurements envisaged by the Agency are:

- strain gages

- pressure belts.
- accelerometers.

Here, for Civil Airplanes, the Agency mention clearly the opportunity to rely on Strain Gage-Based Loads Monitoring Skopinski-type where, on the other hand, on the Military side nowadays is a mainstay input data for monitoring the fatigue of worldwide fleet air forces. In particular, the Operational Loads Measurement (OLM), tool capable to gather all the activities mentioned before, is mandatory for Military Airworthiness Regulations (JSP 553, Defence Standard 00-970 and Joint Airworthiness Publication 100A-01) [95].

Distinctively in UK, OLM programmes, Holford and Sturgeon [95], began in the mid 1970's but progress was initially slow until the fatal loss of a Bucacaneer aircraft during a "Red Flag" exercise in 1983. Nowadays, the RAF's aircraft fleet enter in service with a quantified fatigue life, underwritten by the manufacturers through a formal structural qualification programme. The qualification, however, together with its acceptance by the MOD, are both conditional upon the aircraft being carefully monitored in service for fatigue consumption. So, each design should be subjected to 2 Main Airframe Fatigue Tests (MAFTs):

- Development Airframe Fatigue Standard Tests (DMAFT)
- Production Airframe Fatigue Standard Tests (PMAFT)

The former, would be subjected to a design loads spectrum, and would identify those areas for which major design shortcomings would lead to early in-service problems. The latter, would be expected to be subjected to a refined spectrum, taking into consideration recorded in-flight data, [10]. Interpretation of the results of both MAFTS must be supported by OLM activities, highlighting any differences between actual, in-service structural loads, and the PMAFT spectrum, thereby allowing suitable corrections to be made to the structural lives cleared by full-scale testing. An OLM programme will also allow the structural implications of supplementary sortie profiles and the carriage of new stores to be quantified.

2.5.2 Operational Loads Measurement, OLM, Programmes

2.5.2.1 Ageing Aircraft

Beyond the flight loads design issue of civil aircraft's and the mandatory activities of fatigue monitoring of military fleets, a problem common to both sides, still requiring strain gage-based loads monitoring, is the one to manage and/or extend the Design Service Life (DSL) of airframe ageing structures. As mentioned before, the resulting ageing aircraft problem has been specifically discussed since the Aloha Boeing 737-200 accident. The statistical data given in Figure 2.15 show that the number of aircraft older than 15 years is remarkable. It has increased from 4600 in 1997 to 4730 in 1999 for US and European built civil aircraft. Similarly, the number of civil aircraft older than 25 years has risen from 1900 in 1997 to 2130 in

Aircraft type	Total delivered	Fleet in service 09/01	Ageing aircraft in 1999		
			≥ 15 Years	≥ 20 Years	≥ 25 Years
A300	503	411 (82 %)	220 (46 %)	60 (12 %)	1 (0,2 %)
A310	255	218 (85 %)	54 (21 %)	–	–
707/720	1009	379 (37 %)	–	–	–
727	1831	1247 (68 %)	1381 (75 %)	1127 (62 %)	673 (38 %)
737–100/200	1144	901 (79 %)	853 (75 %)	442 (39 %)	222 (19 %)
737 CFMI	1988	1971 (99 %)	13 (0,7 %)	–	–
747–100/SP/200/300	724	562 (78 %)	490 (68 %)	317 (44 %)	154 (21 %)
757	968	943 (97 %)	51 (6 %)	–	–
767	840	820 (98 %)	109 (14 %)	–	–
DC-8	556	243 (44 %)	268 (48 %)	268 (48 %)	268 (48 %)
DC-9	976	727 (74 %)	776 (79 %)	739 (75 %)	588 (61 %)
DC-10	446	397 (89 %)	333 (75 %)	276 (62 %)	162 (36 %)
L-1011	249	155 (62 %)	185 (74 %)	113 (45 %)	60 (24 %)
Total	11489	8974	4733 (46 %)	3342 (33 %)	2128 (21 %)

Figure 2.15: Ageing civil aircraft overview (Staszewski and Boller), [105].

1999. Nearly half of the entire DC-8 fleet is still in operation.

As illustrated in Figure 2.16, the problem with military aircraft structures is even more serious. An increasing number of military aircraft (e.g. F4, T-38, MiG-21) exceed the age of 40 years. Ongoing mid-life updates of fighter airoplanes show that the service life of 50 years and more is not exceptional. The B-52 aircraft, which needs to be retained for a few more decades, is one of the best examples. The Boeing KC-135 in-flight tanker is intended to be kept in service until 2035 (Brand and Boller) [105]. In 1993, approximately 51 % of the aircraft in the US Air Force inventory were over 15 years and 44% were over 20 years old. In 2000, over 75% of US Air Force aircraft were more than 25 years old (Penney 2000) [105].

Similar trends can be observed in converting older civil aircraft series such as

Aircraft Type	First built	Total in service 09/2001	Life extension until
BAE Hawk/Boeing T-45 Goshawk	1976	641	
Boeing F/A-18 Hornet/Super Hornet	1978	1762	2019
Boeing B-52H Stratofortress	mid 50ies	94	2045
Boeing 707/C-137/C-18/KE-3	60ies	97	2030
McDonnell Douglas F-4 Phantom	1958	889	
Dassault/Dornier Alpha Jet	1973	289	
Lockheed-Martin F-16	1974	3398	
Northrop T-38	1959	685	2040
Panavia Tornado	1974	746	2018
MiG-21 (incl. licences)	mid 50ies	3324	
L-39/L-39 Albatros/L-159	mid 70ies	2233	

Figure 2.16: Ageing military aircraft overview (Staszewski and Boller 2002), [105].

the Airbus A300 and A310 or the Boeing 747, 757 and 767 to freighter aircraft.

The Use of Calibrated Strain Gauges for Flight Load Determination

These upgrades and conversions are often also related to a change in the loading conditions of the aircraft structure, which possibly equipped with more powerful engines, new weapon loads, communication and electronic systems. These aircraft usually fly different envelopes and maneuvers compared to those for which they were initially designed for.

There are two major issues which suffer ageing aircraft:

- Corrosion
- Cracking Damage

These two time dependent factors, Figure 2.17, need to be counted in the operating process of ageing aircraft maintaining reliability standards of the aircraft structure along the extended operational life and at the same time controlling maintenance cost to acceptable minimum. The likelihood of the occurrence of corrosion and fatigue damage in an airplane's structure increases with airplane usage. The design process generally establishes a design service goal (DSG) and any cracking that occurs operating the airplane by that limit is expected to be in isolation (e.g. local cracking), originating from a single source, such as a random manufacturing flaw or a localised design detail. It is considered unlikely that cracks from manufacturing flaws or localised design issues will interact strongly as they grow. It is just the development of cracks at multiple locations with strong interactions that can affect subsequent crack growth; in which case, the predictions for local cracking would no longer apply. That may cause adverse effect on the large damage capability of the structure before the cracks become detectable.

Widespread Fatigue Damage (WFD), simultaneous presence of cracks at multiple

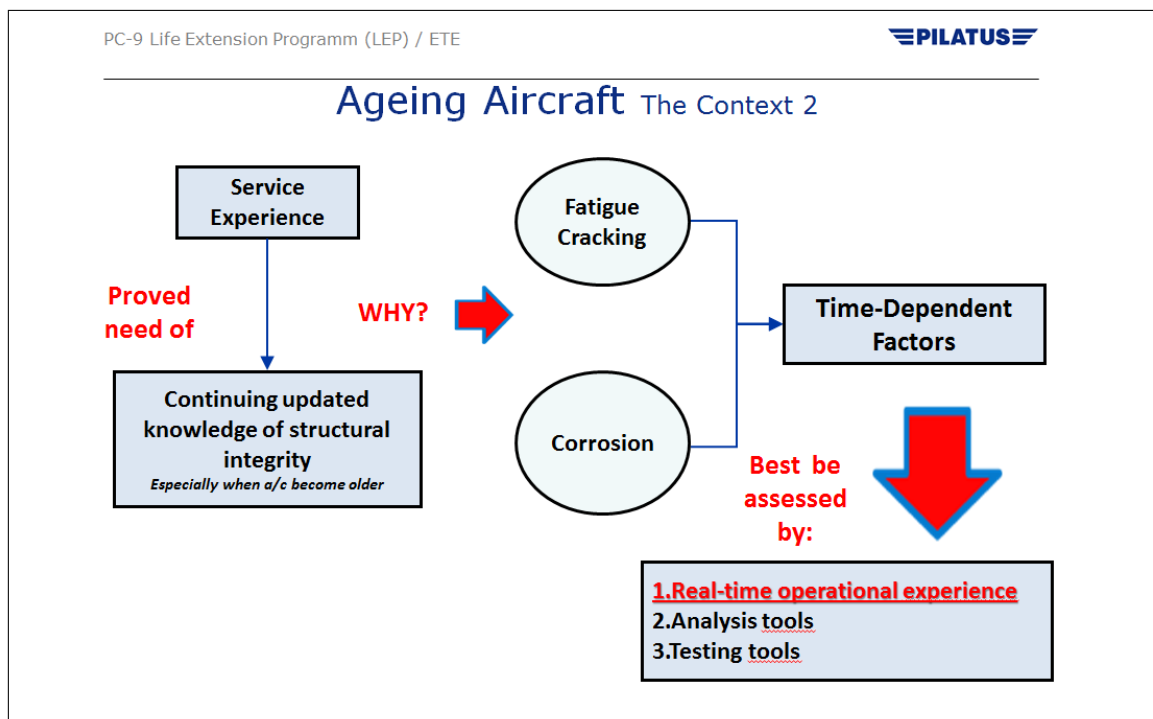


Figure 2.17: Main time-dependent factors of ageing aircraft, [70].

structural details that are sufficient size and density whereby the structure will

no longer meet its damage-tolerance requirement [2], and Multiple Site Damage (MSD), a source of widespread fatigue damage characterised by simultaneous presence of fatigue cracks in the same structural element [2], need to be addressed by the type certificate holders and operators, Figure 2.18, to ensure safe operation with specific inspection programs and tear down activities taking into account the data of DMAFT and PMAFT.

Figure 2.19 describes the main activities recommended to be performed according

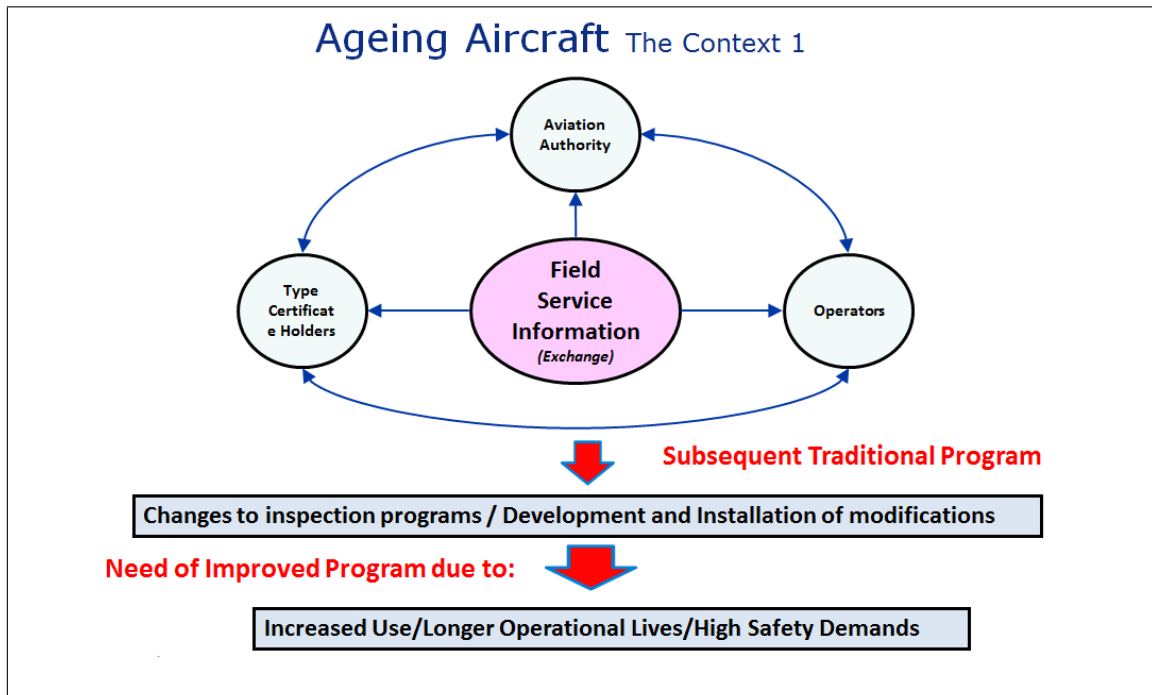


Figure 2.18: Ageing aircraft: Operators, Type certificate holders and Authority data flow.

to the US Department of Transportation advisory circular [2], meant to preclude WFD and MSD situations.

Provision of a system to provide measurements of the loading spectra on critical parts of the structure experienced by the aircraft during the extended service goal life is the "quid" that makes a life extension a successful program.

2.5.2.2 The Operational Loads Measurement (OLM)

With increasing costs, and shrinking budgets, there is considerable economic pressure to get the most out of existing aircraft, extending their in-service life. The involved collection of suitable flight and ground data in order to build up representative fatigue spectra, due to the actual loads being experienced on the Principle Structural Elements (PSE), in terms of internal forces (shear, bending moment and torsion) is an achievable task through a dedicated Operational Loads Measurement Skopinski-Type campaign.

The OLM activity required to meet these aims is thoroughly described by Figure 2.20, where QinetiQ professional Ms Dorothy Holford identifies all the main phases

The Use of Calibrated Strain Gauges for Flight Load Determination

in logical order of execution [95].

This description gives the real picture of OLM as a technically complex sequence of activities and while not everybody involved needs to have full cognisance of all detail, a basic understanding of what has to be done and why is necessary to manage such a programme successfully. However, where deeper technical information can be omitted from the body of this paragraph, since not relevant to the core of this research, the OLM might be broken down in a much more synthetic way as follows:

1. Operational Loads Measurement Design Process:

- Statement of Operating Intent and Usage (SOIU) to characterise the operating characteristics of the fleet to monitor.
- Define components to monitor (measure loads and fatigue).
- Characterisation of Data Acquisition System (DAS):
 - Number, type and strain gauge locations which defines the required load cases.
 - Identify flight parameters.

2. Ground Calibration:

- Identification of load cases to determine load coefficients.
- Development of appropriate test rigs.
- Recording system to acquire strain gauge responses, load cells etc.

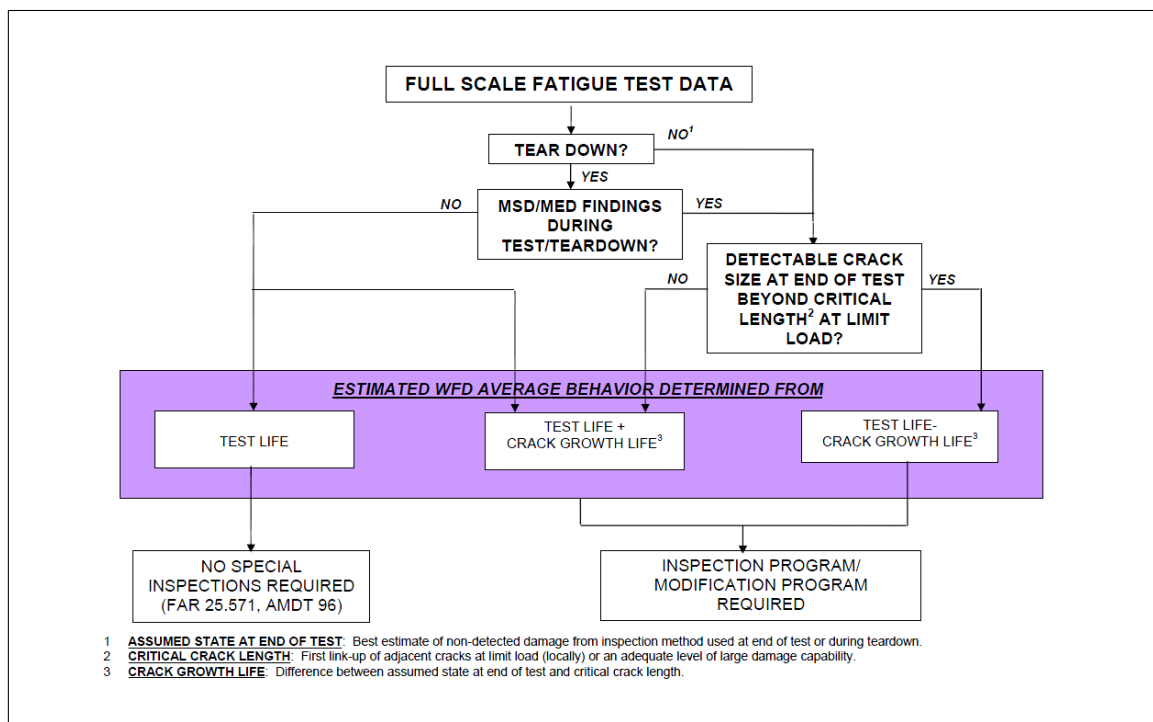


Figure 2.19: Use of fatigue test and tear-down information to determine WFD average behavior, [2].

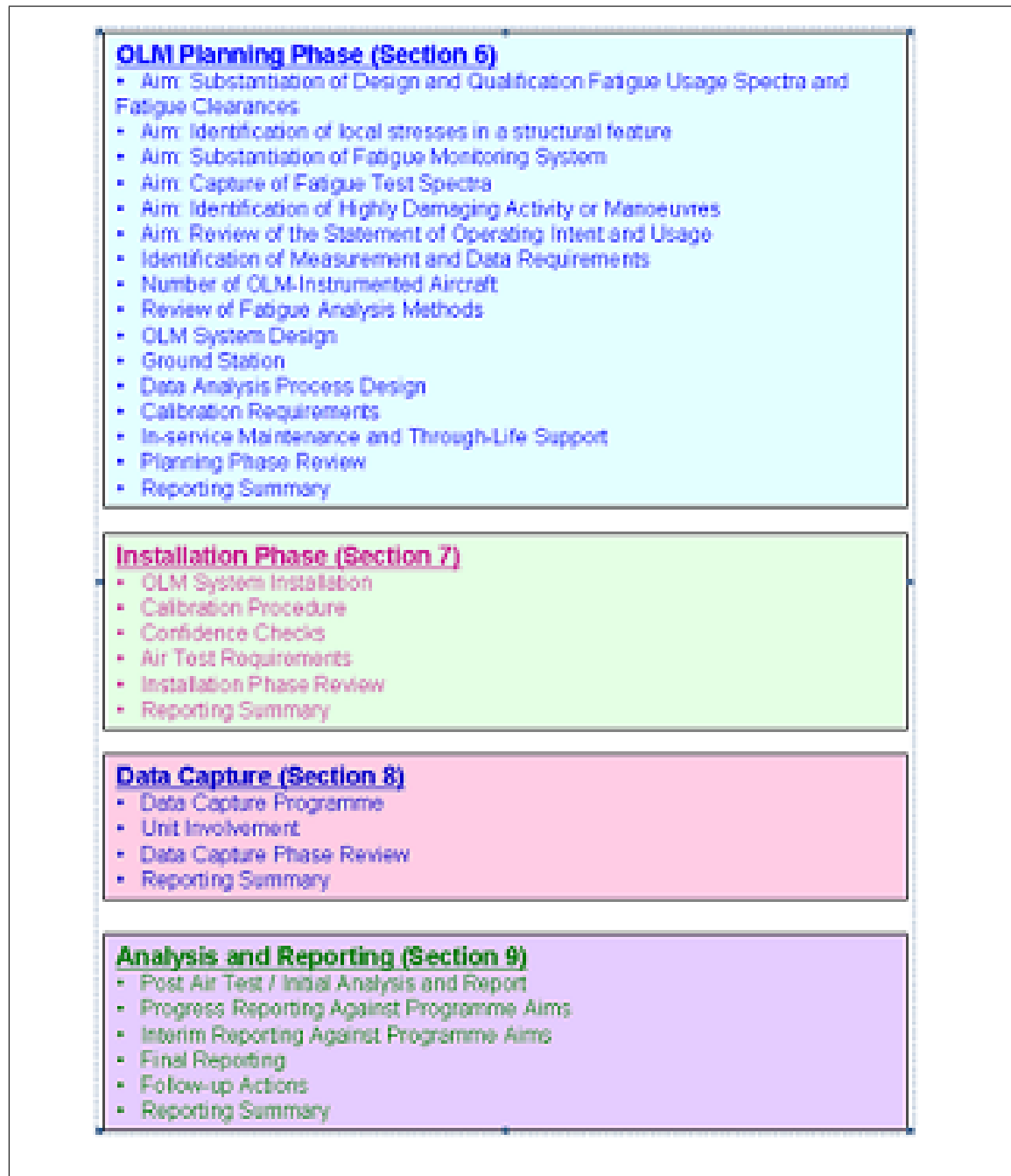


Figure 2.20: OLM thorough detailed schematic activities, [95].

The Use of Calibrated Strain Gauges for Flight Load Determination

- Perform health monitoring of the strain gauge readings.
- Develop initial load equations.

3. In-flight Data Collection:

- Instrumentation monitoring: strain gauge data, flight conditions etc.
- Strain gauge anomaly detections: over/under ranging, spike detection, magnitude variation, initial offset ambient reading, interference issues etc.
- Generation of loads for Points on Ground (POGS) and Points in the Sky (PITS) using load equations for later comparison.

4. Structural Analysis:

- Comparison of in-flight loads to numerical baseline response to investigate any potential discrepancies (stress, strain, displacements etc.) if discrepancies exist, reverse optimisation techniques will be employed to locate and determine extent of damage.
- Perform fatigue Cycle Counting for safe life/ crack growth prediction.

5. Data Statistics:

- Need to ensure sufficient measurements have been obtained, so as to provide reliable and representative data set for entire flight envelope and mission type of aircraft under investigation, which is critical if measurements are to be taken over an extended period.

As mentioned in the previous chapter, the Skopinsky-type OLM develops the loads measurement through the mean of wire resistance strain gauge. Properly installed and calibrated such gauges may be used to determine the structural loads on control surfaces, landing gear structures, fuselage, and built up wing and empennage assemblies. The measured internal structural loads, shear, bending moment and torsion, can, in turn, be converted to aerodynamic loads provided the structural weight distribution is known and the acceleration distribution has been measured. The basic theory behind this technique shows strain is to be used only as a measure of obtaining information about loads and not as stresses. So, the selection of the gage location, which depends on the measure to be made, is a key point. Ideally it would be desirable to place the gages at a position such that a shear bridge would respond only to shear and a moment bridge only to moment and so forth. But this will be possible only with simple structure with a single load path not achievable with the typical aircraft components. So, it will be necessary to identify locations in the same time with high sensitivity to the load to measure, lift or shear will need to select web area and pitching moment/bending will prefer upper/lower cap, and away from areas of local stress concentrations Figure 2.21.

Then, by a proper Ground Calibration the strain gauge responses, proportional to the applied calibrated loads according to the Skopinski's method[111], will be combined using specific algorithm, linear regression, to produce load coefficients.

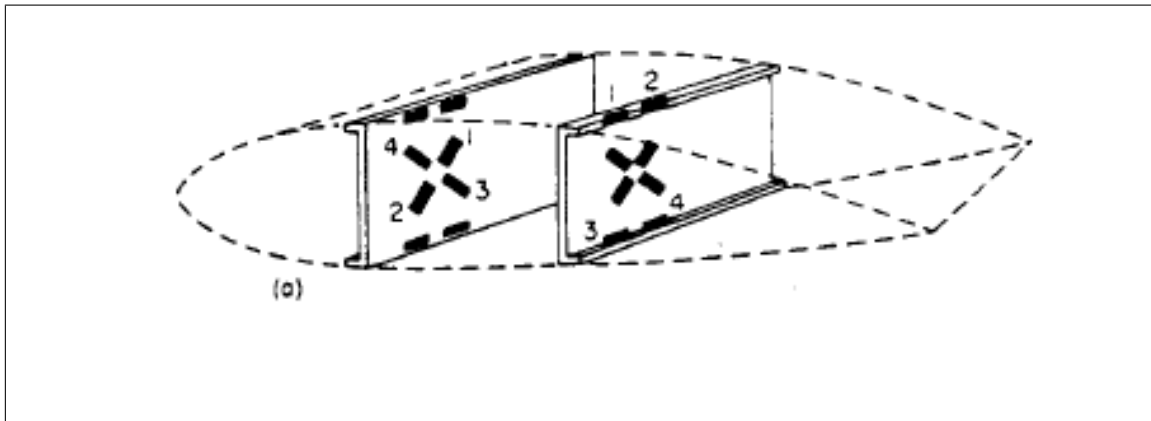


Figure 2.21: Typical strain gage installation of shear and moment bridges of wing box structure, [111].

The quality of the final set of load equations will depend by the probabilistic tools, LPE (load probable error), and Standard Deviation, and non-probabilistic tools, Influence Coefficients, used to select the best set of strain gauge responses according the type of load to measure. In flight the loads will be measurable using the load coefficients, evaluated through the ground calibration, and current strain gauge flight readings. Load models, such as obtained through an extensive FE (Finite Element) analysis, are therefore needed to validate the loads, intended as magnitude and distribution, measured through the load equations previously developed at ground calibration stage. Once confidence on the measured loads has been gained is possible to reach the fatigue index evaluation through basic Palmgren-Miner damage accumulation rule or more complex crack growth model. Prior to ending the recording flight data activity it is expected extreme care to analyse the overall data built up over the whole campaign. Basically, the Statement of Operating Intent and Usage, generated during the OLM design process, including the Sortie Profile Codes (SPCs) in use for each aircraft fleet, must be compared with the data gathered. Once the amount of data recorded prove to be representative, Data Statistics phase, the OLM campaign might be concluded. Figure 2.22 gives an example philosophy of the main phases described so far (OLM design process and Ground Calibration are not included). Here, Tornado OLM aircraft structure, strains from the sensors, once calibrated on the ground, are converted to digital signals and stored in a data acquisition unit (DAU). The signals are then converted to stress histories. This information is used to obtain the load sequence for the given locations including load transfer functions where available and useful. The load sequences are analysed and synthesised using rainflow cycle counting procedure. This evaluation procedure can either be performed in-flight or on-ground.

2.5.2.3 Operational Loads Measurement Disadvantages

The experience gathered with systems based on Operational Loads Monitoring Skopinsky-type philosophy proved over the last 30 years several limitations and area of improvement. This section focuses on these.

The Use of Calibrated Strain Gauges for Flight Load Determination

The vast amount of data collected needs a more efficient data management. This issue becomes more specifically relevant when looking at the increasing average age of aircraft, which will significantly increase the amount of ageing aircraft obstacle data to be handled such that fatigue life consumption and possible retirement time of individual aircraft can be better controlled. This procedure can result in significant cost savings.

OLM systems are not able to directly detect and monitor structural damage. The OLM system can only provide a major input for analytically determining when damage might occur. Being a well-known experience, the experimental and thus real fatigue life can often be two to three times higher than analytically predicted (Boller 1996) [105], which is mainly resulting from scatter in material properties but also due to some security factor which has to be included in the analytical calculation. This gap between predicted and real damage becomes even larger for composite materials where fatigue analysis and fracture mechanics of these materials are relatively less known when compared to metallic materials.

Loads monitoring does also not provide any information regarding environmental effects such as corrosion in metallic and humidity/temperature in composite materials as long as these environmental loads are not recorded with appropriate sensing devices and the respective analytical procedures are not available. These aspects become increasingly important for the case of ageing aircraft.

Since the core of this work is mainly related to the OLM Skopinski's type, the areas of most improvement, responsible of the final quality of the loads magnitude and distribution (the whole damage monitoring activity) can be identified:

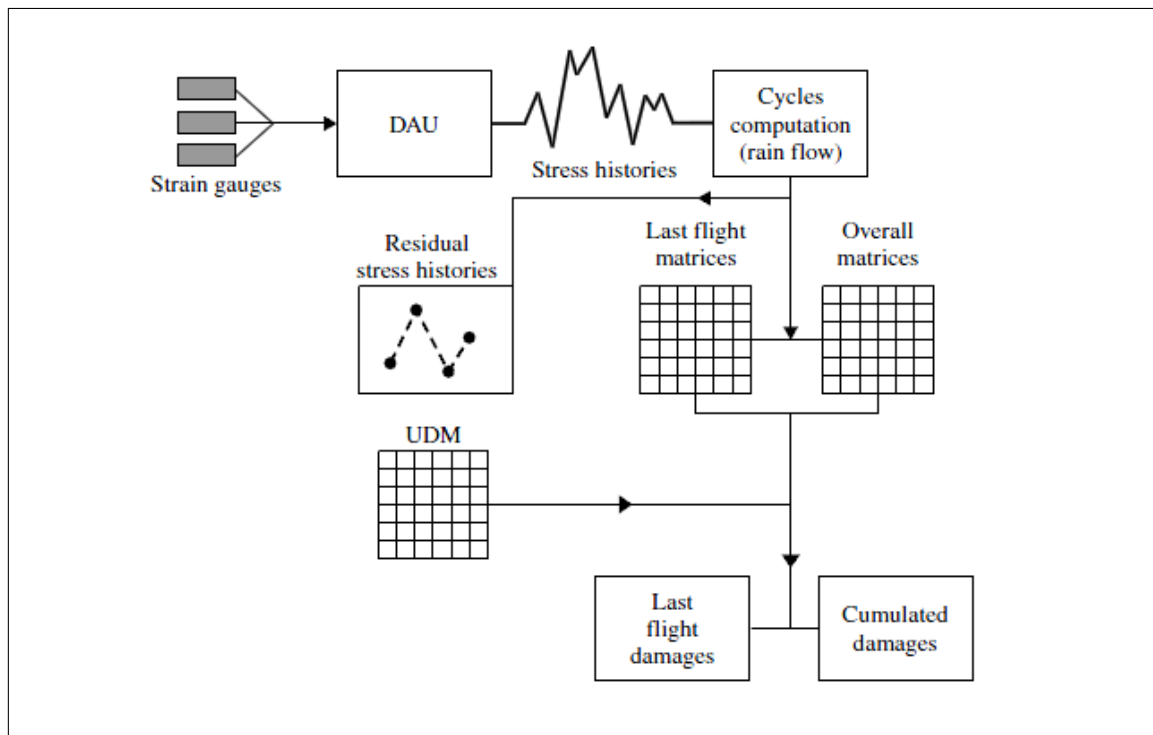


Figure 2.22: Loads monitoring system using strain gauges for Tornado aircraft (Boller 1996), [105].

1. Strain Gauge Measurements:

- Number, type and strain gauge locations, need to ensure reliable data is obtained for load cases considered.
- Calibration; accuracy issues.
- Strain gauge redundancy and ageing issues (quality loss, cabling etc.).

2. Monitoring the Health of an OLM Skoinsky-Type:

- Critical Interrogation of redundant sensors to provide quality assurance of data collected.
- Strain Gauge anomaly detections.

The core of the improvements relies on the device "strain gauge" since is the element supporting the whole loads development activities. Dealing with unreliable strain gauge data it means increase the amount of uncertainty inherited, not by the physical problem under investigation, but by the applied methodology. So, instead of limiting the area of improvement adopting new type of gauge, as fibre optic might be, the intention of this work is based on adopt optimisation tools to select the best set of strain gauge capable to produce robust load equations.

2.6 The Evolution of the Flight Loads Measurement

The development of structural health monitoring systems relies on different research disciplines and in addition it affects design and manufacture as well as operation and maintenance. As primary flight systems such as the airframe, landing gear or engines are considered, the airworthiness authorities will have to be involved. Novelty of the structural health monitoring systems is considerable and thus a broad acceptance among all parties involved is necessary to achieve implementation.

The development of structural health and usage monitoring systems depends largely on the available technology. However, the benefits derived from actual research and application programmes must be recognised and reflected by the potential end-users. Structural health monitoring and usage monitoring systems must satisfy realistic performance requirements to meet end-users needs.

The main driver for the Skopinski type loads monitoring is increasing the reliability and accuracy of the loads measured keeping up with the new generation of aircraft coming up by using the benefit of having available better and more robust Data Acquisition System, DAS, and rapid increases in computer processing power, memory and storage space. Though, this has not completely eliminated computational cost and time constraints on the loads monitoring due to the constant increase in the required fidelity and hence complexity of the loads environment and components typology and consequent supporting models to analyse.

The objectives of the of the remaining part of this chapter are to review the increasing complexity of the problems that flight loads measurement, and all the others sectors indirectly affected, can deal with passing through the major scientists of

each past decade up to date. To accomplish this task it has been necessary, first, to break down the major phases of the evolution of the flight loads measurement, then, to identify a tool, the Three Axes of Complexity, capable to point out the factors that contribute to the complexity of this specific science. This will allow to classify and understand the complexity in a systematic way and to provide a framework that enables flight load measurement practitioners to trade off the different aspects of complexity.

2.6.1 The Three Axes of Complexity, 3AC

The evolution of the science of the flight loads measurement can be described by identifying the starting point, set by Skopinski, Aiken and Huston in 1954, [102], and the periods before and ahead. The first, labelled the "Conception Period", falling into the 1940 Decade, shows those scientists and common methodologies employed that set the ground for something more practical and robust for the flourishing aviation. The latter, the "Development Period", records all the major directions where the new flight loads measurement science has been imposing itself. The "Definition Period" represents the 1950 Decade where everything started from. Each period has been further ranked out by means of the "The Three Axes of Complexity". The terms *difficulty* or *complexity*, as Vankataraman and Haftka [114] experienced with the structural analysis problem, are not easy to quantify in terms of flight loads measurement area. In fact, the number of challenges associated are several, but the two main categories driving the complexity are the object, X-axis, and typology of loads, Y-axis, under investigation. These two characterise the difficulty and so the type of Flight Loads Measurement, Z-axis, whether Strain Gauge-based or Flight Parameter-based or other methods, chosen to understand the design or operational loads environment.

The coming sections are selectively discussing and comparing the findings of other scientists, in order to advance thinking in the area of interest. This will be presented by breaking down each Decade Periods by means of "*Three-Axis of Development*" tables. Table 2.1 acronyms will be used to further narrow the decade scientists topics explored in the area of strain gauge-based flight loads measurement.

Table 2.1: Strain Gauge Based Flight Loads Measurement Phases, (SG FLM).

No	Phases
01	Definition and Design, (D&D)
02	Ground Load Calibration, (GLC)
03	Data Gathering and Analysis, (DG&A 1)
04	Flight Test, (FT)
05	Data Gathering and Analysis, (DG&A 2)
06	Comparison and Validation, (C&V)

2.6.2 Conception/Inception Period: Decade 1940

US War Department, alarmed by German jet bombers like the Arado Ar 234, called for a new family of jet bombers grossing between 80,000 lb (36,287 kg) and 200,000 lb (90,718 kg). The end of World War II resulted in the cancellation of many project and delayed many others. Though, in 1946 the rising tensions with the Soviet Union caused the US Air Force to assign higher priorities to jet bomber development and production.

All this needed a support of the research to assess the correctness of the design criteria employed till that time on High-Speed-type aircraft, such as the North American B-45 Tornado, United States Air Force (USAF) first operational jet bomber, and the first multi-jet engined bomber in the world to be refuelled in mid-air. In fact, similar airplanes, operating at high subsonic Mach numbers, have encountered tail buffeting of sufficient magnitude in manoeuvring flight to be objectionable to pilots and possibly to endanger the airplane structure. This proved a lack of knowledge of the HT Loads and requested new design criteria to be proposed.

The events above characterised the Decade 40's and set the context, for the major scientiststs of Table 2.2, with the research activities highlighted in the Tables A.1 and A.2 and A.3.

Table 2.2: Three-Axis of Development, Part 1 - Decade: 1940

ID	Year	Author	Reference
01	1943	Henry A. Pearson	[88]
02	1945	Cloyce E. Matheny	[71]
03	1947	John B. Garvin	[32]
04	1948	Allen R. Stokke and William S. Aiken, Jr	[1]
05	1948	William S. Aiken, Jr	[6]
06	1949	William S. Aiken, Jr., and Donald A. Howard	[4]
07	1949	Gaulden C. H.	[38]

The correlation studies between different experimental, wind tunnel and pressure distribution, [6], [4], and theoretical approaches, [88], [71], strengthen the Strain Gauge Based Loads Measurement approach. In fact, Aiken, [6], stood out publishing a technical report proving to be one of the first to introduce the Strain Gauge as indirect measurement technique of flight loads. No mention about the Phases of Ground Load Calibration and Data Gathering & Analyses. He compared the more robust and known technique of that time, pressure-distribution, with wing loads obtained by strain-gauge readings. The agreement between shears, bending moments, and span-wise centres of pressure determined in flight was found to be good, [4]. Torque and buffeting loads proved to be an open area of investigation. Last, Table 2.2 includes the most significant statistical theory reference, Goulden [38], used in the next decade by Skopinski to introduce his revolutionary strain gauge-based flight loads measurement technique, [102].

2.6.3 Definition Period: Decade 1950

Departures from aircraft designs on which flight data exist raise questions as to the adequacy of design procedures and the accuracy of methods for extending wind-tunnel data to the flight design conditions. In order to aid in checking design procedures and wind-tunnel data and to present flight data on a swept-wing configuration, the National Advisory Committee for Aeronautics decided to carry out a comprehensive flight-test program on a swept-wing bomber airplane that includes measurements of loads on the component parts, [73]. Following Tables 2.3, A.4, A.5 and A.6, A.7, A.8 will be further breaking down the major scientists and their activities produced through this Decade.

Table 2.3: Three-Axis of Development, Part 1 - Decade: 1950

ID	Year	Author	Reference
01	1950	Henry A. Pearson, William A. McGowan,	[89]
01	1950	and James J. Donegan	[89]
02	1954	T. H. Skopinski, William S. Aiken, Jr., and	[102]
02	1954	Wilber B. Huston	[102]
03	1955	Wilber B. Huston and T. H. Skopinski	[46]
04	1955	William S. Aiken, Jr., and Bernard Wiener	[5]
05	1955	T. V. Cooney, William H. Andrews, and	[17]
05	1955	William A. McGowan	[17]
06	1957	William S. Aiken, Jr., and Raymond A. Fisher	[7]
07	1957	William S. Aiken, Jr.	[3]
08	1957	William A. McGowan and T. V. Cooney	[73]
09	1959	Ezekiel M. and K.A. Fox	[29]

Skopinski, Aiken, and Huston, [102], formalised what Aiken [4], during the previous Decade presented, a new loads measurement technique based on Strain Gauges. In fact, it was developed a general method for calibrating strain gauge installations in aircraft structures, which permits the measurement in flight of the shear, bending moment, and the torque or pitching moment on the principal lifting or control surfaces.

The novelty introduced proved to have applicability for a variety of purposes such as in research investigations, structural integrity demonstrations, and developmental flight testing. Basic calibration procedure and basic concepts of load equation strain gauge selection, influence coefficient plots, were introduced to assess reliability and relevancy of any equation.

Limitations of the time data recording system suggested the extensions of the basic procedure by means of electrical combination of the strain gauge installation time, availability of recording instruments, and data reduction time. Though, channel recording availability limited the loads measurement in single stations instead of span wise distribution.

The flight loads measurement science also progressed in terms of statistical analysis tools as shown by Ezekiel and Fox, [29]. In fact, they introduced methods for data correlation and regression analysis pivotal for the future work of Hovell et Al., [43], Sefic et Al. [101], and Tang et Al., [109].

Buffeting loads were studied, [46], major areas covered of the strain gauge-based loads measurement type focused on the ground experimental and numerical side, Phases, D&D, GLC and DG&A of Table 2.1.

2.6.4 Development Period: Following Decades

2.6.4.1 Decade 1960

This decade starts refining the science of flight loads measurements for different purposes not any more limited to aeroplanes. In fact, the increasing number and scope of manned space missions led to a need for advanced re-entry/recovery concepts. Vehicles having improved manoeuvring capabilities provide distinct advantages. One of the more important areas of investigation with this type of vehicle is low speed flight characteristics, mainly as virtually no flight-test information was available for the wingless, short fuselage, lifting body configuration, [56]. In addition, the absolute values of the loads throughout the flight start being required, rather than incremental loads measured over short time intervals as at the very beginning of Decade 40's, [88] and [71], happened mainly due to system instrumentation limitations and not sufficient knowledge of Strain Gauge Based FLM methods, [80]. Similarly, the experimental, cost and time, implications of thorough ground load calibration campaigns encouraged to investigate the possibility to replace it by numerical models. In particular, by the introduction of distributed load data obtained by numerical superposed individual load data. These concepts were supported by methods of statistical analysis of fitting data models as Goulden first, [38], and then Ezekiel and Fox described, [29].

Tables 2.4, 2.5, A.9 and A.10, A.11 describe the majors scientists and three-axis of complexity of the 1960's Decade.

Table 2.4: Three-Axis of Development, Part 1a - Decade: 1960

ID	Year	Author	Reference
01	1961	Mc Kay, James M. and Scott, Betty J.	[72]
02	1963	Nicholas, O.P.	[80]
03	1966	Hovell, P.B. and Webber, D.A. and	[43]
03	1966	and Roberts, T.A.	[43]
04	1968	Jenkins, Jerald M. and Tang, Ming H. and	[56]
04	1968	Pearson, George PE	[56]

Table 2.5: Three-Axis of Development, Part 1b - Decade: 1960

ID	Year	Author	Reference
05	1969	Hovell, Peter Burns and Webber, Derek Alan,	[44]
05	1969	and Roberts, Thomas Arwel	[44]
06	1969	DeAngelis, VM and Friend, EL and	[18]
06	1969	Jenkins, JM and Monaghan, Richard C	[18]

Hovell, Webber, and Scott followed the natural evolution of the Flight Measurement science pointing out weaknesses related to the new generation of aircraft. In fact, the British scientists highlighted the procedures of N.A.C.A. Report No. 1178, [102], for the interpretation of measured flight strains as structural loads are not entirely satisfactory for applications to delta or slender-body configurations. Problems arise from the severe non-linearities, ref.[80], in the gauge response with the position of the calibrating load and from the need to support the aircraft representatively during the obtained either directly or by superposition, are used in place of individual data. In contrast to the original N.A.C.A. Report, the procedure will then establish directly the reliability of any particular flight load measurement. So, this decade shows the first modified techniques and UK represents the country working in this direction, [43] and [44]. It was concluded that in the problem of the interpretation of strain measurements as flight loads the regression equations based on distributed load data were preferable to those based on the original individual data, Individual Load Calibration (ILC) versus Distributed Load Calibration (DLC).

2.6.4.2 Decade 1970

Decade 70's continues the overall lifting body flight test program at the NASA Flight Research Centre, detailed aerodynamic load studies, already started during 60's with the M2-F2 vehicle, ref.[56]. The concept of manoeuvrable vehicles is here extended to the HL-10 vehicle configuration, [107]. As aircraft speeds approach Mach 3, heating of the aircraft structure presents significant problems. Specifically, the heating produces thermal stress and deformations that must be taken into consideration during aircraft design, [98]. The measurements continue to be focused on lifting surfaces roots and attachment points of mainly swept wings with low aspect ratio.

The modern complex structural arrangements, low aspect ratio multi-spar wings, and different flight operations, high Mach Numbers, of the aeroplane developed in this Decade have complicated the task of measuring flight loads with calibrated strain gauges and new studies and tools will be developed as Tables 2.6, and A.12, A.13, A.14 and A.15, A.16, A.17 describe.

Table 2.6: Three-Axis of Development, Part 1 - Decade: 1970

ID	Year	Author	Reference
01	1970	Roger A. Fields	[30]
02	1970	Harold, M. Wells JR. and Troy, T. King	[41]
03	1971	Ming H. Tang and George P. E. Pearson	[107]
04	1972	Roger A. Fields, Frank V. Olinger, and	[98]
04	1972	Richard C. Monaghan	[98]
05	1973	Monaghan, Richard C and Fields, Roger A	[77]
06	1974	Sefic, Walter J and Reardon, Lawrence F	[101]
07	1975	Peele, Ellwood L and Eckstrom, Clinton V	[90]
08	1976	Eckstrom, Clinton V	[26]
09	1977	Arnaiz, Henry H	[11]
10	1977	Jenkins, Jerald M and	[54]
10	1977	Kuhl, Albert E and Carter, Alan L	[54]
11	1977	Jenkins, Jerald M and Kuhl, Albert E	[53]
12	1977	Jenkins, Jerald M and Kuhl, Albert E	[52]
13	1979	Jenkins, JM and Field, RA and Sefic, WJ	[57]

Flight Loads measurement science is introduced as part of mandatory requirements of structural integrity of the Air Force, [41]. The Airplane Structural Integrity Program (ASIP), systematic procedure applied to a particular aeroplane system to enhance design, diagnose potential or impending failure, provide a basis for corrective actions, and predict operational life expectancy of the airframe, is founded on the Experimental Flight Loads Measurement campaign to measure the operational loads, OLM, needed for monitor the life consumption of the airplane structure system.

Tables of this Decade also point out the benefit of using of a relatively simple structural model to characterize the load responses of strain gauges located on various spars of delta wing. That produced new tools to further assess the value of the numerical model and consequently characterize the most accurate set of loads equations. Influence coefficients of strain gauge, IC, already considered by Skopinski, [102], and loads equation, ICLE, were introduced by Jenkins, Kuhl and Carter, [54], proved that the analytical processes can be an aid in obtaining a good load calibration. In particular, they introduced a matrix approach to equation selection which is based on equation standard error, load distribution, and influence coefficient plots, ICLE, of the strain gauge equations, applied to a complex wing, [53].

The conventional Skopinski method of loads measurement proved to expand to the aerodynamic heating effect of aircraft structures at high speeds, where Fields was one of the first pioneers, [30]. The laboratory tests proved the repeatability of the data and the superposition of the thermal and mechanical loads strain gauge readings, ref.[77].

Though, the analytical processes cannot be used in lieu of an actual load calibration

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of an aircraft wing yet. At the same way the instrumented and calibrated aeroplane to develop the loads equations is the same airframe for measuring the flight loads.

2.6.4.3 Decade 1980

As with conventional aircraft space transportation re-entry vehicle development depends heavily on experimental load verification to expand the operating envelope and to assess useful life. For a number of years the structures research section at the NASA Ames Research Centre, Dryden Flight Research Facility, has been applying the calibrated strain gauge load measurement technique to high-speed vehicles where aerodynamic heating is significant. Unfortunately, the thermal gradients produced by aerodynamic heating cause thermal stresses that interfere with strain gage load measurement, as already preliminary revealed during the first research programmes of the 1970's such as: X-15 programme, [30], [98], and [77], HL-10 programme, [107], XB-70 programme, [26], YF-12 programme, [11], [53], and [52]. Therefore, a structural heating laboratory was constructed at Dryden to develop techniques for separating mechanical and thermal strain gauge outputs. This Decade, Tables 2.7, and A.18, A.19 and A.20, A.21, A.22, will be mainly exploiting the massive amount of data and information gathered by Ground Experimental Test, YF-12 Programme, encouraging the introduction of new supporting tools and concepts.

Table 2.7: Three-Axis of Development, Part 1 - Decade: 1980

ID	Year	Author	Reference
01	1980	Tang, Ming Han and Sheldon, Robert G	[109]
02	1980	Tang, Ming Han	[108]
03	1980	Fields, Roger A and Reardon, Lawrence F and	[31]
03	1980	and Siegel, William H	[31]
04	1982	Carter, Alan L	[14]
05	1984	AGARD Conference Proceedings No.375	[82]
06	1986	Eckstrom, Clinton V	[28]
07	1987	Yao, Kung and Balakrishnan	[118]
08	1988	FAA, Advisory Circular AC 23-9	[112]
09	1989	Reardon, Lawrence F	[94]

A comprehensive program was conducted using the YF-12 aircraft and the Shuttle Orbiter, which were instrumented for strain and temperature, calibrated for load measurement, and flown to Mach 3 speeds, where significant aerodynamic heating was experienced. The vehicles were then returned to the laboratory and heated to simulate the flight environment, and the resulting thermal strain outputs were recorded, [31], [94] and [14].

This period also records a new trend in aerospace research and operations, a flying Drone for aerodynamic and structure research platform (DAST), [28], subjected to a complete Design Loads Measurement campaign according to the principles of Skopinski.

US Civil Aviation Authority issued an Advisory Circular including SG-Based Flight Loads Measurement as an alternative recognised technique to substantiate the theoretical loads evaluated on those non-conventional tail design configurations,[112]. Major contribution to the strain gauge selection technique is coming from Tang and Sheldon, [109] and [108], by introducing the T-Method and T Modified- Method, founded on statistics principles.

2.6.4.4 Decade 1990

Designers of modern high-performance aircraft usually employ electronic automatic control systems either to augment the mechanical control systems or to implement a set of complex control laws. Such control laws often are required to maximise the performance with multiple advanced aerodynamic control surfaces or to give acceptable handling qualities. Such control system provided an excellent opportunity to implement structural load-relieving modes, coupled with real time flight loads measurement systems, in combination with the basic control system, [110]. The 90's flight loads measurement evolution will be focusing on such challenges and on the other area still in need to strengthen, the gage selection process, [79]. Tables 2.8, 2.9, and A.23, A.24 and A.25, A.26, capture the major scientists and events of the decade.

Table 2.8: Three-Axis of Development, Part 1a - Decade: 1990

ID	Year	Author	Reference
01	1993	Locke, James E and Smith, and	[63]
01	1993	Howard W and Gabriel,	[63]
01	1993	Edward A and DeFlore, Thomas	[63]
02	1993	Thornton, Stephen V	[110]
03	1994	Goranson, Ulf G	[37]
04	1994	Nelson, Sigurd A	[79]

Table 2.9: Three-Axis of Development, Part 1b - Decade: 1990

ID	Year	Author	Reference
05	1996	AGARD Conference Proceedings,	[9]
05	1996	No AR-340	[9]
06	1996	Jenkins, Jerald M and Quinn, Robert D	[55]
07	1997	Jenkins, Jerald M and	[50]
07	1997	DeAngelis, V Michael	[50]
08	1998	RTO Research and	[97]
08	1998	Technology Organization	[97]
08	1998	Meeting Proceedings RTO-MP-7	[97]
09	1998	Van den Hoeven, AM	[113]

The advanced fighter technology integration (AFTI)/F-111 aircraft implemented a structural load-relieving modes in combination with the basic control system, [110], by means of strain gauge-based loads inputs.

Though, the research started being not any more the only branch of usage of the science of flight loads measurement. In fact, a strong impetuous was coming from the aircraft operators and the major civil military and civil Authorities, [63], [97], and [113].

The strain gauge selection process evolution is continued by Nelson, [79]. As a result of the increasing number of strain gauges installed on the multi-spar hyper-sonic lifting surfaces, he introduced an improved technique using genetic algorithm driven by a fitness function penalising those loads equation with a large standard deviation. In the years to come this robust optimiser, genetic algorithm based on statistics information, was meant to be overcome by exhaustive search algorithms, that Jenkins and DeAngelis in their past decades review of the loads calibration, [50], reminded the importance to rely on influence coefficient labelled as "the primary tool to evaluate the validity of a load calibration and the primary mechanism by which strain gauges are combined to obtain optimum load equations."

2.6.4.5 Decade 2000

The evolution of sensor, data acquisition, communications, and information analysis technologies enables the development of health monitoring (HM) systems for real-time condition assessment for predicting failures of aircraft components or subsystems. The purpose of many activities of the sector is to assess the connection between Civil Aviation regulations, FAA, and incorporation of HM systems into commercial aircraft. On the Military side, the fatigue monitoring of airframe has developed over the decades to the stage where it is now incumbent for all fighter type aircraft to be fitted with an airborne fatigue monitoring system. These systems typically collect data for the calculation of the safe-life or the inspection interval of the airframe. The flight loads measurement is not always based on strain gauge as

the flight parameter or VGH systems are replacing it, [76] as easier and cheaper to implement and operate.

For more than a decade, wing torsional flexibility has been proposed to aeroelastically enhance the roll manoeuvrability of high-performance aircraft. Although, aeroelastic control behaviour, related to aileron reversal, has always been avoided, even if it meant additional structural weight; when the behaviour is incorporated as a preprogrammed control mode, some significant benefits can be reaped. When the mode is designed into a new airframe, reduced weight, increase manoeuvrability, and other advantages can be exploited. The NASA has been working in this direction modifying the preproduction version of the F/A-18, [64], found to have potential for aileron reversal within its performance envelope. A real-time measured structural loads will be required for research and safety-of-flight purposes of this NASA Active Aeroelastic Wing (AWW) F/A-18 programme. The whole decade will be using all the set of ground and flight test data to investigate and enhance the technical areas affected.

The exact loads measurements for the mechanical parts of dynamic systems will be proving to affect other sectors such as the wind turbine, [47] and [15].

The events and concepts above are presented in the following Tables 2.10, 2.11, and A.27, A.28, A.32 and A.30, A.31, A.32, A.33.

Table 2.10: Three-Axis of Development, Part 1a - Decade: 2000

ID	Year	Author	Reference
01	2000	Molent, L and Aktepe, B	[76]
02	2000	AIMS2000, Aircraft Integrated	[91]
02	2000	Monitoring Systems Proceedings	[91]
03	2000	Munns, Thomas E and Beard,	[78]
03	2000	Richard E and Culp, G, Aubrey M	[78]
03	2000	and Murphy, Dennis A and	[78]
03	2000	Kent, Renee M and Cooper, Eric	[78]
04	2001	Gunther, G	[40]
05	2001	Kim, David and Marciniak, Maciej	[58]
06	2001	Kim, David and Pechaud, Laure	[59]
07	2001	IEC, International Electrotechnical Commission	[47]
08	2002	RTO Research and Technology Organization	[85]
09	2002	Lokos, William A and Olney, Candida D and	[64]

Table 2.11: Three-Axis of Development, Part 1b - Decade: 2000

ID	Year	Author	Reference
09	2002	and Chen, Tony and,	[64]
09	2002	Crawford, Natalie D and	[64]
09	2002	Reichenbach, Eric Y	[64]
10	2003	Voracek, David and Pendleton, Ed and	[116]
10	2003	Reichenbach, Eric and	[116]
10	2003	Griffin, Kenneth and Welch, Leslie	[116]
11	2004	Lokos, William A and Stauf, Rick	[65]
12	2004	Venkataraman, S and Haftka, Raphael T	[114]
13	2005	Airplanes, Boeing Commercial, M. Mohaghegh	[8]
13	2005	Airplanes, Boeing Commercial, M. Mohaghegh	[8]
14	2005	Lizotte, Andrew M and Lokos, William A	[61]
15	2007	Reed, SC and Holford, DM	[96]
16	2009	IEC, International Electrotechnical Commission	[15]
17	2009	Henrichfreise, H and Bensch, L and	[42]
17	2009	Jusseit, J and Merz, L and Gojny, M	[42]

The decade showed that the strain gauge-based loads measurement is employed mainly as part of Life Extension programs or of the operational life fleet monitoring, OLM, of several country air forces, such as USAF, RAF, and RAAF, where the Ministry of Defence established it as mandatory safety tool, [40], [76] and [85]. The Fatigue monitoring reviews of the decade, mainly from Molent, [76], have determined that the majority embedded systems, mainly related on flight hour counting, fatigue meter, flight parameters and hot spot strain gauges, do not require the classical Skopinski calibration.

Lokos and DeAngelis gave another solid contribution to the N.A.C.A. Report No. 1178, [102], for the interpretation of measured flight strains as structural loads in the area of the design of the applied-load test, [65], by a thorough parametric study based on the AWW F/A-18 programme data. Furthermore, Lizotte and Lokos, [61], replaced the strain gauge used in the classical approach by using deflections/deformation as might yield lower testing costs while improving aircraft performance through reduced instrumentation weight. The deflection-based loads measurement revealed a strong bending-moment correlation and slightly weaker torque correlation.

The new science of Wind Turbine Loads Measurement, established by the interaction of designer/manufacturers associated with technical specifications, [15], issued by the International Electrotechnical Commission, leading global organisation preparing and publishing regulations, imposed its existence. This new branch is using strain gauge-based loads measurement techniques raising similar questions as the aerospace field in relation to re-consider the traditional way of calibration as very complicated, time-consuming, weather-dependent and even dangerous. So, reliable calibration methods, analytical-based [15], can replace the traditional one.

These studies might show future aerospace applicabilities.

2.6.4.6 Decade 2010

This is the second decade of the 21st century and it gathers all the very last work of the flight loads measurement science representing the state-of-the-art and offering an idea of the potential future works coming up.

A strong contribution has been given by The Italian Aerospace Research Centre. In fact, it has been developing a research program which is focused on the validation of national aerospace technologies on a flying demonstrator named USV (Unmanned Space Vehicle). The associated papers, [13], [86] and [87], did not contribute heavily on the science, though the USV Flight Loads Measurement campaign likely proved to be one of the most remarkable disclosed project took place during the first decade of the new century. The emphasis is given also as the test cases of Chapter 6 include the USV data.

These first five years of the second decade of the new century show a new trend of development. In fact, the Z direction of "Three-Axis of Complexity" is the most pioneered. The Ground Load Calibration methodology becomes the major topic of contribution of the Science. Fiber bragg sensors load calibration, [115], load calibration uncertainties included in the problem by a numerical method, "Error in the Equation", [36], are significant examples of change of trend compared to the past decades where the object, lifting surface typology, and the type of loads proved to be the major drivers.

Remarkably, a new country started stepping into the research of this sector, Chinese universities and industries dedicated contributions in the area of Structural Health Monitoring, [19], and on Landing Gear loads measurement by proposing a new strain gauge calibration procedure, [106].

The events and concepts above are presented in the following Tables 2.10, 2.11, and A.27, A.28, A.32 and A.30, A.31, A.32, A.33.

Table 2.12: Three-Axis of Development, Part 1a - Decade: 2010

ID	Year	Author	Reference
01	2010	Schmuecker, M	[99]
02	2010	Jebacek, I	[49]
03	2010	Tang, AN and Zhou, ZT and Cao, JT	[106]
04	2010	Belardo, M and Paletta, N,	[13]
05	2011	Schmuecker, M	[100]
06	2013	Gonzalez, M and Gogu, C and Binaud, N and	[36]
06	2013	Espinosa, C and Morlier, J and Quoniam, S	[36]
07	2013	Paletta, N and Belardo, M and	[86]
07	2013	Di Palma, L and Pecora, M	[86]
08	2013	Paletta, N and Belardo, M and	[87]
08	2013	Di Palma, L and Pecora, M	[87]
09	2014	Ding, K and Yuan, S and Wu, Z	[19]
10	2015	Viana, M V P	[115]

2.6.5 Decades Review

Research programmes exploring areas characterised still by many uncertainties, aircraft certified with design spectra different from the real usage and special design features showing lack of understanding of the operational environments, are among the major motivators behind the development of the strain gauge-based flight loads measurement technique.

The reality is that through the decades the complexity, captured by the three-axis of complexity concept, see section 2.6.1, evolved stretching the Skopinski technique till the most critical edge in terms of the three axis directions listed below:

- X- Axis, Object Definition: mainly lifting surface, swept multi-spar low aspect ratio lifting surface and exceptionally a landing gear of civil, general and commercial aircraft/ military fighters/space vehicle/drones. Traditional materials, metal, and non-linear such as composites.
- Y-Axis, Loads Type/Object Operation: The environment where the Object, the aircraft components whose loads are under investigation, is operated. High speed aircraft, Mach 3, Thermal Loads, Design Loads, Buffeting, Control systems.
- Z-Axis, SG-Based FLM Method: It represents the Phases that have been mainly affected, reviewed and enhanced. Definition and Design, D&D, Phase: the strain gauge readings have been replaced by displacements. Ground Load Calibration, GLC, Phase: it has been reviewed in terms, of Heat Temperature Component Rooms, Individual and Distributed Load Cases, Check Load Case, Relevance Coefficient, Load case Magnitude (percentage of the limit loads) and computational calibration. Data Gathering and Analysis, (DG&A 1): This area is the one addressing the strain gauge selection to select high quality load

equations. Major concepts introduced are Loads Probable Error, Influence Coefficient Plots, Influence Coefficient Plots of Loads Equations, T-Method, Modified T-Method, and Genetic Algorithms. Comparison and Validation, (C&V): Mainly comparing the measured loads with evaluated theoretically, wind tunnel, deflection-based evaluated, pressure transducers.

From this break down it comes clear that to enhance the science the areas to focus on are mainly those related to the Data Gathering and Analysis, on Ground, and the Validation and Comparison. In particular, it came evident that the typology of the object under investigation, X-axis, mainly represented by the aspect ratio, and the specific PITS to consider, determining the loads typology, Y-axis, have been the major drivers of the science. So, the parameters chosen to develop the novelties of this research are meant to be in function of the X and Y axes of the 3AC in order to be representative and significant to the science of Flight Loads Measurement. This research will be attempting to contribute in these directions as the next chapters will describe.

2.7 Summary

The chapter highlights the motivations behind the aircraft structural health and usage monitoring, safety and costs. Furthermore, it shows how the aircraft structural integrity is maintained in the different phase of the life of an aircraft. Damage detection and loads monitoring are the two major pillars of this science and special focus is dedicated to the second, mainly on the strain gauge-based loads measurement.

In order to better characterise the science of the flight loads measurement it has been necessary to introduce a specific metric, labelled the Three-Axis of Complexity, 3AC. This identifies the two major directions of evolution through the decades of conception of the Skopinski technique up to date, enabling to capture the most extreme points still reachable nowadays and the future areas of improvements.

The selected parameters to develop the novelties of this research are meant to be in function of the X and Y axes of the 3AC in order to be representative and significant as the science of Flight Loads Measurement shown through the last decades. Moreover, the Test Cases Data employed later on, to validate and assess the performance of the techniques introduced, should be covering, as long as the available literature data will allow, a wide spectrum of aspect ratio and loads typology to offer a representative judgement to be extended to future areas of research.

The translation of the strain gauge selection techniques, identified through the Decades of evolution of the flight loads measurement science, into programming language codes to enable a performance comparison of an unmanned space vehicle dropped transonic flight test data is the heart of the next chapter.

Chapter 3

The LETE Environment

3.1 Introduction

The [chapter 2](#) and last decade scientists researches [[65](#)] showed clearly the accuracy of the strain-gauge measured flight loads science is mainly driven by many variables that can be grouped, for example, into *the design of the strain gauge installation and alternatives*. In fact, Lizotte and Lokos [[61](#)] proposed a deflection measurement system as part of an aeroelastic campaign and Culshaw, Krohn, Udd and Claus took at a higher level the optical fibre sensors studies in this field [[105](#)]. At the same time, another area of potential improvement is *the design and performance of the applied-load test* where Lokos [[65](#)] addressed parametric study of various aircraft wing-load test features on the final flight loads measurement accuracy. Ultimately, *the strain-gauge load equation derivation process* is the reaming direction of investigation of this field that will be addressed by this research within the current chapter and will be continued in [chapter 4](#) through a more detailed analysis of each relevant concepts.

In fact, this very last group of areas of improvement will be the core of [chapter 4](#) where all the most relevant techniques for the calculation of the flight loads equations will be heavily inquired and broken down in a such flow chart template to allow highlighting the commonalities and major differences and setting the context to understand the *new proposed method*.

Over the years, no matters whether dealing with research investigations, structural integrity demonstrations, and developmental flight testing finding loads equations that assure to be the result of reliable strain gauges capable to read the real flight loads experienced proved to be a serious challenge. So, the *Research* came in to offer tools and approaches capable of reducing the uncertainties, though paying a toll requiring further cost and time efforts, and being very limited to a specific structure configuration.

In a similar context LETE (Loads Equations Techniques Evaluator) philosophy is founded on continue using all available techniques from the past and combining

all major findings as part of a new method. These will be choosing, either through a step by step or automated process, the one that can produce best performance tested against an independent set of data representative of the point in the sky load conditions to measure. Though, this will be the topic of [chapter 5](#).

The current chapter will be presenting just the LETE environment, gathering all these methods, interconnected in such a way to allow, under a unique Python code, whose details will be gathered and presented in Appendix B, evaluating the best set of loads equations by means of dedicated test cases data.

At the end a very sensitive topic, regarding the validation of the whole LETE code and process, will be taken up. The basic introduced concepts will be further broken down and detailed inside [chapter 5](#).

3.1.1 Aims and Objectives

The main objectives outlined below justify the necessity of carrying out the study on the niche area of the strain gauge-based flight loads measurement loads equations calculation:

1. Unique environment for performance comparisons.
2. Using simultaneously several methods with different characteristics allows to use the one that best suits the test article configuration.
3. Available option to use a step-by-step or automated approach.
4. Introduction of the the package *I2D* as supporting tool developing numerical distributed loads sample whose centre of gravity is close to the centre of pressure to experience in the flight loads to measure.
5. New ranking criteria, *LPP*, based on linearised physical parameters varying according to the type of loads to measure.
6. The ICLE automated approach can produce same results of the visual investigation once defined a reasonable linearity parameter threshold, Coefficient of Determination (R-Square).
7. Special Adaptation of the past Techniques in order to fit into the LETE Python environment.
8. The adaptation involves the incorporation of special additional parameters, such as performing the Genetic Algorithm of Nelson, [79], by an exhaustive search technique driven by the same initial fitness function.
9. The *proposed new method* performance will be compared to the current state of the art.
10. The LETE environment enables rapid processing of the GLC data and loads equations selection process.

11. According to the reliability of the independent (validation set) data set assessing the best set of loads equations the introduction of a ranking criteria based on physical quantities, instead of just statistical as the standard deviation, gives chance to select best set of loads equations.
12. The environment robustness will be assessed in two major directions; validation of the codes and performance assessment of the new proposed method concepts.
13. The environment will be pioneering the new concept of developing loads equations by use of two, distinctive, though perfectly identical in terms of design and instrumentation configuration, prototypes. Allowing to execute ground load calibration on one and flight test on the other prototype. This is a major point in any Flight Loads Measurement campaign where the *GLC* is always a critical stage as the high magnitude of the load cases might damage the prototype.
14. The usage of an independent (validation set) distributed data set, with similar distribution, centre of pressure, of the loads to measure to assess the generated set of loads equations brings to those methods, such as Skopinski, T and MT-values and Nelson's GA, totally based on statistical concepts, an inherent ability to select better LE closer to the reality. All this possible through an iterations of the ILD check case.
15. The LETE environment will be a powerful tool as offering to choose the technique that best suits the test article configuration and available data.
16. This environment is not a single unique block. That brings extreme flexibility to chose whether make the process automated or not by selecting one technique than another according to the needs of the end-user contextualised by the typology of test article, data and operation of the whole flight loads measurement campaign. Different level of intermediate results, *Specific* or *Global*, see section B.1.6, offers the choice to better understand the major steps of the calculation process and the level of details to support the final results.

3.2 The Framework

The LETE framework is the result of all available different strain gauge selection techniques, past and new, whose detailed load equations computational process will be described in the next [chapter 4](#).

The core of the whole loads equations calculation environment, refined from the list of Table 4.2, is condensed in the areas below:

- **Data:** The two major types of data have already been introduced in section 4.5.1 as Dependent (Training Set)\Independent (Validation Set) Data, DD and ID, where data is a wide label including *loads* and their associated strain

gauge readings. Now, besides the Calibration label used in section 4.5.1, each DD and ID can be of two different types, Individual, single point load cases, or distributed, multi-point loads. Each dependent and independent data can become individual or distributed in different ways. This concept is clearly represented by the Flow Chart of Figure 3.1 under the label of "Double E" Data Type. Data can be Experimental, either Ground or Flight, or Numerical, such as FEM or any other programming package. Alternatively, can be an Hybrid with a combination of Experimental and Numerical. All these can be also considered by the model of LETE that does not make any distinction between numerical or experimental as long as the input data has the same requested format.

- **Ranking Criteria:** As profusely described in sections 4.3, 4.4 and 4.5, each Technique performs differently mainly due to the Ranking Criteria that is the result of two major categories. The first, relates on Statistics Quantities, stats, such as standard deviation, the other on Physical parameters, *physical*, such as influence strain gauge and loads equations coefficients.

Table 3.1: LETE Techniques (Tech.): Ranking Criteria (RK) and Data Type (DT).

Tech. ID	Scientists	RK	DT
01	Skopinski et Al. [102]	Statistic	IDD
02	Hovel et Al. [43], [44]	Statistic	DDD
03	Jenkins et Al. [54], [53]	Physical	IDD
04	Sefic et Al. [101]	Statistic	IDD
05	Tang et Al. [109]	Statistic	IDD
06	Nelson [79]	Statistic	IDD
07	Jenkins et Al. [50]	Statistic	IDD
08	Chedid	Physical	DDD

Data and Ranking Criteria of each *Technique*, employed in the LETE framework, are described and referred by means of code numbers, linked up to the Authors and their Loads Equations Calculation Methods, inside Table 3.1.

The whole LETE framework is easier to comprehend if using a top-down analysis approach by means of the Data and Ranking Criteria just defined that intervene substantially in determining the flow of the major quantities through the whole process. There are three major stages, as Figure 3.2 shows, identified by the number on the right top of each semi-dotted rectangular line, and each has its own **Input**, **Output** and black box **Transfer Function**. For clarity, the *Transfer Function* of each stage varies as it represents any mathematical simple equation or complex algorithm that uses an input to generate an output. The "Output" of one stage becomes "Input" of the next stage. This simple concept is further broken down by introducing the "Double-E" Data Type of Figure 3.1. In fact, Figure 3.3 displays a generic transfer function that works with the two major type of

data already introduced. The *DD*, Dependent Data, always feeds the black box (transfer function), and this according to the available data can be a result of individual or distributed load cases. On the other hand, the *ID*, Independent Data, by definition cannot be used to develop (as input) the loads equations, in fact, normally is employed to check the transfer function output validity. These two common dependencies are shown by the single solid lines of Figure 3.3. The interesting part of this idealisation is described by the other two different types of lines connecting the individual or distributed Dependent or Independent Data with the *Transfer Function* box. The first, semi-dotted line, shows the classic approach of the past load equations techniques using the *DD* also as part of the ranking criteria, normally by means of the Loads Probable Error, Eq. (4.4). On the other hand, the double solid-line describe the proposed LPP technique, section B.1.7.9, where an independent set of data, different from the check case one employed with the output, either individual or distributed load case, is used as part of the final process to define the best set of load equations. This is an essential difference brought in by the novelties of this study whose weakness, not having available enough data, can be bypassed by introducing the concept of the distributed sample data, explained later in the chapter and in Appendix B, and realised by the *I2D* code.

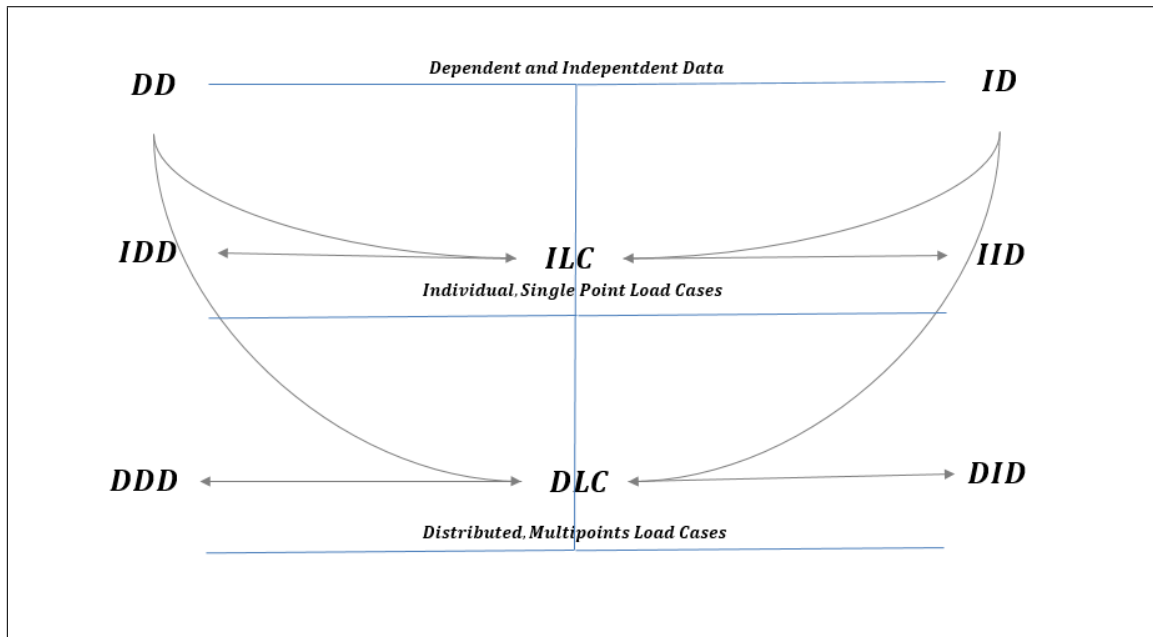


Figure 3.1: "Double E" Data Type: Dependent (Training Set)\Independent (Validation Set) Data combination.

3.2.1 Framework Stages Breakdown

The starting point to translate this LETE framework in a coded program is to clearly point out the following entities; Inputs/Outputs/Transfer Functions of each stage and then link them all as part of this environment. It follows a list of each Stage major entities necessary to characterise the backbone of the next Python Code,

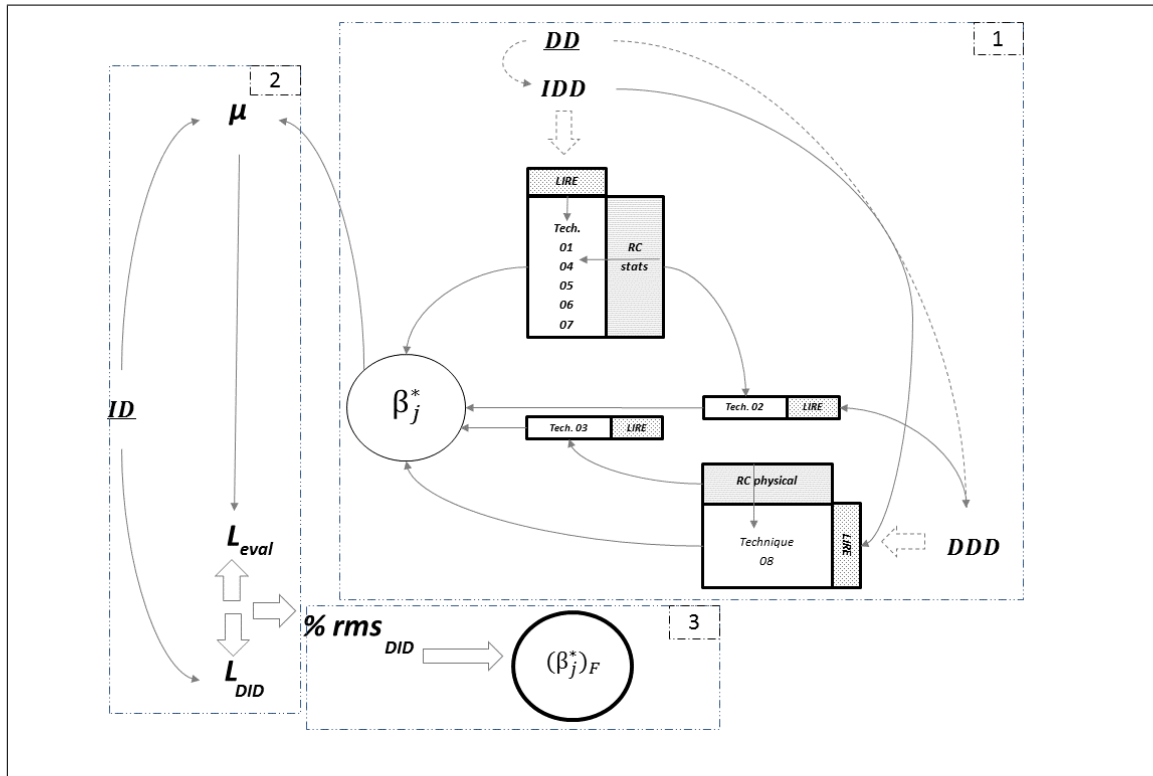


Figure 3.2: LETE Environment: The Framework.

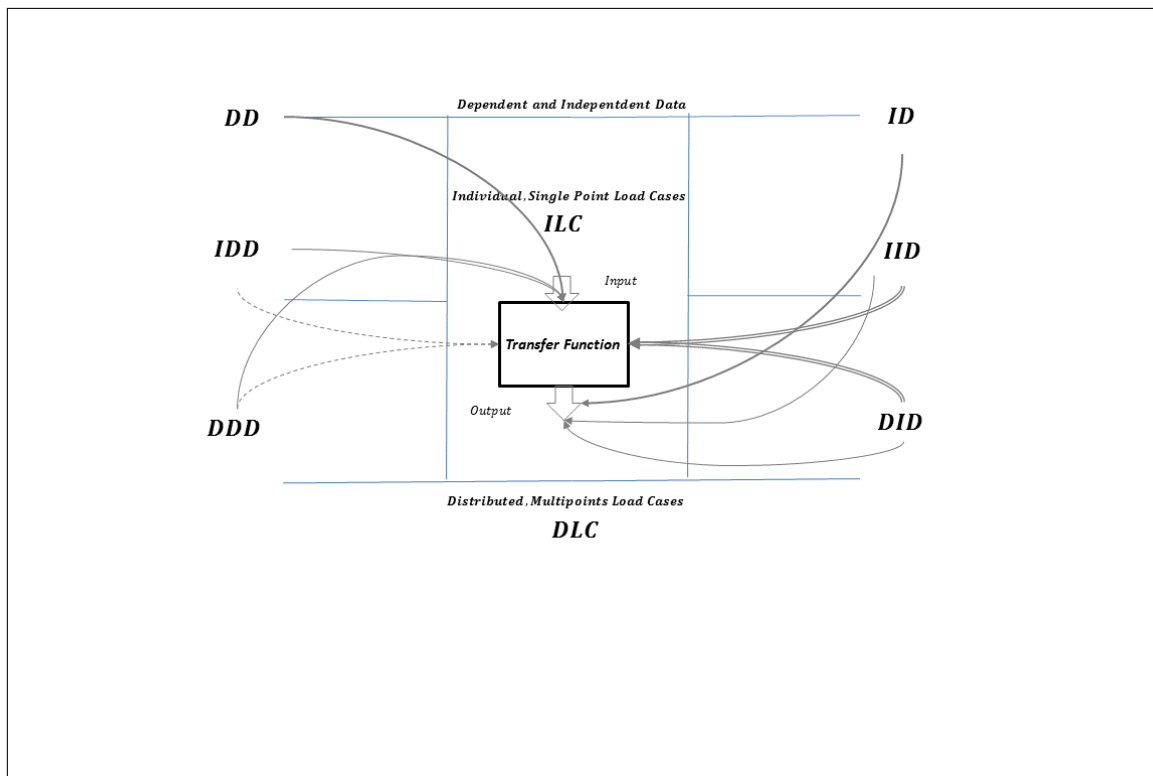


Figure 3.3: LETE Environment - Transfer Function and "Double E" Data Type: Dependent (Training Set)\Independent (Validation Set) Data combination.

Appendix B.

The Stage One, is summarised by the following:

- **Input I & II:** Dependent Data, DD, that divides into Individual and Distributed Data, IDD and DDD. This stage has two Input data sets, both are coming externally from LETE.
- **Transfer Functions:** It is the box of Figure 3.2 displaying the generic functional idealisation of the generic Transfer Function, made up by LIRE, Ranking Criteria, RC, and the Technique, Tech.. The LIRE, Linear Regression, invariant part for all the Techniques employed in this LETE framework, has the role to take on Eq. (4.1) fed by the Data Box, either IDD or DDD, and according to the Ranking Criteria, stats or physical, will produce the best set of load coefficients of each Technique employed. There are two transfer functions, *Tech. 02* and *Tech. 03*, appear detached from the others. This is due to the fact that those have intertwined Data and Ranking Functions as further shown in Table 3.1.
- **Output:** The final product of this stage is given by the best set of load coefficients, $\beta^{(*)}$, highlighted by the solid black circled line of Figure 3.2.

At the end of *Stage One*, LETE is supposed to initiate the phase of checking the performance of the set of loads coefficient, $\beta^{(*)}$, of each technique by employing a Check Load Case Condition.

This is *Stage Two* and the major information is listed below:

- **Input I:** Independent Data, ID, at the same way of the Stage One it can be divided into Individual and Distributed Data, IID and DID. Though, Figure 3.2 shows how the framework is flexible enough to use any of these. Next chapters will show more on this. This input data is external from LETE.
- **Input II:** This Input is represented by the best set of load coefficients, $\beta^{(*)}$, output of *Stage One*. This input data is internal to LETE.
- **Transfer Functions:** Basic application of Eq. (4.1) known the Load Coefficients, $\beta^{(*)}$, and the Strain Gauge readings, $\mu_{(ji)}$.
- **Output:** The final product of this stage is identified by the Measured Loads, obtained as a result of the strain gauge readings of the Independent Data, ID, set multiplied respectively by the best set of load coefficients, $\beta^{(*)}$, output of *Stage One* and Input II of *Stage Two*.

Ultimately, *Stage Three*, is assessing the most suitable loads equations computational Techniques, by comparing the Measured Loads, Output of *Stage Two*, against the Calculated evaluating the % rms by means of this it will be chosen the most suitable, according to the specific test article and input data, set characteristics. In fact, despite of all possible manipulations on the data, such as obtaining Dependent

or Independent Distributed data, DDD and DID, numerically or experimentally, the Techniques Execution, Stage One, and the Checking Phase, Stage Two, all depend heavily on the quality of the Inputs. This will be highlighted to be a crucial double check to execute if the final accuracy of the flight loads measured will be still poor. *Stage Three* basic information follows:

- **Input I II:** There are two independent inputs, the Measured Loads, output of Stage Two, and the Independent Loads, coming from the Independent Data of Stage Two.
- **Transfer Function:** Basic application of the percentage of root mean square error Eq. (B.1) known the Measured and Calculated Loads.
- **Output:** The final product of this stage is given by the best set of load coefficients, $\beta^{(*)}$, highlighted by the solid black circled line of Figure 3.2.

3.3 The LETE Process

The whole framework thoroughly described above is clearly summarised by Figure 3.4. In fact, the major top level information is pointed out. There are two external *Input* sources, double black solid line boxes, and two internals, solid black line circled boxes, Load Coefficients, $\beta^{(*)}$, and Measured Loads, L_M . These two at the same time, as part of each stage, become internal *Outputs* too. In addition, using Figure 3.4 synthetic view it is immediate to see that each stage transfer functions, represented by the solid rectangular boxes, is responsible to transfer the data from one stage to another till the very final LETE output product. In *Stage Two* and *Three* the black boxes, **TF2** and **TF3**, are unique and simple equations, Eq. (4.1) and Eq. (B.1), on the other hand, *Stage One*, **TF1**, is more complex as represented by the different Techniques algorithm.

Each Technique, is represented by the template described in Figure 3.5. The *i-th* *Technique* functional idealisation is encapsulated on basic concepts, on which the next Appendix B sections, describing the LETE Python Code, relies on, listed below:

- All techniques use the output of a Linear Regression Code, *LIRE*.
- *The Ranking Criteria (RC)* determines the final selection of the strain gauges of the final best load equations developed, $\beta_j^{(*)}$.
- *LIRE* and *RC* work together either in series or in parallel as part of the straight process as inside an iteration cycle. This is determined by the type of Technique rules and will be detailed in the next part of this chapter and Appendix B.

The two points above can be repeated as many times as the Techniques require, as represented by the semi-dotted line going back to *LIRE* to develop new load coefficients for a new set of strain gauges Eq. (4.1).

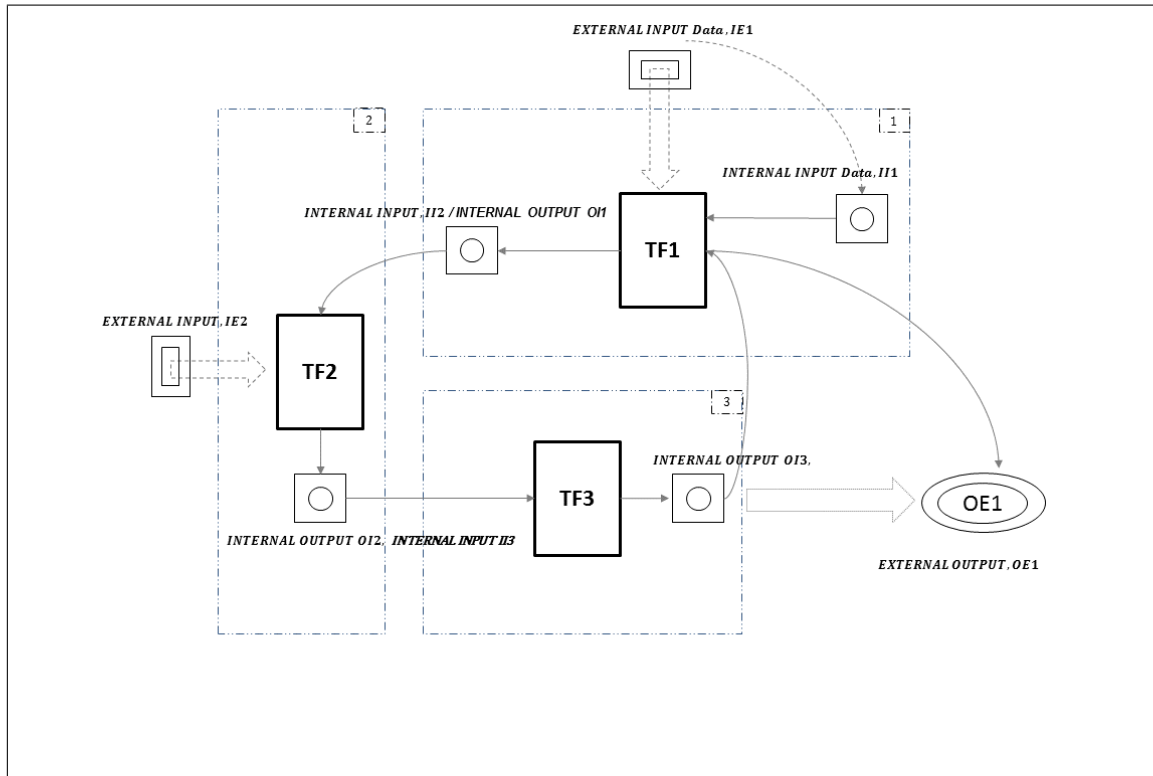


Figure 3.4: LETE Synthesis: Inputs, Outputs and Transfer Functions.

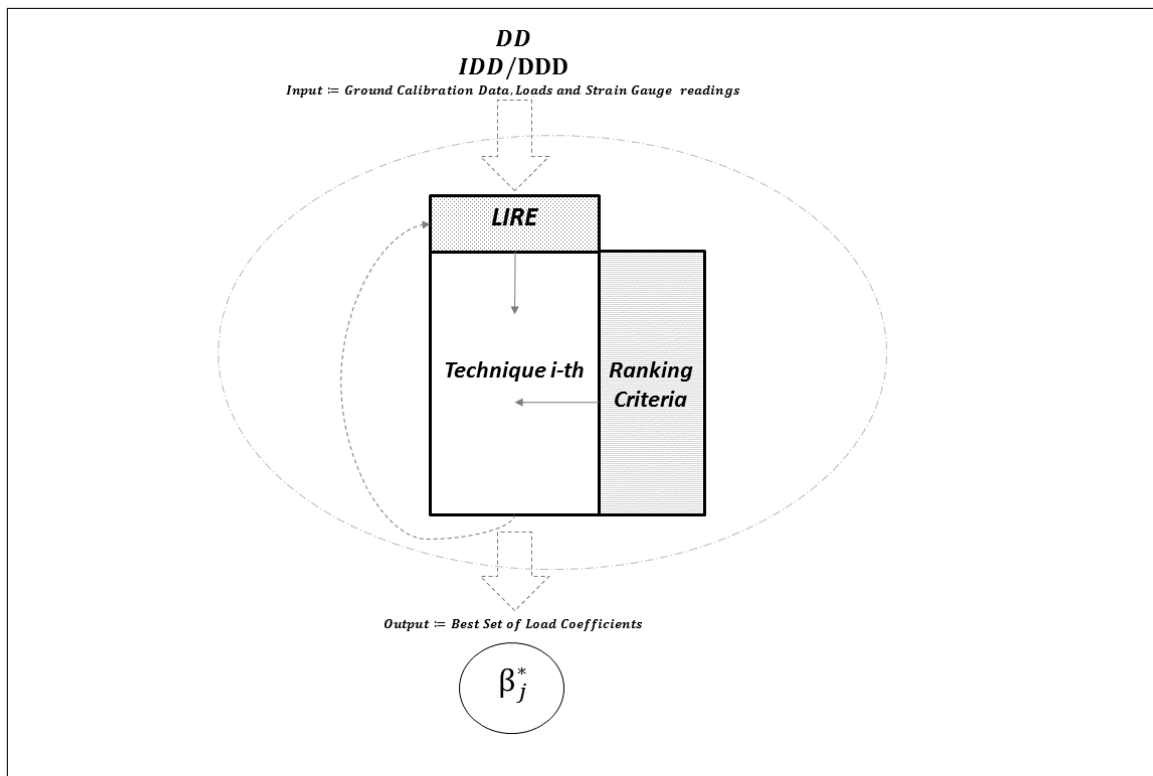


Figure 3.5: LETE Stage 1: Technique Functional Idealisation.

As it will be consistently proved by the next section, the LETE framework has been conceived as such to be flexible enough to host experimental or numerical

data still maintaining the logic invariant. At the same time, the Transfer Function of Stage One, **TF1**, can be expanded embracing any other Technique without affecting the following two stages.

This shows the robust philosophy on which the whole environment is founded justifying to take the all framework to the next level that is represented by coding in a software package in order to apply it to a real test case. The challenge will be represented by using the right programming language and software architecture to perpetuating the same values and characteristics of LETE highlighted above, mainly in section **3.1.1**.

3.4 LETE Validation

At the end of the conceptual and software description of the Appendix B *LETE* environment questioning about its validation becomes a natural step forward.

There are two different levels of validation, one purely related to the codes developed to comply with the clear equations of transfer functions and supporting tools described so far. On the other hand, it is a validation/assessment of the novelties proposed, *the LPP Method*, and its performance compared to the past techniques. Missing to control the robustness of the results produced by the past techniques inside LETE cannot allow to make a reliable assessment, interpreting strength and weaknesses, of the novelty proposed.

These goals will be made possible through the introduction of specific *Test Cases* part of the available literature or research centre projects.

The coming up Chapter 5 will be focusing to take on the task of validation by employing real data experimental test cases.

3.5 Summary

The LETE environment has been introduced by showing its major expectations, aims and objectives of section **3.1.1**, and proving the way will be achieved by translating the ideas into lines of Python codes. Still few of these expectations, in order to be fully appreciated, needs to be tested through the double validation process stage of the following chapter, initiated in section **3.4**.

A logical step-by-step approach has been used to further justify the decision to employ the open source Python as unique programming language, eventually hosted by a freemium scientific complete package, Anaconda, and its own integrated development environment, IDE, Spyder, **B.1.4**.

The LETE code has been dissected by a top-down logic flow chart approach that identified the major pillars of the whole environment under three major categories, Input/Output, Transfer Functions and Supporting Tools. Each of these has been further examined highlighting the basic information necessary to allow testing, maintaining and assessing the quality of the each independent package for the flight loads equations computation task.

Summary

This chapter contributed to continue the description of the evolution process the novelties of this research within a specific framework. Chapter 4 will further detail the strain gauge selection process, witnessing the inception of the proposed method, labelled *LPP*, and the supporting tool *I2D*. Chapter 4 will justify how the harmonisation of *LPP* within the past loads equations calculation techniques requires the existence of *LETE*.

Chapter 4

The Strain Gauge selection Techniques: Past and New

4.1 Introduction

The three-axis of complexity introduced in [chapter 2](#) showed how the science of the strain gauge-based flight loads measurement went through an evolution process influencing mainly the Ground Load Calibration, GLC, and Data Gathering and Analysis, DG&A, respectively Phase 2 and Phase 3 of Table [2.1](#). This as a result of the changing typology of the lifting surfaces, slender and multi-spar low aspect ratio wing, and their consequent different environment of operations, hypersonic aircraft and associate thermal loads. The accuracy of the final loads equations was affected and the research started focusing on the whole computation cycle required.

This chapter will be reviewing the major quantities and steps needed to develop accurate loads equations and will be presenting a new "*Proposed Method*" for the computation of strain gauge loads equations by attempting to improve the accuracy and the readiness of execution of either a design DLM, [2.5.1](#), or operational loads measurement OLM, [2.5.2](#), campaign. In order to do so, the current available methods to develop load equations will be described and the new methodology will be linked to next chapters applications and performance evaluations steps.

4.2 The Structural Problem

The primary emphasis is on explaining the total physical procedures of calibrating strain gauged structures and all the supporting analyses and computational techniques that have been used. The load-calibration science will be studied using the results and experiences obtained from the actual available data and experiences involving the major scientists of this very specific area, [4.3](#) and [4.4](#).

The method is based on applying a significant number of dissimilar point loads to create a variety of combinations of shear force, bending moment and torsion at the

strain gauge positions. The response of each channel to each load will be put into a matrix and a least squares solution will be found to derive a load equation as a function of channel outputs.

Once selected the gauge location and identified the measurement station, strain gauge station, it is necessary to locate the gauges at positions where the stress levels will be adequate to obtain good sensitivity and, at the same time, be away from areas of local stress concentration. Ideally, it would be desirable to place the gauges at a position such that a shear bridge would respond only to shear (the web spar), and, as in reference [45], a moment bridge only to moment (the cap spar), and so forth, but generally it is only in an elementary truss type of beam that locations can be found where such a simple relationship between load and strain exists, and proves to have constant or linear trend, see Figure 4.1. This concept will be shown later as one of the major pillar of the proposed method, 4.5.

Skopinski, Aiken and Huston. [102], stated that a wing structure, or any lifting surface, which obeys Hooke's law, the stress in a member and, therefore, the output of a strain gauge mounted on that member may be taken as some function of the three principal terms pertinent to aerodynamic loads investigations, the lift or shear, the bending moment, and the pitching moment or torque.

Mathematically speaking the response $\mu_1\mu_2\dots$ of the gauges $G_1G_2\dots$ can be combined

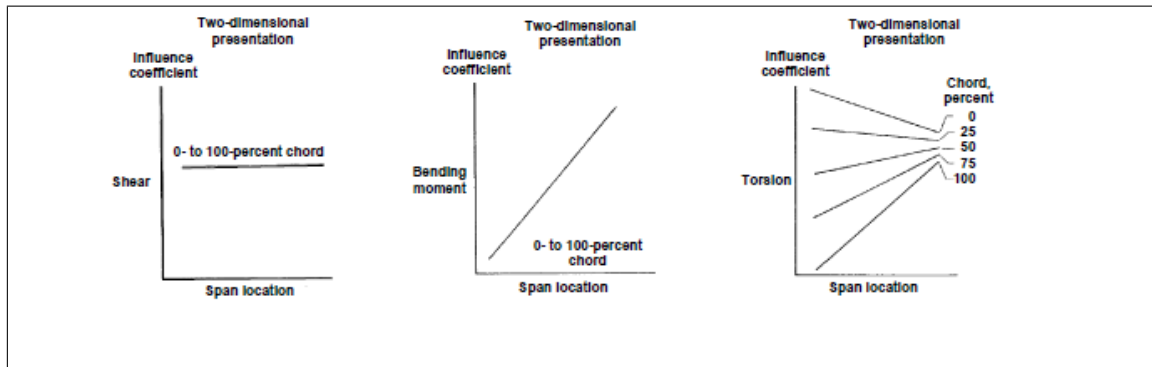


Figure 4.1: Ideal Strain Gauge Influence Coefficient Plots, [51].

such that, for example:

$$M = \beta_{11} \mu_1 + \beta_{12} \mu_2 + \beta_{13} \mu_3 \dots \dots \dots (4.1)$$

where in Eq. (4.1) "M" is the overall bending moment at the chosen section and $\beta_{11}\beta_{12}\dots$ are coefficients obtained from the calibration data by regression analysis. Similar equations to Eq. (4.1) are obtained for the shear "V" and the torque "T".

The statistical Skopinski approach, whose load equation selection criteria is mainly based on the Load Probable Error (LPE) factor (expressed in function of the square residual error defined as the difference between calculated and applied load values), might be unsatisfactory as long as the strain gauge quality health check has not performed too. In fact, linearity of the readings and absence of any hysteresis behaviour is something pivotal for general robust load equation trend but not sufficient yet to establish the inherent predominant loads type, shear, bending or torque. Basically, something else is meant to be produced to rely on.

As pointed out in connection with Eq. (4.1) the number of bridges required for

a given load equation depends upon the response characteristics of the bridges. Experience has shown that, when shear bridges are placed at a given station on the webs of all spars, bending moment bridges on the flanges or skin, and torque bridges in the torque boxes, enough bridges will be available to develop an equation for shear, or moment, or torque. Though, the tool, already suggested in 1954 by Skopinski, Aiken and Huston in the NACA Report 1178, [102], is the strain gauge influence coefficient plot, IC.

The influence coefficient plot, most informative manner of presentation for load calibration data, provides a way to look at the strain per unit applied load as a function of span for a given chord location for each strain gauge bridge. A plot of this nature is useful in determining whether a particular bridge is affected predominantly by shear, bending moment, or torsion loads, by a combination of two, or even by all three.

The influence coefficient is defined as:

$$I_C = \frac{\mu}{L} \quad (4.2)$$

where μ is the strain-gauge bridge output and L is the applied load.

The output can be in strain, volts, or counts, depending on how the user decides to handle the data. The common visual analysis mechanism is to plot the influence coefficient as a function of span and to approximate the contours of constant chord. Figure 4.1 shows an ideal shear, bending, and torsion response while Figure 4.2 depicts examples of combined responses, full linearity is lost, at different percent of the chord of the M2-F2 tip fin, [50]. The influence coefficient plots exhibiting non-linear behaviour are mainly due to the strain gauges root installation area, in proximity of the attachment wing to fuselage. These root trends are characterised by irregularities, and deviations from the general outboard trend. This is justified by the local effects caused by the close proximity of the load, wing-fuselage reaction forces. Additionally, materials and geometry instabilities, buckling, can be other causes of non-linearity, though, not fully applicable to this research.

While the data used to develop the loads equations is by individual load points, Skopinski et al., suggested to introduce a distributed load case to be applied as a check on the final calibration equations. In fact, this would have helped to further assess the accuracy of the chosen loads equations though still mainly based on the statistical metric, the Load Probable Error. In fact, before ranking the loads equations, the Influence Coefficients are just used to assess individually the strain gauge responses quality to prevent redundancy, some bridges may have such similar characteristics that the output of one is a linear multiple of the output of another. This *distributed check case* represents one of the first and major efforts to accomplish the Phase 6 of Strain Gauge-Based Flight Loads Measurement Phases, Table 2.1. The major Phases evinced to be the object of the research to enhance the accuracy of a Flight Loads Measurement campaign are Phase 2 and 3, Ground Load Calibration and Data Gathering & Analysis, where the ultimate goal is generate robust set of loads equations. Next section will be focusing on the major steps needed for the development of Loads Equations.

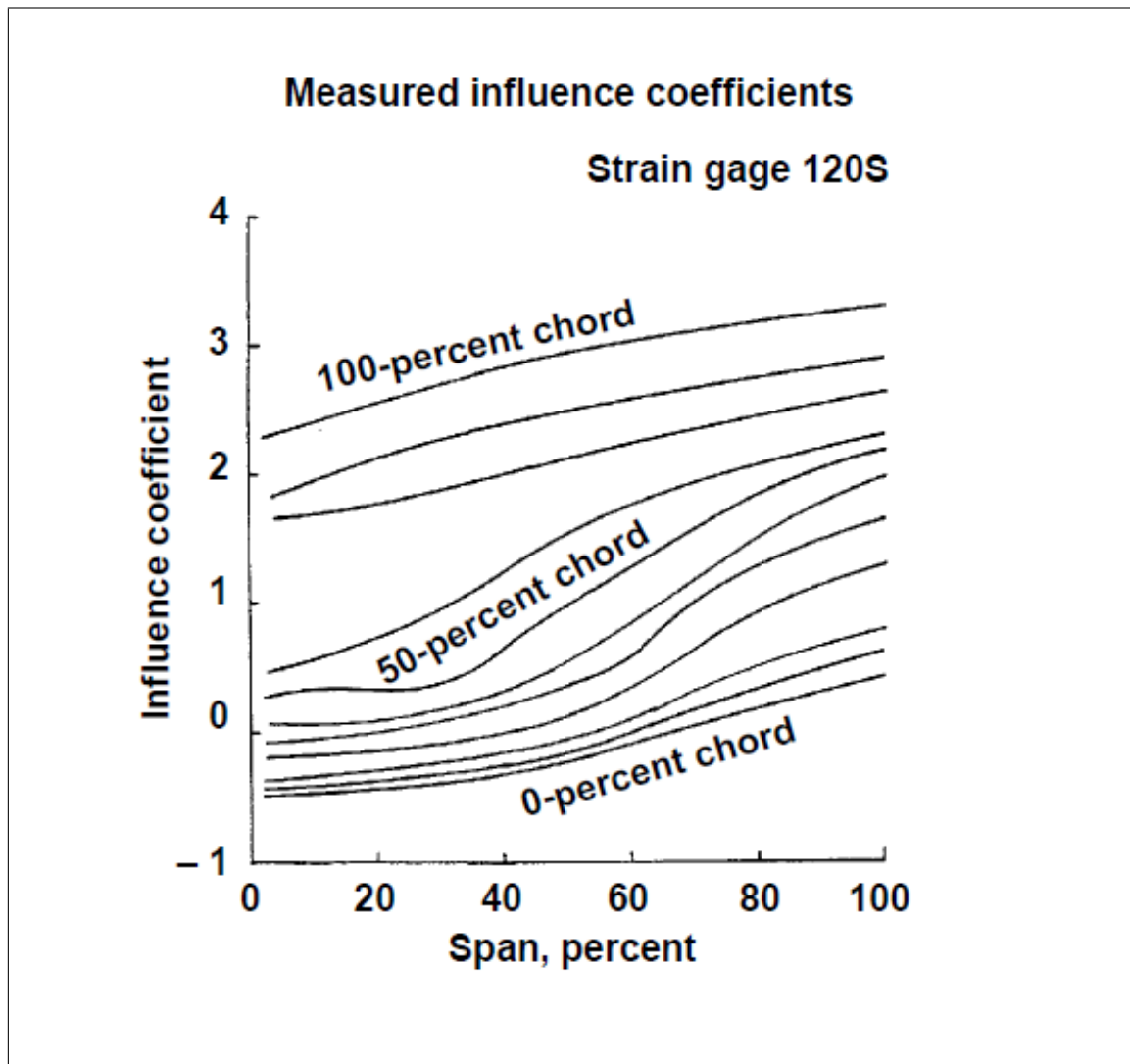


Figure 4.2: Non-Linear Responses: Real Strain Gauge Influence Coefficient Plots, [50].

4.3 Loads Equations Computation: The Original Approach

Before introducing the Proposed Method, 4.5, expected to improve the robustness and the readiness of the loads equations development process, first, it is worth pointing out the major sequence of the interconnected activities captured by Skopinski for the evaluation of the final set of loads equations.

The schematic computation to generate the final set of loads equations, as Skopinski explained, is described in Figure 4.3. The two major Table 2.1 Phases affected are the GLC, Phase 2, and DG&A, Phase 3.

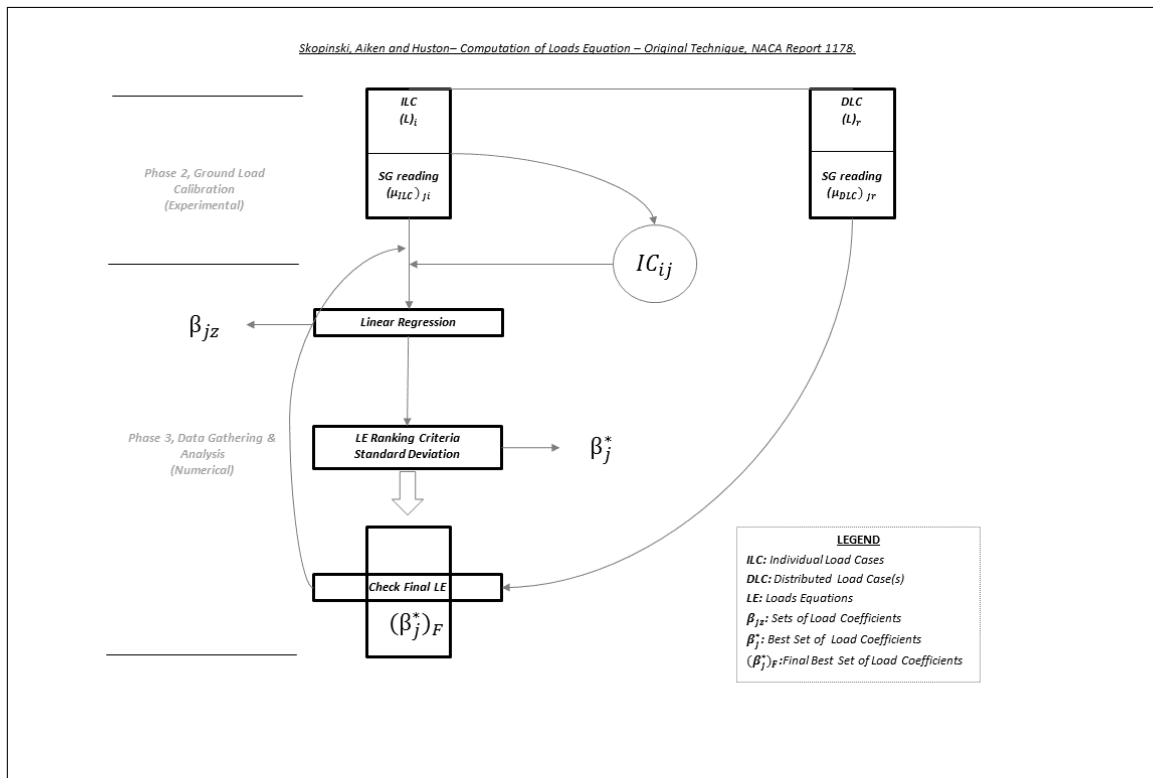


Figure 4.3: Schematic of Computation of the Loads Equations - Original Skopinski Approach, [102] - Decade 40s and 50s.

The first, experimental, once chosen the station to measure the loads and consequently installed the strain gauges is characterised by two different types of load case sets. The Individual Load Calibration, ILC, identifies those loads, (L_i) , generated by single application points, chord and span wise on the lifting surface object of the flight loads measurement, and their associated strain gauge readings, (μ_{ij}) , that will be used to compose the Eq. (4.1) from which evaluating the load coefficients, (β_{jz}) , through least square solution. These load cases are known as dependent load case, as used to generate the final set of loads equations. Each load equation will have as many load coefficients, "j", as the installed strain gauges of the measurement stations. The number of load equations available "z", results as a combination in base 2 of all strain gauges. For instance, a torsion box as the one in

Loads Equations Computation: The Original Approach

Figure 4.5 with four strain gauges, two on the web and cap of the front and rear spar, will have $(2^4 - 1) = 15$ loads equations¹.

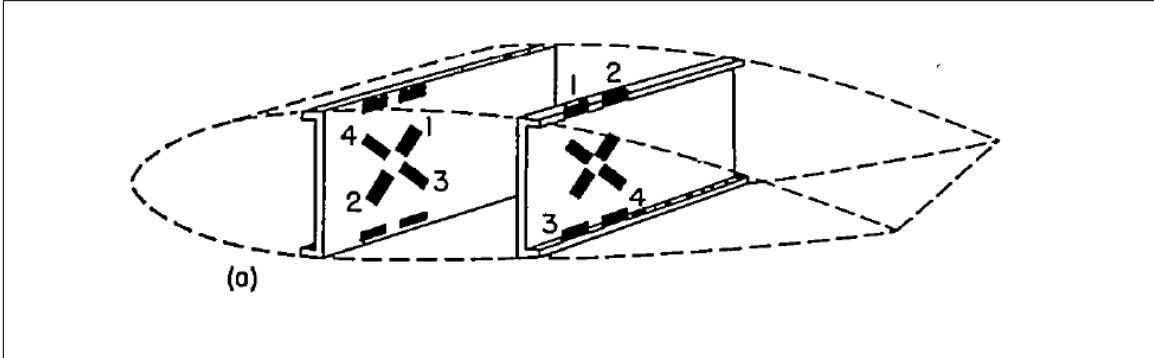


Figure 4.4: Typical Strain Gauge Installation of a Front and Rear Spar Torsion Box, [102].

All possible fifteen combinations of a four strain gauge load equations are shown in Table 4.1. The sixteenth equation, with all zeros, is counted out as does not make sense Eq. (4.1) with all four strain gauges equal to zero. Skopinski^{4.1}, to select the best strain gauges combination out of the fifteen presented^{4.1}, introduced the Load Probable Error, LPE, defined by Eq. (4.4) below:

$$LPE = \sqrt{\frac{\sum_{j=1}^m [V_j - (\beta_0 + \sum_{i=1}^n \beta_i \mu_{ij})]^2}{m - n - 1}} \quad (4.4)$$

Eq. (4.4), despite the label LPE, it represents the well known standard deviation, typically denoted by σ . This ranking criteria helps to quantify the error associated with an equation. It represents the measure of how well an equation matches the actual load applied, V_j . The meaning of the quantities introduced in Eq. (4.4) follows:

- V_j : Calibration Load (shear) applied to the structure
- β_0 : Constant in Loads Equation
- β_i : Coefficient of the i th strain gauge in loads equation
- μ_{ij} : j th reading of the i th strain gauge
- **m**: Number of data points taken during loads calibration
- **i**: Index used for gauges in loads equation
- **j**: Index used for data points

¹Combination without repetition. Binomial Coefficient of n -elements and k -combinations:

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} \quad (4.3)$$

The smaller the Standard Deviation, σ , the more closely the equation matches the dependent calibration data, and therefore the better the equation. Though, this statement highlights the statistical inherent characteristic of the Skopinski ranking criteria heavily driven by the input data.

Table 4.1: Four-Strain Gauge (SG) Torsion Box: All Possible Loads Equations (LE) Combinations.

LE	SG1	SG2	SG3	SG4
01	1	0	0	0
02	0	1	0	0
03	0	0	1	0
04	0	0	0	1
05	1	1	0	0
06	1	0	1	0
07	1	0	0	1
08	0	1	1	0
09	0	1	0	1
10	0	0	1	1
11	1	1	1	0
12	1	1	0	1
13	1	0	1	1
14	0	1	1	1
15	1	1	1	1

The other load case set, is the Distributed Load Calibration, known as Independent Load Case, as part of the whole process to develop the loads equations is not contributing to mathematically obtain the load coefficients (β_{jz}), but just as independent check to assess the final set of load coefficients, $((\beta_j)_F)$. As shows Figure 4.3, if the comparison of the measured loads obtained with the load coefficients resulting after the loads equation selection, by means of the *ranking criteria*, will not satisfy a basic threshold of standard deviation, the process will re-start just before employing the influence coefficient points, (IC_{ij}) . The new loop will require to re-consider if the strain gauges counted out by the IC plots are appropriate and if the ranking criteria employed to reduce all possible loads equation combinations will lead to a new more accurate set.

These activities described above following the strain gauge calibration are part of the Phase 2 and represent the numerical process required to obtain a robust set of loads equation. Through the decades Figure 4.3 has been going through several reviews driven by the attempt to keep up with a new typology of structures, high speed and altitude airplane. Among the several concepts already identified by Skopinski and introduced to reduce the uncertainties of the flight loads measurement science the influence coefficient, supporting tool to assess the reliability of each single strain gauge, and the Distributed Load Calibration data, loads and strain

gauge readings, used to compare and validate the final chosen loads equation, are worth mentioning.

The major research activities took place through the last six decades will be taken in turn reviewing the Skopinski framework of Figure 4.3.

4.4 Loads Equations Computation: Techniques Evolution

The complexity of load calibrations using strain gauges has increased as the complexity of the structure and materials has also increased, as the three-axis of complexity shown before, 2.6.5. Straight wings and tails with few and dominant spars characterized early airplane structures making Skopinski principles appropriate in such environment. Swept wings and delta wings with many spars emerged later. Complex structures such as integrated honeycomb skins and corrugated webs led to strain gauges being located in less-than-optimum places. Composite materials, many of which are anisotropic, also emerged to further complicate the situation. High-speed airplanes experienced significant aerodynamic heating that affected the nature of strain-gauge responses. All of these factors challenged the load-measurement engineer to adapt and create new and better approaches and tools capable to compensate the limitations spotted in the NACA Report 1178, [102].

4.4.1 Distributed Load Data, "DLD" Technique

In 1966 the British Hovell, Webber and Roberts, [43] and [44], were the first to highlight the standard statistical Skopinski's method was not entirely satisfactory applied to delta or slender-body configurations. Problems arise from the severe non-linearities in the gauge response with the position of the calibrating load and from the need to support the aircraft representatively during the ground calibrations, in order to prevent local effect that may bear no resemblance to the way an air load in the same area is distributed to the structure. These difficulties were overcome if distributed loads data, DLC of Figure 4.3, obtained either directly or by superposition, are used in place of individual load data, ILD. In contrast to the original NACA Report 1178, the Load Equation development will be reviewed as highlighted by the red bits of Figure 4.5.

The new schematic of the loads equations computation highlights the major pillar of this modified technique based on the Distributed Load Data, DLD, used to solve the regression for the evaluation of the load coefficients. The DLD can be of three different types as described below:

- Distributed Load Calibration, that means the DLC is not used anymore as a Check Load Case but is becoming dependent load data being the input of the regression to solve Eq. (4.1). This option is extremely time and cost

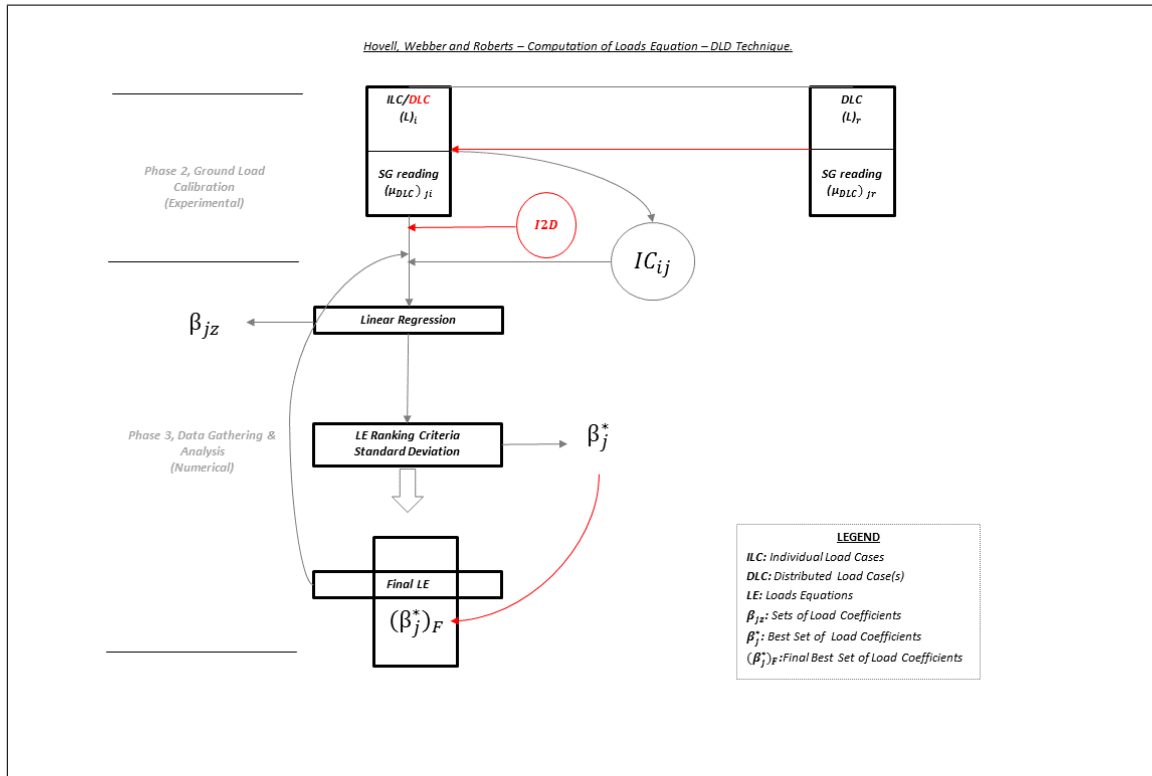


Figure 4.5: Schematic of Computation of the Loads Equations - Hovell, Webber and Roberts, "DLD" Technique, [43] and [44] - Decade 60s.

demanding as requires to generate all set of load cases experimentally. The programmed code supposed to generate the super-positions of the sets of Individual Load Calibration is labelled SDL, Sampling Distributed Loads.

- Individual Load Calibration, superposition of the load cases to generate a set of Distributed Load Sample.
- Partial Load Calibration, combination of individual and distributed load data.

The check case, deployed in Skopinski method by the DLC box of Figure 4.3, is not necessary any more as the "DLD Technique" relies on the standard error representative of the statistical sample inclusive of distributed loads representing a potential limitless range of centre of pressure such as the measured flight loads. The highlighted point of this modified approach is the mesh size of the calibration provides satisfactory representations of the continuously distributed loadings encountered in flight. Once accepted this, the manipulation of the input data of the regression becomes just a numerical matter, as does the supporting tool SDL, Sampling Distributed Loads, of Figure 4.3.

4.4.2 Equation Selection Matrices, "ESM" Technique

During the Seventies, Jenkins, Kuhl and Carter, US NACA scientists, consistently to the limitations spotted by the British researchers a decade before, 4.4.1, decided

to overcome the uncertainties surrounding the application of the conventional calibration philosophies to the more sophisticated structural arrangements, such as those used for low aspect ratio supersonic configurations. Otherwise, the pressure measurements should have been the only reliable, though incomplete as the structural response information can be obtained most readily from calibrated strain gauges, available tool to obtain flight load data.

So, it has been proposed a simple structural model, before the fact, to identify and characterise the load responses of the strain gauges located on various wing spars of a supersonic wing, [54] and [53]. Moreover, it has been introduced alongside the Influence Coefficient Plot, Eq. (4.2), an additional supporting tools, the Influence Coefficient Plots of the Loads Equations, ICLE. The Influence Coefficient plots for complete Load Equations, I_{CLE} , which are developed from the combined information of the individual bridges, are different from I_C plots for individual bridges and the following equation explains why:

$$I_{CLE} = \frac{\beta_1}{(\bar{\beta})} I_{C1} + \frac{\beta_2}{(\bar{\beta})} I_{C2} + \frac{\beta_3}{(\bar{\beta})} I_{C3} + \dots \quad (4.5)$$

Where in Eq. (4.5) β_1 , β_2 , and so forth are the constants determined by the load equations and $\bar{\beta}$ is the average of the constants of the equation. It is not necessary to divide by $\bar{\beta}$ to obtain a valid influence coefficient plot of the equation; division by $\bar{\beta}$ merely reduces the size of the multiplying numbers without altering the shape of the influence coefficient plot of the equation. The influence coefficient plots of the individual bridges are used to form composite influence coefficient plots that represent complete load equations. As shown in Figure 4.6, experimental data from five strain gauge bridges located on four different spars were used to formulate a load equation describing shear forces on the wing. The influence coefficient plot of the equation is shown at the bottom of the figure. The equation does not have a perfect shear expression would appear as a horizontal line, with all chord lines falling on the top of each other. However, bending and torsion effects have been greatly reduced.

Basically, the concept behind the ICLE is the same of the IC, showing the deviation from an ideal expected Shear, Bending Moment or Torsion pattern, though applied to a higher scale is not any more limited to the individual strain gauge level. This allows to recognise those loads equations, a very specific number of strain gauges, with higher ability to predict a particular loads to be measured in flight.

The relatively accurate prediction of the influence coefficient plots does not, however, mean that an actual physical load calibration can be replaced by an analytical calculation through the introduction of a Finite Element Model. Instead, according to Jenkins and Al., the analytical processes should be considered as only an aid in obtaining a good calibration of an aircraft component. This concept is reinforced by the computation flow of Figure 4.7, where the ranking criteria is not including the FEM as classified part of the supporting tools, red coloured circle. On the other hand, the IC and ICLE plots are used together as valuable tool for providing information whether the locations of the strain gauges and load cases on the structure are appropriate. This is why in Figure 4.7 they point the GLC boxes. The last change from the original Skopinski approach is happening inside the

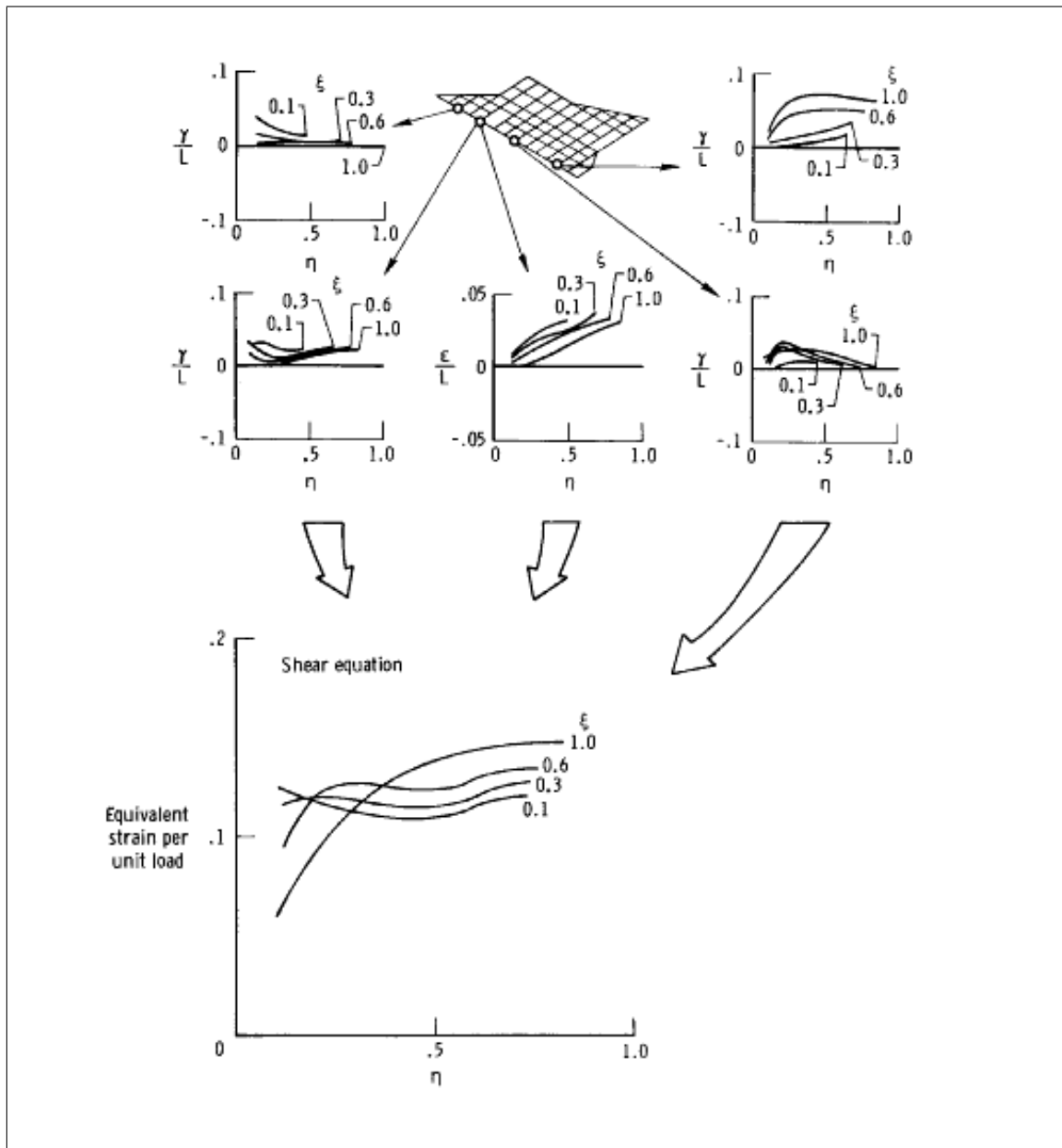


Figure 4.6: Ideal Shear, Bending and Torsion Influence Coefficient plots, [54].

ranking criteria box for the final selection of the best set of load coefficients. In fact, it has been introduced the *Equation Selection Matrices (ESM)*, [53], where the standard errors of the equations, the load distributions, and the influence coefficient plots, single strain gauges and loads equation, are used individually, though presented collectively in matrix form for all the equations, to single out the best load equation.

The "ESM" Technique in contrast to the 50s Distributed Load Data, "DLD" Method, is not automated and at each step requires to review the Influence Coefficient Plots populating a table collecting all relevant information for the final decision.

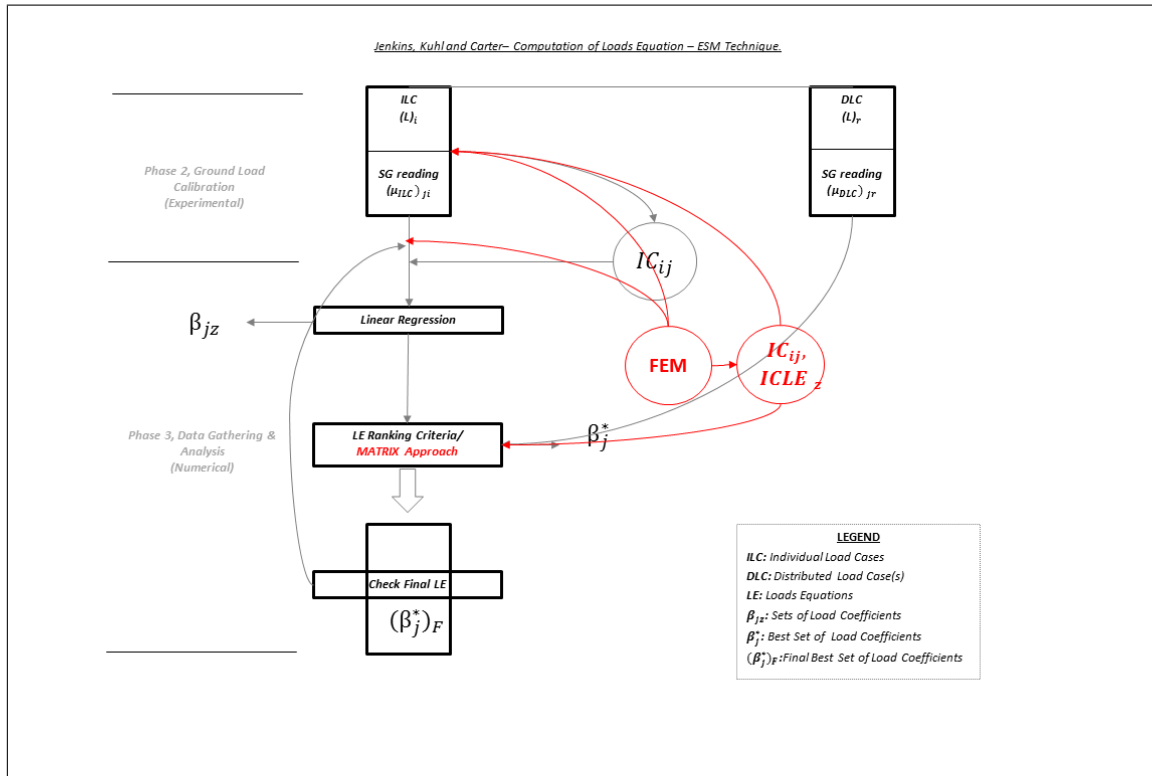


Figure 4.7: Schematic of Computation of the Loads Equations -Jenkins, Kuhl and Carter, "ESM" Technique, [54] and [53] - Decade 70s.

4.4.3 T-Value and Modified T- Value Methods, "T-v" and "MT-v" Techniques

The 1974 is recording the year when Sefic and Reardon, US [101], introduced a new method, on which 6 years later, Tang and Sheldon, US [109] and [108], would have proposed a special adaptation.

The Skopinski method, though clearly withstanding the test of time, has most universally been used on high aspect ratio structures, where load paths from the wing to the fuselage are few, well defined, and minimally redundant. The approach the 70s and 80s decades decided to take, has been moving away from the "DLD" and "ESM" techniques, with low aspect ratio, multispar, structures is to instrument the structure extensively with strain gauges to insure that no crucial load paths are missed. Consequently, a large array of strain sensors is becoming available for use in the load equations amplifying the efforts required to identify and select the best strain gauge combinations. This is why new approaches for selecting the strain gauges to be used in the load equations were investigated and then applied, such as the *T-value method*, "T-Vm" and the *Modified T-value method*, "MT-Vm".

The *T-Value method* for reducing the number of terms in Eq. (4.1) is to use a value known as a T-value as a measure of the relevance of the bridge. The statistic definition is described by the equation below:

$$T_i = \frac{\beta_i}{\epsilon_i} \quad (4.6)$$

where (T_i) in Eq. (4.6) is the T-value that indicates the relevance of the i th strain gauge bridge, (β_i) is the equation constant (load coefficient), and (ϵ_i) is the standard error of the associated equation constant, [109].

The number of bridges in the main load equation, Eq. (4.1) can be successively reduced by eliminating the bridge with the smallest T-value. Each time a bridge is eliminated a new equation is derived from the remaining bridges and new T-values are calculated. For purposes of comparison with the coming Modified T-value method the procedure will be repeated until a set of equations containing the maximum number of strain gauges in the loads measurement station to 2 strain gauges, the smallest available number to apply the regression, was derived.

The *Modified T-Value method* includes strain gauge response magnitude, gauge to gauge inter-correlation factors in the process of selecting the appropriate gauges for the load equations. The MT-values are defined as follows:

$$MT_i = \frac{\beta_i \lambda_i \bar{\mu}_i}{\gamma_i \epsilon_i} \quad (4.7)$$

The terms of Eq. (4.7), [109], are explained below:

- MT_i = the relevance of the i th strain gauge bridge.
- $\bar{\mu}_i$ = the mean absolute magnitude of the nondimensional strain gauge bridge response due to the calibration load.
- λ_i = the coefficient of correlation between the strain gauge bridge response and the calibration load.
- γ_i = the coefficient of correlation between the strain gauge bridge response and all the other bridge responses due to the calibration load.
- ϵ_i = the standard error of the load equation constant.
- β_i = the load equation constant.

As shown in Figure 4.8 the two T-values techniques mainly differ from the ranking criteria equations of Eq. (4.6) and Eq. (4.7). The rest of the computation cycle remains the same for both. The schematic maintains from the past the supporting tools calculating the influence and equations coefficients to aid the loads practitioner in selecting the appropriate gauges for load equations before applying the regression. Another supporting tool introduced, the red circle at the very right top of Figure 4.8, is labelled FLSR, standing for Flight Loads Specified Range. Basically, for the first time since 1940s, when the Skopinski method was already used, the loads equations to be developed vary according to the type of flight loads manoeuvre to measure. In fact, these two computations believe the interpretation of the analysis is relative to the load conditions selected for the

Loads Equations Computation: Techniques Evolution

analysis. If particular equations appear more appropriate than others, then they are so for the range of the load applied and the gauge locations in the load conditions selected.

Based on these concepts, Tang and Sheldon described one of the first computer program which derives load equation coefficients using regression techniques, known as EQDE (EQuation DERivation), [109]. The program does not try to predict the suitability of an equation for flight loads outside the specified range of load conditions. However, the more suitable an equation for the load conditions selected, the more likely it is that it will predict loads outside the specified load conditions range.

The T-value and Modified T- value methods through the computer program EQDE provide the user of a similar approach of the ESM Method, 4.4.2, where many types of information are presented to facilitate the selection of the appropriate strain gauges more than loads equations. In fact, it is a common belief that the best loads equation requires a thorough understanding of the bridge behaviour.

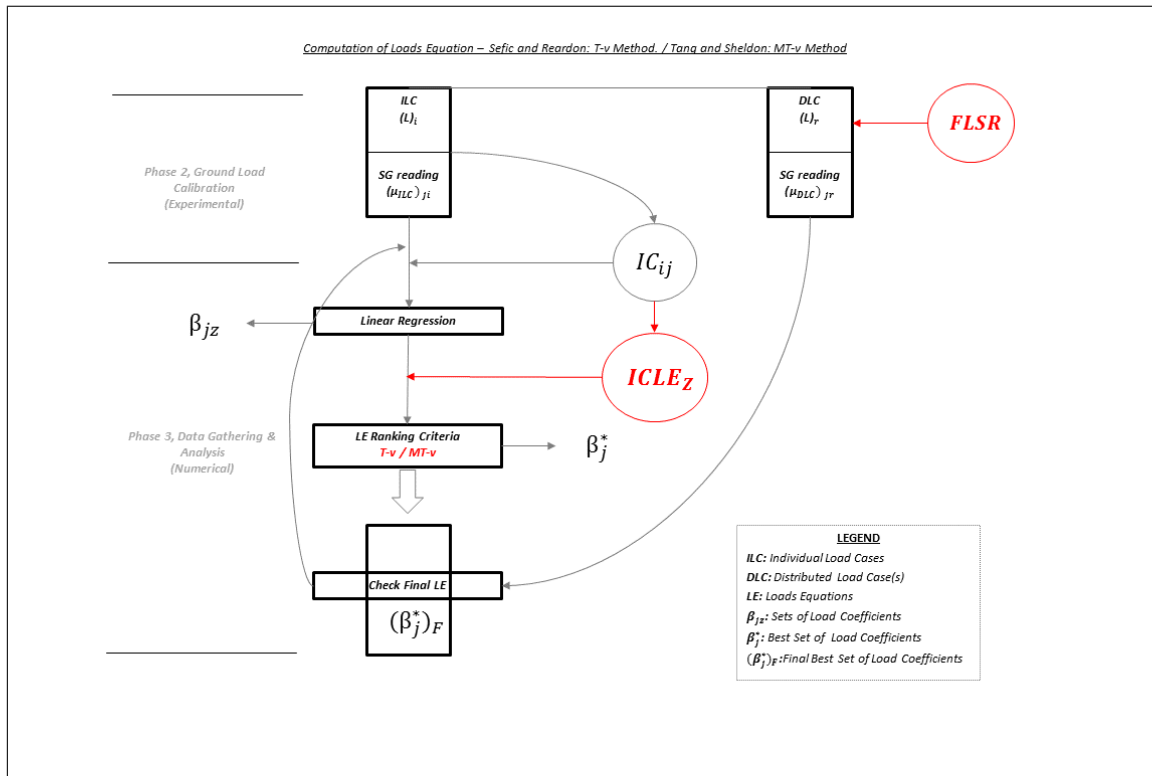


Figure 4.8: Schematic of Computation of the Loads Equations - Sefic and Reardon, "T-v" Technique, [101], & Tang and Sheldon: "MT-v" Technique, [109] - Decades: 70s and 80s.

4.4.4 Genetic Algorithm, "GA" Technique

The difficulty of gauge selection process, has been one of the key driver over the years, mainly with the multi spar wing of the hypersonic aircraft and space vehicle flight test research programmes. In fact, it is sufficient to think that a particular airplane wing is instrumented with 25 strain gauges. If only 5 strain

gauges were used to formulate each load calibration equation, known as a 5-gauge equation, there are 53,130 possible combinations, statistically terminology *combination without repetition*. If the number of gauges had been 40 there would be 658,008 possible 5-gauge load equations. Furthermore, if there were 130 strain gauges, as in the case of the Space Shuttle orbiter, there would be 286,243,776 possible load equations [48]. Clearly this case present a vast number of selections. If an exhaustive search were used to solve and evaluate each equation as a possible candidate, at the rate of 100 equations per second the time required would be in excess of one month (applicable statement with the computer processing power of 1994). Furthermore, it cannot be known in advance how much error is implied in using a 5-gauge equation as opposed to a 6-gauge equation or an 8-gauge equation, [79].

Nelson, during the 1990s suggested, if the structure to be calibrated is complex or highly redundant, such as the Shuttle Orbiter [14] or the F-111 [79], and a large number of strain gauge bridges are available for use in the equations, an approach employs genetic algorithms, GA, [79].

At that time the GAs have been used to solve problems dealing with optimisation and artificial intelligence. Genetic algorithms are search techniques based on the mechanics of natural selection, and they differ from classical optimisation techniques in a number of ways that suit the determination of strain gauge load equations where the desired solution is a set of characteristics. Moreover, the fact these techniques work with a population, which is sampling of several points. This means that not one but many calibration equations are considered at the same time.

The Nelson' GA is based on a fitness function addressing two key issues. First, there must be a penalty of a string uses too many gauges. Second, the equation formed must fit the calibration data to some degree of accuracy. The fitness function used has the form:

$$FF_{(GA)} = e^{(-[A+B]^2)} \quad (4.8)$$

The value of FF_{GA} of Eq. (4.8) is normalised to have a value between 1, perfect equation, and 0, a very poor equation. The coefficient A penalises the string if too many gauges were used, while B does it, if the resulting load equation had a large standard deviation.

The GA method appears to be one of the first automated process based on statistics fitness function for the selection of the best loads equation, though, not correlating with the physical circumstance of the problem such as in the past influence coefficient plots have been doing. This already explains the reason this technique will be employed very carefully in the coming decades of the flight loads measurement science as the major quantities driving the search are mainly statistically-based.

Nelson comparing the performance of this genetic algorithm automated approach to the existing T-value and Modified T-value methods obtained comparable or superior strain gauge load equations. In addition, his technique was able to find

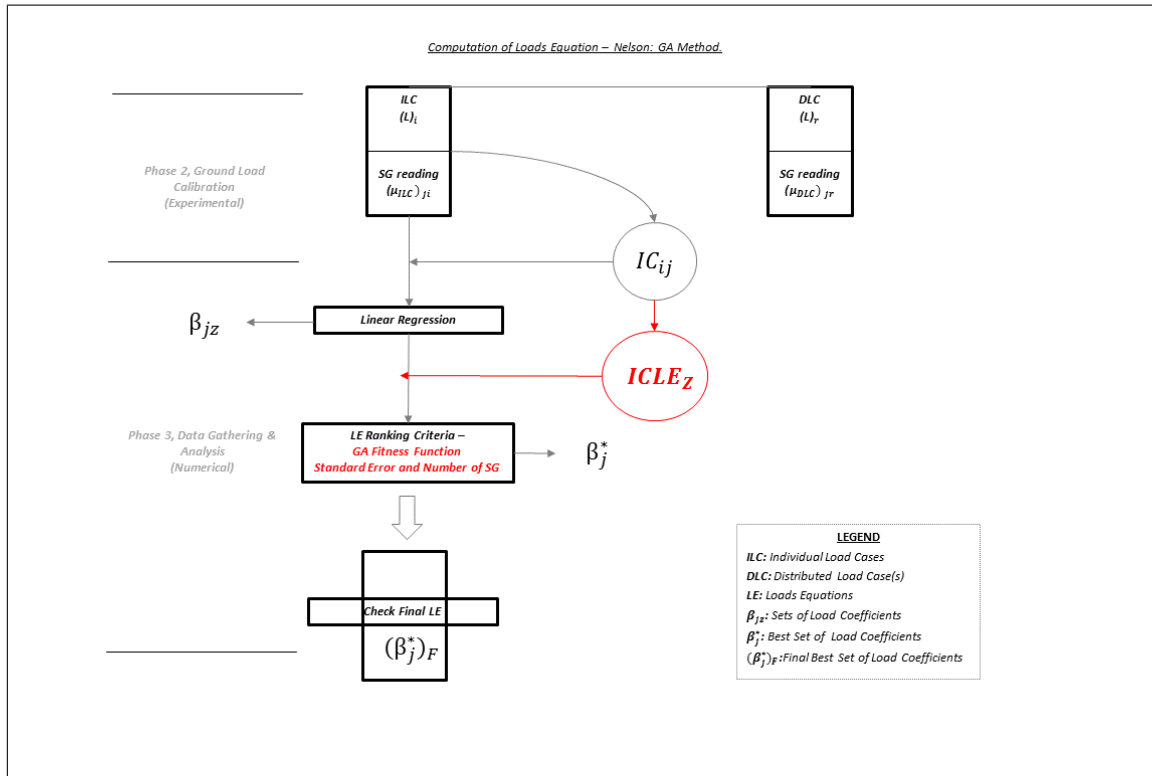


Figure 4.9: Schematic of Computation of the Loads Equations - Nelson, "GA" Technique, [79] - Decade 90s.

loads equations significantly faster than an exhaustive search. This very last point will be one of the major turning points of the coming decades and of the proposed method presented next.

It is worth highlighting that the Nelson's ranking criteria, Eq. (4.8), will be endorsed by two independent search methods, the Exhaustive Search, B.1.7.6 and the GALE, B.1.7.7, a dedicated Genetic Algorithm environment to evaluate Loads Equations. Both the different methods have been translated and coded in Python language. The concepts behind GALE are further detailed inside the next section describing the novelties proposed to either endorse the past techniques in such a way to be coded later on, or to overcome their limited search ability, 4.5.3.2.

The explanation of the reasons that determined the employment of an Exhaustive Search to perform Nelson ranking criteria instead a Genetic Algorithm search, by means of the conceived GALE environment, is diffusely offered in the chapter 3 section B.1.2.

4.4.5 Relevance Coefficient, "RC" Technique

Through so many decades of evolution of the Science it comes out that Nelson with his Genetic Algorithm 4.4.4, represents one the of the last major attempts to improve the selection of the best set of loads equations. In fact, afterwards Jenkins and DeAngelis, [50], in the nineties, and Lokos and Stauff [65] the following decade presented studies whose main scope was to set the very state of the art

of the Science and the very extreme corner points of the three-axis of complexity that are reachable. The level of problem complexity that can be resolved and the remaining directions that can be further explored.

In such scenario there is one concept that has still to be surfaced in order to present a thorough picture for those mathematical tool, used to obtaining robust flight loads equation, though it cannot be really claimed to be a standing technique. The R_C is defined as:

$$R_C = \frac{A_L}{A_T} \quad (4.9)$$

Where A_L is the area loaded and A_T is the total area of the calibrated lifting surface. Figure 4.10 shows the pictorial illustrations of two cases, heavily and sparsely loaded. One case has a calibration structure in which 18 load points are used, and the other case is one in which only 8 load points are used. Both Individual Load Calibrations, ILD, generate completely different errors in final set of loads equations. Obviously, the case with more load points appears to cover more discrete areas on the surface and provide the format for a better load calibration. The total validity of this observation, has been proven by Jenkins and DeAngelis [50] in their four decades overview of physical procedures of calibrating strain gauged structures, where a direct proportional dependence between high relevance coefficient and lower standard error. This concept is directly linked to the influence coefficient plots too as the large number of calibration load points, providing complete information, reduces the amount of data to be interpolated, extrapolated and rounded off when developing IC and ICLE charts.

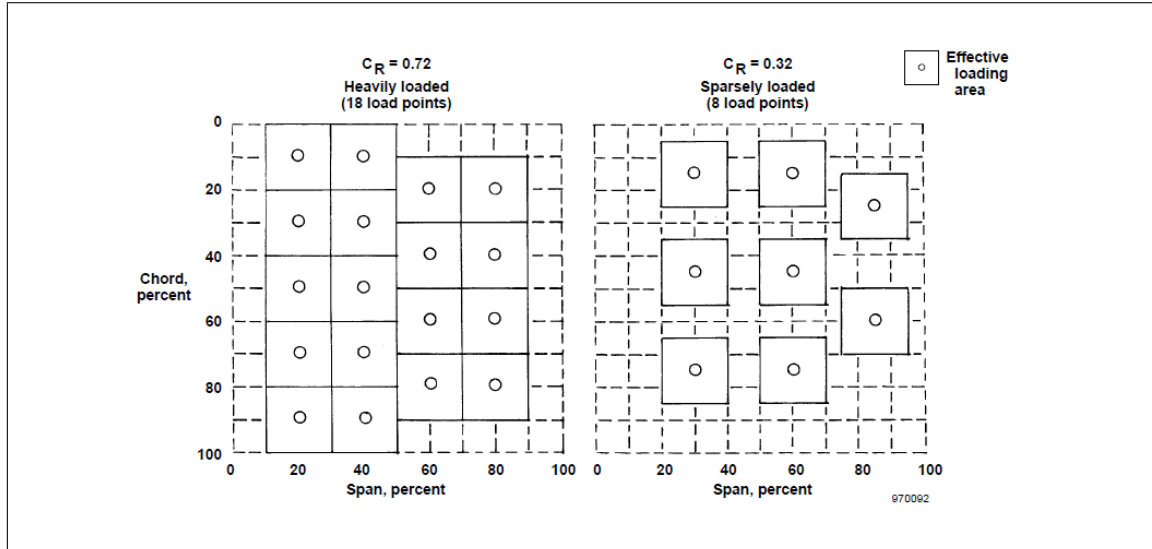


Figure 4.10: Pictorial Illustration of the Relevance Coefficient - Jenkins and DeAngelis, [50] - Decade 90s.

What presented so far, under the label of the *Relevance Coefficient Technique*, inside the Computation Scheme of the loads development of the past decades such as the *Skopinski Original Approach* Figure 4.3, the *DLD Technique* Figure 4.5,

the *ESM Technique* Figure 4.7, the *T-v and MT-v Techniques* Figure 4.8, and *GA Nelson* Figure 4.9, is just represented by the extra supporting tool, RC working to different directions. The first one to affect the dependent load data, data used into the regression to obtain the loads coefficients, β_{iz} , by offering higher performance loads equations as coming out of loads similar to those to measure in flight. The latter, the independent load data, the distributed loads calibration, used exclusively to assess the value of the final set of loads coefficients. It is important to stress that either way to use, the RC is not meant to be part of the ranking criteria.

4.4.6 Areas of Evolution Summary

The techniques introduced through the past eight decades, 1940 up to date, and broken down in the generic flow charts of loads equations computation described in the previous paragraphs identify the major concepts, supporting analyses and computational tools employed. These are categorised and listed in the major areas below:

- **Input Data:** Data represents Load Cases and the strain gauge bridge readings associated. There are two main areas Dependent, used by the regression to generate the load coefficients, and Independent as part of the Check Case to assess the final performance of the chosen set of loads equations. Moreover, each of these can be either part of Individual or Distributed set of load cases.
- **Solution of the Eq. (4.1):** There are mainly two approaches applicable to the load measurement problem to solve the Eq. (4.1) and calculating the load coefficients β_{iz} . The most common, applied by all the Techniques presented before, is called the Linear Regression, where the validity of the approach requires the number of gauges being less or equal to the number of loads. The latter, is called the Singular Valued Decomposition (SVD), however this is basically not fully documented, [50], besides the work of Professor Kung Yao, [118].
- **Loads Equations Ranking Criteria:** It represents those rules that single out the final set of loads equations from all the possible combinations of strain gauges obtained by applying the linear regression above. The rules can be part of an automated strain gauge selection, such as Nelson Genetic Algorithm technique, [79], or strain gauge reduction functions according to the T and Modified T value methods, [101] and [109]. Another ranking criteria is a combination of influence and load equations coefficient plots check alongside standard error threshold as Nelson and Al. introduced in the Equation Selection Matrices technique, [54] and [53].
- **Final Check Case/Iteration:** It is a spot check of the final set of load coefficients, (β_{jF}) , generated by the Dependent Load Data, applied to the linear regression, through the Ranking Criteria, against the Independent Load Data.

- **Supporting Tools:** It gathers all those concepts, computational or analysis means capable to support the major areas listed above. Among these there are Influence and Load Equation Coefficients, Relevance Coefficients, Sample Load Data and Flight Loads Specified Range.

All the areas above, captured in the following Figure 4.3 and the *Original Method*, Figure 4.5 and the *DLD Technique*, Figure 4.7 and the *ESM Technique*, Figure 4.8 and the *T-v and MT-v Techniques*, and Figure 4.9 *GA Nelson*, have been differently reviewed as described by Table 4.3 whose interpretation is possible by mean of the Table 4.2, Areas Affected Identification Codes.

Table 4.2: The Loads Equations Computation Areas Affected: Identification Codes.

ID Codes	Areas Affected Description
01	Input Data: ILC and DLC
02	Solution of the Eq. (4.1): Linear Regression
03	Loads Equations Ranking Criteria
04	Final Check Case/Iteration
05	Supporting Tools

Table 4.3: The Loads Equations Computation through the Decades and Major Evolution Area Codes.

Decades	Scientists	Techniques, Sect.	Affected Code Areas
50	Skopinski et Al. [102]	Original, 4.3	Base Line
60	Hovel et Al. [43], [44]	DLD, 4.4.1	01, 04, 05
70	Jenkins et Al. [54], [53]	ESM, 4.4.2	03, 05
70	Sefic et Al. [101]	T-v, 4.4.3	03, 05
80	Tang et Al. [109]	MT-v, 4.4.3	03, 05
90	Nelson [79]	GA, 4.4.4	03, 05
90	Jenkins et Al. [50]	RC, 4.4.5	05

Table 4.3 shows how the evolution of the load equations computation cycle has been mainly driven by a continuous attempt to improve the Ranking Criteria (Code 03) and by introducing new and revolutionary aids, Supporting Tools (Code 05), such as FEM or ICLE, that if properly harmonised can eventually contribute to introduce new techniques.

The Proposed Method of the next section will be taking in turn the major employed areas of Table 4.2 and the concepts behind.

4.5 Loads Equations Computation: The Proposed Method

The data for the 15 strain gauge load calibrations of Design Loads Measurement of research projects presented by Jenkins and DeAngelis in the late 90s, [50], reviewed the issues, lessons, rules and problems pertinent to the science of flight loads measurement with calibrated strain gauges. This offered the opportunity to strengthen the basic science that alongside the major specific findings presented in the last sections inspired the way to harmonise the areas of the next *Proposed Method*. The importance of reviewing calibration data by means of influence coefficients combined with the introduction of relevance coefficient considerations proved to allow having a better quality of loads equations. Though, it came out that the increased cost/time associated with conducting load calibrations on aircraft introduced an economic factor that has impacted many recent and future aircraft programs. Reed and Halford [65], on the side of the Operational Loads Measurement programmes [96], from an industry perspective highlighted the additional cost, time delays and the Ministry of Defence increasingly moving from a *provider* to a *decider* organisation, in such a context the technical knowledge will only decrease further, making the challenge of conducting successful OLM programmes even greater. Similar scenarios with the dominance of commercial issues in today's engineering environment the technical complexity of these programmes are leading most of the time to undesirable compromises just to make progress.

Therefore, there is a very real need for more detailed guidance to be made available in a very efficient and thorough framework requiring clear proved necessary tasks. On the experimental side, GLC point of view, understand and answering the importance of number of load cases to execute, individual or distributed, the magnitude of each load and the consequent risk to affect the integrity and the airworthiness of the flying object under investigation can make a huge economic and logistic difference putting the DLM and OLM practitioners under less pressure. Lokos and Stauff, [66], in the recent Decade, 2004, identified three main topics in terms of areas of improvements of this science, and these are:

- The design of strain gauge installation.
- The Design and performance of the applied-load test.
- The strain gauge load equation derivation process.

While Lokos and Stauff focused on the second, [65], this work and the following methodologies description will be driven by the attempt to introduce enhancements, directly or indirectly, on the area of the strain gauge load equation derivation process with experimental, Ground Load Calibration, and Numerical, Computational Calibration, data.

The quality rules introduced by the *Proposed Method* below will be affecting three main areas of the Table 4.2 such as Input Data, Ranking Criteria and Supporting Tools.

Inside the ranking criteria section, 4.5.4, will be presented two different options to perform the search of the best set of Loads Equations of the new proposed method.

These antithetic approaches are the Exhaustive Search and the Genetic Algorithm environment, GALE. The exhaustive search will be the one employed through the whole work, and sections 1.3 and B.1.2 will be detailing the motivations behind this strategic decision.

4.5.1 Input Data

It has been clearly proved in the previous sections, 4.4, that the linear regression, for the evaluation of the sets load coefficients, and ranking criteria must rely on distributed load data, typical of the distributions to be measured in flight, in order to generate more performing load equations.

There are different ways to go down to this path. The one presented is labelled as *DDD*, standing for Dependent Distributed Data. To better comprehend the typology of this input data-set the two major categories of flight loads measurement Ground Load Calibration available data, load cases and strain gauge readings, are described below:

- **Dependent Data, (*DD*):** Used in the linear regression. Labelled as dependent as the load coefficients depend on it.
- **Independent Data, (*ID*):** Used as a check case on the final set of loads equation. Labelled as independent as the load coefficients do not depend on it.

Each Dependent and Independent Data set, known also as Training and Validation set of data, see 1.3, can fall into one of the following types:

- **Individual Load Calibration, (*ILC*):** Calibration based on single load pads applied spanwise and chordwise independently.
- **Distributed Load Calibration, (*DLC*):** Calibration based on several single load pads applied spanwise and chordwise simultaneously.
- **Distributed Sample Data, (*DSD*):** Data obtained as super position of the ILC.

Basically, this method instead of using a distributed load calibration to generate strain gauge readings will be applying a numerical supporting tool, see 4.5.2, that will combine the Dependent Individual Load Calibration. This will be avoiding the huge effort to set up an experimental test rig, whiffle trees and consistent ground support, controlling cost and preventing indirect time and structural damage risks of the calibrated component and constrained parts too.

The *DDD* input data will be shaped in order to generate a resultant of the applied forces similar to the expected centre of pressure of the PITS Flight Loads, similarly will be done by the *IDD*, independent distributed data, to be used as part of the check case stage.

4.5.2 Supporting Tools

The tools introduced to contribute defining the new loads equations computation framework follow:

- **Flight Load Specific Range, (*FLSR*)**: It has already been introduced in the T and Modified T value methods, Figure 4.8. It identifies the centre of pressure of the flight loads to measure in order to be recreated similar distributed load cases by the DDD and IDD.
- **Relevance Coefficient, (*RC*)**: It recalls the concept introduced and quantified by Jenkins and De Angelis [50], 4.4.5.
- **Influence and Loads Equations Coefficients, (*IC*, *ICLE*)**: The influence coefficient plots were already introduced in the base line method, The Original Skopinski's Technique [102], Figure 4.3. On the other hand, the ICLE are introduced by Jenkins and Al [53], Figure 4.7.
- **Influence Coefficient Loads Equations Parameters, (*ICLE_P*)**: This is a complete novelty, not just in relation to the stage of the whole process is used but on the way the parameters have been treated to allow being used in the Ranking Criteria as described in the next section.
- **Individual to Distributed, (*I2D*)**: This is a piece of code, python programmed, generating distributed data, dependent and independent, by superposition of the experimental individual load calibration.

The major characteristics of these supporting tools compared to the past, when already introduced, is not just at which level of the flow chart are used but mainly how have been integrated in the whole loads equations computation process. Furthermore, a relevant mention ought to be dedicated to the package *Individual to Distributed, I2D*, whose integration and coding required specific strategy that will be detailed in the coming section.

4.5.2.1 I2D: Individual to Distributed

Among all the supporting tools included in the New Proposed method displayed in Figure 4.21, the *I2D* is the most significant as not coming from other activities, outside of the Loads Equation Calculation process, but pillar to perform the Ranking Criteria concepts and equations as part of the Data Gathering and Analysis, DG&A I, Phase 3 of the "Strain Gauge Based Flight Loads Measurement", Table 2.1.

In fact, the *FLSR*, 4.5.2, is a direct consequence of the theoretical Flight Loads Calculation process, usually not part of the competences and responsibilities of the Loads Measurement practitioner. It is linked to the Flight Test campaign that will be characterising the flight manoeuvre, PITS, to be used for training the developed loads equations and measuring the experimental flight loads. Therefore, not part of any of the "Strain Gauge Based Flight Loads Measurement" phases.

The *RC* is a typical index defined at an early stage of the flight loads measurement campaign, Definition and Design, D&D, Phase 1, Table 2.1, to ensure that the load

cases planned to be executed during the GLC are sufficiently covering the lifting surface under investigation. Though, this information is indicative for the development of the superposed distributed load cases, in fact the concept is included in the input data of the *I2D*.

The idea behind *I2D* is that the individual calibration loads, easier to be recreated experimentally than the distributed, that require whiffle-tree test rigs and with increasing risk of damaging the flying test article, adversely affect the strain gauge responses without reproducing real flight loads patterns. In fact, delta and slender-body configurations show severe non-linearities in the gauge response with the position of the calibrating load and from the need to support the aircraft representatively during the obtained either directly or by superposition, [43] and [44].

Figure 4.11 shows the difficulties of a significant strain gauge response with load calibration span and chord-wise positions, to be approximated by a linear surface equation. In fact, fitting linear surfaces were already an option, though, computationally demanding for that time, Decade 60s, to be adopted as part of the whole ground calibration set of data. This area of the *I2D* is the Strain Gauge Prediction with Load Positions.

The other main area took on by the *I2D*, needed to complete the parts of the current supporting tool computational framework in Figure 4.13, and later on within the Python Code, Figure B.28 and section B.1.7.12, is related to the loading arrangement of the superposed distributed loads. In fact, the closer the dependent sample of data used to develop the loads equations to the flight loads centre of pressure and the higher accuracy is expected. The statistical sample must be representative of all the constituent loads that can produce responses from the gauges. The user of this code, the flight loads measurement practitioner, will be defining the rules of the superposed distributed load by having a centre of gravity, *CG*, of the ground distributed load cases inside the practical range of the centre of pressure, *CP*, of the flight loads to measure. This concept was already considered by Hovell et Al., [43] and [44], while dealing with the lightning fin ground load calibration campaign, Figure 4.12.

Precisely, the British scientists theory introduced in reference [43] was focusing on two major areas, selection of the appropriate gauges from the mass of calibration data and then superposing them all by fitting linear surfaces to the individual response of each gauge. The statistical modelling theory employed to overcome the challenges to fit the experimental set of data is represented by the references of Goulden, [38], and Ezekiel, [29], and the precious support of McKinney, [74] that facilitate the translation to Python programming.

The *I2D* calculation process moves on these two concepts above and further detailed in Figure 4.13. The first one, on the left side labelled Module 1, calculates the Strain Gauge Prediction approximation surfaces. The second, Module 2, is the Loads Superposition that once completed according to basic rules set beforehand, links back to the first module to generate superposed strain gauge responses according to the loads sequence established by the user as part of the input information at the very top of the flow computation.

The major quantities of the whole *I2D* computation flow of Figure 4.13 are the

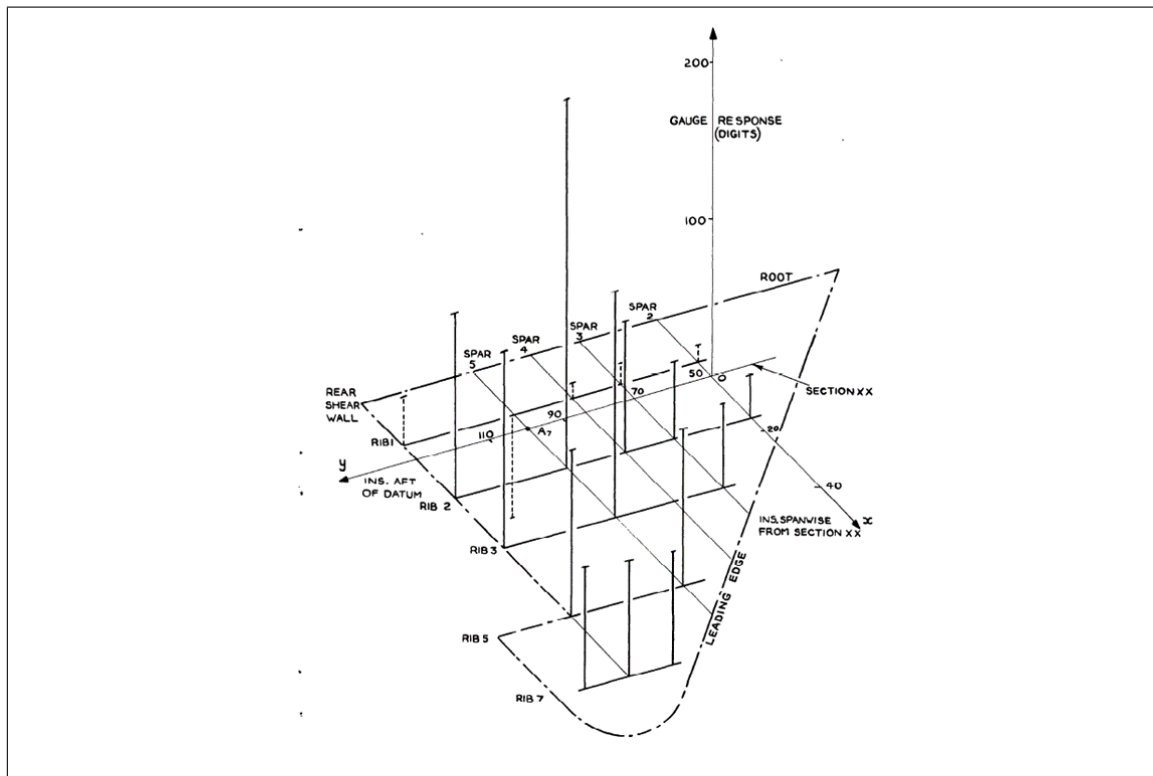


Figure 4.11: Lightning Fin: Response of Gauge with Position of Loads Calibration, [43].

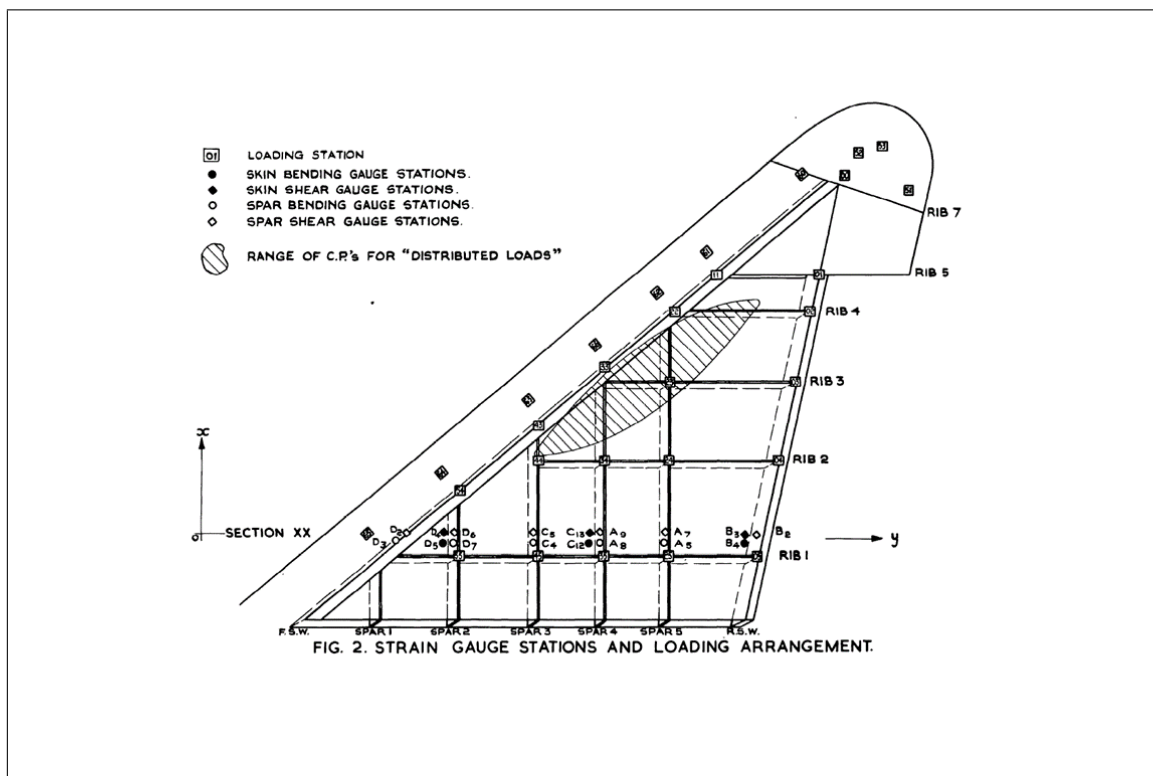


Figure 4.12: Lightning Fin: Strain Gauge Station and Loading Arrangement, [43].

Distributed Load Cases, in terms of Forces, F_j , associated coordinates, $(X, Y)_j$, that will be used to evaluate the induced strain gauge, SG_i , magnitude responses normalised to the applied force, Z_i , by means of the fitting surfaces $f(X, Y)_i$. The final output of the *I2D* becomes the output data for the *DLD* and *LPP* techniques of Figure 4.5 and Figure 4.21 respectively.

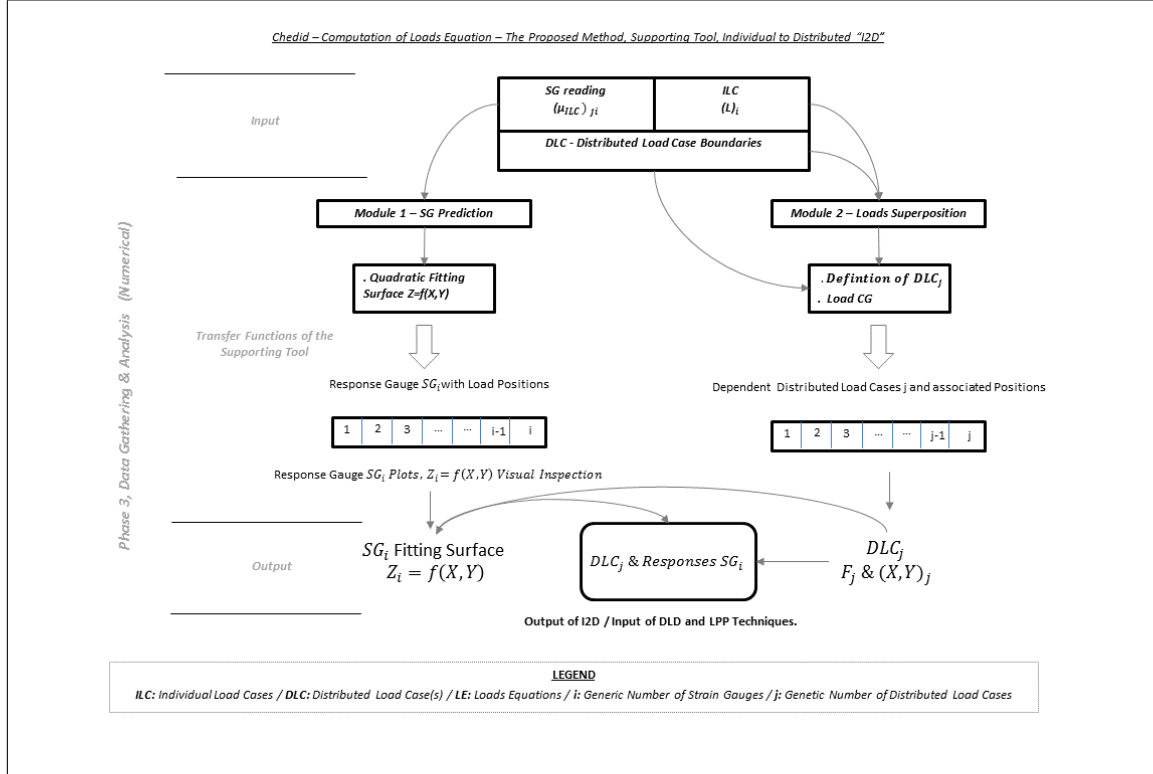


Figure 4.13: Schematic of Computation of the "Individual to Distributed" - "I2D" Supporting Tool of the new proposed method, LPP.

The difficulties to sort the gauges by fitting linear surfaces to the individual response of each gauge, as Figure 4.11 describes, affecting the selection of the best set of loads equations, are expected to be overcome with the distributed load data, obtained either directly experimentally or by numerical superposition, as *I2D* does, as long as used in place of individual data. A change from an individual load sample to a distributed for the statistics automatically reduces the poor fitting surfaces with strain gauge data. In fact, the higher-than-average response(s) of a particular gauge to some load(s) is balanced by the lower-than-average responses of the same gauge to loads at different positions and the regressions fitted to such data will have smaller standard errors, [43]. This statement, whose validity has been reinforced by [43] and [90], applies with a linear superposition of the individual sample data. Though, to expand to different load positions outside of the experimental strain gauge reading data requires capability of approximation of the surface of Figure 4.11.

The *I2D* offers the options to generate superposition of the individual load cases. Basically, the same loads and application points are applied simultaneously. Then, there is the superposition of forces applied in generic positions whose associated

strain gauge response reliability heavily depends on the fitting surface of Figure 4.11. This is a result of this sequence of actions:

- **3-Dimension Points:** The points have three components, X and Y Load Position Coordinates, and Z associated meaning Strain Gauge responses divided by the applied force magnitude. These points are the result of the experimental phase.
- **Grid Data:** It is created to fit a surface of the form $z = f(x,y)$ to the data in the (usually) nonuniformly spaced vectors (x, y, z). Since the contour/wireframe plots used next do interpolations on regularly spaced data, the grid data comes in. It adjusts the data that is not fit to a polynomial (except within nearest neighbour points).
- **Contour/Wireframe plot:** It merely interpolates the sample experimental data to a regular grid using the specific 2D polynomial fit chosen as required, in this case quadratic. Points are interpolated between data.
- **%RMS:** Each plot will associate a percentage of root mean square error, Eq. (B.1), as index of reliability of the fitting surface with the sample data.

The Python results of the approximation surface and its sample data are shown in Figure 4.14. It represents one of the many strain gauge plots to be checked, taking into consideration the associated %RMS value, before deciding to progress with the *Open Superposition*, all load applications are counted, or *Limited Superposition*, only Individual load positions considered.

The right side of the computational flow of Figure 4.13 is driven by a set of Distributed Load Case rules that set the boundaries to be met otherwise affecting the reliability of the whole proposed *I2D* process. These are listed below:

- **Maximum Shear/ Bending Moment/Torque:** This is not driven just by limit design loads but any type of loads, that once overcome, takes the material into plastic field. The most typical threshold is linked to buckling loads. These represent also the other causes of the deviation from the ideal distribution of the influence coefficient-plots Figure 4.1, into a non-linear trend.
- **Centre of Pressure, X and Y coordinates:** It represents the expected position of the flight loads to be recreated by the CG of the distributed superposed loads.
- **Maximum and Minimum X and Y coordinates:** It ensures that the coordinates of the distributed superposed loads, idealised by individual load cases applied simultaneously, are inside the torsion box physical dimensions.

The presented method, to evaluate numerical sample superposition, is not fully automated as a preprocessing has to be performed on fitting surfaces, $Z_i = f(X, Y)_i$, and their index of reliability, %RMS, assessing the level of accuracy of the approximated quadratic curve to the sample experimental data.

This supporting tool represents huge inherent potentialities as it might drastically

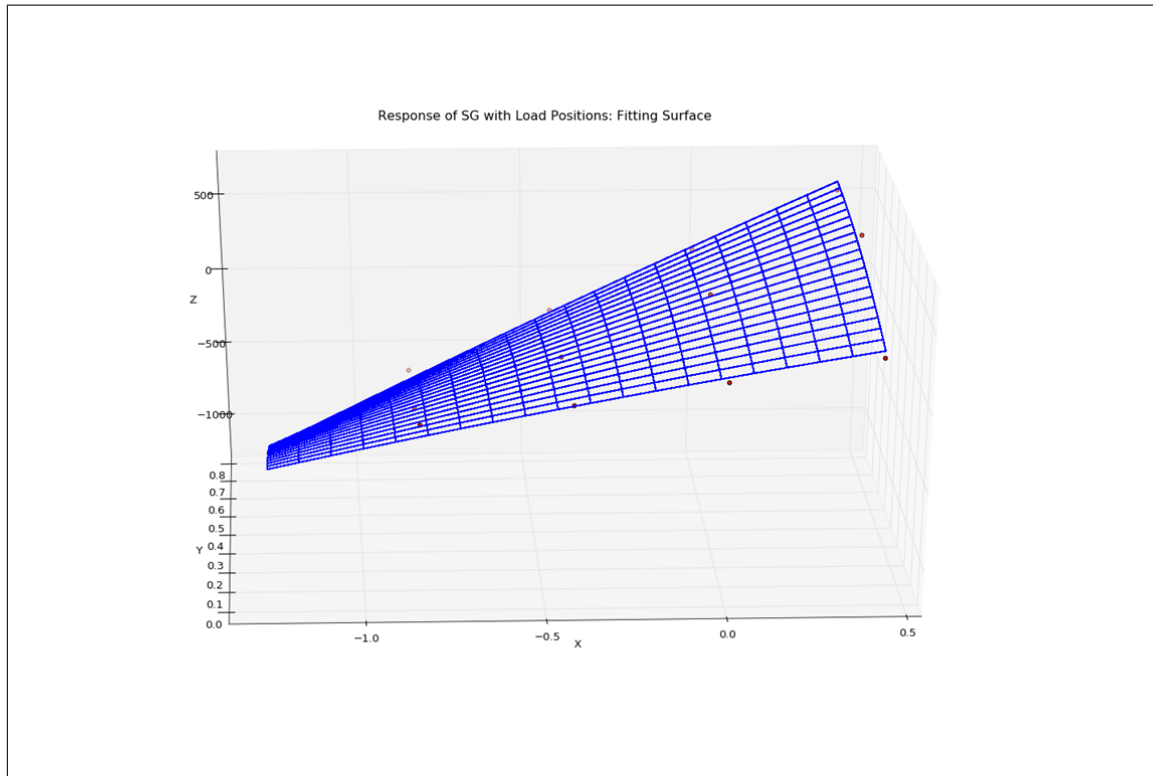


Figure 4.14: "I2D" Supporting Tool: Fitting Quadratic Surface and Sample points - Generic Strain Gauge Response and Load Positions.

reduce the effort of the ground experimental phase, though, the ground individual load cases should have a very high Relevance Coefficient, 4.4.5. This ensures that the just described loads and strain gauges superposition computational process, inspired by the past literature of the British, Hovell, Webber and Roberts, [43] and [44], and US, Peele and Eckstrom, [90] and [26], researchers, is further enhanced and taken to a different level. In fact, due to the limited detailed information shared from the past literature the coming up flow chart of Figure 4.21, novelty of this study, is one of the possible scenarios that is open to improvements. This is possible once enough experimental detailed data, covering a wide spectrum of lifting surfaces typology structure and instrumentation configuration, will be available.

The last areas of the computation of loads equations affected by the introduction of the new proposed method is the Ranking Criteria and is about to be profusely discussed.

4.5.3 Ranking Criteria

The major pillar involved in the Proposed Method is about the Ranking Criteria. It collects all the major experiences happened in the past and it funnels into final equations, different according to the type of loads to measure, that will allow, when needed, to become an automated search criteria too.

The ranking criteria translated in proper fitness functions has been conceived by

applying the same concept driving the last strain gauge selection in loads equation technique of Nelson, [79], basing the search on a Genetic Algorithm. Though, it is flexible to be used as part of an exhaustive search too, as the results will be produced later on.

In fact, the Proposed Method preliminary version of the Python code, introduced in the previous chapter, was a Genetic Algorithm. Each load equation, encoded into a series of bits, string, with each bit holding basic information, such as, if the bit holds the value 0, the gauge will not be used, differently if it has the value 1. All the equations were sorted from an original population, constituting the first generation, through several generations by the application of a fitness function, like the specific GA Technique Eq. (4.8). Therefore, because fitness is related to how well a particular set of gauges can be used to calibrate the structure, the strings in later generations represent successively better calibrations.

The experience accumulated up to date [50], the increasing computational power with the development of faster and cheaper computing equipment affordable to a higher spectrum of the society [114], not just industry or research centres, led this research to be inspired by the past approach of Nelson, [79], but being upgraded by replacing the search engine, genetic algorithm, with an exhaustive search. This is why the ranking criteria, detailed next, will be based on an Exhaustive Search, evaluating the performance of all combinations of loads equations, as shown in Table 4.1, and relying the fitness function, ranking criteria, on physical metric quantities, influence coefficient load equations plot parameters, instead of being limited just to statistics information values such as the standard deviation.

The *proposed method ranking criteria* concepts captured by Eq. (4.10), Eq. (4.11), and Eq. (4.12) will be applicable as fitness functions of Exhaustive Search and Genetic Algorithm. Both searches will be presented.

4.5.3.1 Exhaustive Search and Fitness Function

The characterization of the strain gauge selection process in order to identify the most accurate set of loads equation depending on the physical quantities, IC and ICLE parameters, and not just on the statistical metrics as proposed by the past techniques, proved to be more robust if based on an "exhaustive search" approach instead of relying on potential convergence matters of the genetic algorithm.

In fact, an "exhaustive search" derives loads equations for all possible strain gauge combinations and offers a very thorough scenario of the behaviour given by the fitness functions proposed.

The main terms and considerations to properly shape down the Fitness Functions, FF, are coming through the use of the information gathered in the linear interpolation of the clouds of data obtained once applied the IC and ICLE plots, Eq. (4.2) and Eq. (4.5), according to the ideal response principles described below for different loads:

- **Ideal Shear Response:** the chord contours all fall upon each other to form a flat horizontal response of IC/ICLE in the span direction.

- **Ideal Bending Moment Response:** the chord lines all fall upon each other to form a single line of IC and ICLE increasing linearly in the span direction.
- **Ideal Torsion Response:** the constant IC and ICLE chord lines form a pattern in the span direction that has the shape of the planform of the load points of the structure being calibrated.

The methodology proposed is depicted in the flow diagram of Figure 4.15 that describes independently by the type of load chosen, shear, bending moment or torsion, the main phases.

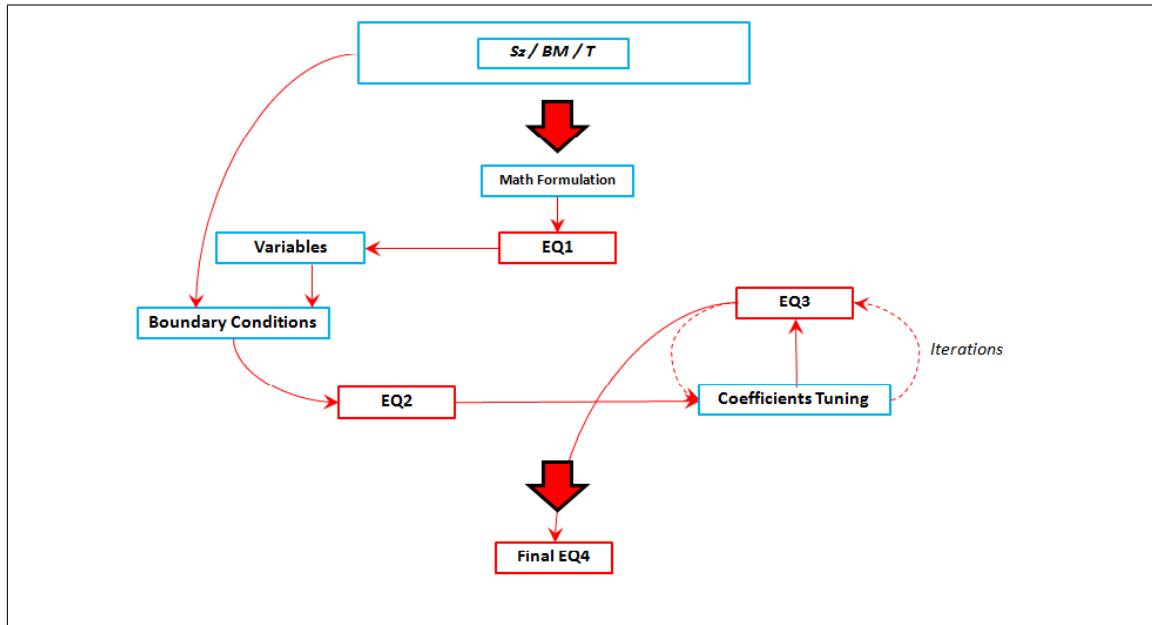


Figure 4.15: Exhaustive Search: Fitness Function Equations Definition Diagram.

The main steps identified in Figure 4.15 are further broken down below:

- **EQ1:** The exponential "math formulation" defines this equation. Exponential function used to normalize the fitness to have a value between 1, a perfect equation, and 0, very poor equation.
- **EQ2:** The variables are the slope, m , and the correlation coefficient, R^2 , of the ICLE linearised equation of the ideal shear, bending moment and torsion response. In function of m , R^2 and N_{all} (penalization factor for small number strain gauge loads equation), the "boundary conditions" are those rules of ideal shear, bending moment and torsion response.
- **EQ3:** The tuning coefficients weigh the combined effects of the variables within the given boundary conditions. These, identified as "A" and "B", see shear, "Sz" Eq. (4.10), "BM" bending moment, Eq. (4.11), and "T" torsion, Eq. (4.12), are the results of dedicated sensitivity analysis, depending on the specific magnitude of given data, meant to produce sensible fitness function outputs inside the boundary conditions.

- **EQ4:** Final shear, bending moment and torsion Loads Equations to be endorsed by Python Codes.

Putting together all the considerations above each shear, "Sz", Eq. (4.10), "BM" bending moment, Eq. (4.11), and "T" torsion, Eq. (4.12), fitness functions embraces the following equations as further depicted by respective pictures.

$$FF_{(S_z)} = e^{\left\{-\left(\frac{A*m+B*(R^2-1)}{N_{all}}\right)\right\}} \quad (4.10)$$

$$FF_{(BM)} = e^{\{-\left(\frac{A*m-1+B*(R2-1)}{N_{all}}\right)\}} \quad (4.11)$$

$$FF_{(T)} = e^{\{-(\frac{A*M+B*(R2-1)}{N_{all}})\}} \quad (4.12)$$

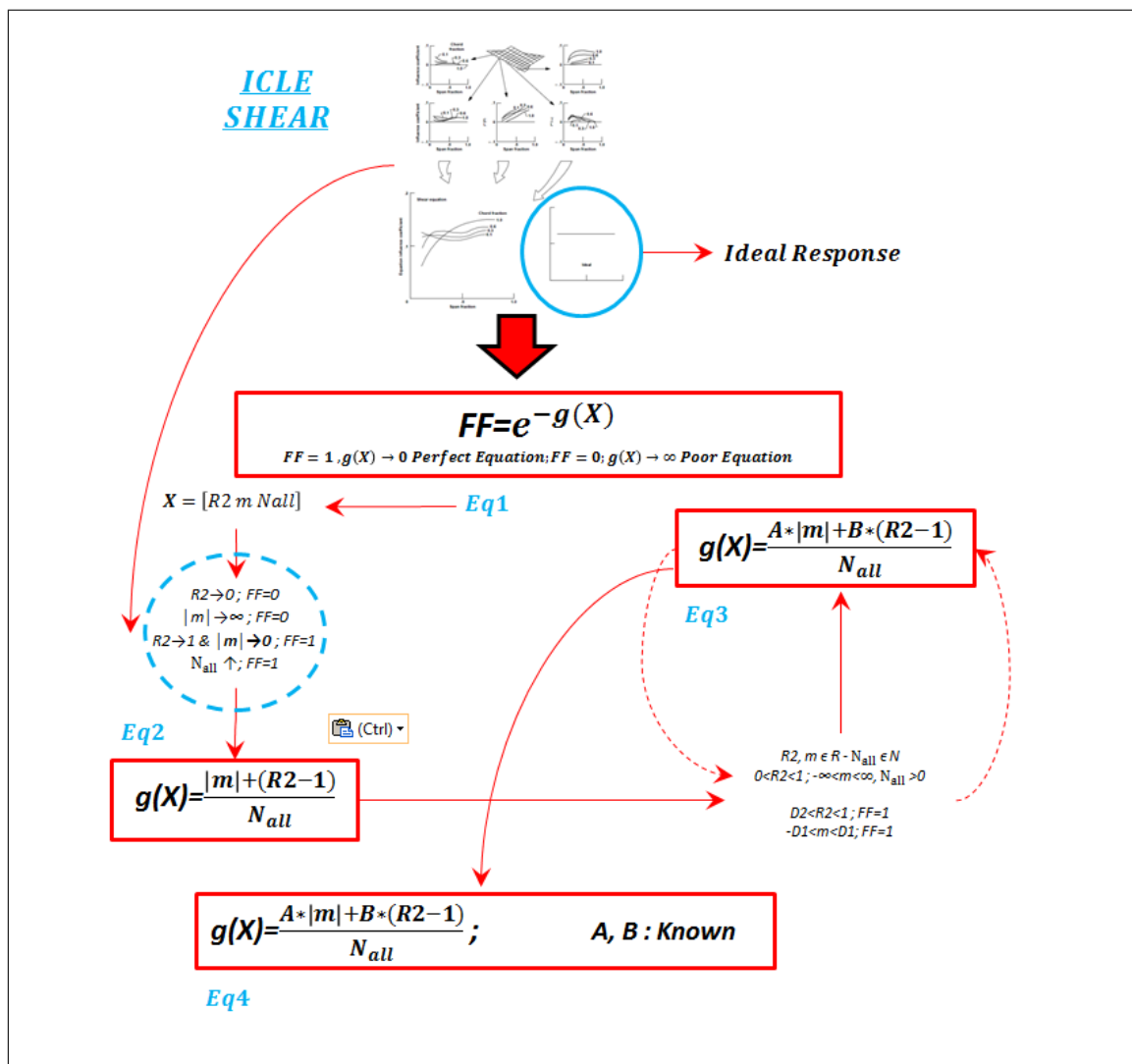


Figure 4.16: Fitness Function Equations Definition: Shear - "Sz" Eq. (4.10).

A detailed flow chart of each of the three equations above, is shown in Figure 4.16, Figure 4.17 and Figure 4.18, where the dotted line circle on the left captures

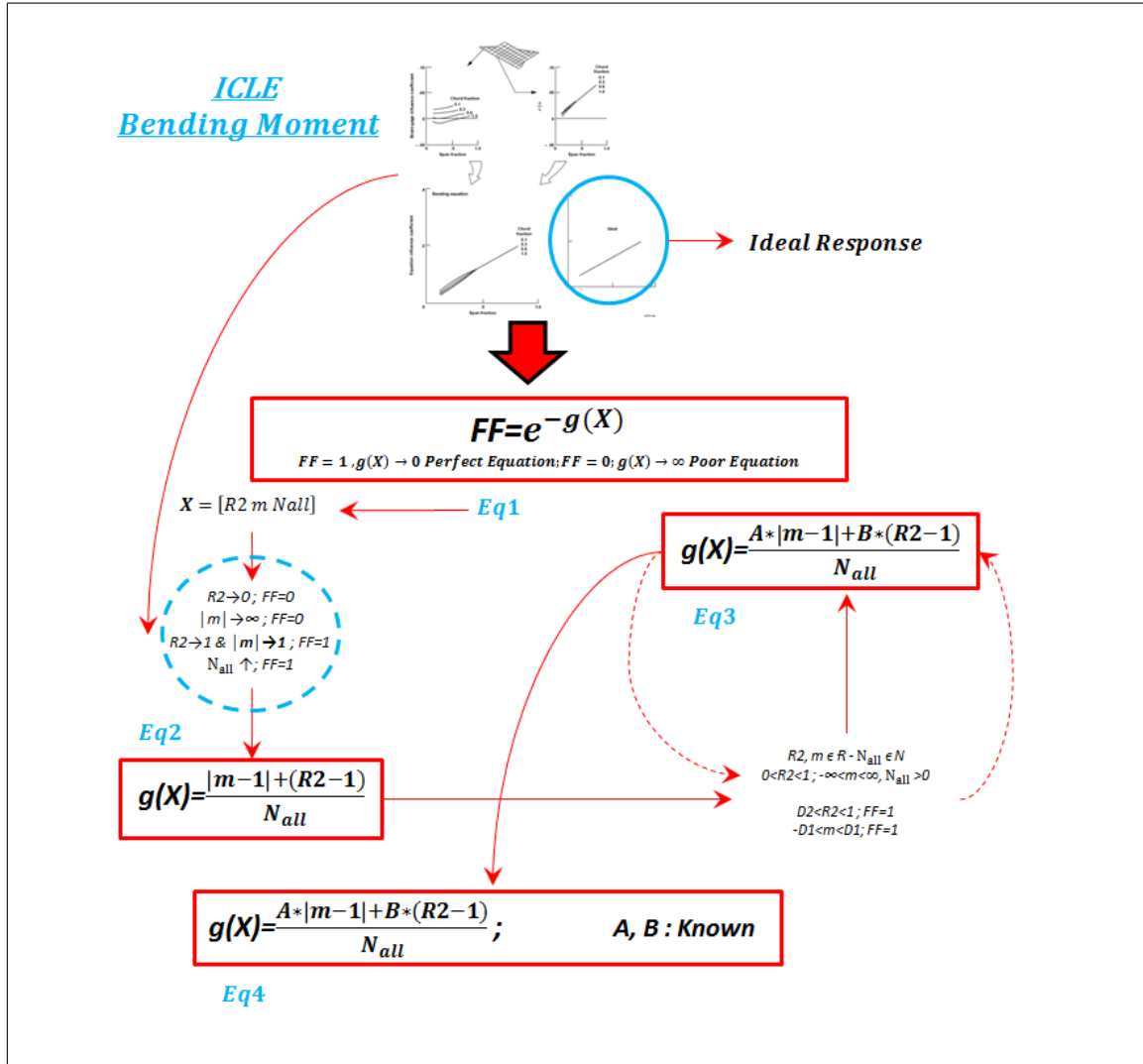


Figure 4.17: Fitness Function Equations Definition: Bending Moment - "BM" Eq. (4.11).

the ideal response conditions that determined the final mathematical $g(x)$ function. In addition, Figure 4.18 describes the main points that identify an extra function, Merit function "M", employed to complete the Ideal Torsion response. The fitness function Eq. (4.10), Eq. (4.11), and Eq. (4.12) will be endorsed by Load Equation Techniques Evaluator, LETE, of the previous chapter.

4.5.3.2 Genetic Algorithm Search: The GALE environment

The conception stage of this research started from the very last past loads equations development techniques, the Genetic Algorithm introduced by Nelson in 1994, [79]. This explains the initial intention to recreate a similar search environment to enable comparing the past and the new techniques.

Though, section B.1.2 offers more information on this, Nelson NASA contractor report, [79], did not detail enough the Genetic Algorithm search leaving a number of

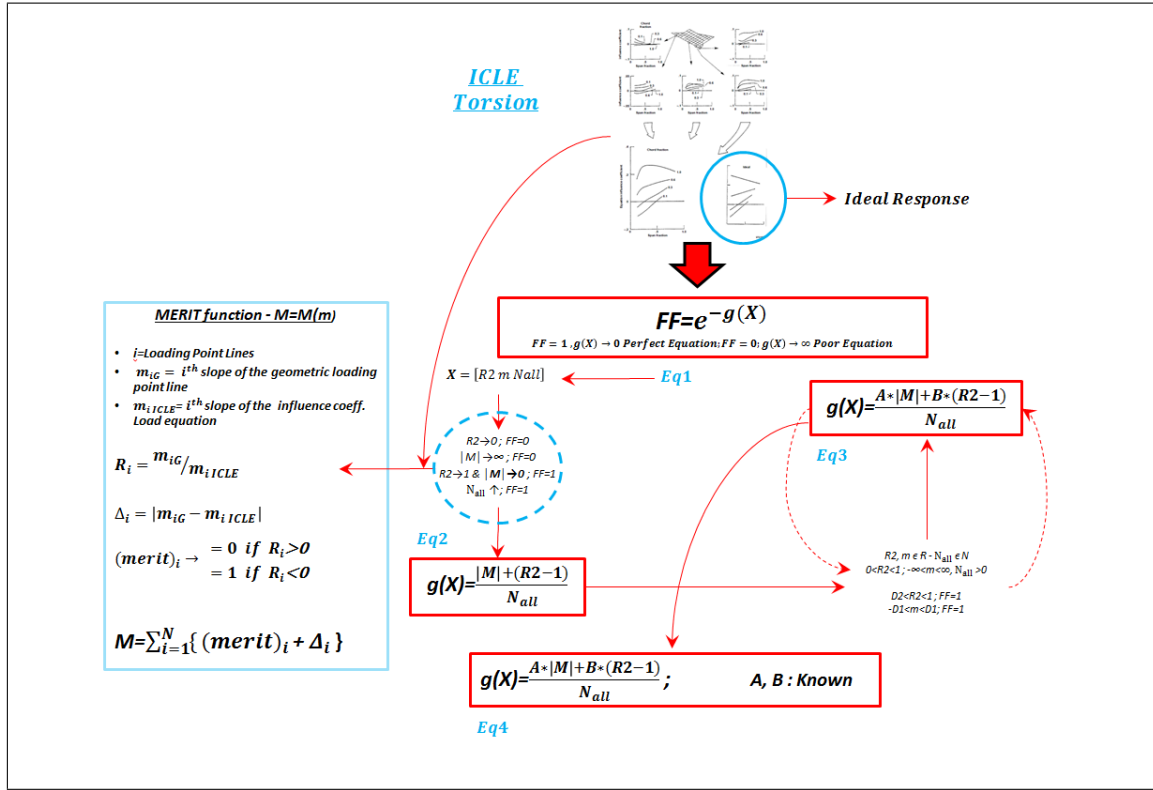


Figure 4.18: Fitness Function Equations Definition: Torsion - "T" Eq. (4.12) and Merit function definition.

undefined information that would have prevented to assess the performance of the ranking criteria proposed while focusing on the searching technique. Furthermore, nowadays with the available computer processing power, [114], an Exhaustive Search, though dealing with multi-spar torsion box, is a very manageable task. In the light of this scenario, it has been decided to concentrate on a common basis search, the exhaustive search, leaving the genetic algorithm as a still valuable tool part of the development of this work whose description is part of this section. Genetic algorithms (GA) work well when the desired solution is a set of characteristics. A characteristic of a strain gauge equation is the use or non-use of a particular gauge. However, there are other features of the GA that differ from more classical techniques such as sampling several points at the same time, populations and not just single point of a large space. Then, each point that is sampled is assigned a fitness. The novelty of this study is just based on this fitness function and its philosophy behind leading to a different mathematical formulation of the Nelson's previous one, Eq. (4.8).

Before taking on the operation flow of the shaped genetic algorithm to host the loads equations physics, a basic overview of the fundamentals and basic terminology associated with very peculiar metaheuristic searching tool inspired by the process of natural selection that belongs to the larger class of evolutionary algorithms. The basic terminology that will be used throughout this work, while dealing with GALE, is displayed in Figure 4.19 and further described below:

- **Population:** It is a subset of all the possible (encoded) solutions to the given problem. The population for a GA is analogous to the population for human beings except that instead of human beings, there are Candidate Solutions representing human beings.
- **Chromosomes:** It is one such solution to the given problem.
- **Gene:** It is one element position of a chromosome.
- **Allele:** it is the value a gene takes for a particular chromosome.

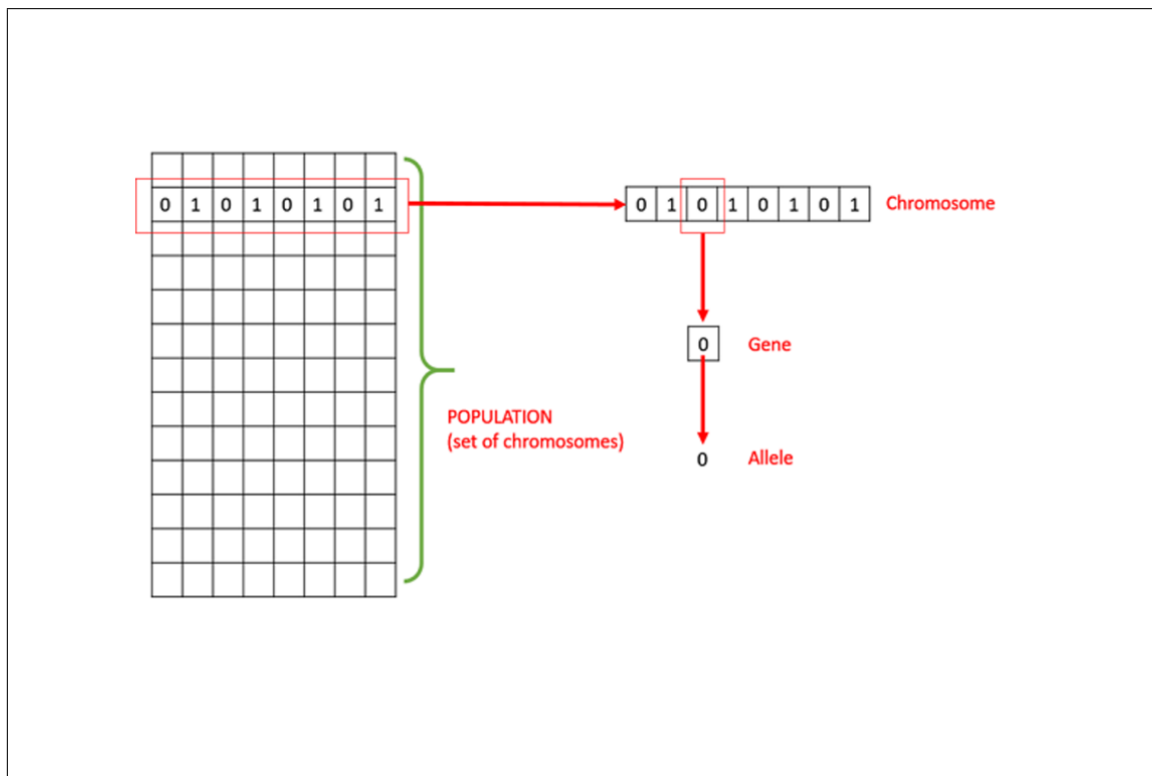


Figure 4.19: Genetic Algorithm: Basic Terminology and Concepts.

The specific GA software package, employed by Nelson, GAn, and for this research, GAm, is outlined in the following main stages:

1. Each equation is encoded into a "string". A string is a series of bits, see Figure 4.20, with each bit holding information about a particular characteristic. If the bits are binary it means either the gauge is used, "1", or not used, "0", by the load equation. Other option, given to the program during the last review of the whole GA, is to employ spare strain gauges too. So, the string might host, "0", No gauge, "1", Main gauge, and "2" Spare strain gauge. This possibility in the current available data, chapter 2, is not deployed. Though, the current loads professional, [96], dealing with more flexibility in the Data Acquisition System (DAS) than forty years ago, are more familiar with. These bits are ordered to represent a specific load equation.

Loads Equations Computation: The Proposed Method

2. Using this coding, several random strings are generated. These constitute the first generation.
3. Evaluation of each string of its fitness function (FF).
4. Sort all of the equations (strings) according to their fitness.
5. Create another generation of strings based on the last generation. This is done by picking two strings from the old generation, favouring the better strings, and creating a new string based on the contents of the two old strings. This is repeated until the next generation is complete.
6. For each string, randomly decide whether or not one of the bits should be changed to enhance the search process. This is known as mutation, and it is performed every generation.
7. Repeat steps 3 through 6 a specific number of generations.

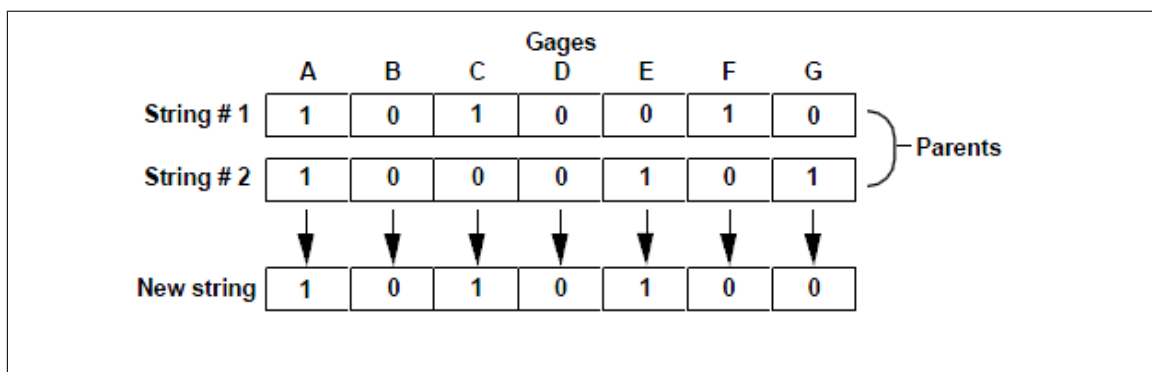


Figure 4.20: GA Load Equations: Bit by bit representation of a string and how new strings are formed based on the characteristics of the older parent strings using the similar trait operator, [79].

All the points above are in agreement to the main standards of the Simple Genetic Algorithm (SGA) of Goldberg, [35], as Nelson initially did when developed his own GAN, [79]. In fact, the classical SGA operators below were employed too:

- Reproduction
- Single Point Cross Over
- Mutation

The strings, load equations, in successive generations are expected to improve their fitness by following these steps. Therefore, since fitness is related to how well a particular set of gauges can be used to calibrate the structure, the strings in later generations represent successively better calibrations. This effect is meant to be more evident dealing with high number of sample data and many generations. At this stage, the employment of the genetic algorithm loads equations, GALE, will be possible by endorsing the requested ranking criteria fitness functions, either

Eq. (4.8) according to Nelson, or Eq. (4.10), Eq. (4.11), and Eq. (4.12) of LPP Technique, described in the previous section 4.5.3.1. This section is coupled with last chapter, B.1.7.7, that focused on the structure of GALE Python code necessary to meet these principles just introduced.

4.5.4 The "LPP" Technique

Putting together the three main pillars, described in the previous section, of the *proposed method*, for the computations of the flight loads equations, it will be obtained the framework of Figure 4.21. The red parts highlight the deviations from the original 1954 Skopinski's method of Figure 4.3. At the same time the LPP Technique is calling back supporting tools, circled boxes, that were already introduced in the past decades, though linked at different stage of the whole cycle process of development of the best set of load coefficients.

The Ground Load Calibration, as warned by Jenkins and DeAngelis [50] and Reed and Holford [96], is driven by the principle of simplicity as relying only on Individual Load Calibration. Though, the regression uses as input the Dependent Distributed Data, DDD, as suggested by Howell and Al., [43], by the means of the Super-Position code, Individual to Distributed, set by the rules provided by the centre of pressure, Flight Loads Specific Range, quantified by the Relevance Coefficient, RC, supporting tools. This enables to generate two new sample load data, one on the left side, the DDD, the other one Independent Distributed Data, IDD, that will be used later on as Check Case to assess unbiased final best set of load equation. At this stage the whole flow chart maintains the past structure besides employing a new Ranking Criteria, driven by a Fitness Function, different according to the type of loads equations to calculate, Shear, Bending Moment or Torsion, whose major terms are coming from the Influence Coefficient Loads Equation Linearised plots, $ICLE_P$. These parameters combined with the Relevance Coefficient, R_C , values of the DDD will be tested against the IDD produced by numerical super-position and miming the centre of pressure of the loads to be measured in flight.

As it will be shown in the description of the LETE python package environment endorsing all the techniques described in section 4.3 and 4.4, the "Proposed Method" can be used as part of an automated selection technique. Otherwise, if required the IC and ICLE plots can be analysed first before going through the final ranking criteria. This offers a functionality that makes the "LPP" Technique flexible enough to fit the end-user needs. In addition, it can be used to assist the other methods and deciding which one is most suited to the specific component under investigation.

4.5.5 The Proposed Method: Coding and Application

The *The Proposed Method*, Influence Coefficient Loads Equation Parameters Exhaustive Search, whose inception and principles have been presented in this chapter and described in Figure 4.21, needs to be coded by an adequate programming language and then tested against a real life application in order to assess its performance

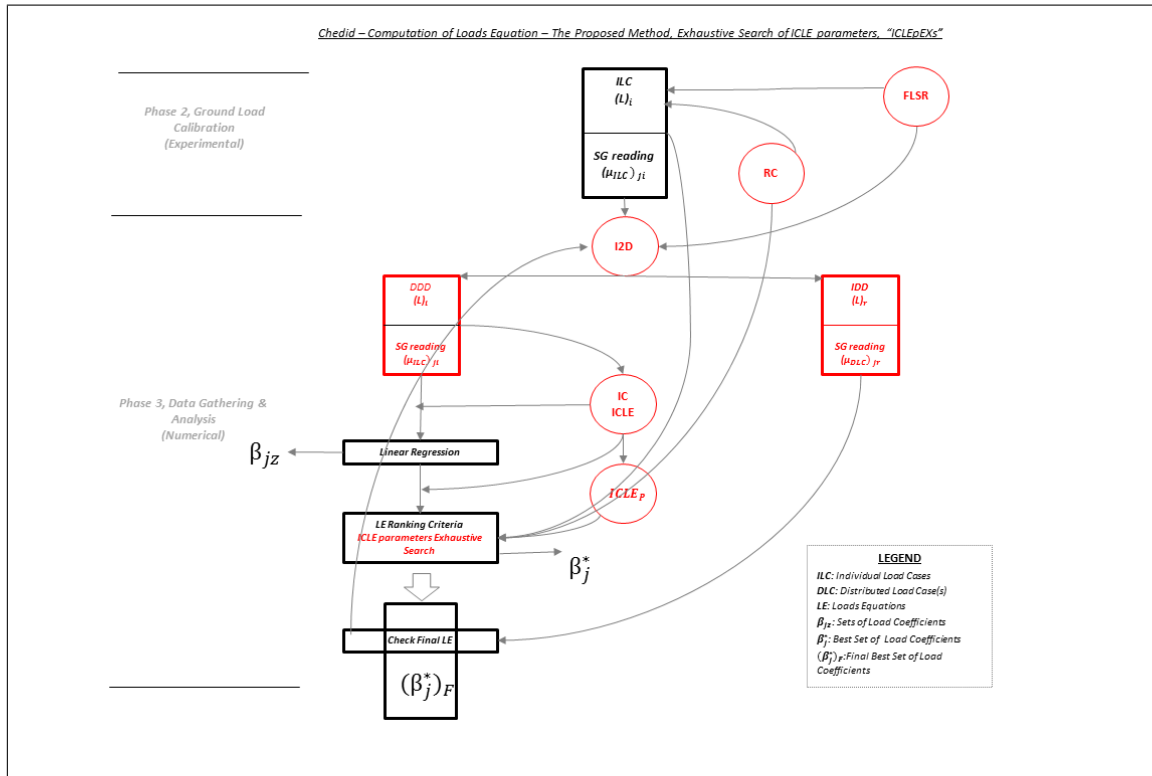


Figure 4.21: Schematic of Computation of the Loads Equations - Chedid, The Proposed Method, "LPP" Technique - 2017.

value.

These major steps have been formalised in the last chapter, where a dedicated Python, open source programming language, environment, described before being applied to the Dropped Transonic Flight Test programme of an USV, unmanned space vehicle data.

The environment, called LETE, Loads Equations Techniques Evaluator, gathers the necessary codes modules to calculate loads coefficients according to the major techniques introduced in this chapter in sections 4.3, 4.4, and 4.5 enabling to compare the performance of the Proposed Method highlighting strength and weakness and so future areas of improvements.

4.6 Summary

Once set the context of the whole Flight Loads Measurement Science, since its inception, 1954, definition and development in chapter 2, narrowing the investigation of its major phases led to focus just on the process of computation of the loads equations.

The calculation cycle has been broken down identifying the concepts on which the supporting analyses and computational techniques have been used since the introduction of the Original Method, Skopinski's one, going through the subsequent decades up to date. At the same time the relevant areas affected by this evolution

process have been highlighted and compared.

In the light of the broad level of information brought from the past it has been possible to introduce a new *proposed method* describing the philosophy behind and the main final supporting framework main characteristics and functions.

The next Chapter will be taking on these novelties natural evolution to the next level where dedicated test cases will allow checking the correctness and robustness of the programmed codes and of the ideas introduced to be critically assessed and debated.

Chapter 5

The Validation Phase

5.1 Introduction

The major task ahead is to show the significant contribution to the science of the topics of this research introduced up to now. Though, before analysing the results generated by the techniques described in the last chapters, a pivotal series of activities has to be considered. In fact, the gain of the necessary confidence on the tools used is the major task that involves the introduction of adequate literature review, combined data and analysis, to compare with. Furthermore, a strategy on how to use the available test cases input data, in order to address to the hypotheses of this work the most general possible validity, becomes another turning point to be described and justified.

The assessment of the inherent abilities of the *LETE* environment, section 3.3, and the specific flight loads equations calculation technique, *LPP*, section 4.21, will be dissected and broken down in three levels, Figure 5.1, where the pillar codes will be identified and validated. Then, a performance analysis of the new proposed technique against the established past methods will allow to come to a final ranking and discussion of the results obtained.

This chapter will be focusing exclusively on the Validation Phase, Level 1, by taking in turn each of those codes to be validated against those test cases representing a complete set of data to allow the necessary confidence of the whole *LETE* environment and its several techniques. The Level 2 and 3, representing the Performance phase are the topics of the next chapter.

Few dedicated test cases have been selected to validate those specific quantities core of the codes under investigation. A low-aspect-ratio, thin, swept wing and the vertical fin of the BQM-34E drone supersonic aircraft whose flight loads measurement campaign has been conducted at Langley Research Center, United States, in the seventies, section 2.6.4.2, [90] and [26], proved to be a valid source to assess the Linear Regression, the individual to distributed sample data, and the search engines (exhaustive search and strain gauge reduction) codes. On the other

hand, the Skopinsky's NACA 1178 report, section 2.6.3, [102], offered the unswept horizontal stabilizer load and strain gauge data to check the Influence Coefficient and the LIRE, Module M2, codes.

Comparisons of the major quantities will be performed by means of Tables and Plots trend as required. Output of codes results necessary to support the discussion will be presented in Appendix C.

At the end of this chapter will be possible to assess and understand the applicability and eventually the limitations of the codes employed by LETE and LPP, not just limited to the Python software generated but applied to the concepts behind too.

5.2 LETE Assessment Strategy: Three-Level Process

The whole amount of concepts introduced by this research had a last goal to contribute to the science of flight loads measurement either to bring methods to be capable to enhance the quality of the final loads measured or to set the conditions for new concepts to be ground of future directions of development. In order to make such expectations real it is needed to start testing them all with real life experimental test cases.

The process described in Figure 5.1 highlights the chosen strategy to follow ensuring the very last outputs are either not affected, or affected in a controlled and known way, by coding or concepts flaws.

Figure 5.1 highlights three levels. The first two levels, the third is an attachment of the second, are structured with the same recurrent template, though internally are interconnected differently. The major items are listed and explained below:

- **Test Case(s):** Tool(s), with an Input (I) and Output (O), used to establish the reliability of the *Black Boxes* under investigation in terms of *Validation and/or Performance*. The interconnection to the *Black Boxes* and *Functions* varies accordingly to the Level.
- **Black Box(es) - BB:** Object(s) of the investigation of reliability, identified as single Python *Codes* or framework, *LETE*.
- **Function of Level:** Each Level has its own functions, *L1, V - L2, C - L3, A*, addressed the role to assess the *Black Boxes*.

Level 1 represents the *Validation* while the others, *Comparison* and *Final Assessment*, depict the *Performance* process of **LETE** and **LPP**. The *Validation and Performance* phases need thorough Test Cases data to work as Input and Output of the relevant codes to be assessed. The way each data will be employed and interconnected within the LETE framework will be further detailed later on inside each level description section.

The right side of the "LETE assessment Strategy - Three Levels Flow Chart" gathers extra information of the *Black Boxes* and *Functions*, such as list of the *Codes* and associated *Quantities* to assess accordingly to the level.

L1 - The Validation Strategy

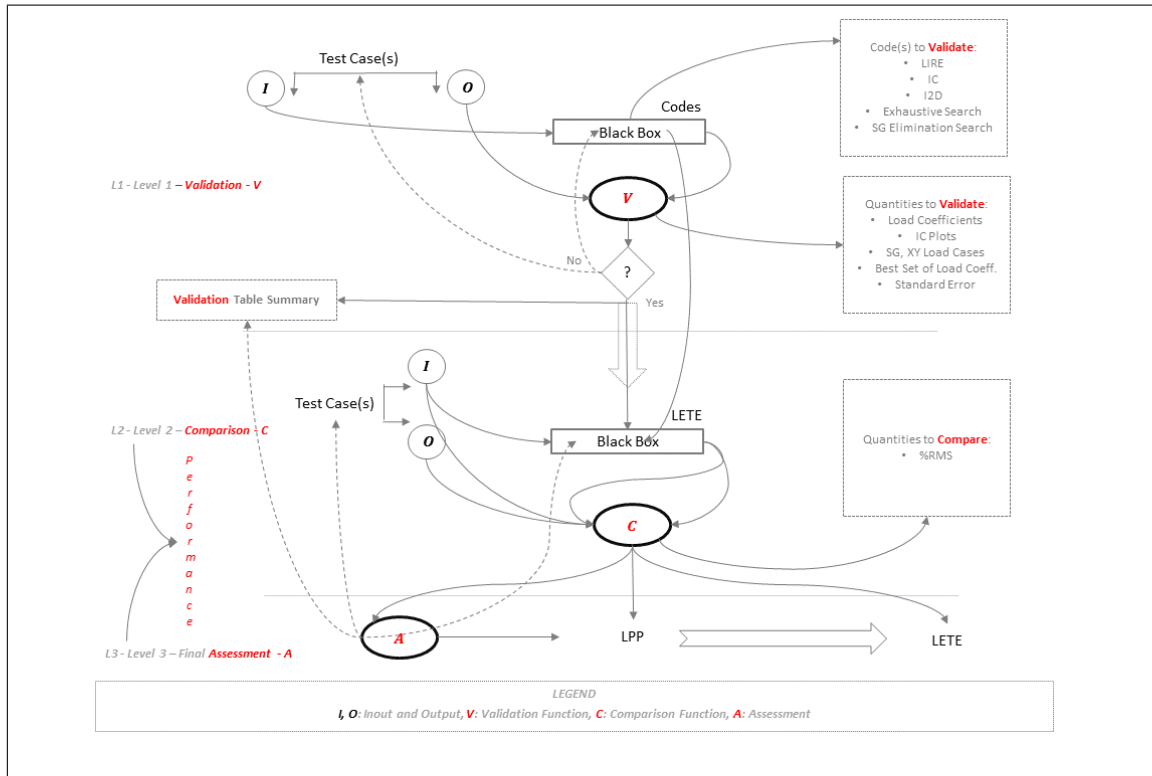


Figure 5.1: LETE Assessment Strategy - Three Levels Flow Chart.

A mention has to be dedicated to the semi-dotted arrowed lines, all characterised to point backwards, representing a further collection of past results, such as *Validation Table Summary*, to better interpret the *Function* outcomes. Sometimes, this might lead to the need of an iteration of the preliminary results produced by reviewing either the *Test Cases* or the *Black Boxes*. This ensures the quality control of the major steps that led to the final, Level 3, phase to rank and assess *LPP* and *LETE*. The *Input and Output* data of the *Test Cases* are determined in function of the *Quantities* selected to be either *Validated* or *Compared* by the ellipse box functions. This through the next *Levels* break down will justify a different interconnection of *Input and Output* to execute the *Validation* and *Comparison* functions. Each of the coming sections about the *Levels* of Figure 5.1 will be describing the contents of the major boxes and criteria behind their selection. Moreover, the test cases chosen will be contextualised identifying the inputs and outputs to use against the *black boxes* outcomes. The results, generated by the codes of Chapter 3, presented and attached in Appendix C, will be discussed too.

5.3 L1 - The Validation Strategy

The ultimate scope of the thesis is to consider the results produced by LETE reliable, Chapter 6, limited to the representativeness of the test case employed, and so assess the novelties introduced. This requires that the tools of Figure 5.1, *Codes* and *LETE*, introduced and python coded up to now, and their interconnection with the

different type of data, dependent and independent data (training and validation set), "Double E Data Type" of Figure 3.1, are tested and proved to produce correct results. This is the aim of *Level 1* and below the contents of the Level template of section 5.2 is populated and next justified.

Table 5.1: Level 1: Validation Contents.

Val. Item	Black Boxes - (BB)	Codes	Test Cases - (TC)
01	Engine Search	EX Search (ExS)	[90], [90]
02	Engine Search	Strain gauge Reduct. (SgR)	[109], [90]
03	Solver	LIRE	[26], [102]
04	Supporting Tool	IC	[102], [26]
05	Supporting Tool	I2D	[43], [26]

Table 5.1 has been populated following the step by step approach of Figure 5.2. At *step 1* the LETE environment, already captured in Figure 3.2, needs to be dissected in such a way to highlight the main parts making up the techniques of stage 1 of Figure B.1. By using the same terminology of Chapter 3 it follows the *LETE Dissection* of Table 5.2.

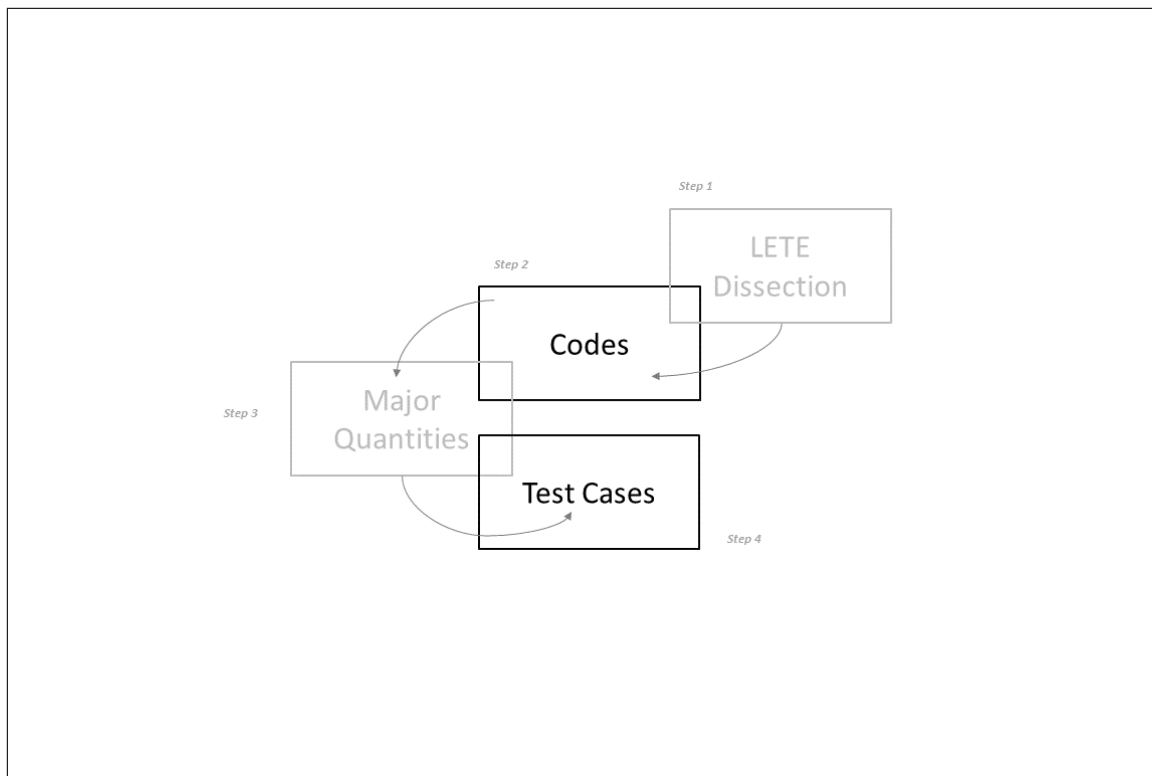


Figure 5.2: Level 1 Contents Definition - Step by Step approach.

Each of the Techniques gathered in Table 5.2 shows clearly, highlighted in bold, the recurrent piece of codes supporting the whole LETE framework and so in need

to be validated. In fact, after this refining step, it is meaningful to include them all in "Level 1: Validation Contents" of Table 5.1 and so completing Step 2 of Figure 5.2. A further analysis of the Table 5.2 meaning shows there are two main "search engines" to validate, the *Exhaustive Search*, ExS, the most used among the Techniques that replaces also the Genetic Algorithm of Nelson, as explained in section B.1.2, and the *Strain Gauge Reduction*, SgR, employed by the *T-value and Modified T-value* methods. Once identified the search engine, that in some way works as an optimiser, the ranking function, or objective/fitness function, can vary as needed though not the validation object. The next item pointed out is labelled "solver" as employed to solve the basic equation of loads measurement, Eq. (4.1), and this, *LIRE*, is clearly universally adopted. The last category requiring investigation will be the "supporting tools", the *influence coefficient* plots, IC, and the *individual to distributed*, I2D, whose *major quantities* to be analysed are the task of the remaining steps of Figure 5.2. Table 5.3 collects the results of step 1 and step 3 that will be further linked with a representative test codes.

Table 5.3: Level 1: Codes and Major Quantities for Validation.

Codes	Transfer Function	Supporting Tools	Major Quantities
LIRE	✓	-	β_i
ExS	✓	-	Best set of β_i
SgR	✓	-	Best set of β_i
IC	-	✓	2-D Plots trend
I2D	-	✓	3-D Plots trend

In fact, the remaining two steps, *step 3 and 4*, for the definition of the contents of the Validation Level expect to further break down each code *major quantities* to compare with representative literature approved data. This will enable to select those significant, and available, test cases inputs and outputs, described in the next section 5.4. In fact, it might happen that to assess the robustness of the codes above by comparing the major quantities generated might require an indirect approach that will come through the identification of lower level results whose correctness will bring the confidence needed at the very top where no data were available for comparison.

Test cases listed in Table 5.2 will be further detailed now in this coming section, and the major set of output codes information will be referred to Appendix C.

5.4 L1 Test Cases

Since the aim of this set of data is just a direct comparison of the outputs of the *Codes* singled out previously with the same results offered by reliable literature

of Table 5.1, there is no real need to make distinction between dependent and independent data.

The test case described below will allow to validate the codes of section B.1.7. Sometimes, the data available to cover a full validation of the *Codes* are not sufficient and this will require an indirect approach as a result of a further break down of the quantities under investigation, as it happened for the strain gauge reduction engine search and the T and/or MT value coefficients.

The following flight-test measurements data of wing and horizontal loads, shear, bending moment, and torque, were obtained by means of strain-gauge bridges mounted on the major load paths of a different aspect-ratio, straight and swept lifting surface.

5.4.1 Langley Research Center: NACA Report 1178, Horizontal Stabiliser Structures - Test Case 1

The data of this test case are coming from the master report of the flight loads measurement techniques described in NACA Report 1178, [102]. Skopinski et Al. illustrate the application of the calibration procedures, outlined in the NACA report, by means of two representative structures. The calibrations of these structures, straight and swept horizontal stabilisers, Structure A and Structure B respectively, presented most of the problem have arisen at that time in the Langley aircraft loads calibration laboratory of Flight Research Division.

The *Structure A* is a three-spar unswept horizontal stabilizer and elevator assembly with aspect ratio 6.7, taper ration 0.29, and 12° dihedral, Figure 5.3. The *Structure B* is a two-spar horizontal stabilizer with the quarter-chord line swept 35.6° , aspect ratio 4.65, taper ratio 0.45 and 10° dihedral, Figure 5.4.

The strain gauge locations, shear and bending moment bridges were installed, and the load cases application points for the two Structures are shown in Figure 5.3, Figure 5.4, Figure 5.5 and Figure 5.6 respectively.

As a check on the applicability of the equations obtained by the point-load calibration, Individual Dependent Data *IDD*, described in Figure 5.4 and Figure 5.6, to the determination of distributed loads as encountered in flight, the distributed load A, Figure 5.7, and load B, Figure 5.8, were introduced too. These extra set of data, labelled as Distributed Independent Data, *DID*, according to the terminology introduced in the "Double E Data Type" of Figure 3.1, will be employed as part of next sections of Level 2 and Level 3 to assess the performance of the novelties introduced in this research.

5.4.2 Langley Research Center: BQM-34E Drone Aircraft - Test Case 2

Eckstrom, in this late 70s NASA Technical Note, [26], details the wing strain-gauge bridge traces, the calibration procedures used, and the flight-test results along with some pressure measurements and theoretical calculations for comparison purposes with the basic concepts of flight loads equation calculation at that time.

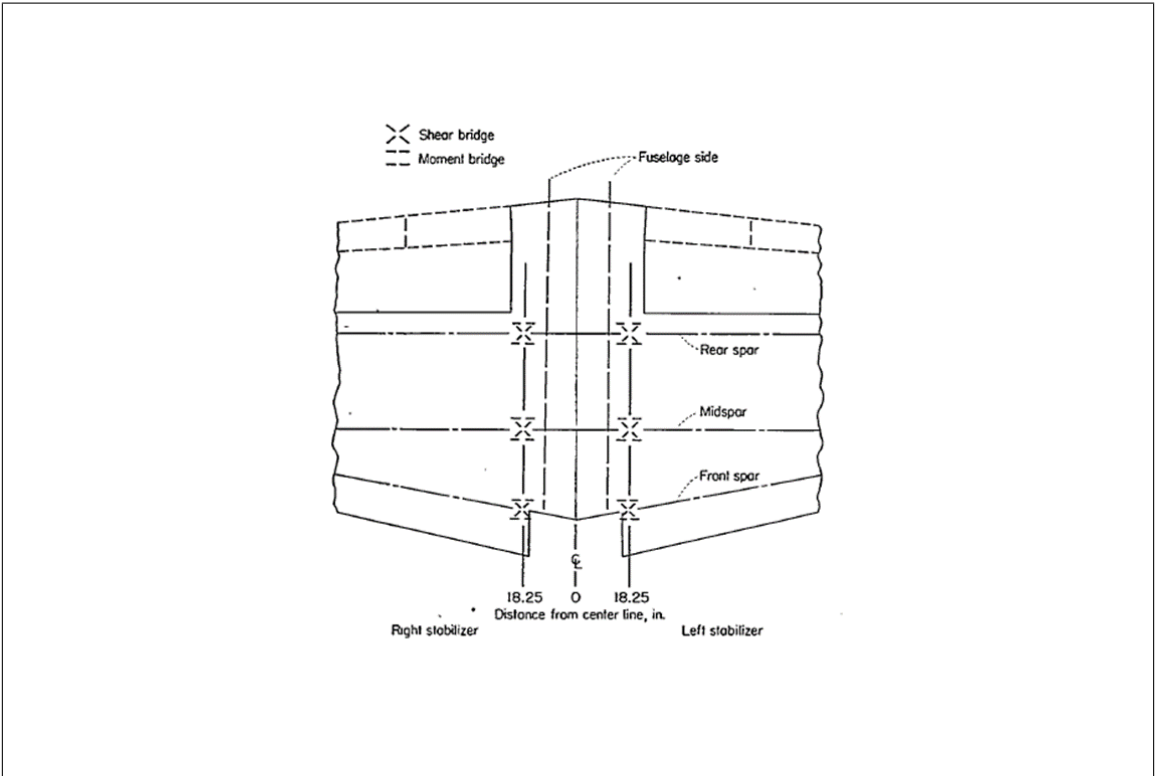


Figure 5.3: NACA Report 1178: Strain gauge bridge locations for Structure A, [102].

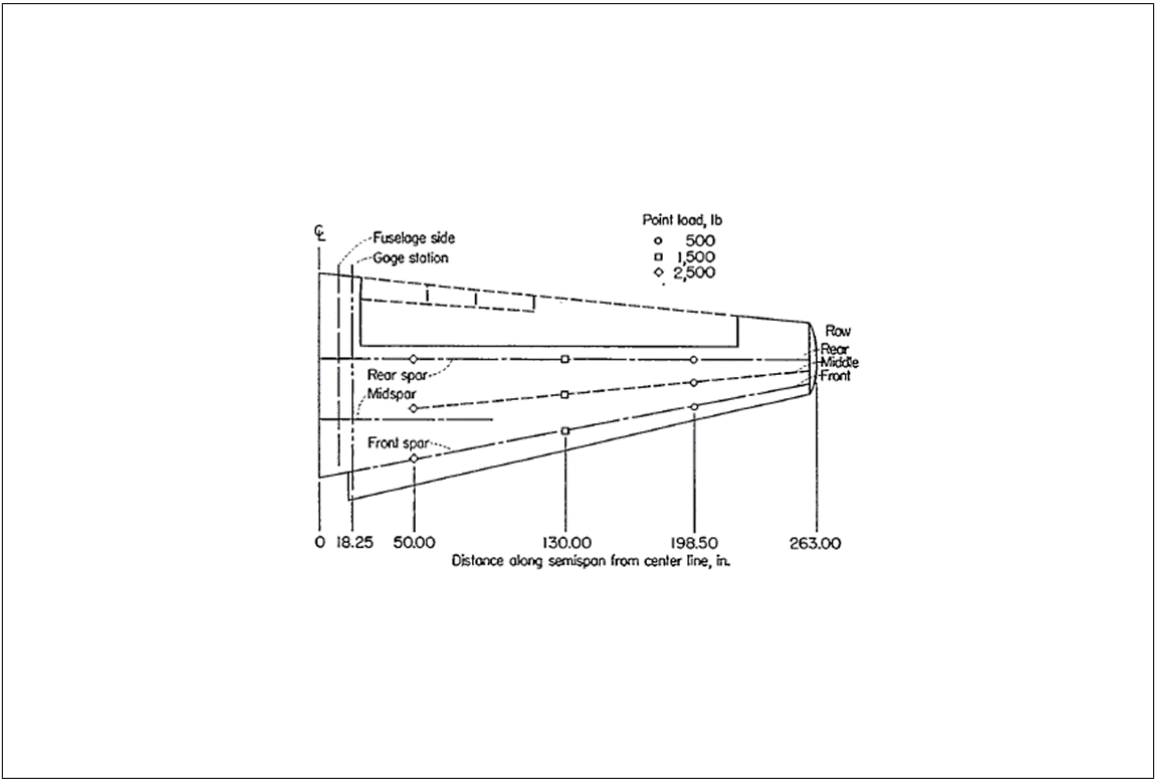


Figure 5.4: NACA Report 1178: Load Cases application points for Structure A, [102].

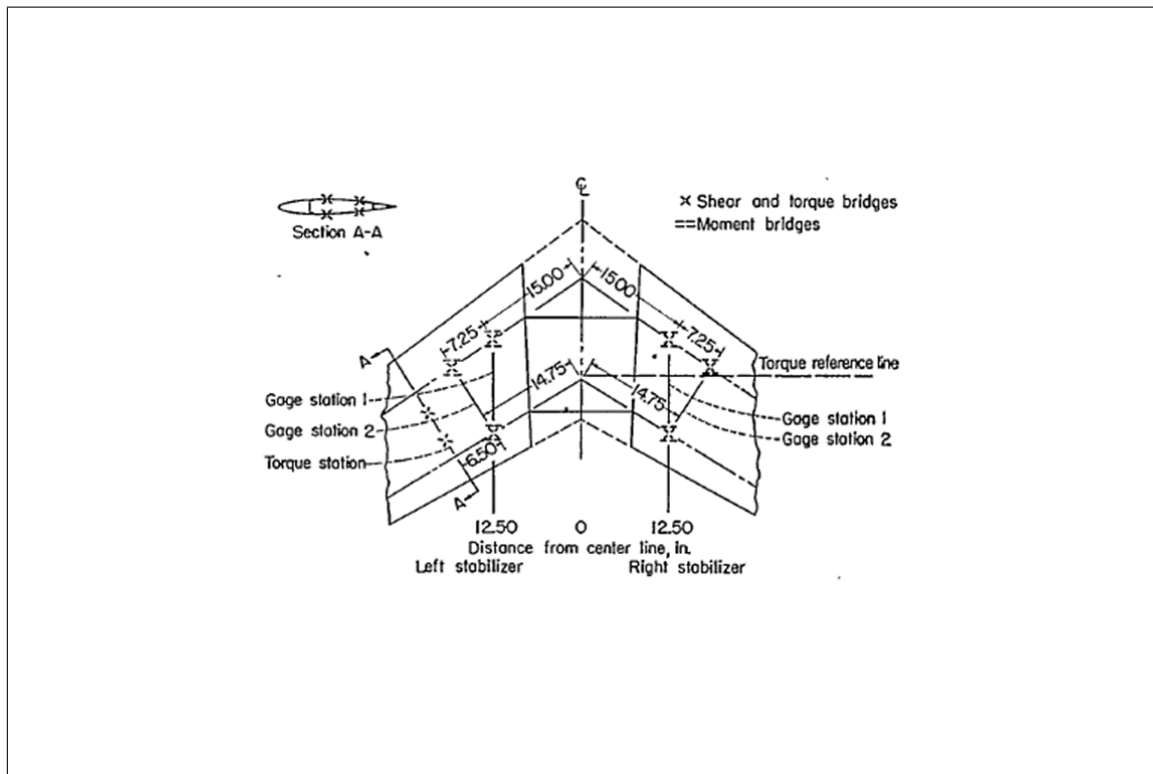


Figure 5.5: NACA Report 1178: Strain gauge bridge locations for Structure B, [102]

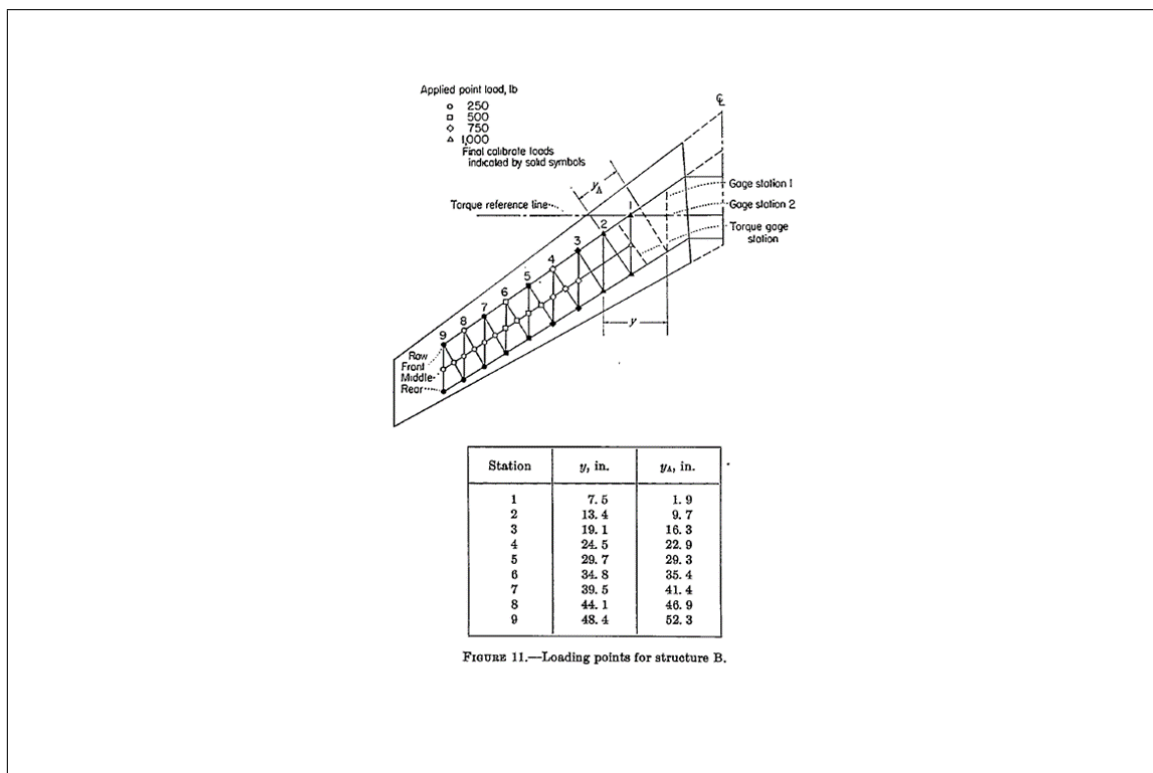


Figure 5.6: NACA Report 1178: Load Cases application points for Structure B, [102].

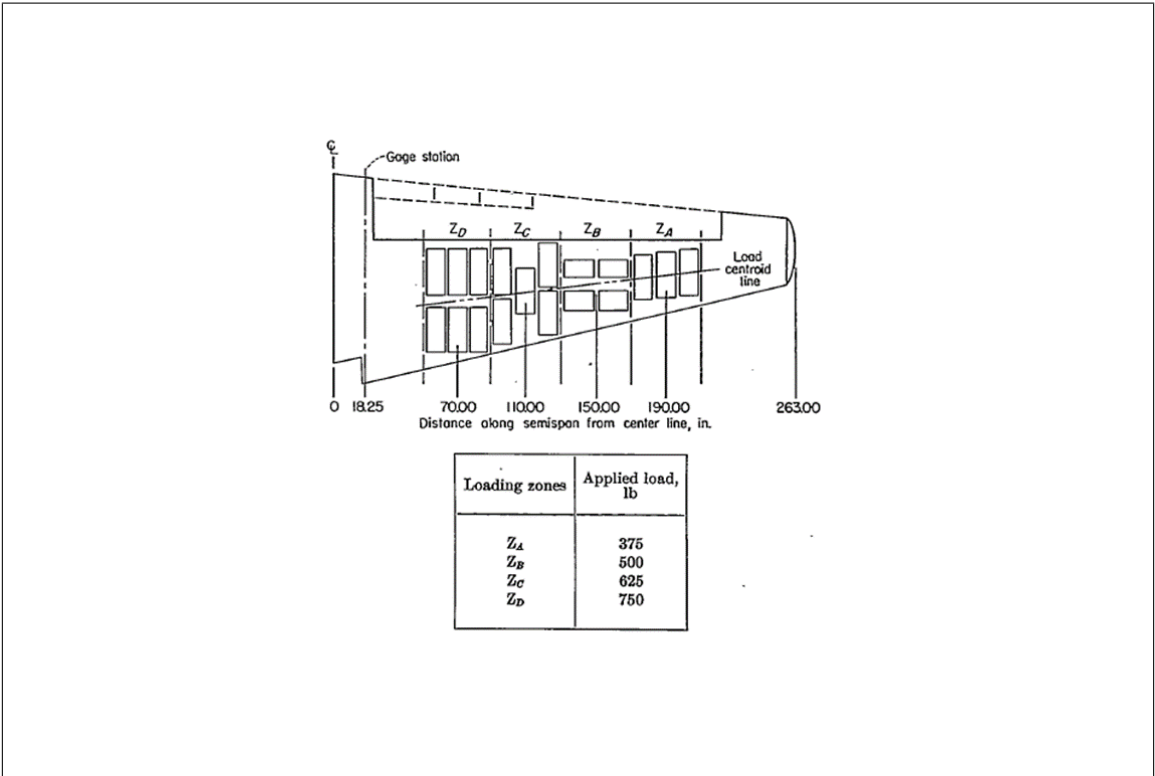


Figure 5.7: NACA Report 1178, Test Case 1 (TC1):Symmetrical distributed check load applied on Structure A, [102].

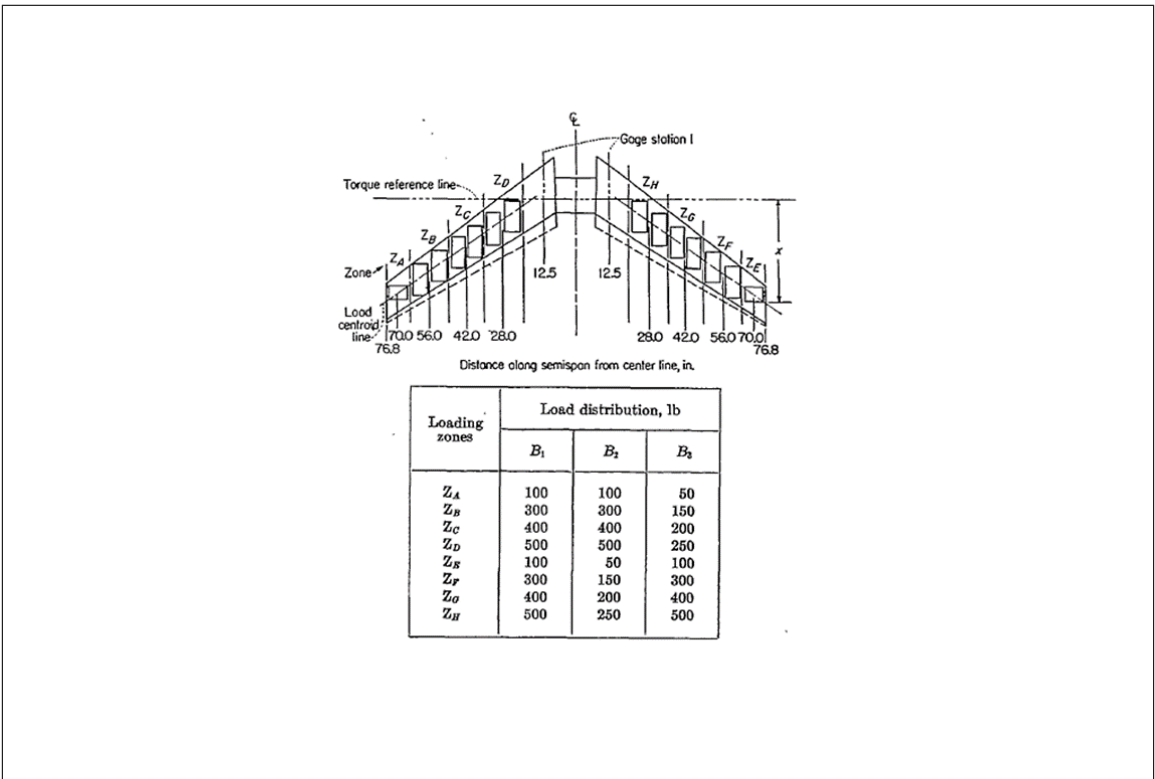


Figure 5.8: NACA Report 1178, Test Case 2 (TC2):Symmetrical distributed check load applied on Structure B, [102].

A thorough experimental ground data and associated analysis are presented, the flight test information are mainly based on time-histories not enough detailed to enable the use, though an extension of this flight loads measurement campaign is offered by Peele, [90], that allowed to access the strain gauge readings of several points in the sky. This will be employed in the next Chapter to assess the accuracy of real flight loads measurement by means of LETE with all embedded loads equation calculation past and new techniques.

The drone aircraft low-aspect ratio, 2.5, thin swept wing of the supersonic BQM-34E drone aircraft, shown in Figure 5.9, reported on herein, was instrumented and ground calibrated at the Langley Research Center, to generate loads equations for the successive flight loads campaign. The wing structure consists of upper and lower tapered thickness stainless steel skins which are bonded to a full-depth aluminium honeycomb core, there are no typical internal spar or rib-type structures in the wing. The wing has an aspect ratio of 2.5, a taper ratio of 0.3, a leading edge sweep angle of 53° , and a maximum thickness of 3 percent of the chord length. The wing has no control surfaces and no incidence angle, dihedral angle, twist or chamber. The airfoil is a NACA 65-003 shape that has been modified to provide a finite thickness trailing edge. The wing has a span of 2.720 meters, a reference area of 2.970 m^2 , a net exposed area of 2.150 m^2 , a projected centre line root chord of 1.676 meters, and a tip chord of 0.503 meter. The total wing structure, including the fuselage crossover section, has a mass of approximately 67 kg, [26].

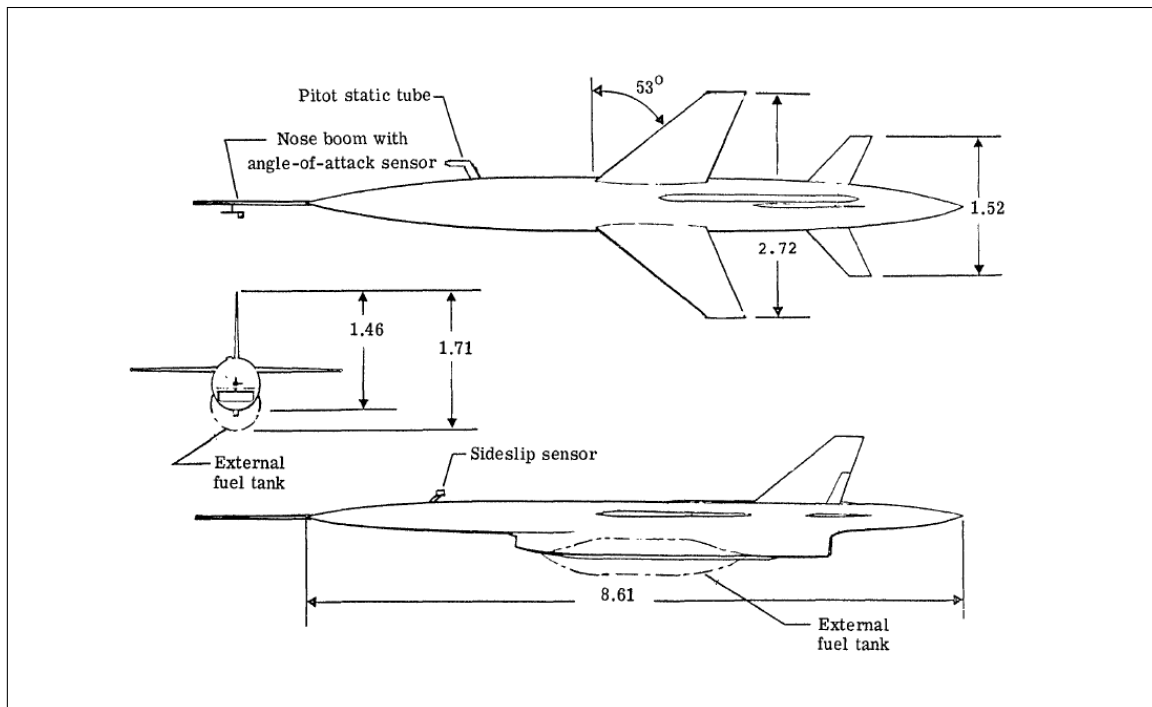


Figure 5.9: BQM-34E drone aircraft: Three View, [26].

Two different instrumentations have been carried out on the no internal spars and ribs swept wing. The first one, labelled *Wing I*, was instrumented with three

strain gauge bridges to the outer skin surfaces and an additional bridge located on a vertical face at the wing crossover section as Figure 5.10 shows alongside the detailed locations, needed later on to generate the results. Both individual and multi-point calibration loads were applied at selected locations on the wing, Figure 5.11.

As part of this NACA Technical Note the analytical superposition of bridge outputs was performed offering data to test the concepts of the novelty supporting tools, *I2D*, section B.1.7.12, that was for the first time introduced by the British scientists, Hovell, Webber and Roberts, during the 60s Decade, [43] and [44]. Unfortunately, the data they offered is very basic to be considered for validation and/or performance purposes of this research.

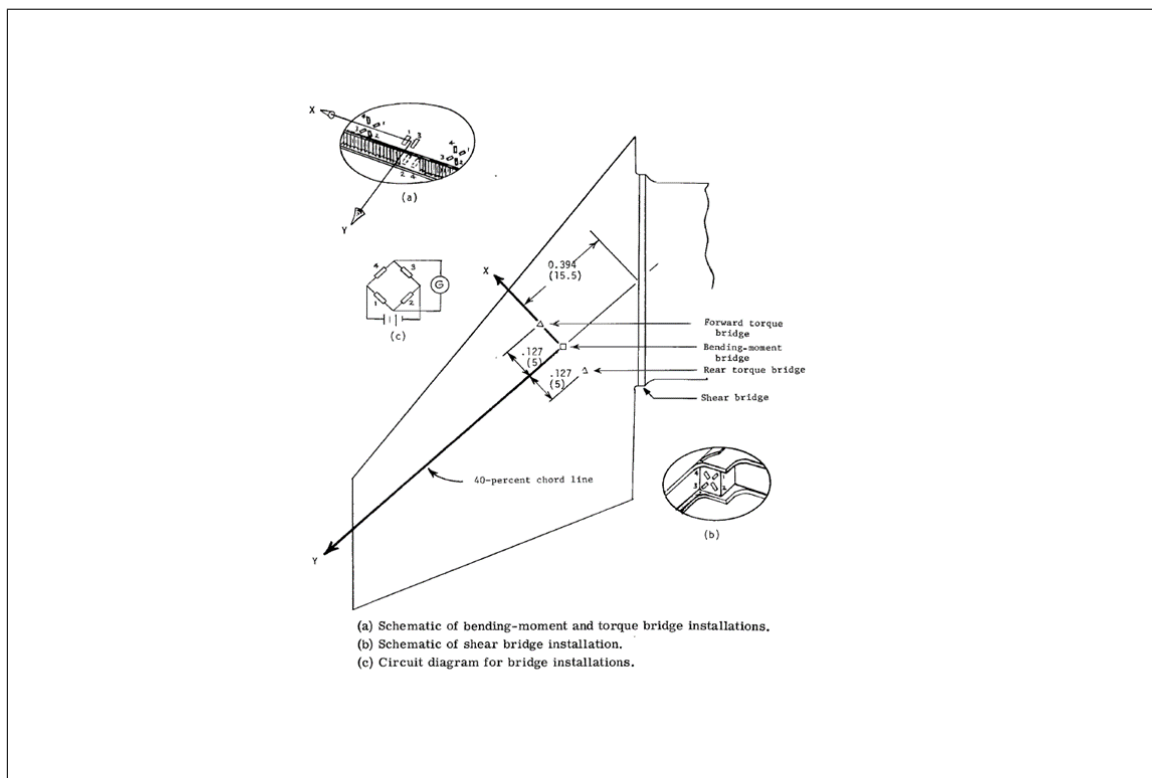


Figure 5.10: BQM-34E drone aircraft: Wing Strain gauge bridge instrumentation locations - *Wing I*, [90].

In order to improve the quality of the flight loads measurement, a year later 1976, Peele, [26], presented a second wing instrumentation, labelled *Wing II*, with all associated experimental ground and thorough flight test data set. The left semi-span of the test wing was instrumented with strain -gauge bridges mounted on the exterior surfaces at three different wing stations, inboard, mid-wing and outboard, covering the main load path, the overall number of locations is 11, Figure 5.12. At each strain-gauge location there are two independent types of strain gauges. One mounted entirely on the wing upper surface, with the four strain gauges positioned in a X-pattern so as to be sensitive primarily to skin shearing strains produced by torque loads. The second type of bridge at each location consists of two parallel gauges on the upper surface and an identical set of two gauges on the lower surface,

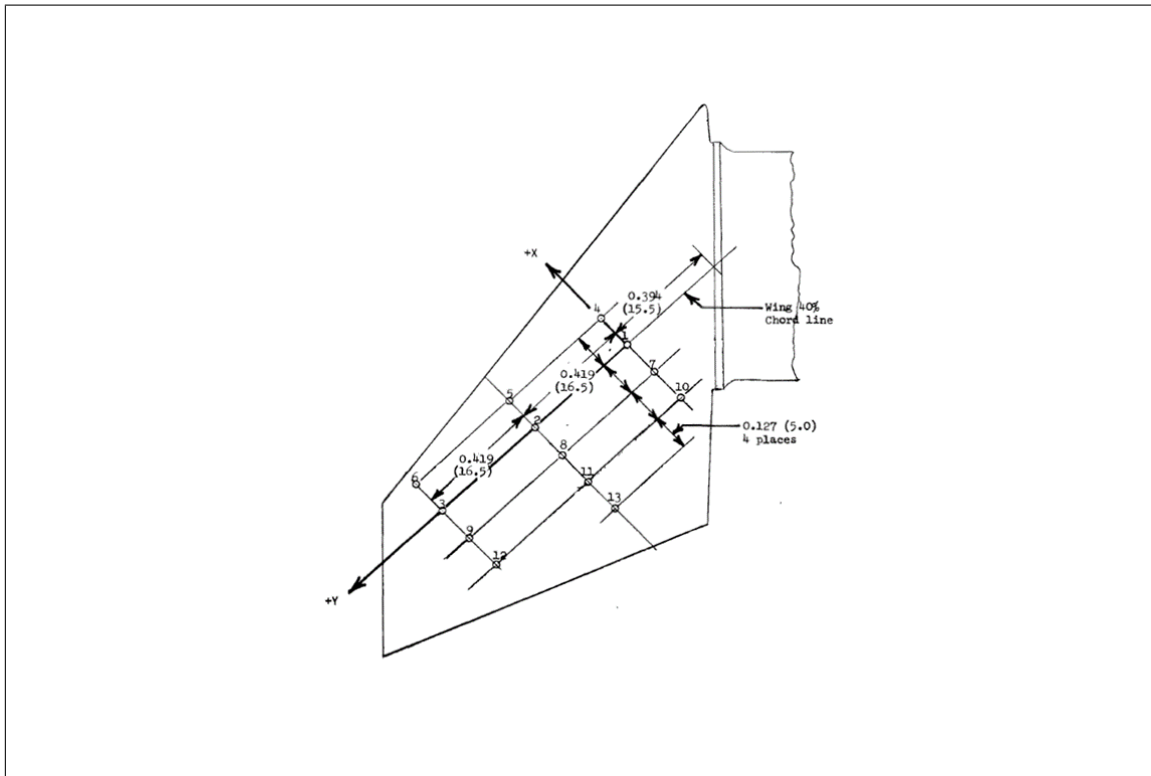


Figure 5.11: BQM-34E drone aircraft: Wing Load Cases application points - *Wing I*, [90].

to be responsive to bending moment loads.

The GLC has been conducted with the same philosophy of the *Wing I* by applying single and multipoint loadings whose table of data will be shown once the results of the coming section will be presented.

The BQM-34E drone aircraft gained experience with the low aspect-ratio, thin, swept wing, instrumented with the two different configurations just introduced, *wing I* and *wing II*, indicating that there might be advantages to using a larger number of strain gauge bridges. This led to instrument a vertical fin, similar in planform and construction to that of the flight test wing, with eight strain gauge bridges at four locations near the fin root and mounted as shown in Figure 5.13. Four of the strain gauges (5,6,7 and 8) were installed in the bending moment bridge configuration, and the remaining four bridges (1,2,3 and 4) were installed in the torque bridge configuration with one bridge of each type being at each of the four locations.

5.5 L1 Results and Discussion

This section merged the two major phases of *Results and Discussion* as the *Validation* task becomes very straight forward in comparing outputs that are meant to be very close, as based on quite simple equations. The only eventuality that might justify a dedicated and thorough investigation, reviewing the input data and the codes

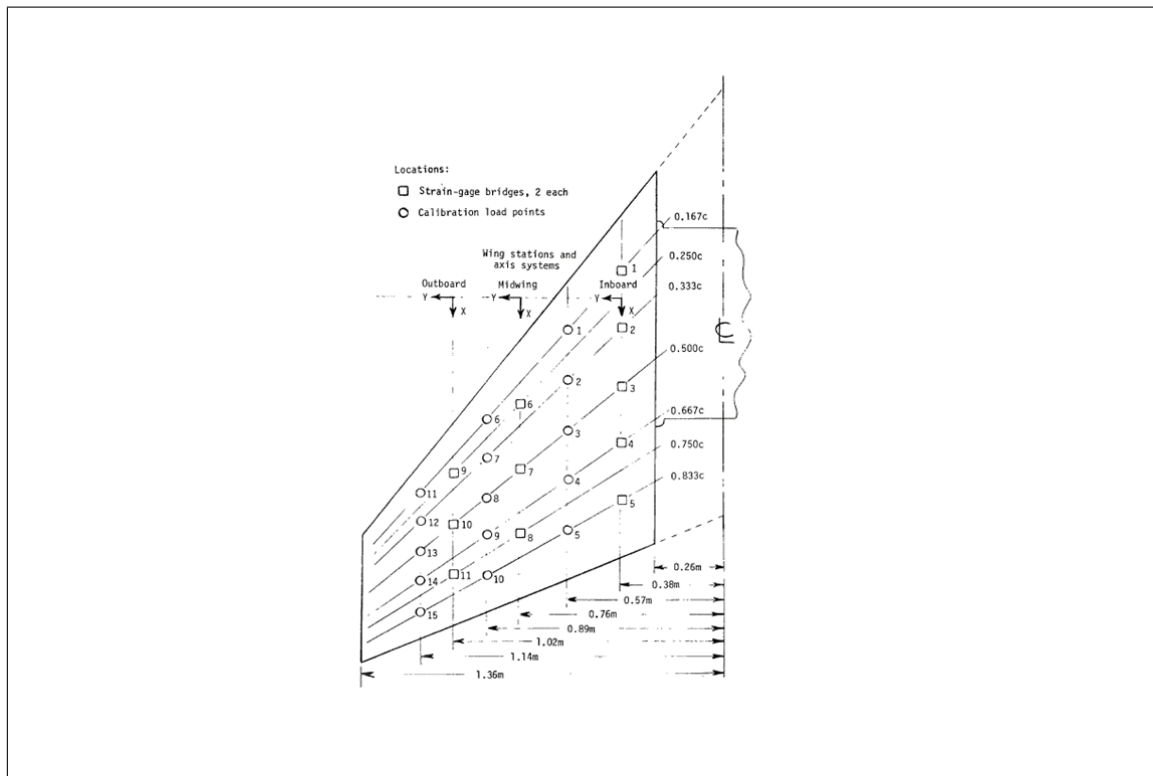


Figure 5.12: BQM-34E drone aircraft: Wing Strain gauge bridge instrumentation locations and Load Cases application points - *Wing II*, [26].

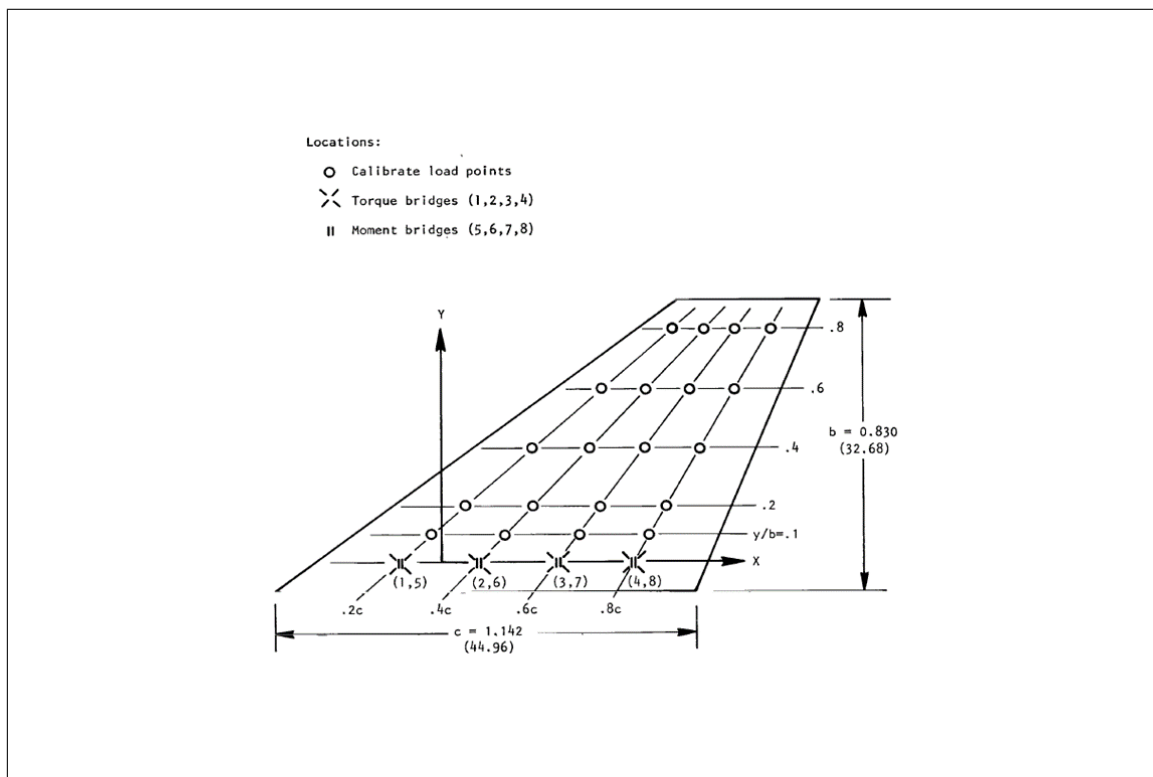


Figure 5.13: BQM-34E drone aircraft: Vertical Fin Strain gauge bridge instrumentation locations and Load Cases application points - *Vertical Fin*, [90].

employed, as previously anticipated by the L-1 semi-dotted line of Figure 5.1, is when the comparison highlights unjustified differences.

The "codes" to be validated have been already captured in Table 5.3 and the following subsection will take in turn each of those highlighting the strategy employed to gain the needed confidence on those piece of software, code. In fact, sometimes the available literature did not always offer data and associated results as the one required by this section.

The Test Cases employed will be mentioned in order to set the context of the results and link with more detailed information collected in section 5.4.

It is important to highlight that as the data available from the literature, Test Cases, might happen to be very old and its quality might be affected and eventually its reliability too. There are tables of numbers that might not allow a clear distinction of the digits listed. Due to all these considerations everytime that a code has been tested several inputs data have been used.

5.5.1 LIRE Validation

LIRE Python code, as described in B.1.7.13, has two modules, **M1** dedicated to to simply evaluate the *Load Coefficients* β_i with Loads and *Strain Gauge* readings known. On the other hand, **M2**, calculates the Load(s), once provided the *Load Coefficients* and the *Strain Gauge* data. The M1 module has been validated against the ground calibration single point load cases of *Wing II*, Test Case 2 5.4.2, [26]. The NASA Technical input data are gathered in Figure 5.14 and the LIRE M1 Inputs and Outputs, covering Shear, Bending Moment and Torque Loads, are shown in Figure 5.15, Figure 5.16, and Figure 5.17. These figure results are compared with Eckstrom Figure 5.18.

The *LIRE Module 1* results highlight quantities, , such as the equation load coefficients, β_i , from independent variables (strains) and dependent variables (loads), Figure 5.14, and the related statistical parameters, according to the basic principles of statistics, [39], probable error of the estimate, and of the coefficients, directly linked to the T-value and MT-value techniques, Eq. (4.6) and Eq. (4.7) of section 4.4.3, enable to characterise the best set of loads accordingly to the engine search employed, Exhaustive, Genetic Algorithm, or Strain Gauge Reduction. Table 5.4, 5.5 and 5.6 gather LIRE M1 software outputs compared to the Eckstrom NACA results, Figure 5.18, pointing out ratio differences too. The outputs comparison of Shear, Bending Moment, and Torsion load coefficients alongside the load probable errors of the tables above show overall the ratios are very close to 1, all of them well above 0.9, giving the needed confidence of the robustness and correctness of the Python LIRE M1 scripts produced up to now.

On the other hand, the *LIRE M2 module 2* reliability is proved by employing the Skopinski NACA Report 1178, [102], Test Case 1 and its associated Structure A loads measurement test case, section 5.4.1. It has been used the Horizontal Stabiliser Distributed Checked Load Case applied to Structure A of Figure 5.7. In particular, LIRE Module 2 has been used as input the Skopinski Shear, V, and Moment, M, load coefficients of the left and right stabiliser shown in Figure 5.19

L1 Results and Discussion

Loading step	Incremental applied load, N	Location	Wing loading			Strain-gage bridge output, mV, for -									
			Shear, N	Bending moment, N-m	Torque, N-m	μ_{1B}	μ_{2B}	μ_{3B}	μ_{4B}	μ_{5B}	μ_{1T}	μ_{2T}	μ_{3T}	μ_{4T}	μ_{5T}
1	667	1	667	127	76	0.147	0.158	0.145	0.034	0.005	-0.050	0.004	-0.002	-0.019	-0.001
2	667	3	1335	254	414	.244	.283	.284	.029	-.016	-.142	-.155	-.223	-.117	-.017
3	444	6	1779	480	631	.396	.512	.592	.133	.022	-.259	-.347	-.433	-.277	-.062
4	444	8	2224	706	984	.515	.704	.863	.222	.071	-.394	-.597	-.787	-.565	-.168
5	222	11	2446	876	1160	.607	.850	1.082	.315	.125	-.487	-.760	-1.004	-.744	-.230
6	667	1	3114	1003	1236	.774	1.019	1.239	.348	.133	-.542	-.748	-1.008	-.761	-.231
7	667	3	3781	1130	1574	.881	1.149	1.386	.346	.115	-.638	-.913	-1.238	-.857	-.245
8	444	6	4226	1356	1791	1.045	1.376	1.704	.459	.159	-.765	-1.105	-1.453	-1.011	-.281
9	444	8	4671	1582	2144	1.176	1.566	1.981	.547	.213	-.907	-1.362	-1.809	-1.293	-.384
10	222	11	4893	1751	2320	1.272	1.714	2.209	.646	.270	-1.000	-1.526	-2.024	-1.474	-.445
11	-667	1	4226	1624	2244	1.118	1.543	2.049	.606	.261	-.951	-1.540	-2.029	-1.456	-.443
12	-667	3	3559	1497	1906	1.024	1.414	1.893	.603	.272	-.864	-1.386	-1.809	-1.362	-.432
13	-444	6	3114	1271	1689	.877	1.185	1.570	.486	.228	-.749	-1.204	-1.600	-1.209	-.395
14	-444	8	2670	1045	1336	.761	.994	1.285	.394	.176	-.618	-.958	-1.252	-.923	-.292
15	-222	11	2447	875	1160	.669	.848	1.059	.297	.120	-.525	-.797	-1.039	-.742	-.231
16	-667	1	1779	749	1084	.521	.690	.907	.265	.112	-.474	-.806	-1.040	-.726	-.230
17	-667	3	1112	621	746	.423	.563	.766	.270	.132	-.380	-.645	-.814	-.629	-.215
18	-444	6	667	395	529	.273	.340	.460	.166	.093	-.256	-.457	-.599	-.477	-.176
19	-444	8	222	169	176	.134	.151	.200	.087	.048	-.105	-.190	-.229	-.190	-.067
20	-222	11	0	0	0	.019	.006	-.008	-.004	-.004	.003	-.011	-.009	-.009	-.004

Figure 5.14: Calibration Wing Loadings and Strain-Gauge Bridge Data for inboard station of Test Case 2 *Wing II* - Single Loadings - Dependent Load Cases, [26].

```
##### Output Data #####
The Load Coefficients are: [[ 4897.74957264 -4125.96505401 296.09260415]]
Probable error of the estimate load is: 90.069128619
Probable error of the coefficients are: [ 229.22474236 247.93728317 92.10868645]
Root Mean Square Error Percent DD: 3.74512641874
```

```
##### END #####
```

Figure 5.15: LIRE M1 Outputs - Test Case 2, *Wing II* Shear Inboard Station, [26].

```
##### Output Data #####
The Load Coefficients are: [[ 528.49085266  276.25567393 -173.64457722]]
Probable error of the estimate load is: 2.63912179702
Probable error of the coefficients are: [ 16.24971491  12.43577946   3.18136127]
Root Mean Square Error Percent DLC: 0.285593825614

##### END #####
```

Figure 5.16: LIRE M1 Outputs - Test Case 2, *Wing II* Bending Moment Inboard Station, [26].

```
##### Output Data #####
The Load Coefficients are: [[ 389.50693516 -1973.95305271 -1001.28803227]]
Probable error of the estimate load is: 35.130785859
Probable error of the coefficients are: [ 64.91157665  142.9880394   38.31408946]
Root Mean Square Error Percent DLC: 2.06535104487

##### END #####
```

Figure 5.17: LIRE M1 Outputs - Test Case 2, *Wing II* Bending Moment Inboard Station, [26].

Load measurement	Selected bridges	Load coefficient $\pm$ probable error	Average wing calibration loading	Probable error of load estimate	Measured range of accuracy, percent (a)
Inboard station					
V	2B	4894 $\pm$ 218	860 N	$\pm$ 85 N	$\pm$ 10
	4B	-4129 $\pm$ 236			
	3T	292 $\pm$ 88			
M	2B	528 $\pm$ 16	343 N-m	$\pm$ 2.5 N-m	$\pm$ 3
	3B	277 $\pm$ 12			
	4T	-174 $\pm$ 3			
T	3B	388 $\pm$ 62	598 N-m	$\pm$ 33 N-m	$\pm$ 5
	5B	-1947 $\pm$ 136			
	3T	-998 $\pm$ 36			

Figure 5.18: Summary of Selected Strain Gauge Bridge Load Coefficients, Probable Errors, and Accuracy of Shear V, Bending Moment M, and Torque T - Test Case 2, *Wing II* Inboard Station - [26].

and their strain gauge readings, applied and calculated loads of Figure 5.20. At this stage the LIRE M2 applies the equation, Eq. (4.1). In particular, Figure 5.21, Figure 5.22, Figure 5.23, and Figure 5.24, show inputs and outputs used by LIRE M2 to be compared with the base line results of Figure 5.20.

Table 5.7 compares, for several similar conditions, the calculated loads, Shear and Moment, left and right side of the Structure A horizontal stabiliser, according to the Test Case 1, 5.4.1, and to the LIRE M2. The row to focus on is the last one, labelled "Calculated Ratio" that says three times out of four the number is closer to 0.999. In one occasion, for the M_L , the ratio, though still closer to one, is bit higher. This does not justify any real concern on the robustness of the Python code, rather Skopinski data approximation variability of the strain gauge data readings, Figure 5.20, or load coefficients. Unfortunately, it has not been possible to calculate with LIRE M1 the reliability of the load coefficients given in Figure 5.19, as the Test Case 1 reference did not mention the set of input load cases used for their calculation. This module has a pivotal role in the next section of this chapter to assess the performance of each techniques employed. In fact, known the load coefficients and the strain gauge readings, it evaluates the loads, labelled measured loads. The closer these loads are to the applied one and the higher the quality of the loads equations. The label "applied load" through the phase L2 and L3 ahead will be very different whether dealing with Experimental Ground or Flight test data. In fact, dealing with POGS, Point on the Ground, the performance assessment will be almost absolute as on Ground Loads are known with higher precision than the

Equation for—	Load coefficient a'_{ij} for equation (39)				Probable error of estimate, P. E.
V_L	a'_{11} 6,846 ± 45	a'_{12} 295 ± 50	a'_{13} 0	a'_{14} 680 ± 30	P. E. (V_L), lb 28
M_L	a'_{21} -11,280 ± 2,150	a'_{22} 500,730 ± 2,270	a'_{23} 0	a'_{24} 34,720 ± 1,340	P. E. (M_L), in-lb 1,505
V_R	a'_{31} 0	a'_{32} 705 ± 40	a'_{33} 4,790 ± 25	a'_{34} 0	P. E. (V_R), lb 37
M_R	a'_{41} 0	a'_{42} 40,810 ± 1,170	a'_{43} -14,180 ± 1,240	a'_{44} 479,970 ± 1,790	P. E. (M_R), in-lb 1,060

Figure 5.19: LIRE M2 Validation - Test Case 1, *Structure A* Left and Right side Shear, V, and Moment, M, Load Coefficients, [102].

DISTRIBUTED CHECK LOAD DATA FOR STRUCTURE A.				
(a) Combined bridge response ρ				
Distribution (fig. 10)	ρ_{V_L}	ρ_{M_L}	ρ_{V_R}	ρ_{M_R}
A_1	0.266	0.405	0.426	0.443
(b) Shear and moment comparison from equation (39)				
	V_L	M_L	V_R	M_R
A_1 : Applied	2,250	226,420	2,250	226,420
Calculated	2,240	228,000	2,320	223,000
Difference	-10	1,580	70	-3,420
Percent difference	-0.4	0.7	3.1	-1.5

Figure 5.20: LIRE M2 Validation - Test Case 1, *Structure A* Distributed Checked Load Data, Loads and Combined Strain Gauge readings, [102].

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```
LIRE - Program (vers 1.0.0) - LInear REgression Module

LIRE Module2: Loads Measurements and %RMS
##### Input Data #####
Strain Gauge Readings - [microstrain] -
-----
      SG 01   SG 02   SG 03   SG 04
      0.26600 0.40500 0.42600 0.44300
-----
Ground Load Calibration - Independent Data - ID - Multi-Point Distributed Loads - Load Case Magnitude Readings, VL - [lb] -
-----
2250.000
-----
Given Load Coefficients - Reference NACA Report 1178, Skopinski et al., Decade 1950 -
6845
295
0
680

##### Output Data #####
Percent Difference: -0.3784
Measured Loads [lb]:
2241.485

##### END #####
```

Figure 5.21: LIRE M2 Inputs and Outputs - Test Case 1, *Structure A* Shear Left Side, V_L , [102].

```
LIRE - Program (vers 1.0.0) - LInear REgression Module

LIRE Module2: Loads Measurements and %RMS
##### Input Data #####
Strain Gauge Readings - [microstrain] -
-----
      SG 01   SG 02   SG 03   SG 04
      0.26600 0.40500 0.42600 0.44300
-----
Ground Load Calibration - Independent Data - ID - Multi-Point Distributed Loads - Load Case Magnitude Readings, ML - [lb*in] -
-----
226420.000
-----
Given Load Coefficients - Reference NACA Report 1178, Skopinski et al., Decade 1950 -
-11280
509730
0
34720

##### Output Data #####
Percent Difference: -3.3560
Measured Loads [lb*in]:
218821.13

##### END #####
```

Figure 5.22: LIRE M2 Inputs and Outputs - Test Case 1, *Structure A* Moment Left Side, M_L , [102].

```

LIRE - Program (vers 1.0.0) - LInear REgression Module

LIRE Module2: Loads Measurements and %RMS
##### Input Data #####
Strain Gauge Readings - [microstrain] -
-----
SG 01 SG 02 SG 03 SG 04
0.26600 0.40500 0.42600 0.44300
-----
Ground Load Calibration - Independent Data - ID - Multi-Point Distributed Loads - Load Case Magnitude Readings, VR - [lb] -
-----
2250.000
-----
Given Load Coefficients - Reference NACA Report 1178, Skopinski et al., Decade 1950 -
0
705
4790
0
##### Output Data #####
Percent Difference: 3.380
Measured Loads [lb]:
2326.065

##### END #####

```

Figure 5.23: LIRE M2 Inputs and Outputs - Test Case 1, *Structure A* Shear Right Side, V_R , [102].

```

LIRE - Program (vers 1.0.0) - LInear REgression Module

LIRE Module2: Loads Measurements and %RMS
##### Input Data #####
Strain Gauge Readings - [microstrain] -
-----
SG 01 SG 02 SG 03 SG 04
0.26600 0.40500 0.42600 0.44300
-----
Ground Load Calibration - Independent Data - ID - Multi-Point Distributed Loads - Load Case Magnitude Readings, MR - [lb*in] -
-----
226420.000
-----
Given Load Coefficients - Reference NACA Report 1178, Skopinski et al., Decade 1950 -
0
40810
-14180
479970
##### Output Data #####
Percent Difference: -1.46008
Measured Loads [lb*in]:
223114.08

##### END #####

```

Figure 5.24: LIRE M2 Inputs and Outputs - Test Case 1, *Structure A* Moment Right Side, M_R , [102].

Flight Loads. PITS, Points in the Sky, loads measurement quality depends heavily on the theoretical loads accuracy employed.

The successful validation of the whole package LIRE is crucial as its several algorithm of python codes, directly validated, are embedded within LETE environment, and all associated techniques, as further verifiable within the *Control Flow Graph* figures of each Python Techniques code of Appendix B.2.

Table 5.7: LIRE Validation: Comparison of LIRE Module 2 and Test Case 1 (TC1), Structure A, "V" Shear [N] and "M" Moment [Nm] Left and Right side, [102].

	V_L	M_L	V_R	M_R
Actual Load	2250	226420	2250	226420
Calculated (TC1)	2240	228000	2320	223000
Error Perc. (TC1)	-0.444	0.698	3.111	-1.510
Calculated (LIRE M2)	2241	218821	2327	223114
Error Perc. (LIRE M2)	-0.378	-3.356	3.381	-460
Calculated Ratio (TC1/LIRE)	0.999	1.0419	0.997	0.999

5.5.2 IC and ICLE Validation

The influence coefficient (IC) plots, defined by Eq. (4.2), are useful assessing the effectiveness of a bridge for purposes of measuring shear, bending moment, and torque loads bringing into the ranking criteria for the strain gauges and load equations selections a physical instead of a statistic limited metric.

The validation of this Python package, section B.1.7.10, happens by a comparison with the Influence Coefficient Plots presented in the Test Case 1, section 5.4.1, NACA Report 1178, [102], structure A. The Influence Coefficient Plots for uncombined right shear bridges for structures A, left and right side loaded, according to Skopinski report are in Figure 5.25, and the input strain gauge readings are grouped in Figure 5.26, "right side loaded" inside the dashed line and "left side loaded" highlighted by solid line.

Using this information of Test Case 1 it has been run the IC software package and the results are grouped in order to compare the left and right column of Figure 5.25.

In order to organise and facilitate the comparison of the results produced by IC Python Software package Table 5.8 has been created. In fact, it shows three main groups of results. First one represents the Influence Coefficient plots of Test Case 1, Figure 5.25, broken down according to the left and right column and with top, bottom and mid diagrams, overall there are six graphs, and their respective generated by IC Software. The second group shows the input data of the Test Case 1, Figure 5.26 and the respective IC Software Output text files, input data to compare with. Last is the IC Software output text file with the output ordered data of the plots of the first group of Table 5.8.

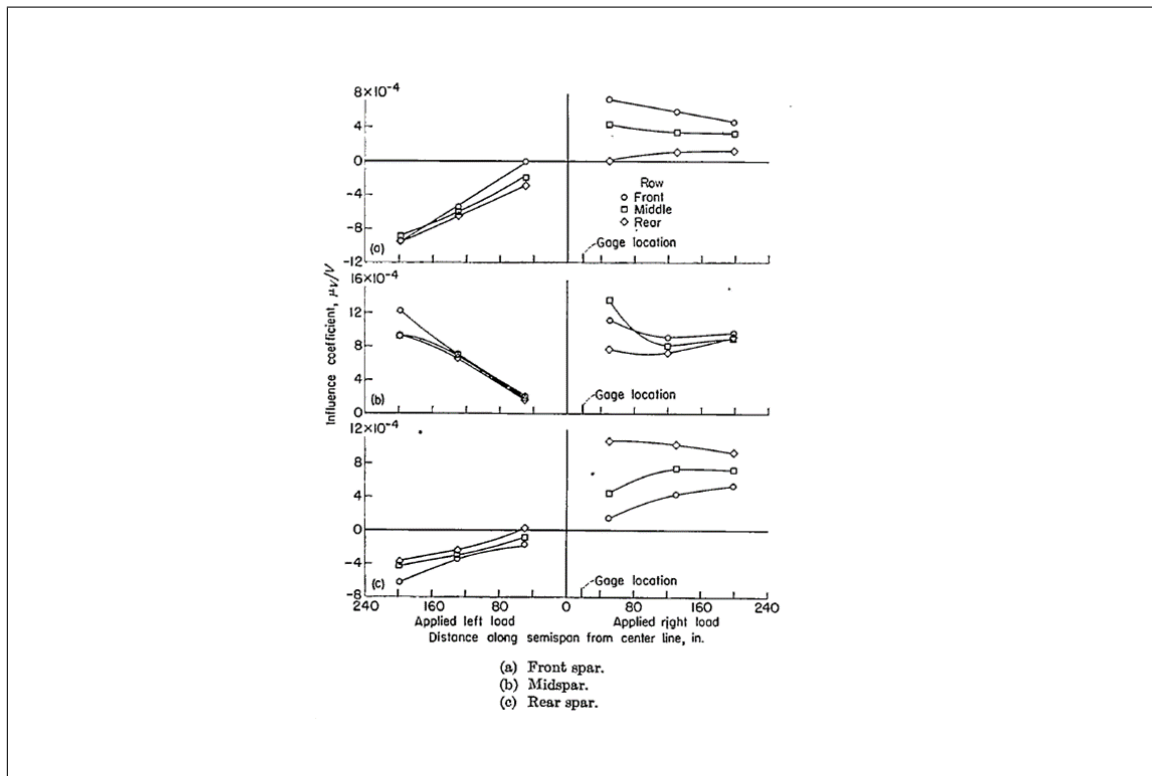


Figure 5.25: IC Validation - Output of Test Case 1, *Structure A* Influence Coefficient Plots for un-combined right shear bridges, "Applied Left Load" left column, and "Applied Right Load" right column - [102].

It has been decided to dedicate for each IC plots generated a single Figure in order to allow higher resolution for comparing the X and Y axis values against the Test Case 1 Figure 5.25 graphs respectively. By following the order of comparison of Table 5.8 it comes evident the matching of the quantities presented in terms of lines trend, slope and axes intercepts, and associated magnitude. The consideration made about the Influence Coefficient Plots is fully applicable to Influence Coefficient Loads Equation Plots of equation, Eq. (4.5), and that is visually explained by the diagrams of Figure 4.6.

In fact, the influence coefficient plots of the individual bridges are used to form composite influence coefficient plots that represent complete load equations, [90]. The Influence Coefficient Plot for a load equation, ICLE, as presented by Jenkins, [53], is the sum of the normalised term of the IC. It has not been possible to compare the trend plots of the Influence Coefficients of the Loads Equations, ICLE, as one of the most representative document showing the potentialities of this tool, Jenkins in the Decade 90's, [50], did not provide the necessary data to reproduce it. Though, considering that the equation defining the ICLE, Eq. (4.5), is based on the Influence Coefficients of the Strain Gauges, IC, just proved its robustness, it will be indirectly assumed its validity too.

The Validation Summary table shows the robustness of the Codes employed giving the necessary confidence to finally assess the performance of LPP and LETE, as Level 2 and Level 3 of Figure 5.1 require.

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Station, in.	Row (Eq. 4)	Applied loads		Uncombined bridges												Combined bridges			
		P' , lb	M' , in-lb	μ_{RF}	μ_{RM}	μ_{RR}	μ_{LF}	μ_{LM}	μ_{LR}	μ_{MF}	μ_{MM}	μ_{MR}	μ_{RF}	μ_{RM}	μ_{RR}	μ_{LL}			
Right side loaded																			
198.5	Front	500	90,150	0.234	0.481	0.270	-0.322	-0.143	-0.283	0.836	0.649	0.680	-0.250	-0.002	-0.194	0.104	-0.017	0.191	-0.013
	Middle	500	90,150	.164	.451	.305	.503	-.121	-.187	.805	.661	1.009	-.243	-.006	-.177	.106	-.017	.191	-.013
	Rear	500	90,150	.063	.450	.471	-.823	-.121	-.179	.790	.642	1.055	-.254	-.000	-.170	.106	-.017	.191	-.013
180.0	Front	1,500	167,630	.881	1.370	.060	.261	-.122	-.394	1.679	1.210	1.834	-.311	-.044	-.408	.206	-.031	.302	-.023
	Middle	1,500	167,630	.516	1.212	1.117	-.369	-.116	-.288	1.637	1.199	2.030	-.374	-.047	-.345	.311	-.031	.303	-.026
	Rear	1,500	167,630	.168	1.088	1.564	-.466	-.118	-.180	1.407	1.173	2.195	-.432	-.047	-.288	.327	-.034	.304	-.026
50.0	Front	2,500	79,350	1.815	2.803	.307	0	-.084	-.373	1.193	.593	.731	-.002	-.018	-.314	.503	-.018	.179	-.013
	Middle	2,500	79,350	1.001	2.401	1.108	.286	-.108	-.281	.921	.616	.842	-.231	.904	-.220	.947	.016	.189	-.013
	Rear	2,500	79,350	-.004	1.928	2.670	-.412	-.081	-.010	.859	.620	1.484	-.318	-.019	-.086	.616	-.020	.182	-.016
Left side loaded																			
198.5	Front	500	90,150	-0.478	0.619	-0.810	0.619	0.187	0.037	-0.372	0.000	-0.317	0.958	0.558	1.060	-0.025	0.007	-0.017	0.179
	Middle	500	90,150	-.442	.469	-.211	.625	.181	.707	-.357	.047	-.252	.968	.560	1.067	-.025	.007	-.018	.178
	Rear	500	90,150	-.474	.464	-.183	.469	.171	.759	-.370	.041	-.221	.941	.550	1.114	-.028	.066	-.014	.178
180.0	Front	1,500	167,630	-.817	1.065	-.516	1.184	-.290	.624	-.605	.056	-.440	1.834	1.128	1.881	-.030	.208	-.027	.396
	Middle	1,500	167,630	-.604	1.050	-.468	.769	-.227	1.155	-.692	.049	-.427	1.738	1.164	1.902	-.060	.210	-.026	.385
	Rear	1,500	167,630	-.681	1.014	-.362	.367	-.207	1.016	-.717	.049	-.371	1.941	1.171	2.106	-.055	.217	-.027	.387
50.0	Front	2,500	79,350	-.020	.594	-.450	2.362	-.617	.641	-.304	.099	-.437	1.452	.444	.810	-.024	.850	-.016	.162
	Middle	2,500	79,350	-.409	.490	-.210	1.361	-.778	1.207	-.392	.042	-.253	.946	.534	.946	-.027	.874	-.015	.174
	Rear	2,500	79,350	-.725	.413	.069	.435	-.413	2.823	-.558	.008	-.048	.891	-.480	1.401	-.031	.850	.018	.161

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Figure 5.26: IC Validation - Input of Test Case 1, *Structure A* Right Shear bridges, "right side loaded" dash-line, and "left side loaded" solid-line, [102].

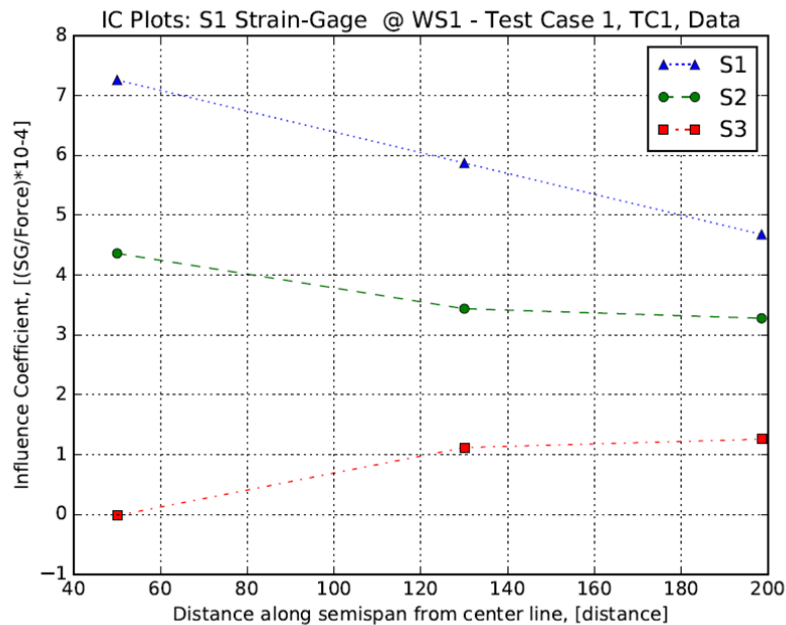


Figure 5.27: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Front Spar Right Shear bridge, "right side loaded" output plot [102].

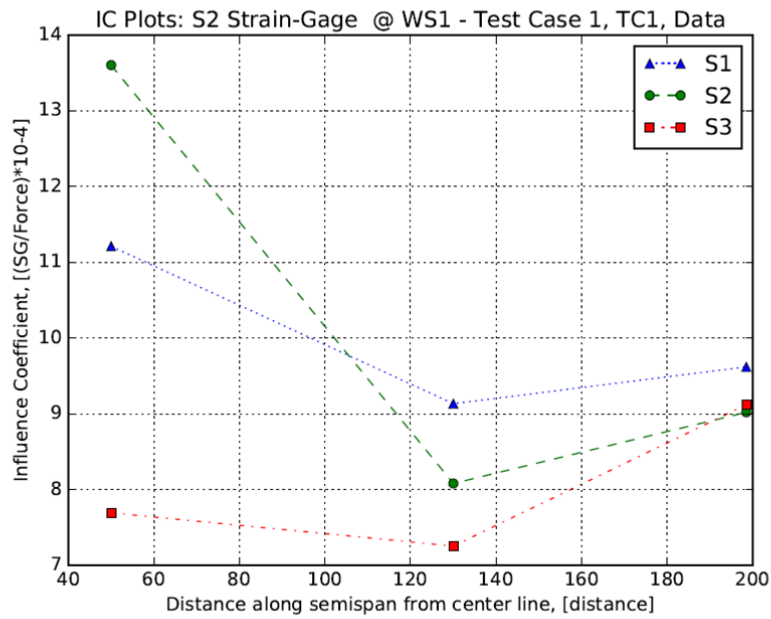


Figure 5.28: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Midspar Spar Right Shear bridge, "right side loaded" output plot [102].

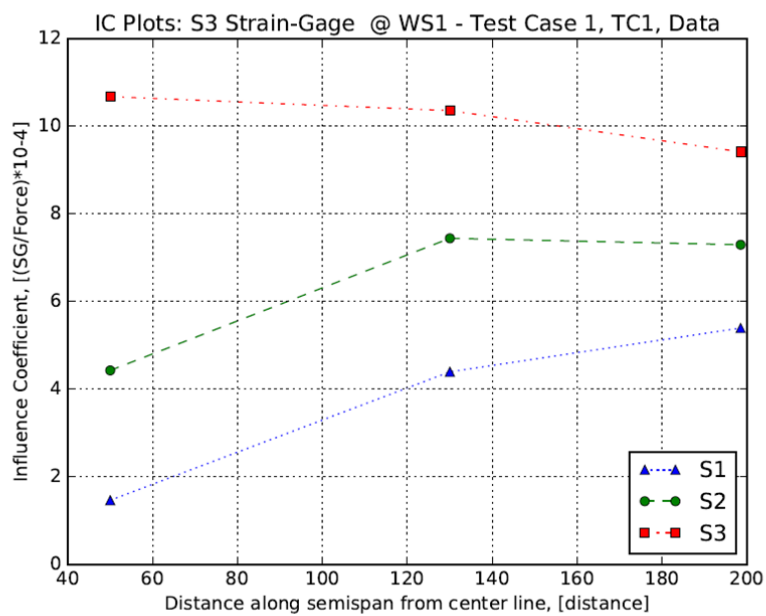


Figure 5.29: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Rear Spar Right Shear bridge, "right side loaded" output plot [102].

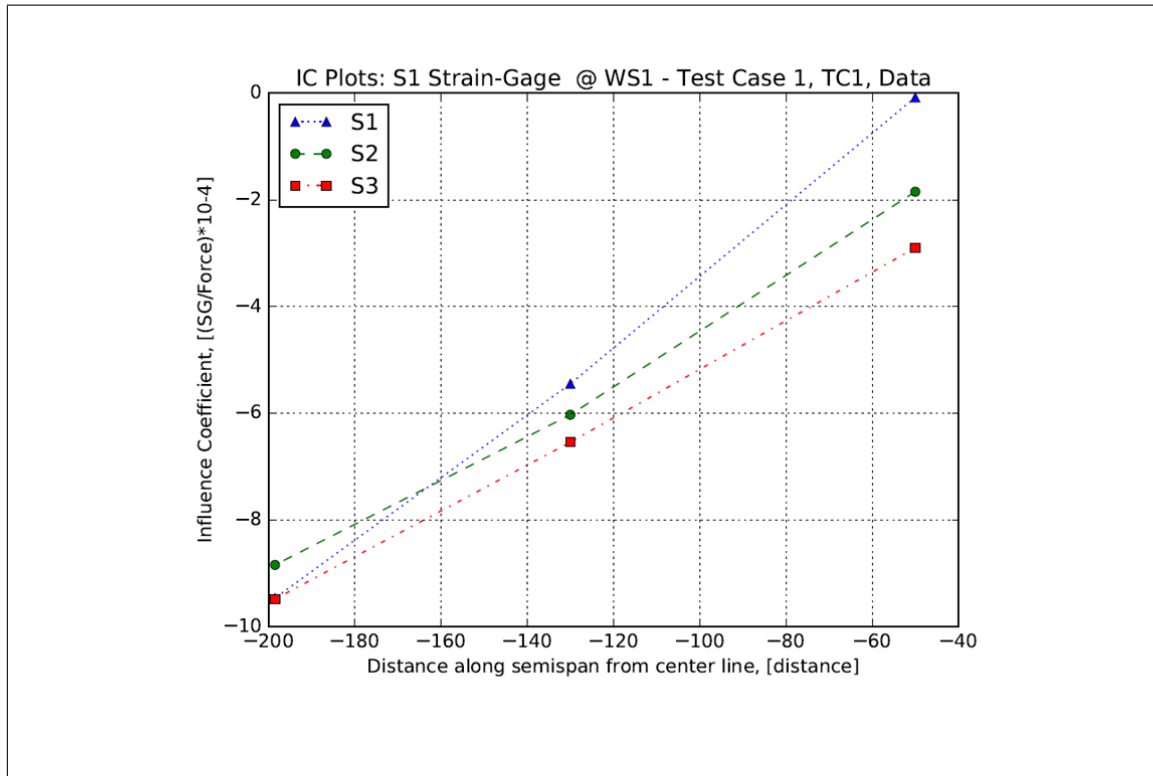


Figure 5.30: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Front Spar Right Shear bridge, "left side loaded" output plot [102].

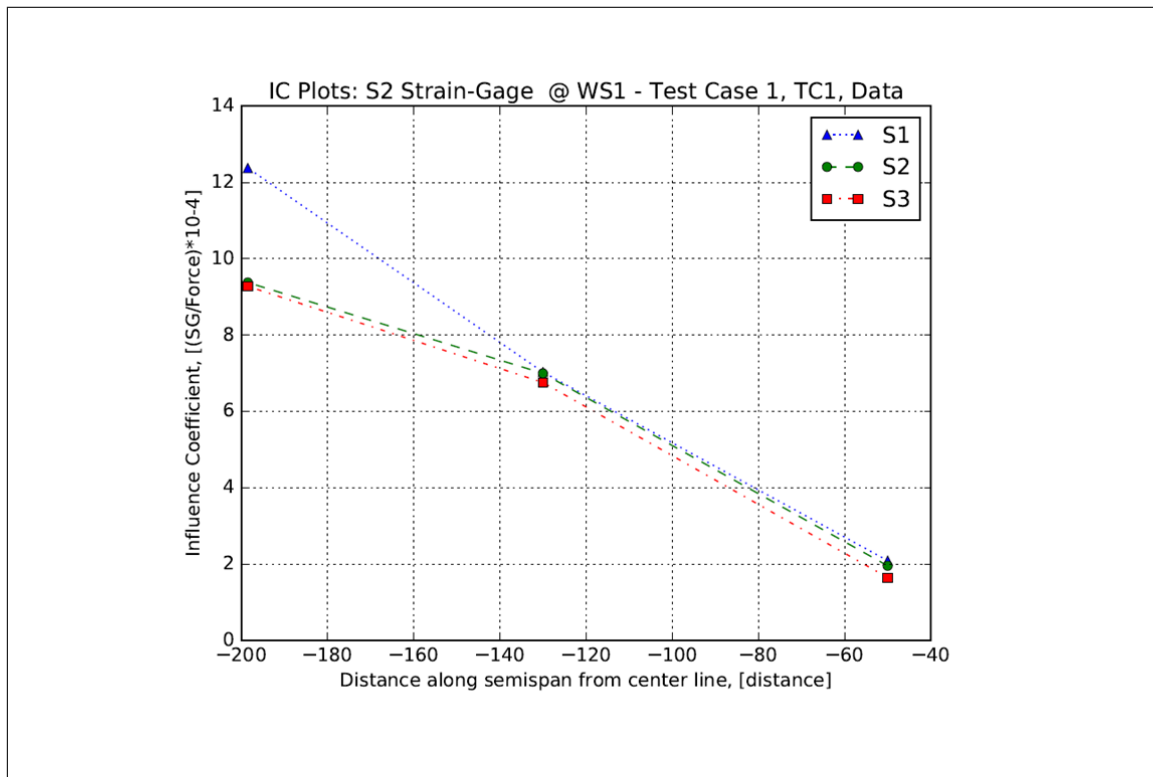


Figure 5.31: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Midspar Spar Right Shear bridge, "left side loaded" output plot [102].

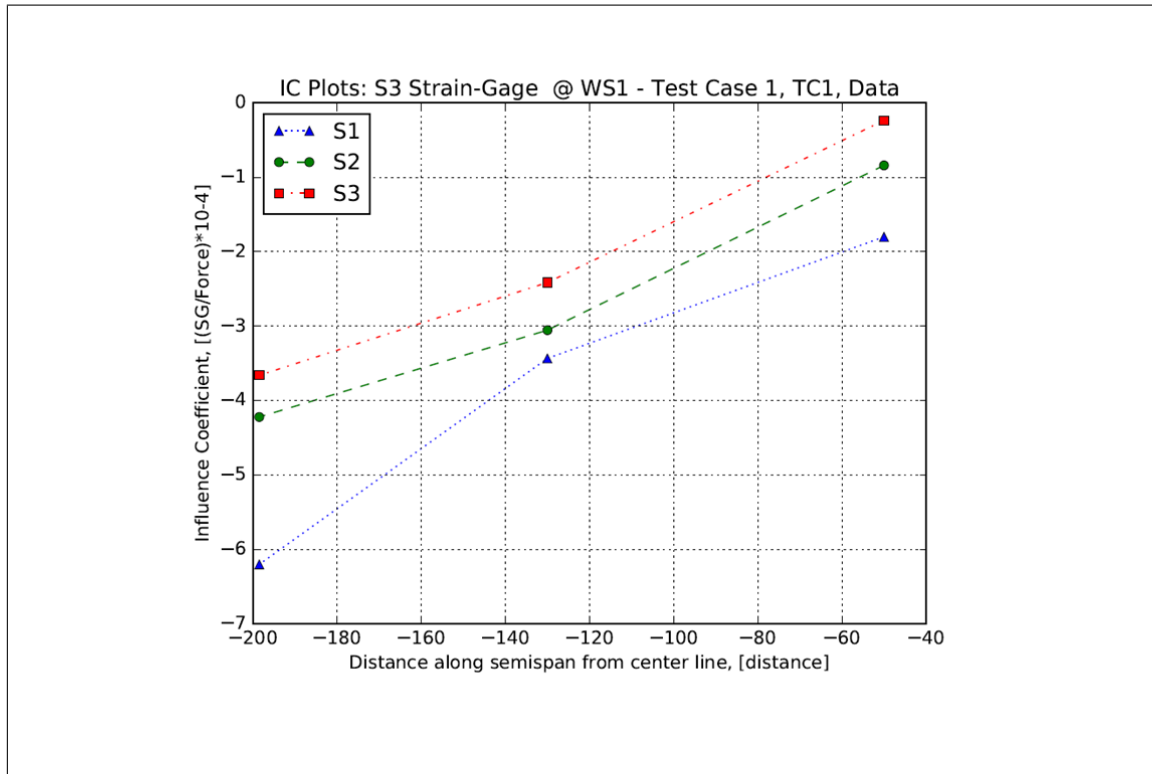


Figure 5.32: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Rear Spar Right Shear bridge, "left side loaded" output plot [102]

5.5.3 ExS & SgR Validation

The validation delivered in the last paragraphs got focused on a direct proof of robustness of those codes identified in Table 5.3, by direct assessment of the major quantities involved. These quantities have been validated by direct comparison with recognised literature data. The validation of the two major search engines of LETE, Exhaustive Search (ExS) and Strain Gauge Reduction (SgR), requires a different approach mainly due to the lack of literature complete set of data, allowing a step by step comparison, as a consequence of their own articulated structure.

However, in order to comply with the needed validation activity, these two search engines have been broken down in the following three main phases:

- Algorithm and logic sequence of operations.
- Independent Packages.
- Specific Equations.

The last two areas, Independent Packages and Specific Equations, are contextualised by Table 5.9. In fact, it is highlighted that the major foundations of the LETE techniques employing these two different engines of loads equations search present software packages and specific equations that have already been investigated in the last three sections, 5.5.1, 5.5.2 and 5.5.4. The Specific Equations listed in Table 5.9

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do not gather the whole set of formulas employed by LETE as those few represent already the core being functions of the others.

Table 5.9: ExS and SgR Validation: Search Engines Breakdown and associated LETE Techniques.

Search Engine	LETE Techniques	Ind. Packages	Spec. Equations
ExS	LPE, DLD, ESM, R_C	LIRE, IC, ICLE, I2D	LPE, IC, %RMS
ExS	GA Nelson, LPP	LIRE, IC, ICLE, I2D	IC, ICLE, %RMS
SgR	T value	LIRE	T-v, %RMS
SgR	Modified T value	LIRE	MT-v, %RMS

Now, to claim that indirectly ExS and SgR perform in robust fashion, as having reliable foundations, it is necessary to show that the *Algorithms and Logic Sequence Operations* linking together *Independent Packages* and *Specific Equations* work correctly. This will be demonstrated analysing the Output Text Files of two major LETE techniques of each engine, ExS LPE, section B.1.7.1, and SgR T-value, section B.1.7.4, whose input data are coming from the calibration loading values and corresponding strain-gauge bridge outputs of the Test Case 2, *Vertical Fin* structure of Figure 5.13 tabled in Figure 5.33, [90].

These values have been the input data used to run the Python Codes, *ExS LPE* and *SgR T-value*.

The interpretation of the *Exhaustive Search* software output text file of Figure 5.34 and Figure 5.35 shows the output data with all possible permutations of the vertical fin eight strain gauges and the associated load coefficients, Probable Error of the Estimate Loads, labelled Load Probable Error LPE by Skopinski, [102], used as ranking criteria to single out the one with the lowest value. In fact, at the very end of the text file, Figure 5.35, is identified and summarised the best solution. The correctness of the algorithm driving this output is further proved by the overall number of possible permutations of loads equations made up by eight strain gauges, is 255, as proved by applying the equation Eq. (4.3). In fact, the very last number of ID Load Equations on the bottom left of Figure 5.35 is 254, that considering the first ID Load Equation counting is zero gives a total of 255.

On the other hand the results of the SgR of the T-value are shown in Figure 5.36 coherently follow the concept of the *Strain Gauge Reduction* search engine. At each stage, identified by "main counter" progressive number, the T-value of each load coefficient is evaluated, and the smallest one determines the strain gauge to be counted off before moving to the next where the same sequence will be executed. This continues till the smallest possible of strain gauges to evaluate the associated load coefficients, as shows Figure C.5 with "main counter 2". At the end of this process the output text file summarises among all the iterations,

Load point	Location		Calibration load, N	Bridge output, mV							
	Percent chordline	y/b		Torque bridges				Moment bridges			
				1	2	3	4	5	6	7	8
1	20	0.1	1334	6	-45	-48	-25	-44	-58	-48	-80
2	40	↓	↓	9	6	-19	-2	-14	-53	-49	-68
3	60			11	12	49	32	3	-42	-41	-30
4	80			13	33	88	231	19	-27	-35	202
5	20	0.2	1112	15	-36	-45	-11	-37	-89	-74	-94
6	40	↓	↓	14	5	-10	17	-8	-75	-79	-85
7	60			14	22	51	68	8	-58	-77	-64
8	80			16	41	99	279	23	-42	-72	-3
9	20	0.4	890	20	6	-19	24	-9	-111	-133	-140
10	40	↓	↓	21	23	22	70	4	-97	-136	-140
11	60			21	37	63	143	16	-83	-135	-144
12	80			23	52	104	241	27	-71	-134	-149
13	20	0.6	178	6	6	5	16	1	-28	-42	-46
14	40	↓	↓	6	9	12	28	3	-25	-42	-48
15	60			7	11	18	40	5	-24	-43	-49
16	80			7	14	25	53	8	-21	-43	-50
17	20	0.8	89	4	5	7	17	2	-17	-29	-33
18	40	↓	↓	4	6	10	21	3	-16	-29	-34
19	60			5	8	12	26	3	-15	-29	-34
20	80			5	9	14	30	4	-14	-29	-35

Figure 5.33: IC Validation: IC Software Output plots - Test Case 1, *Structure A* Rear Spar Right Shear bridge, "left side loaded" output plot, [102].

```

##### Output Data #####
Input Data Correct.Condition of Existence: LC-N-1>0 - Satisfied - LC= Load Cases, N= Number of Strain Gauges,
ID      Load Eq.      LPE      Rank
0 [1 1 1 1 1 1 1] 48.809 0
1 [1 1 1 1 1 1 0] 59.606 5
2 [1 1 1 1 1 0 1] 67.312 9
3 [1 1 1 1 1 0 0] 140.102 35
4 [1 1 1 1 1 0 1 1] 84.731 13
5 [1 1 1 1 1 0 1 0] 101.666 16
6 [1 1 1 1 1 0 0 1] 83.122 12
7 [1 1 1 1 1 0 0 0] 140.374 36
8 [1 1 1 1 0 1 1 1] 165.472 69
9 [1 1 1 1 0 1 1 0] 159.841 61
10 [1 1 1 1 0 1 0 1] 208.528 123
11 [1 1 1 1 0 1 0 0] 243.707 175
12 [1 1 1 1 0 0 1 1] 234.580 152
13 [1 1 1 1 0 0 1 0] 226.565 143
14 [1 1 1 1 0 0 0 1] 241.545 168
15 [1 1 1 1 0 0 0 0] 264.404 192
16 [1 1 1 0 1 1 1 1] 53.152 2
17 [1 1 1 0 1 1 1 0] 57.603 3
18 [1 1 1 0 1 1 0 1] 82.750 11
19 [1 1 1 0 1 1 0 0] 135.604 27
20 [1 1 1 0 1 0 1 1] 106.392 18
21 [1 1 1 0 1 0 1 0] 107.422 19
22 [1 1 1 0 1 0 0 1] 109.069 21
23 [1 1 1 0 1 0 0 0] 139.191 34
24 [1 1 1 0 0 1 1 1] 164.574 68
25 [1 1 1 0 0 1 1 0] 159.626 57
26 [1 1 1 0 0 1 0 1] 200.954 118
27 [1 1 1 0 0 1 0 0] 240.194 167
28 [1 1 1 0 0 0 1 1] 227.287 146
29 [1 1 1 0 0 0 1 0] 219.647 137
30 [1 1 1 0 0 0 0 1] 237.612 160
31 [1 1 1 0 0 0 0 0] 256.043 184
32 [1 1 0 1 1 1 1 1] 154.677 51
33 [1 1 0 1 1 1 1 0] 140.848 44
34 [1 1 0 1 1 1 0 1] 172.596 76
35 [1 1 0 1 1 1 0 0] 208.975 124
36 [1 1 0 1 1 0 1 1] 149.920 46
37 [1 1 0 1 1 0 1 0] 145.580 42
38 [1 1 0 1 1 0 0 1] 171.684 75
39 [1 1 0 1 1 0 0 0] 210.669 126
40 [1 1 0 1 0 1 1 1] 195.241 109
41 [1 1 0 1 0 1 1 0] 190.684 98
42 [1 1 0 1 0 1 0 1] 243.831 176
43 [1 1 0 1 0 1 0 0] 273.025 201

```

Figure 5.34: Exhaustive Search, ExS, Validation: *ExS LPE* Software Output text file - Test Case 2, *Structure: Vertical Fin* output data, part I.

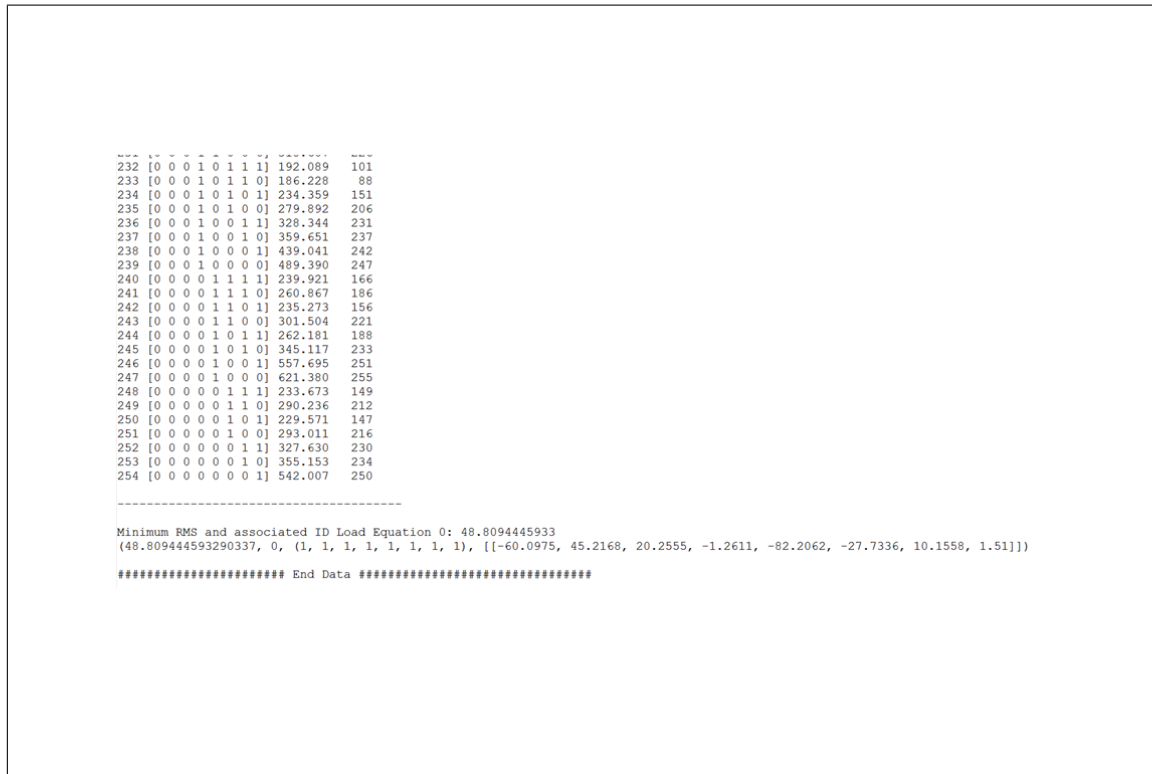


Figure 5.35: Exhaustive Search, ExS, Validation: *ExS LPE* Software Output text file - Test Case 2, *Structure: Vertical Fin* output data and best set of load coefficients, part II.

”main counter”, the best set of load coefficients given by the smallest LPE, Figure C.5.

It is extremely interesting to show that, in this specific Test Case 2 example, the best solution, is the same according to the two different Python search engines software, Figure 5.35 and Figure C.5, that matches the Peele, [90] solution as Figure 5.36 highlights. In fact, the load equation singled out, is the same, all eight strain-gauge load equation, and on top of this the magnitude of the load coefficient is the same evaluated in the NACA Technical Note. Further, proving that the LIRE M1, whose validation has already been confirmed in section 5.5.1, works correctly embedded in the search engines or independently, Figure 5.37.

5.5.4 I2D Validation

The *Individual to Distributed*, *I2D* package, sections 4.5.2.1 and B.1.7.12, has the scope to generate from individual ground calibration data, single point loading cases and associated strain gauge readings, a superposed set of distributed data set. Ultimately, it is supposed to create an input set of loads and strain gauge traces, though superposed numerically, capable to develop best set of load equations, as Hovell et Al., [43], investigated.

The way the individual load cases are combined to generate distributed loadings is meant to be driven by the type of flight loads distribution points, PITS, to be

TABLE VIII. - SUMMARY OF LOAD COEFFICIENTS AND PROBABLE ERRORS

Equation for -	Average fin loading	Probable error of estimate	Load coefficients ± Probable errors							
			$\beta_{V,1}$	$\beta_{V,2}$	$\beta_{V,3}$	$\beta_{V,4}$	$\beta_{V,5}$	$\beta_{V,6}$	$\beta_{V,7}$	$\beta_{V,8}$
V	720 N	±48 N	-65.3 ± 16.2	45.3 ± 3.12	20.7 ± 12.9	-1.22 ± 0.46	-83.4 ± 4.9	28.1 ± 3.67	9.69 ± 1.98	1.54 ± 0.038

Figure 5.36: ExS and SgR Validation: Summary of the Load Coefficients of the best set of loads equations - Test Case 2, *Structure: Vertical Fin* input data, [90].

```

LIRE - Program (vers 1.0.0) - Linear REgression Module
*****
LIRE Module1: Loads Evaluation Coefficients and Load Probable Error
Reference NASA TN D-7979 - Peeler and al. - Decade 70s - Structure: Vertical Fin.
*****
The Load Coefficients are: [[-60.09748769  45.21676821  20.25546515 -1.26110281 -82.20619843
-27.73359712  10.15578457  1.50996536]]
Probable error of the estimate load is: 48.8094445933
Probable error of the coefficients are: [ 16.44166982  3.17660626  1.30556215  0.4732919  4.92180872
 3.72915652  1.99223568  0.38784073]
Root Mean Square Error Percent DD: 1.84452858017

```

Figure 5.37: ExS and SgR Validation: LIRE M1 Load Coefficients - Test Case 2, *Structure: Vertical Fin* input data, [90].

measured. The validation of the strain gauge reading predictions, with specific load application points, and the process to define the pattern of the load points require to find available a very wide set of information and details. In fact, going through the available literature review analysed in section 2.6, from the conception of the flight loads measurement science through the past decades and up to day, it came out not enough data to test the complete conceived package introduced at Chapter 4.

Referring to Figure 4.13 *Module 1*, "Strain Gauge Prediction", is the one that will be fully tested and assessed in the following part of the section. On the other hand, *Module 2* will be assessed without extensively apply its own features, mainly those defining the sequence of the superposed distributed loading similar to the pattern distribution of the flight loads. Nevertheless this lack of an available full set of data, does not expose the whole LETE environment to the risk to generate incomplete and/or unreliable results. In fact, the coming up levels, L2 and L3, dedicated to assess the LETE and LPP performance, will be using data set with same limitation explained above. Though, the importance to have captured all list of valuable concepts and quantities in section 4.5.2.1, defines the correct foundations of the *I2D* package.

5.5.4.1 I2D Validation: Module M1

The *I2D Module M1* is a Python code that calculates the fitting surface, Order II, to the individual responses of each gauge with the varying chord and span-wise ground load calibration coordinates. The output is shown by a 3-Dimensional space where X and Y represent the distances from the references axes of the load application points and Z is the strain gauge reading normalised with the respective applied force. It is important to highlight that this is not the load, such as Shear, Bending Moment or Torque, but is the external applied force of the hydraulic jack or sand bags, as the intention is to map the real strain gauge reading that most of the time is not matching the theoretical definition of internal forces. In fact, it might happen to have strain gauge adjacent to the applying force and generating readings regardless being outboard, and so according to the de Saint-Venant theory supposed to generate no contribution. This situation is very indicative on how the robustness of this module, besides programmed and structured correctly, most of the time depends on the accuracy of the data used and on the configuration of the structure, instrumentation and ground calibration. Similar motivations explain why the *I2D* cannot be an automated code but requires an investigation of the superposed load cases.

The *I2D M1* is tested with the input data of the Test Case 2, *wing I* structure, instrumented as displayed in Figure 5.10. The four strain-gauge readings of thirteen load cases are collected in Figure 5.38, for the First Calibration, and 5.39, Second Calibration, of the NACA TN D-7979, Peeler [90]. The load application coordinates of this First Calibration have already been introduced in Figure 5.11. The validation of this first module, *M1* of *I2D* will be assessing the outputs of the software on two different levels. The first one, *Global Investigation*, will be using

Dependent Data, the same data used to develop the fitting surfaces to the individual responses of each gauge. On the other hand, the *Local Investigation* will be using a specific random load locations that do not belong to the data used to calculate the strain sensors prediction equations, 1st Calibration, but to the 2nd Calibration.

Load point	Calibration load, N	Wing loading			Bridge output, mV			
		Shear, N	Torque, N·m	Moment, N·m	μ_{TF}	μ_{TR}	μ_V	μ_M
1	358	0	0	0	1.56×10^2	1.75×10^2	37.75×10^2	-0.74×10^2
2		358	0	150	2.80	4.42	97.70	27.90
3		358	0	300	1.59	6.78	154.70	56.63
4		0	45	0	3.00	4.09	32.60	.92
5		358	45	150	6.51	8.82	85.70	27.75
6		358	45	300	5.47	12.40	143.30	56.88
7		0	-45	0	.21	-.41	46.10	1.42
8		358	-45	150	-1.17	-1.54	107.50	26.94
9		358	-45	300	-2.39	1.02	66.00	55.71
10		0	-90	0	-.92	-3.75	166.80	2.39
11		358	-90	150	-4.43	-7.61	122.10	25.94
12		358	-90	300	-6.41	-4.88	178.00	55.35
13		358	-136	150	-7.35	-13.60	136.00	24.92

Figure 5.38: Individual to Distributed, I2D M1 Validation: Ground Calibration Data, Loads and Strain Gauge Bridges - Test Case 2, *Structure: Wing I* input data, First Calibration, [90].

The outputs, a text file and 3-Dimensional Plots, of *I2D M1* will allow to perform again, as it happened for the *ExS* and *SgR* in section 5.5.3, an indirect assessment of the Module 1 software. In fact, the code itself is meant to generate fitting surface whose prediction ability of the bridge response with a random load application points and magnitude, depends greatly on the specific type of data provided. The software package robustness required and scope of this section will be proved by comparing the consistency existing between plots and text output relevant quantities under specific runs.

The different runs configuration is explained in Table 5.10, while Table 5.11 shows the independent set of data chosen for the *Local Investigation*, in fact, an 2nd Calibration Load Point is tested with fitting surface coefficients generated by 1st Calibration data set and vice-versa. These particular conditions have been specifically created to verify interpolating and extrapolating situations. The load point 08 has been preferred as stays in a very neutral position, in the middle of the wing, see Figure 5.38, preventing any particular non linearities more typical of those load points closer to the edges of the lifting surface.

Load point	Calibration load, N	Wing loading			Bridge output, mV			
		Shear, N	Torque, N·m	Moment, N·m	μ_{TF}	μ_{TR}	μ_V	μ_M
1	890	0	0	0	5.36×10^2	5.68×10^2	1.03	-0.158
2	↓	890	0	373	8.34	11.46	2.39	.729
3		890	0	746	6.10	17.20	3.70	1.462
4		0	113	0	11.90	11.42	.94	.489
5		890	113	373	19.60	24.46	2.22	.722
6		---	---	---	---	---	---	---
7	---	---	---	---	---	---	---	---
8	890	890	-113	373	-1.70	-3.90	2.62	.709
9	890	890	-113	746	-5.22	1.08	3.90	1.439
10	---	---	---	---	---	---	---	---
11	890	890	-226	373	-9.70	-17.90	2.82	.685
12	890	890	-226	746	-14.36	-11.76	4.10	1.436
13	890	890	-339	373	-17.60	-32.84	2.95	.648

Figure 5.39: Individual to Distributed, I2D M1 Validation: Ground Calibration Data, Loads and Strain Gauge Bridges - Test Case 2, *Structure: Wing I* input data, Second Calibration, [90].

Table 5.10: I2D Module M1 Validation: Different Runs Definition Dependent Data (DD)- Load Point (LP) Combination of Test Case 2, *Structure: Wing I* input data, First and Second Calibration, Figure 5.38 and Figure 5.39, [90].

Run ID	LP Numbers	LP excluded	Average Loads	Data Type
Run1	13	not applicable	358	1st Calibration
Run2	9	4, 1, 7, 10	358	1st Calibration
Run3	8	4, 1, 7, 10, 13	358	1st Calibration
Run4	13	not applicable	890	2nd Calibration
Run5	8	4, 1, 7, 10, 6	890	2nd Calibration
Run6	7	4 1, 7, 10, 13, 6	890	2nd Calibration

Table 5.11: I2D Module M1 Validation: Runs Local Investigation Load Point (LP), Independent Data (ID) - Test Case 2, *Structure: Wing I* input data - Figure 5.38 and Figure 5.39, [90].

LP Number	X [m]	Y [m]	Load	Data Type	Runs
08	-0.127	0.419	890	2nd Calibration	1,2,3
08	-0.127	0.419	358	1st Calibration	4,5,6

Table 5.12: I2D Module M1 Validation: Runs Local Investigation Load Point, LP 8, Independent Data (ID) - Test Case 2, *Structure: Wing I* Strain Gauge (SG) responses and Applied Loads, Figure 5.38 and Figure 5.39 - [90].

SG Type	SG Read. [mV]	Applied Load [N]	Data Type
μ_{TF}	-1.17	358	1st Calibration
μ_{TR}	-1.54	358	1st Calibration
μ_V	107.5	358	1st Calibration
μ_M	-0.127	358	1st Calibration
μ_{TF}	-1.7	890	2nd Calibration
μ_{TR}	-3.9	890	2nd Calibration
μ_V	2.62	890	2nd Calibration
μ_M	0.709	890	2nd Calibration

Each I2D Module 1 Run generates a text file, that has four sections described below and linked with its respective associated Figures, and 3-D plots of the strain response with position of loads, points and fitting surface are shown simultaneously too. The referred outputs and related figures, are grouped with the Run numbers described in Table 5.10 and Table 5.11.

- **Input Data:** It shows the basic information of the ground calibration data, in terms of load points coordinates and magnitude alongside the strain gauges analysed and their readings associated to the loads. Run1: Figure C.10, Run2: Figure C.19, Run3: Figure C.28, Run4: Figure C.37, Run5: Figure C.46 and Run6: Figure C.55.
- **Output Data, i-th Strain Gauge 3-D Plot Z data:** It prints the Z axis data used to plot the 3-Dimensional plots of each strain gauge shown in the Input Data. Run 1: Figure C.6, Figure C.54, Figure C.8 and Figure C.9. Run 2: Figure C.15, Figure C.16, Figure C.17 and Figure C.18. Run 3: Figure C.24, Figure C.25, Figure C.26 and Figure C.27. Run 4: Figure C.33, Figure C.34, Figure C.35 and Figure C.36. Run 5: Figure C.42, Figure C.43, Figure C.44 and Figure C.45. Run 6: Figure C.51, Figure C.52, Figure C.53 and Figure C.54.

- **Output Data, i-th Strain Gauge, Global Output:** It gathers per each strain gauge of the Input Data the fitting surface order II coefficients, the Error of each Load Point strain gauge readings, *Single Error*, and the *Total Error* all calculated against the respective input data used to tune the surface to match the points initially given. So, the data used to evaluate the error are considered *Dependent Data*. *Run 1*: Figure C.11, Figure C.12 , Figure C.13 and Figure C.14. *Run 2*: Figure C.20, Figure C.21 , Figure C.22 and Figure C.23. *Run 3*: Figure C.29, Figure C.30 , Figure C.31 and Figure C.32. *Run 4*: Figure C.38, Figure C.39 , Figure C.40 and Figure C.41. *Run 5*: Figure C.47, Figure C.48 , Figure C.49 and Figure C.50. *Run 6*: Figure C.56, Figure C.57 , Figure C.58 and Figure C.59.
- **Output Data, i-th Strain Gauge, Local Output:** It shows Local Error of the predicted strain gauge response evaluated by means of the fitting surface coefficients of the section Global Output. The Error is calculated comparing the the predicted SG response against the real value not part of the data used to develop the fitting surface, so called *Independent Data*. Associated figures are the same listed in the point above, "Global Output".

The results above, presented in Appendix C, have been generated after selecting the input data in a way to highlight two opposite behaviours, that have been proving to be consistent comparing the respective I2D output text file against the 3-D plots. The four strain gauges under investigation, μ_{TF} , μ_{TR} , μ_V and μ_M , described in Figure 5.10, offered opposite behaviour in terms of fitting surfaces ability to predict the strain gauge responses of an independent random load point such as those in Table 5.12.

The quantities chose to analyse the trend of the results, broken down per Runs, are the *Global Error*, the *Local Error*, representing the absolute difference between real and predicted data, either *Dependent* or *Independent*, and the *Local Error Percentage*.

Table 5.13: I2D Module M1 Validation: Results Summary, **Run1** - Test Case 2, *Structure: Wing I* - [90].

Quantities	μ_{TF}	μ_{TR}	μ_V	μ_M
Global Error (DD)	0.174	0.329	12.52	0.189
Actual SG	-1.7	-3.9	2.62	0.709
Calculated SG	-1.5	-2.5	239.7	67.1
Local Error (ID)	-0.228	-1.415	-237.1	-66.4
Local Error Perc. (ID)	-13.39	-36.3	-9048	-9360

Table 5.14: I2D Module M1 Validation: Results Summary, **Run2** - Test Case 2, *Structure: Wing I* - [90].

Quantities	μ_{TF}	μ_{TR}	μ_V	μ_M
Global Error (DD)	0.0505	0.043	11.37	0.05744
Actual SG	-1.7	-3.9	2.62	0.709
Calculated. SG	-2.4	-3.7	242.8	67
Local Error (ID)	0.704	-0.158	-240	-66.3
Local Error Perc. (ID)	41.4	-4.043	-9167	-9355

Table 5.15: I2D Module M1 Validation: Results Summary, **Run3** - Test Case 2, *Structure: Wing I* - [90].

Quantities	μ_{TF}	μ_{TR}	μ_V	μ_M
Global Error (DD)	0.025	0.061	9,64	0.068
Actual SG	-1.7	-3.9	2.62	0.709
Calculated. SG	-2.36	-3.7	239.8	67.1
Local Error (ID)	0.6636	-0.18	-236	-66.34
Local Error Perc. (ID)	39.04	-4.622	-9037	-9357

Table 5.16: I2D Module M1 Validation: Results Summary, **Run4** - Test Case 2, *Structure: Wing I* - [90].

Quantities	μ_{TF}	μ_{TR}	μ_V	μ_M
Global Error (DD)	4.29	4.1	0.13	0.04
Actual SG	-1.17	-1.54	107.5	26.94
Calculated. SG	12.44	13.32	1.19	0.33
Local Error (ID)	-13.607	-14.86	106.31	26.6
Local Error Perc. (ID)	1163	-965	98.9	98.8

Table 5.17: I2D Module M1 Validation: Results Summary, **Run5** - Test Case 2, Structure: Wing I - [90].

Quantities	μ_{TF}	μ_{TR}	μ_V	μ_M
Global Error (DD)	0.05	0.205	0.0009	0.0019
Actual SG	-1.17	-1.54	107.5	26.94
Calculated SG	-0.606	-1.428	1.051	0.286
Local Error (ID)	-0.564	-0.112	106.4	26.7
Local Error Perc. (ID)	48.24	7.29	99	98.9

Table 5.18: I2D Module M1 Validation: Results Summary, **Run6** - Test Case 2, Structure: Wing I - [90].

Quantities	μ_{TF}	μ_{TR}	μ_V	μ_M
Global Error (DD)	0.03	0.204	0.0009	0.0019
Actual SG	-1.17	-1.54	107.5	26.94
Calculated SG	-0.65	-1.45	1.049	0.286
Local Error (ID)	-0.52	-0.087	106.5	26.6
Local Error Perc. (ID)	-44.4	-5.65	99.1	98.9

The I2D Module M1 results, Table 5.13, Table 5.14 and Table 5.15, representing the three first runs belonging to the 1st Calibration data set of Figure 5.38, and Table 5.16, Table 5.17 and Table 5.18, last three remaining Runs of the Second Calibration input data of Figure 5.39, bring up the following points based on the two areas, Global and Local errors, linked to Dependent and Independent Data, and with first three Runs come from 1st Calibration (lower applied loads) and the remaining three from 2nd Calibration (higher applied loads):

- All Calculated Strain Gauge readings tend to be under predicted in terms of magnitude compared to the real values.
- Run 1, 5.13 and 5.16, tends to offer the worst errors. This is a consequence of having used as input data those load cases on to adjacent to the strain gauge locations.
- Run3, Figure 5.14, and Run6, Figure 5.14, tend to show always the best Global Error proving that the elimination of the load point 13, Table 5.10, makes the results quality higher. This is explained by the location of this application point, Figure 5.11, that is not on the load paths of the strain gauge installation positions.
- It is evident that the incapacity of the strain gauge μ_V to generate good approximation surfaces for Run1, Run2, and Run3, and consequently higher

Global and Local error is due to the unreliable readings of the first calibration. In fact, as shown in Table 5.12 the magnitude of the readings is much lower with the decreasing of the applied loads, this does not make sense. This is further proved by its own 3-D plots too, Figure C.8, Figure C.17, Figure C.26. Opposite behaviour happens with Global Errors and associated plots, Figure C.35, Figure C.44, Figure C.53 of the second calibration, proving the data readings are sensible.

- The only time the Global Error is directly linked to the Local Error is during the interpolation runs, when the independent data has lower load than the dependent one, and with reliable strain gauge readings.
- It is interesting to see the different way to generate the Local Error between the first three runs and the remaining. Run R1, R2 and R3 generate the fitting surface from a lower load and then evaluate the Local Error from a load point with higher load. That means the strain gauge response is an extrapolation consequence. The other set of three Runs works by interpolation, as Dependent Data have higher lower than the Independent Data. Unfortunately, the results have been so sparse not to allow making any absolute consideration. It seems a slight better of Local Error percentage are produced by extrapolation data inside Run1, Table 5.13, Run2, Table 5.14, and Run2, Table 5.15. This applies mainly to the first two strain gauges, μ_{TF} and μ_{TR} as the other two show inconsistencies that have been proved also by their 3D-Plots. The fitting surface order II does not produce the accuracy needed.
- It has not been possible to see any pattern between Global error and Local error. The impression is that the investigation should carry on by increasing the random data of Independent Data and not just limited to the Load Point 8, Table 5.12.
- Table 5.18 proves that the best set of Global Error is obtained with the highest load application points magnitude, 2nd Calibration.
- Not always higher loads offer better strain gauge responses as it should be considered the risk that the structure component might buckle reducing linearities behaviours.

The considerations above will be applied to the definition of the Runs of the coming up section to assess the performance of the LETE techniques.

5.5.4.2 I2D Validation: Module M2

Assessing the *I2D Module M2* is a much straighter process, partially due to the current limited available data related to FLSR and RC supporting tools, see section B.1.7.9, as already anticipated at the beginning of this section, and also as the whole structure has been conceived and developed on Excel spreadsheets. Figure B.28 already highlighted the whole combined Python and Excel process of the whole *I2D Package*.

The *Module M2* executes the functions listed below:

L1 Results and Discussion

- **M1 to M2:** It is a direct link with the Module M1, by taking the fitting surfaces coefficients and set to be applied to as many as needed load points to make up a new distributed sample data. Figure C.60 proves this function by employing the input data of Figure C.12, Test Case 2, Strain Gauge SG02, μ_{TR} , Run1. There is full matching of the strain gauge predicted value.
- **I2D D i:** It structures the necessary steps to realise distributed load data from individual loading. By means of superposing the predicted readings of "M1 to M2" or data coming from other sources such as the example highlighted in Figure C.61.
- **SG D:** It uses the Strain Gauges superposed in "I2D D i" to create the typical input file of LETE, Figure B.8.
- **Load D:** It uses the Loads superposed in "I2D D i" to create the typical input file of LETE, Figure B.6.
- **Rc Cp:** It defines the order of the superposed load sequence once provided.

Note: the acronyms shown above are the same of the Excel file spreadsheets as displayed in Figure C.60.

The application used to show the validation of the *I2D Module M2, excel file spreadsheet "I2D D i"* is the Lightning Fin already introduced in Figure 4.12, and the input data used are grouped in Figure 5.40, the chosen strain gauge is highlighted in the semi-dotted line. The Excel results of Figure C.61 are matching the reference output of Hovell et Al., [43], of Figure 5.41.

Pat. No.	$\sigma(x) \times 10^{-3}$	(V)	$\sigma(x) \times 10^{-3}$	A_5	A_8	B_1	C_1	C_{12}	D_1	D_3	D_5	D_7	A_7	A_9	B_2	B_3	C_5	C_{13}	D_2	D_4	D_6
00	80.3	1000	138.3	73.9	31.2	53.4	58.0	66.7	29.0	21.5	32.8	-34.8	76.2	70.1	71.4	61.9	46.3	-143.3	57.8	89.7	28.6
01	58.8	1000	135.0	57.1	40.7	37.0	42.0	62.9	20.9	18.5	26.3	-24.7	102.2	67.6	125.9	74.6	34.4	-119.8	48.8	72.5	21.4
02	50.8	1000	133.3	53.2	34.7	32.5	37.6	52.8	19.5	18.6	23.2	-22.4	112.3	67.4	145.1	79.8	32.7	-106.6	40.9	63.9	20.9
03	32.8	1000	130.3	38.4	33.7	23.4	27.2	32.3	11.4	15.4	13.2	-15.5	130.9	67.1	184.1	90.0	39.0	-87.5	33.7	45.9	7.5
04	15.6	1000	126.3	22.5	18.8	4.0	16.1	17.9	4.0	10.1	6.5	-11.5	125.5	52.8	296.2	97.4	22.7	-61.4	20.7	30.2	10.1
05	0.0	0	0.0	-2.7	14.0	-35.0	4.9	3.0	0.0	9.0	3.1	-2.5	35.5	27.4	-99.0	-31.3	12.5	-25.7	7.3	13.2	8.1
11	58.8	1000	111.8	58.1	31.6	27.3	48.7	64.5	16.5	13.4	32.2	-31.6	99.6	84.9	53.2	34.1	56.9	-8.4	36.6	67.3	39.4
22	50.8	1000	102.3	52.9	36.3	20.6	46.1	55.7	9.8	-14.0	32.9	-32.0	105.1	90.9	38.7	24.1	63.7	-58.9	28.6	56.0	43.2
23	32.8	1000	102.3	44.9	40.1	12.0	32.3	37.4	5.7	-10.9	22.5	-20.3	151.3	92.8	70.5	30.3	57.0	-49.5	22.5	41.4	37.2
24	15.5	1000	102.3	45.4	11.3	4.8	17.5	16.3	0.0	-9.7	15.1	-12.3	243.8	76.3	65.6	29.9	38.9	-35.0	11.8	25.1	24.6
25	0.0	0	0.0	-13.5	0.0	-4.5	6.4	1.9	-7.3	-4.4	6.1	-4.9	-67.1	12.3	8.5	10.4	14.8	-10.9	3.2	9.6	8.6
33	38.8	1000	87.5	40.7	13.7	13.1	43.8	45.0	-2.7	-24.2	25.0	-31.9	94.9	116.2	18.2	10.2	86.9	-23.8	19.6	44.5	54.9
34	15.5	1000	87.5	20.0	12.5	3.8	21.3	12.3	-3.8	-20.0	15.0	-13.8	83.8	232.5	22.5	12.5	61.3	-40.0	7.5	23.8	31.3
35	0.0	0	0.0	1.5	6.5	0.0	5.0	-10.5	-9.5	-9.5	6.5	-5.0	10.5	-55.0	7.0	5.5	12.5	-9.0	1.5	8.0	8.0
43	25.5	1000	72.0	23.0	30.0	0.0	36.8	24.6	-10.0	-42.0	27.0	-31.0	59.6	93.5	0.0	0.0	163.3	0.0	7.6	35.0	94.0
44	15.5	1000	72.0	20.0	13.0	5.0	31.0	14.0	-9.0	-34.0	20.0	-16.0	48.0	4.0	4.0	0.0	229.0	4.0	1.2	20.0	46.0
45	0.0	0	0.0	6.5	15.0	0.0	0.0	0.0	-18.0	-12.5	5.0	-4.0	15.5	75.0	1.5	1.5	-43.0	0.0	-1.5	4.0	-1.5
51	80.2	1000	145.8	76.0	22.0	56.0	56.0	82.0	30.0	36.0	32.0	-36.0	78.0	55.0	120.0	82.0	38.0	-158.0	66.0	92.0	20.0
52	89.2	1000	141.5	80.0	18.0	58.0	68.0	94.0	30.0	26.0	32.0	-40.0	68.0	70.0	60.0	66.0	46.0	-156.0	68.0	95.0	30.0
53	90.6	1000	148.9	88.0	18.0	62.0	68.0	96.0	34.0	32.0	32.0	-38.0	70.0	62.0	82.0	76.0	36.0	-172.0	70.0	102.0	22.0
54	10.3	1000	53.8	13.0	4.0	0.0	14.0	11.0	-21.0	-124.0	19.0	-4.0	28.0	43.0	-10.0	-4.0	66.0	10.0	-18.0	19.0	323.0
55	0.0	0	0.0	8.0	8.0	0.0	5.0	0.0	-24.0	-29.0	-13.0	20.0	13.0	20.0	6.0	0.0	16.0	0.0	0.0	15.0	-95.0
60	82.2	1000	130.0	74.3	13.8	50.0	61.4	87.4	25.6	11.6	36.1	37.6	72.8	74.1	40.0	44.0	50.2	-133.8	57.6	90.6	34.4
61	63.3	1000	107.3	61.6	19.6	28.6	52.0	68.9	13.0	-8.1	35.1	-35.4	90.3	87.1	28.7	26.0	62.9	-77.8	38.6	71.5	45.7
62	55.8	1000	98.3	65.2	24.5	27.6	59.0	73.3	11.2	-18.6	43.3	-39.8	115.6	111.9	24.3	21.2	81.8	-62.5	35.3	73.7	59.2
63	29.8	1000	68.0	28.1	13.3	4.7	37.9	30.8	-9.2	-43.4	35.2	-34.3	57.3	90.8	-10.1	-5.1	120.8	8.8	0.0	36.6	91.9
64	15.5	1000	49.5	13.8	6.3	0.0	17.5	15.0	-15.0	-87.5	20.0	-16.3	28.8	50.0	-12.5	-10.0	72.5	17.5	-51.3	5.0	243.8
65	0.0	0	0.0	7.5	8.8	0.0	7.5	-3.8	45.0	41.3	2.5	0.0	12.5	22.5	-6.3	0.0	31.3	15.0	-103.8	-28.8	85.0
66	44.1	1000	83.0	41.4	50.0	0.0	45.7	4.6	0.0	-27.1	37.1	-34.3	87.1	110.0	0.0	0.0	87.1	-18.6	17.1	-205.0	60.0

* See Fig.2 for reference axes.

Figure 5.40: Individual to Distributed, I2D M2 Validation - Input Data: Load and Strain Gauge readings - Lightning Fin, Strain Gauge A5, [43].

Measured and superposed strain gauge responses for distributed load (Table 4)

Bridge	A ₅	A ₇	A ₈	A ₉	B ₂	B ₄	C ₅	D ₁	D ₂	D ₃	D ₆	D ₇
Superposed response	183	361	198	362	174	76	308	17	78	-78	284	-115
1st dist. load	187	350	196	362	173	76	298	14	72	-78	283	-118
2nd dist. load	183	363	197	365	169	78	298	14	75	-85	283	-115
Mean	185	356	196	364	171	77	298	14	74	-81	283	-117
% age error on mean	-1.1	1.4	1.0	-0.5	1.8	-1.3	3.4	21.5	5.4	-6.1	0.4	-1.7

TABLE 4
Distributed load

Load lb	1000	500	500	310	290	245	225	190	145	125	100	70
Pad No.	00	61,63	64,66	24	34	35	44	45	04	25	02,03	05

Figure 5.41: Individual to Distributed, I2D M2 Validation - Output Data: Measured and Superposed Strain gauge readings - Lightning Fin, Strain Gauge A5, [43].

A final consideration to be made on the *I2D* package is that not all strain gauges might be suitable to a strain gauge prediction task to have a superposed sample data. This is evident by the results shown on strain gauges μ_V and μ_3 , where 3-D plots Figure C.8, Figure C.17, Figure C.26, and Figure C.36. This could be prevented and spotted at an early stage during the Ground Load Calibration when the applied load is introduced step by step by verifying the load and strain gauge linearity. Unfortunately, the data employed so far represents just one single reading of the whole load calibration preventing an important set of information.

5.5.5 Validation Table Summary

The L1 Validation section has taken in turn all those black boxes of Table 5.1, representing the pillars of the LETE environment and worth assessing their correctness and robustness. The validation process required the use of reference recognised data to compare with, either in direct or indirect way, such as the deduction process employed to *ExS* and *SgR*. The outcome of this investigation shows the needed confidence that the selected codes, Table 5.3, produce correct quantities matching with high accuracy those of reference and maintaining this characteristic against more than one isolated test case as Table 5.1 shows. Table 5.19, as already Figure 5.1 anticipated, collects all previous validation codes reference and successful validation status so that the coming up phases, L2 and L3, expected to appraise the LETE environment and the LPP technique, will be producing absolute and reliable

Summary

performance considerations on the novelties introduced in this research.

Table 5.19: L1 Phase: Validation Table Summary.

Codes	Validation References	Validation Status
LIRE M1	Table 5.4, Table 5.5 and Table 5.6	OK
LIRE M2	Table 5.7	OK
IC	Table 5.8	OK
ExS and SgR	Section 5.5.3	OK
I2D M1	Section 5.5.4	OK
I2D M2	Figure C.60	OK

Note - It is worth highlighting that just for the Validation level it has been decided to allocate details for all results presented in order to allow a straight comparison among all the different cross check provided from the past or offered from text files and plots. This generated a high amount of data results as demonstrated by the Figures employed. Next section, strengthened by the current validation and elevated data of evidence, will be focusing only on those details of the outputs necessary to allow discussion, all the remaining output will be presented either in more compact format or just offered in electronic format.

5.6 Summary

The three-level validation and performance process has been presented. The first level, L1, dedicated to the Validation Phase, became the core of the whole chapter. A strategy has been introduced to identify those Python codes necessary to be validated before moving to the Performance Phase of the next Chapter 6. This required to further dissect the *LETE* environment and understand the major dependencies and quantities involved.

The use of dedicated *Test Cases*, Table 5.1, capable to offer a complete set of results, input and output of specific quantities, whose details are presented in Appendix C, made possible to validate the majority of those codes identified in Table 5.3. On the other hand, when data were not available, the affected software, such as ICLE, and the Search Engines, ExS and SgR, were assessed by deduction of their expected functionalities and interpretation of their dependencies to other piece of codes already validated.

The data selected cover a wide range of test articles and different references in order to give to the final result the robustness and reliability expected by the Performance Phase. At the same time, when the code under investigation, I2D Module M1, required a more articulated analysis, the literature review data have been combined in such a way to offer several runs of the code and consequently a

more comprehensive understanding.

The Individual to Distributed, I2D module M1, software, supposed to predict strain gauge responses for a given load point, offered interesting considerations. In fact, it has been shown how the correct applicability of this supporting tool of the LPP Technique, section 4.5.2.1, has to be adequately planned before the execution of the ground load calibration. Applicable recommendations, that eventually will be taken into account in the next chapter 6, are listed at the end of the section 5.5.4.2. Moreover, two indicators of the reliability of the fitting surface proposed and of the accuracy of the prediction, the Global Error and the Local Error percentage, proved to work properly.

All Python and Excel, I2D Module 2, codes investigated provided the successful validation outcome expected, as summarised in Table 5.19, to authorise to progress to the next two levels, L2 & L3, of the Performance stage.

Table 5.2: Level 1: LETE Dissection - Terminology see Figure 3.2 and Figure B.1.

Techniques	Method/Reference	Engine Search	Ranking Criteria	Supporting Tools	Solver
01	LPE, B.1.7.1	Exhaustive Search (ExS)	Standard Deviation (SD)	Infl. Coeff. (IC)	LIRE
02	DLD, B.1.7.2	Ex. Search (ExS)	Standard Deviation (SD)	IC and I2D	LIRE
03	ESM, B.1.7.3	Ex. Search (ExS)	Matrix Approach and SD	IC and FEM	LIRE
04	T-v, B.1.7.4	Strain Gauge Reduc.	T value	IC	LIRE
05	MT-v, B.1.7.5	Strain Gauge Reduc. (SG Red.)	Modified T Value	IC	LIRE
06	GA, B.1.7.6	Ex. Search (ExS)	SD and Penalisation Coeff.	IC	LIRE
07	RC, B.1.7.8	Ex. Search (ExS)	SD and Relevance Coeff.	IC	LIRE
08	LPP, B.1.7.9	Ex. Search (ExS)	Linearised Physical Param.	IC, ICLE, I2D	LIRE

Table 5.4: Eckstrom Test Case 2 (TC2) [27] VS LIRE: Load Coefficients Comparison.

Loads Coefficients Comparison - Eckstrom [27]/LIRE-Ratio			
Loads	TC2 Data	LIRE Software	Ratio
3*Shear $\beta_{1,2,3}$	4894	4897.7	0.9992
	292	296.1	0.9862
	-4129	-4126	1.0007
3*Moment $\beta_{1,2,3}$	528	528.5	0.9991
	277	276.3	1.0025
	-174	-173.6	1.0023
3*Torsion $\beta_{1,2,3}$	388	389.5	0.9961
	-1947	-1974	0.9863
	-998	-1001.3	0.9967

Table 5.5: Eckstrom Test Case 2 (TC2) [27] VS LIRE Module M1: Loads Probable Error of Coefficients Comparison.

Loads Probable Error of Coefficients Comparison - Eckstrom [27]/LIRE-Ratio			
Loads	TC2 Data	STATE Software	Ratio
3*Shear $\beta_{1,2,3}$	218	219.5	0.9932
	88	88.2	0.9977
	236	237.4	0.9941
3*Moment $\beta_{1,2,3}$	16	15.6	1.0256
	12	11.9	1.0084
	3	3.1	0.9677
3*Torsion $\beta_{1,2,3}$	62	62.1	0.9984
	136	136.9	0.9934
	36	36.7	0.9809

Table 5.6: Eckstrom Test Case 2 (TC2) [27] VS LIRE: Loads Probable Error of Estimate Comparison.

Loads Probable Error of Estimate - Eckstrom [27]/LIRE-Ratio			
Loads	TC2 Data	STATE Software	Ratio
1*Shear $\beta_{1,2,3}$	85	86.2	0.9861
1*Moment $\beta_{1,2,3}$	2.5	2.5	1.00
1*Torsion $\beta_{1,2,3}$	33	33.6	0.9821

Table 5.8: IC Validation: Figures Interpretations of the Comparison of IC Software Package and Test Case 1 (TC1) *Structure A*, Influence Coefficient Plots, [102].

Skopinski Test Case 1 (TC1) "Figures"	IC Software Package "Figures"	Comparison Quantities Description / Strain Gauge
Figure 5.25 Top Left Side	Figure 5.30 Left Side Loaded	IC Plot / Front Spar
Figure 5.25 Top Left Side	Figure 5.31 Left Side Loaded	IC Plot / Midspar Spar
Figure 5.25 Top Left Side	Figure 5.32 Left Side Loaded	IC Plot / Rear Spar
Figure 5.25 Top Left Side	Figure 5.27 Right Side Loaded	IC Plot / Front Spar
Figure 5.25 Top Left Side	Figure 5.28 Right Side Loaded	IC Plot / Mid Spar
Figure 5.25 Top Left Side	Figure 5.29 Right Side Loaded	IC Plot / Rear Spar
Figure 5.26	Figure C.1 and Figure C.2	Numeric Input Data
Numeric Data not available	Figure C.2 and Figure C.4	Numeric Data of the IC Plots

Chapter 6

The Performance Phase

6.1 Introduction

This chapter is expected to complete the "Three Level Flow Chart" process of Figure 5.1, as "Level 1 Validation" has been Chapter 5 main topic, by going through the two remaining levels, "L2 Comparison" of the loads equation accuracy of the different techniques of *LETE*, including *LPP*. Then, the "L3 Assessment" of the best set of load coefficient by ranking the root mean square error, %RMS. These two levels characterise the *Performance* phase of the novelties proposed in this research. The performance requires the availability of dedicated test cases with experimental data so that to execute the Python codes described in Chapter 3.

The data available must be comprehensive of the test article geometry and instrumentation basic characteristics, strain gauge readings, and load cases magnitude and application points, span and chord wise coordinates. Moreover, they expected to offer a different aspect ratio of different lifting surfaces, enabling to interpret the results by linking the techniques employed with the specific test article characteristics under investigation.

The test cases allowing to assess the *LETE* performances, come from flight loads measurement campaigns conducted by two main Research Centres, NASA Langley Research Centre and the Italian Aerospace Research Centre, CIRA. The first one offered since the 1950s up to the early 1980s, several lifting surfaces, such as those already introduced in section 5.4 for the validation phase. Unfortunately, not all of them are meeting the detailed set of data information mentioned above. The ARWg-2 wing, classic aluminium torsion box configuration, has been chosen as having a high aspect ratio, 10.3, opposite of the other available test data. The second, is a Dropped Transonic Flight Test (DTFT) of an unmanned space vehicle (USV), characterised by ground data of two identical prototypes, whose campaign took place during the second half of the 2000 by the Italian Aerospace Research Centre, CIRA.

A particularity of the Test Cases investigated is that most of the time only the

Dependent Data, Training data set, are accessible, creating difficulties to compare the results by means of an Independent and absolute set of data on which evaluate the %RMS, the Validation data set. Though, this limitation offers the possibility to explore other solutions that most of time in the real life of the industry, not for the academic side, it is a common situation. In fact, the introduction of distributed check load cases is a privilege that brings along increase complexity of the ground load calibration set up, and consequently cost and time impacts. This is why it tends not to be frequently available.

Finally, it will be given answers not directly limited to *LETE* and *LPP* efficiency, but to more general challenges that represent the idea behind this thesis. In fact, exploring solutions that are supposed to increase the quality of the final set of loads equations though maintaining the effort for the execution of such massive ground load calibration, analysis and flight test campaign contained in terms of time and cost. Introduction of the "Double E Data Type" concept, Figure 3.3, dependent and independent data, training and validation data, combined with numerical distributed sample data, usage of different test articles, for ground and flight test, reducing the risk to damage the flying test article by too high magnitude of loads, represent well defined aims to be considered.

Specific *Runs* will be defined to explore those challenges and to test the Codes abilities under the boundaries of the available data and in relation to those quantities that the "The Three-Axis of Complexity", section 2.6.1, identified as significant including: single-point loading compared with distributed loading, test load magnitude, number of load cases, and wing surface availability, relevance coefficient.

6.2 L2 & L3 - The Performance Strategy

As just highlighted, this Chapter aim is not limited to test the performance of those Python packages described in section B.1.7 by direct comparison to each other, but also to explore the impact of these quantities below:

1. Individual Load Points - Experimental, GLC.
2. Distributed Load Points - Experimental, GLC.
3. Distributed Load Points - Numerical from GLC.
4. Test Loads Magnitude.
5. Number of Load Cases.
6. Number of Strain Gauges.

The relevance coefficient, R_C section B.1.7.8, and information of flight test loads centre of pressure, *FLSR* section 4.5.2, are not included as not available and already anticipated during the validation phase of the *I2D Module 2*, section 5.5.4.2. Though, it is possible to say, in consideration of the definition of the relevance coefficient of Eq. (4.9), that *point 5.* above is proportional to the R_C . This will allow to understand the contribution and the effect by indirect monitoring of the

Number of ground load cases.

Each test case will generate combination of those quantities by clearly identifying input type of data, Python Code Technique employed and its relevant characteristics, and a final load check case, ideally distributed loads as encountered in flight. This is labelled the *ideal check load case condition*, it must be experimental ground data, and if not available it will be replaced either by an experimental individual load case or a distributed numerical sample. The distributed numerical sample is the results of superposed individual experimental load point by mean of I2D. These *check load case conditions*, CLCC, are expected to generate accurate %RMS values as preventing to increase uncertainties for the final assessment.

The results will be presented in bar chart format and tables, the output of codes will be presented in Appendix D, in order to offer a direct interpretation of the ranking of all available employed techniques. If the test case referenced offers its own results will be taken inside the discussion to better understand the differences of the approaches. In support of the results the codes output text files will be shown focusing just on a specific section, preventing to be confused by an amount of irrelevant data.

Results and Discussion will be combined in a single section for the specific Run Case under-investigation and then cross referenced with other significant test cases in a dedicated section.

6.3 L2 & L3 Test Cases

The challenge of the data used for the L1 Validation phase was to find reliable input and output to be compared with. Basically, trying to be consistent with the terminology employed till now, the input values used at L1 were Dependent Data in relation to the codes validated. On the other hand, the Performance phase data, L2 and L3, require a higher variety of ground and eventually flight test data possibly supported by theoretical loads calculation, of different lifting surface typology, such as construction and aspect ratio, to gain a wider validity to the methodology investigated.

In this regard, the major effort is to have an Independent, Validation, Data set necessary to perform the *check load case conditions* for completing the L3 final assessment by ranking all the techniques employed according to absolute standards. This section is adding to the test cases presented in section 5.4 two flight loads measurement campaign of a drone aircraft, ARWg-2, [28], with high aspect ratio, 10.3, and a multi-mission, re-usable transonic low aspect ratio, 2.3, vehicle, USV (unmanned space vehicle).

Each of these last two test cases, labelled Test Case 3 (TC3) and Test Case 4 (TC4) respectively, has its own characteristics to contribute properly and in line with the expectations of this research. In fact, the Aeroelastic Research Wing ARWg-2, part of the the Drones for Aerodynamic and Structural Testing program, available ground load data includes actual multipoint loads for simulated flight conditions. On the other hand, the Italian Aerospace Research Centre USV gives the chance to

develop the loads equations on one prototype and to apply them on the other, perfectly same design and instrumentation configuration. This offers the opportunity to have different test articles for ground and flight test and understand how much this flexibility might affect the final loads measurement quality.

The results will be coming from all these two test cases, *TC 3* and *TC 4*.

6.3.1 Langley Research Center: ARWg-2 Drone Aircraft - Test Case 3

Eckstrom's contribution on flight loads measurement campaigns, initiated in the 1975 on the BQM-34E drone aircraft with Peele, [90], and continued alone with the 1976 publication, [26], same wing but upgraded instrumentation, is extended by an Aeroelastic Research Wing, ARWg-2, Figure 6.1.

The test article, designed and fabricated as part of the Drones for Aerodynamic and Structural Testing programme, is a supercritical wing of energy efficient aerodynamic conception whose structural design has integrated active control systems for Manoeuvre Load Alleviation and Gust Load Alleviation to reduce structural strength requirements and an active control Flutter Suppression System to reduce structural stiffness requirements, [28].

The strain gauge bridges, located at three stations, Figure 6.2, on both the left and right semi-spans, are used to get measurements of structural loads, shear (V), bending moment (M), and torque (T) to: assure that safe loading levels are not exceeded during testing, provide data for evaluation of the active control systems, and provide data for the evaluation of the effects of wing flexibility and aerodynamic loads measurements obtained over a range of Mach number and dynamic pressure test conditions.

The ARWg-2 is a high aspect ratio, low sweep angle wing designed for energy efficiency at a cruise Mach number of 0.8. The primary structure of the wing semi span panels consists of a front spar, rear spar and an auxiliary spar located inboard in the trailing edge extension area as a support for the inboard control surfaces. Ribs are located perpendicular to the rear spar with the exception of a special stream wise tip rib that also functions as an outboard spar end fitting, Figure 6.3. The loads measurement strain gauges have been installed along this classic torsion box load paths configurations.

For the calibration procedure employed later as LETE input data the left and right semi-spans were calibrated separately, as Figure 6.3 shows, with the mounting being to a backstop rather than to the wing centre section attached to a fuselage as normally done. The input loading conditions were single made of a single point, individual data, and two multi-points, distributed data, each executed with a large number of individual steps. Figure 6.4 displays the load point locations, used to perform both set of single and multi-point loadings, and Figure 6.5 details the coordinates.

Flight test data are not available.

The diagram shows a cantilever beam fixed to a wall on the left. The beam has a rectangular cross-section with a central web and two side flanges. Strain gages are located at various points along the beam, indicated by circles and crosses. The locations are labeled with numbers 1 through 23. Three circular callouts provide the following data:

- Callout 1: W.S. 21.4
- Callout 2: W.S. 60.4
- Callout 3: W.S. 96.5

Strain Gage Bridge Identification

- Shear, Odd Numbers
- Bending, Even Numbers
- ⊗ Torsion

153

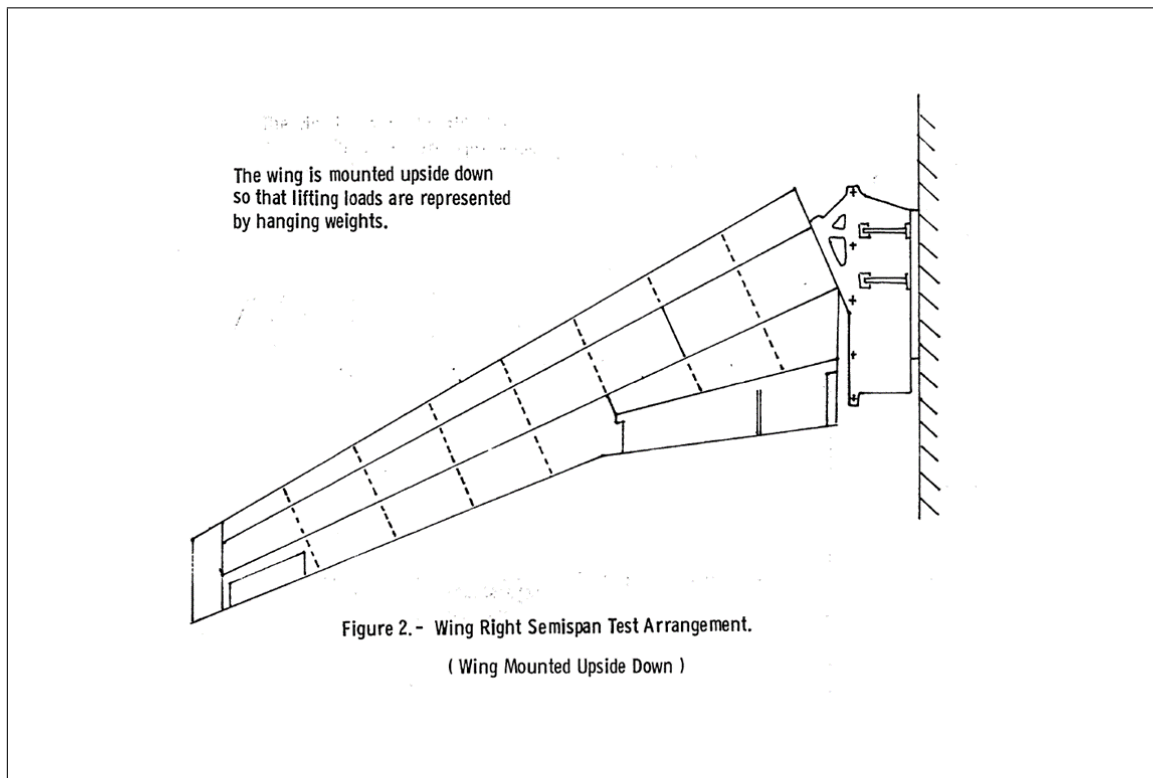


Figure 6.3: ARWg-2 drone aircraft: Wing Front, Rear and Auxiliary Spars, and Test Arrangement, [28].

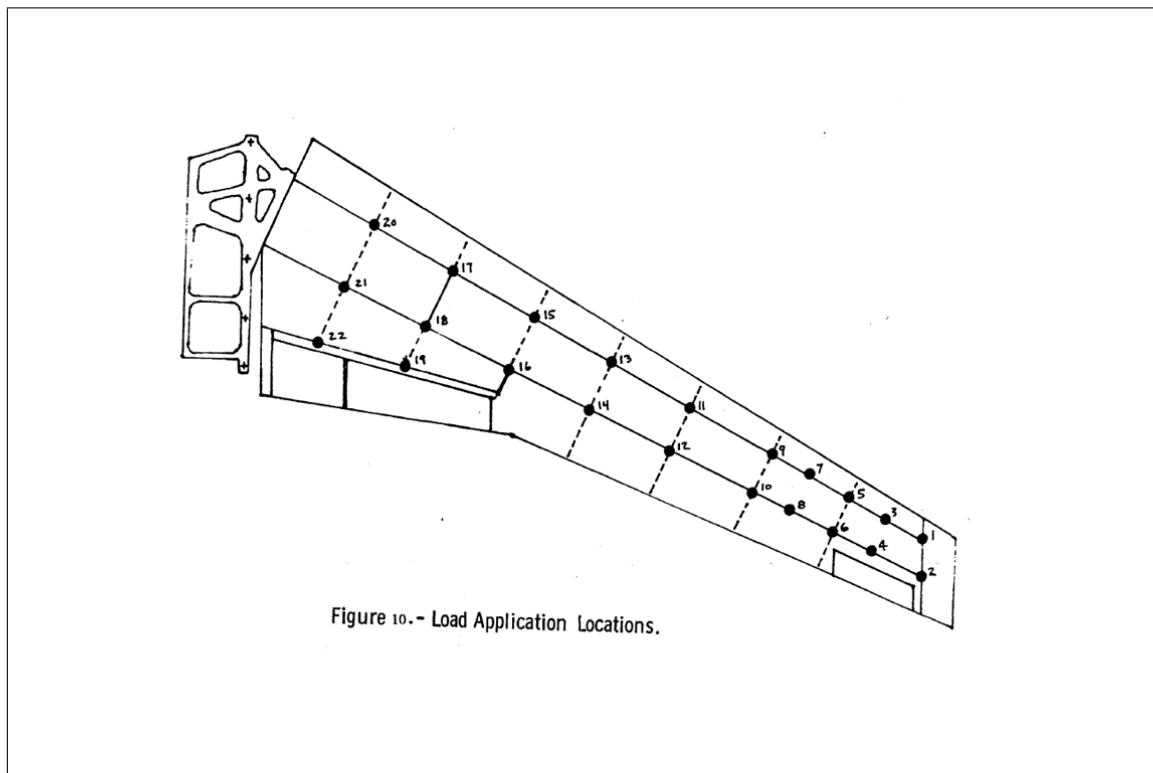


Figure 6.4: ARWg-2 drone aircraft: Load Application Locations, Individual and Distributed Data, [28].

Location number	X_W (in)	Y_W (in)	Y_{WI} (in)	Y_{WM} (in)	Y_{WO} (in)
1	-2.55	117.3	95.9	56.9	20.8
2	2.96	119.4	98.0	59.0	22.9
3	-2.74	111.6	90.2	51.2	15.1
4	2.73	111.6	90.2	51.2	15.1
5	-2.94	105.0	83.6	44.6	8.5
6	2.91	105.0	83.6	44.6	8.5
7	-3.09	98.4	77.0	38.0	1.9
8	3.12	98.4	77.0	38.0	1.9
9	-3.31	91.8	70.4	31.4	---
10	3.24	91.8	70.4	31.4	---
11	-3.62	78.6	57.2	18.2	---
12	3.62	78.6	57.2	18.2	---
13	-4.01	65.4	44.0	5.0	---
14	3.99	65.4	44.0	5.0	---
15	-4.33	52.2	30.8	---	---
16	4.34	52.2	30.8	---	---
17	-4.70	39.0	17.6	---	---
18	4.71	39.0	17.6	---	---
19	11.23	39.0	17.6	---	---
20	-5.07	25.8	4.4	---	---
21	5.01	25.8	4.4	---	---
22	14.19	25.8	4.4	---	---

Figure 6.5: ARWg-2 drone aircraft: Load Application Location Coordinates, [28].

6.3.2 CIRA: Unmanned Space Vehicle - Test Case 4

The Italian Aerospace Research Centre has been developing a research program which is focused on the validation of national aerospace technologies on a flying demonstrator named USV (Unmanned Space Vehicle), Figure 6.6.

The program aims at the realization of unmanned Flying Test Beds, conceived as multi-mission flying laboratories, in order to test innovative materials, verify structural and aerodynamic behaviour, advanced guidance, navigation and control functionalities and critical operational aspects typical of future Reusable Launch Vehicles. The development of such a vehicle requires, in particular, the availability of a number of specific key technologies, [87].

In this framework, a series of missions of increasing complexity has been planned, the first of which is the Dropped Transonic Flight Test, DTFT, mainly aimed at testing the aerodynamics and flight behaviour in transonic flight regime, in conditions likely to be experienced by a winged launcher stage during its atmospheric re-entry trajectory.

Two dropped transonic flight tests were carried out from Arbatax airport, Sardinia, Italy, the first one on 24th February 2007, USV1 Castore, the second one on 11th April 2010, USV2 Polluce.

In this scenario the Unmanned Space Vehicle has offered an interesting platform to validate experimentally the flight loads used in the design phase offering the opportunity to better understand the level of accurateness reached and applying improvements for successive missions.

The left wing of the vehicle has a four aluminium spars layout, Figure 6.7. Different

types of strain gauges are installed on the main load paths of a standard torsion box. Details of the strain sensors instrumentation are:

- Spar caps (top and bottom): Mono-axial strain gauges.
- Spar Web: Tri-axial, Rosette.
- Panels: Shear and Tri-axial.

USV1 and USV2 have identical configuration and instrumentation in order to make consistent the information gathered from the two DTFT.

The left wing test article highlighted, in Figure 6.8, was calibrated by single load points, with the intention to record data to measure loads in three different bays, Figure 6.9. Two separate ground load calibrations have been conducted, GLC1 on USV1 Castore, and GLC2 on USV2 Polluce. This research has access to both. Table 6.1 gathers all most significant dates of the DTFT campaigns of the two prototypes. Ground load calibrations took place at Capua CIRA's head-quarter, while the flight test in the Italian Island of Sardinia, at Arbatax.

Table 6.1: CIRA flying demonstrator: USV significant Dropped Transonic Flight Test Dates, [13].

USV Prototype	USV Name	GLC Date	First Flight Date
USV1	Castore	GLC1, 20.09.2005	12.02.2008
USV2	Polluce	GLC2, 24.02.2007	11.04.2009

In order to better comprehend the flight test data it is worth describing the USV Mission Scheme summarised in Figure 6.10. The design of the DTFT is based on using a two-stage system that is composed by an expendable first stage, a carrier based on a stratospheric balloon, and the winged re-entry flight test bed (FTB1 vehicle), as the second stage. The nominal mission profile is described by the basic operations three phases below, [13]:

- The ascent Phase: from lift-off to the release, about 20 km altitude, during which the carrier system brings the FTB1 to the release altitude by means of the stratospheric balloon.
- The Flight Phase: from vehicle release to parachute opening, where the FTB1 leaves the carrier and flies accelerating to achieve the required velocity to perform the experiments. In this phase the FTB1 passes through the transonic regime, Mach number around 1.1, between 10 and 15 km, in stabilised attitude while performing an autonomous aero controlled flight.
- Deceleration Phase: from Parachute opening to splashdown, in which the FTB1 opens the parachute and ends its mission by sea splashdown and recovery.

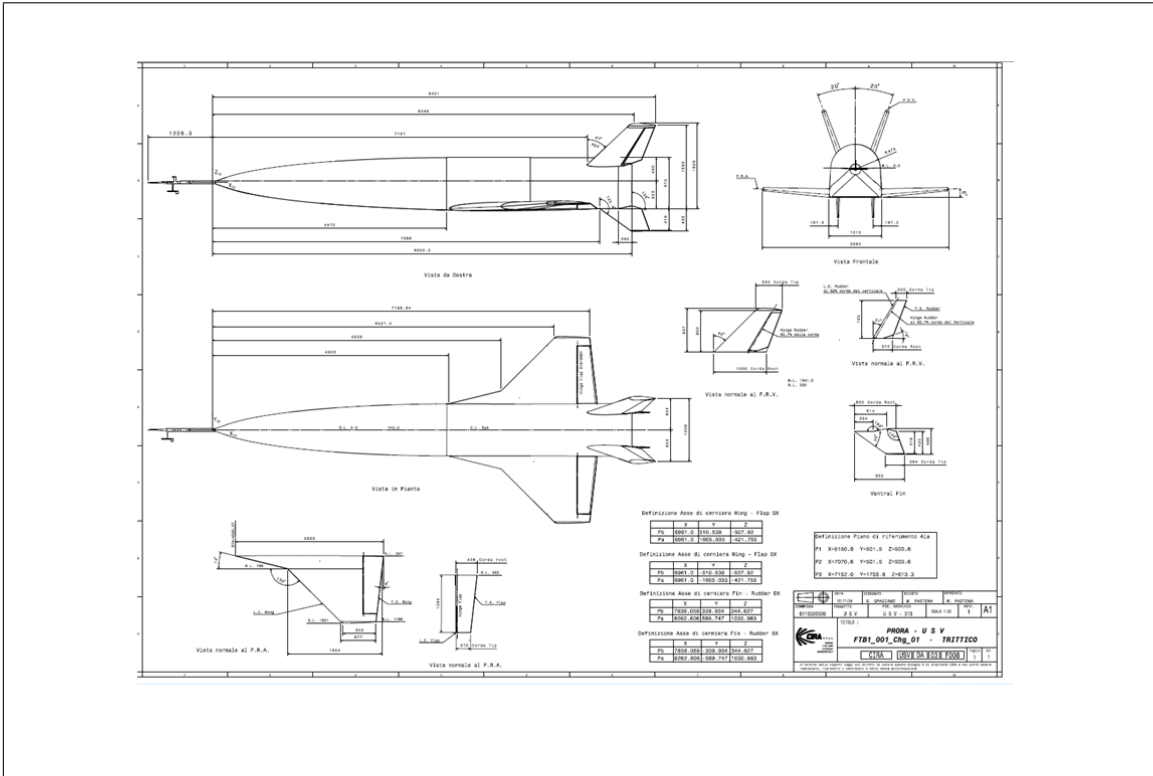


Figure 6.6: CIRA Unmanned Space Vehicle: USV Three - View Aircraft, [13]

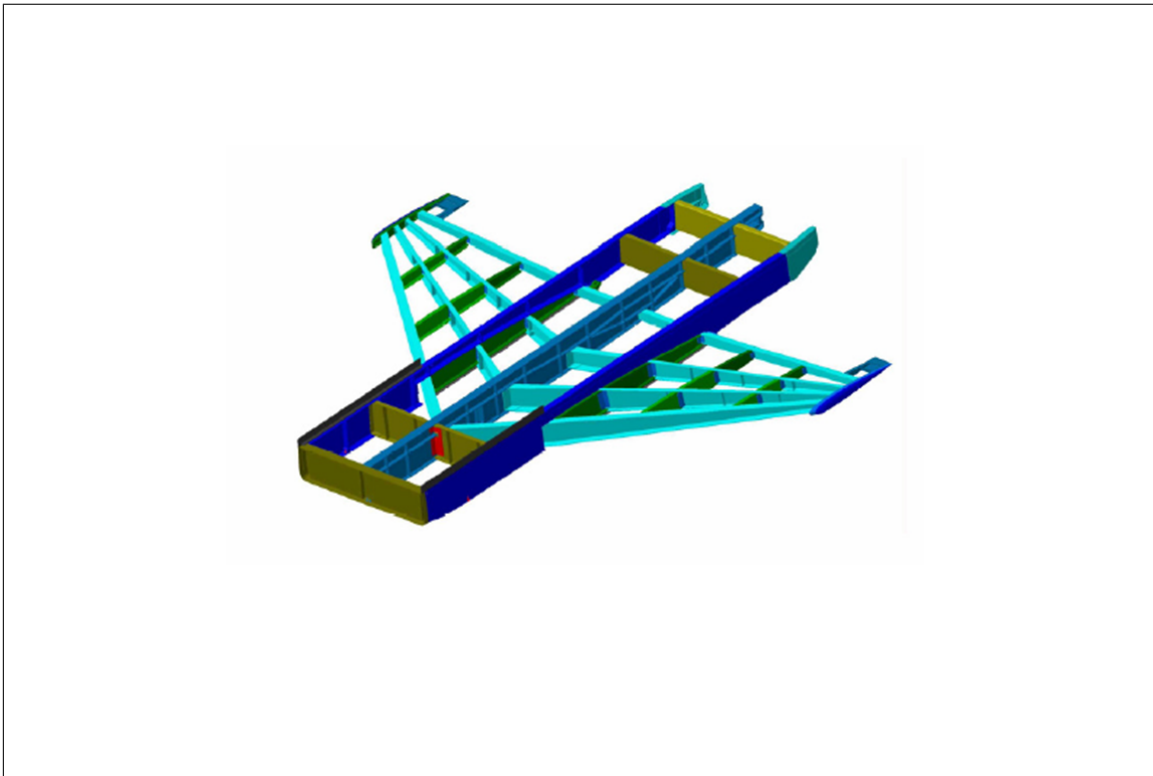


Figure 6.7: CIRA flying demonstrator: USV Wing Scheme, [13].



Figure 6.8: CIRA flying demonstrator: USV Ground Load Calibration, Wing Test Article , [87].

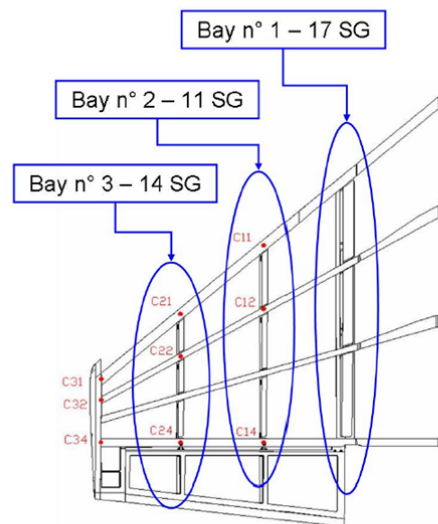


Figure 6.9: CIRA flying demonstrator: USV, Loading Point Positions and Strain Gauge measurement stations, [87].

The flight test data of USV2 Polluce are the sole available, Figure 6.11 shows the nominal trajectory, as USV1 Castore went missing in the Mediterranean Sea.

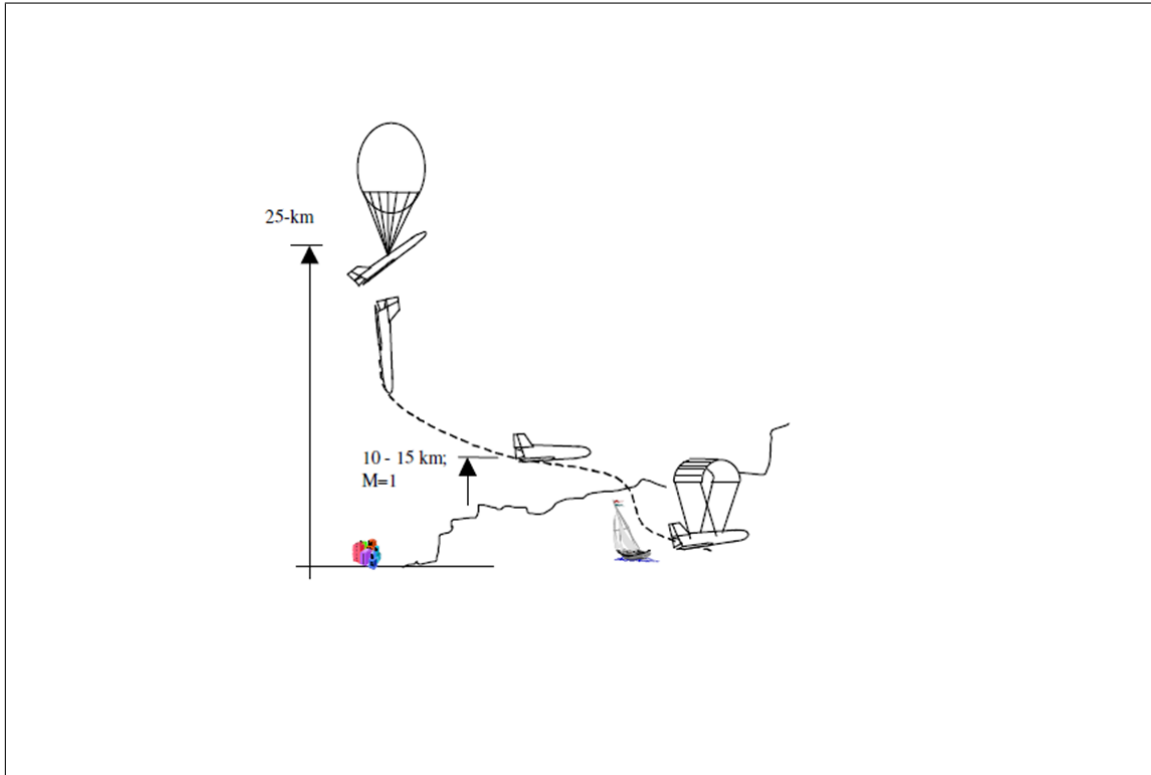


Figure 6.10: CIRA flying demonstrator: USV, DTFT Mission Scheme, [13].

6.4 L2 & L3 Results and Discussion

This section presents the results generated by specific Run-Cases created by combining the available *Test Cases* data and executed by the Codes presented in Chapter 3. In order to have an adequate discussion each Run case has to be defined and detailed to facilitate the final cross referenced comments.

The logic sequence of steps to generate the Results of the generic *Run Case* is highlighted in Figure 6.12 that gathers all those top level information necessary to have a right interpretation leading to the final discussion.

Furthermore, Figure 6.12 shows different steps of execution, identified by different box line typologies. Each step is described below:

- Step 1: Test Cases (TC) gathering the major characteristics. Solid line representing the box feeding Dependent and Independent Data within the Run Case. The TCs are represented by Table 6.2, collecting Test Article and Independent-Dependent Data information, and Table 6.3, populated by Load Cases and Strain Gauge detailed information.
- Step 2: Combination of each available TC data to make up the Input Data to feed LETE codes. Double-Solid line box shows basic information referred

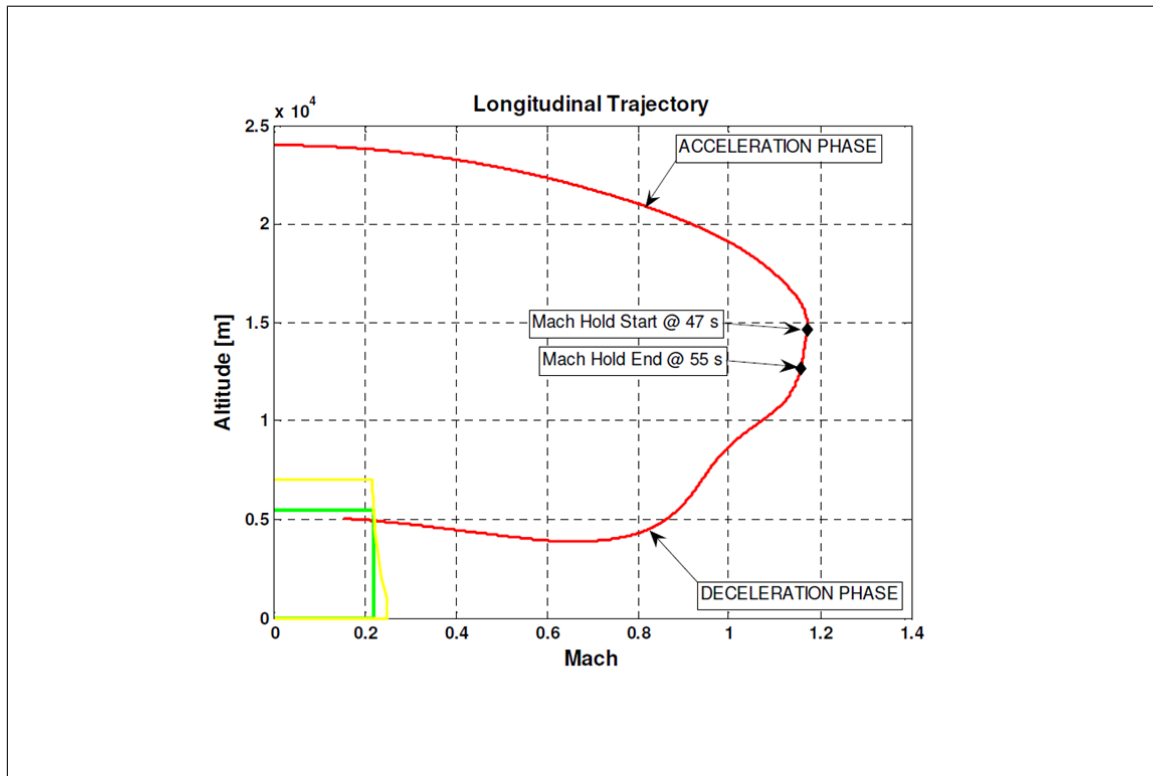


Figure 6.11: CIRA flying demonstrator: USV2 Polluce , DTFT2 Nominal Trajectory and Usage Envelope, [13].

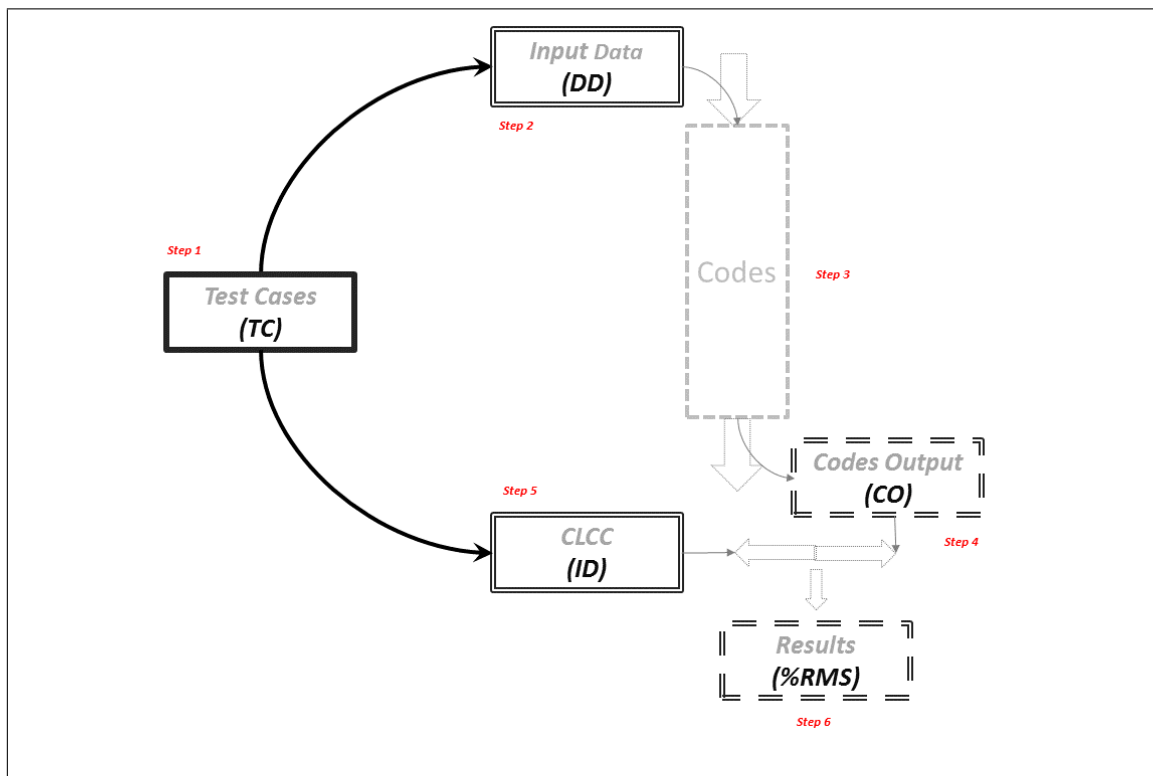


Figure 6.12: L2 & L3, Performance Phase: Run Cases definition.

within each Run Case necessary to characterise it. These basic data are broken down in individual, IDD, and distributed dependent data, DDD. Usually, DDD is a numerical result of the *I2D Module 2*.

- Step 3: Execution of the Python Code Techniques according to those principles listed in section 4.4, for the past methods, and section 4.5.4, for the *LPP* new technique. Single-dashed line box. It might happen that due to the type of data available, see step 2., some technique cannot be fully executed.
- Step 4: All output significant data of each LETE technique are presented within Figures displaying section of output text files or plots when available, attached in the Appendix D. Double-dashed line box information will be summarised within a dedicated table.
- Step 5: Extraction from the Test Case Table 6.3 of those Independent Data significant quantities such as Distributed or Individual load Independent Datas. Double-Solid line box like *Step 2 Box* above. The top level information of this box is grouped with step 1. Input Data as part of the Test Case Data.
- Step 6: Final Run Case Results of each LETE codes. Double-dashed line box information is highlighted within a Run Case Result Table showing as part of the results those relevant quantities such as number of load cases, mean loads applied, number of strain gauges of the final set of loads equation and the root mean square error percentage, see Eq.(B.1).

Before progressing to specific Run Cases it is worth underlining that Table 6.2 and Table 6.3 recall quantities and concepts that have been the driving forces of the whole research as it is explained below:

- "Three axis of Complexity", section 2.6.1: The X-axis, the "object" (component) of the flight loads measurement is described. Its major quantity responsible of the science development, the aspect ratio, is covered in a wide range from 2.54, [102], up to 10.3, [28].
- "The Double E Data Type", section 3.2: The Dependent and Independent Data, respectively DD and ID. Each of these can be, as Figure 3.1 shows, represented by load cases of individual loads or distributed. These Test Case data distinction are pivotal for the execution of the different Flight Loads Calculation Techniques and for their final appraisal. Figure 3.3 introduced this relationship among the Data and the generic LETE Technique Code.

The coming Run Cases sections will be presenting the flow of the step-by-step concepts of Figure 6.12 grouped by the following areas:

- **Data Definition:** Dependent, as input of the codes executed, and Independent Data, as Check Load Case Condition *CLCC*, to evaluate the Performance of each technique. The data can be Individual and Distributed of experimental or numerical load cases.
- **Strain Gauges Investigation:** Assessment of the quality of the Strain Gauges by employing two different tools, *IC* and *I2D Module 1*.

- **Loads Coefficients Computation:** Execution of all Techniques defined in Chapter 3 highlighting input data employed.
- **Technique Performance Results:** Calculation of the %RMS results by using a dedicated Check Load Case Condition, *CLCC*.

6.4.1 Run-Case 1, RC1

This Run Case, *RC1*, is described by the *Data Definition* Table 6.4. The data come from the Test Case 3, TC3, Eckstrom NASA Technical Memorandum 87677, [28].

6.4.1.1 RC1 Data Definition

Table 6.4 explains the two major data types used and their direct references too.

Table 6.4: Run Case 1, RC1: Data Definition, Data Type (DT), Load Type (LT).

DT	LT, Figure Refer.	Source, Refer.	Identif.
DD	Ind. Dep. Data, Figure D.1	Exp., [28]	IDD1
DD	Dist. Dep. Data, Figure D.2	Exp., [28] and I2D M2	DDD1
DD	Ind. Dep. Data, Figure D.3	Exp., [28] and IC	IDD2
CLCC	Dist. Indep. Data, Figure D.4	Exp., [28]	DID1
CLCC	Dist. Indep. Data, Figure D.5	I2D M2	DID2
CLCC	Ind. Indep. Data, Figure D.6	Exp., [28]	IID1

Table 6.4 Comments:

- ✓ IDD, Individual Dependent Data, of this TC 3 is always experimental.
- ✓ DDD1 and DID2 are generated numerically by *I2D Module M2*. In particular, DDD1 is an hybrid superposed data, as is the result of Numeric and Experimental load cases, Figure D.2.
- ✓ DDD1 has been created in order to have: Higher Magnitude Load, 9 load cases, and three chord wise stations, Figure D.2.
- ✓ DDD1 numerical sample, 3 chord wise and 3 span wise load cases, is an attempt to feed *LPP* with more IC plots. In fact, the extra chord wise load case creates generates one more IC curve per strain gauge useful for the linearisation phase of the Fitness Functions. Higher sample should offer better accuracy.
- ✓ IDD2 is obtained removing strain gauges after visual inspection of IC plots. This is requested by *ESM* technique, section 4.4.2.

- ✓ IID1 is an individual load cases extracted from the IDD1 and so becomes, as not used to evaluate load coefficients, Individual Independent Data. In function of the results generated and their accuracy it can be considered as an option to assess the best set of loads equations. Whether to use the IDD1 the strain gauge investigation, section 6.4.1.2, will help to decide.

6.4.1.2 RC1 Strain Gauge Investigation

Table 6.5 highlights the software packages used and their direct references too.

Table 6.5: Run Case 1, RC1:Strain Gauge Investigation, Software Package (SP).

SP	Data Input	Results Identif., Figure Refer.
IC	IDD1	RIC1, Figure D.7
IC	DDD1	RIC2, Figure D.8
I2D M1	IDD1	RI2D1, Figure D.9
I2D M1	DDD1	RI2D2, Figure D.10

Table 6.5 Comments:

- ✓ There is a consistency with the trend of the strain gauges captured by the two different tools, *IC* and *I2D*. In fact, Figure D.7 and Figure D.9 confirm that the IDD1 input data are extremely reliable. Similar statement in negative in relation to the numerical distributed dependent data, DDD1, Figure D.7 and Figure D.9.
- ✓ The input data of the *ESM*, requires to decide if any strain gauge needs to be removed after analysing the IC plots of the Individual Dependent Experimental Data, IDD1. After inspecting Figure D.7 it has been assessed SG6, bottom right of the figure, that presents the less linear trend, to remove it. As a consequence the new input data of the *ESM* method is entitled IDD2, Table 6.4. It will be used as one of the input data to evaluate the load coefficients.
- ✓ Combined use of IC and I2D M2. In fact, the sequence of the sample distributed data, superposing the experimental individual load cases by applying the Module of I2D package, should be assessed by the Influence Coefficient plots that confirms the result of the I2D M1 3-D plots. In fact, Figure D.8 shows no pattern at all and little linearity.
- ✓ To better comprehend the IC strain gauge selection criteria is worth referring to Figure 4.3 and Figure 4.1 that highlight the trend of a Non-Linear and Ideal IC plots respectively.
- ✓ Figure D.8 and Figure D.10 trend might be due to the approximation taken in the coordinates, x and y, given to the DDD1, Figure D.2.

- ✓ The analysis of the DDD1 data with *I2D* shows that sequence defined in Figure D.2 is not ideal as the 3-D plots are worse than those of IDD1. This is confirmed by the comparison of the text I2D M1 output text files Global Error, Figure D.11. That means the ideal sequence can be obtained by means of iteration of these quantities. Eventually, the random sequence chosen could be improved once these strain gauge tools of investigation, *IC* and *I2D Module M1*, show smooth 2-D and 3-D trend.
- ✓ *I2D Module M1* offers in addition to the visual inspection of the three dimensional plot the *Global Error*, analysed in chapter 5 validation phase, that underlined the consistency of this index.

6.4.1.3 RC1 Loads Equations Computations

Table 6.6 highlights the LETE input and output codes used in the next section to complete the Performance assessment of the different techniques employed.

Table 6.6: Run Case 1, RC1: LETE Techniques: Codes Input, Table 6.4, and Output, Shear (S), Bending Moment (BM) and Torque (T).

Code Labels	Codes Input	Codes Output: S-BM-T
LPE	IDD1	Figure D.12
GA	IDD1	Figure D.13
T-v	IDD1	Figure D.14
MT-v	IDD1	Figure D.15
LPP1	IDD1	Figure D.16
ESM	IDD2	Figure D.17
DLD	DDD1	Figure D.18
LPP2	DDD1	Figure D.19

Table 6.6 Comments:

- ✓ The Technique outputs take in turn load coefficients of *S*, *BM*, and *T* to indicate Shear, Bending Moment and Torque results respectively. The results vary by changing the input data file of the loads before applying the linear regression, LIRE Module M1.
- ✓ The DDD1 is applied just to *DLD* and *LPP* techniques as their computational flow chart says.
- ✓ There are two *Linearised Physical Properties*, LPP1 and LPP2, as identify to different modes of use of the package determined by the type of input data. *LPP2* uses DDD1 that needs to be properly generated by the supporting tool I2D. That means LPP2 is working in a semi-automated mode. On the other hand, *LPP1* is automated as no side tool is executed alongside. This definition applies to the coming up Run Case 2, section 6.4.2.

- ✓ Due to the insufficient data available, the Relevance Coefficient Technique, section 4.4.5, will not be tested in RC1 and RC2. Though, this will not affect the assessment of the presented codes, as this methodology uses the same search engine, *ExS*, of *LPE* and the same ranking, fitness function. The only difference relies on the sequence of the input data defined so that to have *RC* coefficient closer to one.
- ✓ The incomplete data of *RC* is affecting the *I2D M2* leaving the combination of the individual data to generate the distributed sample totally blind. In fact, just to generate the sequence *DDD1* it has been decided to use a random combination. Unfortunately, the random approach produced poor IC and 3-D I2D plots, as highlighted in section 6.4.1.2.
- ✓ The loads coefficients presented in the respective figures of Appendix D start already offering information on their accuracy, in fact, the smallest load coefficient ensures that measurement noise will not lead to high errors, too much difference among loads coefficients generates unbalances that the measurement noise might affect, and the total number of strain gauges used. These considerations, already introduced by Skopinski, [102], and later on by the industry professionals, [99], will be pointed out, mainly the one of the number of strain gauges used, in the performance summary tables of next section, 6.4.1.4.
- ✓ *LPP* final best set of Loads Equations have not been considering, due to the little data available, to perform a further screening of the results by using the principles introduced in Figure 3.3.

6.4.1.4 RC1 Technique Performance Results

Table 6.7, 6.8, 6.9, 6.10 and 6.11 summarise the root mean square error, Eq. (B.1), calculated by using LETE techniques best set of load coefficients of Table 6.6, against the Independent Data, ID, CLCC of Table 6.4.

Refer to Chapter 7, section 7.2 for a detailed performance discussion of RC1.

L2 & L3 Results and Discussion

Table 6.7: Run Case 1, RC1: LETE Techniques: **Shear**, Figure D.1 Cruise Condition, RMS Percentage - Mean Load (Lbs), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.4 and Table 6.6.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	100, 8 (IDD1)	160, 1, (DID1)	5	3rd	0.942
GA	100, 8 (IDD1)	160, 1, (DID1)	5	3rd	0.942
Tv	100, 8 (IDD1)	160, 1, (DID1)	3	1st	0.552
MTv	100, 8 (IDD1)	160, 1, (DID1)	4	2nd	0.876
LPP1	100, 8 (IDD1)	160, 1, (DID1)	3	1st	0.552
LPE	100, 8 (IDD2)	160, 1, (DID1)	5	3rd	0.942
DLD	211.11, 9 (DDD1)	160, 1, (DID1)	6	-	89.87
LPP2	211.11, 9 (DDD1)	160, 1, (DID1)	2	-	61.37

Table 6.8: Run Case 1, RC1: LETE Techniques: **Bending Moment**, Figure D.1 Cruise Condition, RMS Percentage - Mean Load (inLbs), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.4 and Table 6.6.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	1184, 8 (IDD1)	1878, 1, (DID1)	6	3rd	8.674
GA	1184, 8 (IDD1)	1878, 1, (DID1)	4	1st	6.817
Tv	1184, 8 (IDD1)	1878, 1, (DID1)	3	1st	6.817
MTv	1184, 8 (IDD1)	1878, 1, (DID1)	5	2nd	7.644
LPP1	1184, 8 (IDD1)	1878, 1, (DID1)	4	1st	6.817
ESM	1184, 8 (IDD2)	1878, 1, (DID1)	5	2nd	7.644
DLD	2514, 9 (DDD1)	1878, 1, (DID1)	6	-	174.97
LPP2	2514, 9 (DDD1)	1878, 1, (DID1)	4	-	60.61

Table 6.9: Run Case 1, RC1: LETE Techniques: **Torque**, Figure D.1 Torsion Condition, RMS Percentage - Mean Load (inLbs), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.4 and Table 6.6.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	288, 8 (IDD1)	566, 1, (DID1)	6	NA	44.54
GA	288, 8 (IDD1)	566, 1, (DID1)	6	NA	230.95
Tv	288, 8 (IDD1)	566, 1, (DID1)	6	NA	106.71
MTv	288, 8 (IDD1)	566, 1, (DID1)	6	NA	106.71
LPP1	288, 8 (IDD1)	566, 1, (DID1)	6	NA	86.76
ESM	288, 8 (IDD2)	566, 1, (DID1)	6	NA	181.35
DLD	344, 9 (DDD1)	566, 1, (DID1)	6	NA	492.28
LPP2	344, 9 (DDD1)	566, 1, (DID1)	2	NA	115.58

Table 6.10: Run Case 1, RC1: LETE Techniques: **Torque**, Figure D.1 Bending Condition, RMS Percentage - Mean Load (inLbs), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.4 and Table 6.6.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	288, 8 (IDD1)	28, 1, (DID1)	6	NA	645.67
GA	288, 8 (IDD1)	28, 1, (DID1)	6	NA	177.209
Tv	288, 8 (IDD1)	28, 1, (DID1)	6	NA	507.76
MTv	288, 8 (IDD1)	28, 1, (DID1)	6	NA	507.76
LPP1	288, 8 (IDD1)	28, 1, (DID1)	6	NA	489.82
ESM	288, 8 (IDD2)	28, 1, (DID1)	6	NA	284.84
DLD	344, 9 (DDD1)	28, 1, (DID1)	6	NA	3794
LPP2	344, 9 (DDD1)	28, 1, (DID1)	2	NA	391.6

Table 6.11: Run Case 1, RC1: LETE Techniques: **Torque**, Figure D.1 Cruise Condition, RMS Percentage - Mean Load (inLbs), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.4 and Table 6.6.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	288, 8 (IDD1)	95, 1, (DID1)	6	NA	7.379
GA	288, 8 (IDD1)	95, 1, (DID1)	6	NA	221.97
Tv	288, 8 (IDD1)	95, 1, (DID1)	6	NA	74.99
MTv	288, 8 (IDD1)	95, 1, (DID1)	6	NA	74.99
LPP1	288, 8 (IDD1)	95, 1, (DID1)	6	NA	66.79
ESM	288, 8 (IDD2)	95, 1, (DID1)	6	NA	168.6
DLD	344, 9 (DDD1)	95, 1, (DID1)	6	NA	443.47
LPP2	344, 9 (DDD1)	95, 1, (DID1)	2	NA	86.88

Table 6.7, 6.8, 6.9, 6.10 and 6.11 Comments:

- ✓ These gather the most significant quantities responsible to the final ranking of the final root mean square error, %RMS. The second and third column shows the input and Check Load Case Conditions in terms of Mean Loads magnitude, varying according to the type of Shear, Bending Moment and Torque equations. Then, the number of load cases employed. The DID1 is always just a single load case. This approach will be also employed for RC2 section.
- ✓ The ranking column, in order to not confuse the interpretation of the results, highlighted just the three first ranking positions.

6.4.2 Run-Case 2, RC2

This Run Case, RC2, is described by the *Data Definition* Table 6.12. The data come from the Test Case 4, TC4, CIRA Unmanned Space Vehicle DTFT, [87].

6.4.2.1 RC2 Data Definition

Table 6.12 explains the two major data types used and their direct references too.

Table 6.12: Run Case 1, RC1: Data Definition, Data Type (DT), Load Type (LT).

DT	LT, Figure Refer.	Source, Refer.	Identif.
DD	Ind. Dep. Data, Figure D.20	Exp., [87]	IDD1
DD	Dist. Dep. Data, Figure D.21	Exp., [87] and I2D M2	DDD1
DD	Ind. Dep. Data, Figure D.21	Exp., [87] and IC	IDD2
CLCC	Ind. Indep. Data, Figure D.22	Exp., [87]	IID1

Table 6.12 Comments:

- ✓ Castore GLC1 ground experimental data will be used as Input, Dependent Data, to evaluate the best set of load coefficients with LETE Techniques. The label given is IDD1.
- ✓ Polluce GLC2 ground experimental data will be used as Check Load Case Condition, Independent Data, to assess the ability to predict loads generated from a different test article. The label given is IID1.
- ✓ IDD, Individual Dependent Data, Validation Set, of this TC 4 is experimental and the source is Castore USV Ground Load Calibration, GLC1. If the strain gauge investigation section 6.4.2.2 will offer enough confidence on the quality of data, mainly on the DDD1, it might be decided to use one of these as CLCC.
- ✓ DDD1 data are generated numerically by *I2D Module M2*. In particular, DDD1 is an hybrid superposed data, as is the result of Numeric and Experimental load cases, Figure D.21. DDD1 source is GLC1, Castore USV1.
- ✓ DDD1 has been created in order to have: Higher Magnitude Load, same load cases, and same chord wise stations, Figure D.21.
- ✓ DDD1 numerical sample has been generated by using a random combination of the individual dependent data. The same approach was used with RC1, section 6.4.1.1.
- ✓ IDD2 is obtained removing strain gauges after visual inspection of IC plots. This is requested by *ESM* technique, section 4.4.2. The selected strain gauges to be removed are a result of the *Strain Gauge Investigation* section 6.4.2.2 coming up.

6.4.2.2 RC2 Strain Gauge Investigation

Table 6.13 highlights the software packages used and their direct references too.

Table 6.13: Run Case 2, RC2:Strain Gauge Investigation, Software Package (SP).

SP	Data Input	Results Identif., Figure Refer.
IC	IDD1	RIC3, Figure D.23
IC	DDD1	RIC4, Figure D.24
IC	IID1	RIC5, Figure D.25
I2D M1	IDD1	RI2D3, Figure D.26
I2D M1	DDD1	RI2D4, Figure D.27
I2D M1	IID1	RI2D5, Figure D.28

Table 6.13 Comments:

- ✓ The decision of evaluating the influence coefficients of Polluce GLC2, IID1, is to use this tool, *IC* in conjunction with *I2D M1*, to assess preliminary the consistency of the data which come from different test articles and calibrations. In fact, developing loads equations from one test article and applying them to another prototype, similar in terms of design and instrumentation, is one of the novelties of the research that could bring a lot of benefit on the Authority and Industry side.
- ✓ The Influence Coefficient and 3-D I2D M1 plots have been generated with substantial assumption that might be considered once comparing the Castore and Polluce trends. In fact, as no clear information is available on the X coordinate position, chord wise, it has been decided to give consistent locations between the two calibrations along the major loads path. Therefore, the input values of these two software packages come from dividing the Torque over the associated Force, Figure D.20 and Figure D.22.
- ✓ The analysis the IC IDD1 plots , Figure D.23 it comes clear that for the good linearity and trends the ESM technique will be run with the same IDD1.
- ✓ The IDD2 does not need to be different from IDD1 as the IC and I2D investigations, section 6.4.2.2, show the good quality of the plots does not require any strain gauge to be removed.
- ✓ The DDD1 plots, Figure D.24 confirm to improve heavily the trend compared with the RC1, though there is always a point, the most span-wise, that does not follow the very linear trend. By saying this, the loads equations developed with DDD1 should be improved compared to what happened in RC1.
- ✓ There is a consistency between the spotted trend of the strain gauges by the two different tools, *IC* and *I2D* , by comparing Figure the following couple of plots: Figure D.23 and Figure D.26, Figure D.24 and Figure D.27, and Figure D.25 and Figure D.28.
- ✓ To better comprehend Castore and Polluce data comparison it is worth saying that Figure D.23 and Figure D.26 do not show comparable trends. In fact, only Polluce consistently shows a mid-span load case generating a strain

gauge reading, always S1 (front spar), out of the linear pattern. The idea to use the IC and 3-D plots to justify the combined use of prototypes data for loads equations purposes should have been planned in advance offering similar ground load case conditions, in terms of position and magnitude of the loads. Though, the current information could be extended by the use of numerical IC and 3-D plots by introducing a Finite Element Model.

- ✓ In support to what just stated Castore GLC1 has three chord-wise stations as Figure D.23 shows clearly. Though, if at least one of chord-wise stations of GLC1 and GLC2 were similar it could have been used the slope of only one line of the Influence Coefficient Plots.
- ✓ The last word on the feasibility to apply Castore's Loads Equations to Polluce data will be coming from the next Technique Performance Results, section 6.4.1.4.

6.4.2.3 RC2 Loads Equations Computations

Table 6.14 highlights the LETE input and output codes used in the next section to complete the Performance assessment of the different techniques employed.

Table 6.14: Run Case 2, RC2: LETE Techniques: Codes Input, Table 6.12, and Output, Shear (S), Bending Moment (BM) and Torque (T).

Code Labels	Codes Input	Codes Output: S-BM-T
LPE	IDD1	Figure D.29
GA	IDD1	Figure D.30
T-v	IDD1	Figure D.31
MT-v	IDD1	Figure D.32
LPP1	IDD1	Figure D.33
ESM	IDD2 (IDD1)	Figure D.29
DLD	DDD1	Figure D.34
LPP2	DDD1	Figure D.35

Table 6.14 Comments:

- ✓ As already mentioned the ESM technique uses as Input Data IDD1 due to the high linearity of the Influence Coefficient strain gauge plots.
- ✓ The order of magnitude of the load coefficients is greater than those of RC1 as the input strain gauge readings of CIRA, micro-strain measure of unit, are extremely small. The NASA test case was using microvolt and pounds.
- ✓ The number of loads coefficients of the first three ranking performance techniques of RC1, T-v, MT-v and LPP, keeps showing to be very low, with the expectation to maintain good quality results if consistent.

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- ✓ The average number of strain gauges used by LPP is almost three out of six.
- ✓ LPP final best set of Loads Equations have been considering, though the little data available, to perform a further screening of the results by using the principles introduced in Figure 3.3. Table 6.18 will further provide more details.

6.4.2.4 RC2 Technique Performance Results

Table 6.15, 6.16, and 6.17 summarise the root mean square error, Eq. (B.1), calculated by using LETE techniques best set of load coefficients of Table 6.14, against the Independent Data, ID, CLCC of Table 6.12.

Refer to Chapter 7, section 7.2 for a detailed performance discussion of RC2.

Table 6.15: Run Case 2, RC2: LETE Techniques: **Shear**, Figure D.22 First Condition, %RMS Percentage - Mean Load (N), ML, Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.12 and Table 6.14.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	2882, 9 (IDD1)	2587, 1, (IID1)	4	-	16.877
GA	2882, 9 (IDD1)	2587, 1, (IID1)	4	-	16.877
Tv	2882, 9 (IDD1)	2587, 1, (IID1)	2	1st	0.005
MTv	2882, 9 (IDD1)	2587, 1, (IID1)	2	1st	0.005
LPP1	2882, 9 (IDD1)	2587, 1, (IID1)	3	3rd	1.157
LPE (ESM)	2882, 9 (IDD1)	2587, 1, (DID1)	4	-	16.877
DLD	4759.8, 9 (DDD1)	2587, 1, (IID1)	5	-	116.59
LPP2	4759.8, 9 (DDD1)	2587, 1, (IID1)	3	2nd	0.578

Table 6.16: Run Case 2, RC2: LETE Techniques: **Bending Moment**, Figure D.22 First Condition, %RMS Percentage - Mean Load (mN), ML, Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.12 and Table 6.14.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	2169.3, 9 (IDD1)	1220.91, 1, (IID1)	6	-	1.647
GA	2169.3, 9 (IDD1)	1220.91, 1, (IID1)	5	3rd	0.321
Tv	2169.3, 9 (IDD1)	1220.91, 1, (IID1)	4	2nd	0.264
MTv	2169.3, 9 (IDD1)	1220.91, 1, (IID1)	4	2nd	0.264
LPP1	2169.3, 9 (IDD1)	1220.91, 1, (IID1)	3	1st	0.173
LPE (ESM)	2169.3, 9 (IDD1)	1220.91, 1, (DID1)	6	-	1.647
DLD	3230.57, 9 (DDD1)	1220.91, 1, (IID1)	5	-	445.97
LPP2	3230.57, 9 (DDD1)	1220.91, 1, (IID1)	4	-	118.34

Table 6.17: Run Case 2, RC2: LETE Techniques: **Torque**, Figure D.22 First Condition, %RMS Percentage - Mean Load (mN), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.12 and Table 6.14.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	4013.3, 9 (IDD1)	3960.37, 1, (IID1)	2	-	34.58
GA	4013.3, 9 (IDD1)	3960.37, 1, (IID1)	4	-	20.70
Tv	4013.3, 9 (IDD1)	3960.37, 1, (IID1)	3	1st	2.321
MTv	4013.3, 9 (IDD1)	3960.37, 1, (IID1)	4	2nd	13.9
LPP1	4013.3, 9 (IDD1)	3960.37, 1, (IID1)	2	3rd	15.27
LPE (ESM)	4013.3, 9 (IDD1)	3960.37, 1, (IID1)	3	-	34.58
DLD	5844.6, 9 (DDD1)	3960.37, 1, (IID1)	5	-	184.14
LPP2	5844.6, 9 (DDD1)	3960.37, 1, (IID1)	3	-	22.97

Table 6.15, Table 6.16 and Table 6.17 gather all RC2 results of CIRA USV test case TC4. The same basic comments of RC1 performance results, section 6.4.1.4, apply here.

In consideration to the higher quality of the RC2 strain gauge investigation, section 6.4.2.2, it is possible to explore another direction of the research related to the use of the *I2D* to generate a numerical distributed sample of loads to be employed as CLCC and assess the best set of loads equations. Then, to verify the reliability these results are compared to an independent, validation, numerical data set, obtained from those individual experimental load cases, becoming the Check Load Case Contion, *CLCC*, DID1 of Table 6.18.

Table 6.18: Run Case 2, RC2: LETE Techniques: **Shear**, Figure D.36, %RMS Percentage - Mean Load (N), ML , Load Cases Number, LC N. of Dependent and Independent Data, DD and ID - see Table 6.12 and Table 6.14.

Code	ML, LC N. (DD)	ML, LC N. (ID)	SG N.	Rank.	%RMS
LPE	2882, 9 (IDD1)	6300, 1, (DID1)	4	3rd	4.56
GA	2882, 9 (IDD1)	6300, 1, (DID1)	4	3rd	4.56
Tv	2882, 9 (IDD1)	6300, 1, (DID1)	2	1st	2.56
MTv	2882, 9 (IDD1)	6300, 1, (DID1)	2	1st	2.56
LPP1	2882, 9 (IDD1)	6300, 1, (DID1)	3	2nd	1.76
LPE (ESM)	2882, 9 (IDD1)	6300, 1, (DID1)	-	3rd	4.56
DLD	4759.8, 9 (DDD1)	6300, 1, (DID1)	5	-	10.8
LPP2	4759.8, 9 (DDD1)	6300, 1, (DID1)	3	-	14.3

6.5 L2 & L3 Performance: LPP Procedure

The *LPP* technique proposed in the last chapters, 4.5.4, and now tested with real data confirmed to have potentialities. At the same time the coupling with the supporting tools, mainly I2D, requires to pay attention on some new parameters came across in the last sections.

Now, it is possible to summarise the major points of the *LPP1*, semi-automated procedure, still supported by the detailed concepts and Python codes of Chapter 4 and Chapter 3:

1. use IDD1 to combine use of IC and I2D Module M1 to spot strain gauges anomalies or ground calibration data issues in the PLOts.
2. I2D Module 2 generating DDD1. Respect the GLR1 and GLR2 conditions.
3. use DDD1 Run IC and I2D Module M1. Assess the Plots trend if is linear and meeting expected loads equations ideal pattern.
4. Iterate the last points as long as the Plots have reasonable trend and the GLR1 and GLR2 conditions are met.
5. Finalise the DDD1 set of data and pull out a number of independent numerical load cases to recreate the Table 6.18 Check Load Case Condition.
6. Reproduce results by means of similar template of Tables 6.13, 6.14, 6.15 and 6.18 by running the LPP code using the new DDD1 and CLCC cases.

6.6 Summary

This section focussed on three main areas, Test Cases, Run Cases and Results, whose definition and understanding allow to complete the Performance Phase initiated in the previous chapter with the Validation Phase.

The appraisal of the novelties, developed and detailed in the previous chapters, has been possible by employing the data offered by those specific Test Cases that allowed to investigate test articles with two opposite aspect ratio characteristics. In fact, the defined Runs have been dealing with several different typologies of lifting surfaces, as the "Three-Axis of Complexity" already suggested. Table 6.2 and Table 6.3 show the two different low and high aspect ratio swept Wings and their design ground load calibration information. These opposite characteristics of conditions determined different loads measurement instrumentations, in terms of strain gauge placement and typology, and indirectly load case points. Though, the impression is that more variety of data should be used to better assess the areas of investigation. The results analysis of different Run Cases have been described through a step by step process, Figure 6.12, that allowed to understand from which directions and how the different type of data were combined before reaching the evaluation of the %RMS error of the different techniques employed.

The analysis has been focusing on the role of different quantities, such as number of strain gauges and load cases in the best loads equations, loads magnitude, role

of individual and distributed loads, numerical or experimental.

The *LETE* environment proved its flexibility and ability to adapt to the end-user needs and typology of test article, low or high aspect ratio, individual or distributed load cases. At the same time, the option to use any supporting tools, such as *LIRE*, *IC* and *I2D*, to operate independently from the major codes, is a significant aid to be employed at any stage of the flight loads measurement campaign. This has been further shown by the proposal of a refined semi-automated procedure of LPP, section 6.5.

On the other hand, *LPP* requires to make two distinctions to properly qualify its current ability. The importance of the combined use of the *I2D* is significant and the impact whether applying Module 1 or Module 2 also. Module 1, allowing to predict strain gauge responses due to random load points could not be used as the Global Error of the second order approximation surface was always too high. This is logically linked to a number of controls that should have been done earlier during the ground load calibration, as already anticipated in section 5.5.4.1. The way *I2D* has been conceived allows to generate anyway distributed sample by means of Module 2. Then, its deployment proved to open a new dimension of the design space. In fact, generating numerical combined strain gauge readings offered to a completely new set of load coefficients within all possible combinations available with the normal input data. As relevant example there is the LPP2 extremely low %RMS of Table 6.15 that none of the other exhaustive search could find better.

The LPP idealised fitness functions proved to work properly mainly for Shear and Bending Moment. On the other hand, Torque ones, though tested only by RC2, require further investigation.

The comparison of the results of the two run cases led to identify a common flow chart of accuracy that pointed out the major parameters affecting the quality of the loads equations, and the Ground Load Ratio coefficients, GLR1 and GLR2, are useful indexes.

Last, the loads equations developed on Castore USV1 proved to be extremely applicable to the Polluce USV2 prototypes opening interesting considerations for the Civil Authority and the Industry.

Table 6.2: L2 & L3 Performance Phase: Test Cases (TC) Description - Test Article and Data.

Test Case ID	Component	Aspect, Taper Ratio	Depend. Data, DD	Independ. Data, ID
TC3, [28]	Wing, 3-spar	10.3	IDD Set A. Calib.	DID Check Load Cases, GLC
TC3, [28]	swept 25°	0.4	-	Simulated Flight Conditions
TC4, [87]	Wing, 3-spar	1.94	IDD GLC1	-
TC4, [87]	swept	swept 45°	0.23	IDD GLC2
-				

Table 6.3: L2 & L3 Performance Phase: Test Cases (TC) Description - Strain Gauges (SG) and Load Cases (LC).

Test Case ID	Measur. Stations	SG Number, Type	LC Number, DD	LC Number, ID
TC3, [28]	1 Right wing side	6, 2 Shear - 2 Moment	8	
TC3, [28]	Outboard Stat.	2 Torque	-	3 CLCC
TC4, [87]	Left Wing	8, 3 Shear - 3 M	9 GLC1	-
TC4, [87]		2 T	6 GLC2	-

Chapter 7

Discussion

7.1 Introduction

The *Novelties*, defined by the three different categories of Figure 1.4, *Tools*, *Data* and *Concepts*, have been tested through specific test cases in Chapter 5 and Chapter 6 and now, after a dedicated Run Cases discussion, will be related to the initial objectives of Chapter 1.5.

At the same time, the *Novelties* determine the other two major next sections, *Findings* and *Future Works*.

The *Future Works* are a logic consequence not only of the *Novelties* but also of the key *Findings* which come from the Results and Discussion of the last two chapters.

7.2 Run Cases Discussion

A discussion of the Chapter 6 two Run Cases emphasizes the major detailed results implications, in relation to the performance stage of Figure 5.1, setting the ground to connect with the issues raised in the Introduction of Chapter 1.5 and further analysed in the coming up section about the *Novelties*, section 7.3.

Each Run Case will be taken in turn and then will be compared to each other looking for commonalities to interpret.

7.2.1 Run-Case 1, RC1

Run-Case 1, *RC1*, is linked with the Input Data of Test Case 3, as Table 6.4 describes. This test case, *TC3*, refers to Eckstrom NASA Technical Memorandum 87677, [28]. By adopting the comments already introduced in section 6.4.1 in relation to the input data, strain gauge investigation, and load equations computation, it is now

possible to make the following considerations on the performance of the novelties proposed in this study by referring to these results Table 6.7, 6.8, 6.9, 6.10 and 6.11.

- ✓ It was chosen the Check Load Case Condition, CLCC, Distributed Independent Data DID1 as proved to be the most reliable among the other two referred in Table 6.4. In fact, DID1 is experimental and distributed while DID2 is numerical, *I2D M2* source, Figure D.8 and Figure D.10 already shown the poor quality, and IID1 is a just a single experimental loading point. The data available for numerical superposition do not have enough quality.
- ✓ The Torque results proved to be consistently inconsistent as generating huge %RMS with all available LETE techniques employed. In fact, to further reinforce this idea it has been decided to evaluate the torque equations to three different set of distributed data, 6.9, 6.10 and 6.11, and the outcomes do not change.
- ✓ This Torque inconsistency proves how the LETE environment reduced the uncertainty of the final measured loads. In fact, having so many different search engines and ranking criteria, based on statistical and physical parameters, giving all the same outcome helps to convince that the issue is within the data. It is believed that the torque data provided, [28], is not reliable to perform any deduction on the tools employed.
- ✓ ID loads is much higher than the average loads used to develop the loads equations with the First Calibration data set. That means the results are an extrapolation of the linear equations.
- ✓ The importance of the loads is also applicable to the DDD1 input data results. In fact, by comparing the magnitude of the load used to develop the DDD1 with the *I2D M2* tool describes similar trend. It is proved again that the higher the force and the worse the quality. It appears evident that extrapolations do not contribute to quality. Furthermore, the design and limit loads should be known, as responsible of the threshold of the linear field of the material. The same has to be considered on the instabilities, such as buckling of the panels and crippling of caps, that introduce non linearity too. The whole concept behind the flight loads measurement, the linear regression (LIRE), the IC and ICLE plots, and the 3-D plots of *I2D M1*, are all relying on linearity concepts that the loads magnitude might heavily affect, as the RC2 will be proving too, section 6.4.2.4. All this explains why the interpolation should be preferred to extrapolation within this context.
- ✓ The IC of the DDD, Figure D.2, proved to generate worse trend compared to those of the IDD, Figure D.1. This shows how the sequence of superposed data should pay attention on this that might affect the final loads equations quality.
- ✓ The distributed superposed data as input of the LPP proved to generate a further level of approximation as in order to apply the Eq. (4.10) and

Eq. (4.11), the input file should maintain a clear pattern and sequence of load cases span and chord wise. This is the input of the DDD requested to re-arrange the input data adding another series of approximation, Figure D.4.

- ✓ The T-v technique proves to be consistently the better technique but at the same time the LPP automated method is consistently capable to capture good results without using any statistic information.
- ✓ The T-v and MT-v strain gauge reduction techniques show that the lower the number of strain gauges used in the final loads equations and the higher the final accuracy. In this regard, LPP seems to be capable to capture low strain gauge equations.
- ✓ The exhaustive search with statistic ranking criteria, LPE, ESM and DLD, proved to offer consistently equations with high number of strain gauges, therefore, poor results.
- ✓ The Nelson method results should be taken by paying attention that the equation used in GA software is consistent to Nelson's NASA publication, [79], though the two constants A and B, Eq. (4.8), are not fully detailed. This might affect the real Nelson final outcomes.
- ✓ The DLD and LPP2 results are heavily affected by the poor strain gauge quality, shown by IC and I2D plots, section 6.4.1.2. Anyway, a consideration can be made that the LPP ranking equations show to have the ability to select low strain gauge equations and consequently offering better %RMS compared to DLD, that has always 6 strain gauge loads equations.

7.2.2 Run-Case 2, RC2

Run-Case 2, RC2, is linked with the Input Data of Test Case 4, as Table 6.12 describes. This test case, TC4, refers to CIRA Unmanned Space Vehicle DTFT, [87]. By adopting the comments already introduced in section 6.4.2 in relation to the input data, strain gauge investigation, and load equations computation, it is now possible to make the following considerations on the performance of the novelties proposed in this study by referring to these results Table 6.15, Table 6.16 and Table 6.17.

- ✓ T-v, MT-v and LPP1 show to be the most consistent technique across the three type of loads.
- ✓ The quality of loads equations decrease in quality from shear, bending moment and torque. In fact, as it was already known, [50] and [99], the torque loads are the most difficult loads equations to predict depending on the strain gauge installation, most of the time capture shear and bending loads path, and the load cases definition.

- ✓ The lower the strain gauges used and the higher the final loads equations accuracy. All the first ranking techniques through the three different types of loads have always just 3 strain-gauges.
- ✓ As an average the Exhaustive Search techniques driven by pure statistical ranking criteria, LPE, ESM, DLD, cannot consistently select low strain gauge equations and as a consequence they loose accuracy.
- ✓ All LPP techniques have the lowest number of strain gauges per equation.
- ✓ The combined use of LPP and I2D, LPP2, cannot find consistently good results besides Shear loads equations.
- ✓ The quality of the results of all techniques depend on the magnitude of the CLCC. If it is lower or higher than the input data set, IDD1. In fact, all the time CLCC loads are smaller, Shear and Bending Moment, the accuracy is extremely good. With torsion, CLCC load is almost the same of the IDD1 and the accuracy drops. On the other hand the DDD1 are consistently higher than the respective check load case condition, and %RMS is high. An exception is coming from Shear LPP2. The explanation is coming from the very low equation strain gauge number, 3, and to be using a physical parameters to select the equations. Interpolation is more controlled than extrapolation.
- ✓ The Exhaustive Search driven by pure statistical ranking functions cannot spot reasonable equations with superposed sample data. All three DLD outputs are worse than the similar DDD1 input data LPP2 technique.
- ✓ The ESM Technique is listed to show the conceptual process has been consistent to RC1. Though, since no strain gauges have been eliminated due to IC, the execution of the software is exactly the same of *LPE*.
- ✓ The overall good quality of results produced, besides the technique employed, shows that it is possible to combine loads equations and strain gauge readings between two different similar prototypes. That says the Castore GLC1 and Polluce GLC2 data can be interchangeable used.

Table 6.18 is important not in terms of the magnitude of the root mean square error, marginal as coming from a numerical CLCC, Figure D.36, but by comparing the ranking with the analogue Table 6.15. In fact, it says that the numerical sample created, Distributed Independent Data, DID1, is capable to capture the best set of loads equations as the Experimental, by definition reliable, does. This statement applies without considering the one off ranking of the *LPP2*, Figure 6.15, coming from the Distributed Superposed Data Sample.

The meaning behind this outcome, though limited to one single condition and more investigation needed, is substantial. In fact, the possibility to extend this concept by reducing the level of uncertainty of loads equations that cannot be assessed by proper experimental distributed Check Load Case Conditions is not to underestimate mainly in the industry sector. The costs associated to an extra

experimental distributed load case is significant and the possibility to reduce it by replacing it with hours of simulation is an accepted and preferred option.

It has been decided to perform this comparison on *Shear* loads equations as the most representative of good quality mainly in relation to the LPP fitness function. Furthermore, the approximation of *DDD1*, from where *DID1* of Figure D.36 is coming, with bending moment is higher as in the process of calculation with I2D Module 2 the locations of the force are approximated with an average value and higher mean loads.

7.2.3 Run-Cases Results Comparison

The comments dedicated on the results of RC1, section 6.4.1.4, and RC2, section 6.4.2.4, can be grouped and harmonised by the flow chart of Figure 7.1.

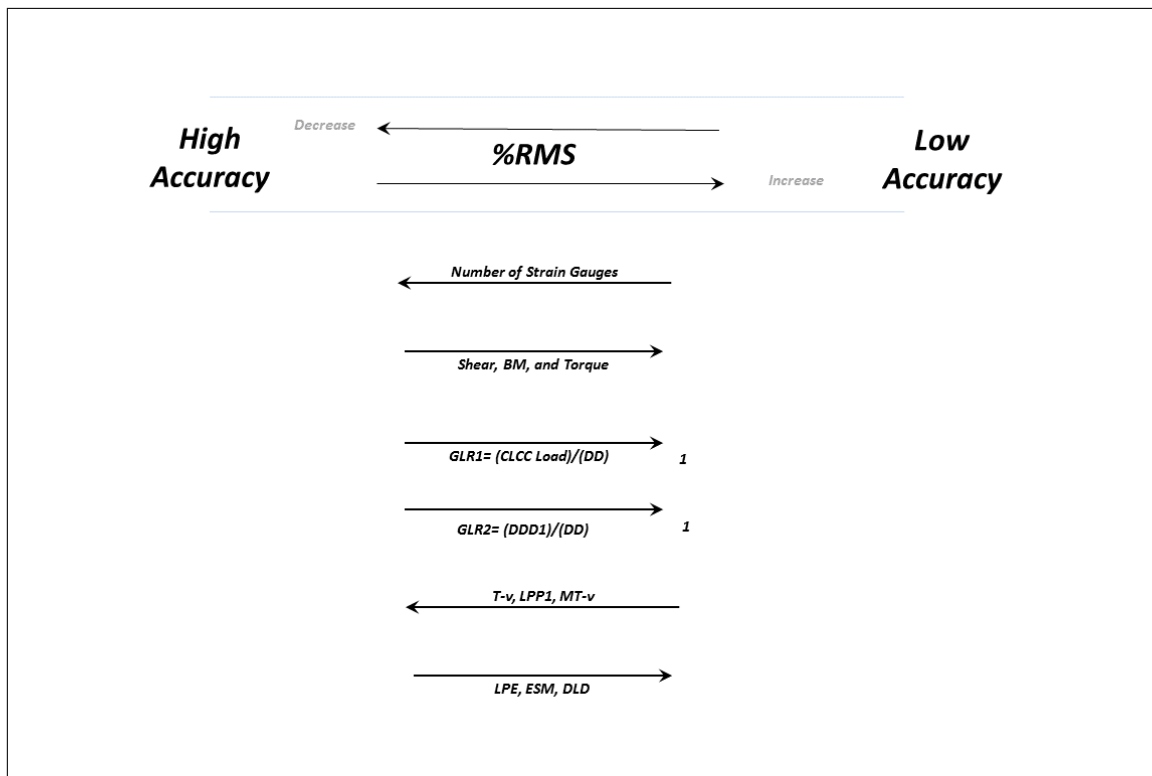


Figure 7.1: RC1 and RC2 Results Summary: Loads Equations Accuracy flow chart.

Figure 7.1 identifies the major consistent parameters, between the two test cases, affecting the %RMS quality of the LETE techniques employed with these two limited run cases, RC1 and RC2. The accuracy of the loads equations grows with the decreasing of the root mean square error and of the number of strain gauges. At the same time the low accuracy of the loads equations grows moving from Shear, Bending Moment and Torque, that usually presents the worst set of %RMS, and then with two parameters defined as ratio of two quantities. Both the ratios proved that getting closer to one and the quality of the loads equations is affected.

These two Ground Load Ratios, GLR, are driven by the loads magnitude of the Check Load Case Condition, CLCC, and of the Numerical Distributed Sample Data, DDD1, always divided by the Dependent Data used to evaluate the loads coefficients. In fact, GLR1 and GLR2 closer to one say the process employed to assess the %RMS is an extrapolation than an interpolation, and consequently worse results. All these points come together saying that the overall best techniques are T-v, LPP1, automated version of LPP not using the I2D supporting tool, and MT-v. On the other hand, the worst trend tends to be all those statistical exhaustive searches such as LPE, ESM and DLD.

A special consideration has to be spent on a more specific topic. The LPP fitness functions equations of Shear and Bending Moment prove to compete, mainly Shear, the best techniques, not always true to the Torsion. That means the equations introduced to represent the IC concept might be further assessed mainly with more data.

These Run Case sections above will be narrowed down to contribute creating the coming up two paragraphs, Novelties and Findings.

7.3 Novelties

This section discusses and relates to the *Novelties*, objectives of Chapter 1.5, by means of the same terminology and bullet point numbering used in section 1.4. First, a review of the full and partial achievements follows.

The uncertainties of the Flight Loads Measurement science conducted by strain gauges have been taken on through the last chapters. The LETE environment proved to fully meet the expectations as using a such thorough framework, with fully independent loads equations techniques and supporting tools, allowed to help to spot the best set of loads coefficient in unbiased way not linked to the ranking criteria employed or the data test article characteristics.

The specific LPP loads equations computation techniques, whose ranking criteria is exclusively in function of physical parameters, proved to have two sides of different level accomplishments. The first, LPP1 automated technique confirmed its own expectation in terms of Shear and Bending Moment equations. In fact, it proved to be consistently among the best three techniques in terms of %RMS. The Torque, not only due to the limited data, shown to require better investigation offering worse results. The latter, the LPP semi-automated technique, LPP2, contributed as requested to expand the design space by means of using the supporting tool I2D. Unfortunately, the data available did not offer the chance to fully explore the potentialities of this tool that so far generated quite poor results in terms of the %RMS. The understanding is clear and relies on the quality and type of input numerical data created, the numerical superposed distributed data, DDD1. At this stage it has not proved yet the practical control of this side, though the concept and the way forward have been discussed. The Ground Load Ratio indexes, GLR1 and GLR2, represent the basic concepts that combined with the use of Influence Coefficient plots will help to numerically characterise the phenomena.

A full achievement, though limited to the CIRA data set, has been taken in relation to the development of loads equation on one test article and apply on a completely different, though similar in terms of design and instrumentation. This, for the Civil Aviation Authority and the Industry, is a starting point that might facilitate the compliance of the theoretical loads by flight loads measurement which come from higher ground calibration load cases without affecting the integrity of the flying prototype.

The other important confirm received by Table 6.18, is that it is possible to assess the best LETE technique in terms of accuracy of loads equations preventing to use an experimental Check Load Case Condition, but employing a numerical distributed set of data. This has been shown with data having GLR1 and GLR2 that can still be improved.

1. **Overview of the Science:** This has been the starting point of the research as it has been introduced the *Three-Axis of Complexity*, 3AC, section 2.6.1, to identify through the years those significant directions affecting the inception, conception, and development of the Flight Loads Measurement Science. Each decade of the past has been analysed and broken down highlighting the three axes of complexity, 3AC, collecting the outcomes in detailed tables of section 2.6 (Literature Review & Data).
2. **Complete Loads Equations Environment:** The LETE environment has been introduced and described its functioning in Chapter 3. It hosts all available techniques from the past in addition to the new *LPP*. The environment offers three different engines of search, Exhaustive Search, section B.1.2, Strain Gauge Reduction, section 4.4.3, and a Genetic Environment, GALE, section B.1.7.7. Furthermore, the different ranking criteria of each *transfer function*, section B.1.7, have been exactly recreated according to the principles of section 4.4. (Tools & Concepts).
3. **The Environment Flexibility:** The Environment offers a number of *supporting tools* such as *LIRE*, *I2D*, *IC*, and *ICLE*, section 4.5.2 and Figure B.1. Furthermore, the Validation Phase, section 5.4, and Performance Phase, section 6.4, Run Cases proved the different ways to call each code according to the needs of the flight loads measurement practitioner (Tools & Concepts).
4. **Ground and Flight Data Framework Adaptability:** The LETE framework top level flow chart, section B.1, has a centre code, *Linear Regression*, *LIRE*, that evaluates the load coefficients by solving the basic equation Eq.(4.1). At the same time this supporting tool has two modules, as Figure B.2 and Figure B.3 describe. Module 2 is structured to receive type history traces and evaluate the associate loads by giving the load coefficients and strain gauge data (Tools).
5. **New Loads Equations Technique:** A new Loads Equation (LE) Computation technique, *LPP*, has been introduced in section 4.5. The Linearised Physical Parameters, *LPP*, ranking criteria is based on different quantities, the most significant are the Influence Coefficient of strain gauges, *IC*, and of loads

equations, *ICLE*. Section 4.5.4 describes the concepts of the fitness functions presented reinforcing the meaning of these two quantities. In fact, *IC* and *ICLE* are tools that allow to identify the strain gauge inherent ability to predict shear, bending moment, or torque loads, by analysing their plots trend, section 4.2. *LPP* can work as automated package, or semi-automated if combined with the supporting tool *I2D*, section ?? and section 6.5 (Tools & Concepts).

6. **Fitness Function Equations Characteristics:** The new LE specific fitness function equations differ according to the type of loads measured as shown by their equations, Eq. (4.10), Eq. (4.11) and Eq. (4.12), (Tools & Concepts).
7. **Fitness Functions Development Methodology:** A dedicated methodology to define the final fitness functions equations of the new *LPP* technique has been presented in section 4.5.3.1. Furthermore, the logic flow to refine the Shear, Figure 4.16, Bending Moment, Figure 4.17, and Torsion, Figure 4.18, have been explained and discussed, section 4.5.3.1 and Figure 4.15 (Concepts & Tools).
8. **Data Role:** The *Double E Data Type* concept has been introduced with the intention to gather and organise in a single chart all those possible combinations of data affecting the loads equations computation. First, the data has been broken down in dependent and independent, and each of these can be either single point loading or distributed load, Figure 3.1. Then, each of these areas have been shown the possible role inside the compilation of each loads equations selection technique, as described in Figure 3.3. These concepts have been further applied to the Performance Phase as determinant quantities of each Run Cases of section 6.4, Table 6.2 and Table 6.4. The supporting tool *I2D* has been developed based on these concepts. (Data & Concepts)
9. **Numerical Data Generator:** A new tool, *I2D*, conceived to produce distributed data from individual experimental data has been presented in section 4.5.2.1. The *Individual to Distributed* Python code, *I2D*, schematic of computation has been explained in Figure 4.13, and two major Modules offer the flexibility according to the quality of the data provided. In fact, the fitting quadratic surface, Figure 4.14, can spot data anomalies of each strain gauge. As Figure C.6 and Figure C.15 of the Validation Phase show (Data & Tools).
10. **Loads Equations Expanded Design Space:** The *I2D* supporting tool generates new numerical input data, loads and strain gauge readings, and consequently different load coefficients from the basic equation Eq. (4.1). The design space of the loads equations is widened. The way to define the numerical sample is depending on the flight loads distributed characteristics to measure. In fact, section 4.5.2 points out two major supporting tools, *Flight Load Specific Range*, *FLSR* and *Relevance Coefficient*, *RC*, that unfortunately have not been possible to apply to the limited available test cases, section 6.3.1 and section 6.3.2 (Data & Concepts & Tools).
11. **Different Ground and Flight Test Articles:** The unmanned space vehicle ground calibration data, USV1, Castore, have been used to develop loads equation applied and on USV2, Polluce, flying prototype, section 6.3.2. The

comparison and discussion of the results, section 7.2.1, demonstrated the need to execute in advance specific checks. The checks that matter and shown to be reliable means of judgement are *IC* and *I2D M1* for strain gauges comparison of the two different test articles, section 6.4.2.2 (**Data & Concepts**).

7.4 Findings

The key findings, obtained by the Validation and Performance phases of chapters, 5 and 6, and related to the limited variety of the test cases applied, Table 6.2 and Table 6.3, are listed below:

1. *I2D Module M1* allows to spot anomalies of the whole strain gauge readings by means of the *Global Error*, section 5.5.4.1. The combined effect of *I2D* and *IC*, Influence Coefficient strain gauge, allows to complement the information provided. In fact, *IC* gives more physical local information of its trend plots. This allows to execute the *ESM* technique alongside *I2D M1* for strain gauge reductions based on the *Global Error*, or visual inspection of the 3-D plots.
2. A detailed list of activities to be performed before relying on the 3-D prediction of the strain gauge response generated by random loading points has been described, section 5.5.4.1. This sequence of actions, section 6.5, was not captured during the conception and definition of the package *I2D*, section 4.5.2.
3. The *I2D Module M2* output used as input data, sample Distributed Dependent Data, to develop the loads equations of *DLD* and *LPP* techniques proved to generate worse results than without. This is further confirmed by the *IC* plots generated, that consistently, are worse than those obtained with individual load experimental data, *IDD*. The explanation is that the superposed data have not been driven by the two major supporting tools, *Flight Load Specific Range*, *FLSR* and *Relevance Coefficient*, *RC*, section 4.5.2, that identified the criteria behind. This due to incomplete Test Cases information on these quantities. Though, another information came out that another criteria should be added, in order to make the whole code more robust. The superposed sample of data should be tuned with predefined Influence Coefficient plots that can affect the accuracy of the final set of load coefficients.
4. *LETE* framework, by having the supporting tools structured separately, proved to allow the end-user to combine as needed the codes. Therefore, creating new techniques, and different abilities to explore the load coefficient design space, see point 1. The role of the Ground Load Ratio, *GLR1* and *GLR2*, introduced in the results discussion should be considered as sensitive values of the current results.
5. NASA Run Cases 1, *RC1*, section 6.4.1, highlighted a limitation of the *LPP*. In fact, both versions, automated and semi-automated version, with and without use *I2D*, relies on the automated analysis of the Influence Coefficient plots.

Then, the ranking criteria of three different fitness functions, Eq. (4.10), Eq. (4.11) and Eq. (4.12), is founded on the linearisation of the IC and ICLE plots. This test case, has a two chord wise stations, Table 6.3 in its input data, and as the IC plots show, Figure 6.1, the line through two points will be always a line. That means the linearisation process does not contribute any real and significant information for the strain gauge selection when at each span wise stations there are two chord wise load points.

6. CIRA Run Cases 2, RC2, section 6.4.2, exploring the use of loads equations developed from USV1 ground load calibration, Castore, Table 6.1, on a different prototype, though exactly same design and instrumentation, USV2, Polluce, highlighted misalignments. A further investigation has been taken proving that a comparison of respective prototype Influence Coefficient and *I2D Module M1* 3-D plots helped to foresee that the strain gauge generated at the time of the different ground calibration is not consistent. Unfortunately, not enough knowledge of the data provided. Though, other considerations and guess can be made on the way the constraints of the ground calibration have been performed. In the Sixty Decade, the British scientist Hovell, [43], already raised the importance of using adequate and consistent ground calibration constraint fixture concepts. Other two justifications, to understand the Castore and Polluce not fully consistent data might come from differences in the prototype configurations of the design and of the instrumentation.
7. The numerical superposed sample data, if properly tuned by the criteria mentioned in point 3., can be used as independent distributed sample data applicable as Check Load Case Condition, CLCC, section 6.2. This results in a possible solution to be adopted when the available ground load experimental data are not thorough, due to cost and time limitations typical of the industry. Hybrid Distributed Independent Data, HIDD, as it comes from the Dependent Data and then has been numerically superposed, not full Independent Data.
8. The basic concept of the CLCC has to be always employed by *LETE* to really understand which code generates best set of results in that specific test case. So, it cannot be used as a performance tools the same input raw data. One solution has already presented in point 7. above, by introducing an Hybrid Distributed Independent Data. Another solution is to take out one individual load case to evaluate the load conditions and then apply it as CLCC, though becoming Individual Independent Data.
9. The trend of the 3-D plots generated from *I2D M1* with IDD1 data of Run Cases 1, section 6.4.1.2, show another way to use the package. In fact, to assess the quality of the sample distributed data combinations, defined with Module 1, could be worth iterating the process and assess the Global Error of the three dimensional plots, Figure D.10. This can be considered another criteria to assess the best combination of individual loading cases.
10. The %RMS of the *LPP* for Torsion Loads, section 6.4.1.4 and section 6.4.1.4, gave overall poorer results compared to other techniques, confirming that the final equation, Eq.(4.12), should be reviewed and eventually simplified too.

11. It is interesting to underline that the *I2D M2* generate a numerical distributed sample of Test Case 1 that has been transformed from the experimental individual load case with two chord-wise stations, Figure 6.5 and Figure D.2, to another one with different chord-wise locations, Figure D.2. This shows that the proper use of the *I2D* code helps to overcome the issue raised in *Finding point 5* above.
12. The possibility to assess the best set of Shear Loads Equations by employing a numeric distributed sample, DID1, instead of using an experimental load case is relevant. This limited outcome, shown in Table 6.18, as more data of different type of ground calibrations should be tested, implies that a proper numerical study to generate superposed distributed load cases, as *I2D* did, with similar distribution to those expected in flight, is a real possibility. Mainly, since the concept of the GLR1 and GLR2 have been introduced.

7.5 Future Works

This section will be covering future works in two main directions. The former directly linked to this thesis and the latter in relation to the outcomes gathered in the literature review of Chapter 2.

1. LETE: Implementing handy tools to assess the IC not just by visual inspections or digging into the output text files of the codes. Using all these tools put together defining a new sequence of activities, as those listed in section 6.5. A solid basis is already there what is missing to develop it is a solid wide set of experimental data of different aspect ratio aircraft, as those investigated by Jenkins in the 90s, [50].
2. GALE: The Genetic Algorithm, third search engine option, once dealing with the *I2D* package mainly in terms of the second Module it might be useful to select the most suitable combination of individual load cases. The genetic algorithm search is already in place it is just a matter to develop an adequate fitness function. This is an opposite task compared to the one set here. In fact, instead of having a given load case sequence and choose the best set of strain gauges satisfying IC plots parameters, in this case search the loads sequence by given IC desired quantities.
3. LPP: Torsion and Bending Moment Equations and better way to monitor the trend.
4. *I2D*: The possibility to use numerical distributed sample load data to select the best set of loads equation should be a starting point to develop new tools and methodologies. The aim should be to introduce random application point load cases, and not as here, where the superposed data were using the same experimental load points. Tools to assess what generated should be coupled with detailed numerical FEM.
5. *I2D*: Reverse approach to combine the independent experimental dependent data by designing a desired IC trend and then moving backwards. (see the note above about GALE).

6. Define an Hybrid Ground Load Calibration by means of Global Finite Element Methods, GFEM. This combined and numerical approach has been already pioneered and partially recognised by the Wind turbine sector and its own Authority, [15] and [47].
7. The most Flight Loads Measurement time and cost consuming phase is coming from the Experimental Ground Load Calibration. The main reason is the typology of loads to introduce that should be closer to those experienced in flight, so distributed and not individual loading. Therefore, a flight load calibration would improve extremely the effectiveness and reducing the cost. The major limit is to identify reliable theoretical tools to associate the PITS with the loads expected. The flight test campaign might take longer as the PITS must be in a very controlled and steady attitude.
8. *LETE* environment with independent feature to evaluate theoretical flight loads. For telemetry flight envelope opening purposes preventing to exceed structural safety thresholds. The Authority is pushing in this direction, [24].
9. Improve *I2D* in terms of Fitting surface order.
10. Usage of *I2D* by defining the most suitable IC plot trend. Backwards process for the selection of best loads equations.
11. *LPP* printing the Influence Coefficient of loads equations plots, ICLE.
12. Culshaw, Krohn, Udd and Claus by replacing the strain-gauge bridge with optical fibre sensors studies that recreate and assess critically the current phase of the flight loads measurement campaign described in Table 2.1, [105].
13. *LETE* and the FLM science are mainly developed and tested on lifting surfaces, other components such as Fuselage and undercarriage should be explored, [106].

7.6 Conclusions

Various issues regarding the science of aircraft calibrated strain-gage flight load measurement have been discussed in this thesis including: single-point loading compared with distributed loading of dependent (training set) and independent (validation set) data, test load magnitude, number of load cases, number of wing strain gauge data, and numerical superimposed against experimental data.

The importance of understanding the linearity of the influence coefficients, of strain-gage and of loads equations, plots has been emphasized, as Jenkins investigated [54], [53] and [50], as well as the importance of using independent flight-like load cases for interpreting equation quality, in line with the intuition of Hovel et Al., [43] and [44]. The former, as fitness function of a new strain gauge selection technique driven exclusively by physical, instead of statistical quantities. The latter, as check distributed load case condition to assess the best set of loads equation.

It was found that in general the new technique was able to determine comparable or superior strain gauge load equations than the existing methods, in relation to the shear and bending moment loads. The torque still requires, though already known

Conclusions

to be the most critical load according to Jenkins, DeAngelis and Schmucker, [50] and [99], to be improved as the two strain gauge reduction techniques, T-value, [101], and Modified T-value, [109], offered better results. It was also determined that the introduction of numerical distributed sample data, obtained from individual experimental data, are capable to assist the selection of representative loads equations.

The comparison of the results of the past and the new strain gauge selection techniques have been possible within a Python coded flexible framework that fed by different source of dependent, training set, and independent, validation set, data allowed to reduce the number of unknowns intrinsic to the specific method employed, as all working together.

The results generated by the CIRA unmanned space vehicle data proved that the load equations developed on Castore , can be applied to Polluce second flying prototype, as long as the design and instrumentation are the same. This is a substantial experimental advantage as reducing the testing effort and the risk to damage the flying test article allows to introduce higher loads in the test article and recreating a calibration load case similar in magnitude to the corner points of the flight envelope. The field of the wind turbine, manufacturers and the Authority, [47] and [15], has been successfully investigating and adopting similar experimental benefits alongside the introduction of numerical ground load calibration data.

Appendix A

Appendix - Chapter 2

Table A.1: Three-Axis of Development, Part 2 - Decade: 1940

ID	X-Axis	Y-Axis	Z-Axis
01	Wing, HTU, W=12K lbs	Tail Load Increment under dynamic conditions.	no (SG FLM) method. Charts method based on equations of motion of rigid body. Flight Test and Wind Tunnel Test Data.
02	Wing, HTU, Six Airplanes Range in Weight 4.7K to 48K lbs	Pull-up Manoeuvres	no (SG FLM) method. Charts method based on equations of motion of rigid body. Flight Test and Wind Tunnel Test Data.
03	Fighter-Type Airplane. HTU	Flight Aerodynamic Loads. Manoeuvring Flights. Pull-up Manoeuvres.	Differential Pressure Distribution. (C&V) as the measured loads analysed along theoretical lines.
04	Fighter Airplane, W=8.75K lbs. HTU stabiliser root stat. AR=4.23.	Buffeting Conditions. Abrupt Pull-up Manoeuvres.	(SG FLM) method introduced. (SG FLM) Phases: (FT) and (DG&A 2)
05	Fighter Airplane, W=8.75K lbs. Wing and HTU stabiliser root stat. Wing AR=5.27, HTU AR=4.23.	Mach Number range 0.2 to 0.8. Below Buffeting boundary.	(SG FLM) method used. (C&V) introduced by mean of lifting line theory. Comparison of the aerod. parameters with Wind Tunnel Test data.
06	Fighter Airplane, W=8.75K lbs. Wing and HTU stabiliser root stat. Wing AR=5.27, HTU AR=4.23.	Buffeting Conditions. Low Speed Stalls.	(SG FLM) method used. (C&V) Pressure Distribut. combined with spanwise accelerometers. against (SG FLM).

Table A.2: Three-Axis of Development, Part 3a - Decade: 1940

ID	Objectives	Comments / Findings
01	Tail Loads investigation. Calculate wing and tail loads increments.	Solution of the longitudinal motion equations involves three simultaneous non linear differential equations. Due to mathematical complexity transient effect omitted.
02	Tail Loads investigation. Calculate wing and tail loads increments.	Use of the Equations of motion of a rigid body. The accuracy of the final results depends on: 1. accuracy of aerodyn. parameters, 2. Not violation of the flight test manoeuvre assumptions.
03	Determine and quantify the parameters affecting the total tail loads such as: speed, normal and angular acceleration, power and sideslip.	Quality of the model/results given by the accuracy of the tail load aerodyn. parameters. Critical Design Loads occurs at high values of pitching angular accel., high positive load factors and medium speed. Pitching angular accel. tail load increment confined to elevator surfaces.

Table A.3: Three-Axis of Development, Part 3b - Decade: 1940

ID	Objectives	Comments / Findings
04	Measure HTU Buffeting : Magnitude Frequencies and Increment of Loads. Investigate correlation of Mach No. (up to 0.8) with Buffeting and impact with Design and Limit Loads.	Buffeting Loads Investigation for Design Purposes. Studies to be done of effect of Altitude and Structural Frequencies on Magnitude of Buffeting.
05	Flight Investigation, below Buffeting boundary, to determine contribution of Wing, Tail and Fuselage to total Loads. Understand existing correlation of flight test data with wind tunnel data and/or theoretical calculations.	Mentioned the SG calibration to measure loads. The (SG FLM) has been used to generate results. First Report linked to Skopinski method. As author will be contributing the Main NACA 1178. It is said that the SG theory appears to be reliable.
06	Pressure distribution measurement on the wing to determine the span loading and compare the centre of pressure results with those of (SG FLM).	Pressure Distribution results and Strain Gauge Based Flight Loads Measurement showed good agreement.

Table A.4: Three-Axis of Development, Part 2a - Decade: 1950

ID	X-Axis	Y-Axis	Z-Axis
01	Airplane Weight, $W=12,000$ lbs Wing, $AR=5.6$ HTU, $AR=4.27$	HT Loads in manoeuvring flight Buffeting effect.	no (SG FLM) method. Theoretical Simplified Approach. Load factor Variation. Flight Test and Wind Tunnel . Test Data. Spanwise distribution by Lifting surface Meth.
02	Two-a/c typical construction Straight and Swept Stabiliser Single Engine Single Engine	HT Loads (Data available for analysis.)	First Ever SG Based method. Introduced SG Based FLM , Phases Table 2.1, (D&D), (GLC) and (DG&A 1).
03	Fighter-Airplane (F-51D). see Decade 1940, Authors ref. [1], [6] Wing $AR=5.71$ and HTU, $AR=4.24$	Buffeting Loads. Stalling Regime. Shock Regime, $Mach=0.8$	SG Based Skopinski method. (FT), (DG&A 2) and (C&V)
04	Four-engine Jet Bomber, B-45A. HTU $AR=6.64$. Tapered and Swept Stabiliser.	Critical HT Loads beyond the range of the tests. and (C&V). Two different Temperature and Flexibility Effects included.	SG FLM Skopinski method. (SG FLM) Phases: (FT) a/c configurations. Single station instrumented.

Table A.5: Three-Axis of Development, Part 2b - Decade: 1950

ID	X-Axis	Y-Axis	Z-Axis
05	B-47A Strategic Bombers. Long Range, 6-engine, turbojet-powered. High subsonic and Altitude a/c. B-47A: Wing AR=9.43, HTU AR=4.06. Swept wing and HTU. MTOW = 215,000 lb	Wing and HTU Loads. Gradual-turn manoeuvre for for altitudes range 15,000 to 35,000 ft. Mach Number range 0.44 to 0.8. Flexible effects as high aspect ratio.	SG Based Skopinski method. (FT), (DG&A 2) and (C&V) Comparison with Wind tunnel data Single station instrumented.
06	See Decade 1950, ID 05.	Horizontal-tail parameters. in longitudinal manoeuvres and for longitudinal stabilities.	See Decade 1950, ID 05.
07	See Decade 1950, ID 05.	Design Tail Loads and Stability Characteristics.	See Decade 1950, ID 05.
08	See Decade 1950, ID 05 Vertical Tail, AR=1.55	Vertical Tail internal loads: Shear, Bending Moment and Torque. Flight tests made at altitudes of 15,000, 25,000 and 35,000 feet. Mach Numbers from 0.49 to 0.82.	See Decade 1950, ID 05.

Table A.6: Three-Axis of Development, Part 3a - Decade: 1950

ID	Objectives	Comments / Findings, Novelities
01	Develop load-factor approach. Present HT loads which is comprehensive and simple. Theoretical and Statistical Data of flight tests of widely varying airplane size used.	If load-factor variation with time is available and corresponding tail load, elevator angles, and load distributions are determined, a simpler and equally rational approach can be proposed.
02	Strain Gauge properly installed and calibrated can determine structural loads on control surfaces landing gear and relatively complex built-up wing and empennage assemblies (torsion box).	SG Based FLM general method introduced. Introduced Influence Coefficient (IC) Concept. Carry-over effect/Check Point Case (DLD). Procedure for Bridge Combinations.
03	Buffeting Investigation of its Magnitude on the Horizontal Tail. Stall Buffeting Loads investigated.	Buffeting Loads primary variables: Speed and Altitude. Loads of an analytical study in which the methods of generalised harmonic analysis are applied to a simplified wing buffeting model are successfully compared to the measured loads. The good agreement suggests the examination of buffeting of other a/c on the same basis.
04	Measure critical tail loads in pitching manoeuvres within the diagram V-n which are compared with the design horizontal-tail loads.	Aerodynamic-Loads data were analysed to include structural temperature effects and fuselage flexibility.

Table A.7: Three-Axis of Development, Part 3b - Decade: 1950

ID	Objectives	Comments / Findings, Novelities
05	Loads investigation on 35 degrees sweepback, high aspect ratio, flexible wing. Collect info on aeroelasticity, dynamic stability and loads and handling qualities.	Test results showed not significant spanwise change of centre of pressure, because of Mach number throughout the test range. Chordwise slight forward movement with increasing Mach number.
06	Analyse Tail Loads Measured in long. manoeuvre in estimating a/c response to specified elevator inputs. Determine zero shift in Tail Loads Measurement.	The effects of horizontal-stabiliser flexibility on tail-lift curve could not be determined. The effects of horizontal-elevator flex. were found to be almost linear with dynamic pressure over the complete Mach numb. range. No effect of wing flexibility on the downwash factor.
06	Analyse Tail Loads Measured in long. manoeuvre in estimating a/c response to specified elevator inputs. Determine zero shift in Tail Loads Measurement.	The effects of horizontal-stabiliser flexibility on tail-lift curve could not be determined. The effects of horizontal-elevator flex. were found to be almost linear with dynamic pressure over the complete Mach numb. range. No effect of wing flexibility on the downwash factor.

Table A.8: Three-Axis of Development, Part 3c - Decade: 1950

ID	Objectives	Comments / Findings, Novelties
07	Flight measurements of: wing-fuselage aerodynamic-centre position, zero-lift pitching-moment coeff., effective airplane moment of inertia.	The rigid wing-fuselage the aerodynamic centre position was constant up to Mach 0.78 then shifted rearward as Mach increased to its maximum flight of 0.81. Large difference between wind-tunnel and flight determined values of zero-lift wing-fuselage pitching moment coeff.
08	Shear, Bending Moment and Torque loads measured on the vertical tail during rudder-step, rudder-pulse, aileron-roll, and steady-slip manoeuvre to assess effect of Mach Number and Altitudes. Compare flight test results with Wind Tunnel Test data.	Lift-curve slope for the rigid-fuselage case agreed with theoretically derived values corrected for compressibility effects from low speed wind tunnel data. Flight values for the flexible a/c and theoretical values corrected for flexibility at the three test altitudes was good.

Table A.9: Three-Axis of Development, Part 2 - Decade: 1960

ID	X-Axis	Y-Axis	Z-Axis
01	X-15 unpowered rocket airplane. Airplane Weight, $W=34,000$ lb skid-type main gear and conventional dual-wheel nose gear	Approach and Landing operation. Strain Gauge on: Nose and Main Landing Gear HTU root station. Fuselage axial compression.	SG Based Skopinski type method. Introduced SG Based FLM Phases, Table 2.1, (D&D), (GLC) and (DG&A 1)
02	Hawker Hunter F.2 single-seat a/c. Fighter Airplane Weight, $W=15,500$ lb Tail Plane $AR=2.60$ Sweepback @ $1/4$ chord line = 41.5 deg	Measuring Tailplane Loads in level flight, pitch-ups and transonic dives and transonic dives	SG Based Skopinski type method. Two measuring systems on: A. modified tailplane mountings. B.fuselage sides Detailed the GLC, D and FT phases.
03	Five Spar Lightning Fin bolted to a rear fuselage to ensure representative mounting.	Fin Loads	First Ever critical review. of Skopinski method. Focus on (D&D), GLC, (DG&A 1) . (First British and non-US research).
04	M2-F2 lifting body vehicle. right vertical tail control surfaces. MTOW = 6000 lbs, $AR=0.655$.	Vertical Tail Loads. Control Surface Hinge Moment. Unpowered glide flights. Subsonic Mach numbers, 0.4 to 0.6	SG FLM Skopinski type. Focus on GLC, FT and (DG&A 2) and (C&V). Wind tunnel Data comparison.
05	Low aspect ration multi spar structures (Fin). See Decade 1960, ID 03.	See Decade 1960, ID 03 Fin Loads.	SG Based Skopinski type. Further modification of Decade 1960, ID 03. (D&D), GLC, (DG&A 1)
06	XB-70 High Performance airplane. Long range supersonic bomber. MTOW = $500,000$ lbs. Folding wing tips.	Canard, Elevation and Wing tip flight load. Mach Number range 0.4 to 3.00 . Canard buffeting.	SG Based Skopinski type method. (DG&A 2) and (C&V)

Table A.10: Three-Axis of Development, Part 3a - Decade: 1960

ID	Objectives	Comments / Findings, Novelties
01	Verify the landing gear system is capable of sustaining high landing speeds, 145 and 238 knots, and provide satisfactory directional stability during the runout phase of the landing.	The highest main-gear shock strut force, drag reaction and horizontal tail load occurred during the nose-gear touchdown.
02	Gain better understanding of the FLM techniques. Measuring absolute values of steady flight static loads and rapid loads applied during manoeuvres. Tailplane subject of the investigation under SG excessive drift due to thermal stress. and non-linearities.	SG measurement methods proved to be better than pressure plotting. Under conditions tested the loads were well below the structural strength limitations of the aircraft.
03	Review NACA report 1178, [102] Overcome the limitation of the low aspect ratio a/c . Multiplicity of the load path managed by distributed Load Calibration instead single Load Data (non-linearities in SG responses). GLC supporting position consistent with flight conditions.	Skopinski method application to future aircraft may not be entirely straightforward. The proposed distributed GLC reduces SG non-linearities. The US statistical method, single load cases, requires large number of calibrations and it is suggested by superposition of individual load data. (Data available for analysis.)

Table A.1.1: Three-Axis of Development, Part 3b - Decade: 1960

ID	Objectives	Comments / Findings, Novelties
04	Low speed flight characteristics investigation. Measure and compare the magnitude of the aerodynamic loads for design M2-F2 unique configuration.	Discrepancies of the Hinge Moments coefficients of upper/lower-flap. Insufficient data to justify it. Rudder hinge-moment coefficients compared well. Suggested to designers conservatism approach.
05	Overcome the difficulties of flight loads measurements on low aspect ratio structures. Proposed Mixed GLC Load Sample. Reviewed the (D&D).	Accuracy increase with mixed load sample. Increase mesh size of the load pad. Gauge sensitivity of the structural response verified by comparison of the pre-flight GLC with post-flight GLC. (Data available for analysis.)
06	Verify existing design/predictive techniques with flight results on a comparable configuration.	General good correlation with predicted wind tunnel and design practice except in the transonic region.

Table A.12: Three-Axis of Development, Part 2a - Decade: 1970

ID	X-Axis	Y-Axis	Z-Axis
01	X-15 unpowered rocket a/c. See Decade 1960, ID 06. Horizontal Stabiliser.	Laboratory heating tests simulating the flight heating on horizontal stabilizer. Flight to a Mach number of 4.63.	SG Based Skopinski type method. Reviewed the (D&D), (GLC) and (DG&A 1) of a new a/c operational condition.
02	Air Force Aircraft Structural Integrity Program: Airplanes Requirements. Bomber, Cargo, Fighter and Trainer Aircraft. @	Measuring Loads within and to the extremes of its structural design envelope.	SG or Pressure Survey Methods. Included as mandatory tool of AF ASIP in Phase III Testing.
03	HL-10 Lifting Body vehicle. Three-Spar Centre Fin root station.	Subsonic, transonic and supersonic aerodyn. loads. for the centre fin and control surfaces. wind-tunnel data.	SG Based Skopinski type method. Phases (FT) and (C&V). Flight test aerod. loads compared with full-scale and small-scale
04	X-15 unpowered rocket airplane. Mach 3 cruise-flight. Multispar wing structure.	Mach 3 Profile flight. Wing loads and temperature effects.	SG Based Skopinski type. GLC reviewed in relation to a high temperature environment. Role of Thermal Calibration and (C&V).

Table A.13: Three-Axis of Development, Part 2b- Decade: 1970

ID	X-Axis	Y-Axis	Z-Axis
05	X-1.5 wing; short, thin, tapered, low aspect ratio, multi-spar Strain gauges placed on wing attachments and root station. Spar caps and web.	Wing Loads. Laboratory Aerodynamic Heating Loads. Thermal and Mechanical Loads.	SG Based Skopinski type method. Thermal Calibration. Superposition of SG data coming from flight loads and thermal effects. See Decade 1960, ID 03 and 05.
06	Slender wing and multi-spar torsion box.	High Mach Number and Thermal Effect.	SG Based Skopinski type method. GLC and DG&A.
07	BQM-34E supersonic drone a/c. Low-Aspect-Ratio (2.5), thin, swept wing of stainless steel skin-aluminium alloy honeycomb core sandwich construction. Instrumented with SG on outer skin. Wing root section.	Wing Loads at various subsonic and supersonic airspeeds.	SG Based Skopinski type method. GLC, Flight Test and Comparison of the measured loads with theoretical based on analytical pressure distributions. To better understand this type structure a vertical fin test case was considered.
08	See Decade 1970, ID 06. Three wingspan stations.	See Decade 1970, ID 06. More detailed studies.	See Decade 1970, ID 06. Two flight test configurations.
09	XB-70 airplane. Large, flexible high supersonic cruise a/c. MTOW= 500,000 lbs Mach 3, 70,000 ft Altitude. Canard and elevon configuration.	Flight measurements of lift, drag and angle of attack. Performance measurements at Mach from 0.72 to 3.07, Altitude from 25,000 ft 70,000 ft.	No SG means. Performance parameters: Mach, Dynamic Pressure, Angle of attack, Nx and Nz. Net propulsive thrust Engine gross thrust.

Table A.14: Three-Axis of Development, Part 2c - Decade: 1970

ID	X-Axis	Y-Axis	Z-Axis
10	YF-12 supersonic aircraft. Multi-spar delta wing. Wing root section strain gauge.	wing loads. A load calibration by applying discrete loads in a grid pattern over wing surface.	SG Based Skopinski type method. Phases investigated (GLC) and (DG&A 1) .
11	See Decade 1970, ID 09. Delta Wing.	See Decade 1970, ID 09.	See Decade 1970, ID 09,
12	See Decade 1970, ID 09. Delta Wing.	See Decade 1970, ID 09.	See Decade 1970, ID 09. and thermal calibration.
13	See Decade 1970, ID 09. YF-12A airplane.	Temperature-induced effect on transonic and supersonic aircraft.	GLC and Loads Equations reviewed under thermal effect.

Table A.15: Three-Axis of Development, Part 3a - Decade: 1970

ID	Objectives	Comments / Findings, Novelities
01	Establish the effect of the inaccuracies introduced by flight-heating on the SG responses and ensuing load measurements.	The thermal effects were found not negligible as to invalidate load measured inside that operations. simulating the heating useful in correcting data.
02	Measure loading conditions producing critical structural and temperature distribution. Verification of the analytical structural loads and temperatures used to design the a/c. Determination and definition of suspected new critical loading conditions indicated by previously conducted investigations.	Mandatory Requirement of any Air Force, AF. for reliable, maintainable, on-line airplane systems such as the airframe structure. Defined a detailed requirements for the Flight and Ground Loads Survey, contained in Specification MIL-A-8871M (USAF).
03	Study effects of vehicle attitude, control surface deflection, Mach Number, on outboard and inboard tip fin flaps, rudder, elevon hinge-moment coefficients.	In general wind tunnel values adequately predicted the aerodynamic measured loads. Fin normal-force coefficients and centre of pressure locations primarily affected by angle of sideslip, rudder and aileron deflection, secondarily by angle of attack and Mach Number.
04	Laboratory experiments investigation. Compare calculated Mach 3 structural temperatures with experimental laboratory simulation. Evaluate the effect of temperature on FLM.	Flight-measured temperatures be used for simulations. The surface be painted to achieve a uniform emissivity for heating of this type. SG response to heating-simulation tests were found to be large and varied to be significant to aerodynamic loads measurements.

Table A.16: Three-Axis of Development, Part 3b - Decade: 1970

ID	Objectives	Comments / Findings, Novelities
05	Study changes in SG load calibrations on a wing heated to temperatures up to 589 Kelvin. Extend the use of SG to high-temperature applications. to high-temperature applications.	The validity of superposition of bridge outputs due to the thermal and mechanical loads during a heating simulation of Mach 3 flight was established. . The data proved to be repeatable.
06	Improve the Skopinski Technique for high speed aircraft configurations.	Introduced T-Method to select best set of strain gauges of loads equation.
07	In-flight measurement of a low aspect ration, thin, swept wing having full depth honeycomb sandwich type structure. GLC single and multipoints effect to improve quality. Linear regression used to evaluate load coefficients.	Importance to use Multipoint GLC procedure to increase quality of the Shear and Torque LE.
08	See Decade 1970, ID 06. Presented a lot of data to use (GLC). Flight test data incomplete. Flight test data incomplete.	See Decade 1970, ID 06. Three wingspan stations measured. The internal forces distribution is the goal.
09	Flight measurements of ft, drag and angle of attack. Provide data for evaluating the techniques used to design and predict the performance of aircraft of this category.	Lift and drag characteristics subject to the effects of structural flexibility, propulsion system/airframe interactions.

Table A.17: Three-Axis of Development, Part 3c - Decade: 1970

ID	Objectives	Comments / Findings, Novelities
10	Correlation of the root section strains of a delta wing. Calculated from a FEM structural model against laboratory measured strains.	Introduced the strain gauge and loads equation influence coefficient plot , IC and ICLE, proving useful in determining whether a affected predominantly by shear, bending moment, or torsion loads. The predicted response of the wing proved to be accurate.
11	See Decade 1970, ID 09. The computational procedure presented as a link between the load calibration and the load to be measured in flight.	A matrix approach to equation selection. Based on equation standard error, load distribution, and Influence Coefficient of strain gauge equations.
12	Measure Loads on the wing of a large, flexible, and supersonic aircraft. Deal with thermal effect. Use a simple FEM to predict strains.	High temperature and large thermal gradients affect the validity of load measurements with calibrated SG. FEM proved to help to define SG locations and developing Loads Equations.
13	Measure Loads with calibrated strain gauges in the supersonic environment.	No load-path changes at elevated structural temperatures. The thermal responses of the loads equations were highly relevant. A thermal-calibration approach is the suggested way forward.

Table A.18: Three-Axis of Development, Part 2a - Decade: 1980

ID	X-Axis	Y-Axis	Z-Axis
01	Low aspect ratio multispar wing Hypersonic aircraft.	Compute loads from three applied load distributions.	SG Based Skopinski type method. Introduced a method for selection of strain gauges. (GLC) and (DG&A 1)
02	see Decade 80s, ID 01.	see Decade 80s, ID 01.	see Decade 80s, ID 01.
03	Hypersonic Aircraft Wing Mach 8 aircraft. Aft fuselage turbofanjets operating on hydrocarbon fuel.	Hypersonic Wing Test Structure. (HWTs) Pushover-pullup loads maneuver. Loads affected by Aerodynamic heating. Wing loads.	SG Based Skopinski type method. The whole FLM reviewed with effect of the Temperature. Test data compared to 3-D FEM.
04	Space transportation reentry vehicle. Three stations on the right wing. Wing root station data presented.		SG Based Skopinski type method. Detailed the GLC and FT phases. GLC: introduce a check load condition be using three points simultaneously. SG selection by means of Modified T- Method, [109].
05	Military Operators Aircraft. Current and next generation Military a/c.	Operational Loads Data.	SG Based Skopinski type method. The flight test phase is inside the flight envelope and not corner point. Data gathering and Analysis is mainly for fatigue purposes.

Table A.19: Three-Axis of Development, Part 2b - Decade: 1980

ID	X-Axis	Y-Axis	Z-Axis
06	Drone for Aerodynamic and Structural Testing (DAST). Aspect Ratio = 10.3, Taper Ratio = 0.4. Right and Left wing, three span wise stations each.	Wing structural loads at M=0.8.	SG Based Skopinski type method. GLC results and procedures used to increase accuracy.
07	General Application.	General Application.	SG Based Skopinski type method. DG& A to develop Loads Equations.
08	Applicable to airplanes with non conventional empenage configurations.	Empennage component loads including rolling moments at intersecting surfaces.	Flight loads measurement by means of Strain Gauges or pressures.
09	wing designed for high speed aircraft structure.	wing loads and its thermal effect at high Mach regime.	SG Based Skopinski type method. GLC room and elevator temperatures.

Table A.20: Three-Axis of Development, Part 3a - Decade: 1980

ID	Objectives	Comments / Findings, Novelities
01	Improve the performance of the Load Equations derived from T-Value method. T-Value and Modified T-Value method efficiency compared.	The MT-Method proved to be consistently more accurate than the T-Method. Improved accuracy most notable for equations containing less bridges. Applicability with structures with less spars still has to be proved. A computer program, EQDE, Equation Derivation, is introduced implemented by the MT-Method.
02	see Decade 80s, ID 01.	see Decade 80s, ID 01.
03	Define the room-temperature aspects of a full-scale wing component test. Structural concept of metallic heat shield exter surface.	Introduced Hot Structures definition. Where the primary load-carrying structural members are required to function at the elevated temperature. Heat shield: existence of active cooling such as liquid-hydrogen fuel, which is circulated structural skin panels to absorb and carry away the surface heat load. The heat shield, beaded panels, proved to be conservative. Experimental stress levels lower than predicted by analysis.

Table A.21: Three-Axis of Development, Part 3b - Decade: 1980

ID	Objectives	Comments / Findings, Novelties
04	Investigate techniques to separate mechanical and thermal effects on strain gauges readings used in loads measurement.	Designed a structural heating laboratory. Heat shield made of a layer of insulating ceramic tiles on aluminium structure. Greatest thermal correction for bending as largest thermal stresses are axial in the spar caps and lower cover panels. The largest percentage discrepancy is with torque as measured centre of pressure is aft of prediction.
05	Verify that the design loads spectra are conservative, and in which case the fatigue or strength analyses are under control.	Military operators interested to ensuring that accurate operational loads data is fed back to the designer.
06	The calibrated SG are part of the Aeroelastic Research Wing (ARW) program to assure safe loading levels, provide data for evaluation of active control system and for the wing flexibility on aerodynamic M=0.8 loads	Aluminium wing needed to be covered with fiberglass/honeycomb sandwich skills to prevent thermal effect. Loads Equations developed by by means of Single and Multipoint ground loads produced better accuracy.

Table A.22: Three-Axis of Development, Part 3c - Decade: 1980

ID	Objectives	Comments / Findings, Novelities
07	The historical Linear Regression, normal equation approach to evaluate loads equation is compared with the Singular Value Decomposition, SVD, technique.	SVD approach is always computationally more costly as well as numerically more stable. SVD generates same results under all conditions of the number of loads m and number of gauges n.
08	Information and guidance for acceptable means, not the only means, of demonstrating compliance with the requirements of Part 23 regarding evaluation of design flight loads for small airplanes with T, V, +, or Y empennage.	US Civil Aviation Authority, FAA, Advisory Circular alternative of flight loads analysis. Flight test acceptable means of compliance of design load data rather than validation requires extensive survey.
09	Environmental aspect of elevated temperature and how it relates to the science of strain gauge calibrations of aircraft structures.	A heating Ground Load Calibration is required to determine thermal shifts. Load Equations derived from room temperature and elevated GLC room temperature must be compared with a distributed load case. Each structure might show different behaviour.

Table A.23: Three-Axis of Development, Part 2a - Decade: 1990

ID	X-Axis	Y-Axis	Z-Axis
01	77 airplanes as part of NASA VGH General Aviation Program.	Gust and Manoeuvre loads affecting Fatigue. No lateral gust investigation.	Flight VGH measurement. Airspeed, Load factor Altitude for Operational purposed related purposed related with Fatigue.
02	Transonic fighter-bomber a/c. Swept supercritical wing. Advanced Fighter Technology Integration, AFTI, F-111. 83,000 lb gross weight.	Manoeuvre loads.	Manoeuvre Load Control, MLC, System. Automatic Control Mode system. SG Based Skopinski type method.
03	Modern Jet a/c transport.	Design Operational Loads.	Loads Monitoring with Fatigue purposes.
04	Wings of F-111 and Shuttle Orbiter.	Ground Load Data.	SG Based Skopinski type method. GLC and (DG&A 1).
05	F-16 and F-18 NATO fleet aircraft in operation and one in development.	Operational Manoeuvre Loads.	Procedure of using Flight Test Data.
06	See Decade 1970, ID 09. YF-12A blackbird aircraft. Platform for aerodynamic and thermal experiments.	Thermal Loads.	SG Based Skopinski type method. GLC and Loads Equations reviewed under thermal effect.

Table A.24: Three-Axis of Development, Part 2b - Decade: 1990

ID	X-Axis	Y-Axis	Z-Axis
07	15 aircraft structures. Wings, Fins and Tails with a wide variety of aspect ratios. Straight, swept and delta configurations.	Ground Calibration Loads.	SG Based Skopinski type method. GLC and (DG&A 1) past programmes review.
08	Current and Next Generation Aircraft. Eurofighter and 707 aircraft.	Operational Loads.	Structural Health Monitoring System.
09	The Canadian CC130 fleet.	Operational Loads.	Operational Loads Monitoring and Individual Aircraft Tracking, IAT. Parameter-based approach and direct measurement.

Table A.25: Three-Axis of Development, Part 3a - Decade: 1990

ID	Objectives	Comments / Findings, Novelities
01	Analyse the Operational Usage of single and twin engine general aviation airplanes. Load spectra used for wing fatigue test or safe life estimation.	Produced a revised fatigue evaluation report for commuter airplane certification of Part 23 of FAA.
02	MLC system to implement a technique to reduce the inboard bending moment in the wing as load factor increases.	Introduced Manoeuvre load alleviation changing the lift distribution along the span by automatically changing either wing twist or the wing camber distribution along the span by deflecting appropriate flaps.
03	The aim is at the structural integrity. Design evolution and maintenance requirements.	Interaction between structural damage tolerance and durability characteristics must be recognised in design.
04	Improving the accuracy of the loads equations by proposing a new strain selection technique (Genetic Algorithm).	The Genetic Algorithm, GA, was able to determine comparable or superior strain gauge load equations than the past techniques. Faster than an exhaustive search. It can be used to assist other methods.
05	Derive loads from operational flight manoeuvres. Standard Manoeuvre, SM, as normalised parameter time histories.	Considering the operational manoeuvre performed in service as a set of Standard Manoeuvre. SM Load relevant parameters generated sufficient accuracy for load calculations.

Table A.26: Three-Axis of Development, Part 3b - Decade: 1990

ID	Objectives	Comments / Findings, Novelties
06	The salient technical results of the Program YF-12A structures and loads efforts are reviewed, so the experiences and results can be preserved.	The Program demonstrated the ability to duplicate the complex flight temperatures of an advanced supersonic airplane in a ground-based laboratory and numerically too.
07	Studying the physical procedures of calibrating strain-gauged structures and all the supporting analyses and computational techniques used. Identify the issues rather than establish rules and laws. Consolidate the FLM science.	The Matrix of variables is concluded to be too large to constrain the options available. The relevance coefficient, RC, parameter relating to the Load Calibration Relevancy and Load Measurement Error, no clear trend shown.
08	Military aircraft operators having the means to understand the loading environment and the ongoing health of their weapon platforms.	Benefits of integration of monitoring systems with maintenance activities could be exploited at an early stage rather than wait for life extension programmes. Including fully integrated monitoring systems should imply a review of the design safety factors.
09	Assess fleet usage severity and detail the analysis process of the data to interpret the trends of the aircraft structural fatigue.	Developed a Data Analysis System to process and analyse both parametric and strain data and assess usage severity using a fracture mechanics basis.

Table A.27: Three-Axis of Development, Part 2a - Decade: 2000

ID	X-Axis	Y-Axis	Z-Axis
01	Agile Military Aircraft. Australian Military Fleets.	Operational Loads. Fatigue Loads.	Fatigue Monitoring Systems and Operational Loads Measurement.
02	Military and Commercial Aircraft. Helicopter and Engines.	Operational Loads.	Fatigue Monitoring Systems and Operational Loads Measurement.
03	Commercial Airline Aircraft.	Operational Loads Environment.	Structural Health Monitoring Systems.
04	Two types of fixed wing aircraft. Tornado and CF-18 military aircraft.	Loads due to different usage compared to the initial design spectrum.	Fatigue Monitoring Programme. Health and Usage Monitoring Systems.
05	General Aviation Aircraft. Cessna 172P, Empennage.	Manoeuvre Empennage Loads.	Flight parameter-based and neural networks.
06	See Decade 2000 ID05.	See Decade 2000 ID05.	See Decade 2000 ID05.

Table A.28: Three-Axis of Development, Part 2b - Decade: 2000

ID	X-Axis	Y-Axis	Z-Axis
07	Wind Turbines.	Mechanical Loads in steady state and transient conditions.	Strain Gauge Measurement techniques.
08	NATO airplanes and future designs. Transport type aircraft.	Design Loads.	Loads Monitoring Systems to prove calculated loads and monitor fatigue loads to establish the remaining structural life.
09	Active Aeroelastic Wing AAW F/A-18 Airplane. High Aspect Ratio, thin, swept wing of fighter aircraft.	Design Loads. Supersonic Flight Envelope.	SG Based Skopinski type method. Review of the GLC phase.
10	See Decade 2000 ID09.	Ground Loadings up to 70% design limit loads.	SG Based Skopinski type method. D&D and GLC Phases.
11	See Decade 2000 ID09.	Ground Loading features parametric study.	SG Based Skopinski type method. GLC and DG&A Phases.
12	Three-Axis of complexity concept. FEM Model Complexity.	Analysis Complexity.	Design Structural Optimisation complexity.

Table A.29: Three-Axis of Development, Part 2c- Decade: 2000

ID	X-Axis	Y-Axis	Z-Axis
13	Commercial airplanes. FAA-25 rules.	Design and Fatigue Loads.	Strain Surveys methods.
14	Individual component of a structure or machine. AAW F/A-18 Airplane.	Aerodynamic Loads.	Deflection Based Skopinski type Method.
15	Military Aircraft.	Operational Loads.	SG Based Skopinski type method. Operational Loads Measurement, OLM Programmes.
16	Offshore Wind Turbines. structural components and supporting structure.	Mechanical Loads and hydrodynamic loading.	Strain Gauge Measurement techniques and analyses..
17	Commercial aircraft.	Structural Loads.	Structural Health Monitoring system, model based approach.

Table A.30: Three-Axis of Development, Part 3a - Decade: 2000

ID	Objectives	Comments / Findings, Novelties
01	State-of-the-art review of fatigue monitoring systems and examines current systems and practises. It also investigates the issues of strain gauge utilisation and calibration. Requirements for future fatigue monitoring systems proposed.	<p>Little uniformity in fatigue management practises of operators and many aspects of the process have been overlooked. Philosophy or aims of the monitoring systems are not clearly specified.</p> <p>Individual Aircraft Tracking necessary with fleet usage variability.</p> <p>At least one aircraft in the fleet should be set for strain survey programme.</p>
02	State of the art of the Structural Health Monitoring applications through the different possible affected areas such as related data systems, special applications, engine condition monitoring, analysis techniques and general safety/benefit perspectives.	<p>Improved technology has enhanced safety and effectiveness of the monitoring process.</p> <p>Benefit to integrate the Health Monitoring systems and introduce diagnostic systems aided by Neural Network architecture.</p>
03	Approval of Health Monitoring Systems for commercial aviation and acceptance by operators of commercial air transports as part of the airline maintenance programme.	<p>HMS compliance would have to be shown primarily by analysis supported by ground, flight or simulator tests.</p>
04	Monitoring of the life consumption to assess practicability and cost effectiveness of planned upgrades and modifications. Optimum utilisation of the structural life of a fleet.	<p>Fully integrated HUMS on individual component level will lead to higher exploitation of structural life for existing structures, an option for on condition maintenance if cost effective and the reduction of some conservatism in the design process of new weapon systems.</p>

Table A.31: Three-Axis of Development, Part 3b - Decade: 2000

ID	Objectives	Comments / Findings, Novelties
05	Develop a methodology for the prediction of strains in the tail section without requiring installation of strain gauges and to determine the minimum set of sensors required for such small aircraft category.	Flight loads by using a back-propagation Neural Networks. Inexpensive and effective technique where installation of strain gauge is impractical. Neural networks and angular accelerometers needed.
06	Develop an improved methodology for the prediction of empennage manoeuvre loads.	Compared to ID05 of Decade 2000 the new methodology is based on manoeuvre recognition using Neural Networks and numerically differentiated rate-gyro signals. Successfully predicted the strains within the the set boundaries with 100% of Horizontal expected Loads.
07	Overcome the shortcomings and uncertainties of loads prediction with aeroelastic models and codes.	Direct determination of loads as Basis for design and certification. Defined specific guidance on load measurements on key structural component and load path of wind turbine.
08	Comparisons of regulations and descriptions of new specifications. Complete procedures how to establish design loads for future airplanes. Provide agreement on requirements and design loads within NATO.	NATO USAF Standard MIL-A-87221 used in the 1970's is obsolete today.
09	Generate databases of wing root and fold strain gauges and deflections suitable for deriving load equations.	GLC loads up to 70 % of design limit loads. Developed loads equations by introduction of wing deflections measured by string potentiometer and onboard flight deflection measurement system.

Table A.32: Three-Axis of Development, Part 3c - Decade: 2000

ID	Objectives	Comments / Findings, Novelties
10	Technical contents of AAW Flight Research Program and ground and flight test results presented. Goal to demonstrate in full scale the AAW technology to be implemented on future aircraft designs.	Introduced synergistic technology that integrates air vehicle aerodynamic, active controls, and structures advanced technology maximising vehicle performance. Wing Flexibility used to improve performance (aerodynamic).
11	Parametric study of various aircraft wing-load test features that affect the quality of the resultant derived load equations.	Results show the benefit of distributed loading and diminishing-return of test load magnitudes and number of load cases. The use of independent check cases as a quality metric is overcoming blind extrapolating beyond the load data used to derive the load equations.
12	Review how increases in computer power were utilised in structural optimisation.	Three-axis of complexity concept and universality of the message.
13	Describe the design and certification process of a Large Aeroplane.	All requirements are satisfied by analysis, and tests are run to validate it. Correlation with previous ariplane accepted. Certification Agencies, for paragraphs FAR/JAR 25.307, 25.301 and 25.305 often require that analytical predictions be corroborated with static test and/or flight test results.

Table A.33: Three-Axis of Development, Part 3d - Decade: 2000

ID	Objectives	Comments / Findings, Novelities
14	Explore the utility of a deflection-based load estimation, using the active aeroelastic wing F/A-18 aircraft Comparisons between the strain-gage and deflection-based methods are presented.	may yield lower testing costs while improving aircraft performance through reduced instrumentation weight. Flight validation revealed a strong bending moment correlation and slightly weaker torque correlation.
15	Provide a basis for guiding those involved in an OLM through the major phases, such as planning, installation, data capture and analysis, and reporting. Valuable comments of practitioners as lessons learned future OLM programmes.	OLM, mandated in MoD policy, is technically complex, costly and often takes many years to complete.
16	Overcome the shortcomings and uncertainties of loads prediction with aeroelastic models and codes for mechanic and hydrodynamic loads.	Direct determination of loads as Basis for design and certification. Defined specific guidance on load measurements on key structural component and load path of wind turbine and supporting structural. Sub-systems considered to, such as control and protection mechanisms, internal electrical and mechanical systems.
17	Enhancing the efficiency of aircraft operation, monitoring of the system state of aircraft in-service to feed the maintenance scheduling. Performance of the proposed approach validated by simulation and flight test results.	Diagnosis of the airframe loading based on a model-based approach supported by observer concept obtained reliable info on external gust disturbances and internal airframe loading of commercial aircraft during operation.

Appendix B

Appendix - Chapter 3

B.1 The Code

A LETE Python computer programme is designed to measure the loads, produced on various aircraft structures using strain gauges, and to assess the best technique to employ in relation to the specific component under investigation and the data, load cases and strain gauge readings, provided. The program to derive the loads equation coefficients, using regression techniques, has been adapted to implement the major techniques presented in sections 4.3, 4.4 and 4.5.

The philosophy behind the code is the same presented in Figure 3.4 with three stages working in series. The core of the whole process takes place in *Stage One* where all the major loads equations calculation techniques happen. Figure B.1 helps to better comprehend the flow of the initial data and the major python functions links broken down as supporting tools, circle boxes and techniques, square boxes. The ranking criteria code lines are either embedded in the square boxes or supported by dedicated functions, circle boxes, according to the sequence and dependency displayed in the *Python Code Flow Chart* of Appendix B.2. The supporting tools, the same introduced in Figure 4.3 as the *Original Method*, Figure 4.5 as the *DLD Technique*, Figure 4.6 as the *ESM Technique*, Figure 4.8 as the *T-v and MT-v Techniques*, Figure 4.9 as *GA Nelson*, and Figure 4.21 as *LPP* the new Proposed Method, respectively, are presented in two separate sides. The left one, shows the SD, Standard Deviation, that is a statistic entity employed by all Techniques as the main or part of their ranking criteria. On the opposite side, all those physical quantities, contributing partially in the *ESM* approach, and fully with the *LPP* new proposed method. At the same time, *IC* and *ICLE* have been structured in a way to be called up in the whole software package any time requested by the end-user. That means the process is not any more automated, as the employment of the influence and load equations coefficient plots requires a visual inspection, either before or after the linear regression box, *LIRE*. This particularity is highlighted by the dotted line. Things go differently with the *ICLE_P* that represents the loads equations influence coefficient plots linearised parameters that are evaluated by a dedicated and automated routine linking with the ranking criteria of the *LPP* and making the technique fully automated, though still monitored and controlled as further explained in section B.1.7.9.

A special mention has to be dedicated to the supporting tool *I2D*, that allows to generate Numerical Distributed Load Samples from the Individual Experimental Load Cases. The potentiality of this, already emphasized and tested by the British Hovell, Webber, and Robers, [43] and [44], and further applied by the American Eckstrom and Peele, [90] and [26], is taken here to a wider environment, LETE, directly connected to other techniques, such as the relevance coefficient, 4.4.5. Moreover, it is linked to other concepts such as the flight PITS centre of pressure CoP, and the specific response gauge with load positions plots, as test cases results, already introduced in the previous chapter, will be further explaining.

In relation to *Stage Two and Three*, Figure B.2 and Figure B.3, illustrate the programming concepts. The linear regression becomes the transfer functions itself assuming the role of a proper Python code with two distinct modules. As previously anticipated in Figure 3.2, *Stage Two*, is employing Eq. (4.1) not to evaluate loads

coefficients but Measured Loads, L_{Meas} , while *Stage Three* applies Eq. (B.1), to calculate the percent root-mean-square (rms) error. In fact, %rms is the Standard Deviation, depending on the applied load, Evaluated (or Imposed Load), L_{Eval} , and the Measured load, L_{Meas} , divided by the sum of the square of the applied load. These two figures flow charts highlight circled dotted line with the quantities of the data streaming from input to output through the respective transfer functions. Stage Two and Three represent the comparison of the best set of load equations calculated with the respective *Techniques* of *Stage One* against the independent set of data, ID, coming from IE2. The loads comparison will say which one is the *Technique* most accurate as with the lowest %rms. Now, it is easy to understand why it has been created a Python GUI, Graphical User Interface, labelled LOCO, LOads COMparison, gathering the codes of these last two stages. More details will be presented in Section B.1.8.

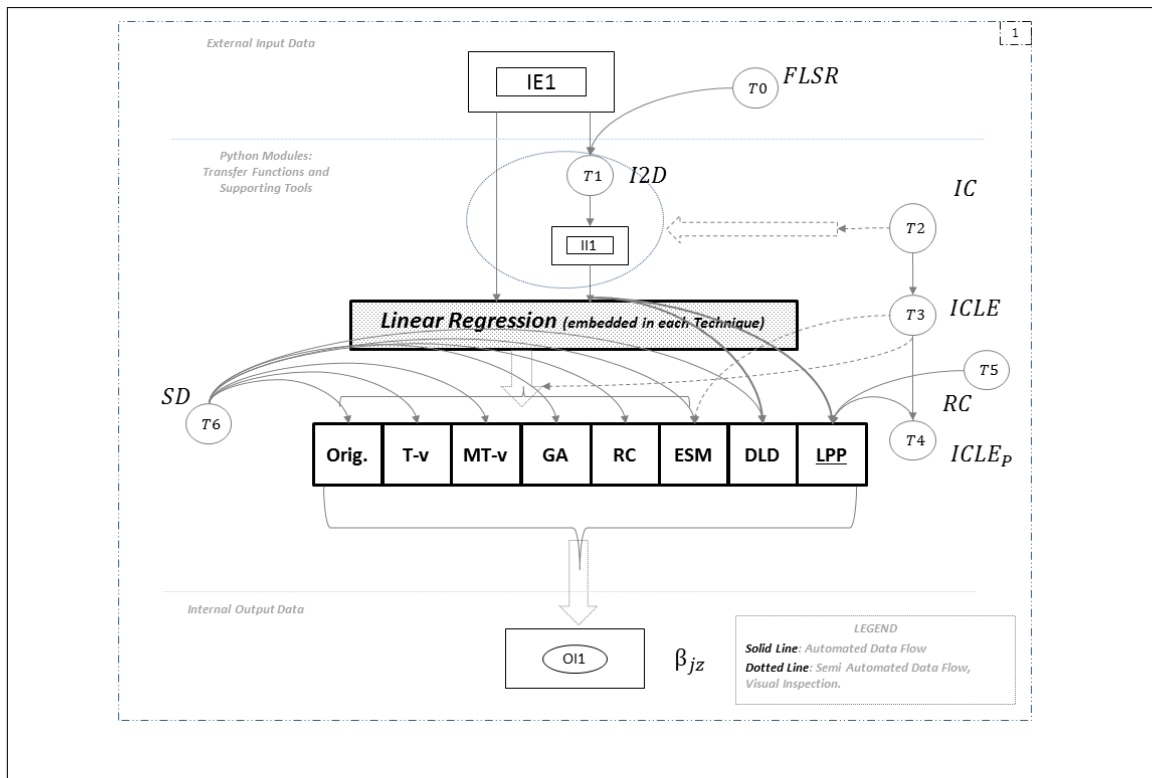


Figure B.1: LETE Stage 1: Python Code Flow chart.

B.1.1 The Spiral Approach

The structure offered in Figure B.1 says each technique works independently from the others. This provides the flexibility to add and remove, as needed, the techniques in the main running python code. This is a natural consequence of the way the whole LETE environment has been translated in programming lines. The bottom-up approach has been deployed by realising the common features of each Techniques, such as *LIRE* and *IC* and *ICLE*, must be used as python functions

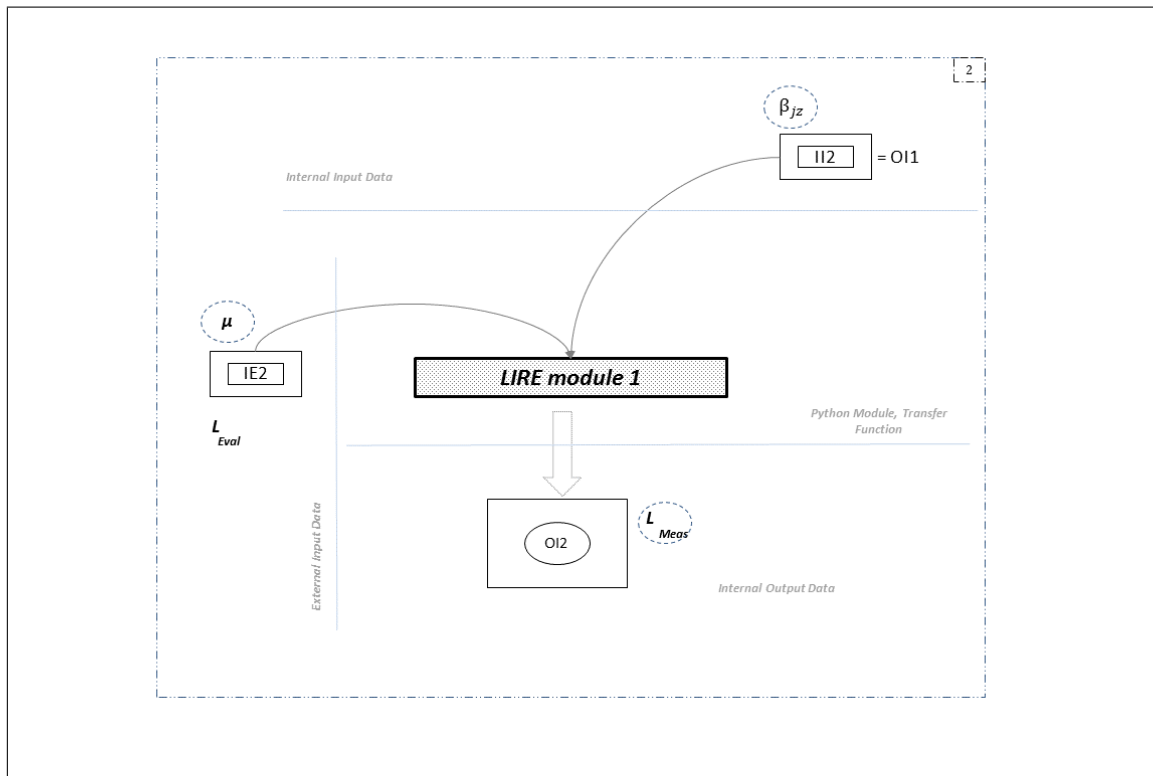


Figure B.2: LETE Stage 2: Python Code Flow chart.

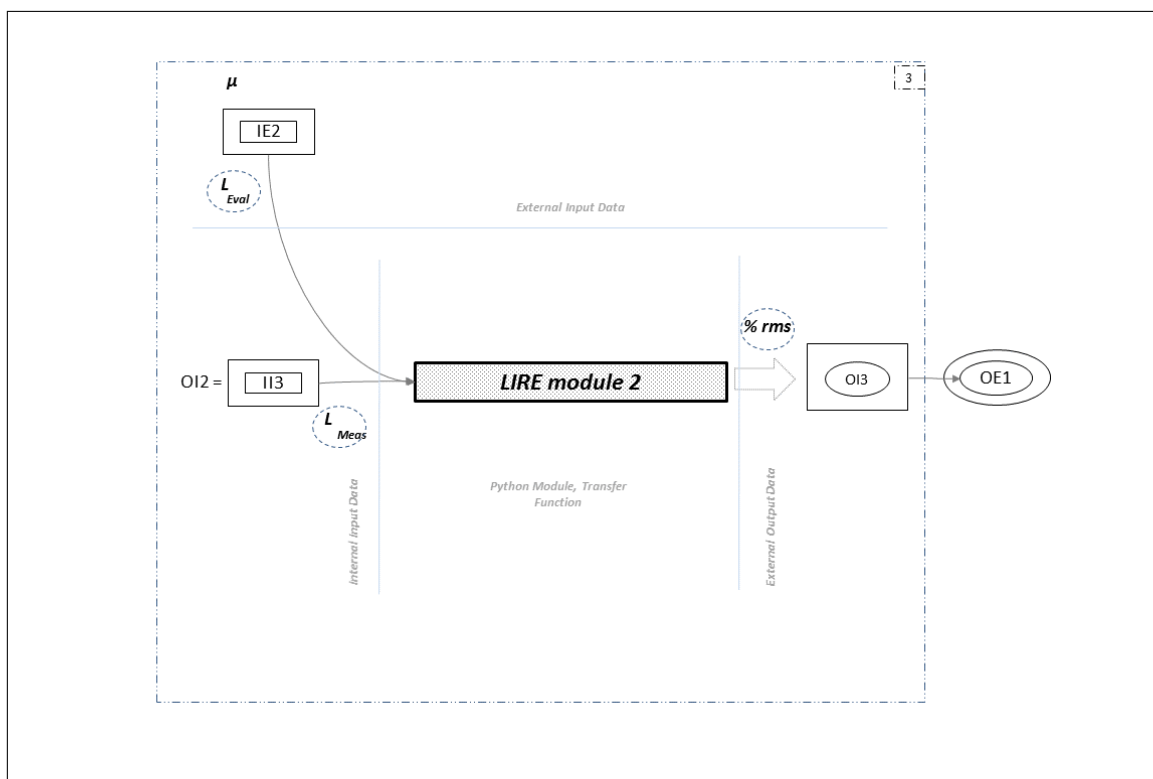


Figure B.3: LETE Stage 3: Python Code Flow chart.

available to be recalled as long as useful preventing to generate unnecessary redundancies. Afterwards, the whole LETE environment coding has been attached

in a series of short life cycles, as illustrated in Figure B.4, each one ending with a release of an executable software. This approach, known as spiral, allows to work on the entire life cycle, Analysis, Design, Code, Test, rather than spending too long time on a single activity, enabling to progress the research on the real core that was the flight loads measurement enhancement techniques and not the software itself. In fact, this allowed to receive feedback on the areas investigated and spot potential problems before going too far with the development, or appreciating down the line the real areas to be improved. Furthermore, the scale and complexity of the whole project has been discovered earlier.

The design phase of LETE cycles software systems has been performed using the Structured (sometimes called functional) approach. In fact, the general method has been aimed to look at the problem, and then design a collection of functions (eventually becoming modules when independent Python files) that can carry out the required tasks. Once these functions proved to be too large, then the functions were broken down until small enough to handle and understand. This process is known as *functional decomposition*.

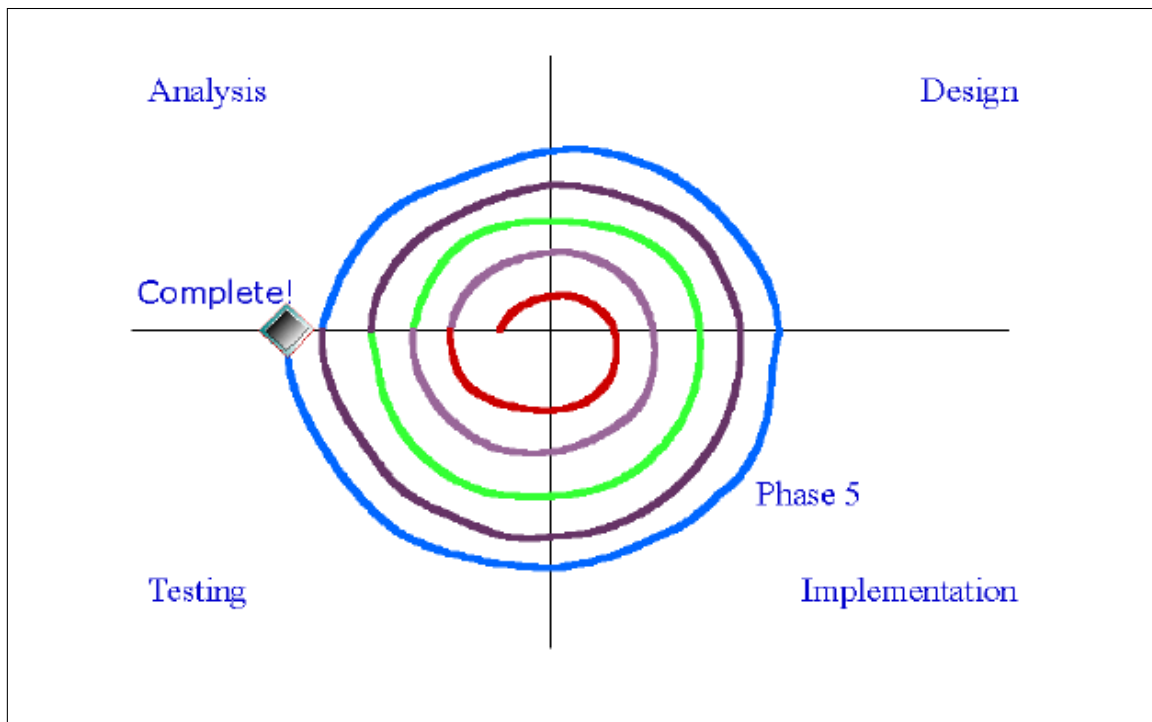


Figure B.4: LETE Development Approach: Spiral Process, [16].

B.1.2 Conception Phase and GALE

It is worth providing a little of insight on how the whole LETE code has been developed in order to better comprehend some future programming solution and decision that apparently deviate from the natural final framework. The spiral approach is the philosophy employed and applied to an initial concept that goes back to the literature review, section 2.6.5.

Since the beginning it was already clear that the natural improvement direction

of the science of the strain gauge-based flight loads measurement was going on the development of enhanced load equations techniques capable to overcome the limitations of the past and though maintaining those robust novelties. In this regard, the last relevant researcher contributing the science was Nelson, [79], that introduced, as NASA contractor, a new research tool based on Genetic Algorithm. Genetic algorithms work well when the desired solution is a set of characteristics. Besides, the typical advantages of this optimisation approach, introduced in section 4.4.4, it comes quite natural and functionally efficient to encode each equation into a "string". Where the string is a series of bits, with each bit holding information about a particular characteristic. If the bit holds the value 1, then the gauge corresponding to that bit's position on the string will be used. If the bit holds the value 0, then the gauge will not be used. This basic concept has been fully embraced developing a Genetic Algorithm Environment, labelled Genetic Algorithm Loads Equations, GALE. This environment has been conceived by making the Fitness Function, easy to plug in/off as such to be replaced according to the different techniques employed, such as Nelson, GALEN, and the new one proposed here linked to the name Mao, GALEM.

This explains why the current LETE environment evolved by employing, with the current available computer power than the early 90s, exhaustive search algorithm instead of genetic algorithm. Nevertheless, the system description of each technique has its own pillars on the string encode and decode routine more typical of a genetic algorithm. In fact, the output of *Stage One* described next, Figure B.12, shows clearly the strain gauge load equations idealisation just mentioned.

At that time the search of an adequate programming language meeting the genetic algorithm needs was another criteria considered, as Object Oriented techniques do. Then, it has been decided that the real problematic of employing a robust genetic algorithm, such as GA-Hard Function, use of crossover operator vs. trait operator, Nelson [79], would have deviated from the real research goal. Mainly considering that the Exhaustive Search with a ranking criteria equivalent to the initial fitness function would have brought less uncertainties. In fact, the risk was to loose perception of the real pros and cons between the different ranking criteria as the genetic algorithm was facing numerical issues out of the scope.

B.1.3 Requirements

Python, version 2.7, has been chosen as the open source programming language to develop the LETE environment.

Python, [68], is a general purpose programming language created in the late 1980s, and named after Monty Python, that's used by thousands of people to do things from testing microchips at Intel, to powering Instagram, to building video games with the PyGame library, and to scientific application of research centre such as NASA. Moreover, it has hundreds of existing third-party libraries, that hook very easily into the C programming language.

Specifically, the major reasons that justify the employment of this language come down to the three listed below:

- **Readability:** Python very closely resembles the English language, using words like ‘not’ and ‘in’ to make it to where you can very often read a program, or script, aloud to someone else and not feel like you’re speaking some arcane language. This is also helped by Python’s very strict punctuation rules which means you don’t have curly braces all over your code. Also, Python has a set of rules, known as PEP 8, that tell every Python developer how to format their code. This means you always know where to put new lines and, more importantly, that pretty much every other Python script you pick up, whether it was written by a novice or a seasoned professional, will look very similar and be just as easy to read. The fact that my Python code, with five or so years of experience, looks very similar to the code that Guido van Rossum (the creator of Python) writes is such an ego boost.
- **Libraries:** Python has been around for over 20 years, so a lot of code written in Python has built up over the decades and, being an open source language, a lot of this has been released for others to use. Almost all of it is collected on (<https://pypi.python.org>), pronounced “pie-pee-eye” or, more commonly called “the CheeseShop”. You can install this software on your system to be used by your own projects. For example, if you want to use Python to build scripts with commandline arguments, you’d install the “click” library and then import it into your scripts and use it. There are libraries for pretty much any use case you can come up with, from image manipulation, to scientific calculations, to server automation.
- **Community:** Python has user groups everywhere, usually called PUGs, and does major conferences on every continent other than Antarctica. PyCon NA, the largest Python conference in North America, gathering several thousands of user last year. All this makes Python an open source programme that fits well in the research idea to offer to the peers a code that can be accessed on a wider scale of researcher either for understanding or enhancement purposes.

Furthermore, Python fits well the concept presented by Eric S. Raymond, [93], who claims the Open source provides the competitive advantage in the internet Age. Software development of projects under open source and free software licenses, are initiated and maintained, and the effect that license choices can have on software development is relevant to think first.

The analysis of two opposite models, *The Cathedral*, in which source code is available with each software release, but code developed between releases is restricted to an exclusive group of software developers, and the *Bazaar*, in which the code is developed over the Internet in view of the public, shows clearly the pros and cons of these two opposite worlds. The potentialities for a natural and faster development of projects embracing the *Bazaar* model is reinforced by Raymond crediting Linus Torvalds, leader of the Linux kernel project, as the inventor of this process, [93]. Python seems to perfectly fit in the *Bazaar* model allowing to hand this research off to a wider community of potential competent and passionate successors.

B.1.4 Python and Python Codes: Folders/Files

Python is normally located, the basic version without libraries, in the start menu Python, if this is not apparent a system administrator skilled person will be helping to the right direction. Otherwise, the installation from scratch of a full scientific package, labelled Anaconda, will allow to have already available all necessary libraries to smoothly run the LETE Python codes. In fact, Anaconda, a Premium open source distribution of Python with a large-scale data processing, predictive analytics, and scientific computing, that aims to simplify package management and deployment, [20].

The LETE Python files, broken down in those Input and Output, and Transfer Functions, sections B.1.6 and B.1.7, should be structured as displayed in Figure B.5.

A full package of the program is stored in the Root Directory, made up by a Folder and all those necessary files creating the GUI, Graphical User Interface, section B.1.8. The folder's name is *CODES*, all white typing represents the real name of the folders, while the black writing boxes describe the contents, within it there are, at a lower level L1, all those Python codes representing the transfer functions and supporting tools. Next lower level of each of these folders, whose name will be described in the section B.1.7, Major Transfer Functions, will have a common structure, three folders, *I*, storing all input files, *O*, storing all output files, and *X*, folder to save anything needed but not directly linked to Input and Output. At this same level, Level L2, are stored all python files associated to those specific transfer functions or supporting tools with the Master File to commence the run.

B.1.5 Program Operation

The objective of running this program is to determine load coefficients, for as many techniques as those embedded like *transfer functions* of Figure 3.4, and assess their performance by means of root-mean-square (%rms) error, Eq. (B.1) will present the details, for strain gauges attached to a wing, horizontal and vertical stabiliser or a any other torsion box-like lifting surface. The program goes through three phases:

- **Import of Data:** Including strain gauge data, load point data and test data, requiring manual input.
- **Calculation:** The theory behind the Transfer Functions to generate outputs at each LETE stage.
- **Export of Data:** Files/program locations to run and collect results.

B.1.6 Program Inputs and Outputs

In the case of structures such as the wing, the stabilisers or any other torsion box-like lifting surface, strain gauges are positioned on the structure along the

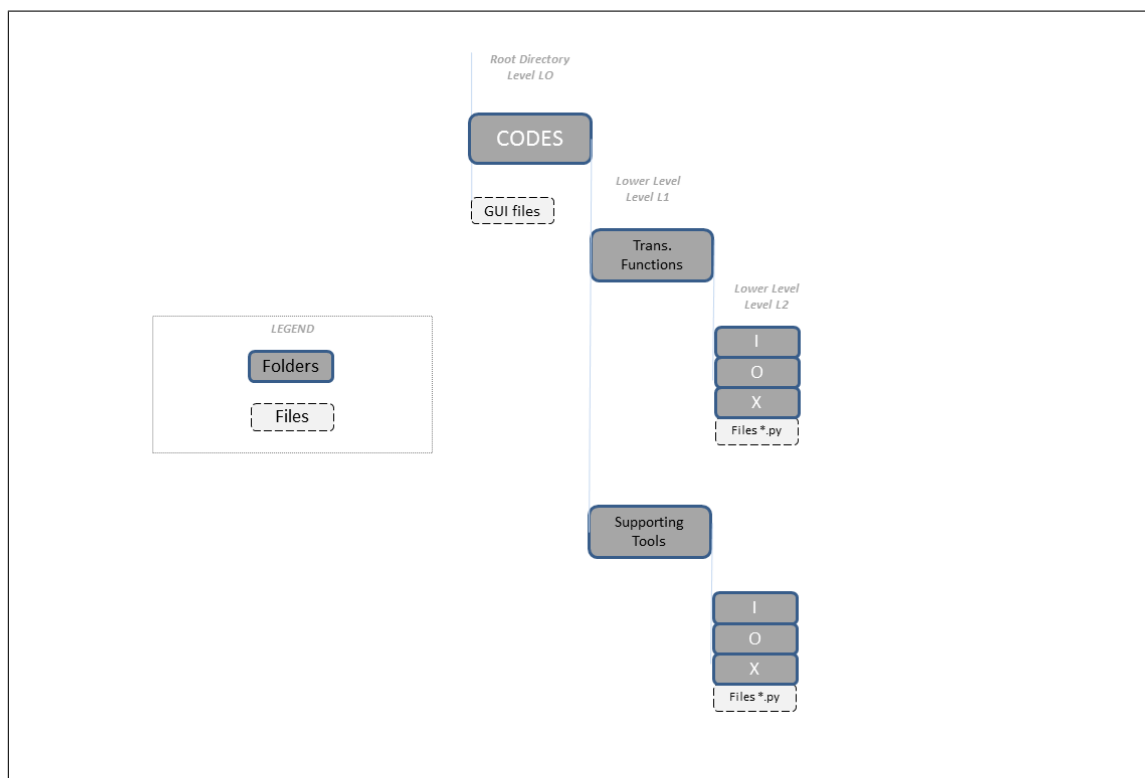


Figure B.5: LETE Python Files Structure.

major load paths such that the forces of shear, bending moment and torque are measured in that specific station. Before the responses of the strain gauges can be used for analysis, the measure of force to response must be verified. This is achieved by calibrating the structure.

The calibration, already identified as GLC, one of the six phases of the strain gauge-based flight loads measurement campaign in Table 2.1, is performed by applying a number of dissimilar loads, greater than the number of strain gauges, to the structure. From this dependent data, training set, a load coefficient, representing the output, can be calculated which describes the strain gauge response to load.

The two following paragraphs will be focusing respectively on those different types of Inputs and Outputs according to the scheme of Figure 3.4 in terms of files and their structure needed to comply with the LETE software correct run.

B.1.6.1 Input Files

These readings, *dissimilar loads* and associated *strain gauge traces*, are the inputs of the whole package. According to the idealised LETE flow chart of Figure 3.4 there are *External Inputs*, labelled as *IE1* and *IE2*, and *Internal Input*, *II1*. The former, are originated from several different sources, such as Experimental Ground and/or Flight Data, Numerical, FEM, and Analytical, theoretic equations. The latter, are numerical results of the external input as shown in Figure B.4 by means of the supporting tool code, *T1*, "Individual to Distributed", *I2D*.

The data required by the program, to be input by the user, is that for the strain

gauge bridges, load points and the test data. All input files should be stored in the directory in which the user wishes to work.

- **IE1:** *I_Loads.txt* and *I_SG.txt*. There are three different *load* files, Bending Moment, Shear and Torque of that specific station under investigation. Figure B.6 and Figure B.7 show and describe details.
- **IE2:** *I2_Loads.txt* and *I2_SG.txt*. There are three different *load* files, Bending Moment, Shear and Torque of that specific station under investigation. In this case the typology of the data can be either a single point, Point in the Sky, PITS or Point on Ground, POGS, labelled *PP*, or a Time History, *TH*. For simplicity the template of Figure B.6 and Figure B.7 remains applicable.
- **II1:** *I_I2D_L_SG.txt* and *I_I2D_DB.txt*. There are two different *load* file categories, the first one, Figure B.8, is describing the Load Cases application points, Cartesian coordinates (details on the reference system will be described in each test case), and their external loads, with the associated strain gauge readings. That means files like this will be as many as the strain gauges used to develop the load equations. The second, Figure B.9, displays the boundaries of the requested numerical distributed sample, in terms of coordinates of the PITS centre of pressure to recreate, and the maximum internal forces, Shear, Torsion, and Bending Moment not to overcome to prevent encountering buckling effect that might invalidate the equation of interpolation for the prediction of the strain gauge readings. Moreover, there are two more boundaries, the expected relevance coefficient and the number of individual loads to apply simultaneously, these two requests are linked to each other.
- **II2:** see OI1
- **II3:** see OI2

Note:

- ✓ The Input data above are all text files.
- ✓ The order of the rows of the files must not be changed independently as must be consistent among input files and output files too.
- ✓ The "Load Station" refers to the position of the gauge along the structure, the load station measurement.
- ✓ Figure B.6 and Figure B.7 remain applicable as template for all the Input files above as the function code philosophy employed to import the data is always the same.

Note: This Input Load File contains Loads on only the station under investigation.

Note: Load Magnitude has to be consistent to the type of load representing, Bending Moment, Shear or Torque. This column represents the magnitude of the load in the station under investigation of the associated row load cases.

Further Outboard	Load Case Station	Load Magnitude
	977	-3092
	977	-3092
	977	-3092
	1325	-2777
	1325	-2777
	1325	-2777
	1725	-2777
	1725	-2777
	1725	-2777

Note: Only the information in Black Type is required in the text file.

Figure B.6: LETE Input External, IE1: System Description - Load Cases.

Note: This Input Load File contains strain gauge readings of only the station to measure the loads

Load Cases, Front to Rear Spar and further Outboard	Strain Gauge Readings, From Front Spar, to Rear Spar / Strain Gauge Type, Bending Moment (BM), Shear, Others.					
	Spar1 / BM	Spar1 / Shear	Spar2 / BM	Spar2 / Shear	Spar3 / BM	Spar3 / Shear
	0.000100	0.000031	0.000081	0.000026	0.000052	0.000008
	0.000093	0.000023	0.000125	0.000026	0.000066	0.000011
	0.000077	0.000013	0.000091	0.000018	0.000095	0.000012
	0.000187	0.000037	0.000171	0.000039	0.000136	0.000020
	0.000175	0.000036	0.000182	0.000041	0.000153	0.000022
	0.000156	0.000028	0.000178	0.000035	0.000185	0.000025
	0.000260	0.000051	0.000257	0.000051	0.000240	0.000036
	0.000255	0.000047	0.000260	0.000051	0.000249	0.000035
	0.000245	0.000042	0.000265	0.000050	0.000268	0.000036

Note: Only the information in Black Type is required in the text file.

Figure B.7: LETE Input External, IE1: Strain Gauge Readings.

Note: This Input Load File contains Loads, application point coordinates and magnitude, and associated readings of just one strain gauge.

Note: There will be as many files like this as the overall strain gauges used in the input file, I_SG.txt to develop the regression for the load coefficients calculation.

Strain Gauge Reading	Load Case X Station, [m]	Load Case Y Station, [m]	Load Case Magnitude, [N]
536	0	0	890
8.34	0	0.394	890
6.1	0	0.788	890
11.9	0.419	0	890
19.6	0.419	0.394	890

Note: Only the information in Black Type is required in the text file.

Figure B.8: LETE Input Internal, II1: I2D, Individual to Distributed, System Description - Individual Load Positions and Magnitude, and Generic Strain Gauge Readings.

B.1.6.2 Output Files

After going through the Input data, mainly about load cases and the strain gauge readings of the station of analysis, the Output data will be generating the best set of Load Coefficients of each Technique and their respective performance indexes, percent of root mean square, evaluated against an independent set of data, validation set *IE1* just introduced in the previous section.

There will be two categories of outputs, one global showing the major intermediary steps before reaching the final major quantity result. The other, specific, will be representing the sole final result quantity coming out of the transfer function involved. The two major transfer functions, *Techniques* and *LIRE*, produce the outputs below:

- **OI1:** *O_G_”Tech”.txt* and *Beta_”Tech”.txt*. The first text file represents the Global output of the Stage 1, one for each technique employed, in fact in the output names will compare the *”Tech”* label replaced by the Loads Equations Ranking Criteria used. The latter file is the specific one storing only the best set of load coefficients generated according to the Ranking Criteria of the technique. The load coefficients populate the file following the same order of the Input strain gauge files of *IE1*, though in column format. Figure B.10 and Figure B.11, B.12 and B.13 show and describe details.
- **OI2:** *O_LIRE_G_”wsNL”.txt*. The Measure Load outputs, of each *Technique* employed are included in the Global LIRE output file, as Figure B.14

Relevance Coefficient	Centre of Pressure, X [m]	Centre of Pressure, Y [m]	Nr of Individual Loads	Maximum Internal Loads		
				Shear [N]	Bending Moment [Nm]	Torsion [Nm]
0.8	0.211	0.3	7	900	400	800

Note: Only the information in Black Type is required in the text file.

Figure B.9: LETE Input Internal, I11: I2D, Individual to Distributed, Basic Boundaries.

- **OI3:** *O_LIRE_G "wsNL".txt* and *O_LIRE_RMS "wsNL".txt*. The first text file, is a Global output, as collects all major information necessary to summarise the road to the final output, RMS. The second file is a column file storing all RMS of each technique according to the same order of the Global file. Figure B.14 and Figure B.15 show and describe details.
- **OE1:** *O_BELE.txt*. Figure B.15 shows and describes details as being an extract of the Global Output file of LIRE.
- **IO0:** *O_G_I2D.txt*. It describes the Global Output data of I2D.

Note:

- ✓ Global Data files take the name of transfer function involved.
- ✓ Specific Data files take the name of quantity streaming through the transfer function linked.
- ✓ The Global Output of LIRE, OI3 displayed in Figure B.15 is made up by as many similar templates as the techniques employed at Stage One.

B.1.6.3 Input and Output Files

All input and output files should be located in the directory "I" and "O" respectively. These folders will be automatically created by each Master File, see section B.1.7,

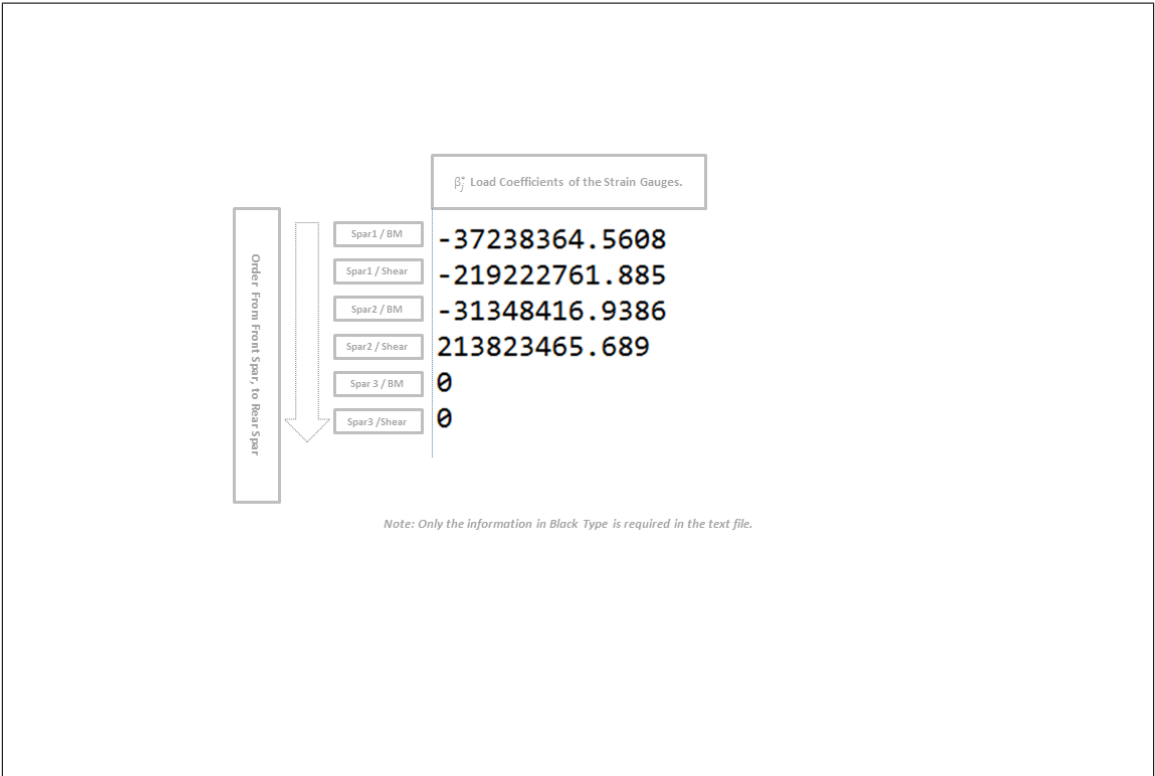


Figure B.10: LETE Output Internal - OI1, II2: Specific Output - Load Coefficients.

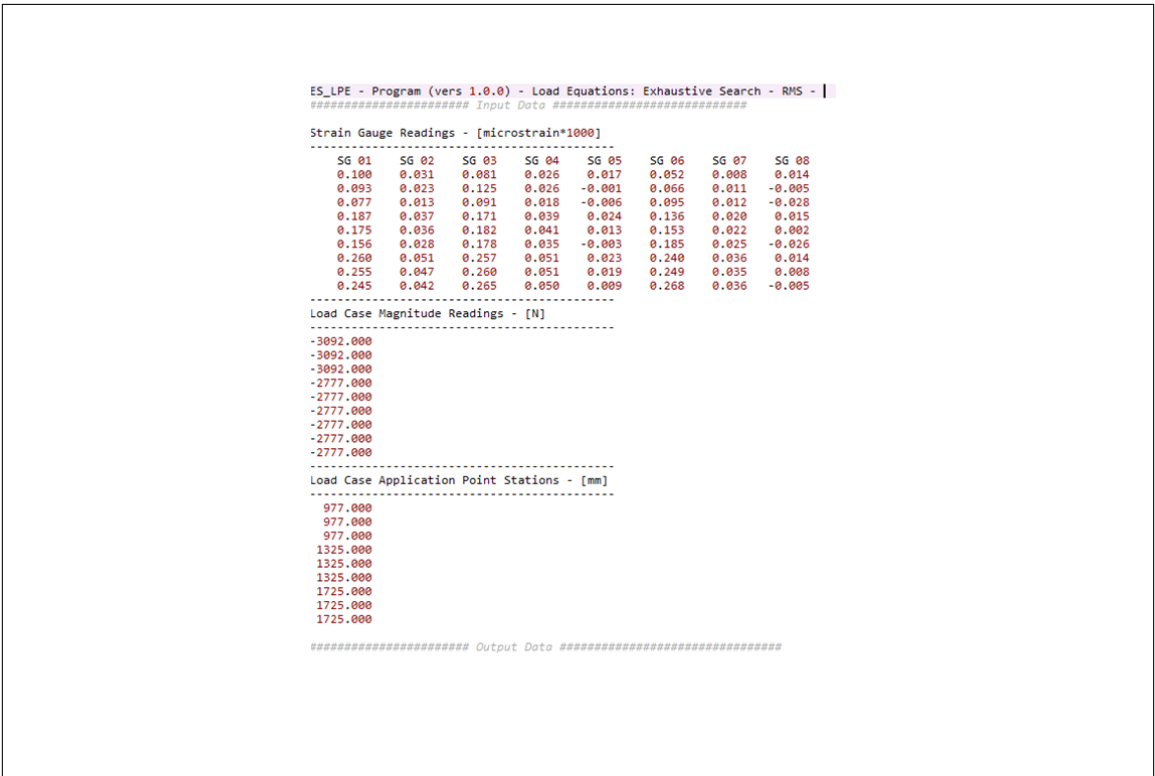


Figure B.11: LETE Output Internal - OI1, II2: Global Output - Generic Technique Transfer Function - Part A, Input Data System Description.

***** Output Data *****			
ID	Load Eq.	LPE	Rank
0	[1 1 1 1 1 1 1 1]	224.597	3
1	[1 1 1 1 1 1 1 0]	339.672	49
2	[1 1 1 1 1 1 0 1]	501.572	127
3	[1 1 1 1 1 1 0 0]	354.781	52
4	[1 1 1 1 1 0 1 1]	257.318	10
5	[1 1 1 1 1 0 1 0]	289.247	24
6	[1 1 1 1 1 0 0 1]	455.787	103
7	[1 1 1 1 1 0 0 0]	558.676	153
8	[1 1 1 1 0 1 1 1]	239.685	6
9	[1 1 1 1 0 1 1 0]	814.135	219
10	[1 1 1 1 0 1 0 1]	385.754	63
11	[1 1 1 1 0 1 0 0]	687.932	182
12	[1 1 1 1 0 0 1 1]	190.350	0
13	[1 1 1 1 0 0 1 0]	697.374	190
14	[1 1 1 1 0 0 0 1]	469.413	110
15	[1 1 1 1 0 0 0 0]	605.827	166
16	[1 1 1 0 1 1 1 1]	407.940	75
17	[1 1 1 0 1 1 1 0]	288.504	23
18	[1 1 1 0 1 1 0 1]	356.244	53
19	[1 1 1 0 1 1 0 0]	291.091	25
20	[1 1 1 0 1 0 1 1]	325.173	42
21	[1 1 1 0 1 0 1 0]	295.677	27
22	[1 1 1 0 1 0 0 1]	375.946	60
23	[1 1 1 0 1 0 0 0]	580.839	159
24	[1 1 1 0 0 1 1 1]	328.000	45
25	[1 1 1 0 0 1 1 0]	694.907	189
26	[1 1 1 0 0 1 0 1]	317.412	35
27	[1 1 1 0 0 1 0 0]	758.207	207
28	[1 1 1 0 0 0 1 1]	269.533	13
29	[1 1 1 0 0 0 1 0]	742.595	202
30	[1 1 1 0 0 0 0 1]	433.965	86
31	[1 1 1 0 0 0 0 0]	681.354	179
32	[1 1 0 1 1 1 1 1]	267.403	12
33	[1 1 0 1 1 1 1 0]	452.953	99
34	[1 1 0 1 1 1 0 1]	384.271	62
35	[1 1 0 1 1 1 0 0]	607.389	167
36	[1 1 0 1 1 0 1 1]	190.447	1
37	[1 1 0 1 1 0 1 0]	397.291	70
38	[1 1 0 1 1 0 0 1]	439.823	92
39	[1 1 0 1 1 0 0 0]	558.686	154
40	[1 1 0 1 0 1 1 1]	329.658	46
41	[1 1 0 1 0 1 1 0]	671.583	177
42	[1 1 0 1 0 1 0 1]	315.350	33
43	[1 1 0 1 0 1 0 0]	598.477	163
44	[1 1 0 1 0 0 1 1]	277.893	19
45	[1 1 0 1 0 0 1 0]	605.310	165
46	[1 1 0 1 0 0 0 1]	421.830	83

```

220= [ 0 0 0 0 0 0 0 1 ] 2398.129 220
255 [ 0 0 0 0 0 0 0 ] 224.597 4
-----
Minimum RMS and associated ID Load Equation 12: 190.350323098
(190.35032309847023, 0, (1, 1, 1, 1, 1, 0, 0, 1, 1), [{"-3723864.56079355, -219222761.88548034, -31348416.93580047, 213823465.6869574, 384266167.5678302, 100015583.9614484}])
***** End Data *****

```

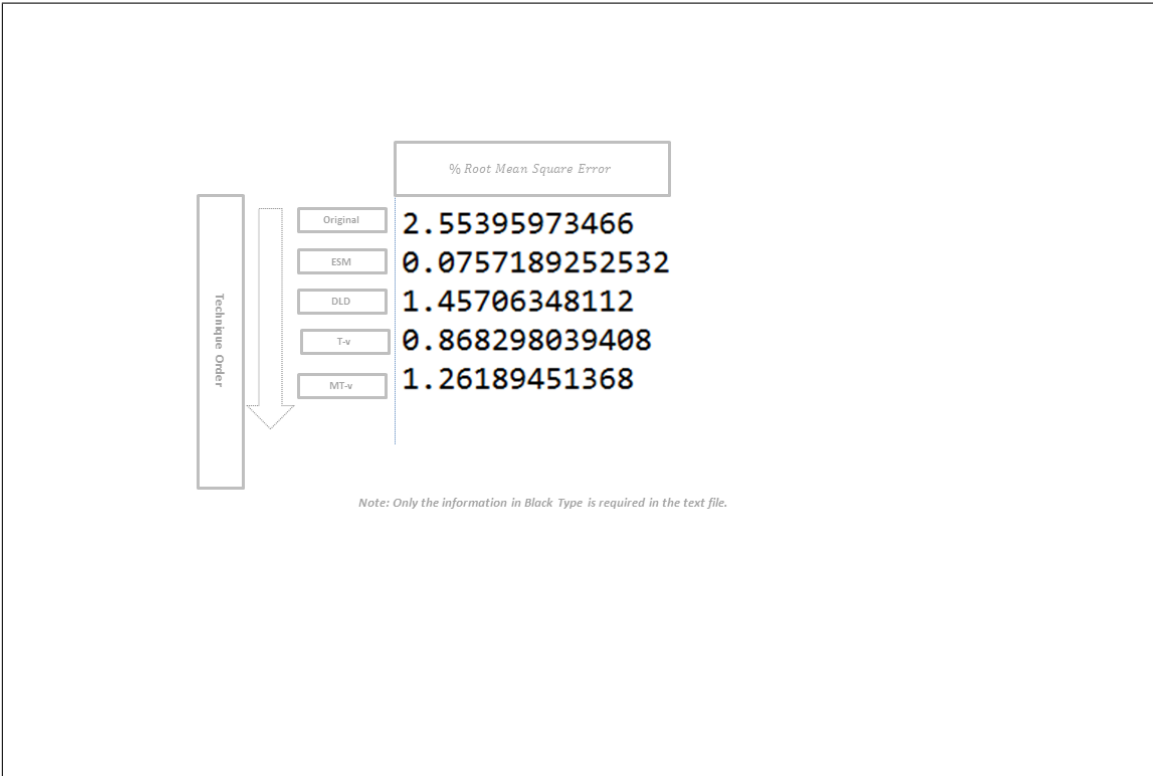


Figure B.14: LETE Output Internal - OI3: Specific Output - Techniques Percent Root Mean Square Error.

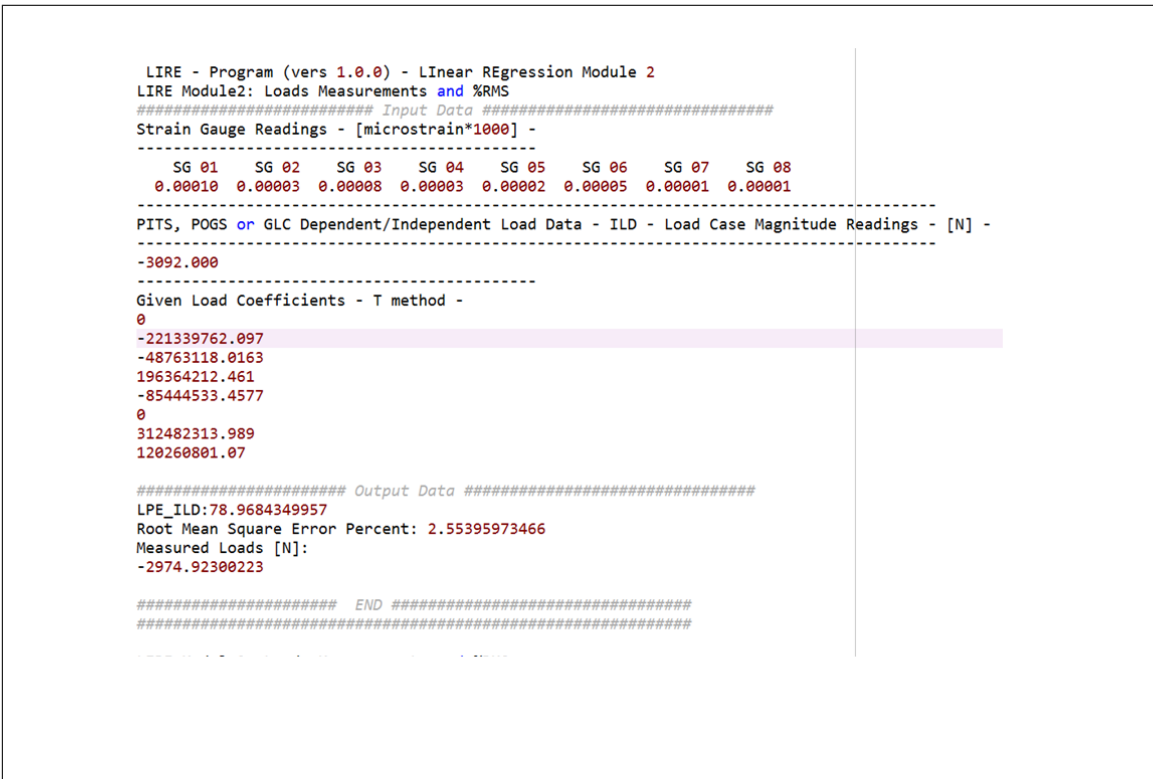


Figure B.15: LETE Output Internal - OI3: Global Output - Generic Technique Transfer Function Major Information Summary - LIRE Loads Comparison.

- **Function:** is a device that groups a set of statements so they can be run more than once in a program. Functions also can compute a result value and allow to specify parameters that serve as function inputs, which may differ each time the code is run. Coding an operation as a function makes it a generally useful tool, which can be used in a variety of contexts, [68].
- **Module:** corresponds to Python program files, extension .py , or extensions coded in external languages such as C, Java, or C #. Each file is a module, and modules import other modules or functions to use the names they define. Modules are processed with two statements and one important function, [68].
- **Master File:** It is the file at the top of the hierarchy of the *Transfer Function* or *Supporting Tools* module. It is characterised by using functions and modules but it does not return any new Python variables but generating the final output file of the whole independent package. If the packages will be run without the GUI the file to be called and then executed is the Master File.

Note:

- ✓ At the top of each Python module there is a description in terms of basic description and function, and Input and Output quantities associated, this function prologue is shown in Figure B.19. Information easy to be recalled with basic Python command once known the Module name. The modules have a printing factor, d , that sets whether generating all major steps of the calculation. Normally, is set off. If "d" is negative the print option is "on". Option contained at the very top of the Master *Transfer Function* module.
- ✓ In the coming sections each *Transfer Function* will be shown the dependencies starting from the master top level file going down to sub-modules.
- ✓ If not said differently each following transfer function can be run independently.
- ✓ Besides the basic embedded Python packages, LETE has been designed and completed by means of very dedicated mathematical libraries such as: Numpy, Scipy and Pylab, [68].
- ✓ The coming explanation of each transfer function of LETE will be using a bullet point format and the final modules dependencies will be captured by a call graph picture, presented in the following sections of this Appendix B.2, which represents calling relationships between subroutines of the specific Transfer Function Python program. Each node represents a procedure and each edge. Thus, a cycle in the graph indicates recursive procedure calls. Solid line arrows display the direct dependencies to the module pointing to, as input data.
- ✓ The *control flow graph* screen shot of the transfer functions lists the modules in order of appearance within the main master file.

- ✓ The *algorithm typology* coded are two, as already anticipated in sections 4.3, 4.4 and 4.5, the "Exhaustive Search" and the "Strain Gauge Counting-Out", or Strain Gauge Reduction. In addition, it has been explored the benefits of the Genetic Algorithm, though appraised, see section B.1.2 not convenient within the boundaries of this research, mainly related to the typology of the available data.
- ✓ The *supporting tools* item, inside the description of each transfer function below, refers to those codes special algorithms that contribute to perform the ranking criteria of the technique. These, already introduced in the description of the evolution of the flight loads equations computation, section 4.4, can be either embedded or external to the main code. This will be further detailed in the *control graph call* figures while showing the dependencies and hierarchy of the Python code associated.
- ✓ The *Code Execution* item describes basics command to execute in order to comply with the transfer function theoretical rules and so running properly to generate the expected outputs.
- ✓ As already mentioned that LETE is the result of several transfer functions linked sequentially in three stages, each transfer function code of *Stage 1* can be run having two options. *Option1*: going directly to its code folder, *Level 1*, and running the master file, *Level 1*, after storing the input files in the *I*, populated as required and described in section B.1.6.1. Option 2 staying in the Root Directory, *Level 0*, and run the GUI of the different stages as needed. The *Level 0*, *Level 1* and *Level 2* directory levels and their associated folders and files will be described in the Control Flow Graph figures of Appendix B.2.
- ✓ The *Folder Names* describe the name that the end-user will be finding on the master folder containing the code intended to be run.

B.1.7.1 Stage One: The Original Approach, LPE

The schematic of the computation displayed in Figure 4.3 has been translated by the Python Code description below:

- **Ranking Criteria:** The Load Probable Error, $\text{textbf{LPE}}$. Section 4.3 & Eq. (4.4).
- **Algorithm Typology:** Exhaustive Search and "supporting tools".
- **Folder Name:** *ES_LPE*
- **Master File:** *A_LE_ES_LPE_TheOne.py*.
- **Input:** *I_Loads.txt* and *I_SG.txt*. Section B.1.6.1.
- **Output:** The Global File - *O_ESlpe_G_wsNL.txt* and The Specific File - *Beta_ESlpe_wsNL.txt*. Section B.1.6.2.

- **Modules List:** Input_OF.py, Z_HDRprint_Input.py, Z_HDRprint_Input.py, Exaus_ES.py, Decode_ES_GALE.py, Beta_OF.py, LPE_OF.py
- **Supporting Tools:** Embedded codes. External Codes:IC.
- **Dependencies/Hierarchy:** Figure B.20.
- **Code Execution:** Go to Level 1 and choose IC and run its master file in its Level 2. Do visual inspection of the IC plots stored in O. Adjust input strain gauge data as required. Go to Level 1 folder ES_LPE, store last Input Files in I folder and run the Master File all at Level 2. Find outputs in O folder of the LPE associated code. Figure B.5 to understand Code folders/files locations.
- **Approach Type:** Semi-automated, as IC plots inspection needed.

B.1.7.2 Stage One: The Distributed Load Data, DLD

The schematic of the computation displayed in Figure 4.5 has been translated by the Python Code description below:

- **Ranking Criteria:** The Distributed Load Data, DLD. Section 4.4.1 & Eq. (4.4).
- **Algorithm Typology:** Exhaustive Search and dedicated Input files, generated by the "supporting tools" I2D.
- **Folder Name:** ES_LPE
- **Master File:** A_LE_ES_LPE_TheOne.py.
- **Input:** I_I2D_Loads.txt and I_I2D_SG.txt. Section B.1.6.1.
- **Output:** The Global File - O_ESlpe_G_wsNL.txt and The Specific File - Beta_ESlpe_wsNL.txt. Section B.1.6.2.
- **Modules List:** Input_OF.py, Z_HDRprint_Input.py, Z_HDRprint_Input.py, Exaus_ES.py, Decode_ES_GALE.py, Beta_OF.py, LPE_OF.py
- **Supporting Tools:** Embedded codes. External Codes: I2D and IC.
- **Dependencies/Hierarchy:** Figure B.20.
- **Code Execution:** Go to Level 1 and choose I2D, and Run its master file in its Level 2, in this level take the associated output files from O and store to the next Input folder needed. Then, Go to Level 1 and choose IC and run the Master File in its Level 2 with the outputs of I2D. Do visual inspection of the IC plots stored in O. Adjust input strain gauge data as required. Go to Level 1 folder ES_LPE, store last Input Files in I folder and run the Master File all at Level 2. Find outputs in O folder of the LPE associated code. Figure B.5 to understand Code folders/files locations.

- **Approach Type:** Semi-automated, as **I2D** and **IC** plots inspection needed.

Note:

- ✓ The **DLD** technique, mixed of Automated and Step by Step approach, has been translated in Python by using the same exhaustive search of the Original Approach as the ranking criteria is the same. Only differences are that down the path is the manipulation of the input individual data to distributed one.
- ✓ The output files, as generated by the *ES_LPE* code, will have its file name label as shown above. Afterwards, the name will have to be manually changed in order to replace *ESlpe* by the *DLD* label.

B.1.7.3 Stage One: The Equation Selection Matrices, ESM

The schematic of the computation displayed in Figure 4.7 has been translated by the Python Code description below:

- **Ranking Criteria:** The Distributed Load Data, **DLD**. Section 4.4.1 & Eq. (4.4).
- **Algorithm Typology:** Exhaustive Search and "supporting tools".
- **Folder Name:** *ES_LPE*
- **Master File:** *A_LE_ES_LPE_TheOne.py*.
- **Input:** *I_Loads.txt* and *I_SG.txt*. Section B.1.6.1.
- **Output:** The Global File - *O_ESlpe_G_wsNL.txt* and The Specific File - *Beta_ESlpe_wsNL.txt*. Section B.1.6.2.
- **Modules List:** *Input_OF.py*, *Z_HDRprint_Input.py*, *Z_HDRprint_Input.py*, *Exaus_ES.py*, *Decode_ES_GALE.py*, *Beta_OF.py*, *LPE_OF.py*.
- **Supporting Tools:** Embedded codes. External Codes: **IC** and **ICLE**.
- **Dependencies/Hierarchy:** Figure B.20.
- **Code Execution:** Go to *Level 1* and choose *I2D*, and Run its master file in its *Level 2*, in this level take the associated output files from *O* and store to the next Input folder needed. Then, Go to *Level 1* and choose *IC* and run the Master File in its *Level 2* with the outputs of *I2D*. Do visual inspection of the *IC* plots stored in *O*. Adjust input strain gauge data as required. Go to *Level 1* folder *ES_LPE*, store last Input Files in *I* folder and run the Master File all at *Level 2*. Find outputs in *O* folder of the *LPE* associated code. Figure B.5 to understand Code folders/files locations.

- **Approach Type:** Semi-automated, as **I2D and IC** plots inspection needed. Eventually, **FEM** might be employed too though the results presented next, Chapter 5, will not be taking into account the FEM as strain gauges already installed.

Note:

- ✓ The **ESM** technique, mixed of Automated and Step by Step approach, is using as main code the Original Approach to determine the best set of loads equations, the reason behind is the same of the *DLD* technique above.
- ✓ The output files, as generated by the *ES_LPE* code, will have its file name label as shown above. Afterwards, the name will have to be manually changed in order to replace *ESlpe* by the *ESM* label.

B.1.7.4 Stage One: The T value method, T-v

The schematic of the computation displayed in Figure 4.8 has been translated by the Python Code description below:

- **Ranking Criteria:** The T-value Method, T-v. Section 4.4.3 & Eq. (4.6).
- **Algorithm Typology:** Strain Gauge Elimination and "supporting tools".
- **Folder Name:** *ES_T_MT_v*
- **Master File:** *A_TM_TheOne.py*.
- **Input:** *I_Loads.txt* and *I_SG.txt*. Section B.1.6.1.
- **Output:** The Global File - *O_Tm_G_wsNL.txt* - and The Specific File - *Beta_Tm_wsNL.txt*. Section B.1.6.2.
- **Modules List:** *Input2_OF.py*, *Z_HDRprint_Input.py*, *Z_HDRprint_Input.py*, *T_OF.py*, *Enc_T_Hybrid_OF.py*, *Beta_OF.py*, *LPE_OF.py*.
- **Supporting Tools:** Embedded codes. External Code: **IC**
- **Dependencies/Hierarchy:** Figure B.21.
- **Code Execution:** Go to *Level 1* and choose *IC* and run its master file in its *Level 2*. Do visual inspection of the IC plots stored in *O*. Adjust input strain gauge data as required. Go to *Level 1* folder *ES_T_MT_v*, store last Input Files in *I* folder and run the Master File all at *Level 2*. Find outputs in *O* folder of the *T-v* associated code. Figure B.5 to understand Code folders/files locations.
- **Approach Type:** Semi-automated, as **IC** plots inspection needed.

B.1.7.5 Stage One: The Modified T value method, MT-v

The schematic of the computation displayed in Figure 4.8 has been translated by the Python Code description below:

- **Ranking Criteria:** The MT-value Method, **MT-v**. Section 4.4.3 & Eq. (4.7).
- **Algorithm Typology:** Strain Gauge Elimination and "supporting tools".
- **Folder Name:** *ES_T_MT_v*
- **Master File:** A_MTM_TheOne.py.
- **Input:** I_Loads.txt and I_SG.txt. Section B.1.6.1.
- **Output:** The Global File - O_MTM_G_wsNL.txt - and The Specific File - Beta_MTM_wsNL.txt. Section B.1.6.2.
- **Modules List:** Input2_OF.py, Z_HDRprint_Input.py, Z_HDRprint_Input.py, MT_OF.py, Enc_T_Hybrid_OF.py, Beta_OF.py, LPE_OF.py.
- **Supporting Tools:** Embedded codes. External Code: **IC**
- **Dependencies/Hierarchy:** Figure B.22.
- **Code Execution:** Go to *Level 1* and choose *IC* and run its master file in its *Level 2*. Do visual inspection of the IC plots stored in *O*. Adjust input strain gauge data as required. Go to *Level 1* folder *ES_T_MT_v*, store last Input Files in *I* folder and run the Master File all at *Level 2*. Find outputs in *O* folder of the *T-v* associated code. Figure B.5 to understand Code folders/files locations.
- **Approach Type:** Semi-automated, as **IC** plots inspection needed.

B.1.7.6 Stage One: The Genetic Algorithm method, GA

The schematic of the computation displayed in Figure 4.9 has been translated by the Python Code description below:

- **Ranking Criteria:** The GA Technique, **GA**. Section 4.4.4 & Eq. (4.8).
- **Algorithm Typology:** Exhaustive Search and "supporting tools".
- **Folder Name:** *ES_N*
- **Master File:** A_LE_ES_Nelson_TheOne.py..
- **Input:** I_Loads.txt and I_SG.txt. Section B.1.6.1.
- **Output:** The Global File - O_ESNelson_G_wsNL.txt - and The Specific File - Beta_ESn_wsNL.txt. Section B.1.6.2.
- **Modules List:** Input_OF.py, Z_HDRprint_Input.py, Z_HDRprint_Input.py, Exaus_ES.py, Decode_ES_GALE.py, Beta_OF.py, LPE_OF.py, FF_ES_Nelson.py.

- **Supporting Tools:** Embedded codes. External Code: IC and ICLE
- **Dependencies/Hierarchy:** Figure B.23.
- **Code Execution:** Go to *Level 1* and choose IC and run its master file in its *Level 2*. Do visual inspection of the IC plots stored in O. Adjust input strain gauge data as required. Go to Level 1 folder *ES_N*, store last Input Files in *I* folder and run the Master File all at *Level 2*. Find outputs in O folder of the *ES_N* associated code. Figure B.5 to understand Code folders/files locations.
- **Approach Type:** Semi-automated, as IC and ICLE plots inspection needed.

Note:

- ✓ The initial code to translate Nelson concept, was meant to be a genetic algorithm, though it has been decided that, as section B.1.2 explained, for the scope the research an Exhaustive Search with the same initial Fitness Function will have the same effect.

B.1.7.7 Stage One: The Genetic Algorithm Loads Equations, GALE

The schematic of the computation of this Genetic Algorithm Loads Equation environment, displayed in Figure B.16, has been translated by the Python Code description below, though, as already explained it will not be used as the main code to assess the performance of the past and new technique. However, GALE is included in this section as the ranking criteria can be any of those introduced till now and the input files are the same. The only difference is the search engine behind that for real heavy computational project might be considered.

The GALE Python code is described below :

- **Ranking Criteria:** The GA Technique, GA. Section 4.4.4 & Eq. (4.8).
- **Algorithm Typology:** Exhaustive Search and "supporting tools".
- **Folder Name:** GALE
- **Master File:** A_GALE_TheOne.py..
- **Input:** I_Loads.txt and I_SG.txt. Section B.1.6.1.
- **Output:** The Global File - O_GALE_G_wsNL.txt - and The Specific File - Beta_GALE_wsNL.txt. Section B.1.6.2.
- **Modules List:** Input_OF.py, Z_HDRprint_Input.py, Z_HDRprint_Input.py, Exaus_ES.py, Decode_ES_GALE.py, Beta_OF.py, LPE_OF.py, FF_ES_Nelson.py.
- **Supporting Tools:** Embedded codes. External Code: as required Fitness Function files.
- **Dependencies/Hierarchy:** Figure B.24.

- **Code Execution:** Go to *Level 1* and choose *IC* and run its master file in its *Level 2*. Do visual inspection of the IC plots stored in *O*. Adjust input strain gauge data as required. Go to *Level 1* folder *ES_N*, store last Input Files in *I* folder and run the Master File all at *Level 2*. Find outputs in *O* folder of the *ES_N* associated code. Figure B.5 to understand Code folders/files locations.
- **Approach Type:** Semi-automated, before accepting the best chromosome, the GALE summary table should be checked and assessed if the solution converges throughout the generations. In fact, the termination criteria is a given number of generations, that could be varied, and other variables too might be tuned as required.

In relation to the general genetic algorithm flow chart of Figure B.16 the following information characterises GALE.

Note:

- ✓ Population Initiation: Random.
- ✓ Reproduction: Roulette Wheel Selection.
- ✓ Mutation: Site random selected and bit flip.
- ✓ Termination: selected number of generations.
- ✓ Every time the random process will generate an individual whose gene will have zero allele (IA, Individual to Avoid), being physically not acceptable, it will be replaced automatically by an individual with all "ones" alleles.
- ✓ This environment allows to plug in any fitness function. In fact, initially it was conceived to host the Nelson's, **GA**, and present research, **LPP**, fitness functions. Now, the dotted-pattern fill boxes of Figure B.24 shows the python codes driving the fitness function, responsible of the ranking criteria, that in this case is the Load Probable Error.
- ✓ GALE Validation: Next chapter will compare the results produced by same ranking criteria with different engine searches, genetic algorithm and exhaustive search.

GALE it could be useful if decided to use of each strain gauge not two to the power of the number of strain gauge per station but three to the power, the base is three when, it is practice of the loads measurement practitioner, to use a redundancies. This brings to choose among A. no strain gauge, B. Strain Gauge I, C. Strain Gauge II (redundancies).

B.1.7.8 Stage One: The Relevance Coefficient, Rc

The schematic of the computation displayed in Figure 4.5 for the *DLD* technique applies to the *RC* method as the structure is maintained, the input file is manipulated in order to meet the relevance coefficient described in section 4.4.5. The *RC* Python Code description follows:

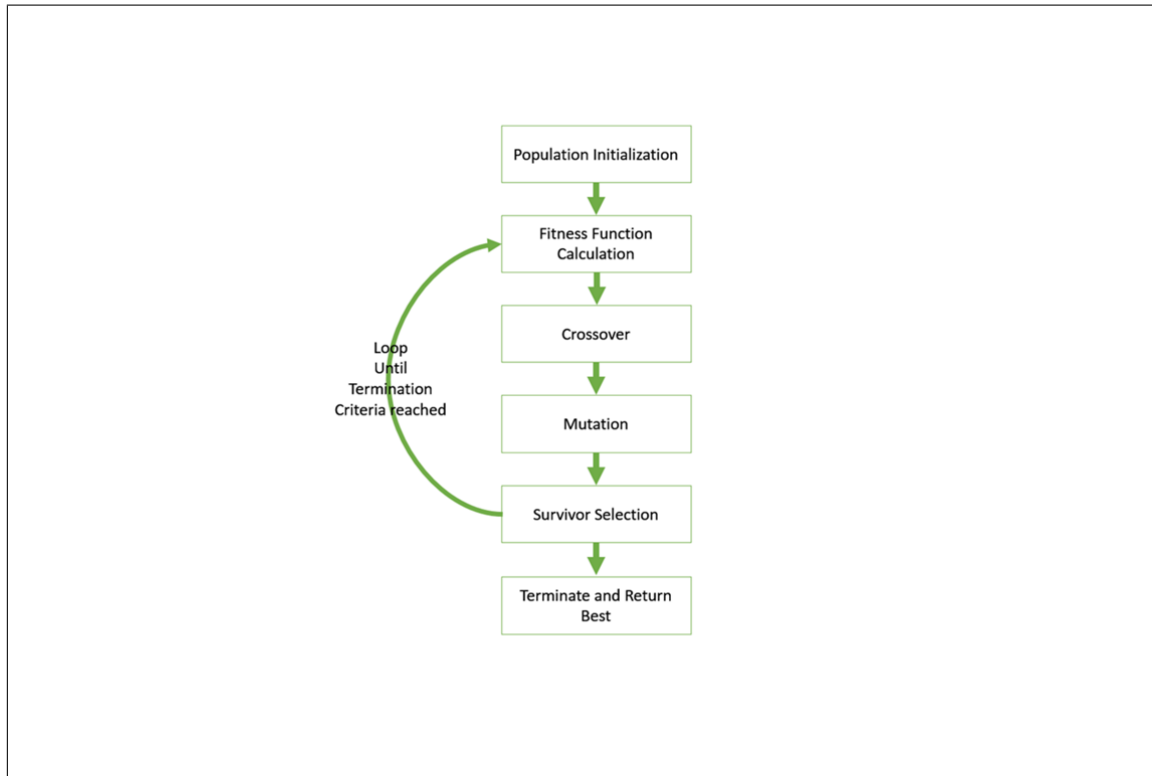


Figure B.16: GALE Basic Structure.

- **Ranking Criteria:** The Distributed Load Data, **DLD**. Section 4.4.5 & Eq. (4.9).
- **Algorithm Typology:** Exhaustive Search and "supporting tools".
- **Folder Name:** *ES_LPE*
- **Master File:** A_LE_ES_LPE_TheOne.py.
- **Input:** I_Loads.txt and I_SG.txt. Section B.1.6.1.
- **Output:** The Global File - O_ESlpe_G_wsNL.txt - and The Specific File - Beta_ESlpe_wsNL.txt. Section B.1.6.2.
- **Modules List:** Input_OF.py, Z_HDRprint_Input.py, Z_HDRprint_Input.py, Exaus_ES.py, Decode_ES_GALE.py, Beta_OF.py, LPE_OF.py .
- **Supporting Tools:** Embedded codes. External Codes: **IC** and **RCR**.
- **Dependencies/Hierarchy:** Figure B.20.
- **Code Execution:** Go to *Level 1* and choose *RCR*, and Run its master file in its *Level 2*, in this level take the associated output files from *O* and store to the next Input folder needed. Then, Go to *Level 1* and choose *IC* and run the Master File in its *Level 2* with the outputs of *I2D*. Do visual inspection of the *IC* plots stored in *O*. Adjust input strain gauge data as required. Go to *Level 1* folder *ES_LPE*, store last Input Files in *I* folder and run the Master File all at

Level 2. Find outputs in *O* folder of the LPE associated code. Figure B.5 to understand Code folders/files locations.

- **Approach Type:** Semi-automated, as **RCR** and **IC** plots inspection needed.

Note:

- ✓ The **RC** technique, mixed of Automated and Step by Step approach, is using as main code the Original Approach to determine the best set of loads equations, the reason behind is the same of the *DLD* technique described above.
- ✓ The output files, as generated by the *ES_LPE* code, will have its file name label as shown above. Afterwards, the name will have to be manually changed in order to replace *ESlpe* by the **RC** label associated with the technique employed.

B.1.7.9 Stage One: The Linearised Physical Parameters method, LPP

The schematic of the computation displayed in Figure 4.21 has been translated by the Python Code description below:

- **Ranking Criteria:** The Linearised Physical Parameters, **LPP**. Section 4.5 & Eq. (4.10), Eq. (4.11) and Eq. (4.12).
- **Algorithm Typology:** Exhaustive Search and "supporting tools".
- **Folder Name:** *ES_LPP*
- **Master File:** *A_LE_ES_Mao_TheOne.py*.
- **Input:** *I_Loads.txt* and *I_SG.txt* and or *I_I2D_Loads.txt* and *I_I2D_SG.txt*. Section B.1.6.1.
- **Output:** The Global File - *O_ESlpp_G_wsNL.txt* - and The Specific File - *Beta_ESlpp_wsNL.txt*. Section B.1.6.2.
- **Modules List:** *Input_OF_IC.py*, *Z_HDRprint_Input.py*, *Z_HDRprint_Input.py*, *Exaus_ES.py*, *Decode_ES_GALE.py*, *Beta_OF.py*, *LPE_OF.py*, *IC_CZ_New.py*, *ICLE_CZ.py*, *Merit_CZ.py*, *Polyfit_GAm.py*, *FF_ES_Mao.py*.
- **Supporting Tools:** Embedded codes. External Codes: **I2D** and **RCR**.
- **Dependencies/Hierarchy:** Figure B.25.
- **Code Execution:** Go to *Level 1* and choose **RCR**, and Run its master file in its *Level 2*, in this level take the associated output files from *O* and store to the next Input folder needed. Then, Go to *Level 1* and choose **I2C** and run its master File in its *Level 2* with the outputs of **I2D**. Go to *Level 1* folder *ES_LPE*, store last Input Files in *I* folder and run the Master File all at *Level 2*. Find outputs in *O* folder of the LPE associated code. Figure B.5 to understand Code folders/files locations.

- **Approach Type:** Fully automated, as **RCR** and **I2D** act just on the Input stage.

Note:

- ✓ The **RC** technique, mixed of Automated and Step by Step approach, is using as main code the Original Approach to determine the best set of loads equations, the reason behind is the same of the *DLD* technique described above.
- ✓ The output files, as generated by the *ES_LPE* code, will have its file name label as shown above. Afterwards, the name will have to be manually changed in order to replace *ESlpe* by the *RC* label asociated with the technique employed.
- ✓ The *IC* and *ICLE* supporting tools are not mentioned as used codes as, being the backbone of the whole technique, have been embedded in the whole code to have a better harmonised and fully automated search tecnique.
- ✓ The LPP is not requiring any visual inspections on the *IC* and *ICLE* as the linearised parameters of the influence coefficients of loads equations will be filtered by a predefined threshold controlling the three main factors of the linearisation, as described in section 4.5. These factors in a post processing stage will allow to have an indirect control on the reliability of the final set of loads equations, as already in the 90s Nelson. [50], was recommending against all those fully automated techniques. The ability of the end user is to tune the R-squared coefficient coherently to the experimental input data available.

B.1.7.10 Stage One: Supporting Tool - Influence Coefficient of strain gauges, IC

The concept of the influence coefficient of strain gauges has been translated by the Python Code description below:

- **Ranking Criteria:** The Influence Coefficient of strain gauges, **IC**. Section 4.3 & Eq. (4.2). It is part of the category of Ranking Criteria, *RC Physical Properties* as displayed in Figure
- **Algorithm Typology:** Supporting tool contributing to review the input files.
- **Folder Name:** *IC_ICLE*
- **Master File:** *A_IC_TheOne.py*.
- **Input:** *I_Loads.txt* and *I_SG.txt*. Section B.1.6.1.
- **Output:** Global File - *O_IC_G_wsNL* - and Specific File, Plots as many as the Input of strain gauges (*n*) - *IC_Global_n.pdf* . Section B.1.6.2.
- **Modules List:** *Input_OF_IC.py*, *Z_HDRprint_Input.py*, *Z_HDRprint_Input.py*, *IC_CZ_New.py*

- **Transfer Functions:** IC interacts with all codes but the **LPP** as embedded in it.
- **Dependencies/Hierarchy:** Figure B.26.
- **Code Execution:** Go to *Level 1* and choose *IC_ICLE*, and Run its master File in its *Level 2*, in this level take the associated output files from *O* and post process the results accordingly.
- **Approach Type:** Automated, at the end plots inspection needed.

B.1.7.11 Stage One: Supporting Tool - Influence Coefficients of Loads Equations, ICLE

The concept of the influence coefficient of loads equations has been translated by the Python Code description below:

- **Ranking Criteria:** The Influence Coefficient of loads equations, **ICLE**. Section 4.3 & Eq. (4.5). It is part of the category of Ranking Criteria, *RC Physical Properties* as displayed in Figure
- **Algorithm Typology:** Supporting tool, directly linked with *IC* by definition, contributing to review the input files.
- **Folder Name:** *IC_ICLE*
- **Master File:** *A_ICLE_TheOne.py*.
- **Input:** *I_Loads.txt* and *I_SG.txt*. Section B.1.6.1.
- **Output:** Global File - *O_ICLE_G_wsNL*. Section B.1.6.2.
- **Modules List:** *Input_OF_IC.py*, *Z_HDRprint_Input.py*, *Z_HDRprint_Input.py*, *IC_CZ_New.py*, *ICLE_CZ_New.py*
- **Transfer Functions:** **ICLE** interacts with **ESM**, with **LPP** is embedded in it.
- **Dependencies/Hierarchy:** Figure B.27.
- **Code Execution:** Go to *Level 1* and choose *IC_ICLE*, and Run its master File in its *Level 2*, in this level take the associated output files from *O* and post process the results accordingly.
- **Approach Type:** Automated, the post processing on stats stored in the Global output files as no plots offered.

B.1.7.12 Stage One: Supporting Tool - Individual to Distributed, I2D

The basic concept of of Hovell, Webber and Roberts, [43] and [44], to apply distributed load data into the calculation process of flight loads equations, has been generated by superposition of the individual input data by the Python Code details below:

- **Ranking Criteria:** The Individual Load data to Distributed, **I2D**. Section 4.4.1 and 4.5.1. It is part of the category of Ranking Criteria, *RC Physical Properties* as displayed in Figure
- **Algorithm Typology:** Supporting tool contributing to review the input files.
- **Folder Name:** *ES_I2D*
- **Master File:** *A_I2D_TheOne_M1.py*. and *A_I2D_TheOne_M2.xlsx*.
- **Input:** *I_I2D_Loads.txt* and *I_I2D_SG.txt*. Section B.1.6.1.
- **Output:** *I_ID2_Loads.txt* - and *I_I2D_SG.py*, Global file *I_I2D_G.py*. . Section B.1.6.2.
- **Modules List:** *Input_I2D.py*, *Input_OF_IC.py*, *Z_HDRprint_Input.py*, *Z_HDRprint_Input.py*, *LSGi_I2D.py*.
- **Supporting Tools:** Embedded codes. External Codes: **RQR**, **Relevance Coefficient Requests** and **FLSR**, Flight Load Specific Range, Figure 4.21.
- **Dependencies/Hierarchy:** Figure B.28.
- **Code Execution:** Go to *Level 1* and choose *I2D*, and Run the Master File in its *Level 2*, in this level take the associated output files from *O* and store to the next Input folder needed.
- **Approach Type:** Semi Automated, as few checks should be performed to gain confidence on the final results and it is requiring the use of Python and Excel codes.

Note:

- ✓ Particular LETE Supporting Tools using the contribution of Python and Excel codes.
- ✓ The **FLSR**, Flight Load Specific Range, already introduced in section 4.4, is not coded here as is mainly conceptual than driven by any specific Algorithm. In addition, it requires flight test information than needs to be specifically generated, as detail coordinates of the Centre of Pressure, CoP flight loads to measure. Once, available the flight CoP, evaluated by **FLSR**, the information will be used by **I2D** in order to generate a set of distributed load case closer to those one meant to be measured in flight. This information might be used in the Phase of conception and design of the flight loads measurement campaign once defining the ground load calibration load cases.

- ✓ The **RCR**, Relevance Coefficient Request, concept already introduced in Figure 4.21, represents the employment of a single equation, Eq. (4.9), to assess how much surface of the test article is covered during the ground load calibration compared to the wet surface of the real flight test. In order to apply this single module master file supporting tool, `A_RCR_TheOne.py`, it is necessary to know details of the experimental phase such as the size of the rubber pad used to introduce the individual or distributed load.

B.1.7.13 Stage Two and Stage Three: The Linearised Regression, LIRE

The concept of the linear regression employed to generate the load coefficients has been translated by the Python Code description below:

- **Ranking Criteria:** The LInear REgression, **LIRE**. Section 4.3 & Eq. (4.5). It is part of the category of Ranking Criteria, *RC Physical Properties* as displayed in Figure
- **Algorithm Typology:** Supporting tool, directly linked with *IC* by definition, contributing to review the input files.
- **Folder Name:** *LIRE*
- **Master File:** `A_LIRE_TheOne.py`.
- **Input:** `I_Loads.txt` and `I_SG.txt`. Section B.1.6.1.
- **Output:** Global File - `O_LIRE_RMS_wsNL`. Section B.1.6.2.
- **Modules List, Module 1:** `LIRE_Module1_CZ.py`, `Input2_OF.py`, `Beta_OF.py`, `LPE_OF.py`
- **Modules List, Module 2:** `LIRE_Module2_CZ.py`, `Input2_OF_ILC.py`, `Z_HDRprint_Input.py`, `Z_HDRprint_Input.py`, `Beta_OF.py`, `LPE_OF_New.py`
- **Transfer Functions:** *ICLE* interacts with *ESM*, with *LPP* is embedded in it.
- **Dependencies/Hierarchy:** Figure B.29.
- **Code Execution:** Go to *Level 1* and choose *LIRE*, and Run its master File, either Module 1 or Module 2, in its *Level 2*, in this level take the associated output files from *O* and post process the results accordingly.
- **Approach Type:** Automated, the post processing on stats stored in the Global output files as no plots offered.

Note:

- ✓ The **LIRE Module M1** technique is calculating the load coefficients without calculating all permutations available. It provides just one set of load equations and for this offers the *LPE*. This module does not take into account any Independent set of Input Data as Module 2 does.

- ✓ The **LIRE Module M2** technique is calculating the Measured Loads and then comparing the Independent Load, either Point in the Ground or Point the Sky *PP* or Time Histories *TH*, evaluates the percent of root mean square error. This is coded by a sub-module labelled *LPE_OF_New.py*. The label "LPE" comparing in this name is just inherited by the past coding of Module1.
- ✓ This code represents the only tool used to accomplish the role of transfer function of *Stage Two and Stage Three*, TF2 and TF3 as shown in Figure B.2 and Figure B.3.

The calculation of the best techniques to employ is based on the Percent Root-Mean Square Error. Using the Standard Deviation, though it could have worked well, does not relate the magnitude of the error to the size of the load. This is the same reason that convinced Nelson, [79], to present the comparison of all Techniques employed by means of Eq. (B.1) below:

$$\%rms = \frac{100(LPE)}{\sqrt{\sum_{j=1}^m (V_j)^2}} \quad (B.1)$$

Eq. (B.1) above is expanded by replacing the LPE, Loads Probable Error, definition of Eq. (4.4) and the new thorough formulation is:

$$\%rms = \frac{100\left(\sqrt{\frac{\sum_{j=1}^m [V_j - (\beta_0 + \sum_{i=1}^n \beta_i \mu_{ij})]^2}{m-n-1}}\right)}{\sqrt{\sum_{j=1}^m (V_j)^2}} \quad (B.2)$$

B.1.7.14 Final Considerations

It is crucial to highlight the difference between the codes and concepts introduced here and their application to a specific test case. In fact, the introduction of some of the supporting tools or transfer functions above, such as **DLD**, **RC**, **I2C** and **RCR**, requires a specific set of input data, in terms of load cases and associated readings, that eventually, are not always available as should be beforehand planned and executed.

This point will be initially considered in section 3.4 and profusely addressed in the next chapter.

B.1.8 LETE Graphical User Interface

The execution of the LETE software has been conceived to be not just with the text-based interfaces, by means of DOS Command line, or any integrated development environment (IDE) for scientific programming in the Python language, such as Spyder that links well with Anaconda Python scientific environment. In fact, for an ease of use, shorter learning curves, preventing the user to memorize or being literate with specific input text commands, the Graphical User Interface, GUI has been employed maximising the simplified interactive graphical elements. Two

distinct GUIs have been designed and shown in Figure B.17 and Figure B.18. The GUIs have been conceived similarly, the green button allows access to *Level 0* of the folders to check and open any input/output files generated by the supporting tools or transfer functions run. The yellow button of the *LETE Stage 1 GUI* highlights the proposed method of this research. *LOCO GUI*, Loads Comparison Stage two and three of LETE, uses just LIRE Module 2, as allows to compare the Loads Measured against Independent set of data coming either from a single point, in the sky or on ground, *PP*, or eventually a full time history reading of strain gauges and known loads.

The Python engine codes described above, section B.1.7, are behind the graphical icons and visual indicators as secondary notation.

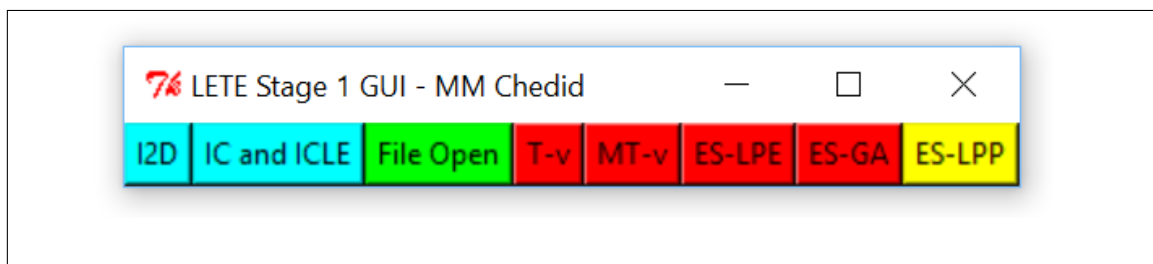


Figure B.17: LETE Stage 1 GUI:Transfer Functions and Supporting Tools.

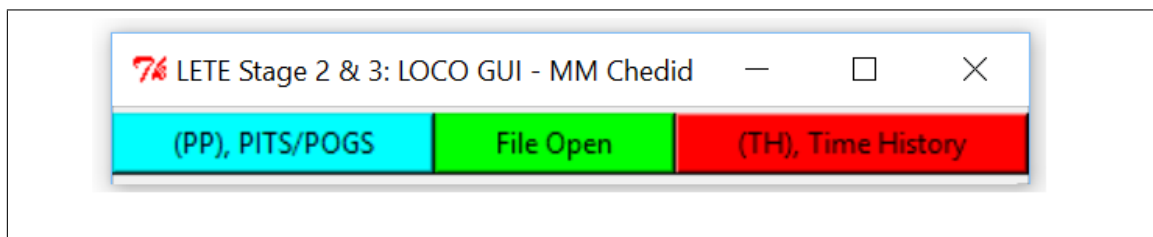


Figure B.18: LETE Stage 2 and 3 GUI:Transfer Functions and Supporting Tools.

The GUI Python files just mentioned above, labelled as "LETE_Stage1_Last.py" and "LETE_Stage2_3_Last.py", represents the two *Master Files* that are stored at *Level 0* of Figure B.5.

B.1.9 Software Process: Version and Configuration Control

The development process of LETE and any other relevant software have been done in compliance with basic common sense principles to ensure that the final version meets the expected conceived and designed functions.

Proper archival and configuration control of software development and its artefacts developed was ensured. In addition, the final code version has been frozen in a well defined fashion, as partially described in this section B.1.1, in order to enable the *Source Code* to be:

- predictable.
- clear and well structured.

- robust.
- well documented and maintainable.
- configuration controlled.
- traceable to requirements and design.

In fact, within each Python module, captured by the control flow graph figures of this appendix, a function prologue introduces the function to the reader/end user and the input and output quantities involved. Figure B.19 displays a generic example of Python module function prologue. That level of information has been presented in every file prologue.

```
#####
def print_HDR( n, fmt):
    """
    print Header A

    INPUT:
    A: Matrix to be printed
    n = amount of columns of A
    fmt = format to be used to print elements of the matrix

    REMARKS:
    A is an array or m arrays.
    Each of the m arrays is a row of the matrix
    The rows contain all n elements
    This file is combined with the file MATprint.py
    """
```

Figure B.19: LETE Generic Python Module: "Z_HDRprint_Input.py", Function Prologue.

The predictability concept has been followed by assuring the source code should be kept as simple as possible preventing the complexity of each package. In fact, the control flow complexity increases with the number of level of nesting and looping incorporated into the code. This may lead to less predictable program control flow. In fact, where control flow complexity is unavoidable, additional testing will be necessary offering less ability to control potential logic errors, difficult to be detected, and reducing the understandability, maintainability, and testability. Program flow may be affected by multiple points of entry and exit of functions and procedures and thus have been carefully avoided.

The robustness has been another pillar of the software development of LETE. In

fact, the variables have been conceived to be initialised. This eliminates reliance on the compiler to set initial set values. Not doing so may lead to using a garbage value residing at a particular memory location. Data validity checking, including type and range validity, has been considered as stored in the Global file of each package as a further indirect control step. The idea is to prevent incorrect results and the propagation of bad data.

All these inherent principles of LETÉ programming are evident, not only in the code lines of each module and function, but also in the structure and hierarchy of the Control Flow Graph figures of the LETÉ transfer functions and supporting tools presented in the coming up section of this Appendix **B.2**.

B.2 LETÉ Transfer Function Python Code Diagrams

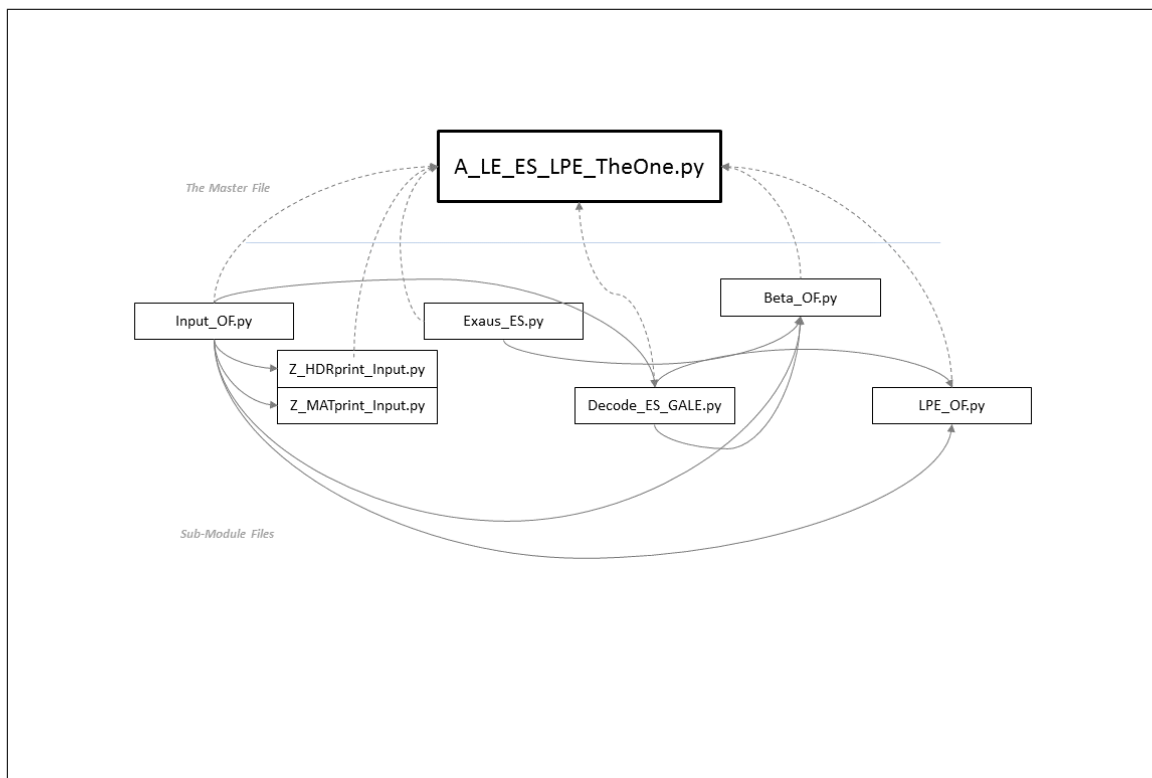


Figure B.20: The "Original Approach, Exhaustive Search", ES_LPE, Stage One - Transfer Function: Control Flow Graph Python Code.

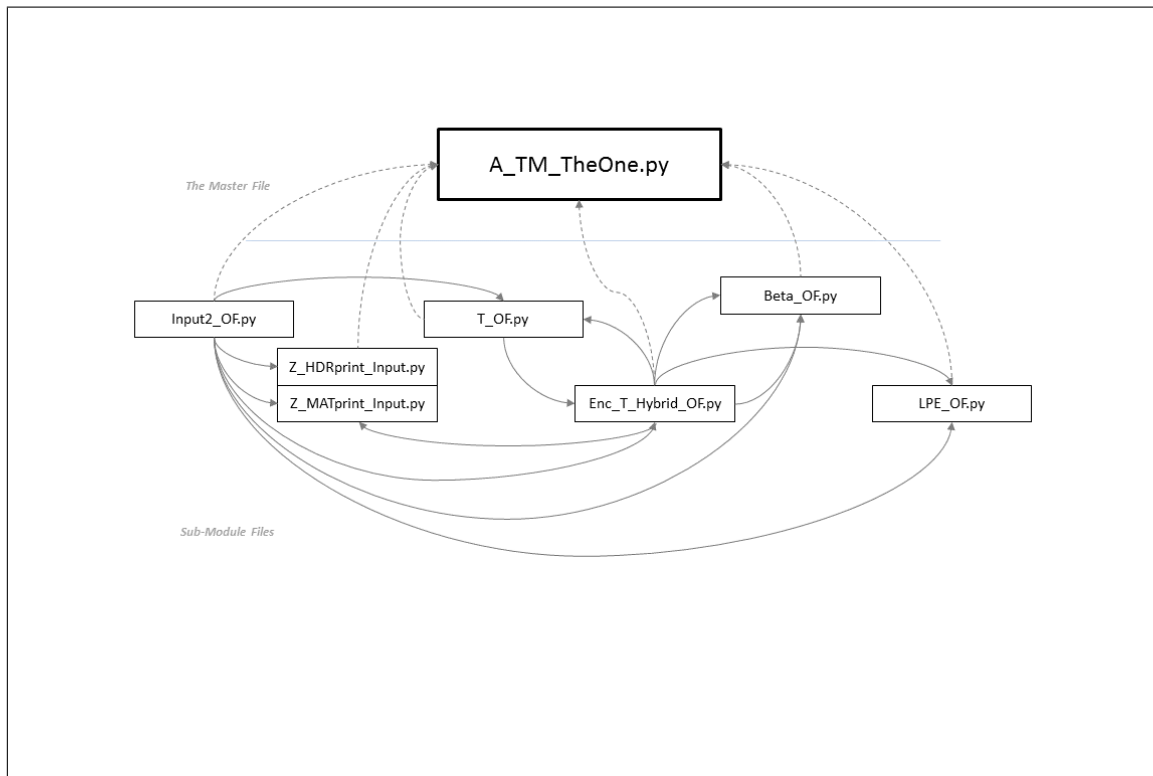


Figure B.21: The "T-value Method", T-v, Stage One - Transfer Fucntion: Control Flow Graph Python Code.

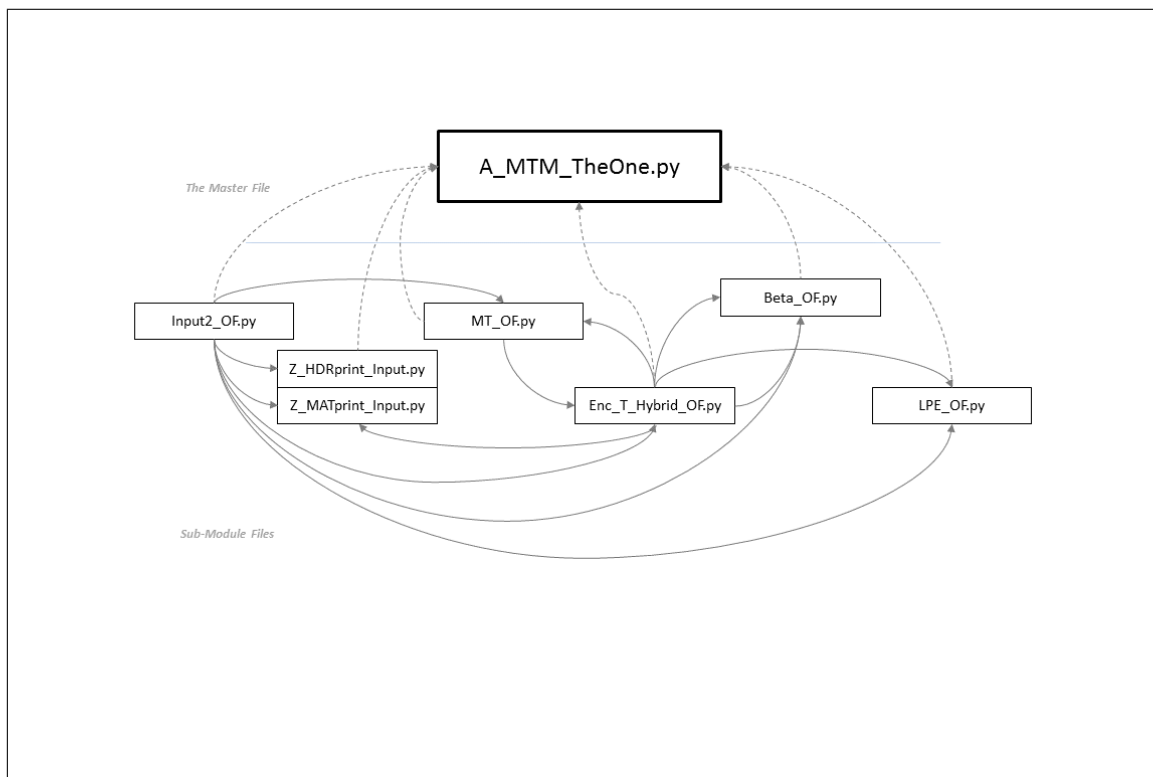


Figure B.22: The "MT-value Method", MT-v, Stage One - Transfer Fucntion: Control Flow Graph Python Code.

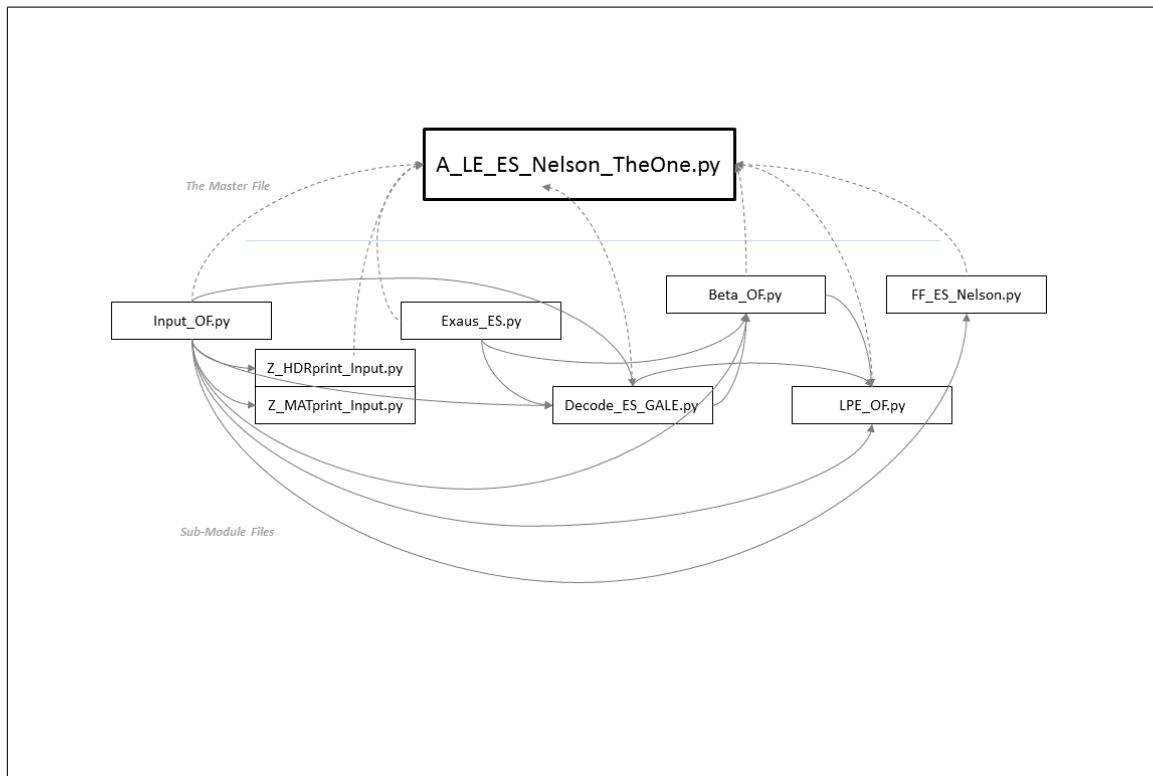


Figure B.23: The "GA Method, Exhaustive Search Nelson", ES_N, Stage One - Transfer Fucntion: Control Flow Graph Python Code.

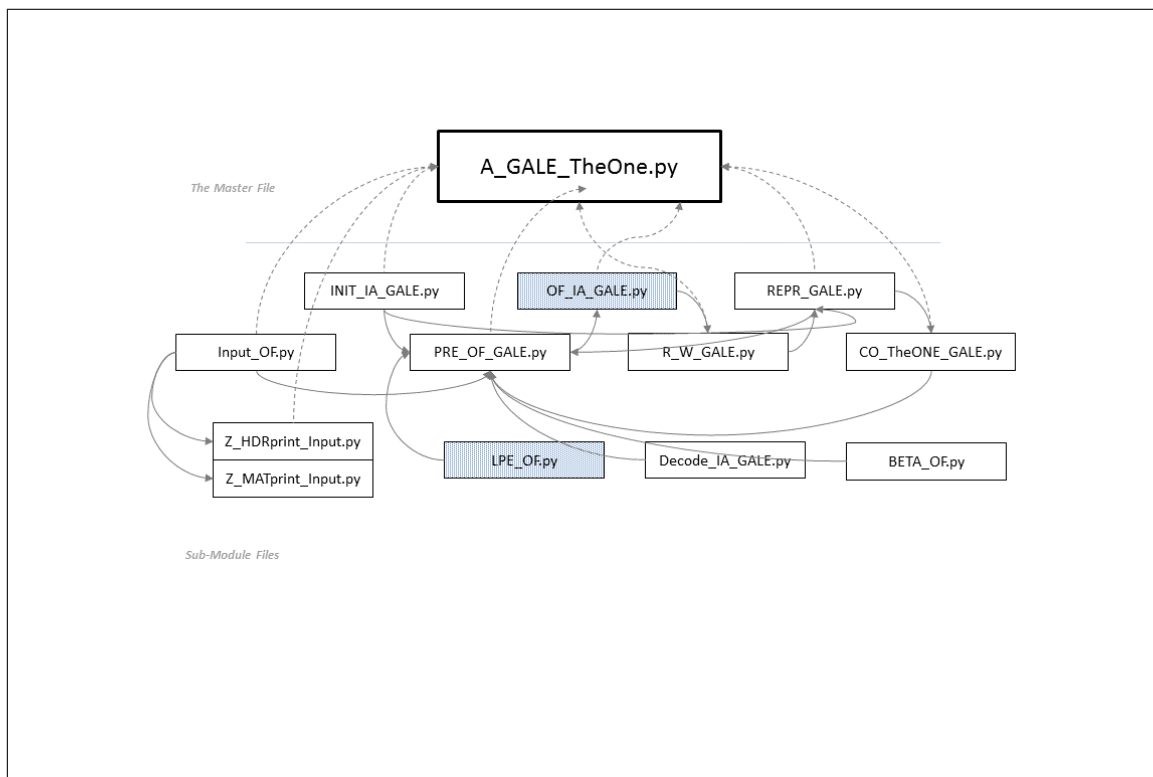


Figure B.24: The "Genetic Alortihm of Loads Equations" environment, GALE, Stage One - Transfer Fucntion: Control Flow Graph Python Code.

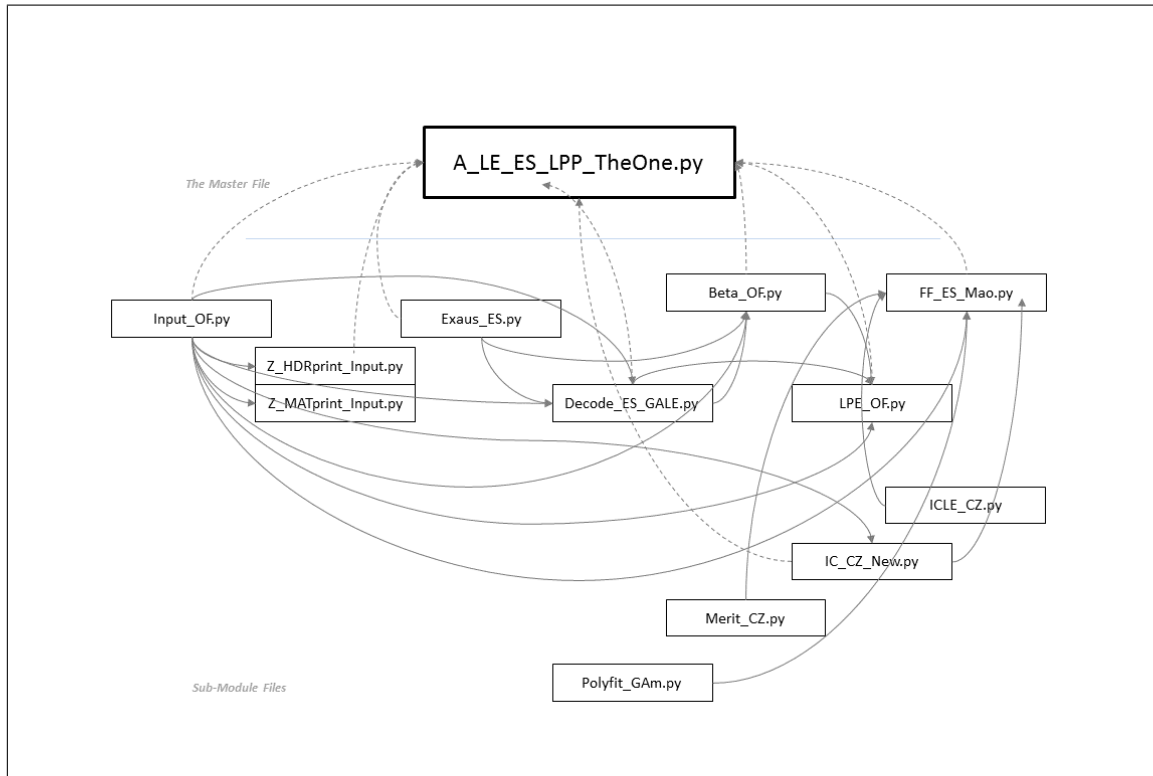


Figure B.25: The "Linearised Physical Parameters Method, Exhaustive Search LPP", ES_LPP, Stage One - Transfer Fucntion: Control Flow Graph Python Code.

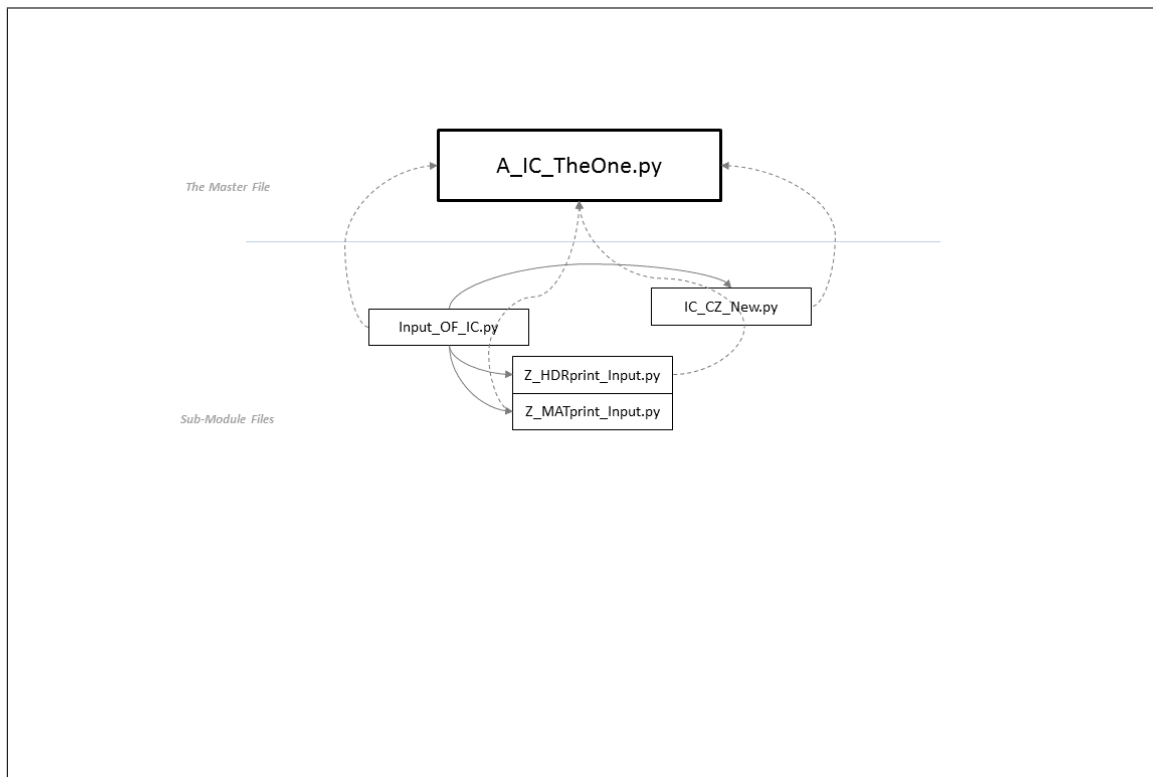


Figure B.26: The "Influence Coeffcieints of Strain Gauges", IC, Stage One - Supporting Tool: Control Flow Graph Python Code.

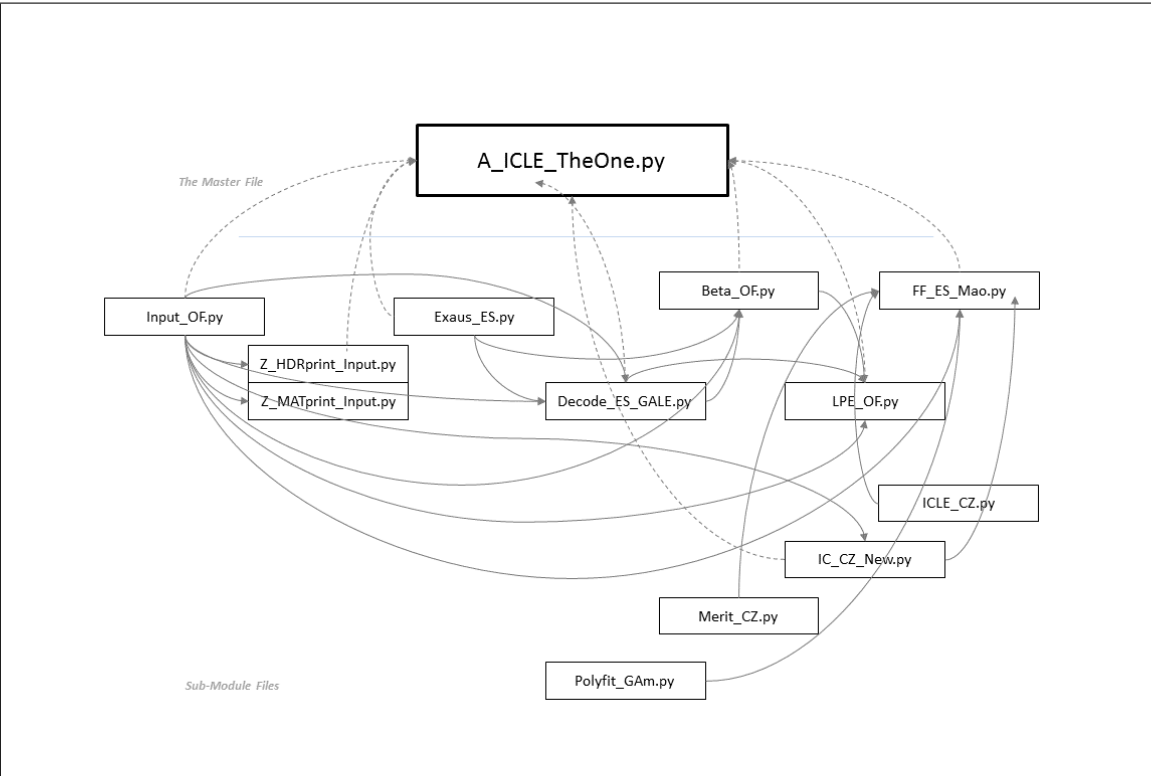


Figure B.27: The "Influence Coefficients of Loads Equations", ICLE, Stage One - Supporting Tool: Control Flow Graph Python Code.

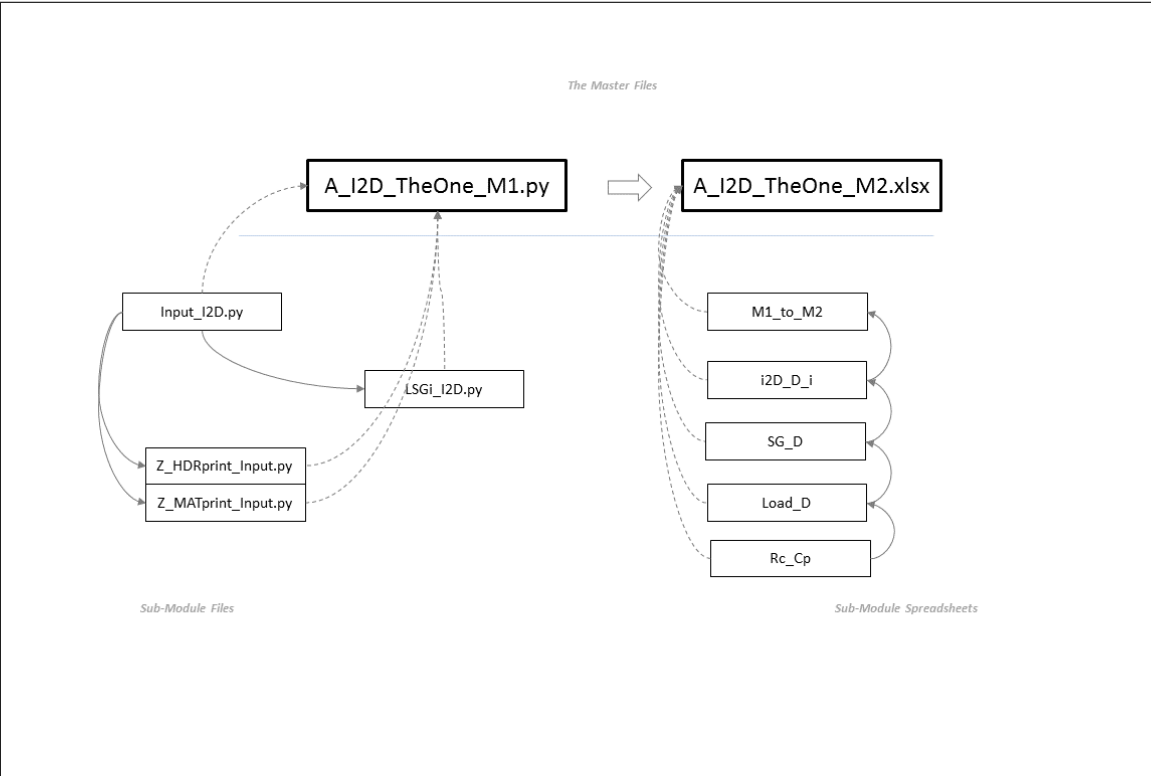


Figure B.28: The "Individual to Distributed", I2D, Stage One - Supporting Tool: Control Flow Graph Python Code and Excel Spreadsheets.

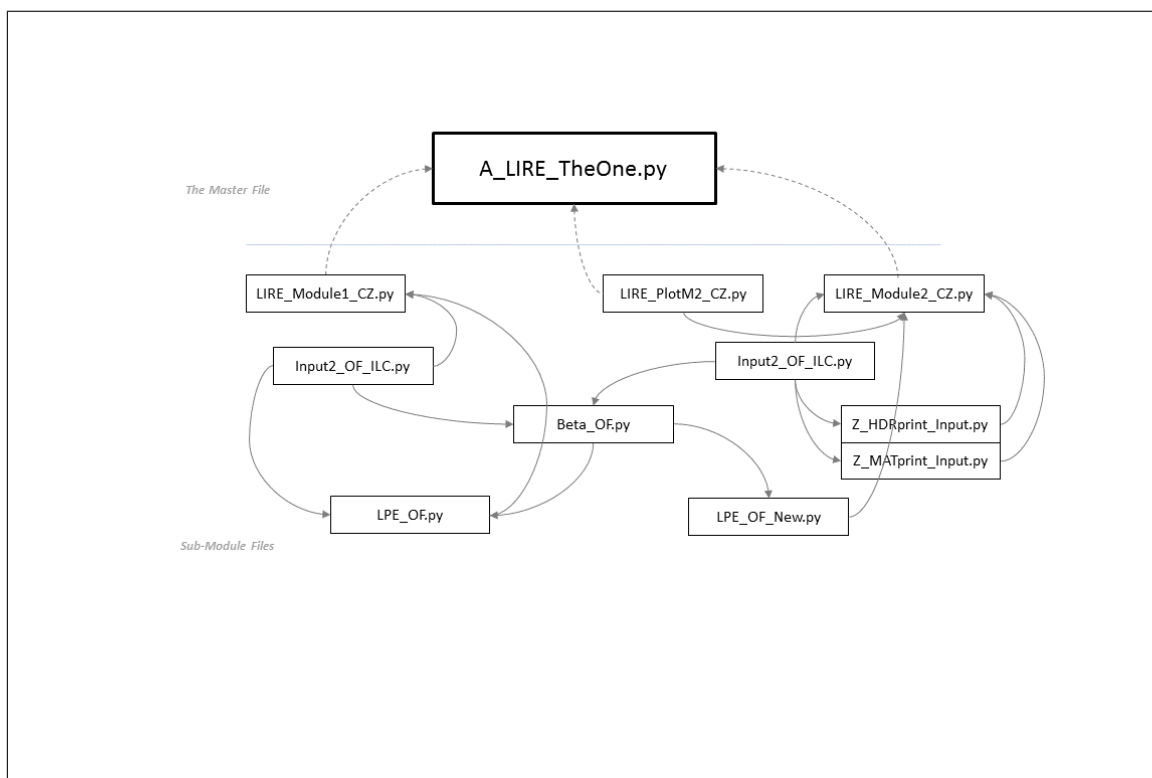


Figure B.29: The "Linearised REgression", **LIRE**, Stage One - Supporting Tool: Control Flow Graph Python Code.

Appendix C

Appendix - Chapter 5


```

Influence Coefficient - Program (vers 1.0.0) - Mao
##### Input Data #####
Reference NCH Report 1179, Skopinski et al., Decade 1990 - Structure A
Calibration Data Basics
-----
Number of load cases= 9
Number of Spanwise load case stations= 3
Number of Chordwise load case stations= 3
Number of Strain Gauges measured= 3

Strain Gauge Readings - [microstrain*10**4]
-----
          SG 01      SG 02      SG 03
1.815      2.809      0.267
1.091      3.401      1.108
-0.004      1.922      2.670
0.881      1.370      0.660
0.816      1.212      1.117
0.168      1.088      1.554
0.234      0.481      0.270
0.164      0.451      0.265
0.068      0.486      0.471

Load Case Magnitude Readings - [lb]
-----
2500.000
2500.000
2500.000
1500.000
1500.000
1500.000
500.000
500.000
500.000

Load Case Spanwise Application Point Stations - [in]
-----
50.000
50.000
50.000
150.000
150.000
150.000
198.500
198.500
198.500

Load Case Chordwise Application Points Stations - [in]
-----
20.000
40.000
60.000
20.000
40.000
60.000
20.000
40.000
60.000
##### Output Data #####

```

Figure C.1: IC Validation: Output text file of IC Software - Test Case 1, *Structure A* Right Shear bridges, "right side loaded" input data - [102].

```

##### Output Data #####
-----
msomomomomomo
-----
Influence Coefficients [(10**4)*(microstrain/lb)] @ Different SG1, SG2 and SG3
-----
IC_1[-] IC_2[-] IC_3[-]
7.2600 11.2120 1.4680
4.3640 13.6040 4.4320
-0.0160 7.6920 10.6800
5.8733 9.1333 4.4000
3.4400 8.0800 7.4467
1.1200 7.2533 10.3600
4.6800 9.6200 5.4000
3.2800 9.0200 7.3000
1.2600 9.1200 9.4200
-----
Influence Coefficients [(10**4)*(microstrain/lb)] of SG1 per each Spar Load Point
-----
Span St. S1[-] S2[-] S3[-]
50 7.2600 4.3640 -0.0160
130 5.8733 3.4400 1.1200
198 4.6800 3.2800 1.2600
-----
Influence Coefficients [(10**4)*(microstrain/lb)] of SG2 per each Spar Load Point
-----
Span St. S1[-] S2[-] S3[-]
50 11.2120 13.6040 7.6920
130 9.1333 8.0800 7.2533
198 9.6200 9.0200 9.1200
-----
Influence Coefficients [(10**4)*(microstrain/lb)] of SG3 per each Spar Load Point
-----
Span St. S1[-] S2[-] S3[-]
50 1.4680 4.4320 10.6800
130 4.4000 7.4467 10.3600
198 5.4000 7.3000 9.4200
-----
##### End Data #####

```

Figure C.2: IC Validation: Output text file of IC Software - Test Case 1, *Structure A* Right Shear bridges, "right side loaded" output data - [102].

```

Influence Coefficient - Program (vers 1.0.0) - Mac
##### Input Data #####
Reference NACA Report 1175, Skopinski et al., Decade 1950 - Structure A

Calibration Data Review
-----
Number of load cases= 9
Number of Spanwise load case stations= 3
Number of Chordwise load case stations= 3
Number of Strain Gauges measured= 3

Strain Gauge Readings - [microstrain*10**4]
-----
SG 01 SG 02 SG 03
-0.020 0.524 -0.450
-0.462 0.490 -0.210
-0.725 0.413 -0.059
-0.817 1.055 -0.515
-0.904 1.050 -0.455
-0.981 1.014 -0.362
-0.473 0.619 -0.210
-0.442 0.469 -0.211
-0.474 0.464 -0.183

Load Case Magnitude Readings - [lb]
-----
2500.000
2500.000
2500.000
1500.000
1500.000
1500.000
500.000
500.000
500.000

Load Case Spanwise Application Point Stations - [in]
-----
-50.000
-50.000
-50.000
-130.000
-130.000
-130.000
-198.500
-198.500
-198.500

Load Case Chordwise Application Points Stations - [in]
-----
20.000
40.000
60.000
20.000
40.000
60.000
20.000
40.000
60.000

##### Output Data #####

```

Figure C.3: IC Validation: Output text file of IC Software - Test Case 1, *Structure A* Right Shear bridges, "left side loaded" input data - [102].

```

##### Output Data #####
-----
maomamaomao
-----
Influence Coefficients [(10**4)*(microstrain/lb)] @ Different SG1, SG2 and SG3
-----
IC_1[-] IC_2[-] IC_3[-]
-0.0800 2.0960 -1.8000
-1.8480 1.9600 -0.8400
-2.9000 1.6520 -0.2360
-5.4467 7.0333 -3.4333
-6.0267 7.0000 -3.0533
-6.5400 6.7600 -2.4133
-9.4600 12.3800 -6.2000
-8.8400 9.2800 -4.2200
-9.4800 9.2800 -3.6600
-----
Influence Coefficients [(10**4)*(microstrain/lb)] of SG1 per each Spar Load Point
-----
Span St. S1[-] S2[-] S3[-]
-50 -0.0800 -1.8480 -2.9000
-130 -5.4467 -6.0267 -6.5400
-198 -9.4600 -8.8400 -9.4800
-----
Influence Coefficients [(10**4)*(microstrain/lb)] of SG2 per each Spar Load Point
-----
Span St. S1[-] S2[-] S3[-]
-50 2.0960 1.9600 1.6520
-130 7.0333 7.0000 6.7600
-198 12.3800 9.2800 9.2800
-----
Influence Coefficients [(10**4)*(microstrain/lb)] of SG3 per each Spar Load Point
-----
Span St. S1[-] S2[-] S3[-]
-50 -1.8000 -0.8400 -0.2360
-130 -3.4333 -3.0533 -2.4133
-198 -6.2000 -4.2200 -3.6600
-----
##### End Data #####

```

Figure C.4: IC Validation: Output text file of IC Software - Test Case 1, *Structure A* Right Shear bridges, "left side loaded" output data - [102].

```

-----
main counter5
-----
-45.000 -48.000 -44.000
6.000 -18.000 -14.000
12.000 49.000 3.000
33.000 88.000 19.000
-36.000 -48.000 -37.000
5.000 -10.000 -8.000
22.000 51.000 8.000
41.000 99.000 23.000
6.000 -19.000 -9.000
23.000 22.000 4.000
37.000 63.000 16.000
52.000 104.000 27.000
6.000 5.000 1.000
9.000 12.000 3.000
11.000 18.000 5.000
14.000 25.000 8.000
5.000 7.000 2.000
6.000 10.000 3.000
5.000 12.000 3.000
9.000 14.000 4.000
T-Coefficients[10.704273218644328, 9.3519377682047917, -24.541857220803984]
Load Coefficients[ 41.2470801 15.91506356 -93.295855491]
Probable Error of the Estimate:136.977911256
percentage of RMS:3.49151328971
-----
main counter6
-----
-45.000 -44.000
6.000 -14.000
12.000 3.000
33.000 19.000
-36.000 -37.000
5.000 -8.000
22.000 8.000
41.000 23.000
6.000 -9.000
23.000 4.000
37.000 16.000
52.000 27.000
6.000 1.000
9.000 3.000
11.000 5.000
14.000 8.000
5.000 2.000
6.000 3.000
5.000 3.000
9.000 4.000
T-Coefficients[14.31652372019062, -13.37446594462275]
Load Coefficients[ 68.00603407 -90.75662171]
Probable Error of the Estimate:248.142705058
percentage of RMS:6.22506454672
-----
The Best Loads Equation, with the lowest Probable Error of Estimate (LPE), follows:
[1, 1, 1, 1, 1, 1, 1]
[[-60.0978, 45.2168, 20.2355, -1.2611, -52.2062, -27.7336, 10.1558, 1.511]]

```

Figure C.5: Strain Gauge Reduction, SgR, Validation: *SgR T-value* Software Output text file - Test Case 2, *Structure: Vertical Fin* output data, part III.

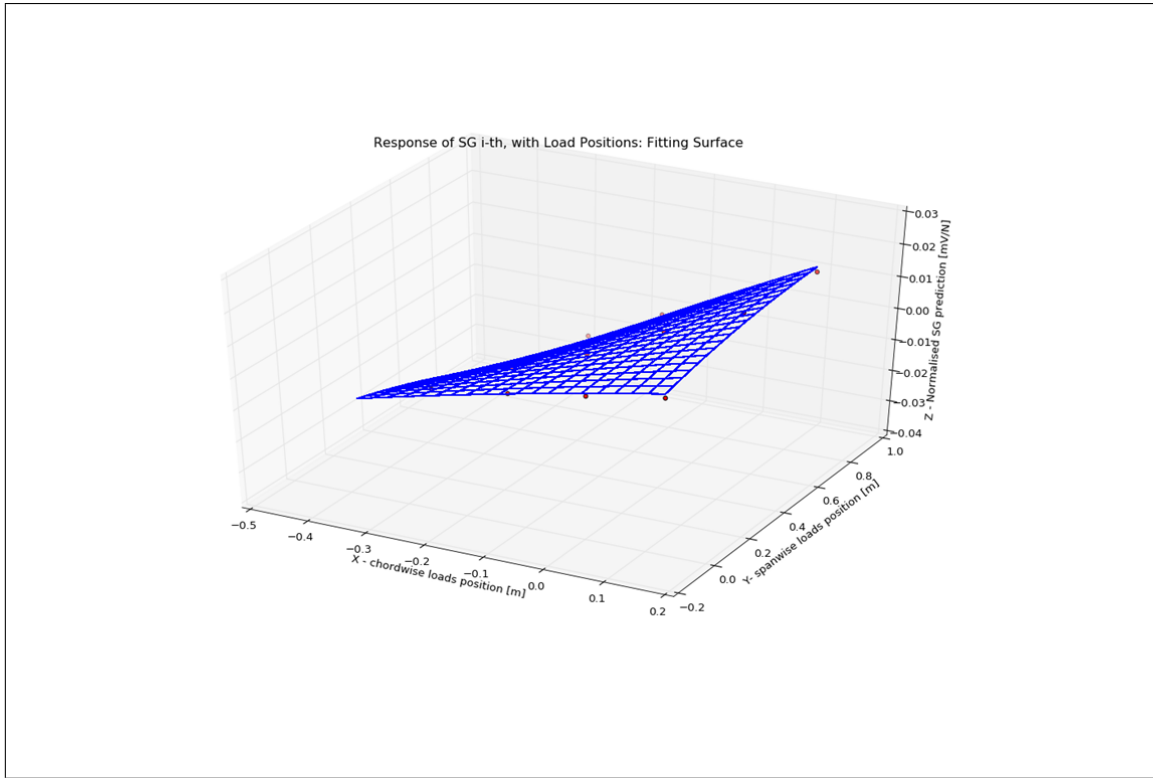


Figure C.6: I2D M1 Validation: **Run1**, Response of Gauge SG01: μ_{TF} with position of load and fitting surface - Test Case 2 - [90].

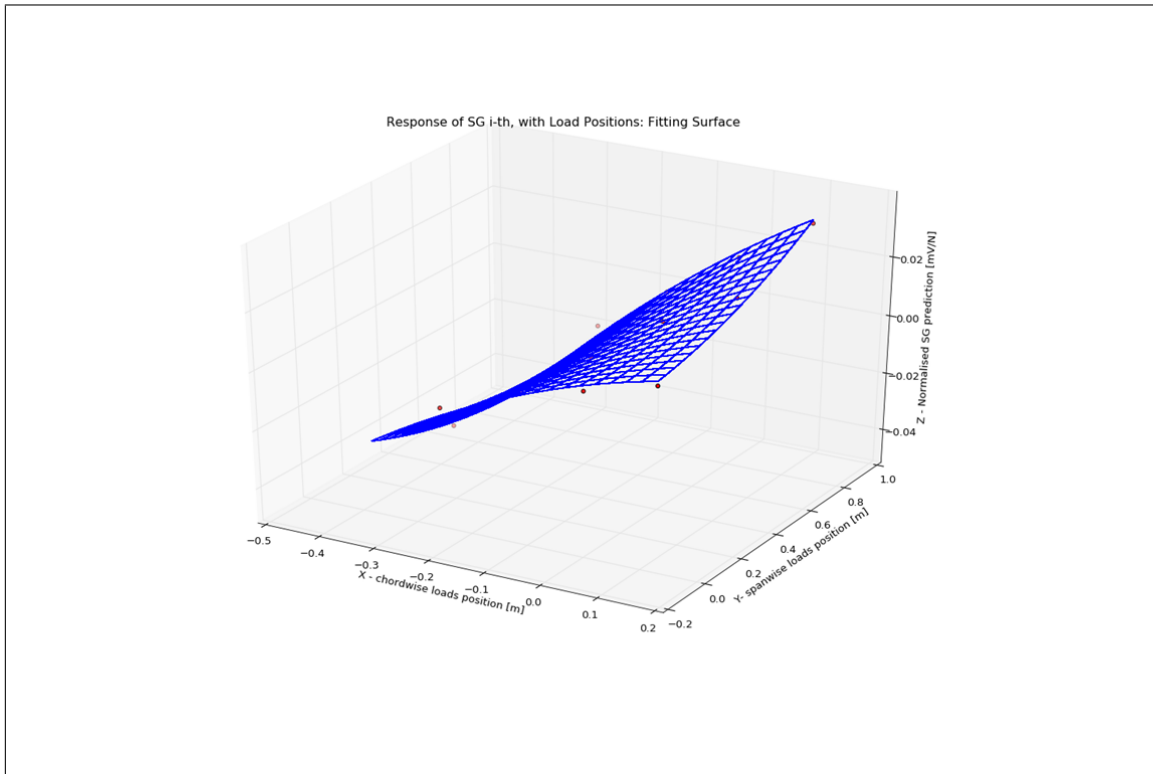


Figure C.7: I2D M1 Validation: **Run1**, Response of Gauge SG02: μ_{TR} with position of load and fitting surface - Test Case 2 - [90].

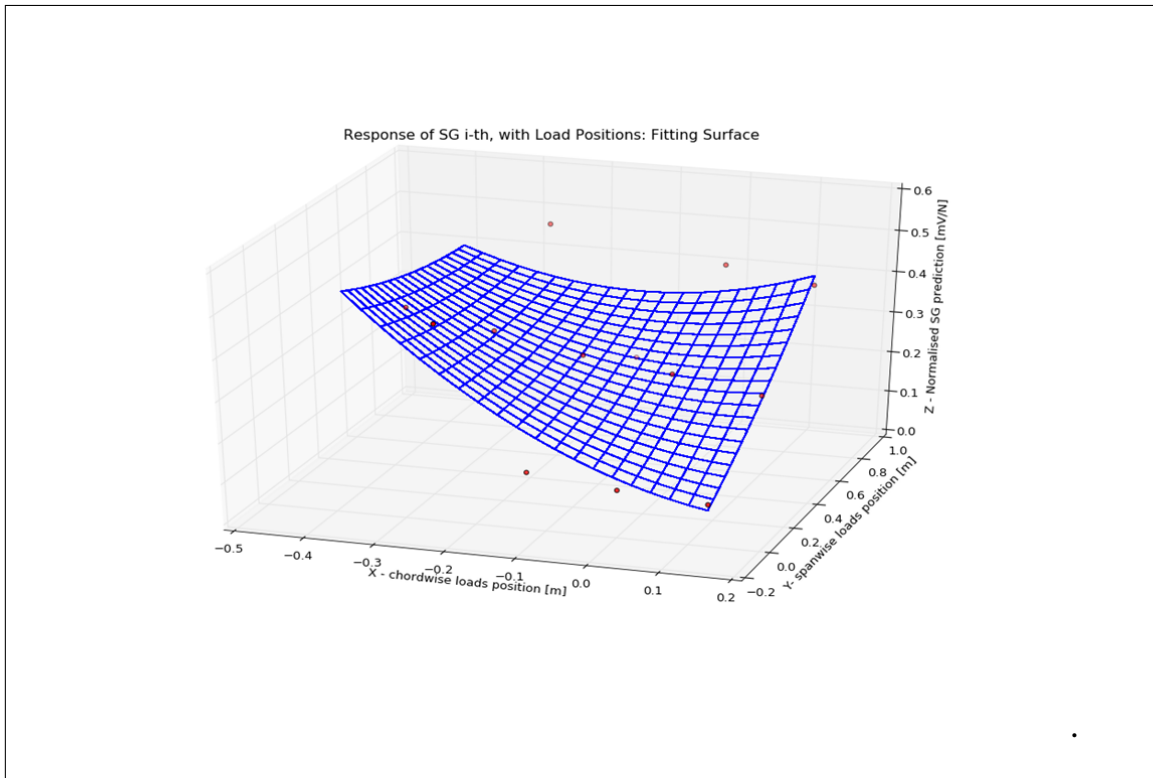


Figure C.8: I2D M1 Validation: **Run1**, Response of Gauge SG03: μ_V with position of load and fitting surface - Test Case 2 - [90].

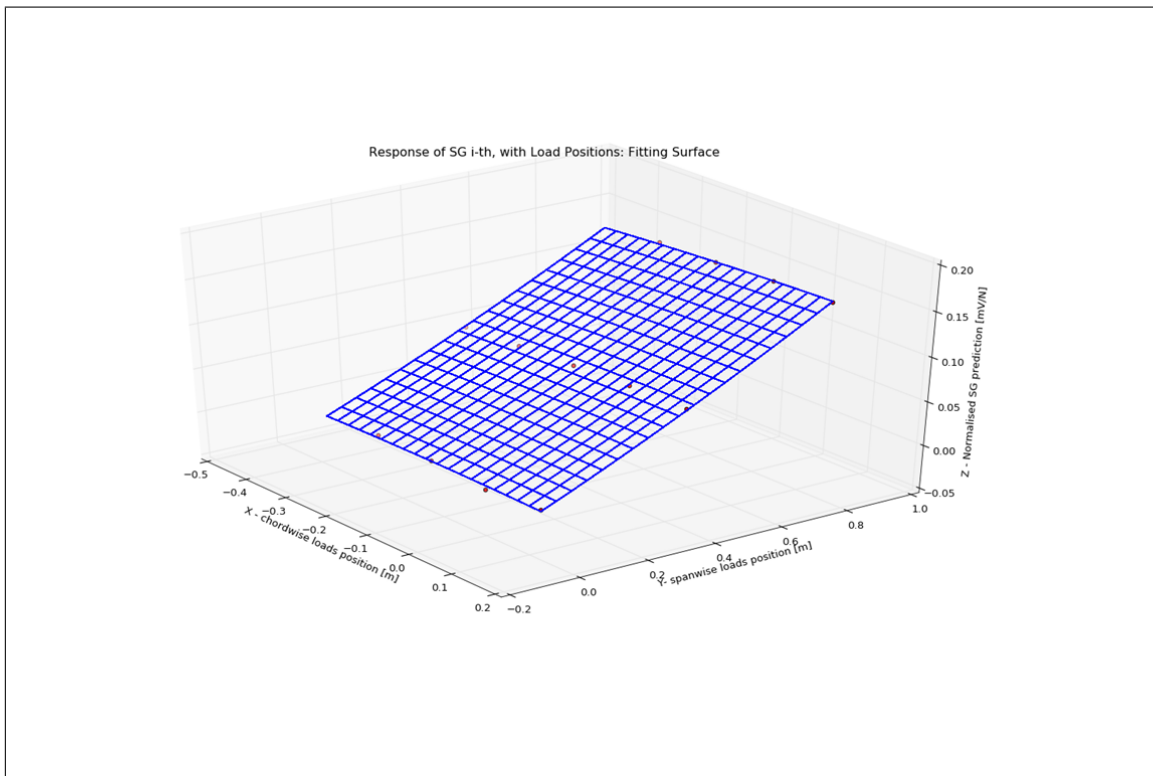


Figure C.9: I2D M1 Validation: **Run1**, Response of Gauge SG04: μ_M with position of load and fitting surface - Test Case 2 - [90].

```

Individual to Distributed, I2D Module M1 - Program (vers 1.0.0) - Mao
Reference NASA TN D-7979 - Peeler et al. - Decade 70s - Test Case 1: Structure Wing I
***** Input Data *****

Calibration Data Basics
-----
Number of load cases= 13
Number of Spanwise load case stations= 4
Number of Chordwise load case stations= 3
Number of Strain Gauges measured= 4

Strain Gauge Readings - [(10**-3)microstrain]
-----
      SG 01   SG 02   SG 03   SG 04
      0.003   0.004   0.033   0.001
      0.002   0.002   0.038  -0.001
      0.000  -0.000   0.046   0.001
     -0.001  -0.004   0.167   0.002
      0.007   0.009   0.086   0.028
      0.003   0.004   0.098   0.028
     -0.001  -0.002   0.107   0.027
     -0.004  -0.008   0.122   0.026
     -0.007  -0.014   0.136   0.025
      0.005   0.012   0.143   0.057
      0.002   0.007   0.155   0.057
     -0.002   0.001   0.066   0.056
     -0.006  -0.005   0.178   0.055

      X       Y       Loads
      ---
      0.127   0.000  358.000
      0.000   0.000  358.000
     -0.127   0.000  358.000
     -0.254   0.000  358.000
      0.127   0.419  358.000
      0.000   0.419  358.000
     -0.127   0.419  358.000
     -0.254   0.419  358.000
     -0.381   0.419  358.000
      0.127   0.838  358.000
      0.000   0.838  358.000
     -0.127   0.838  358.000
     -0.254   0.838  358.000

***** Output DATA *****

```

Figure C.10: Individual to Distributed, I2D M1 Validation: **Run1**, Output Text File, Input Data - Test Case 2, *Wing I* input data, First Calibration [90].

```

***** Output DATA *****
.. Load Positions and SG Responses Predictions: 3-D Plot, Z Data - Global Output, DD - Local Output, ID.

|Basic Data Base (BDB), SG01 Response
NMM
0.227623629216
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00964833  0.00526125  0.00049501 -0.0046504  0.01490399  0.0068144
 -0.00165436 -0.01050228 -0.01972936  0.01685224  0.00506013 -0.00711114
 -0.01966157]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00526125  0.0360367  0.0076536  0.06957912 -0.01175411 -0.00941957]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.12594519  0.08973046  0.00909349  0.20658217  0.32571174  0.0999693
 0.16023645  0.18587593  0.07956866  0.15617635  0.06144075  0.04320755
 0.17440955]
Fitting Surface Order II: Total Error of the Load Cases:0.174409554753
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =-0.00165435547279
Predicted Strain Gauge =-1.47237637078
Real Strain Gauge =-1.7
Local Error=0.227623629216

```

Figure C.11: Individual to Distributed, I2D M1 Validation: **Run1**, Output Text File: Output Data of Response of Gauge SG01: μ_{TF} .

```

*****
|Basic Data Base (BDB), SG02 Response
NMM
1.4154396855
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.01291755  0.00676878 -0.0019012 -0.01309239  0.02094331  0.01033644
-0.00279164 -0.01844093 -0.03661142  0.03581699  0.02075202  0.00316584
-0.01694155]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00676878  0.05834152  0.00034296  0.08377841 -0.07815762  0.01950297]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.14823849  0.18671825  0.07505915  0.25989759  0.36673901  0.1995688
 0.14993341  0.27960999  0.13676442  0.11717528  0.18006185  0.03144328
 0.32868041]
Fitting Surface Order II: Total Error of the Load Cases:0.328680410715
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =-0.00279164080281
Predicted Strain Gauge =-2.4845603145
Real Strain Gauge =-3.9
Local Error=1.4154396855
*****

```

Figure C.12: Individual to Distributed, I2D M1 Validation: **Run1**, Output Text File: Output Data of Response of Gauge SG02: μ_{TR} .

```

*****
|Basic Data Base (BDB), SG03 Response
NMM
237.07736706
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.07679534  0.13254462  0.22567492  0.35618625  0.23093213  0.231437
 0.26932288  0.3445898  0.45723774  0.42321992  0.36848037  0.35112184
 0.37114435]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.13254462 -0.58614007  0.19049376  1.03817513  1.15881413  0.10865452]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 1.41650142  2.6905656  9.62172431  10.89578849  0.83934357
 4.11741629  3.07370678  0.35033426  7.68013238  2.27780188
 6.31915234  16.55825027  12.51689981]
Fitting Surface Order II: Total Error of the Load Cases:12.5168998098
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =0.269322884337
Predicted Strain Gauge =239.69736706
Real Strain Gauge =2.62
Local Error=237.07736706
*****

```

Figure C.13: Individual to Distributed, I2D M1 Validation: **Run1**, Output Text File: Output Data of Response of Gauge SG03: μ_V .

```

*****
|Basic Data Base (BDB), SG04 Response
NMM
66.3678673702
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.0010285  0.00274317  0.00364365  0.00372993  0.07612642  0.07615394
  0.07536727  0.0737664  0.07135133  0.16012627  0.15846664  0.15599281
  0.15270479]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00274317 -0.01029585  0.16458188  0.03170561 -0.02524007  0.0253528 ]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.15304076  0.47761228  0.03205448  0.29251704  0.13777109  0.1766412
  0.01150489  0.12990257  0.17300483  0.12347729  0.02802777  0.03756039
  0.18906545]
Fitting Surface Order II: Total Error of the Load Cases:0.189065452993
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =0.075367266708
Predicted Strain Gauge =67.0768673702
Real Strain Gauge =0.709
Local Error=66.3678673702
*****
##### END #####

```

Figure C.14: I2D M1 Validation: **Run1**, Output Text File: Output Data of Response of Gauge SG04: μ_M .

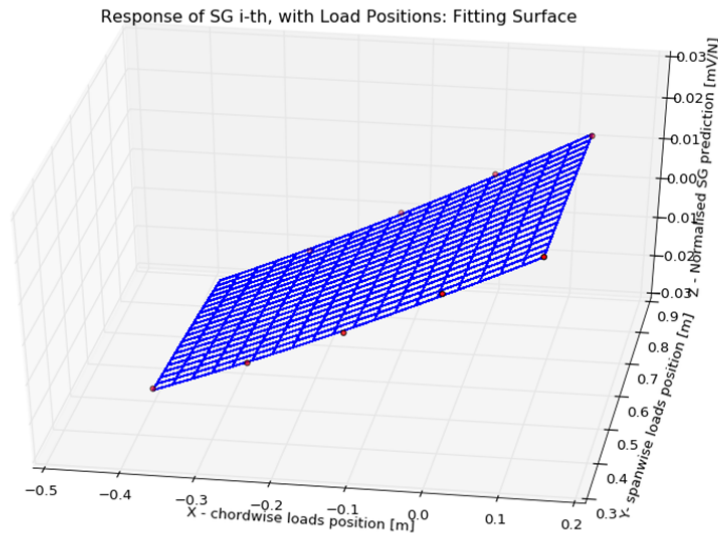


Figure C.15: I2D M1 Validation: **Run2**, Response of Gauge SG01: μ_{TF} with position of load and fitting surface - Test Case 2 - [90].

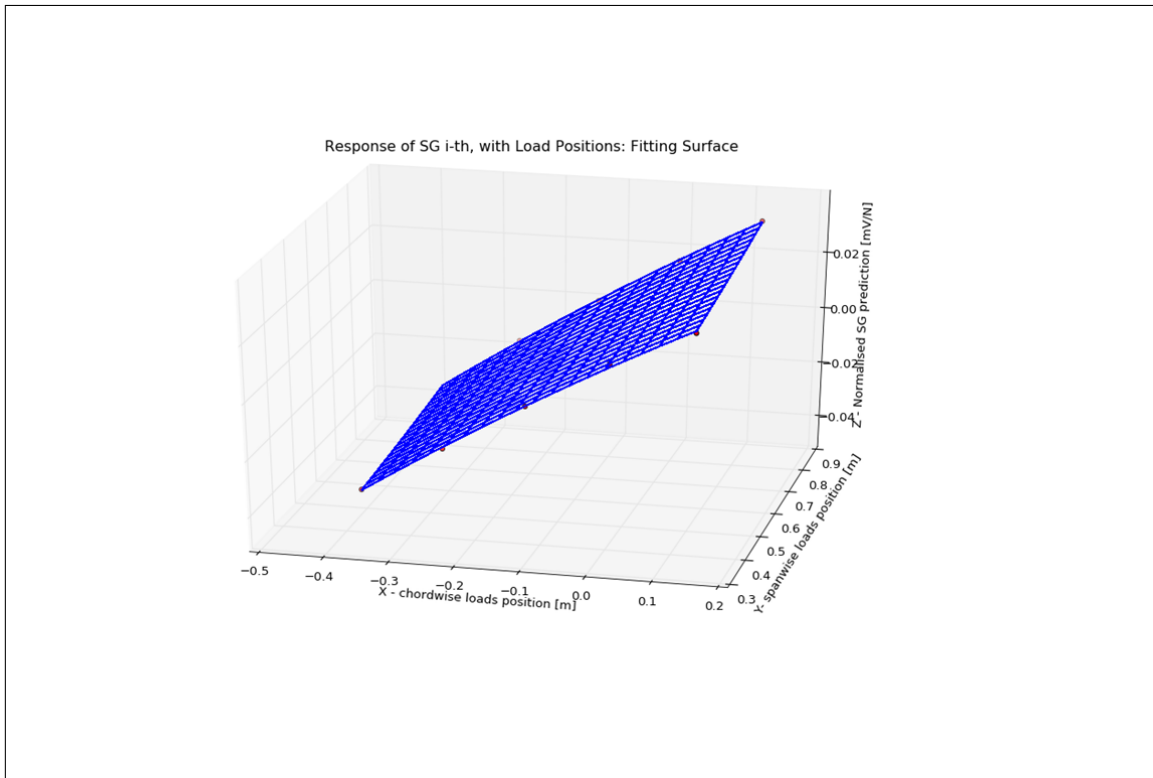


Figure C.16: I2D M1 Validation: **Run2**, Response of Gauge SG02: μ_{TR} with position of load and fitting surface - Test Case 2 - [90].

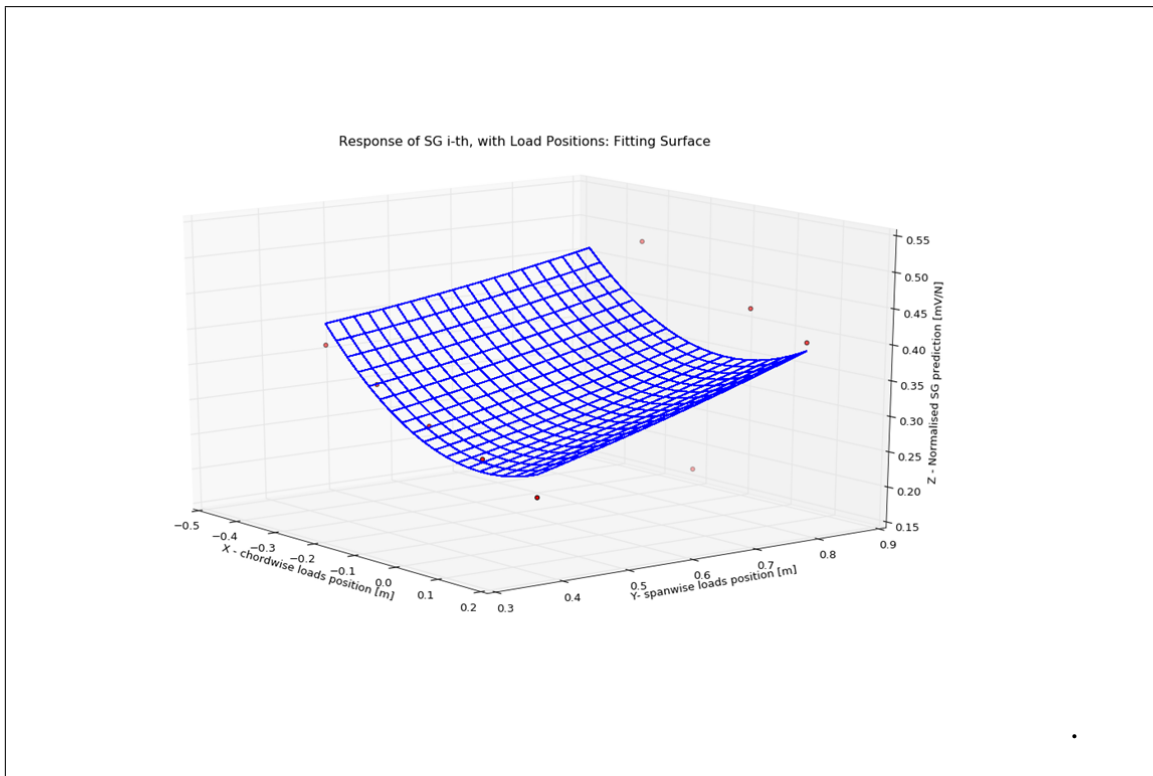


Figure C.17: I2D M1 Validation: **Run2**, Response of Gauge SG03: μ_V with position of load and fitting surface - Test Case 2 - [90].

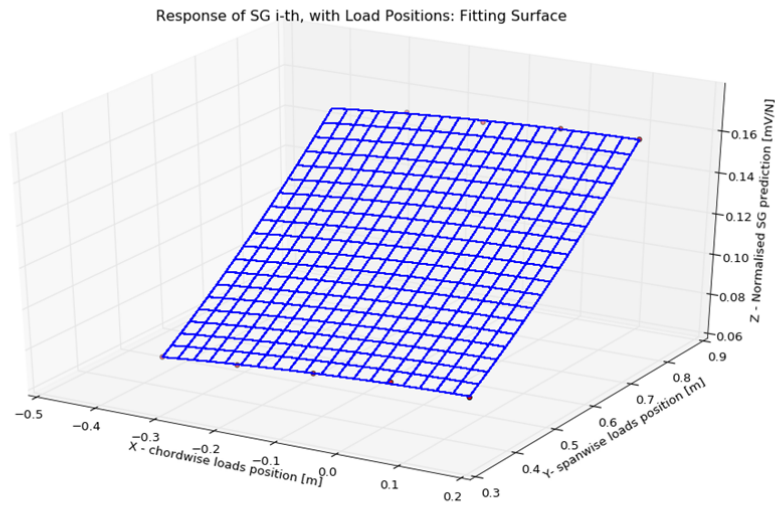


Figure C.18: I2D M1 Validation: **Run2**, Response of Gauge SG04: μ_M with position of load and fitting surface - Test Case 2 - [90].

```
-----
Individual to Distributed, I2D Module M1 - Program (vers 1.0.0) - Mao
Reference NASA TN D-7979 - Peeler et al. - Decade 70s - Test Case 1: Structure Wing
*****
##### Input Data #####
-----
Calibration Data Basics
-----
Number of load cases= 9
Number of Spanwise load case stations= 3
Number of Chordwise load case stations= 3
Number of Strain Gauges measured= 4
-----
Strain Gauge Readings - [(10**-3)microstrain]
-----
   SG 01   SG 02   SG 03   SG 04
0.007   0.009   0.086   0.028
0.003   0.004   0.098   0.028
-0.001  -0.002   0.107   0.027
-0.004  -0.008   0.122   0.026
-0.007  -0.014   0.136   0.025
0.005   0.012   0.143   0.057
0.002   0.007   0.155   0.057
-0.002   0.001   0.066   0.056
-0.006  -0.005   0.178   0.055
-----
   X       Y       Loads
-----
  0.127   0.419   358.000
  0.000   0.419   358.000
 -0.127   0.419   358.000
 -0.254   0.419   358.000
 -0.381   0.419   358.000
  0.127   0.838   358.000
  0.000   0.838   358.000
 -0.127   0.838   358.000
 -0.254   0.838   358.000
-----
*****
##### Output DATA #####
*****
```

Figure C.19: Individual to Distributed, I2D M1 Validation: **Run2**, Output Text File, Input Data - Test Case 2, *Wing I* input data, First Calibration [90].

```

*****
##### Output DATA #####
... Load Positions and SG Responses Predictions: 3-D Plot, Z Data - Global Output, DD - Local Output, ID.
-----
|Basic Data Base (BDB), SG01 Response
NMM
-0.703718187461
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.01815891 0.00739541 -0.00270081 -0.01212973 -0.02089137 0.01571912
  0.00398479 -0.00708225 -0.017482 ]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00898425 0.07448056 -0.00161803 0.01824414 0.02068595 -0.00518843]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.00303704 0.05081481 0.0677037 0.02918519 0.04303704 0.05248148
  0.05448148 0.04848148 0.05048148]
Fitting Surface Order II: Total Error of the Load Cases:0.0504814814815
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =-0.0027008069522
Predicted Strain Gauge =-2.40371818746
Real Strain Gauge =-1.7
Local Error=-0.703718187461
*****

```

Figure C.20: Individual to Distributed, I2D M1 Validation: **Run2**, Output Text File: Output Data of Response of Gauge SG01: μ_{TF} .

```

*****
|Basic Data Base (BDB), SG02 Response
NMM
0.157690875233
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.02535009 0.01112663 -0.00420484 -0.02064432 -0.03819181 0.0342784
  0.01929702 0.00320764 -0.01398976]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00600504 0.11039018 0.00858516 0.01424303 -0.0343483 0.00868304]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.08511111 0.14555556 0.01155556 0.07311111 0.02422222 0.04277778
  0.04277778 0.04277778 0.04277778]
Fitting Surface Order II: Total Error of the Load Cases:0.0427777777778
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =-0.00420484171322
Predicted Strain Gauge =-3.74230912477
Real Strain Gauge =-3.9
Local Error=0.157690875233
*****

```

Figure C.21: Individual to Distributed, I2D M1 Validation: **Run2**, Output Text File: Output Data of Response of Gauge SG02: μ_{TR} .

```

*****
|Basic Data Base (BDB), SG03 Response
NMM
240.182607076
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.2707635  0.25484171  0.27281192  0.32467412  0.41042831  0.3889851
   0.35939479  0.36369646  0.40189013]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.18417421 -0.11569085  0.12822129  0.25686447  1.05065387  0.09650654]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 3.74444444  2.15555556  3.27777778  1.95555556  3.64444444
  1.34777778  8.67888889  21.40111111  11.37444444]
Fitting Surface Order II: Total Error of the Load Cases:11.3744444444
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =0.272811918063
Predicted Strain Gauge =242.802607076
Real Strain Gauge =2.62
Local Error=240.182607076
*****

```

Figure C.22: Individual to Distributed, I2D M1 Validation: **Run2**, Output Text File: Output Data of Response of Gauge SG03: μ_V .

```

*****
|Basic Data Base (BDB), SG04 Response
NMM
66.3310372439
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.07803724  0.07706797  0.07532588  0.07281099  0.06952328  0.15874488
   0.15797858  0.15643948  0.15412756]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.02785976  0.01227291  0.079611  -0.00381447 -0.02395722  0.09028885]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.06244444  0.10322222  0.00888889  0.04211111  0.01022222  0.01644444
  0.02455556  0.09844444  0.05744444]
Fitting Surface Order II: Total Error of the Load Cases:0.05744444444444
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =0.0753258845438
Predicted Strain Gauge =67.0400372439
Real Strain Gauge =0.709
Local Error=66.3310372439
*****
##### END #####
-----

```

Figure C.23: I2D M1 Validation: **Run2**, Output Text File: Output Data of Response of Gauge SG04: μ_M .

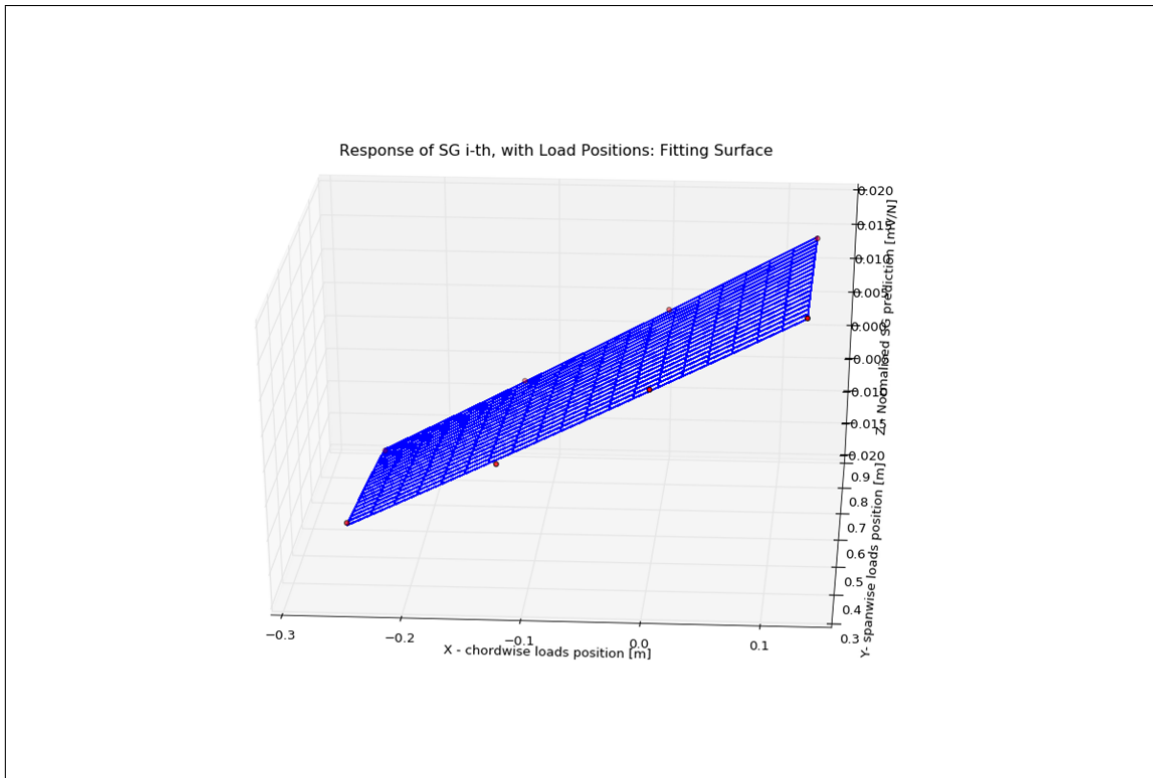


Figure C.24: I2D M1 Validation: **Run3**, Response of Gauge SG01: μ_{TF} with position of load and fitting surface - Test Case 2 - [90].

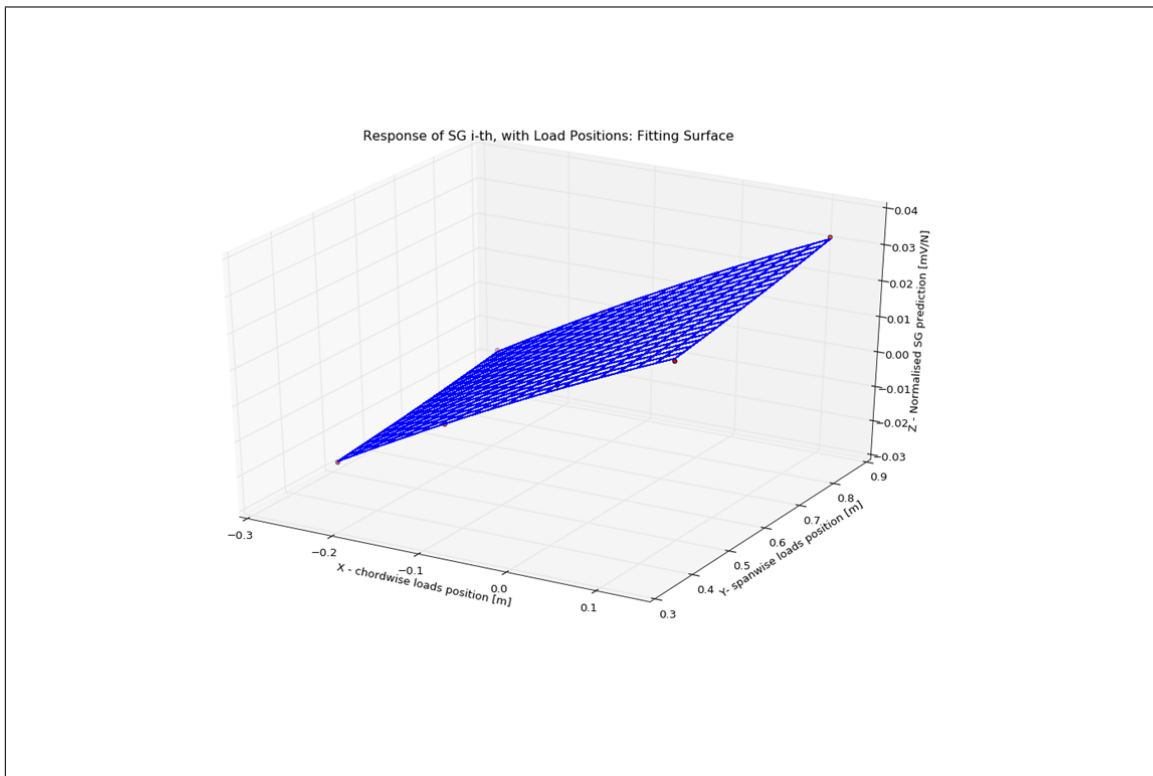


Figure C.25: I2D M1 Validation: **Run3**, Response of Gauge SG02: μ_{TR} with position of load and fitting surface - Test Case 2 - [90].

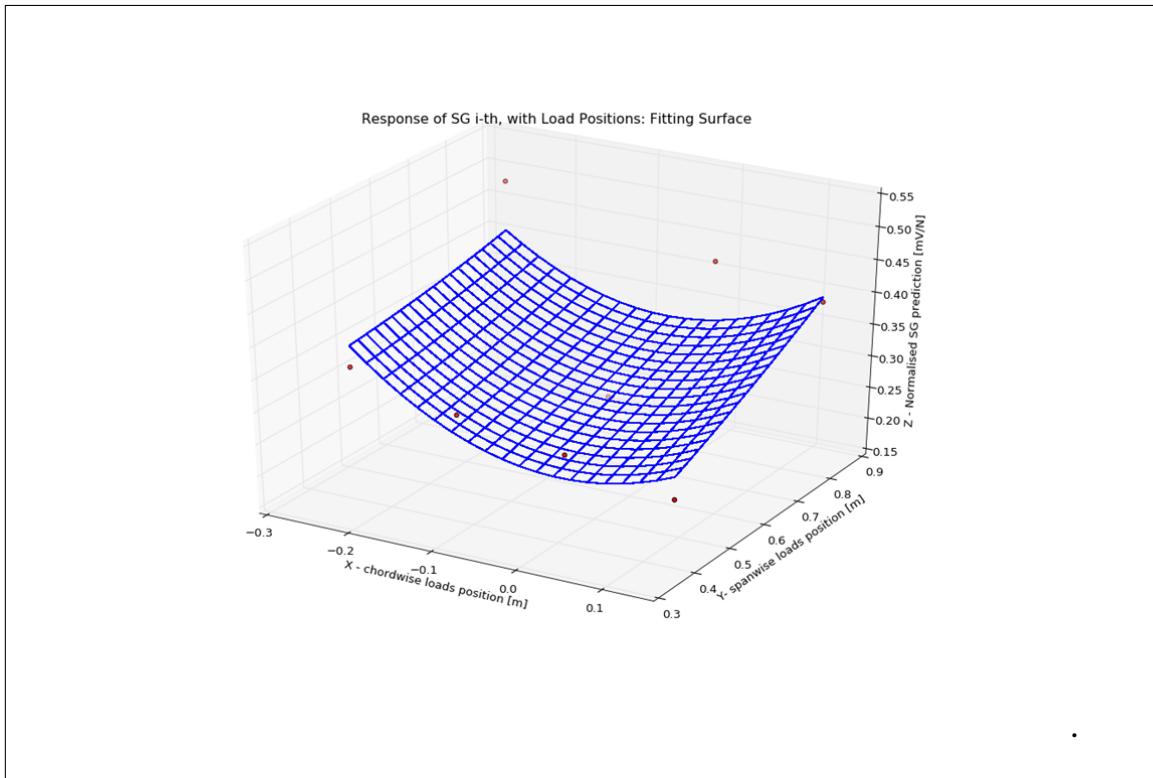


Figure C.26: I2D M1 Validation: **Run3**, Response of Gauge SG03: μ_V with position of load and fitting surface - Test Case 2 - [90].

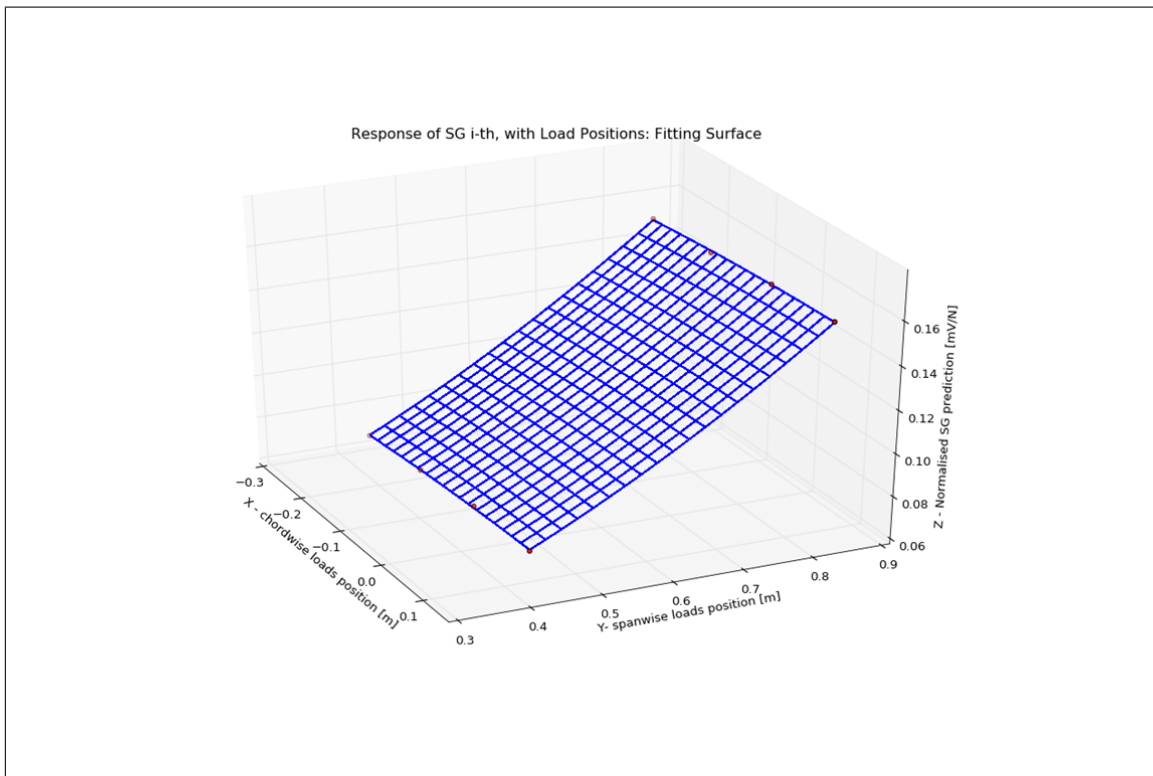


Figure C.27: I2D M1 Validation: **Run3**, Response of Gauge SG04: μ_M with position of load and fitting surface - Test Case 2 - [90].

```

-----
Individual to Distributed, I2D Module M1 - Program (vers 1.0.0) - Mao
Reference NASA TN D-7979 - Peeler et al. - Decade 70s - Test Case 1: Structure Wing I
-----
##### Input Data #####

Calibration Data Basics
-----
Number of load cases= 8
Number of Spanwise load case stations= 2
Number of Chordwise load case stations= 3
Number of Strain Gauges measured= 4
-----
Strain Gauge Readings - [(10**-3)microstrain]
-----
SG 01   SG 02   SG 03   SG 04
0.007   0.009   0.086   0.028
0.003   0.004   0.098   0.028
-0.001  -0.002   0.107   0.027
-0.004  -0.008   0.122   0.026
0.005   0.012   0.143   0.057
0.002   0.007   0.155   0.057
-0.002   0.001   0.066   0.056
-0.006  -0.005   0.178   0.055
-----
X       Y       Loads
-----
0.127   0.419   358.000
0.000   0.419   358.000
-0.127   0.419   358.000
-0.254   0.419   358.000
0.127   0.838   358.000
0.000   0.838   358.000
-0.127   0.838   358.000
-0.254   0.838   358.000
-----
##### Output DATA #####

```

Figure C.28: Individual to Distributed, I2D M1 Validation: **Run3**, Output Text File, Input Data - Test Case 2, *Wing I* input data, First Calibration [90].

```

-----
##### Output DATA #####
.. Load Positions and SG Responses Predictions: 3-D Plot, Z Data - Global Output, DD - Local Output, ID.
-----
|Basic Data Base (BDB), SG01 Response
NMM
-0.663596368715
-----
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.01811383  0.00762081 -0.00265573 -0.01271578  0.01549372  0.0042102
  -0.00685684 -0.0177074 ]]
-----
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00919937  0.07554546 -0.00158123  0.01485544  0.00671091 -0.00521771]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.00892722  0.02536746  0.07751658  0.0432219  0.02713522  0.02925654
  0.02289258  0.0250139 ]
Fitting Surface Order II: Total Error of the Load Cases:0.0250139023845
-----
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =-0.00265572625698
Predicted Strain Gauge =-2.36359636872
Real Strain Gauge =-1.7
Local Error=-0.663596368715
-----

```

Figure C.29: Individual to Distributed, I2D M1 Validation: **Run3**, Output Text File: Output Data of Response of Gauge SG01: μ_{TF} .


```

*****
|Basic Data Base (BDB), SG02 Response
NMM
0.180272346369
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.02532472  0.01125349 -0.00417947 -0.02097416  0.03415154  0.01942388
   0.0033345  -0.01411662]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00612612  0.11098953  0.00860587  0.01233579 -0.04221377  0.00866656]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.08706252  0.13832776  0.01546796  0.03579728  0.0614299  0.0614299
  0.0614299  0.0614299 ]
Fitting Surface Order II: Total Error of the Load Cases:0.0614299016156
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =-0.00417946927374
Predicted Strain Gauge =-3.71972765363
Real Strain Gauge =-3.9
Local Error=0.180272346369
*****

```

Figure C.30: Individual to Distributed, I2D M1 Validation: **Run3**, Output Text File: Output Data of Response of Gauge SG02: μ_{TR} .

```

*****
|Basic Data Base (BDB), SG03 Response
NMM
236.785027933
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.27458101  0.23575419  0.26899441  0.37430168  0.40807263  0.34030726
   0.34460894  0.42097765]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.16595718 -0.20586812  0.12510496  0.54382477  2.23408268  0.09898572]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 4.45477272  4.70226009  3.95979797  4.20728535  0.98641396
  11.62129995  20.28335802  9.64847203]
Fitting Surface Order II: Total Error of the Load Cases:9.64847202929
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =0.268994413408
Predicted Strain Gauge =239.405027933
Real Strain Gauge =2.62
Local Error=236.785027933
*****

```

Figure C.31: Individual to Distributed, I2D M1 Validation: **Run3**, Output Text File: Output Data of Response of Gauge SG03: μ_V .


```

*****
|Basic Data Base (BDB), SG04 Response
NMM
66.3405670391
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.07802654 0.07712151 0.07533659 0.07267179 0.15869134 0.15803212
  0.15649302 0.15407402]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.02791086 0.01252584 0.07961974 -0.00461936 -0.02727659 0.0902819 ]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.06487705 0.10270726 0.01078338 0.02704683 0.02421841 0.01926866
  0.11119254 0.06770547]
Fitting Surface Order II: Total Error of the Load Cases:0.0677054742986
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=890
Predicted Normalised Strain Gauge =0.0753365921788
Predicted Strain Gauge =67.0495670391
Real Strain Gauge =0.709
Local Error=66.3405670391
*****
##### END #####
-----

```

Figure C.32: Individual to Distributed, I2D M1 Validation: **Run3**, Output Text File: Output Data of Response of Gauge SG04: μ_M .

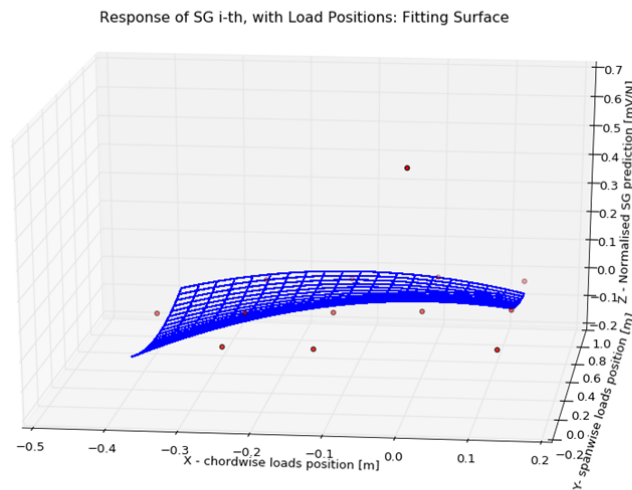


Figure C.33: I2D M1 Validation: **Run4**, Response of Gauge SG01: μ_{TF} with position of load and fitting surface - Test Case 2 - [90].

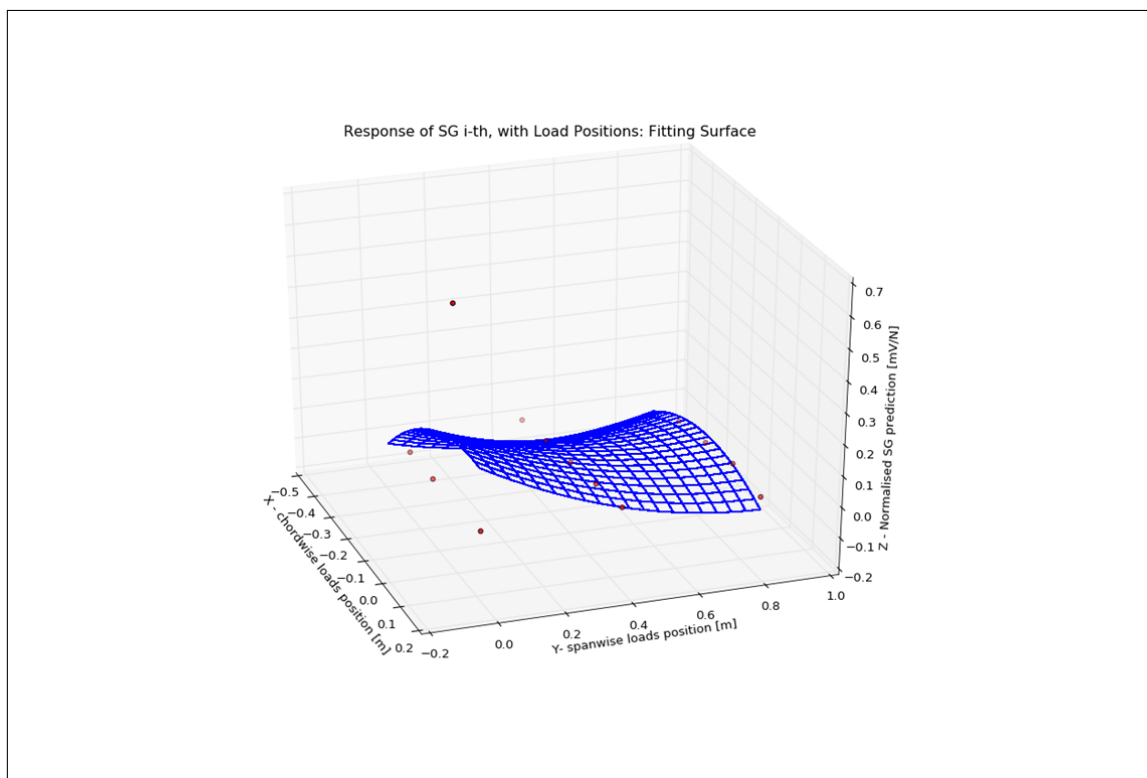


Figure C.34: I2D M1 Validation: **Run4**, Response of Gauge SG02: μ_{TR} with position of load and fitting surface - Test Case 2 - [90].

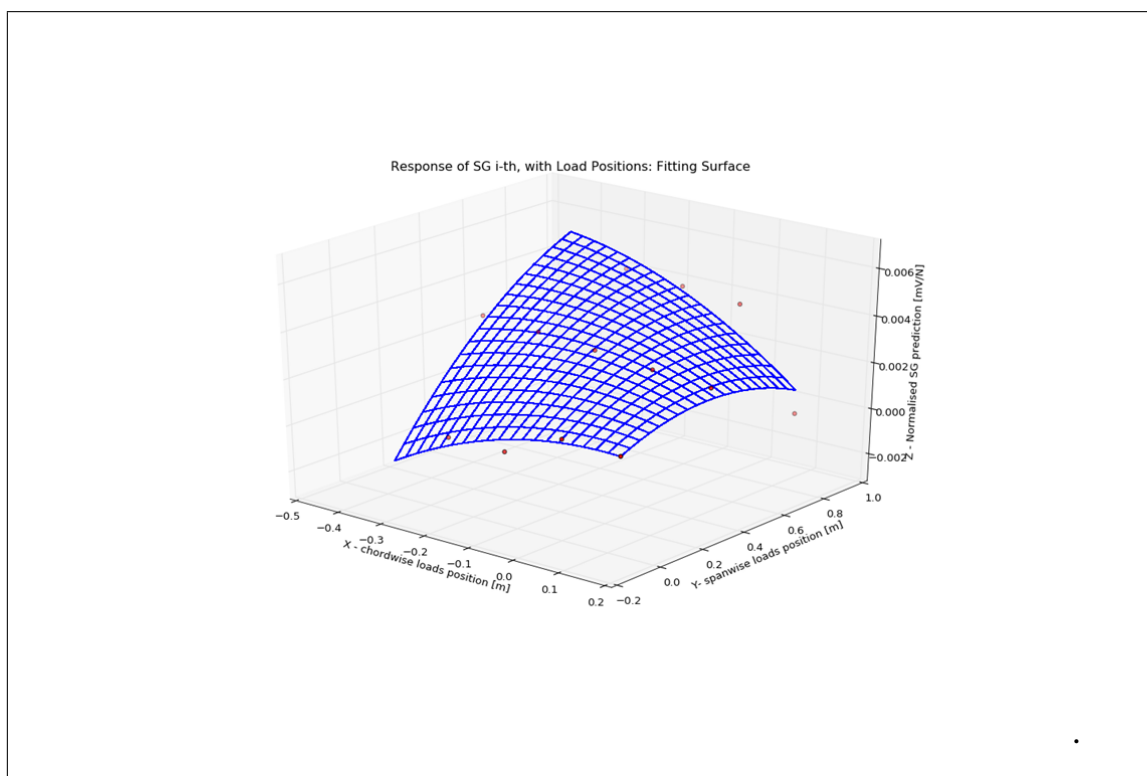


Figure C.35: I2D M1 Validation: **Run4**, Response of Gauge SG03: μ_V with position of load and fitting surface - Test Case 2 - [90].

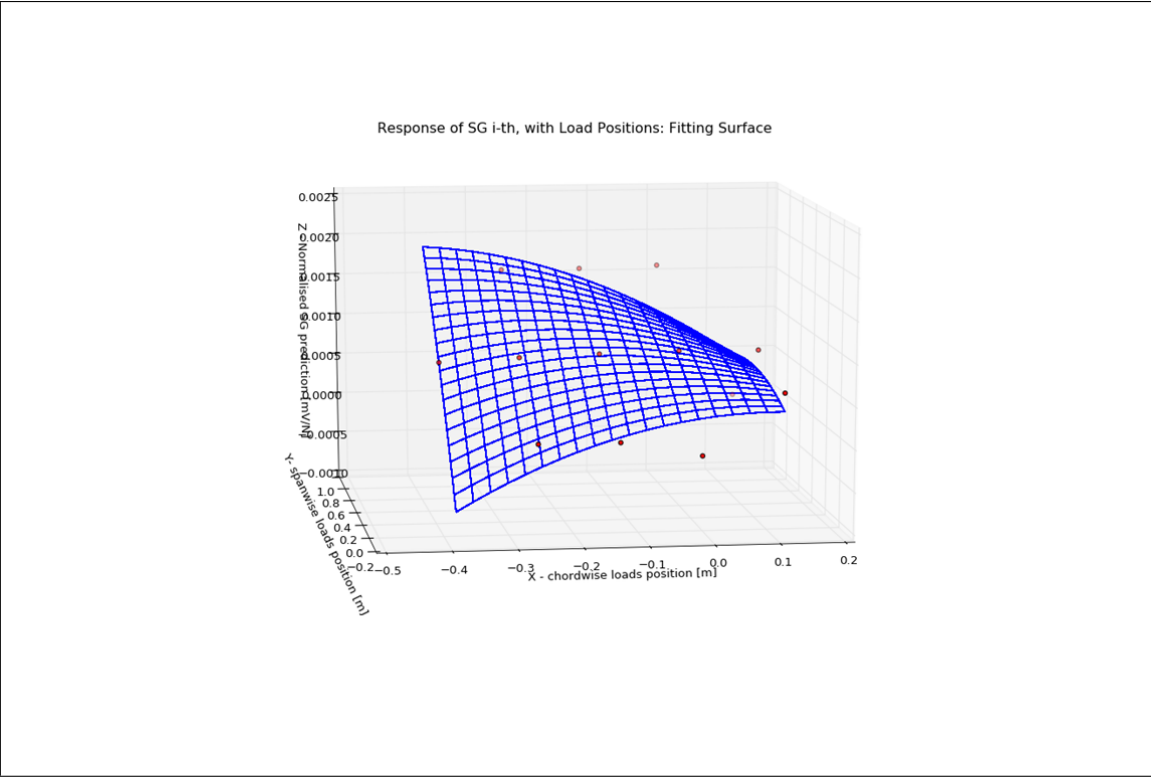


Figure C.36: I2D M1 Validation: **Run4**, Response of Gauge SG04: μ_M with position of load and fitting surface - Test Case 2 - [90].

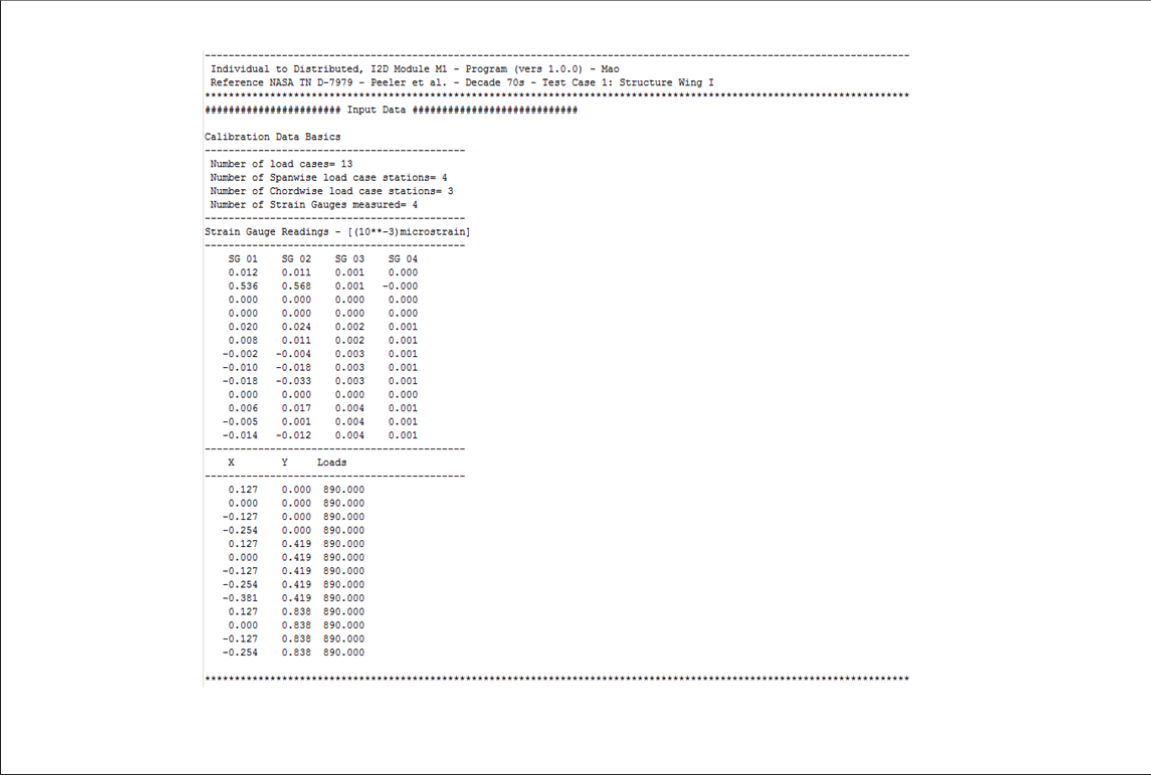


Figure C.37: Individual to Distributed, I2D M1 Validation: **Run4**, Output Text File, Input Data - Test Case 2, *Wing I* input data, First Calibration [90].

```

##### Output DATA #####
.. Load Positions and SG Responses Predictions: 3-D Plot, Z Data - Global Output, DD - Local Output, ID.
-----
|Basic Data Base (BDB), SG01 Response
|NM
|13.6072745734
|.....3-D Plot, Z Data.....
|Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
|[[ 0.2010609  0.19294276  0.14984542  0.07176889  0.02783288  0.04877653
|  0.03474099 -0.01427374 -0.09826767 -0.0438155  0.00618995  0.02121621
|  0.00126328]]
|.....Global Outputs, DD.....
|Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
|[a1, a2, a3, a4, a5, a6]
|[[ 0.19294276  0.20163575 -0.46528891 -0.54614094 -1.08435714  0.28930016]]
|Fitting Surface Order II: Single Error of each Load Cases:
|[ 46.32972629 101.03335568 36.98808192 17.71554748 1.43424926
|  9.72697611  9.04701639  0.83305697 19.37518479 10.81548793
|  0.1638985  6.6848102  4.29457623]
|Fitting Surface Order II: Total Error of the Load Cases:4.2945762331
|.....Local Outputs, ID.....
|Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
|x=-0.127 y=0.419 L=358
|Predicted Normalised Strain Gauge =0.0347409904286
|Predicted Strain Gauge =12.4372745734
|Real Strain Gauge =-1.17
|Local Error=13.6072745734
|
|.....

```

Figure C.38: Individual to Distributed, I2D M1 Validation: **Run4**, Output Text File: Output Data of Response of Gauge SG01: μ_{TF} .

```

#####
|Basic Data Base (BDB), SG02 Response
|NM
|14.8636486059
|.....3-D Plot, Z Data.....
|Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
|[[ 0.21260685  0.20699032  0.15995017  0.07148637  0.02797919  0.05330986
|  0.0372169 -0.02029971 -0.11923995 -0.04116169  0.01511617  0.02997039
|  0.00340098]]
|.....Global Outputs, DD.....
|Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
|[a1, a2, a3, a4, a5, a6]
|[[ 0.20699032  0.20730976 -0.50459152 -0.581572 -1.28413532  0.32890781]]
|Fitting Surface Order II: Single Error of each Load Cases:
|[ 4.93128731e+01  1.06441035e+02  3.94823530e+01  1.76458093e+01
|  1.22444932e-01  9.98065900e+00  1.02653430e+01  4.62455608e-02
|  2.03252013e+01  1.01604178e+01  1.03912296e+00  7.09840082e+00
|  4.10113995e+00]
|Fitting Surface Order II: Total Error of the Load Cases:4.101139948
|.....Local Outputs, ID.....
|Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
|x=-0.127 y=0.419 L=358
|Predicted Normalised Strain Gauge =0.0372168955472
|Predicted Strain Gauge =13.3236486059
|Real Strain Gauge =-1.54
|Local Error=14.8636486059
|
|.....

```

Figure C.39: Individual to Distributed, I2D M1 Validation: **Run4**, Output Text File: Output Data of Response of Gauge SG02: μ_{TR} .

```

*****
|Basic Data Base (BDB), SG03 Response
NNM
-106.30763504
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00104932 0.00099154 0.00052448 -0.00035186 0.00201839 0.00287915
  0.00333063 0.00337283 0.00300574 0.00102685 0.00280615 0.00417617
  0.0051369 ]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00099154 0.00206631 0.00684467 -0.01726156 -0.01268771 -0.00558385]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.00169235 0.04091684 0.12946343 0.08685424 0.11749372 0.04782748
  0.09548034 0.05042636 0.07624046 0.25346974 0.3335212 0.05081413
  0.13086559]
Fitting Surface Order II: Total Error of the Load Cases:0.130865589349
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =0.00333062838119
Predicted Strain Gauge =1.19236496047
Real Strain Gauge =107.5
Local Error=-106.30763504
*****

```

Figure C.40: Individual to Distributed, I2D M1 Validation: **Run4**, Output Text File: Output Data of Response of Gauge SG03: μ_V .

```

*****
|Basic Data Base (BDB), SG04 Response
NNM
-26.606846958
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 3.27723679e-04 2.68327091e-04 6.32792343e-05 -2.87419892e-04
  5.66500208e-04 8.21373283e-04 9.30595089e-04 8.94165626e-04
  7.12084894e-04 5.10195589e-04 1.07933833e-03 1.50282980e-03
  1.78067000e-03]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00026833 0.00104112 0.00167204 -0.00590588 -0.0045152 -0.00084039]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.05472836 0.1100556 0.01561995 0.07094718 0.06041096 0.00056086
  0.03306835 0.03073245 0.0039507 0.12593749 0.13906026 0.0281459
  0.04126867]
Fitting Surface Order II: Total Error of the Load Cases:0.0412686673766
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =0.000930595089471
Predicted Strain Gauge =0.333153042031
Real Strain Gauge =26.94
Local Error=-26.606846958
*****
***** END *****

```

Figure C.41: Individual to Distributed, I2D M1 Validation: **Run4**, Output Text File: Output Data of Response of Gauge SG04: μ_V .

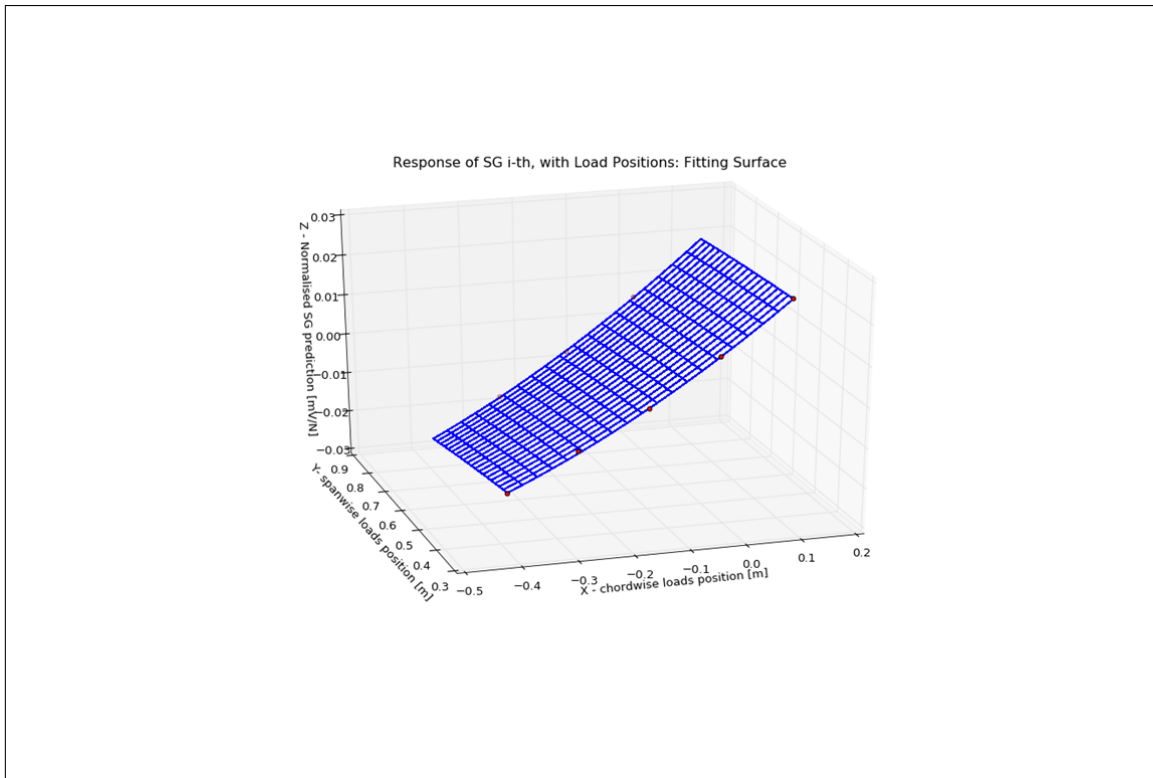


Figure C.42: I2D M1 Validation: **Run5**, Response of Gauge SG01: μ_{TF} with position of load and fitting surface - Test Case 2 - [90].

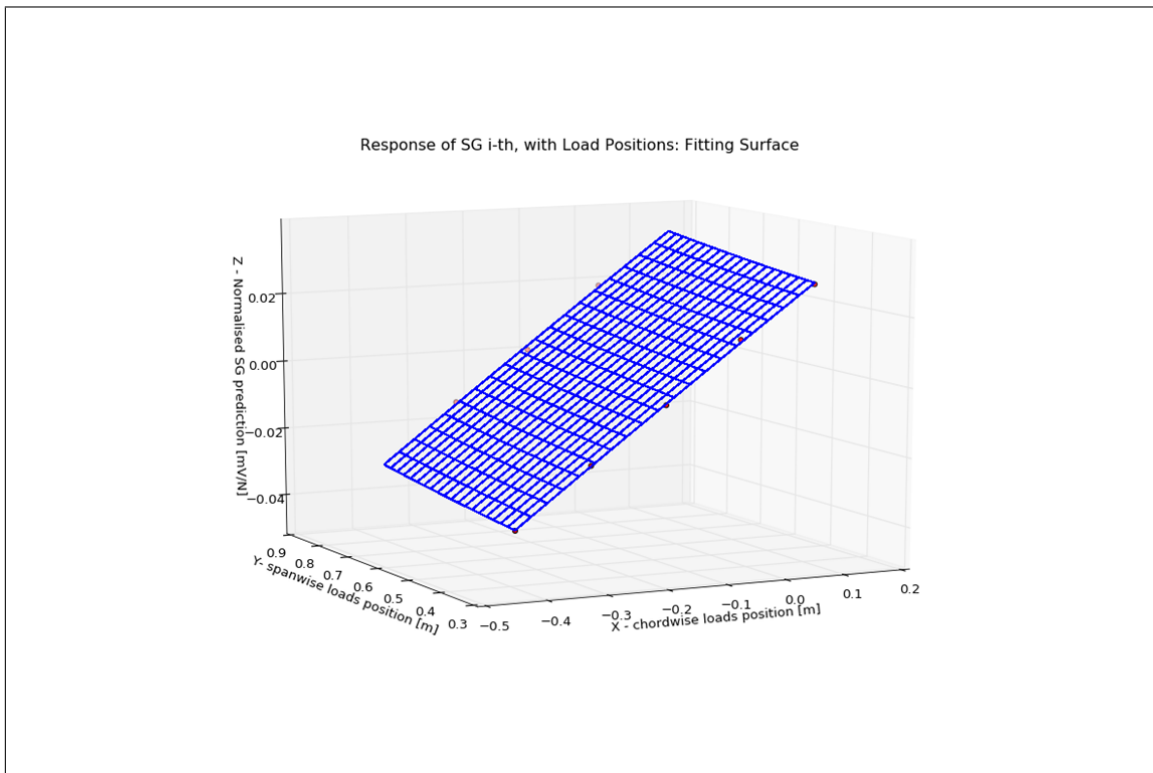


Figure C.43: I2D M1 Validation: **Run5**, Response of Gauge SG02: μ_{TR} with position of load and fitting surface - Test Case 2 - [90].

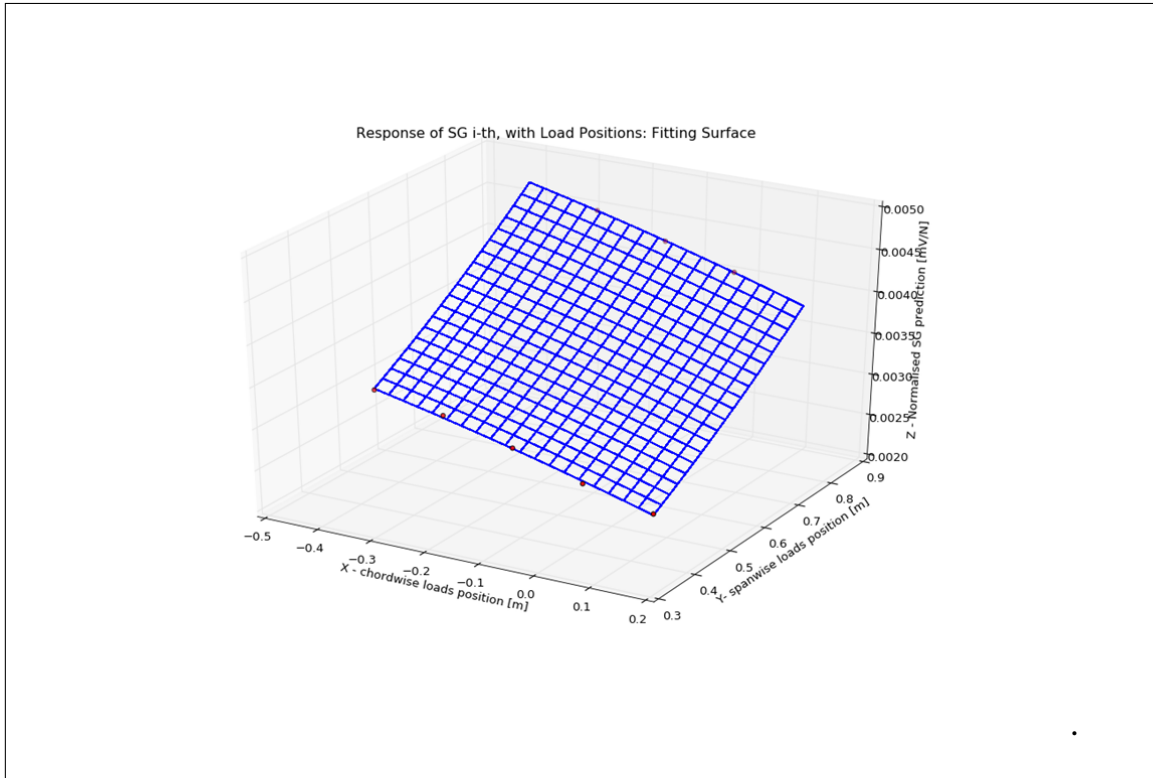


Figure C.44: I2D M1 Validation: **Run5**, Response of Gauge SG03: μ_V with position of load and fitting surface - Test Case 2 - [90].

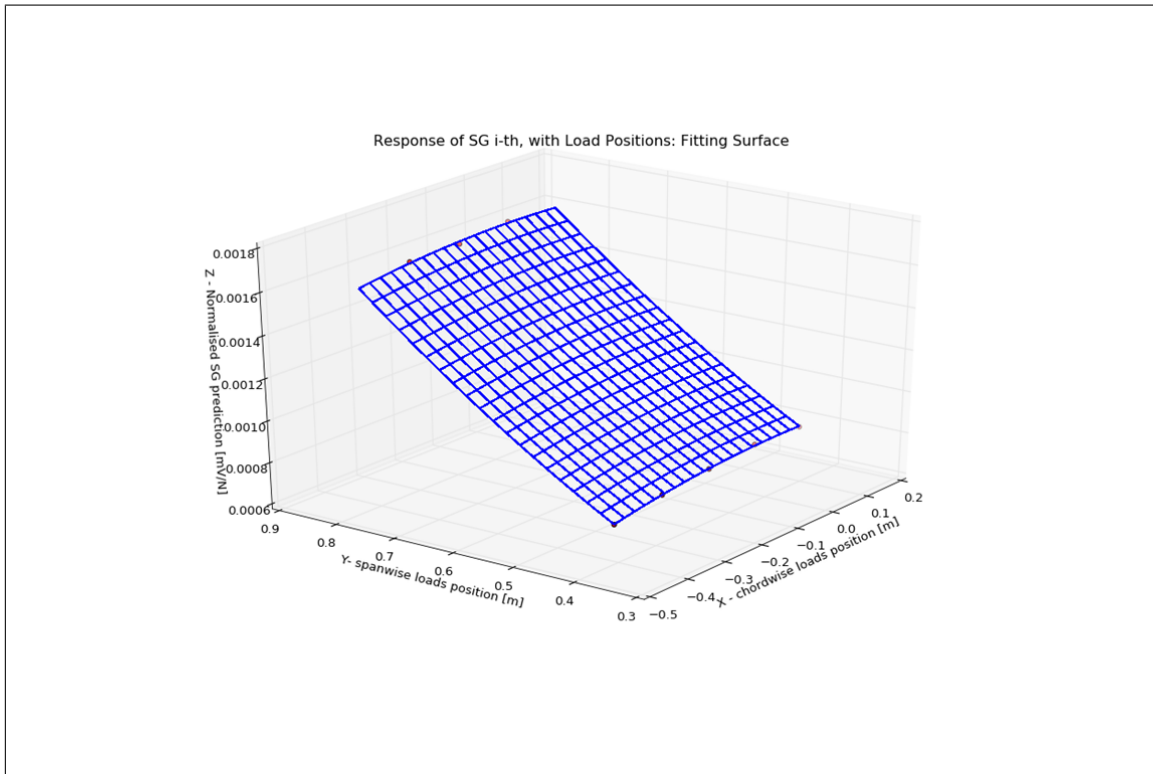


Figure C.45: I2D M1 Validation: **Run5**, Response of Gauge SG04: μ_M with position of load and fitting surface - Test Case 2 - [90].

```

-----
Individual to Distributed, I2D Module M1 - Program (vers 1.0.0) - Mao
Reference NASA TN D-7979 - Peeler et al. - Decade 70s - Test Case 1: Structure Wing I
*****
##### Input Data #####

Calibration Data Basics
-----
Number of load cases= 8
Number of Spanwise load case stations= 2
Number of Chordwise load case stations= 3
Number of Strain Gauges measured= 4
-----
Strain Gauge Readings - [(10**3)microstrain]
-----
      SG 01      SG 02      SG 03      SG 04
      0.020      0.024      0.002      0.001
      0.008      0.011      0.002      0.001
      -0.002     -0.004      0.003      0.001
      -0.010     -0.018      0.003      0.001
      -0.018     -0.033      0.003      0.001
      0.006       0.017      0.004      0.001
      -0.005      0.001      0.004      0.001
      -0.014     -0.012      0.004      0.001
-----
      X          Y          Loads
-----
      0.127      0.419      890.000
      0.000      0.419      890.000
      -0.127      0.419      890.000
      -0.254      0.419      890.000
      -0.381      0.419      890.000
      0.000      0.838      890.000
      -0.127      0.838      890.000
      -0.254      0.838      890.000
-----
*****
##### Output DATA #####

```

Figure C.46: Individual to Distributed, I2D M1 Validation: **Run5**, Output Text File, Input Data - Test Case 2, *Wing I* input data, First Calibration [90].

```

*****
##### Output DATA #####
.. Load Positions and SG Responses Predictions: 3-D Plot, Z Data - Global Output, DD - Local Output, ID.
-----
|Basic Data Base (BDB), SG01 Response
NMM
0.564362002043
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.02198836  0.00942155 -0.00169173 -0.01135148 -0.01955771  0.00668795
  -0.0055332  -0.01630082]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.01053566  0.08450532 -0.00072638  0.02081945  0.04505933 -0.00461236]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.01073517  0.01597419  0.06871792  0.14241773  0.06846079  0.05222948
  0.10445896  0.05222948]
Fitting Surface Order II: Total Error of the Load Cases:0.0522294781558
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =-0.00169172625128
Predicted Strain Gauge =-0.605637997957
Real Strain Gauge =-1.17
Local Error=0.564362002043
*****

```

Figure C.47: Individual to Distributed, I2D M1 Validation: **Run5**, Output Text File: Output Data of Response of Gauge SG01: μ_{TF} .


```

*****
|Basic Data Base (BDB), SG02 Response
NMM
0.112241879469
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.02792523  0.01207783 -0.00398815 -0.02027273 -0.03677589  0.01867518
   0.00251481 -0.01386415]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00780123  0.12490007  0.0074373  0.00177366 -0.00677632  0.00660951]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.13910719  0.25128004  0.12393653  0.05046171  0.03869803  0.20473955
  0.40947911  0.20473955]
Fitting Surface Order II: Total Error of the Load Cases:0.204739554371
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =-0.00398815117467
Predicted Strain Gauge =-1.42775812053
Real Strain Gauge =-1.54
Local Error=0.112241879469
*****

```

Figure C.48: Individual to Distributed, I2D M1 Validation: **Run5**, Output Text File: Output Data of Response of Gauge SG02: μ_{TR} .

```

*****
|Basic Data Base (BDB), SG03 Response
NMM
-106.448123596
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00247978  0.00271742  0.0029382  0.00314213  0.00332921  0.00415449
   0.00438764  0.00460393]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00178191 -0.00170751  0.00163417 -0.00023227 -0.00052247  0.00142849]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.00459619  0.01007627  0.00176777  0.0083085  0.00459619  0.00088388
  0.00176777  0.00088388]
Fitting Surface Order II: Total Error of the Load Cases:0.000883883476481
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =0.00293820224719
Predicted Strain Gauge =1.05187640449
Real Strain Gauge =107.5
Local Error=-106.448123596
*****

```

Figure C.49: Individual to Distributed, I2D M1 Validation: **Run5**, Output Text File: Output Data of Response of Gauge SG03: μ_V .

```
*****
|Basic Data Base (BDB), SG04 Response
NMM
-26.6543094178
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00081502 0.00081305 0.00079802 0.00076991 0.00072872 0.00163677
  0.0016287 0.00160756]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00031079 0.00012177 0.00081513 -0.00013091 -0.00040531 0.0009155 ]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 1.18922504e-03 1.90276007e-03 4.37120556e-04 7.71389216e-05
  1.99275547e-04 1.86419060e-03 3.72838121e-03 1.86419060e-03]
Fitting Surface Order II: Total Error of the Load Cases:0.00186419060495
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =0.000798018386108
Predicted Strain Gauge =0.285690582227
Real Strain Gauge =26.94
Local Error=-26.6543094178
*****
##### END #####
```

Figure C.50: Individual to Distributed, I2D M1 Validation: **Run5**, Output Text File: Output Data of Response of Gauge SG04: μ_V .

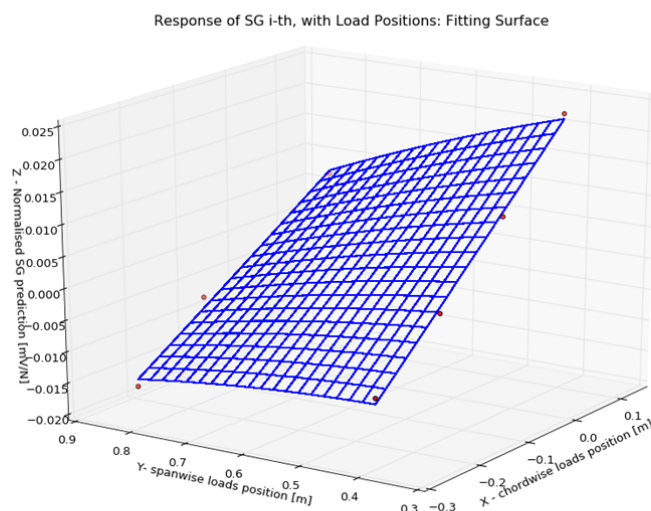


Figure C.51: I2D M1 Validation: **Run6**, Response of Gauge SG01: μ_{TF} with position of load and fitting surface - Test Case 2 - [90].

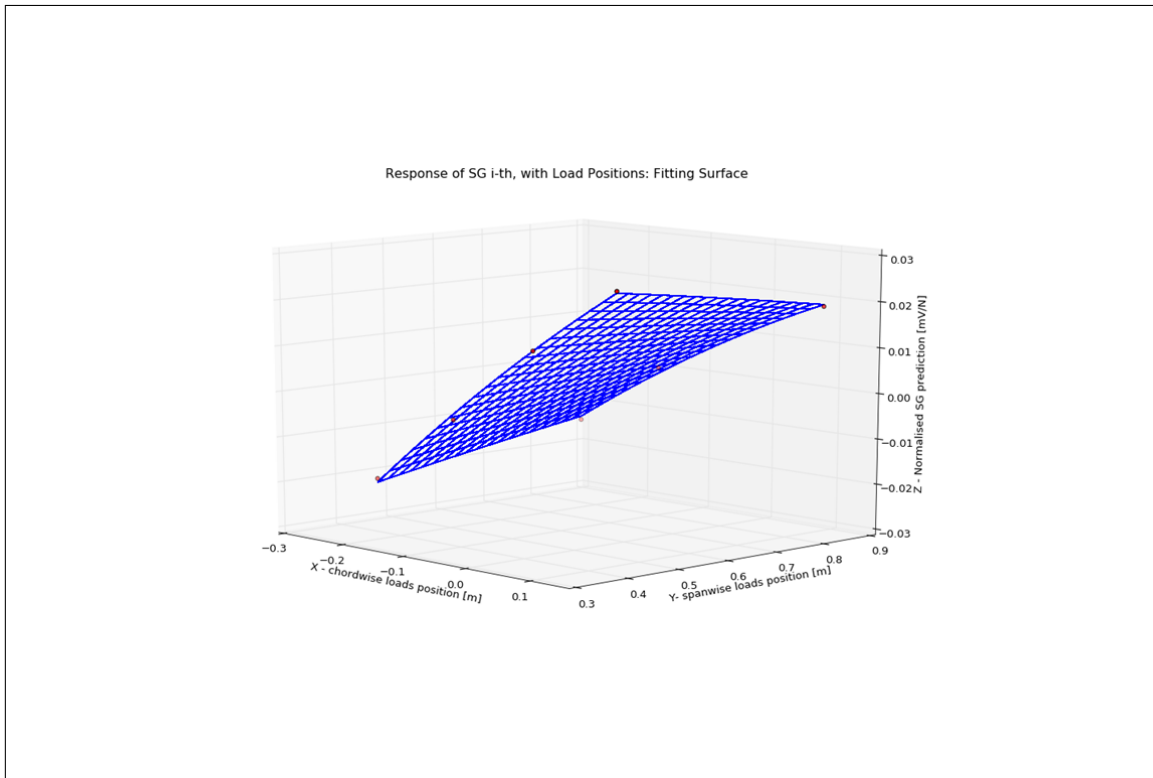


Figure C.52: I2D M1 Validation: **Run6**, Response of Gauge SG02: μ_{TR} with position of load and fitting surface - Test Case 2 - [90].

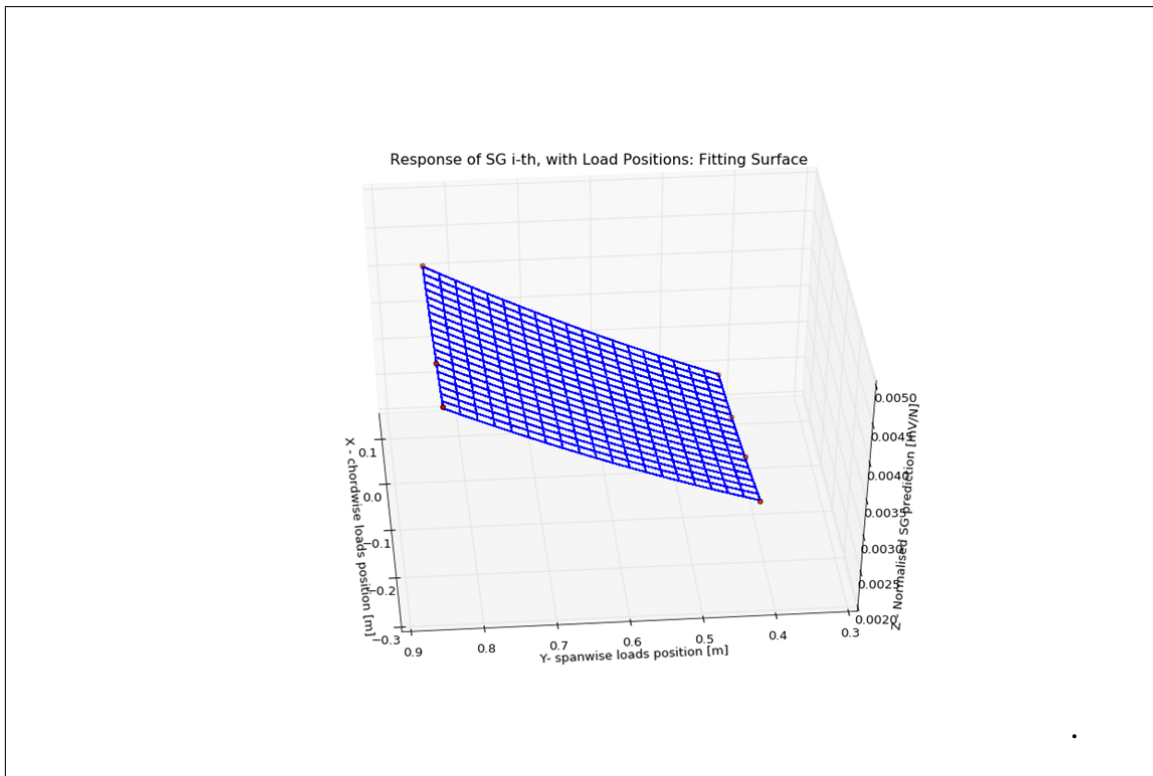


Figure C.53: I2D M1 Validation: **Run6**, Response of Gauge SG03: μ_V with position of load and fitting surface - Test Case 2 - [90].

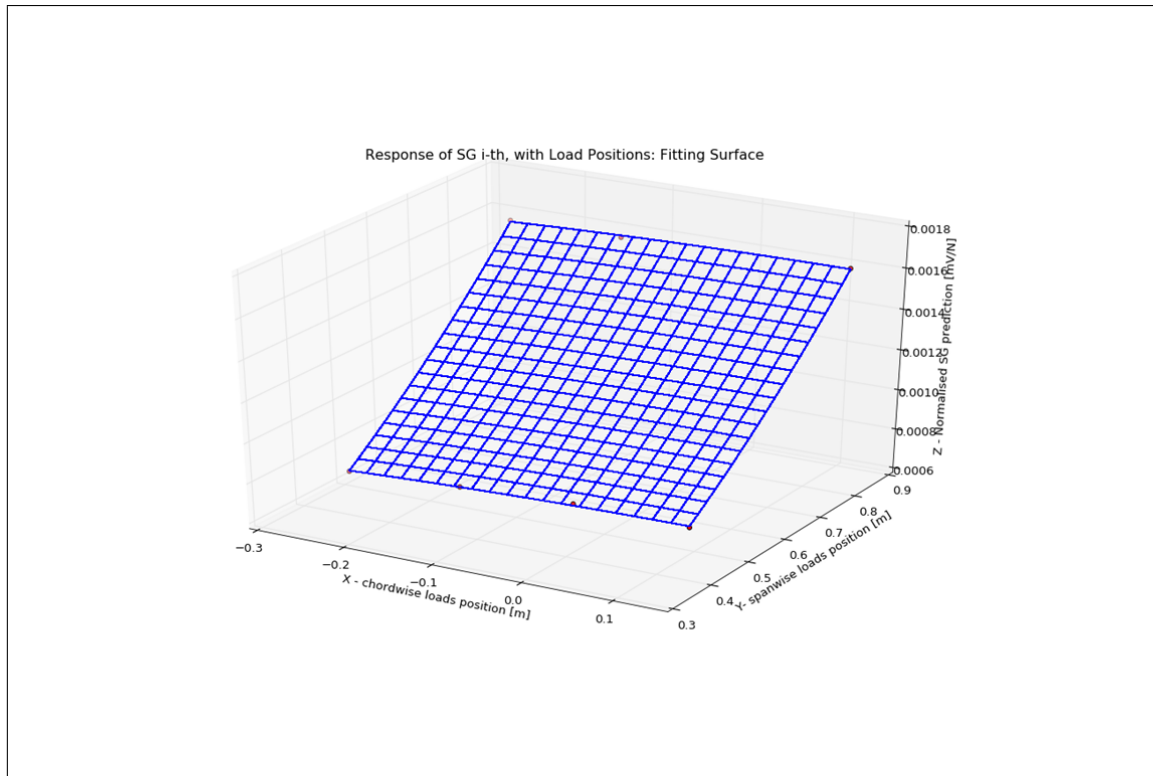


Figure C.54: I2D M1 Validation: **Run6**, Response of Gauge SG04: μ_M with position of load and fitting surface - Test Case 2 - [90].

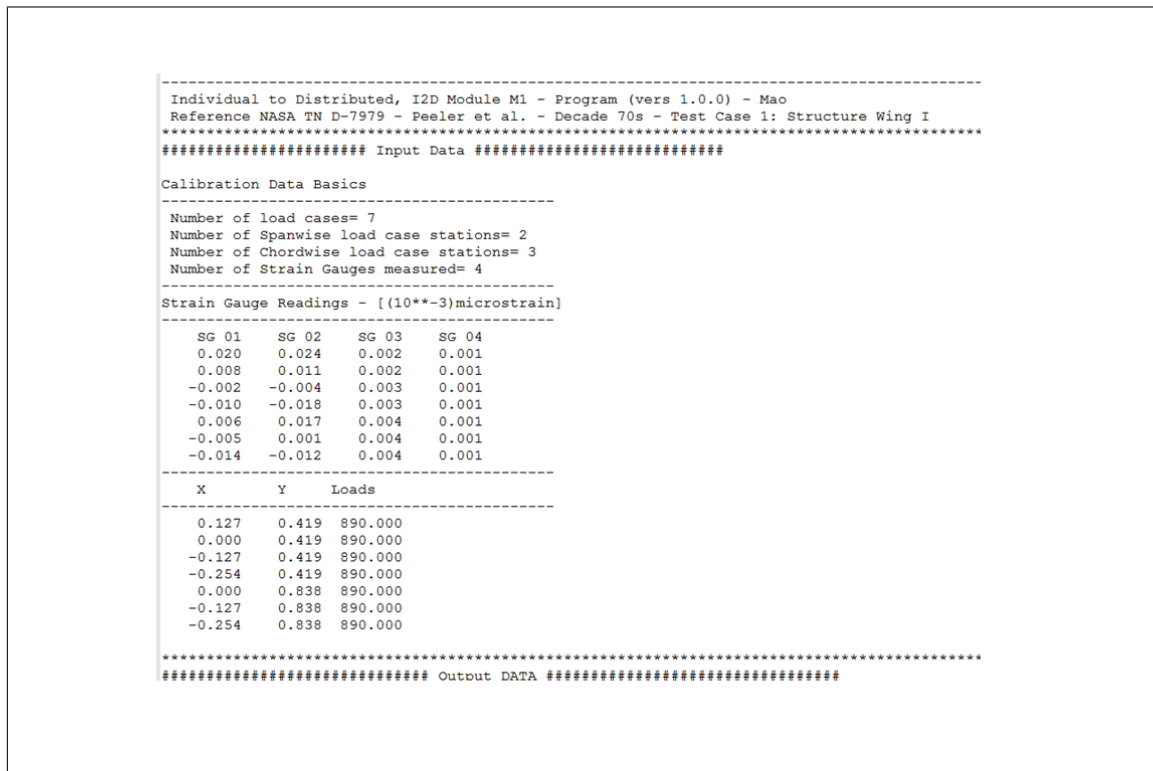


Figure C.55: Individual to Distributed, I2D M1 Validation: **Run6**, Output Text File, Input Data - Test Case 2, *Wing I* input data, First Calibration [90].

```

*****
##### Output DATA #####
.. Load Positions and SG Responses Predictions: 3-D Plot, Z Data - Global Output, DD - Local Output, ID.
-----
|Basic Data Base (BDB), SG01 Response
NMM
0.519853611557
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.02211268 0.00918844 -0.00181605 -0.0109008 0.00676565 -0.0056886
-0.01622311]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.01013765 0.08279218 -0.00050695 0.02724446 0.05951216 -0.00419679]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.03034515 0.06133823 0.03164103 0.00064794 0.02969721 0.05939442
0.02969721]
Fitting Surface Order II: Total Error of the Load Cases:0.0296972085936
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =-0.00181605136437
Predicted Strain Gauge =-0.650146388443
Real Strain Gauge =-1.17
Local Error=0.519853611557
*****

```

Figure C.56: Individual to Distributed, I2D M1 Validation: **Run6**, Output Text File: Output Data of Response of Gauge SG01: μ_{TF} .

```

*****
|Basic Data Base (BDB), SG02 Response
NMM
0.0870831460674
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.02799551 0.01194607 -0.00405843 -0.02001798 0.0187191 0.00242697
-0.01382022]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00757626 0.1239317 0.00756134 0.00540545 0.00139326 0.00684441]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.1723518 0.31295458 0.10885377 0.03174902 0.20410082 0.40820163
0.20410082]
Fitting Surface Order II: Total Error of the Load Cases:0.204100815425
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =-0.00405842696629
Predicted Strain Gauge =-1.45291685393
Real Strain Gauge =-1.54
Local Error=0.0870831460674
*****

```

Figure C.57: Individual to Distributed, I2D M1 Validation: **Run6**, Output Text File: Output Data of Response of Gauge SG02: μ_{TR} .

```

*****
|Basic Data Base (BDB), SG03 Response
NMM
-106.451111717
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00248812 0.00270177 0.00292986 0.00317239 0.00415971 0.00437721
  0.00460915]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00175519 -0.00182252 0.0016489 0.00019908 0.00044783 0.00145639]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.0021058 0.00550748 0.00469756 0.00129588 0.00080992 0.00161985
  0.00080992]
Fitting Surface Order II: Total Error of the Load Cases:0.000809923870734
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =0.0029298553772
Predicted Strain Gauge =1.0488882825
Real Strain Gauge =107.5
Local Error=-106.451111717
*****

```

Figure C.58: Individual to Distributed, I2D M1 Validation: **Run6**, Output Text File: Output Data of Response of Gauge SG03: μ_V .

```

*****
|Basic Data Base (BDB), SG04 Response
NMM
-26.6544389727
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00081538 0.00081238 0.00079766 0.00077122 0.001637 0.00162825
  0.00160778]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficcients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[a1, a2, a3, a4, a5, a6]
[[ 0.00030963 0.00011678 0.00081577 -0.00011221 -0.00036324 0.00091671]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.00139307 0.00226239 0.00034557 0.00052375 0.00191682 0.00383364
  0.00191682]
Fitting Surface Order II: Total Error of the Load Cases:0.0019168198274
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=0.419 L=358
Predicted Normalised Strain Gauge =0.000797656500803
Predicted Strain Gauge =0.285561027287
Real Strain Gauge =26.94
Local Error=-26.6544389727
*****
##### END #####

```

Figure C.59: Individual to Distributed, I2D M1 Validation: **Run6**, Output Text File: Output Data of Response of Gauge SG04: μ_M .

Appendix D

Appendix - Chapter 6

C.- Right semispan, outboard station.									
Loading location	-- Applied Loading --			--- Strain Gage Bridge Output, mV ---					
	Shear	Bending	Torque	$\mu 13$	$\mu 14$	$\mu 15$	$\mu 16$	$\mu 22$	$\mu 23$
1	100	2080	-255	2.782	5.986	1.207	4.899	-.101	.301
2	100	2290	296	1.949	6.310	1.996	5.659	-.195	.381
3	100	1510	-274	2.786	4.392	1.362	3.417	-.013	-.262
4	100	1510	273	2.006	4.149	2.436	3.774	-.146	.761
5	100	850	-294	2.976	2.570	1.286	1.954	-.090	-.661
6	100	850	291	1.653	2.474	2.991	2.031	.086	.972
7	100	190	-309	2.946	.404	.584	.686	-.377	-.387
8	100	190	312	.894	1.044	4.088	.012	.569	.634

Figure D.1: Run Case 1: RC1, Individual Dependent Datam, IDD1 experimental sample - Table 6.4 [28].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2		Test Case 1, 01, TCI_01 - Run Cases 1, RC1 -					Reference 80_06, Eckstrom Experimental Data							
3		Loads Points, LP Y [in]					Right wing out							
4				Loads	% Chord		SG1	SG2	SG3	SG4	SG5	SG6		
5		N1	98.4	100	-3.09		2.946	0.404	0.584	0.686	-0.377	-0.387		
6		N2	98.4	100	3.12		0.894	1.044	4.088	0.012	0.569	0.634		
7		N3	105	100	-2.94		2.976	2.57	1.286	1.954	-0.09	-0.661		
8		N4	105	100	2.91		1.653	2.474	2.991	2.031	0.086	0.972		
9		N5	111.6	100	-2.74		2.786	4.392	1.362	3.417	-0.013	-0.262		
10		N6	111.6	100	2.73		2.006	4.149	2.436	3.774	-0.146	0.761		
11		N7	117.3	100	-2.55		2.782	5.986	1.207	4.899	-0.101	0.301		
12		N8	119.4	100	2.96		1.949	6.31	1.996	5.659	-0.195	0.381		1
13														
14														
15		Data Treated with I2D Module 2, Spreadsheet I2D_D_i					SG1	SG2	SG3	SG4	SG5	SG6		
16		LP Combined	YCG [in]	Loads (Mean)	Chord CG									
17		1,4,7	108.2027	123.3333333	-0.9251351		1.0074	0.661467	0.799933	0.7602	2.7454	1.1766		
18		4,5,7	112.127	123.3333333	-1.1359459		0.819833	0.520667	1.1395	1.079167	3.2375	1.3875		
19		4,7,8	114.827	123.3333333	1.15945946		0.587	0.360667	0.959333	0.9075	3.367	1.443		
20		1,2,3	101.0757	123.3333333	-1.0151351		0.3495	0.2373	0.1148	0.1055	0.5439	0.2331		
21		4,5,6	109.8162	123.3333333	1.00459459		0.215267	0.135933	0.2638	0.248067	0.6216	0.2664		
22		7,8,1	110.3189	123.3333333	0.14486486		0.198	0.1112	0.418	0.3985	1.8648	0.7992		
23		2,5,7	110.3432	123.3333333	-1.0791892		0.528	0.3416	0.4422	0.4213	1.6317	0.6993		
24		7,7,1	109.6378	123.3333333	-2.7689189		0.4186	0.2678	0.3716	0.3642	1.7094	0.7326		2
25														
26														
27		Ordered Data, From I2D M2, DDD1					SG1	SG2	SG3	SG4	SG5	SG6		
28		New LITE Order	LP Combination: YCG [in]	Loads (Mean)	Chord CG									
29		LP1	N1	98.4	100	-3.09	2.946	0.404	0.584	0.686	-0.377	-0.387		
30		LP2	1,2,3	101.0757	123.3333333	-1.0151351	0.3495	0.2373	0.1148	0.1055	0.5439	0.2331		
31		LP3	N2	98.4	100	3.12	0.894	1.044	4.088	0.012	0.569	0.634		
32		LP4	N5	111.6	100	-2.74	2.786	4.392	1.362	3.417	-0.013	-0.262		
33		LP5	1,4,7	108.2027	123.3333333	-0.9251351	1.0074	0.661467	0.799933	0.7602	2.7454	1.1766		
34		LP6	4,5,6	109.8162	123.3333333	1.00459459	0.215267	0.135933	0.2638	0.248067	0.6216	0.2664		
35		LP7	7,7,1	109.6378	123.3333333	-2.7689189	0.4186	0.2678	0.3716	0.3642	1.7094	0.7326		
36		LP8	4,7,8	114.827	123.3333333	1.15945946	0.587	0.360667	0.959333	0.9075	3.367	1.443		
37		LP9	N8	119.4	100	2.96	1.949	6.31	1.996	5.659	-0.195	0.381		3
38														
39														
40		Sample Distributed Data, I2D M2, DDD2, CLCC					SG1	SG2	SG3	SG4	SG5	SG6		
41			7,8,1	110.3189	123.3333333	0.14486486	0.198	0.1112	0.418	0.3985	1.8648	0.7992		4
42														
43														
44														

Figure D.2: Run Case 1: RC1, Distributed Dependent Data, DDD1, numerical sample, source I2D Module M2 - Table 6.4 [28].

	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1						RC1	ESM Input Data, From Visual Inspection of IC plots, IDD2							
2														
3	LC order	Yw [in]	Load [lb]	Xw [in]		Shear [lb]	BM [lb-in]	T [lb-in]		sg13	sg14	sg15	sg16	sg22
4	7	98.4	100	-3.09		100	190	-309		2.946	0.404	0.584	0.686	-0.377
5	8	98.4	100	3.12		100	190	312		0.894	1.044	4.088	0.012	0.569
6	5	105	100	-2.94		100	850	-294		2.976	2.57	1.286	1.954	-0.09
7	6	105	100	2.91		100	850	291		1.653	2.474	2.991	2.031	0.086
8	3	111.6	100	-2.74		100	1510	-274		2.786	4.392	1.362	3.417	-0.013
9	4	111.6	100	2.73		100	1510	273		2.006	4.149	2.436	3.774	-0.146
10	1	117.3	100	-2.55		100	2080	-255		2.782	5.986	1.207	4.899	-0.101
11	2	119.4	100	2.96		100	2290	296		1.949	6.31	1.996	5.659	-0.195
12														

Figure D.3: Run Case 1: RC1, Individual Dependent Data, IDD2, experimental sample, filtered by IC - Table 6.4 [28].

C. Right Semispan, Outboard Station.

				u13	u14	u15	u16	u22	u23
Cruise	160	1878	95	3.656	5.581	3.378	4.490	.275	.503
Bending	400	5762	28	9.738	16.566	7.035	13.838	-.502	.725
Torsion	0	0	566	2.192	.409	2.844	-.487	1.910	2.086

Figure D.4: Run Case 1: RC1, Distributed Independent Data, DID1, CLCC, experimental sample, - Table 6.4 [28].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2		Test Case 1_01, TCI_01 - Run Cases 1, RC1 -					Reference 80_06, Eckstrom Experimental Data							
3		Loads Points, LP Y (in)	Loads	% Chord			SG1	SG2	SG3	SG4	SG5	SG6		
4		N1	98.4	100	-3.09		2.946	0.404	0.584	0.686	-0.377	-0.387		
5		N2	98.4	100	3.12		0.894	1.044	4.088	0.012	0.569	0.634		
6		N3	105	100	-2.94		2.976	2.57	1.286	1.954	-0.09	-0.861		
7		N4	105	100	2.91		1.653	2.474	2.991	2.031	0.086	0.972		
8		N5	111.6	100	-2.74		2.786	4.392	1.362	3.417	-0.013	-0.262		
9		N6	111.6	100	2.73		2.006	4.149	2.436	3.774	-0.146	0.761		
10		N7	117.3	100	-2.55		2.782	5.986	1.207	4.899	-0.101	0.301		
11		N8	119.4	100	2.96		1.949	6.31	1.996	5.659	-0.195	0.381		1
12														
13														
14														
15		LP Combined					Data Treated with I2D Module 2, Spreadsheet I2D_D_i							
16		YCG (in)	Loads (Mean)	Chord CG			SG1	SG2	SG3	SG4	SG5	SG6		
17		1,4,7	108.2027	123.3333333	-0.9251351		1.0074	0.661467	0.799933	0.7602	2.7454	1.1766		
18		4,5,7	112.127	123.3333333	-1.1359459		0.819833	0.520667	1.1395	1.079167	3.2375	1.3875		
19		4,7,8	114.827	123.3333333	1.15945946		0.587	0.360667	0.959333	0.9075	3.367	1.443		
20		1,2,3	101.0757	123.3333333	-1.0151351		0.3495	0.2373	0.1148	0.1055	0.5439	0.2331		
21		4,5,6	109.8162	123.3333333	1.00459459		0.215267	0.135933	0.2638	0.248067	0.6216	0.2664		
22		7,7,1	110.3189	123.3333333	0.14486486		0.198	0.1112	0.418	0.3985	1.8648	0.7992		
23		2,5,7	110.3432	123.3333333	-1.0791892		0.528	0.3416	0.4422	0.4213	1.6317	0.6993		
24		7,7,1	109.6378	123.3333333	-2.7689189		0.4186	0.2678	0.3716	0.3642	1.7094	0.7526		2
25														
26														
27		Ordered Data, From I2D M2, DID1					SG1	SG2	SG3	SG4	SG5	SG6		
28		New LETE Order	LP Combination	YCG (in)	Loads (Mean)	Chord CG								
29		LP1	N1	98.4	100	-3.09		2.946	0.404	0.584	0.686	-0.377	-0.387	
30		LP2	1,2,3	101.0757	123.3333333	-1.0151351		0.3495	0.2373	0.1148	0.1055	0.5439	0.2331	
31		LP3	N2	98.4	100	3.12		0.894	1.044	4.088	0.012	0.569	0.634	
32		LP4	N5	111.6	100	-2.74		2.786	4.392	1.362	3.417	-0.013	-0.262	
33		LP5	1,4,7	108.2027	123.3333333	-0.9251351		1.0074	0.661467	0.799933	0.7602	2.7454	1.1766	
34		LP6	4,5,6	109.8162	123.3333333	1.00459459		0.215267	0.135933	0.2638	0.248067	0.6216	0.2664	
35		LP7	7,7,1	109.6378	123.3333333	-2.7689189		0.4186	0.2678	0.3716	0.3642	1.7094	0.7526	
36		LP8	4,7,8	114.827	123.3333333	1.15945946		0.587	0.360667	0.959333	0.9075	3.367	1.443	
37		LP9	N8	119.4	100	2.96		1.949	6.31	1.996	5.659	-0.195	0.381	3
38														
39		Sample Distributed Data, I2D M2, DID2, CLCC					SG1	SG2	SG3	SG4	SG5	SG6		
40		LP Combination	YCG (in)	Loads (Mean)	Chord CG									
41		7,8,1	110.3189	123.3333333	0.14486486		0.198	0.1112	0.418	0.3985	1.8648	0.7992		4
42														
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100														

Figure D.5: Run Case 1: RC1, Distributed Independent Data, DID2, CLCC, numerical sample, source I2D Module M2- Table 6.4 [28].

(C) RIGHT WING, OUTBOARD STATION

WING LOADINGS			STRAIN GAGE BRIDGE OUTPUTS, MILLIVOLTS					
SHEAR, LBS	MOMENT, IN-LBS	TORQUE, IN-LBS	$\mu 13$	$\mu 14$	$\mu 15$	$\mu 16$	$\mu 22$	$\mu 23$
50.0	1093.0	10.0	1.273	3.092	.812	2.660	-.084	.167
100.0	1518.0	9.0	2.426	4.314	1.869	3.711	-.085	.249
150.0	2611.0	19.0	3.665	7.485	2.703	6.384	-.294	.400
200.0	3036.0	18.0	4.844	8.791	3.727	7.457	-.309	.480
250.0	4129.0	28.0	6.047	11.936	4.460	10.188	-.523	.627
300.0	4554.0	27.0	7.180	13.225	5.433	11.247	-.531	.697
250.0	3462.0	17.0	5.840	10.221	4.530	8.681	-.551	.515
200.0	3037.0	18.0	4.740	9.014	3.493	7.624	-.547	.453
150.0	1945.0	8.0	3.503	5.927	2.681	4.992	-.324	.305
100.0	1520.0	9.0	2.316	4.605	1.606	3.933	-.316	.230
50.0	428.0	-1.0	1.093	1.481	.819	1.197	-.101	.088
.0	.0	.0	-.067	.161	-.223	.123	-.088	.004

Figure D.6: Run Case 1: RC1, Individual Independent Data, IID1, CLCC, experimental sample, - Table 6.4 [28].

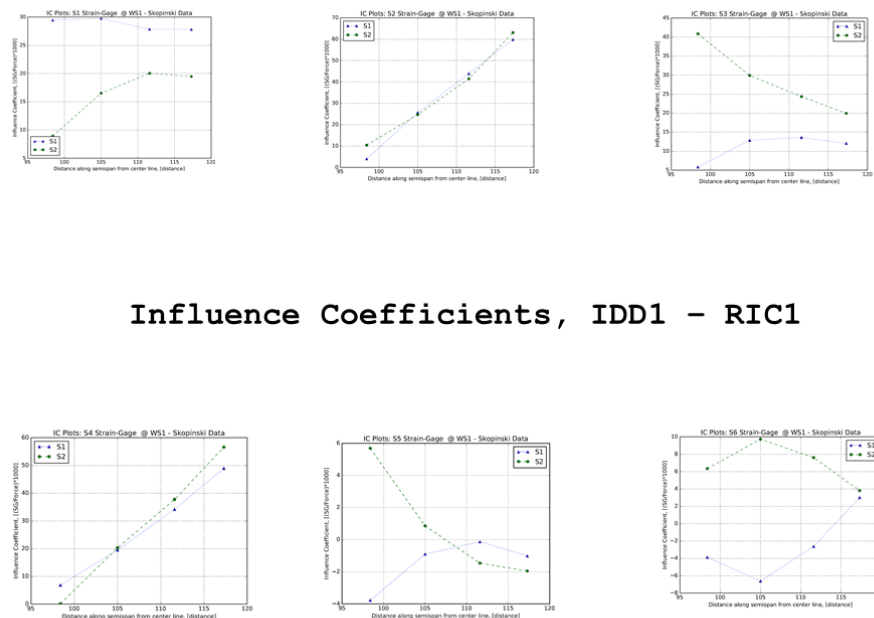


Figure D.7: Run Case 1 - RC1, Strain Gauge Investigation Result: RIC1, IC package, IDD1, - Table 6.5 [28].

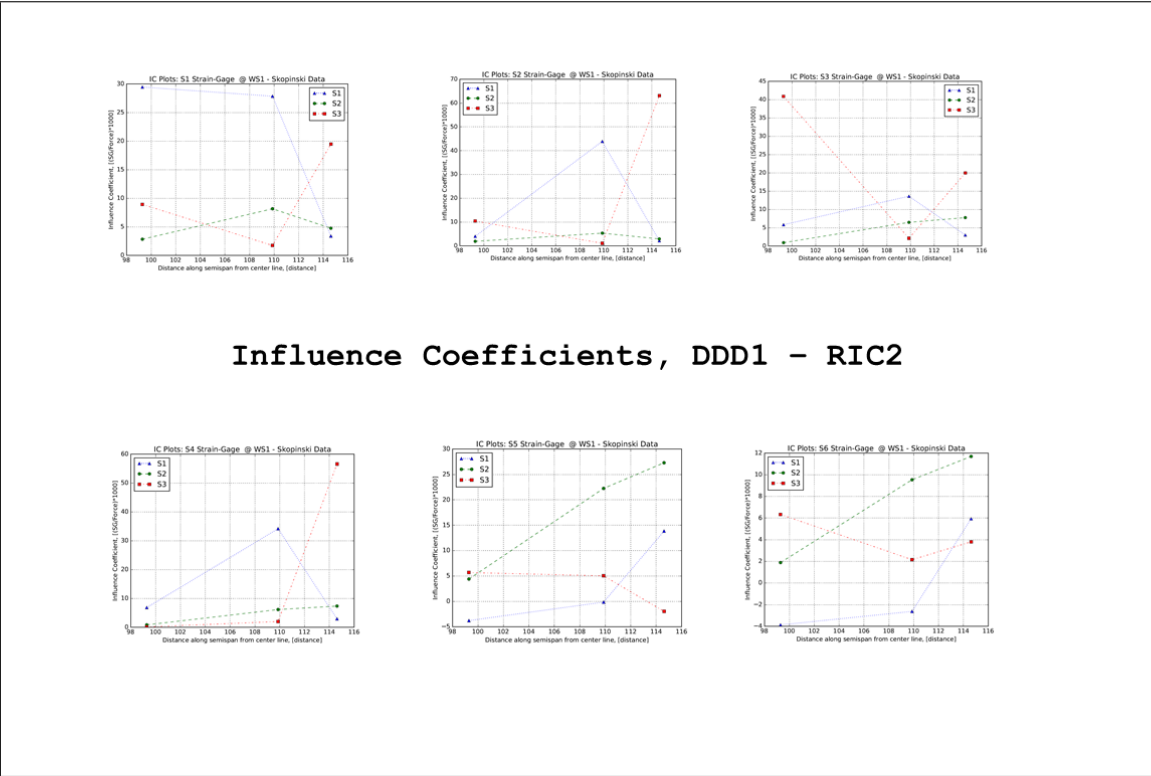


Figure D.8: Run Case 1 - RC1, Strain Gauge Investigation Result: RIC2, IC package, DDD1, - Table 6.5 [28].

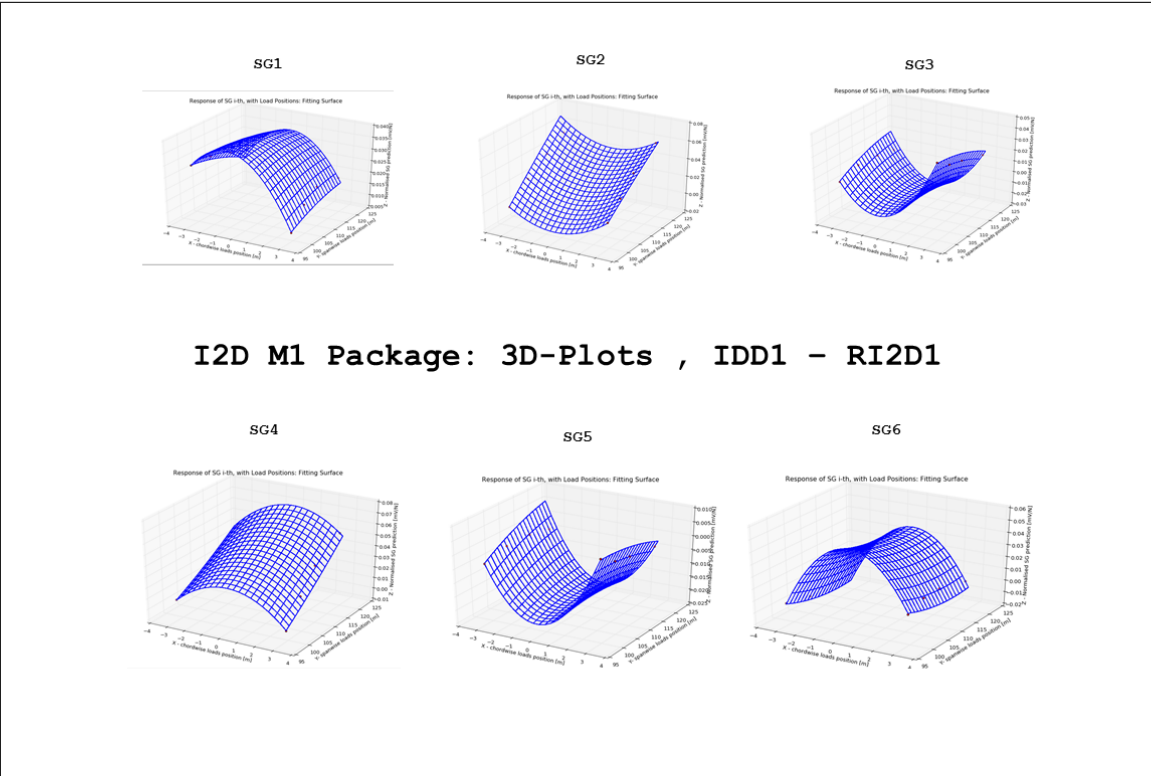


Figure D.9: Run Case 1 - RC1, Strain Gauge Investigation Result: RI2D1, Response of Gauges with position of load and fitting surface I2D M1 package, IDD1, - Table 6.5 [28].

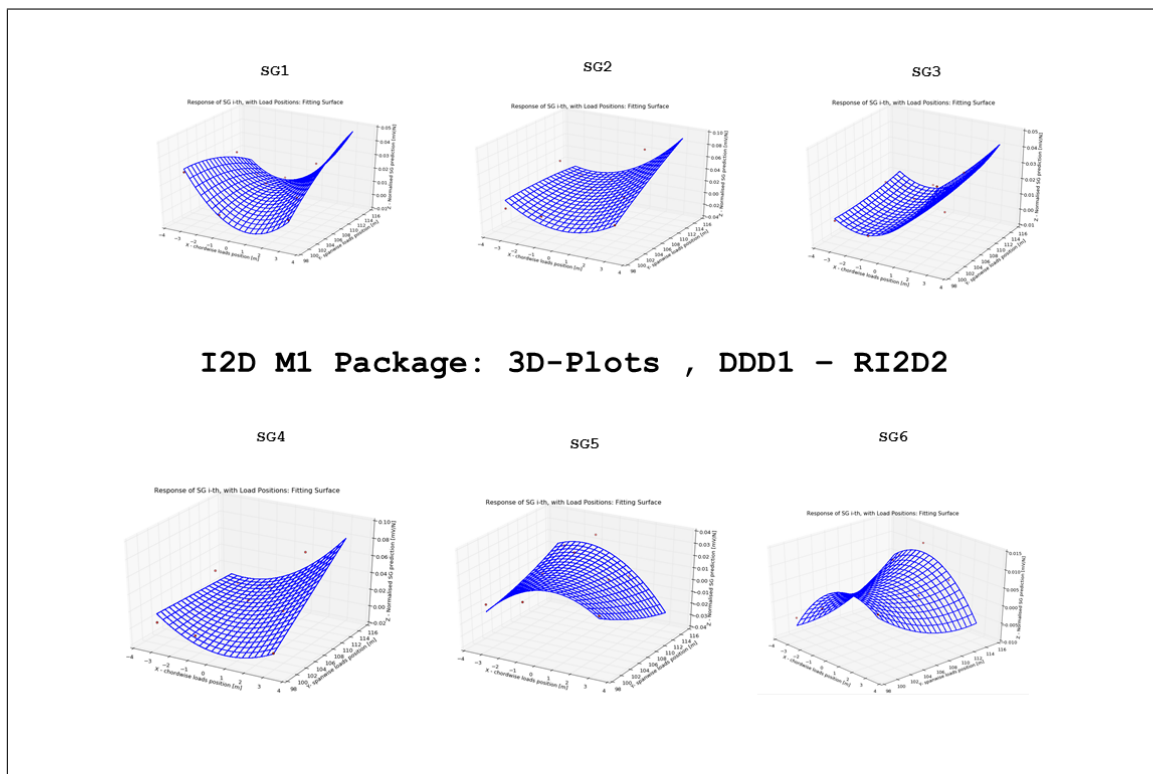


Figure D.10: Run Case 1 - RC1, Strain Gauge Investigation Result: RI2D2, Response of Gauges with position of load and fitting surface *I2D M1* package, DDD1, - Table 6.5 [28].

```

.....
|Basic Data Base (BDB), SG04 Response
I2D M1 / RC1 / IDD1 / Globa Error
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.00673557 0.00055039 0.01959741 0.01932438 0.03451326 0.03836323
  0.04870549 0.05653028]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[[ -2.48960162e-02 -1.28518878e-02 -8.26932826e-04 1.21244349e-04
  -2.48532626e-03 1.38274030e-05]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.00439925 0.0152165 0.00202969 0.03484691 0.01213591 0.02203456
  0.01005905 0.00211146]
Fitting Surface Order II: Total Error of the Load Cases:0.00211145576183
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=90 L=100
Predicted Normalised Strain Gauge =0.0128882744218
Predicted Strain Gauge =1.28882744218
Real Strain Gauge =26.94
Local Percentage Error=95.2159337707
.....
I2D M1 Package: 3D-Plots , IDD1 and DDD1 Global Error Comparison
.....
|Basic Data Base (BDB), SG04 Response
I2D M1 / RC1 / DDD1 / Globa Error
.....3-D Plot, Z Data.....
Fitting Surface, Z-axis data: Normalised Strain Gauge prediction - [mV/N]
[[ 0.01717946 -0.00882311 -0.00051689 0.01221203 0.00855056 0.02158041
  0.01251006 0.01657424 0.03781924]]
.....Global Outputs, DD.....
Fitting Surface Order II Normalised Coefficients, Z=a1+a2(X)+a3(Y)+a4(XY)+a5(XX)+a6(YY):
[[ -2.77164174e-01 -9.19158339e-02 2.75131539e-03 8.96305212e-04
  2.34140446e-03 -1.03646583e-06]]
Fitting Surface Order II: Single Error of each Load Cases:
[ 0.34398216 0.39806028 0.0212297 0.73193246 0.09818859 0.80452568
  0.39296785 0.3787168 0.62569194]
Fitting Surface Order II: Total Error of the Load Cases:0.625691941926
.....Local Outputs, ID.....
Strain Gauge Prediction: Load Application Coordinates x y and Magnitude L
x=-0.127 y=90 L=100
Predicted Normalised Strain Gauge =-0.0364748551803
Predicted Strain Gauge =-3.64748551803
Real Strain Gauge =26.94
Local Percentage Error=113.53929294
.....

```

Figure D.11: Run Case 1 - RC1, Strain Gauge Investigation Result Global Error SG 4 Comparison: RI2D1 vs RI2D2 , Response of Gauges with position of load and fitting surface I2D M1 package, IDD1 vs DDD1, - Table 6.5 [28].

RC1 - LPE - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1	Loads Coefficients: RC1/ LPE Technique			
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	24.85332522	56.59892139	-177.6125486
4	mu14	0.201630628	-76.59532401	-460.4465117
5	mu15	21.55981604	-48.37211762	197.9016427
6	mu16	0	513.9621747	574.92477
7	mu22	-21.92700099	730.4941642	343.1297782
8	mu23	-2.033692834	-10.1861778	-80.6640164
9				
10				
11				
12				

Figure D.12: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - LPE Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - GA Nelson- Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/GA Nelson Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	24.85332521	42.7837475	-253.2822627
4	mu14	0.20163063	0	0
5	mu15	21.55981604	-39.63681799	242.4851022
6	mu16	0	422.4537191	23.27476514
7	mu22	-21.92700099	539.829377	-782.7493958
8	mu23	-2.03369283	0	0
9				
10				
11				
12				

Figure D.13: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - GA Nelson Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - T-v Method - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/ T-v Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	25.70314141	42.7837475	-206.6046754
4	mu14	0	0	-328.7022073
5	mu15	20.76133337	-39.63681799	218.5861577
6	mu16	0	422.4537191	418.5757563
7	mu22	-19.67635916	539.829377	0
8	mu23	0	0	-76.67786229
9				
10				
11				
12				

Figure D.14: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - T-v Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - MT-v Method - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/ MT-v Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	25.23159633	50.03063617	-206.6046754
4	mu14	0	-31.38954569	-328.7022073
5	mu15	21.40865089	-44.91986871	218.5861577
6	mu16	0	459.6208721	418.5757563
7	mu22	-21.66930987	622.3240355	0
8	mu23	-1.35806984	0	-76.67786229
9				
10				
11				
12				

Figure D.15: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - MT-v Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - LPP1 - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/ LPP1 Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	25.70314141	42.7837475	-184.5245449
4	mu14	0	0	-297.1538942
5	mu15	20.76133337	-39.63681799	192.2374547
6	mu16	0	422.4537191	375.1860152
7	mu22	-19.67635916	539.829377	0
8	mu23	0	0	0
9				
10				
11				
12				

Figure D.16: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - LPP1 Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - ESM - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/ ESM Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	24.85332522	50.03063617	-229.6265893
4	mu14	0.201630628	-31.38954569	-102.4633983
5	mu15	21.55981604	-44.91986871	225.2398914
6	mu16	0	459.6208721	144.5977317
7	mu22	-21.92700099	622.3240355	-513.4660129
8	mu23	-2.033692834	0	0
9				
10				
11				
12				

Figure D.17: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - ESM Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - DLD - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/ DLD Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	173.330784	4078.279956	-599.2483795
4	mu14	223.3359779	5957.857118	-1180.997556
5	mu15	-155.6364737	-3734.818314	739.4637879
6	mu16	-285.8639595	-7983.878761	1474.059561
7	mu22	-130.163934	-4842.581457	558.4574233
8	mu23	672.6728444	16668.01153	-2023.087424
9				
10				
11				
12				

Figure D.18: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - DLD Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

RC1 - LPP2 - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC1/ LPP2 Technique		
2		Shear [Lb/mV]	BM [inLb/mV]	T [inLb/mV]
3	mu13	52.92906586	683.2707555	-216.162317
4	mu14	0	0	0
5	mu15	0	0	150.5867075
6	mu16	0	0	73.93127246
7	mu22	0	0	0
8	mu23	222.8010628	2122.350415	-154.500668
9				
10				
11				
12				

Figure D.19: Run Case 1 - RC1, Loads Coefficients Computations, Codes Output - LPP2 Technique: Shear, Bending Moment and Torque - Table 6.6 [28].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	Load Cases										RC2 - Test Case 4, CIRA - Castore Ground Load Calibration, GLC1 - IDD1 / WS1						
2	LP	y [mm]	Force [N]	BM [Nmm]	T [Nmm]	x [mm]				Spar1 BM	Spar1 She	Spar2BM	Spar 2 She	Spar3 BM	Spar 3 Shear		
3	1 C11	977	-3092	1102	2404	0.77749				9.97E-05	3.13E-05	8.08E-05	2.56E-05	5.23E-05	8.01E-06		
4	2 C12	977	-3092	1102	3391	1.096701				9.29E-05	2.3E-05	0.000125	2.64E-05	6.61E-05	1.1E-05		
5	3 C14	977	-3092	1102	5469	1.768758				7.71E-05	1.32E-05	9.08E-05	1.82E-05	9.48E-05	1.24E-05		
6	4 C21	1325	-2777	2150	3116	1.122074				0.000187	3.75E-05	0.000171	3.93E-05	0.000136	1.97E-05		
7	5 C22	1325	-2777	2150	3697	1.331293				0.000175	3.6E-05	0.000182	4.05E-05	0.000153	2.23E-05		
8	6 C24	1325	-2777	2150	4912	1.768815				0.000156	2.82E-05	0.000178	3.49E-05	0.000185	2.45E-05		
9	7 C31	1725	-2777	3256	3902	1.405113				0.00026	5.09E-05	0.000257	5.13E-05	0.00024	3.61E-05		
10	8 C32	1725	-2777	3256	4317	1.554555				0.000255	4.74E-05	0.00026	5.12E-05	0.000249	3.46E-05		
11	9 C34	1725	-2777	3256	4912	1.768815				0.000245	4.19E-05	0.000265	5.01E-05	0.000268	3.61E-05		
12																	

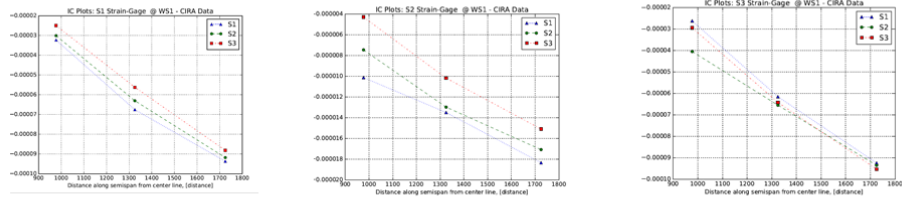
Figure D.20: Run Case 2: RC2, Individual Dependent Datam, IDD1 experimental sample, Castore GLC1 - Table 6.12 [87].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1																
2																
3	Loads Combination	Shear	BM	T	LP Combinations		YCG [mm]	Loads (Mean)	XCG [mm]		SG1	SG2	SG3	SG4	SG5	SG6
4	1,4,7	6000	4646.045	6637.66	Distributed Load Case1	1,4,7	1207.91	1833.33333	0.98558		0.00029	6.9E-05	0.00026	6.5E-05	0.00021	3.1406E-05
5	4,5,7	6000	5043.572	7538.53	Distributed Load Case2	4,5,7	1466.18	2833.33333	1.28351		0.00064	0.00013	0.00063	0.00013	0.00054	8.0368E-05
6	4,7,8	6300	6390.997	8428.56	Distributed Load Case3	4,7,8	1566.27	2100	1.33787		0.00052	0.0001	0.00051	0.00011	0.00046	6.6068E-05
7	1,2,3	7500	2673.027	9107.37	Distributed Load Case4	1,2,3	977	2500	1.21432		0.00022	5.5E-05	0.00024	5.7E-05	0.00017	2.5379E-05
8	4,5,6	5500	4258.192	7669.34	Distributed Load Case5	4,5,6	1325	1833.33333	1.39442		0.00034	6.7E-05	0.00035	7.6E-05	0.00031	4.3722E-05
9	7,8,1	4700	4286.568	5886.76	Distributed Load Case6	7,8,1	1486.28	1566.66667	1.04605		0.00035	7.2E-05	0.00034	7.2E-05	0.00031	4.4642E-05
10	2,5,7	5000	3344.304	6165.95	Distributed Load Case7	2,5,7	1255	1666.66667	1.23319		0.00027	5.8E-05	0.0003	6.3E-05	0.00023	3.5406E-05
11	7,7,1	7400	6309.768	8577.73	Distributed Load Case8	7,7,1	1431.86	2466.66667	1.15915		0.00051	0.00011	0.00049	0.00011	0.00044	6.5987E-05
12																
13																
14	Ordered and Combined to respect IC input data															
15	Loads Combination	Shear	BM	T	LP Combinations		YCG [mm]	Loads (Mean)	XCG [mm]		SG1	SG2	SG3	SG4	SG5	SG6
16	1	-3092	1102	2404	1		977	-3092	0.77749		1E-04	3.1E-05	8.1E-05	2.6E-05	5.2E-05	8.0085E-06
17	2	-3092	1102	3391	2		977	-3092	1.0967		9.3E-05	2.3E-05	0.00012	2.6E-05	6.6E-05	1.0963E-05
18	1,2,3	-7500	2673.027	9107.37	Distributed Load Case4	1,2,3	977	-2500	1.21432		0.00022	5.5E-05	0.00024	5.7E-05	0.00017	2.5379E-05
19	4	-2777	2150	3116	4		1325	-2777	1.12207		0.00019	3.7E-05	0.00017	3.9E-05	0.00014	1.97E-05
20	4,5,6	-5500	4258.192	7669.34	Distributed Load Case5	4,5,6	1325	-1833.33333	1.39442		0.00034	6.7E-05	0.00035	7.6E-05	0.00031	4.3722E-05
21	6	-2777	2150	4912	6		1325	-2777	1.76882		0.00016	2.8E-05	0.00018	3.5E-05	0.00018	2.4538E-05
22	7,8,1	-4700	4286.568	5886.76	Distributed Load Case6	7,8,1	1486.28	-1566.66667	1.04605		0.00035	7.2E-05	0.00034	7.2E-05	0.00031	4.4642E-05
23	7,7,1	-7400	6309.768	8577.73	Distributed Load Case8	7,7,1	1431.86	-2466.66667	1.15915		0.00051	0.00011	0.00049	0.00011	0.00044	6.5987E-05
24	4,5,7	-6000	5043.572	7538.53	Distributed Load Case2	4,5,7	1466.18	-2833.33333	1.28351		0.00064	0.00013	0.00063	0.00013	0.00054	8.0368E-05
25																
26																
27																
28																
		M1_GLC1_Loads	M1_GLC1_IDD1	Sheet2	M1_GLC1_DDD1		M1_GLC2_IDD1									

Figure D.21: Run Case 2: RC2, Distributed Dependent Data, DDD1, numerical sample, source I2D Module M2 - Source Castore GLC1 - Table 6.12 [87].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Load Cases														
2		y [mm]	Force [N]	BM [Nmm]	T [Nmm]	x [mm]									
3	C1	977	-2587.33	1220.91	3960.37	1.530678									
4	C2	977	-2166.67	1046.4	3579.37	1.652014									
5	C3	1325	2003.37	976.75	3774.06	-1.88386									
6	C4	1325	-2769.56	1289.49	4526.51	1.634379									
7	C5	1725	-2921.33	1472.4	6650.73	2.27661									
8	C6	1725	-2380.09	1174.52	4284.34	1.800075									
9															

Figure D.22: Run Case 2: RC2, Individual Independent Data, IID1, CLCC, experimental sample - Source Polluce GLC2 - Table 6.12 [87].



Castore, USV1 -Influence Coefficients, IDD1 - RIC3

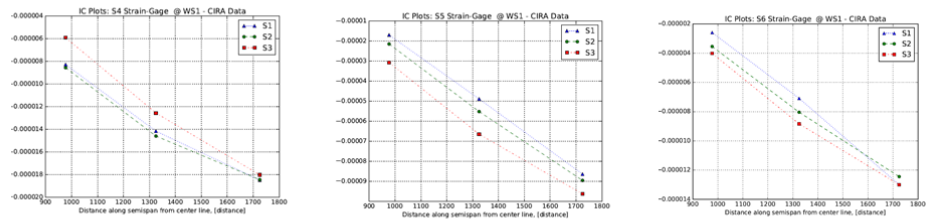
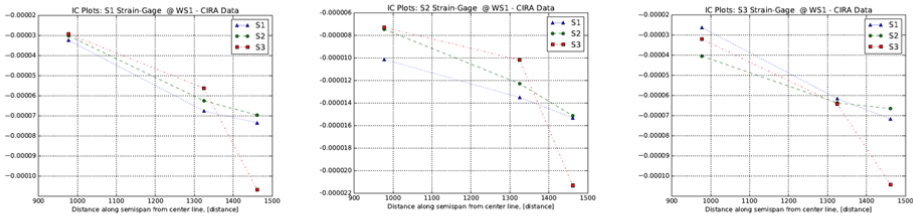


Figure D.23: Run Case 2 - RC2, Strain Gauge Investigation Result: RIC3, IC package, IDD1 - Table 6.13 - Source Castore GLC1 - [87].



Castore, USV1 -Influence Coefficients, DDD1 - RIC4

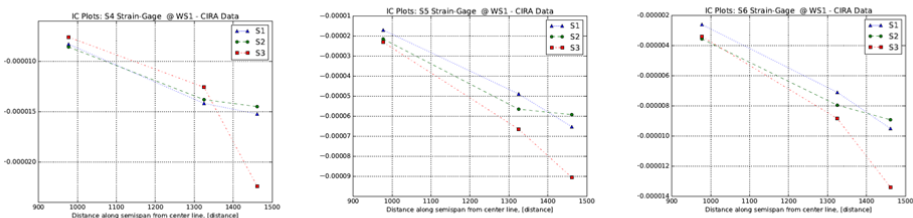
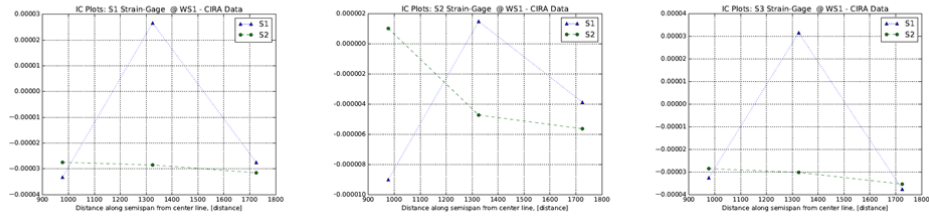


Figure D.24: Run Case 2 - RC2, Strain Gauge Investigation Result: RIC4, IC package, DDD1, - Table 6.13 [87].



Polluce, USV2 -Influence Coefficients, IID1 - RIC5

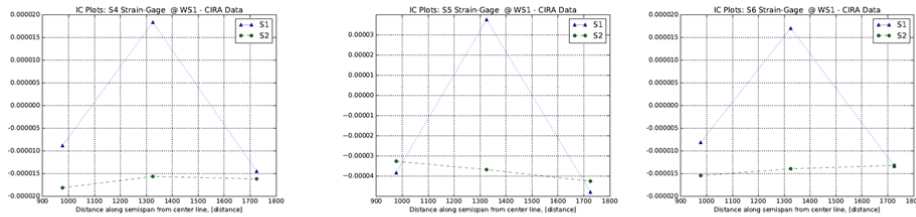
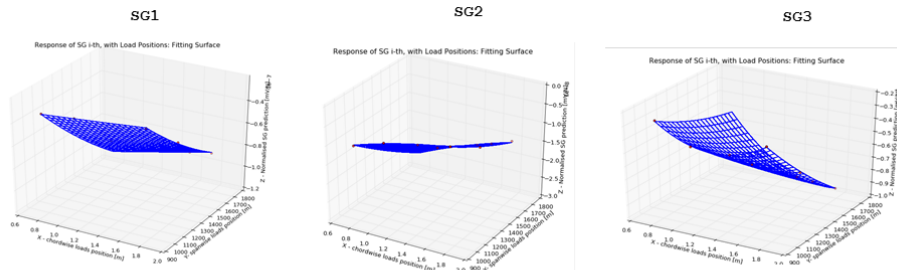


Figure D.25: Run Case 2 - RC2, Strain Gauge Investigation Result: RIC5, IC package, IID1 - Table 6.13 - Source Polluce GLC2 - [87].



Castore USV1 - I2D M1 Package: 3D-Plots , IDD1 - RI2D3

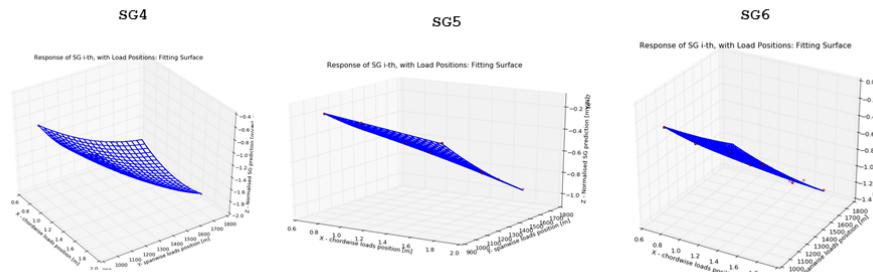


Figure D.26: Run Case 2 - RC2, Strain Gauge Investigation Result: RI2D3, Response of Gauges with position of load and fitting surface I2D M1 package, IDD1, - Table 6.13 - Source Castore GLC1 - [87].

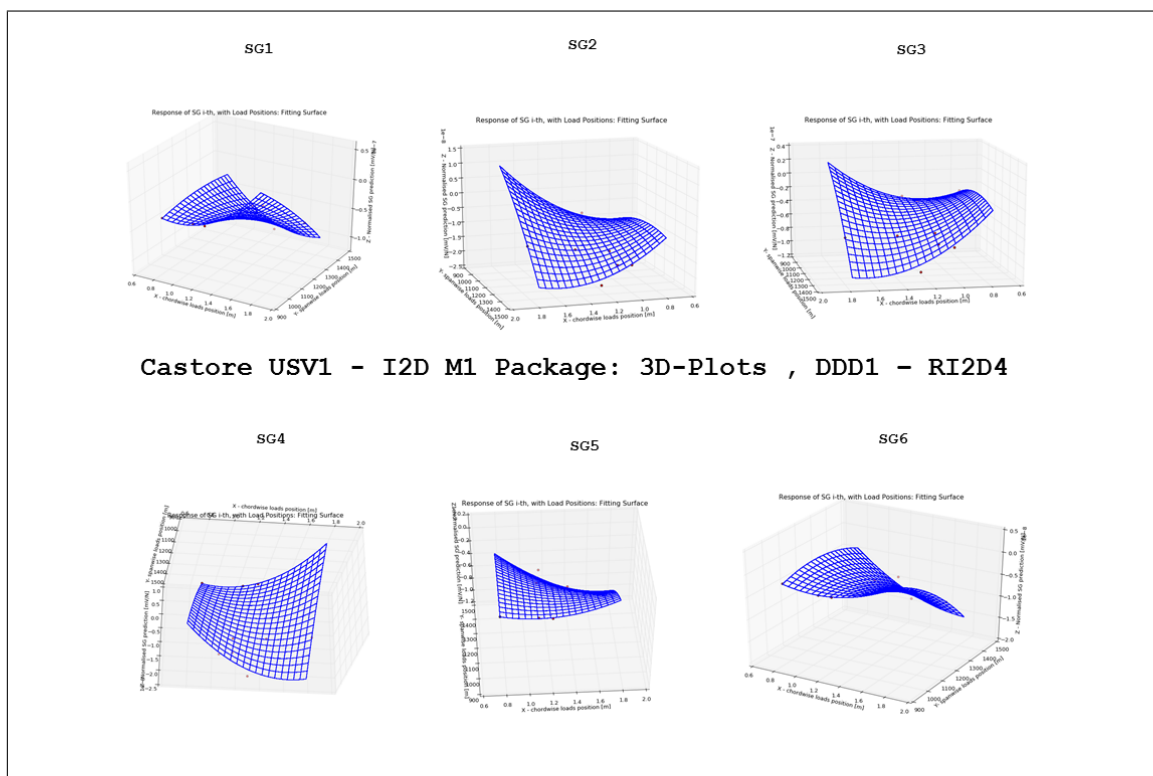


Figure D.27: Run Case 2 - RC2, Strain Gauge Investigation Result: RI2D4, Response of Gauges with position of load and fitting surface *I2D M1* package, DDD1, - Table 6.5 - Source Castore GLC1 - [28].

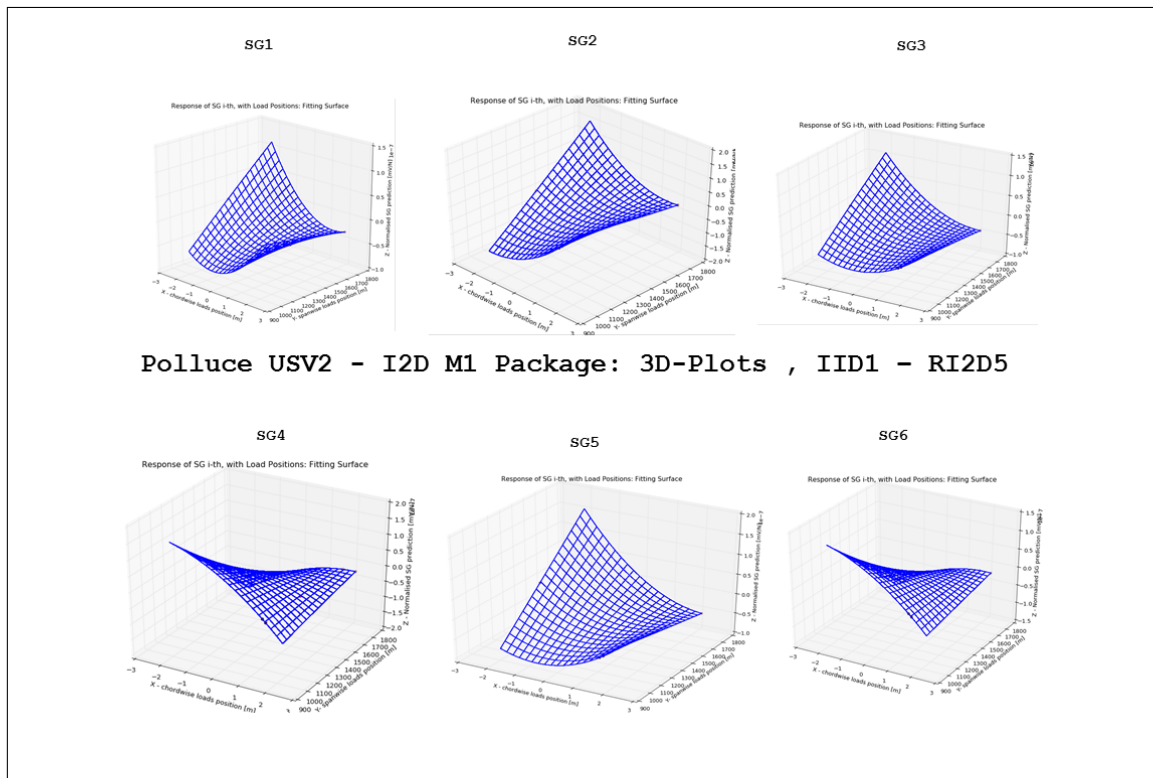


Figure D.28: Run Case 2 - RC2, Strain Gauge Investigation Result: RI2D5, Response of Gauges with position of load and fitting surface *I2D M1* package, IID1, - Table 6.13 - Source Polluce GLC2 - [87].

RC2 - LPE - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC2/ LPE Technique		
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	53409087.23	6233877.473	3550428.557
4	Spar1 Shear	0	6512427.823	0
5	Spar2BM	21197557.63	671916.5671	0
6	Spar 2 Shear	-367447982.1	-1683325.925	0
7	Spar3 BM	-12394544.88	5475954.463	16391874.65
8	Spar 3 Shear	0	-2741640.929	0
9				
10				
11				
12				
13				
14				
15				

Figure D.29: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - *LPE* Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

RC2 - GA Nelson- Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC2/GA Nelson Technique		
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	53409087.23	6198422.81	-137280081.6
4	Spar1 Shear	0	5951047.385	134819276.9
5	Spar2BM	21197557.63	447658.8183	0
6	Spar 2 Shear	-367447982.1	-553435.2282	403192538
7	Spar3 BM	-12394544.88	5231088.944	46786611.06
8	Spar 3 Shear	0	0	0
9				
10				
11				
12				
13				
14				
15				

Figure D.30: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - GA Nelson Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

RC2 - T-v Method - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC2/ T-v Technique		
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	47996475.88	6218872.658	-91091652.85
4	Spar1 Shear	0	5639517.72	0
5	Spar2BM	0	363068.3828	0
6	Spar 2 Shear	-294272234.5	0	377534816.2
7	Spar3 BM	0	5241606.736	33443428.39
8	Spar 3 Shear	0	0	0
9				
10				
11				
12				
13				
14				
15				

Figure D.31: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - T-v Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

RC2 - MT-v Method - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1	Loads Coefficients: RC2/ MT-v Technique			
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	47996475.88	6218872.658	-93657417.19
4	Spar1 Shear	0	5639517.72	0
5	Spar2BM	0	363068.3828	-24710282.94
6	Spar 2 Shear	-294272234.5	0	455937997.2
7	Spar3 BM	0	5241606.736	45481504.26
8	Spar 3 Shear	0	0	0
9				
10				
11				
12				
13				
14				
15				

Figure D.32: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - MT-v Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

RC2 - LPP1 - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1	Loads Coefficients: RC2/ LPP1 Technique			
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	4.57E+07	6324925.253	-3.91E+07
4	Spar1 Shear	0	6091256.882	0
5	Spar2BM	3.57E+06	0	0
6	Spar 2 Shear	-3.01E+08	0	2.82E+08
7	Spar3 BM	0	5431502.078	0
8	Spar 3 Shear	0	0	0
9				
10				
11				
12				
13				
14				
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Figure D.33: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - LPP1 Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

RC2 - DLD - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC2/ DLD Technique		
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	80500653.92	0	0
4	Spar1 Shear	-292757691.5	307723641.6	307723641.6
5	Spar2BM	-47032867.59	88203078.56	88203078.56
6	Spar 2 Shear	0	-508655013.6	-508655013.6
7	Spar3 BM	-82584368.24	105762029.8	105762029.8
8	Spar 3 Shear	664259966.7	-969168842.3	-969168842.3
9				
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11				
12				
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Figure D.34: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - DLD Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

RC2 - LPP2 - Loads Coefficients: Shear, Bending and Torsion

	A	B	C	D
1		Loads Coefficients: RC2/ LPP2 Technique		
2		Shear [N/microStrain]	BM [mmN/microStrain]	T [[mmN/microStrain]]
3	Spar1 BM	9.34E+07	0	-1.14E+08
4	Spar1 Shear	-2.59E+08	1.10E+08	2.17E+08
5	Spar2BM	-5.43E+07	0	8.70E+07
6	Spar 2 Shear	0	-7.09E+07	0
7	Spar3 BM	0	5.37E+07	0
8	Spar 3 Shear	0	-3.43E+08	0
9				
10				
11				
12				
13				
14				
15				

Figure D.35: Run Case 2 - RC2, Loads Coefficients Computations, Codes Output - LPP2 Technique: Shear, Bending Moment and Torque - Table 6.14 [87].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1									RC2 - Test Case 4, CIRA - Castore Ground Load Calibration, GLC1 - DDD1 / WS1							
2					Distributed Sample				Data Treated with I2D Module 2, Spreadsheet I2D_D_J							
3	Loads Combination	Shear	BM	T	LP Combinations		YCG [mm]	Loads (Mean)	XCG [mm]		SG1	SG2	SG3	SG4	SG5	SG6
4	1,4,7	6000	4646.045	6637.66	Distributed Load Case1	1,4,7	1207.91	1833.33333	0.98558		0.00029	6.9E-05	0.00026	6.5E-05	0.00021	3.1406E-05
5	4,5,7	6000	5043.572	7538.53	Distributed Load Case2	4,5,7	1466.18	2833.33333	1.28351		0.00064	0.00013	0.00063	0.00013	0.00054	8.0368E-05
6	4,7,8	8500	4590.997	6438.36	Distributed Load Case3	4,7,8	1566.27	2100	1.23787		0.00052	0.0001	0.00051	0.00011	0.00046	6.6688E-05
7	1,2,3	7500	2673.027	9107.37	Distributed Load Case4	1,2,3	977	2500	1.21432		0.00022	5.5E-05	0.00024	5.7E-05	0.00017	2.5379E-05
8	4,5,6	5500	4258.192	7669.34	Distributed Load Case5	4,5,6	1325	1833.33333	1.39442		0.00034	6.7E-05	0.00035	7.6E-05	0.00031	4.3722E-05
9	7,8,1	4700	4286.568	5886.76	Distributed Load Case6	7,8,1	1486.28	1566.66667	1.04605		0.00035	7.2E-05	0.00034	7.2E-05	0.00031	4.4642E-05
10	2,5,7	5000	3344.304	6165.95	Distributed Load Case7	2,5,7	1255	1666.66667	1.23319		0.00027	5.8E-05	0.0003	6.3E-05	0.00023	3.5406E-05
11	7,7,1	7400	6309.768	8577.73	Distributed Load Case8	7,7,1	1431.86	2466.66667	1.15915		0.00051	0.00011	0.00049	0.00011	0.00044	6.5987E-05
12																

Figure D.36: Run Case 2: RC2, Distributed Independent Data, DID1, numerical sample, source DDD1 I2D Module M2 - Source Castore GLC1 - Table 6.12 [87].

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