

CRANFIELD UNIVERSITY

EBITIMITULA TARI-INEI ETEBU

RELIABILITY AS A METRIC FOR STRUCTURAL HEALTH
MONITORING SYSTEMS PERFORMANCE: APPLICATION ON
FIXED JACKET OFFSHORE STRUCTURES

SCHOOL OF WATER, ENERGY, AND ENVIRONMENT
Energy And Power

PhD

Academic Year: 2016 – 2023

Supervisor: Prof. Chris Sanson, Prof. Nigel Simms.
Associate Supervisor: Dr Mahmood Shafiee

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This thesis is submitted in partial fulfilment of the requirements for
the degree of PhD

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ABSTRACT

This research work addresses the need for reliability performance metrics for Structural Health Monitoring (SMH) systems on a fixed offshore jacket platform. The most common metric used to quantify SHM performance is the probability of detection (POD), it only quantifies the probability of detecting damage of a specific size. While POD is of high importance, it does not fully quantify the total performance of SHM systems. SHM systems can produce outcomes on the detection of damage, its predicted location of damage on the monitored structure and severity of damage detected at the predicted location. These outcomes are of interest for maintenance of the monitored structure. It is paramount to quantify the quality of information attained from all three SHM outcomes.

This work proposes the use of Reliability as a metric to quantify outcomes from SHM systems. Furthermore, it also proposes the use of conditional reliability to quantify the interdependence of the predicted damage severity, given damage was localized, and damage was detected. The dependency of the Monitored structured reliability on the reliability of the SHM system was also proposed a metric of overall SHM performance.

Probability performance metrics were also proposed in this work to extend the widely used POD, to other outcomes of SHM systems. The Probability of accurate localization and probability of accurate assessment were presented. Additionally, conditional probabilities were also proposed to address the interdependencies between SHM outcomes.

Methods used in this work to estimate reliability include the First order reliability method (FORM), and Monte Carlo simulation. Finite element models of Fixed offshore platform were created, the modal response under specific loading conditions, and simulated damage events were used as inputs for Vibration based SHM methods. Hit/Miss techniques were implemented to calculate the probability-based parameters for each SHM outcome. A framework was developed to capture the uncertainties associated with the SHM process, with a limit state function generated for each SHM outcome. Fatigue reliability was implemented using Paris Law to estimate the reliability of structure members in the Fixed offshore platform. Bayes method was implemented to calculate conditional reliabilities.

The outcomes from the proposed approach presented in this thesis, present a pathway to quantify SHM system performance beyond damage assessment.

Presented in this work is a comparison between two SHM systems, where their performance outcomes are quantified for damage detection, localization, and severity assessment. The contribution of the overall SHM systems reliability on the predicted monitored structure members predicted fatigue reliability was presented. Furthermore, a comparison between different vibration based SHM systems at all levels of SHM performance was also presented. In addition, the fusion of multiple SHM systems and their potential contribution to the improvement in predictions of the monitored structure's reliability was also described. This methodology can stand as a generic approach that can be applied to non-vibration based SHM systems or structures that are not fixed offshore platforms.

Keywords: Structural health monitoring, damage detection, damage location, fixed offshore platform, reliability, SHM reliability, probability of detection, remaining useful life.

DECLARATION

I, ETEBU, Ebitimitula (Student ID 219494) declare that this thesis represents my original work and has not been previously submitted elsewhere or in this University for the award of a degree of Doctor of Philosophy in Mechanical Engineering.

ACKNOWLEDGEMENTS

I hereby thank my supervisors Prof. Chris Sanson, Prof. Nigel Simms.

Associate Supervisor Dr Mahmood Shafiee for their concerted effort to see to it that I successfully completed this research work. I owe them immense gratitude.

My wife, Mrs. Jessica Etebu who was very supportive and patient for the duration of my studies, I thank you.

To my parents, Prof. E.N. Etebu and Prof. Mrs. O.M.O. Etebu and siblings, God bless you for your strong support. It is worthy of mention that it was my mother who obtained her third Ph. D in Energy and Power from the University of Cranfield that introduced me to this Institution of high repute.

Finally, to God Almighty, I give all the acknowledgement and praise for seeing me through this rewarding programme.

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NOMENCLATURE

Abbreviations

SHM	Structural Health Monitoring
NDI	Non-destructive inspection
RUL	Remaining useful life
POD	Probability of detection
AFOSM	Advanced First Order Second Moment method
FORM	First order reliability method
FLS	Fatigue limit state
MAC	Modal assurance criterion
COMAC	Coordinate modal assurance criterion
FEM	Finite element model
ANN	Artificial neural networks
GA	Genetic algorithm
NDE	Non-destructive evaluation
GW	Guided wave
POD	probability of detection
NDT	non-destructive testing
MAPOD	model assisted probability of detection
RSE	response surface modelling
SORM	second order reliability method
DOE	design of experiments
SCF	stress concentration factor
FLS	fatigue limit state
MSE	Modal strain energy
$ZMSE_j$	normalization of the modal strain energy
PFA	probability of false alarm
ZTDL	zone of true damage location
PLD	predicted location of damage occurrence
TDL	true damage location
ALT	allowable localization tolerance

PAOL	probability of accurate localization
PDS	predicted damage severity
ADS	actual damage severity
DST	damage severity threshold
POAA	probability of accurate assessment
DD	damage detection
DL	damage localization
DA	damage assessment
COV	coefficient of variance
FEA	Finite Element Analysis
PFN	probability of false negative
SD	Slope difference
ZDS	Normalized slope difference
CZSD	cumulative modal normalized slope difference
DICSD	Damage index cumulative slope difference

Symbols

$R(\mathbf{X})$	Capacity
$S(\mathbf{X})$	Demand
$g(\mathbf{X})$	Limit state function
$\mathbf{X}$	Input variables
P_f	Systems performance
$f_{\mathbf{x}}(\mathbf{X})$	Joint probability density function
R	Reliability
μ_y	Mean
σ_y	Standard deviation
β	Reliability index
ϕ	Cumulative distribution function
U_i	Normalized variables
ΔK	Stress intensity factor
C	Paris Law material constant

m	Paris Law material constant
a	Crack size
N	Stress cycles
a_0	Initial crack length
$E[\Delta S^m]$	Stress range distribution
a_n	Crack length after N stress cycles
ω	Average frequency for long term stress range of all sea states
Γ	Gamma function
A	Scale functions of the Weibull distribution
B	Weibull distribution shape function
T	Time history of stress
a_{shm}	SHM system detectable crack size
$O_{detection}$	Outcome of crack detection by the SHM system
$O_{non-detection}$	Outcome of no crack detection by the SHM system
ϕ_{jr}	Mode shape at correlated modes and location
λ_i	Eigen value of mode
ϕ_i	Mode shape
K_{j0}	Stiffness matrix of a structure member
K	Global stiffness matrix
α	Reduction factor in the stiffness of a given structural member
k^e	equivalent stiffness
k_1	stress intensity factor
ν	Poisson ratio
E	Young's modulus
O_{dd}	Output of SHM damage detection
D_d	Occurrence of damage
D_{nd}	No damage detected
D_{th}	Damage threshold
ψ	Weight assigned
ε_1	Uncertainty associated with sensor measurement
ε_2	Uncertainty from signal processing
ε_3	Uncertainty associated with damage detection technique

ε_4	Damage localization uncertainty
ε_5	Damage assessment uncertainty
β_{DD}	Local reliability index for damage detection
β_{DL}	Local reliability index for damage localization
β_{DA}	Local reliability index for damage assessment
β_{SHM}	Local SHM reliability index
R_{DD}	Local reliability for damage detection
R_{DL}	Local reliability for damage localization
R_{DA}	Local reliability for damage assessment
R_{FP}	Reliability of false positive
R_{FN}	Reliability of false negative
R_{Total}	Total Reliability
R_{SHM}	Local SHM reliability
E_i	Failure functions for the SHM system
E_{SHM}	Failure functions for the monitored structure
$R_{SHM_STRUCTURE}$	SHM reliability associated with the predicted monitored structure's reliability
h_{nd_i}	Limit state functions for the event where no crack is detected
h_{dd_i}	Limit state functions for the event where crack is detected
$R_{Structure_i}^u$	Updated reliability of Structure
$R_{SHM_Structure_i}^u$	Updated reliability of Structure, given SHM reliability
φ'	Slope of Beam
M	Bending moment
I	Second moment of the cross-sectional area
h	Height of element
$ \varphi_{d,i}' $	Magnitude of the displacement eigen vector
$ X_{d,i} , X_{d,i+1} $	Magnitude of the displacement components for eigen vector at each end of the element
$ \varphi_{r,i}' $	Magnitude of the rotation eigen vector
$ X_{r,i} , X_{r,i+1} $	Magnitude of the rotation components for eigen vector at each end of the element
a_{pcs}	Predicted crack severity
nn	Inputs to learning algorithm

RR	Residue matrix
$\widehat{\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}}_{mr}$	Mean residual damage indicator
$\boldsymbol{DI}_{mr}$	Damage indicator for the mean residual
$\widehat{\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}}_{cme}$	Mean covariance matrix estimates
$\boldsymbol{DI}_{cme}$	Damage indicator for the covariance matrix estimates
$\widehat{\boldsymbol{\varepsilon}\boldsymbol{\varepsilon}}_{sc}$	Mean scalar covariance
$\boldsymbol{DI}_{sc}$	Damage indicator for the scalar covariance

1. INTRODUCTION TO SHM

1.1 Background and Motivation

The use of sensors and communication technology to generate continuous real time measurements from a structure as a means of detecting the existence of damage, identifying the location of damage, assessing the type and severity of damage, and estimating the remaining useful life (RUL) are objectives for structural health monitoring [1]. Information attained from structural health monitoring provides real time analysis of the health of structures, which can be used to assess a structure's performance, maintenance schedule, and prevention of catastrophic failure.

Sensors are implemented in Structural Health Monitoring (SHM) to measure parameters in a structural member that can be analyzed to detect damage [2]. Sensors commonly used in SHM include optical imagery sensors, acoustic sensors, lamb wave sensors, RADAR, global positioning systems, fiber optic strain gauge, impedance sensors, and accelerometers [3]. Sensors are also available in different technological forms, for instance an accelerometer used to measure acceleration are available in optical, piezoelectric, and laser forms.

The detection of damage in SHM is conducted as global structural health monitoring or local SHM, where global monitoring systems are used to analyze the integrity of a structure in its entirety, where the occurrence of damage can be detected but the location of damage is not always identified [4]. Local monitoring is implemented to assess damage based on a designated location. Damage detection can also be characterized based on linear analysis, and non-linear analysis, as linear behavior cannot describe the mechanical behavior of some damaged systems. Commonly used damage detection systems in SHM are based on damage sensitive features which include resonant frequency shift, change in structural mode shape, natural frequency shift, mode of curvature, Ritz vector, matrix update method, time of flight and damage locating vector [1]. Some commonly used damage sensitive features are unable to identify the location of damage, type of damage, or are not sensitive enough to detect local damage.

The ability of a SHM system to identify damage is generally conducted using either a parametric or non-parametric method [5][6]. For parametric methods, the initial structural health in an undamaged state is identified via experimentation. Initial data measured from parameters such as mass, stiffness, damping, displacement, acceleration, velocity, temperature, and other environmental parameters are analyzed and fused together via analytical or numerical models to attain beneficial structural behavior. Changes to the structural behavior are used as a measure for the detection of damage using a time domain or frequency domain obtained from time history transformation, for instance a ratio of the selected damage feature in time or frequency domain may be used to determine damage, or the fit ratio of the frequency or time domain is used to categorize damage in noisy scenarios [1][3].

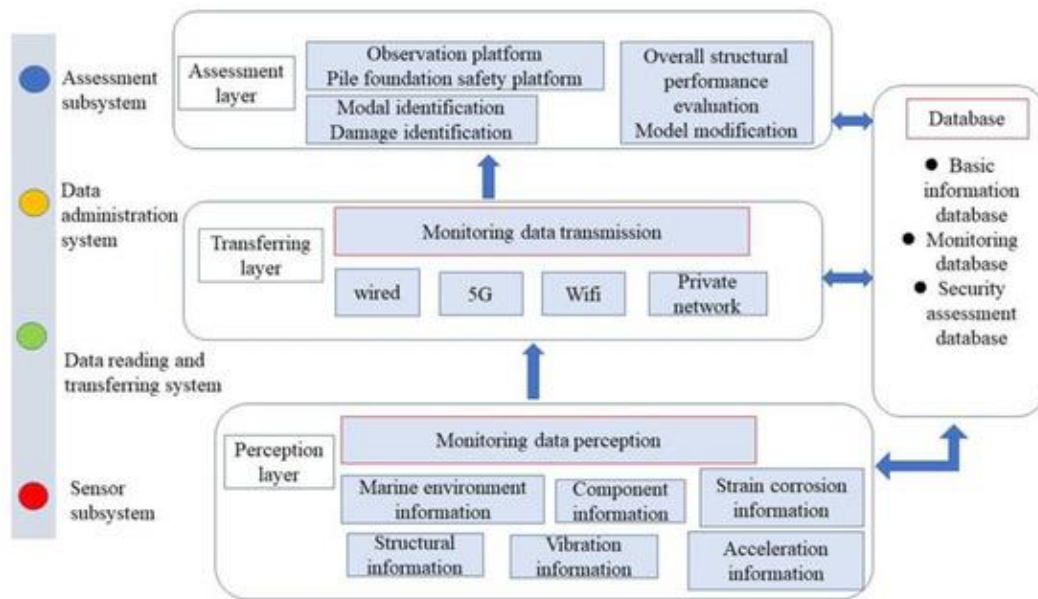


Figure 1-1. Schematic process of a structural health monitoring system for a fixed offshore jacked platform. Reference from Ye et al 2022 [105].

For non-parametric methods, the structural behavior of the initial undamaged condition is not required, rather structural behavior obtained from an arbitrary state is compared to the structural behavior obtained in its present state where a statistical approach is adopted to investigate the level of similarities in the structural behavior [1][4][5].

In some structural health monitoring systems, learning techniques are employed to enrich the results attained [7]. Learning models are employed to assess uncertainties that arise in the SHM process [2][8][9][10]. Learning models are grouped into two techniques namely [8][9]:

- Supervised learning is a technique where initial knowledge of the damaged and undamaged structure is available and commonly used methods include artificial neural networks, Bayes learning, and linear discriminants.
- Unsupervised learning techniques are employed when there is no knowledge of the structures damaged state and commonly used methods for this approach include control chart analysis, and novelty detection.

SHM is applied to monitor the condition of a structure, where a time variant probability of detection is determined for a given type of damage [1][11][12][13]. Structural fatigue reliability is the one of the common damage mechanisms assessed, where signals attained from SHM sensors are processed using cycle counting, and fatigue theory to attain a fatigue time variant reliability index [14][15].

Uncertainties associated with the sensors, communication system, data processing, and damage sensitive feature extraction can result in a false positive outcome from SHM which could trigger maintenance or shut down that is not required, whilst a false negative outcome from the SHM system could lead to catastrophic failure where the system is deemed to be undamaged [1][12][13].

The performance of SHM systems is most commonly judged by the probability of detection (POD) [11], which is a metric that measures the probability of detecting damage as function of the damage severity. The probability of false negative and probability of false positive associated with damage detection are also used as performance indicators.

Although highly important, POD is only a measure of the SHM systems ability with respect to damage detection. It is not a direct measurement of the additional outcomes that can be generated from a SHM system with respect to localization

of detected damage, assessment of the severity for damage detected, and predicting the remaining useful life of the structure.

The accuracy, uncertainty, and sensitivity of sensors, sensory communication network, damage sensitive parameters, damage identification system, learning techniques, and structural reliability index affects the results produced by a SHM system [1], thus a quantitative assessment of the reliability of a SHM system is of importance. Information obtained from sensors for a non-parametric structural health monitoring may indicate a deviation in structural behavior. However, the change measured by the sensors could be due to changes in environmental conditions that affect the sensors measurements instead of a change in the structure [1]. A deviation of structural behavior in its present state in comparison to a previously arbitrary state might also not be an indication of possible structural damage. The detection of damage may also be limited by the damage identification method. Errors due to improper installation of reliable and accurate sensors can lead to the collection of unreliable data. Limitations of the type of measurement a sensor can perform, sensor placement, sensor contact, power requirement, as well as sensor degradation could also lead to unreliable information for parametric and non-parametric structural health monitoring. For instance, a flaw detection sensor that detects only surface flaws will not provide information on subsurface flaws, or a low density of placement might result in an ability to detect flaws in a structure [1][6][7].

In order to assess the reliability of a structural health monitoring system, test procedures are generated and conducted for a given sample size, after which the systems reliability and confidence, are characterized using probability models [13]. The integration of information sources from various sensors, and potential external sources are merged into probability models. Probability models such as Bayesian method, and Fuzzy logic method, are commonly used to merge information from multiple sources to attain the systems reliability [16][17].

The first objective of this research program was to assess the ability of commonly used SHM techniques to detect, localize, and assess damage in energy

structures as well as the system's ability to predict remaining useful life. It was observed through numerical simulations of a fixed offshore platform that Vibration based SHM techniques were capable of level 3 SHM performance. (See Chapter 3). A translation from damage severity to damage type was required to generate the remaining useful life estimates.

The second objective of this research work was to develop a SHM performance function framework that could be used to assess uncertainties which arise in the SHM process. It was depicted that the application of a Bayes network to the damage detection, localization, and assessment scheme could be employed to calculate the reliability of damage detection of a SHM system. Furthermore, the conditional reliability of damage location given damage detected was proposed as a damage localization performance parameter (See Chapter 3). An additional SHM performance parameter for the reliability of accurate damage assessment, given the event of damage localization and damage detection is also presented. A cumulative performance parameter for comparing SHM systems based on a weighted combination of damage detection, localization, and assessment was proposed (See chapter 3 and 5). This weighted parameter was proposed to address any perceived importance of a specific SHM function over another.

The third objective of this work was to assess the potential combination of SHM techniques to improve the systems reliability performance metrics. A combination of vibration based SHM, in addition to the use of supervised learning was infused to assess the potential improvements in the SHM systems ability to detect, localize, and assess damage through numerical simulation of a fixed offshore platform (See chapter 4).

The fourth objective of this work is to investigate the use of a single reliability metric as an output from the framework that defines the combined SHM reliability performance while the last objective is to investigate the effect of combined SHM reliability performance.

1.2 Statement of the problem

By reason of the wide variation of techniques used to identify damage, in addition to the numerous types of sensors that can be employed to attain a given measurement, as well as the multiple data fusion techniques available, the reliability of a SHM system is dependent on the sensors, damage identification techniques, data fusion method, and reliability theory method selected.

The key task is to determine the reliability of the SHM system, and its contribution to the reliability of the structure being monitored. Quantifying the reliability of the SHM system provides a metric that can be used to adequately judge improvements in the SHM system.

1.3 Project Scope

Performance functions for SHM systems are currently based on the probability of detecting damage in a structure. This performance function can be misleading because it does not provide a complete outlook on the type 1 (false-positive) and type 2 (false-negative) errors associated with the SHM system [1][4]. Furthermore, damage detection is one of four functions a SHM system can perform, and these include:

- The opportunity to assess SHM performance from a single parameter that encompasses type 1 and type 2 error associated with damage detection, localization, and assessment.
- A holistic comparison of SHM systems based on the ability to detect, localize, and assess damage.
- Quantifying the potential improvement of the monitored structures' reliability based on improvement of the SHM systems reliability.

1.4 Aim and Objectives

This project aim is to demonstrate numerically the application of reliability-based techniques to quantify the performance of vibration based SHM systems when applied to a fixed offshore platform.

Objectives in this research work include:

- To demonstrate the application of vibration based SHM technique on an energy structure, with varying degrees of damage, using data attained from a numerically simulated fixed offshore platform.
- To assess the reliability of the fixed offshore platform, and estimate its remaining useful life based on the outcome from the SHM system.
- To develop a framework that engulfs the uncertainty associated with the SHM process, where the reliability of damage detection, damage localization, and damage assessment are outputs of the framework.
- To investigate the use of a single reliability metric as an output from the framework that defines the combined SHM reliability performance.
- To investigate the effect of the combined SHM reliability performance on the monitored structure's reliability and estimate remaining useful life for fatigue damage.

1.5 Methodology

In this work, the contribution of SHM to the fatigue reliability of an offshore fixed jacket platform structural member is assessed, using an updated fatigue reliability index generated from the outcome of SHM was assessed (see chapter 2, 3). The initial fatigue reliability index was calculated using Advanced First Order Second Moment method (AFOSM) and first order reliability method (FORM) (see chapter 2, 3). Fatigue limit state (FLS) was defined using fracture mechanics. Updated reliability index is calculated using a conditional probability of failure based on FLS and SHM event detection. SHM damage detection and localization was conducted using modal frequencies generated from a 3D fixed jacket platform model, with varying levels of damage. This current work is limited to theoretical and numerical analysis, applications to real world offshore jacket platforms which are feasible representatives of this research work.

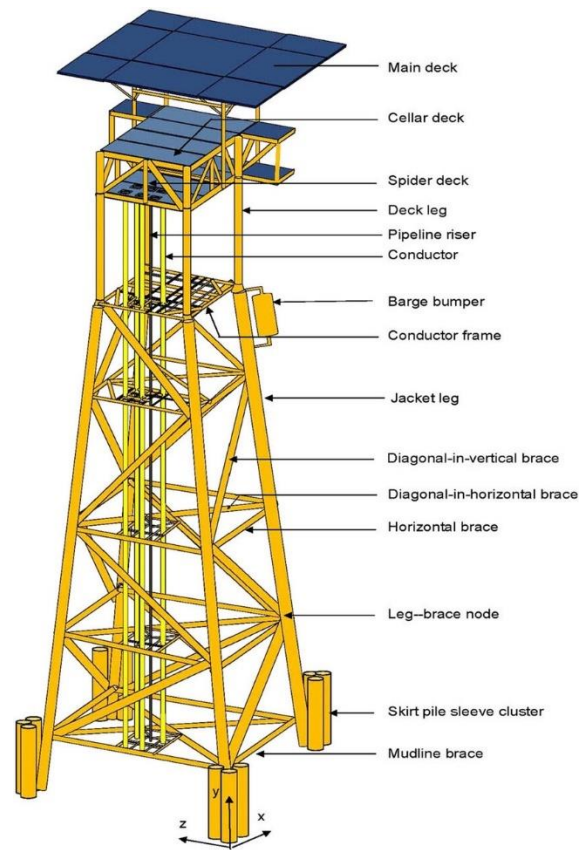


Figure 1-2. Major components of a typical fixed offshore jacked platform.
Reference from Okoro and Kolios [104].

1.6 Contribution to Knowledge

Previous researchers have investigated and developed SHM techniques for extracting damage sensitive information from vibration and strain-based sensors used to monitor energy structures. However, prior investigations into the performance of outcomes obtained from these techniques have been limited to probabilities and mostly focused on damage detection. This work addresses the reliability associated with outputs from vibration and strain based SHM systems, applied to an energy structure. The main contributions of knowledge from this study are the establishment of:

- A performance function that quantifies a SHM systems reliability to localize damage, given the occurrence of damage.

- A second performance function that quantifies the reliability of a SHM system to assess damage severity, given damage was localized, and detected.
- A weighted reliability performance function that could be used to compare level 3 SHM systems, based on the perceived importance of damage detection, localization, and severity assessment.
- The conditional reliability of a structure monitored by SHM, given the reliability of the SHM system.

1.7 Limitations of the Study

The gathering of data and materials for the construction of an experimental testing rig posed a challenge which was limitation of the study.

Publications

- 1 Etebu, E., and M. Shafiee. "Reliability analysis of structural health monitoring systems." *Safety and Reliability–Safe Societies in a Changing World*. CRC Press, 2018. 2243-2247.
 - 2 Etebu, E., and M. Shafiee. "Contributions of structural health monitoring to the reliability of an offshore fixed platform." *European Safety and Reliability (ESREL) Conference, Portoroz, Slovenia*. Vol. 18. 2017.
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1.8 Thesis Outline

This thesis contains seven chapters, wherein chapter 1 encapsulates Introduction while chapter 2 covers a comprehensive literature review of SHM techniques and Reliability methods and knowledge gap. The application of vibration based SHM techniques is discussed where damage is simulated at varying locations with varying severities. Chapter 3 describes the process of calculating the reliability of an energy structure, where the fatigue reliability of a fixed offshore platform is calculated. Chapter 4 is dedicated to a vibration based SHM technique for jacket structures. A new SHM technique was proposed for damage detection,

localization, and assessment based on the change in slope of a structure's mode shape. This technique was tested on a numerically simulated fixed offshore platform. Chapter 5 focuses on a framework that combines multiple SHM techniques to improve the reliability of a monitored structure. Chapter 6 contains validation of reliability as a metric for SHM performance using data from published research. Lastly, conclusions, summary, recommendations for future work, and contribution to knowledge are presented in chapter 7.

2 LITERATURE REVIEW

2.1 Generalized Algorithms

A structure is characterized as an assembly of mechanically resistant members, connected via joints, where these mechanical members transmit forces with no relative motion [18][19]. The only function of a structure is to modify and transmit forces. Examples of structures include trusses, bridges, machine frames, risers, pipelines, etc. Structures used in industries such as energy, civil, aerospace, etc., are an expensive investment to the owner, as they require an intensive initial cost to erect the structure, and costly maintenance throughout the structures operational life [5]. Structures deteriorate due to ageing, faulty installation, operational conditions, environmental conditions, lack of maintenance, and poor inspection [2]. Maintaining a structure's integrity is of importance to the social, environmental, economic, and political welfare of a society, hence the need to assess structures integrity in its current operational condition and predict its remaining service life is of importance.

There are two approaches to damage identification namely non-destructive inspection (NDI) and structural health monitoring (SHM). NDI is implemented as a traditional time based on-site schedule maintenance technique that detects and assesses damage based on reference measurements[6][1]. SHM is implemented to determine the integrity of a structure using a network of sensors that are mounted on a structure, where the critical information on the structure's behaviour obtained from the sensor's measurement is monitored continuously in an autonomous manner throughout the structure's life span. The physical principles implemented to detect damage in NDI and SHM are equivalent, however SHM provides a maintenance schedule that is condition driven instead of time driven. Furthermore, it reduces the need to access difficult to reach structural members that are difficult or hazardous to access.

SHM techniques can be classified into local method and global method where the local method is implemented to detect minute damage on the local scale, while global method provides a holistic view of a structures behaviour, the change in

global behaviour indirectly provides insight on the structures material integrity [4]. SHM operates by detecting damage in the system, registering the time of damage occurrence, indicating the location of damage, quantifying the damage, and executing a predetermined action based on the detection of damage. Damage in a structure can be characterized as a change introduced to the structure that undesirably affects its present or future integrity. Since damage is categorized as a change introduced into a structure, a comparison is thus required between two states of structural behaviour, where one of the two states is considered as an undamaged state. Damage detection is carried out in SHM using a statistical analysis, or a simple comparison between the measured value and an ultimate value, or a comparison between the measured value and designed value.

For energy structures, SHM is commonly applied to platforms, wind turbines, and pipelines [1][4]. Platform structures are used in offshore exploration of oil and gas in deep waters, which present hazardous and problematic challenges during inspection. Offshore platforms are characterized into two groups namely fixed platforms, and floating platforms, where fixed platforms are the most commonly used type of offshore platforms [20][21]. Initial studies of SHM were conducted on fixed offshore platforms in the early 1970s [1], using SHM systems that included accelerometer sensors placed at three locations on the platform decks, where data attained from sensors was processed using Fourier transforms, and computational models were used to obtain the platforms resonant frequency in an undamaged state. The change in resonant frequency was used as an indication of damage, however due to the limited number of sensors implemented in the study, damage identification was limited. An active SHM system comprising of an electro-magnetic shaker, and piezoelectric accelerometer, were applied to multiple offshore platforms, where it was observed that failures in a group of structure members were witnessed to generate a significant change in the platforms resonant frequency, and mode shapes. Effects of environmental conditions, geometry of platform, and SHM sensor systems on measurements obtained from offshore platforms were studied, where the variation of mode shapes, and resonant frequencies were observed to display minor variation with

changes of mass on the platform, and tide changes [1]. Variation in structural members of the platform resulted in major changes of resonant frequencies. Specific environmental conditions on offshore platforms such as corrosion, variation of soil foundation, marine growth, change in deck mass were assessed using finite element analysis in conjunction with data attained from an accelerometer based SHM system and results from analytic and measured resonant frequencies varied by 7-12% [4]. The identification of mode shape associated with resonant frequency was reported as essential part of tracking variation in resonant frequency by multiple studies. Numerous studies reported that several variants of damage in platform structures such as multiple damage locations, flooding of a structure member, partial severance of a structure member, cuts in structural member less than 6 mm, were not detected by change in resonant frequency, or the change in resonant frequency during operational conditions was not different from the change caused by damage to a platforms structure member [4][22]. However severe damage to platform structure members resulted in detectable change in resonant frequency.

Due to the limitations of the damage identification, and inability to localize damage in platform structures using resonant frequency as a global parameter, a vast array of damage identification techniques has been applied to identify, locate, and assess damage in platform structures over the last 3 decades.

Modal assurance criterion (MAC) has been applied to determine the damage in platforms by previous studies [23][24][25]. A scaled model for a fixed platform with 4 legs was assessed using MAC to detect damage at multiple structure members. Furthermore, the deck mass was varied to analyse its effect on damage identification. The results obtained indicated that MAC was able to identify most of the damage present in the structure when the first three modes were analysed for damage. MAC as a matrix-based method is used to identify damage by conducting comparison between the Eigen vector attained from an undamaged structure and a damaged structure. Modes from the reference state and current state are determined to be similar when the MAC matrix has a main diagonal that displays unity and when unity is not observed, damage is deemed

to be present. The drawbacks of the MAC include its inability to localize damage. However, the MAC was modified to attain a correlation factor between the reference state and the current state for modes in a specified degree of freedom. This method is called the coordinate modal assurance criterion COMAC [25][26]. COMAC has been applied as a damage identification method in multiple offshore studies where it was observed to identify most of the damage present in the structure and localize the damage identified: it was also reported to identify and differentiate the structural behaviour due to change in deck mass and damage.

Modal vectors are used to identify damage in platforms by assessing the change in modal vectors [27][28]. Modal vectors are related to structures' stiffness, mass and damping behaviour. Change in the perpendicular components of the modal vector in the predominant modal direction is used to monitor variations in platform structure stiffness. Measurements obtained from solely the deck of platforms have been used to assess damage in platform structures.

Updating structural model is a common technique used in damage identification for platforms [29][30]. A scaled fixed jacket model was assessed using structural model updating where damage was simulated by either replacing a structural member with a similar structural member made of a different material or eliminating the structural member. The damage detection technique identified 80% of the damage scenarios tested. The method for Updating structural model is typically conducted using an optimization process based on the principle that modal properties of a structure obtained from SHM measurements, should correlate with the modal properties obtained from a numerical model of the structure, where a finite element model (FEM) is generally used for numerical modelling. The error between the measured structural modal properties and simulated structural modal properties are minimized using an optimization process to regulate parameters with uncertainty [1][4]. Uncertainty can arise from the variation of loads, structural intricacies, and boundary conditions between SHM measurements and FEM. A comparison is made between the optimized properties and properties obtained from an undamaged state to detect and localize damage. The general limitations encountered in using the updating

structural model technique include that a unique solution is not obtained during the process; hence the solution obtained may not reflect the true properties of the structure, as the stiffness of undamaged structural member have been reported to change during the optimization process.

Less common modal methods of damage identification and location techniques used in platform structures include Modal scale factor, Mode shape relative difference method [1][4][6].

Due to the data intensive nature of damage identification and location, a manual approach applied to the comparison of damage sensitive properties between a structure in its current state and undamaged state is inefficient, time consuming and impractical for large structures with multiple criteria of damage. Pattern recognition algorithms have been applied to identify, localize and quantify damage in structures [31][32][8][33]. Pattern recognition algorithms can be classified based on supervised learning and unsupervised learning. Supervised learning is conducted by creating a database for all damage scenarios that could occur in a structure, where the data base is used to train the pattern recognition algorithm. Supervised learning techniques include neural networks, genetic algorithm, Bayes network, fuzzy logic [31][7][34]. Common unsupervised learning techniques used include neural networks, and control chart analysis.

Artificial neural networks ANN are statistical models designed to work in a similar manner as the human brain using layers of connected neurons that perform mathematical tasks, where input data from multiple locations are treated by neurons which are then used to generate a single output [35]. ANN was used to identify damage in jacket platforms, where it was observed to be a feasible technique for online damage detection. Forms of damage included in the training set were identified as well as damage patterns not included using unsupervised learning. A general ANN is composed of an input layer, hidden layers, and output layer. Commonly used ANN includes back propagation, and adaptive resonance theory. In back propagation, inputs are received by neurons simultaneously, after which the incoming signal is multiplied by the weight of the connected pathway.

The outgoing signal from the neuron is passed through a squashing function, after which it is transmitted to the next layer where this process repeats itself until an output is attained. Training an ANN is conducted by providing input data and output data [35]. Trained ANN is established when the ANN yields the desired output based on a given input. For unsupervised learning ANN accepts the inputs from SHM system and employs slow learning techniques to detect sudden changes in the input signal. ANN can be employed to solve linear, and nonlinear problems [31][32]. Furthermore, ANN is reported to display lower levels of sensitivity to uncertainty. Limitation observed in the use of ANN include the training process accuracy, number of data sets required to cover all damage scenarios, and the results attained from ANN are not unique [31][32][33].

Genetic algorithm GA are used for pattern recognition and reducing the uncertainties that arise during SHM of platform structures [29]. Studies on scaled offshore jack-up platforms have employed GA to combat uncertainties in wave loading and sensor data with up to 10% noise levels to measure rotational stiffness in the legs of the platform, where the mean rotational stiffness of the platform legs were within 6% to 9% of the measured baseline values. GA is a pattern recognition technique based on biological evolution and it is a stochastic optimization method implemented on problems with an extensive number of variables. A basic level GA process undergoes reproduction, crossover, and mutation. GA is conducted with an initial population referred to as chromosomes. The initial chromosomes are generated by guesswork, after which the fitness of each chromosome in the population is assessed [34]. A biological based evolution process is then conducted where chromosomes displaying higher levels of fitness attain a greater chance of reproducing an offspring population. Crossover entails a process where two parents' chromosome are randomly selected to create new offspring, while mutation is employed to replace a random gene in a chromosome where a gene is a component of a chromosome.

Table 2-1. A summary of SHM techniques applied to Platform structures [23-25] [103-105].

DATA GENERATION	ACCELEROMETER	DISPLACEMENT SENSOR	PZT	LOAD SENSOR	FIBRE OPTIC
SIGNAL PROCESSING	FOURIER ANALYSIS	WAVELET TRANSFORMATION			
LINEAR DAMAGE FEAURE EXTRACTION	FREQUENCY	MODE SHAPE CHANGE	MAC	MATRIX UPDATE	TIME OF FLIGHT
PATTERN RECOGNITION	FUZZY LOGIC	ANN	BAYESIAN	GA	ARTIFICIAL IMMUNE SYSTEM
RELIABILITY	FORM	SORM			
FATIGUE RELIABILITY	RAIN FLOW	PEAK COUNTING METHOD			
FATIGUE AND CRACK MODEL	PALM GREN-MINER LINEAR RULE				

2.2 Local Methods

Local SHM methods are used to monitor regions of a structure that are vulnerable to damage and enumerated below are some of these techniques.

2.2.1 Ultrasonic

The ultrasonic method used in SHM has previously been proven as a method of detecting structural integrity in non-destructive evaluation NDE [13]. The ultrasonic method detects flaws and characterizes flaws by the transmission of ultrasonic waves through the thickness of a structure member, where the reflected propagated wave signal is sensitive to discontinuities in the structure [13]. Testing parameters such as amplitude, frequency, phase angle, angle of

wave dependence, time of flight, are recorded. The signal obtained from the propagated wave can be used to obtain additional information about the discontinuity such as orientation, size, and location. Waves are transmitted in ultrasonic testing using pulse echo method, pulse-transmission method, and pulse-resonance method. Ultrasonic waves generated in traditional methods are in for a P wave, S wave, or a combination of P and S wave. The waves generated from traditional ultrasonic method, cover a minute portion of a structural members volume [13].

2.2.2 Infrared thermography

The infrared thermography method involves the use of infrared measuring sensors to obtain the infrared radiation emitted by a structural member where the obtained infrared images are processed to detect damage [36][37][38]. Infrared thermography is either conducted in a passive or active method, where external stimulation is absent in the passive method, and present in the active method. It should also be noted that Infrared thermography technique can also be employed for global SHM systems.

2.2.3 Eddy Current

The eddy current method employs the use of a coil with alternating current that generates a primary magnetic field around the coil, when the coil range is of a structure member; it induces eddy currents in a structure member. Eddy currents produced on a member generate a secondary magnetic field that opposes the primary magnetic field on the coil. The variation of eddy current in a structure member can be used to detect damage [39][40][41].

2.2.4 Electromechanical Impedance

The electromechanical impedance method is conducted using a piezoelectric sensor bonded to a structure member. The generation of stress on the piezoelectric sensor results in production of an electric charge. The piezoelectric sensor induces mechanical strain under an applied electric field [42][43]. The piezoelectric sensors' electric impedance is related to the structural member

mechanical properties due to the bonding, hence the structure member mechanical dynamic response is measured based on the measured electromechanical impedance.

2.3 Global Methods

Global SHM methods are implemented to cover a large area of a structure. The region of coverage may include sections vulnerable to damage and sections with no initial damage susceptibility. Global SHM methods may not determine the location of observed damage [1-4].

2.3.1 Guided wave

Guided wave is an advanced ultrasonic method which covers a larger material volume by generating stress waves that are forced to propagate through a route that is governed by the material boundaries of a structure member [44][45][46]. Guided waves can travel across joints connecting structural members, as well as curvatures in structural members; hence GW can be applied over a large structural volume. Rayleigh waves are GW that propagate near a structures surface, where their amplitudes decrease with increasing depth. Lamb waves are GW that occur between two free surfaces that are parallel to each other, and Lamb waves can occurs in symmetric and antisymmetric modes while Rayleigh waves are not dispersive hence it displays a constant wave speed [47]. Shear horizontal waves are guided waves that display particle motion and wave propagation on two different axes, hence dispersive and non-dispersive wave forms can occur. Guided Waves are also transmitted in ultrasonic testing using the pulse echo method, and the pulse-catch method. Guided waves can be used in active and passive SHM systems.

2.3.2 Acoustic Emission

The occurrence of events such as crack initiation, crack propagation, impact, deformation, delamination, etc., on a structural member generates a change in the local transient elastic wave energy within the structural member. Acoustic emission is used to detect damage in their real time occurrence, but it cannot be

employed to detect inactive damage [3]. The elastic waves generated from acoustic emission are detected on a structural member using piezoelectric sensors, the elastic waves detected are characterized based on energy, counts to peak, rise time, duration signal level and their properties are used to identify damage and the damage properties [1 - 6].

2.3.3 Thermal Imaging

The thermal imaging method is used to detect subsurface damage using the potential difference in thermal diffusivity in a structure member [48][49]. Thermal imaging often employs an external source that generates a thermal difference within a structural member which commonly uses external stimulus include heat lamps, air gun, and mechanical shaker generating oscillating or ultrasound stress. The generation of thermal difference results in a change in stress of the structural member, where higher stress concentration and acoustic emission are expected at regions of a structural member with damage. This leads to an increase in temperature for regions that are potentially damaged. Techniques used to characterize damage in thermal imaging include thermoelastic stress analysis, vibro-thermographic, and sono-thermographic. It should also be noted that thermal imaging technique can also be employed for local SHM systems.

2.3.4 Modal Method

Modal methods are the most used SHM techniques; the excitation of a structural member is monitored using sensors such as strain gauges, accelerometers and piezoelectric transducers[50][51]. The systems of sensors are used to attain modal parameters of the structure such as mode shape, frequency, and modal damping which are physical properties of a structure member. Changes in the structure member modal properties are used to detect damage. Damage is characterized by comparing the modal properties attained from a structure member deemed to be in a damage free state and its current state, hence pattern recognition is required.

Modal features that are damage sensitive are extracted from the sensor network by curve fitting physics-based model or data-based model to the measured modal response. Parameters attained from the curve fitting procedure are used as damage sensitive features. Damage sensitive features are also generated by directly comparing wave forms recorded by the sensor.

When data is attained from a system of sensors, the data is condensed and fused together where damage sensitive techniques such as mode shapes, mode shape curvature, dynamically measured flexibility, matrix update, frequency change, neural networks, and non-linear methods are commonly used in pattern recognition for modal analysis. Changes in modal parameters are used as means of identifying damage using the forward problem, while damage location is attained using the inverse problem.

2.3.5 Strain Method

The strain method involves the monitoring of strain distribution on structure member to detect damage based on the alteration of strain distribution [25][52][53]. Strain sensors such as electrical strain gauges, and fibre optic sensors are implemented to measure the strain distribution in a structure. The strain method can be conducted by comparing the strain distribution between a structure member with a known undamaged state, and its present state to detect damage. Furthermore, data attained from the strain sensors can be incorporated into theoretical models where damage criteria can be established.

2.4 Reliability

The reliability of a system is characterized as the capacity $R(\mathbf{X})$ of system to meet a given demand $S(\mathbf{X})$ for a given period and this can be characterized from a mathematical perspective as the probability that a system will not realize its limit state for a definite period [56][57][58][59]. The reliability of a system is modelled using a limit state function $g(\mathbf{X})$, which characterizes failure of the system based on the system's capacity and demand. The limit state function is the performance of a system based on its input variables $\mathbf{X}$, where the systems performance Y is

safe below the limit state and unsafe above the limit state. An analytical expression for $g(\mathbf{X})$ is not always available hence numerical models can be applied to approximate $g(\mathbf{X})$. Generally, the limit state is set at zero, thus safe regions are characterized by a value of performance greater than zero, and unsafe as performance less than zero [56-59].

$$Y = g(\mathbf{X}) = R(\mathbf{X}) - S(\mathbf{X}) \quad (2-1)$$

$$g(\mathbf{X}) > 0, \text{ Safe region} \quad (2-2)$$

$$g(\mathbf{X}) = 0, \text{ Limit state function} \quad (2-3)$$

$$g(\mathbf{X}) < 0, \text{ Unsafe region} \quad (2-4)$$

Due to the uncertainties associated with the input variables $\mathbf{X} = (X_1, X_2, X_3, \dots, X_n)$, uncertainties will also arise in the systems performance Y . Uncertainties from the input variable X is described as a combination of uncertainties from $R(\mathbf{X})$ and $S(\mathbf{X})$, where the combination of probability distribution is for the system and demand which results in a joint probability density function $f_x(\mathbf{X})$.

The probability of failure P_f for a system is expressed using the performance function or in integral form as:

$$P_f = P[g(X) < 0] = P[R(X) - S(X) < 0] \quad (2-5)$$

$$P_f = \int_{g(\mathbf{X}) < 0} f_x(\mathbf{X}) d\mathbf{x}$$

While reliability R is expressed as:

$$R = P[g(\mathbf{X}) \geq 0] = P[R(\mathbf{X}) - S(\mathbf{X}) \geq 0] \quad (2-6)$$

$$R = \int_{g(\mathbf{X}) > 0} f_x(\mathbf{X}) d\mathbf{x}$$

When the input variable $\mathbf{X}$ is time dependent, reliability is also time dependent. Time dependent reliability is expressed as:

$$R(t) = P[g(\mathbf{X}(t)) \geq 0] = P[R(\mathbf{X}(t)) - S(\mathbf{X}(t)) \geq 0] \quad (2-7)$$

The methods used to assess reliability in the literature include first order second moment method FOSM, first order reliability method FORM, second order reliability method SORM, Markov Process, Monte Carlo simulation, hazard functions, response surface modelling RSE, design of experiments DOE and fault tree analysis FTA [60][61][57][62]. FOSM, FORM, SORM, and Monte Carlo simulation, are the most used reliability methods.

In FOSM, the reliability index β of a system is calculated based on the mean μ_y and σ_y standard deviation of the limiting state function which is approximated by a first order Taylor series [63][64], where $g(\mathbf{X})$ is normalized to $G(\mathbf{X})$. Mathematically this is expressed as:

$$\beta = \frac{\mu_y}{\sigma_y} \quad (2-8)$$

$$\mu_y = \mu_R - \mu_S \quad (2-9)$$

$$\sigma_y = \sqrt{\sigma_R^2 + \sigma_S^2 - 2\rho_{RS}\sigma_R\sigma_S} \quad (2-10)$$

$$G_Y = \frac{Y - \mu_y}{\sigma_y} \quad (2-11)$$

The correlation coefficient between $R(\mathbf{X})$ and $S(\mathbf{X})$ is expressed using ρ_{RS} , where this value is zero when $R(\mathbf{X})$ and $S(\mathbf{X})$ are uncorrelated. The relationship between reliability index and probability of failure if expressed using a cumulative distribution function Φ as:

$$\beta = -\Phi^{-1}(P_f) \quad (2-12)$$

Limitations of FOSM occurs when non-linear $g(\mathbf{X})$ [63][65], are normalized which results in ascending errors, with a rise of distance from the point of normalization. Additional limitations of FOSM include the sole use of $g(\mathbf{X})$ with normal distribution, and β is dependent on the formulation of $g(\mathbf{X})$.

FORM is implemented to address the limitations of FOSM [3][64], by normalizing $g(\mathbf{X})$ on the failure surface to attain normalized variables U_i , which is expressed as:

$$U_i = \frac{X_i - \mu_{X_i}}{\sigma_{X_i}} \quad (2-13)$$

Where the normalized variables U_i is a standard normal variable with a standard deviation equal to one, and its mean is zero. β is obtained by locating the shortest distance between the origin and the normalized failure surface using the following equations [64]:

$$G(U_1^*, U_2^*, U_3^*, \dots, U_n^*) = 0 \quad (2-14)$$

$$U_i^* = -\alpha_i^* \beta \quad (2-15)$$

$$\alpha_i^* = \frac{\left(\frac{dG}{dU_i}\right)_{U_i^*}}{\sqrt{\sum_i \left(\frac{dG}{dU_i}\right)_{U_i^*}^2}} \quad (2-16)$$

The values for P_f and R are attained using [64]:

$$\begin{aligned} P_f &= P[G(U) < 0] \\ &= \Phi(-\beta) \end{aligned} \quad (2-17)$$

$$R = 1 - P_f = \Phi(\beta) \quad (2-18)$$

SORM follows a related principle to FORM, however a second order Taylor series function is used to approximate the limit state function, in order to obtain a better estimate for nonlinear limit state functions [64][63][61].

Monte Carlo simulation is conducted by generating random input variables $\mathbf{X}$ based on the distribution of $\mathbf{X}$, after which the output variable Y is calculated based on its performance function $Y = g(\mathbf{X})$ using simulated experiments [60][57]. Statistical analysis is implemented on Y to attain P_f and R as [57][60] :

$$P_f = \frac{1}{N} \sum_{i=1}^N I(\mathbf{X}_i) = \frac{N_f}{N} \quad (2-19)$$

$$I(\mathbf{X}) = \begin{cases} 1 & \text{if } g(\mathbf{X}) \leq 0 \\ 0 & \text{otherwise} \end{cases} \quad (2-20)$$

$$R = P[g(\mathbf{X}) > 0] = \frac{N - N_f}{N} \quad (2-21)$$

2.5 Fatigue limit state function

The fatigue limit state function was described based on fracture mechanics where the Paris-Ergodan equation relates the rate of crack growth per load cycle and range of stress intensity factor ΔK as [66][14]:

$$\frac{da}{dN} = C[\Delta K]^m, \quad \Delta K > 0 \quad (2-22)$$

where parameters C and m are material properties [66][14]. The range of the stress intensity factors is generally expressed as a function of crack size a , range of stress ΔS , and structural geometric function Y using [66][14]

$$\Delta K = Y\Delta\sigma\sqrt{\pi a} \quad (2-23)$$

A combination of equation 2-22 and 2-23, arises in the change of crack size over a structures service life for a total number of stress cycles N as expressed in equation 2-24, where a_o is the initial crack length, a_n is the crack length after N stress cycles, and $E[\Delta S^m]$ is the stress range distribution [66][14].

$$\int_{a_o}^{a_N} \frac{da}{Y^m[\pi a]^{0.5 \cdot m}} = C \cdot N \cdot E[\Delta S^m] \quad (2-24)$$

To describe the vast number of long term distribution of the range of stress on an offshore structure at varying sea states, the Weibull distribution is fitted to multiple short term stress ranges which results in equation 2-25 [67][68][69]. Parameter A

represents scale functions of the Weibull distribution, as Γ is a gamma function, and B is the Weibull distribution shape function [67][68][69].

$$E[\Delta S^m] = A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \quad (2-25)$$

To represent the change of crack size over a structures service life with time, the total number of stress cycles over a structures service life can be expressed as a function of the time history of stress T , and the average frequency for long term stress range of all sea states ω as [67][68][69]:

$$N = \omega \cdot T \quad (2-26)$$

Substitution of equation 2-25 and 2-26 into 2-24, results in a transient relationship for the change in crack size as given by equation 2-27 [67][68][69].

$$\int_{a_0}^{a_t} \frac{da}{CY^m[\pi \cdot a]^{0.5 \cdot m}} = T\omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \quad (2-27)$$

The fatigue limit state function is defined in equation 2-28, where equation 2-27 is used to represent the resistance to fatigue and load applied. Uncertainties due to stress concentration factor SCF , numerical calculation of stress S , and loading conditions F were also added to the fatigue limit state function [67][68][69].

$$g(\mathbf{X}) = \int_{a_0}^{a_t} \frac{da}{CY^m[\pi \cdot a]^{0.5 \cdot m}} - T\omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \cdot SCF^m \cdot F^m \quad (2-28)$$

2.6 Fatigue reliability index

The reliability index was calculated via FORM to determine the shortest distance between the origin and the failure surface of limit state function using MATLAB. Random variables in the limit state function with non-Normal distribution were transformed to standard normal variables [55-61].

2.7 Update fatigue reliability index

The output from a SHM system mounted to an offshore fixed jacket infers the detection or non-detection of cracks in structure member(s). The detection or non-detection of crack was implemented to calculate an updated probability of failure P'_f using a conditional probability between the FLS and outcome from the SHM system O_i [64][70][67].

$$P'_f = P[g(\mathbf{X}) \leq 0 | O_i] \quad (2-29)$$

An outcome of crack detection by the SHM system is represented in the conditional probability based on time of occurrence T_o and crack size detected a_d as [64][70][67]

$$O_{detection} = \int_{a_0}^{a_d} \frac{da}{CY^m[\pi \cdot a]^{0.5 \cdot m}} - T_o \omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \cdot SCF^m \cdot F^m \cdot S^m = 0 \quad (2-30)$$

For non-detection of crack, the SHM system detectable crack size a_{shm} , and time of occurrence are used to assess the SHM system outcome with [64][70][67]

$$O_{non-detection} = \int_{a_0}^{a_{shm}} \frac{da}{CY^m[\pi \cdot a]^{0.5 \cdot m}} - T_o \omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \cdot SCF^m \cdot F^m \cdot S^m > 0 \quad (2-31)$$

Uncertainty in a_{shm} was characterized by its distribution function attained using model assisted probability of detection (MAPOD) [13].

2.8 SHM techniques

2.8.1 Coordinate Modal Assurance Criterion

Damage detection and localization was performed by analysing modal frequencies generated from a fixed offshore platform using coordinate modal assurance criterion COMAC [71]. COMAC was implemented to detect the variation in the mode shape for each component in the structure at multiple modes via equation 2-32.

$$COMAC_j = \frac{[\sum_{r=1}^L |\phi_{jr} \phi_{jr}^d|]^2}{\sum_{r=1}^L \phi_{jr} \sum_{r=1}^L \phi_{jr}^d} \quad (2-32)$$

Subscript r represents the number correlated modes attained from modal assurance criterion, j represents the mode shape location in the structure, while superscript d indicates mode shapes not attained from the structures reference state [71].

COMAC values were normalized to obtain a more sensitive damage index represented by equation 2-33, where $\mu COMAC_j$ and $\sigma COMAC_j$ are the mean and standard deviation of $COMAC_j$. The damage index signals the occurrence of damage by displaying a positive value that is relatively large. Furthermore a value of damage index more than 2 indicates a potential location of damage [72].

$$DamageIndex_j = \frac{\mu COMAC_j - COMAC_j}{\sigma COMAC_j}$$

$$Damage Index_j = \frac{\mu COMAC_j - COMAC_j}{\sigma COMAC_j} \quad (2-33)$$

2.8.2 Modal Strain Energy

Modal strain energy MSE is used to identify damage in structures based on the mode shapes, structure member stiffness, and global structure stiffness [51][73][74][75]. Modal strain energy is capable of detecting and localizing damage to a specific member in a structure. The initial derivation of modal strain energy assumed damage solely affected the change in mode shapes [51][73][74][75], however there has been multiple improvements made so that includes the differentiation axial and torsional mode shapes, addition of natural frequency, and local member mass, and change in local stiffness. These modifications have improved the performance of MSE [51][73][74][75].

Damage detection is conducted by MSE based on the observed change in each structure member j at vibrational mode i by using the following equation [51]:

$$MSE_j = \frac{\sum_{i=1}^3 [\phi_i^{dT} K_{j0} \phi_i^d + \sum_{j=1}^{118} \phi_i^{dT} K_{j0} \phi_i^d] \phi_i^T K \phi_i}{\sum_{i=1}^3 [\phi_i^T K_{j0} \phi_i + \sum_{j=1}^{118} \phi_i^T K_{j0} \phi_i] \phi_i^{dT} K \phi_i^d} \quad (2-34)$$

For each mode, λ_i represents the eigenvalue, ϕ_i represent the mode shape, while K_{j0} represent the stiffness matrix of a structure member, and K is the global stiffness matrix.

Damage localization in the structure is based on the normalization of the modal strain energy based on its mean σ_{MSE} and standard deviation $\overline{MSE}$ as [51]:

$$ZMSE_j = \frac{MSE_j - \sigma_{MSE}}{\overline{MSE}} \quad (2-35)$$

Assessment of damage in each structural member is conducted by quantifying the damage magnitude using the cross-modal relationship in equation 2-26, written in matrix form. Parameter α is the reduction factor in the stiffness of a given structural member [76]. The magnitude of α varies from 0 to -1, where -1 indicates a total loss in stiffness [73-74.76].

$$[\alpha] = ([\gamma]^T [\gamma])^{-1} [\gamma]^T [\varphi] \quad (2-36)$$

$$\text{Where } \varphi = \left[\frac{\lambda_j^d}{\lambda_i} - 1 \right] \phi_i^T K \phi_j^d \text{ and } \gamma = \sum_{n=1}^{DE} \phi_i^T K_n \phi_j^d \quad (2-37)$$

In order to simulate crack size as damage, an equivalent stiffness k^e of a structural member with crack depth a was modelled as [77]

$$k^e = \left[\frac{1 - \nu^2}{E} \int_{-b}^b \int_0^a \frac{d^2 k_1^2}{dM^2} dx dy \right]^{-1} \quad (2-38)$$

in which k_1 is the stress intensity factor, ν and E are Poisson ratio and Young's modulus, b and a represent crack dimension [77].

2.9 Application of Vibration Based SHM On a Fixed Offshore Platform, a consideration of fatigue damage.

Fixed jacket platform structures used in the offshore exploration of oil and gas are subjected to operational and environmental loads such as deck load, ship

impact, waves, current, wind, and seismic activity, which lead to the build-up of damage on the structure during its operational life. To prevent catastrophic failure, the ability to detect and locate damage on a structure is vital. Due to the cyclical nature of environmental offshore loads applied over the structure's operational life, it is of critical to assess a structures resistance to fatigue damage. Fatigue damage is generally evaluated using a fatigue limit state (FLS), this provides a relationship between the effect of operational and environmental loads to the structures fatigue resistance [78]. Uncertainties from physical, statistical, and model parameters arises in the formulation of FLS, thus reliability analysis is performed to determine fatigue reliability index, which indicates the probability that fatigue failure will not occur [78]. The ability to accurately assess fatigue reliability is paramount to understanding the state of a structure, and determination of an inspection schedule. The effect of inspection on the fatigue reliability index is generally conducted by updating the failure reliability index based on the outcome of a scheduled inspection [64][70]. Structural health monitoring (SHM) is a tool used to detect, localize, and analyse damage present in a structure by continuously monitoring the structures behaviour, thus providing real time information of the structures integrity rather than periodic structural integrity obtained from scheduled inspection [4].

2.9.1 Numerical modelling and deployment

Numerical analysis was conducted via finite element model in a program called SAPOS. SAPOS was used to assess an example 3D offshore jack platform from a previous work by Karadeniz [79], using the same geometry, loading conditions, and material properties (See table 2-1) [79][80][69]. The first order reliability method using the Hasofer-Lind method, which was implemented in MATLAB was used to solve the fatigue limit state function. The initial fatigue reliability was calculated using the random variables listed in table 2-2. The effect of the SHM system on fatigue reliability was assessed by comparing the updated fatigue reliability index attained from two SHM systems with varying sensor placement density used to assess the integrity of the fixed offshore platform. Sensor densities for the two SHM systems are represented in table 2-3 where the

corresponding node locations on the structure are represented in figure 2-1. Three stages of damage were simulated in structural member 105 using three different crack lengths, where damage with a crack length of 2.5 mm occurred at year 5. The crack is then set to a length of 5 mm at year 8, and 10 mm at year 15. The stiffness of structural member 105 was reduced to an equivalent stiffness corresponding to the given crack length for each damage scenario.

Table 2-2 Environmental and operational loads applied in the numerical simulations.

Mass of Deck	4800 ton
Water Depth	50 m
Significant wave height	2.5 m
Drag coefficient	1.3
Inertia Coefficient	2.0
Sea spectrum	Pierson-Moskowitz

Table 2-3 Distribution of random variables

Variable	Distribution	Mean	Coefficient of Variation
a_t	Normal	8.0	0.04
a_0	Exponential	0.11 ^a	
y	Normal	1	0.1 ^a
$\ln C$	Normal	-29.84	0.55* ^a
Y	Fixed	1.0	
m	Fixed	3.1 ^a	
F	Lognormal	1.0	0.1 ^a
S	Lognormal	1.0	0.1 ^a
SCF	Lognormal	2.50	0.15 ^a
ω	Fixed	6,277,000 ^a	
A	Fixed	10.9	
B	Fixed	1.22 ^a	

**This value is a standard deviation. Superscript ^a indicates reference from Shabakhty 2004. Units are in N, and mm. All other values from Karadeniz 1990.*

Table 2-4 SHM system information. Based on FEA simulation parameters.

SHM systems	# of sensors	Sensor Location	Element crack length (mm)
SHM 1	8	24, 25, 26, 28, 34, 35, 37, 38	2.5, 5, 10
SHM 2	8	6, 8, 9, 11, 30, 31, 32, 33	2.5, 5, 10

The initial reliability of element 105 is displayed in figure 2-2 for a service life of 25 years, where β decreases with increasing service life. At a crack length of 2.5 mm, the structure modal frequencies were observed to display a faint reduction, and mode shapes from the first three modal frequencies were implemented to calculate COMAC, after which damage index was attained. Output for damage detection for SHM systems 1 indicates the detection of damage at node 38, where a relatively large positive value is indicated as seen in figure 2-3. For SHM system 2, there was no detection of damage as the positive values of the damage index were below 2 (See figure 2-2).

When a crack length of 5.0 mm was assessed, the maximum positive values for damage index increased in comparison to values attained from a 2.5 mm crack length, however a similar event observation was made by the SHM systems where SHM systems 1 and 2 indicated, damage and no damage respectively. A 10.0 mm crack length generated the detection of damage from SHM systems 1 and 2 where node 32 and 38 displays a value of damage index greater than 2.

The updated reliability index for structure member 105 using SHM system 2 in the presence of a 2.5mm long crack that occurred in year 5, and a 5 mm crack length that occurred in year 8 displays a similar reliability index pattern, where the updated reliability index is always greater than the initial reliability index through its operational life of 25 years. At year 15 where a 10 mm crack occurs, the updated reliability index displays values larger than the initial calculated reliability index for service time close to the detection time. This trend was observed to change as the service time increased, where the updated reliability index dropped below the initial reliability index calculated.

Reliability index obtained from SHM system 1 over the operational life structure member 105, in the presence of a 2.5 mm, 5mm, and 10mm crack length occurring at year 5, 8, and 15 respectively displayed similar trends. This trend was also identical to the reliability index attained from SHM system 2 in the presence of a 10 mm crack length.

The false negative outcomes from SHM system 2 for crack lengths of 2.5 - 5 mm, generate an overestimation of reliability index for member 105, when compared to SHM system 1. However, at a crack length of 10 mm, both SHM systems display similar reliability index.

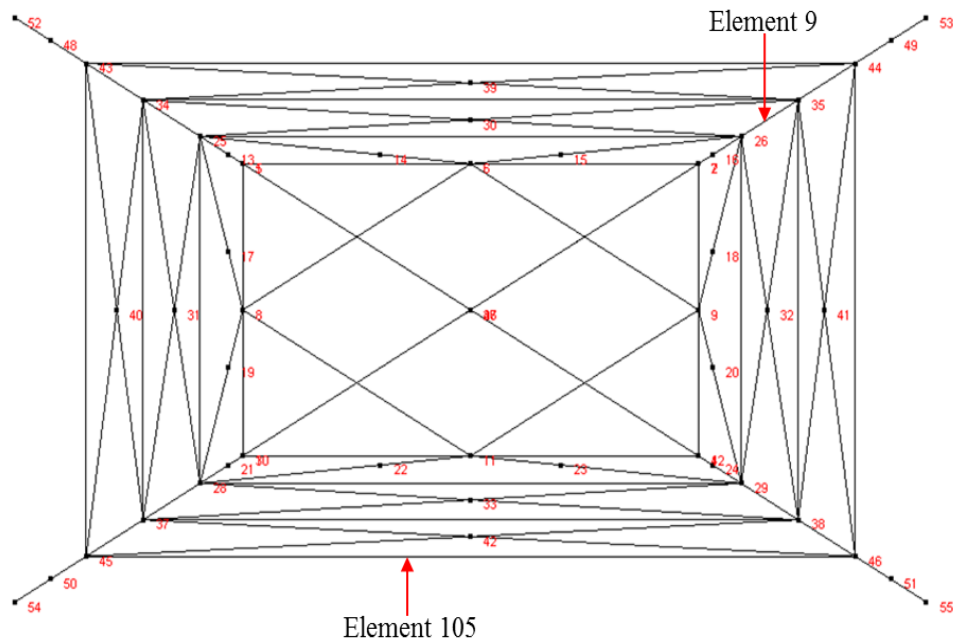


Figure 2-1. Nodal coordinates of the fixed offshore platform.

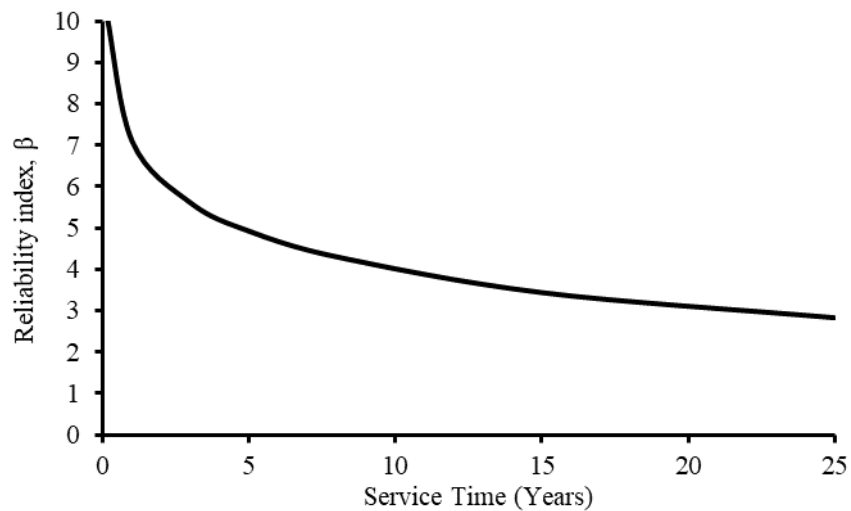


Figure 2-2. Initial reliability index of member 105. Calculated from equation 2-28.

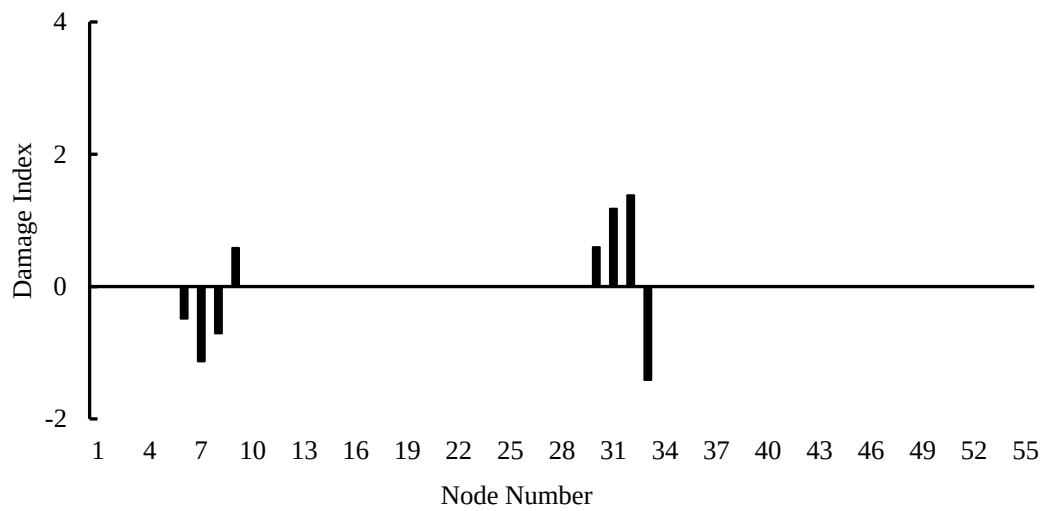
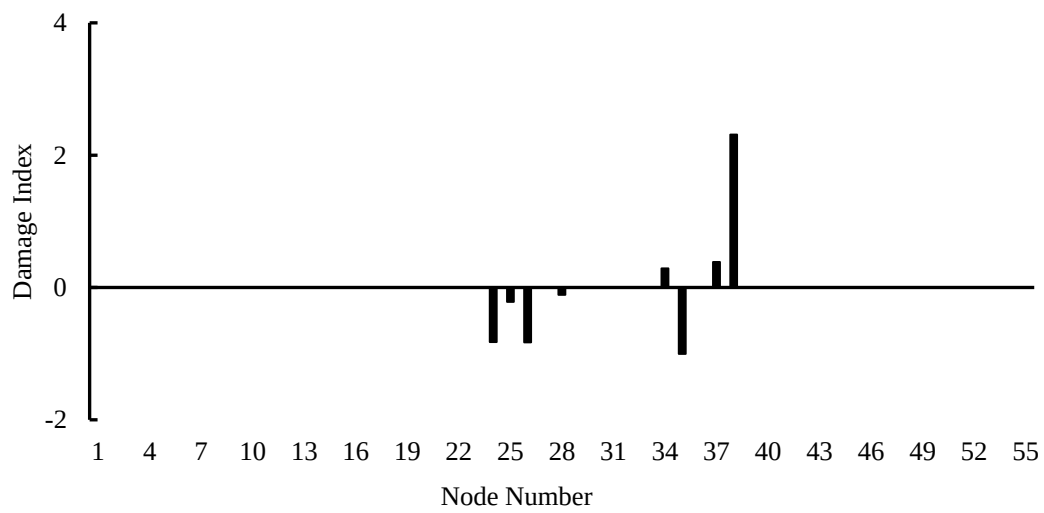


Figure 2-3. Damage index for the occurrence of a 2.5 mm crack length from (Top) SHM system 1 and (Bottom) SHM system 2. Calculated from equation 2-33.

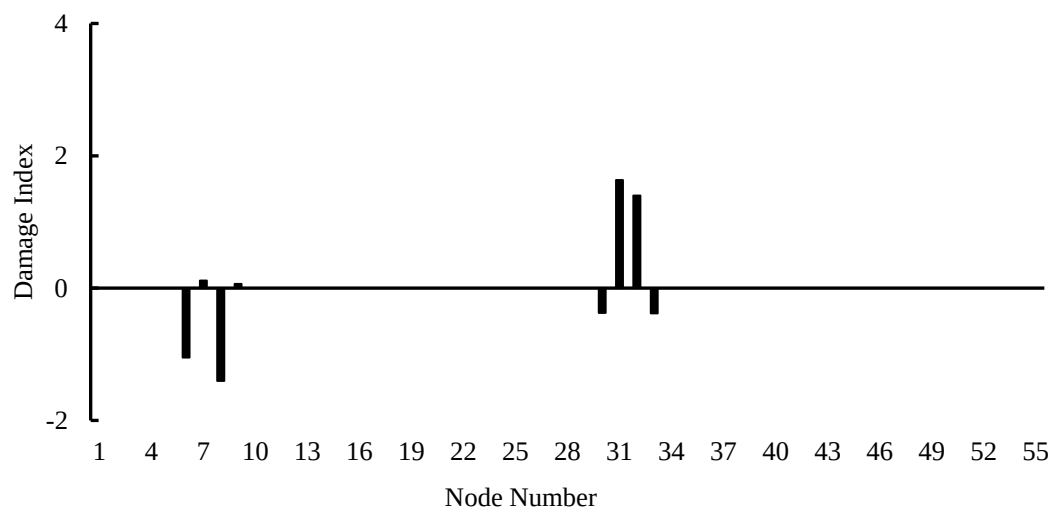
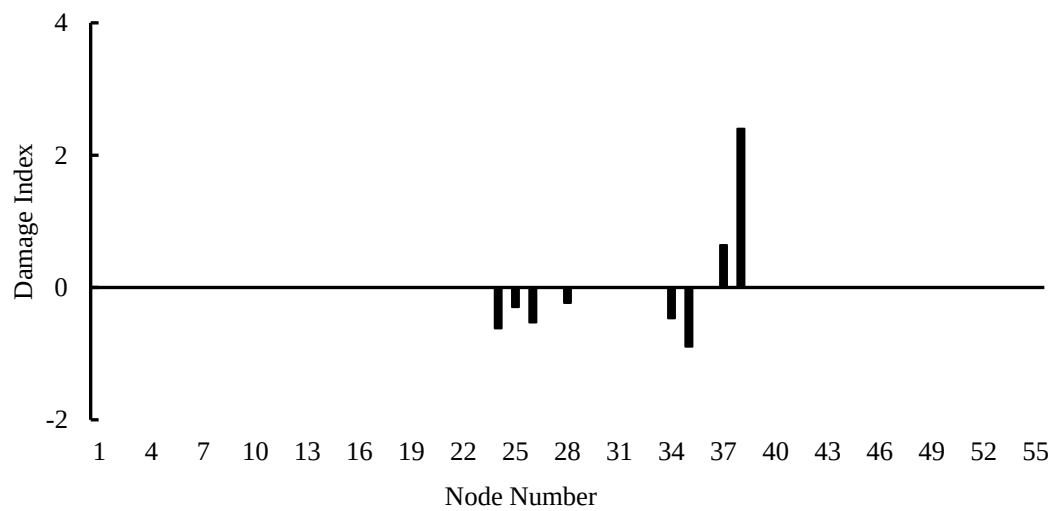


Figure 2-4. Damage index for the occurrence of a 5 mm crack length from (Top) SHM system 1 and (Bottom) SHM system 2. Calculated from equation 2-33.

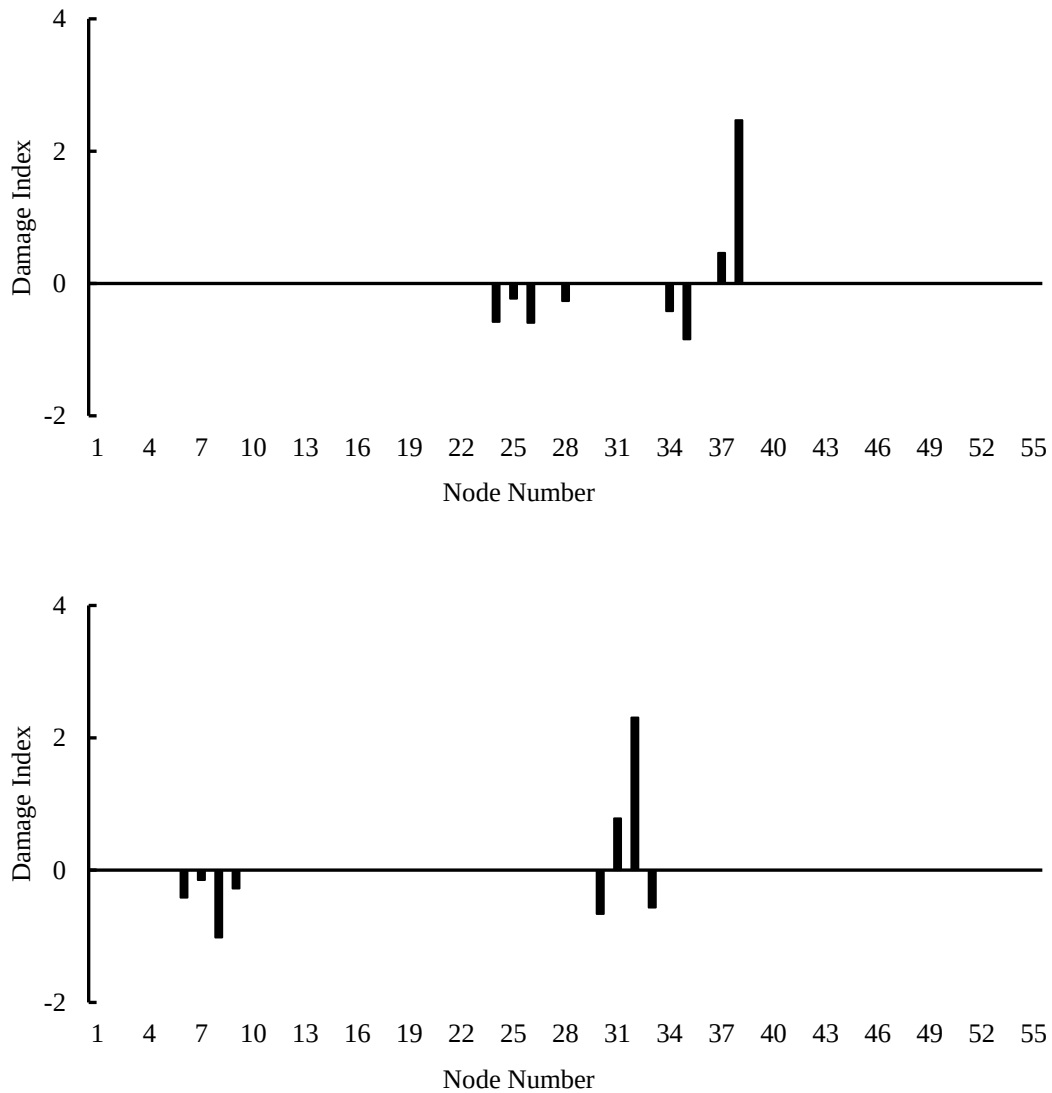


Figure 2-5. Damage index for the occurrence of a 10 mm crack length from (Top) SHM system 1 and (Bottom) SHM system 2. Calculated from equation 2-33.

2.10 Knowledge Gap

Despite the fact that multiple studies have been conducted to improve damage sensitive parameters, damage detection techniques, damage localization, and damage identification, the reliability of SHM systems have not been characterized based on all uncertainties in the SHM process [54][55]. Previous works have

attempted to characterize the reliability of SHM systems based on their ability to detect damage which is characterized by the probability of detection POD [54][13]. POD is an indicator used for assessing non-destructive testing (NDT) where the probability of detecting damage is assessed based on the size of damage.

The Gaps in Knowledge to be addressed in this work are as follows:

- Reliability of Damage localization: This is an indication of the SHM's systems ability to accurately localize damage in the global structure. This parameter is of importance for assessment of the SHM systems performance, furthermore it can be used in predictive maintenance of the monitored structure.
- Reliability of Damage Assessment: This is an indication of the SHM's systems ability to accurately predict damage severity. This parameter is of importance for assessment of the SHM systems performance and predictive maintenance of the monitored structure.
- Probability of Damage localization. This is an indicator that is an extension of POD for SHM systems. NDE is performed at specific locations hence this not required for NDE, however it is a metric of importance for SHM systems.
- Probability of Damage Assessment. An extension in the probability performance functions to damage severity is paramount for SHM systems with the capacity to predict damage severity.
- Conditional probability and reliability of the dependence of SHM functions and monitored system reliability is a knowledge gap that was identified in this work. The conditional reliability provides a metric to quantify the potential contribution of the SHM systems reliability to the measured reliability of the monitored structure.

2.11 Summary

In this chapter, the impact of SHM systems on the calculated reliability for an offshore platform structural member was assessed using fracture mechanics to

model a fatigue limit state function. The initial structural member reliability index was calculated via first order reliability method, where uncertainties from initial crack length, final crack length, detectable crack length, geometric factor, fatigue material properties, force calculations, stress calculations, and stress concentration factors were characterized using their respective distributions. Two SHM systems with varying spatial locations were used to assess an example offshore platform system modeled using finite element analysis. Damage detection was conducted by means of coordinate modal assurance criterion, using 8 nodes to attain spatially incomplete modal data. Damage was simulated in the structural member using a partially connected beam with a spring, where the spring stiffness was modified to correlate with a given crack length. An outcome from the each SHM system was used to update the reliability index of the structure member for a given type of damage.

The results for an updated fatigue reliability index showed that false negative outcomes from the SHM system generated updated reliability index that were above the initial reliability index as seen when SHM system 2 assessed the damaged member with crack length of 2.5 mm and 10 mm. Results from SHM system 1, indicated an accurate detection of 2.5mm and 10 mm crack length, the observed reliability index was less than the initial reliability index.

The contributions of the SHM system to monitored structure's reliability, in this work was based on the numerical detection of fatigue damage, however the additional forms of damage can be assessed by changing the limit state function. Furthermore, the damage detection technique used in this study does not specify the member where damage occurs, it only specifies the position of the spatially incomplete mode shape suspected of damage. Additionally, the COMAC damage detection technique does not provide explicit information on the severity of damage, hence this technique cannot be applied to update fatigue reliability without information from an external source.

Future work assesses the contribution of SHM systems to damage detection, localization, and severity assessment in offshore platforms using numerical analysis.

3 FRAMEWORK FOR CALCULATING THE RELIABILITY OF A SHM SYSTEM

3.1 SHM Probabilities

This chapter describes additional probabilistic reliability performance characteristics for SHM systems in the presence of uncertainties with respect to damage localization, damage assessment, and calculates the reliability of SHM performance with respect to damage detection, localization, and assessment. An overall performance assessment based on these 3 outputs of the SHM system was also determined.

This chapter is formulated as follows; the background of current probabilistic approach used in SHM is presented in section 3.1. Section 3.2 describes the proposed probabilistic performance functions for SHM damage detection, and localization. Section 3.3 describes the uncertainty network involved in SHM measurements, and reliability assessment of SHM performance. A vibration based SHM method was implemented in numerical simulation study to incorporate the proposed probabilistic and reliability-based performance metrics.

3.1.1 Background.

The statistical characterization of SHM systems performance based on probability of detection Probability of Detection (POD) and probability of false alarm Probability of False Alarm (PFA) has been established by previous studies [81][82][83], where the output O_{dd} of a SHM damage detection system either generates an event that indicates the occurrence damage D_d in a structure, or no damage detected D_{nd} [81]. The classification of damage occurrence O_{dd} for SHM is based on a minimum detectable damage size known as the damage threshold D_{th} which separates D_d and D_{nd} . The limit state function for damage detection, POD and PFA are then expressed as

$$g_{DD}(x, t) = D_d - D_{th} \quad (3-1)$$

$$POD(t) = P(O_{dd}|D_d - D_{th} \geq 0) \quad (3-2)$$

$$PFA(t) = P(O_{dd}|D_d - D_{th} < 0) \quad (3-3)$$

Uncertainties associated with POD and PFA are reported to arise from SHM technique, damage type, damage threshold, environmental conditions, noise, sensor integrity, geometrical and material properties of the structure [84]. The effect of uncertainties on POD and PFA, has also been addressed in previous literature.

POD and PFA are also applied in the process of calculating the initial and updated the reliability of a monitored structure based on SHM outcome via Bayes theorem. The transient structures capacity is updated, which in turn provides a measure of the structures reliability based on the updated reliability index [70]. To effectively update the reliability of a structure, the accuracy associated with localization of damage and extent of damage are paramount, hence it is of essence to quantify these performance characteristics.

3.2 Limit State Functions for SHM Performance

3.2.1 Damage Localization

To characterize the performance of a SHM system with respect to locating damage on a structure in the event of damage being detected, a limit state function is constructed based on the zone of true damage location (ZTDL) and the predicted location of damage occurrence (PLD). The zone of true damage location is characterized by the true damage location (TDL) and an allowable localization tolerance (ALT) corresponding to a specific TDL. Based on the given definition the limit state function is expressed mathematically as

$$g_{DL}(x,y,z,t) = ALT - |PLD - TDL| \quad (3-4)$$

When the limit state function is greater than 0, then an accurate location of damage was attained from the SHM system. An event where the limit state

function is greater than zero indicates the occurrence of an error in damage localization; this error either indicates a false positive or false negative location. The probability of accurate localization (POAL) can be expressed in Cartesian coordinates using the localization limit state function as

$$POAL(t) = P[O_{dd} = Dd | -ALT(x, y, z, t) + |PLD(x, y, z, t) - TDL(x, y, z, t)| \leq 0] \quad (3-5)$$

3.2.2 Damage Assessment

Evaluation of damage severity in SHM is conducted by either quantifying or qualifying its magnitude. The error between the predicted damage severity (PDS) and actual damage severity (ADS) is implemented to construct a damage assessment limit state function. To construct a suitable range of error associated with damage assessment, an acceptable damage severity threshold (DST) is required. The probability of accurate assessment (POAA) is constructed using conditional probability as

$$POAA(t) = P[O_{dd} = Dd | -DST + |PDS - ADS| \leq 0] \quad (3-6)$$

3.3 SHM Uncertainty Network

A framework that calculates the reliability of SHM system outcome based on its ability to detect, localize, assess and estimate the remaining useful life of a structure in the presence of operational uncertainties is addressed. A flowchart of the proposed performance function, and the reliability associated with the output for each SHM function is presented in figure 3-1. The physical uncertainties associated with SHM include environmental loads, operational loads, and geometric dimension. Statistical uncertainties arise from sensor installation, degradation, and limitation, as well as noisy data. Numerical uncertainties arise from signal processing, extraction of damage sensitive features, computation of damage index, selection of damage threshold, damage localization and assessment. Additional numerical uncertainties arise from the resistance and capacity of a structure to withstand a specified damage mechanism.

First order reliability method (FORM) is employed to calculate the reliability index for damage detection, localization, assessment, and structure damage, based on their limit state function and uncertainties associated with their corresponding random variables.

An overall SHM reliability performance function that merges the reliability of damage detection, localization, and assessment were combined as weighted parallel systems, where the weight assigned to each SHM function was attained using analytical hierarchy process. In equation 3-7, β is the reliability index, while ψ is the weight assigned, subscript DD, DL, and DA represent damage detection, damage localization, and damage assessment.

$$R_{SHM} = 1 - [\{\Psi_{DD}\Phi(-\beta_{DD})\} * \{\Psi_{DL}\Phi(-\beta_{DL})\} * \{\Psi_{DA}\Phi(-\beta_{DA})\}] \quad (3-7)$$

3.3.1 Case Study

The proposed approach was applied to a numerical study to evaluate SHM performance and reliability. Vibration based Modal strain energy (MSE) by Stubbs et al (1995) [85], was employed to assess the integrity of fixed offshore platform with varying degrees of damage at its structure members. The topology and foundation stiffness of the fixed offshore platform used was given in detail by Karadeniz 2001 [79]; the operational and environmental loads applied are presented in table 3.1. Finite element model of the fixed offshore platform was constructed using beam elements, where damage was modelled by reducing the stiffness of a given structure member. The reduction in stiffness of a given structural member was used as a mechanism to represent the presence of crack in a structure member. A correlation between stiffness reduction and crack size was implemented to convert the predicted stiffness reduction to a predicted crack length. Steel was assigned as the material property of all members in the structure.

3.3.2 Vibration based Modal Strain Energy (MSE)

Damage detection is conducted by MSE based on the observed change in each structure member j at vibrational mode i using

$$MSE_j = \frac{\sum_{i=1}^3 [\phi_i^{d^T} K_{j0} \phi_i^d + \sum_{j=1}^{118} \phi_i^{d^T} K_{j0} \phi_i^d] \phi_i^T K \phi_i}{\sum_{i=1}^3 [\phi_i^T K_{j0} \phi_i + \sum_{j=1}^{118} \phi_i^T K_{j0} \phi_i] \phi_i^{d^T} K \phi_i^d} \quad (3-8)$$

At each mode, λ_i represents the eigenvalue, ϕ_i represent the mode shape, while K_{j0} represent the stiffness matrix of a structure member, and K is the global stiffness matrix. Damage localization in the structure is based on the normalization of the modal strain energy [75] based on its mean σ_{MSE} and standard deviation $\overline{MSE}$ as

$$ZMSE_j = \frac{MSE_j - \overline{MSE}}{\sigma_{MSE}} \quad (3-9)$$

Illustrated below is a display chart of the SHM reliability structure as contained in figure 3.1.

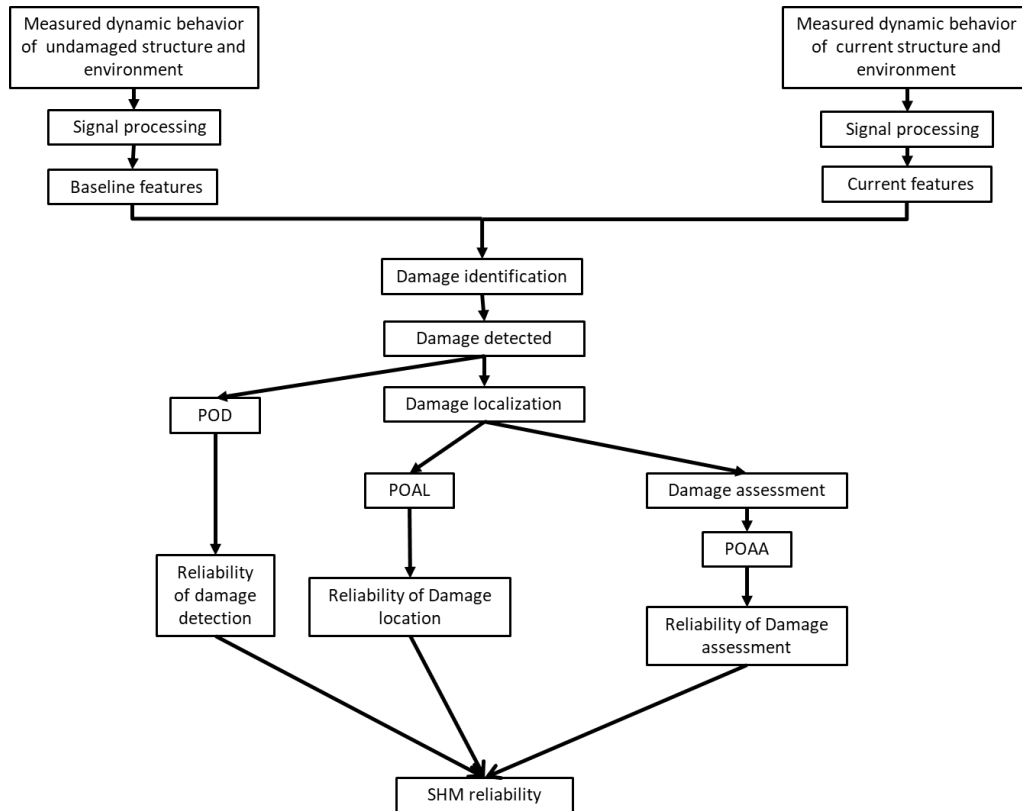


Figure 3-1. A network of SHM displaying the suggested performance parameters for damage localization and damage assessment, as well as the reliability index associated with damage detection, damage localization, damage assessment, and the monitored structure.

Assessment of damage in each structure member is conducted by quantifying the damage magnitude using the cross-modal relationship in equation 3.10, written in matrix form. Parameter α is the reduction factor in the stiffness of a given structure member [76][84]. The magnitude of α varies from 0 to -1, where -1 indicates a total loss in stiffness.

$$[\alpha] = ([\gamma]^T [\gamma])^{-1} [\gamma]^T [\varphi] \quad (3-10)$$

$$\text{Where } \varphi = \left[\frac{\lambda_j^d}{\lambda_i} - 1 \right] \phi_i^T K \phi_j^d \text{ and } \gamma = \sum_{n=1}^{DE} \phi_i^T K_n \phi_j^d \quad (3-11)$$

3.3.3 SHM system probabilities

Baseline condition was initially attained where no damage was present in the fixed offshore platform, after which cracks were simulated at 8 different locations, where 10 levels of damage severities were simulated at each location. In this work only the first 3 modes of vibration are implemented during the SHM process.

3.3.4 SHM reliability analysis

A second set of damage scenarios were simulated on structure members not used in the previous section, where 5 structure members were assigned damage levels as prescribed in table 3.3. The outcome of each damage event was employed to calculate the SHM systems reliability.

The limit state function for damage detection, localization, and assessment with respect to ZMSE are constructed using equations 3.12 to 3.14 and thresholds described in section 3.3.

$$g_{DD}(x) = ZMSE_j(x) + \varepsilon_1 + \varepsilon_2 + \varepsilon_2 - D_{th} \quad (3-12)$$

$$g_{DL}(x) = ALT - |ZMSE_j(x) - TDL| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 \quad (3-13)$$

$$g_{DA}(x) = ADS - |\alpha(x) - DST| + \varepsilon_1 + \varepsilon_2 + \varepsilon_5 \quad (3-14)$$

Parameter ε_1 represents uncertainty associated with sensor measurement, ε_2 represents uncertainty from signal processing, ε_3 is the uncertainty associated

with damage detection technique (3.18), ε_4 represent damage localization uncertainty, and ε_5 is the damage assessment uncertainty.

Uncertainties associated with the noisy mode shapes, and eigen values were assigned using 0.1% noise, and a random number Ω described by a normal distribution with unit variance and zero mean.

$$\lambda_i = \lambda_i(1 + 0.001 * \Omega) \quad (3-15)$$

$$\phi_i = \phi_i(1 + 0.001 * \Omega) \quad (3-16)$$

In this chapter the ε_1 to ε_5 were modeled as fixed numbers with a value of zero. This is due to the use of a numerical model that does not possess the uncertainties associated with ε_1 and ε_5 .

Uncertainties associated with ALT were assessed using the magnitude damaged structure member nodal coordinate vector and the corresponding nodal coordinate vectors for all structure members that share the same node as the damaged structure member. DST was characterized using a normal distribution with a mean based on 90% of ADS and 0.1 coefficient of variance (COV). Normal Distribution is also implemented to describe D_{th} using a mean of 2 and COV of 0.1.

Table 3-1. Environmental and operational loads applied in the numerical simulation. (Karadeniz 2001)

Mass of Deck	4800 ton
Water Depth	50 m
Significant wave height	2.5 m
Drag coefficient	1.3
Inertia Coefficient	2.0
Sea spectrum	Pierson-Moskowitz

Table 3-2. Characteristics of variables in SHM limit state functions

Variable	Distribution	Mean	COV
Young's Modulus (GPa)	Normal	203.39 ^b	0.006
Mode shape	Normal	^a	^a
Eigenvalue	Normal	^a	^a
D_{ST}	Normal	0.9*ADS	0.1
ALT	Normal	14.64	0.56
D_{th}	Normal	2	0.1
Poisson's Ratio	Fixed	0.3	

^a See equation 14&15, for Mode Shape and eigen value uncertainty.

^b Reference from Mansour et. Al (1984) [86].

Monte Carlo simulation was implemented to solve equations 3-8 to 3-11, using 500 samples to generate the mean and standard deviation for the SHM outcomes. In this work the values of ALT were calculated based on the magnitude of vectors between the starting node of the damaged structure member and the starting and ending nodes of all structure members with the same connecting nodes as damaged structure member. Suspected damaged structure members were described as structure members with a local maximum value of ZMSE. Hit/Miss technique was applied to attain the relationship for POD, POAL, and POAA based on the output attained from FEA simulation and the performance of the improved modal strain energy.

3.4 Results and Discussion

3.4.1 SHM System Probability

The undamaged structures modal frequencies were 7.328 Hz, 7.328 Hz and 33.193 Hz for the first 3 modes respectively. The directions of excitement for the first two modes were in the diagonal direction of the X-Y plane, while the third mode displayed torsional motion.

The 80 scenarios of damage assessed with the mean Stubbs damage index resulted in at least one-member element with ZMSE value greater than 2, thus generating a constant POD of 1 for this simulation. The PDL, from ZMSE was observed to predict more than 1 damaged structure member for all simulations conducted. This prediction typically included the damaged member, and its corresponding load sharing members. At higher damage states, the inclusion of

the TDL in the PDL increased, additional factors that affected the performance of PDL include structure member type and orientation. The behavior of PDS attained from α displayed similar dependence on structure member type, orientation, and extent of damage state.

The local values of PDL and PDS were used to generate curves representing POAL and POAA on a local and global scale. The hit/miss data for POAL and POAA fitted to a logit model are presented in figure 3-3.

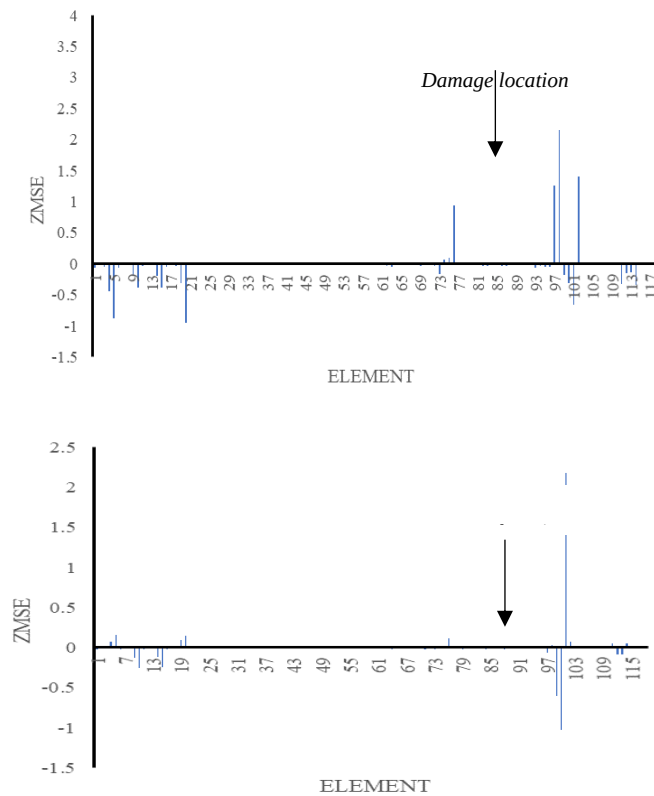


Figure 3-2. Mean ZME Index when structure member 76 displays a reduction of stiffness by (Top) 50% and (Bottom) 10%. Calculated using equation 3-9.

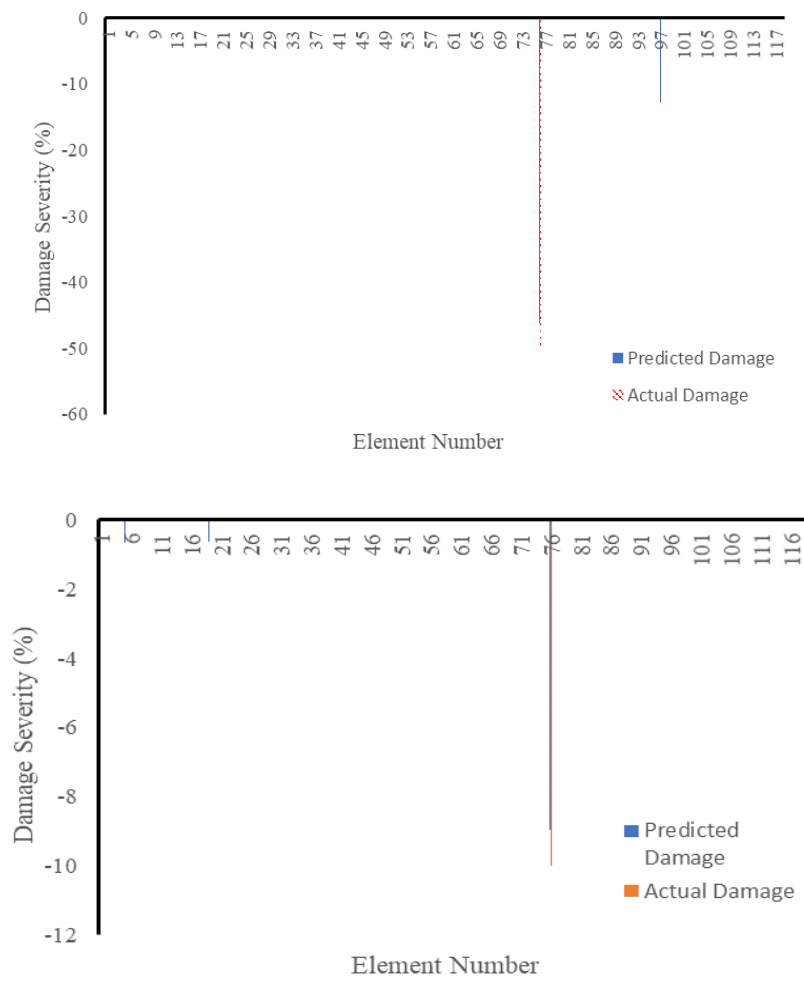


Figure 3-3. Mean α when structure member 76 displays a reduction of stiffness by (Top) 50% and (Bottom) 10%. Calculated using equation 3-10.

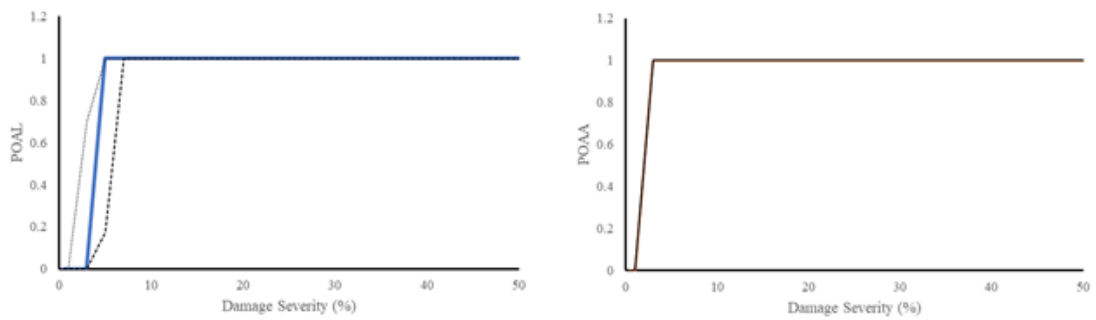


Figure 3-4. (Left) POAL and (Right) POAA curves for local element 76. Dashed lines indicate 95 % confidence interval. Calculated using equation 3-10.

The local and global reliability for the SHM systems ability to detect, localize and assess damage was calculated using the limit state functions in equation 3-12 to 3-14, using the mean and standard deviations from Monte Carlo simulation for $ZMSE$ and α the corresponding variables associated with each limit state capacity.

The local reliability index for damage detection β_{DD} on the same member was observed to be highly influenced by the number of structure members displaying mean $ZMSE$ values greater than D_{th} , for a given damage scenario. This is due to the parallel arrangement for damage detection process where a single value of $ZMSE$ exceeding D_{th} signals the detection of damage. The severity of damage was also observed to affect the number of structure members with mean $ZMSE$ values above D_{th} . Although damage was detected at for all damage scenarios, the values of $ZMSE$ generated from Monte Carlo simulation displayed a high variance where COV was greater than 1 for most instances.

Local curves for β_{DL} was observed to display a dependence on the damage severity level, where the mean factor of safety was less than 1 when the true damage severity was less than 5%. At higher levels of damage severity, the calculated values for β_{DL} was observed to increase. The relatively low values reflect the occurrence of multiple suspected damaged structure members that are not connected to the damaged member. Load sharing occurs between adjacent structure members in addition to connected members, hence skewing the variance of the magnitude of nodal position vectors.

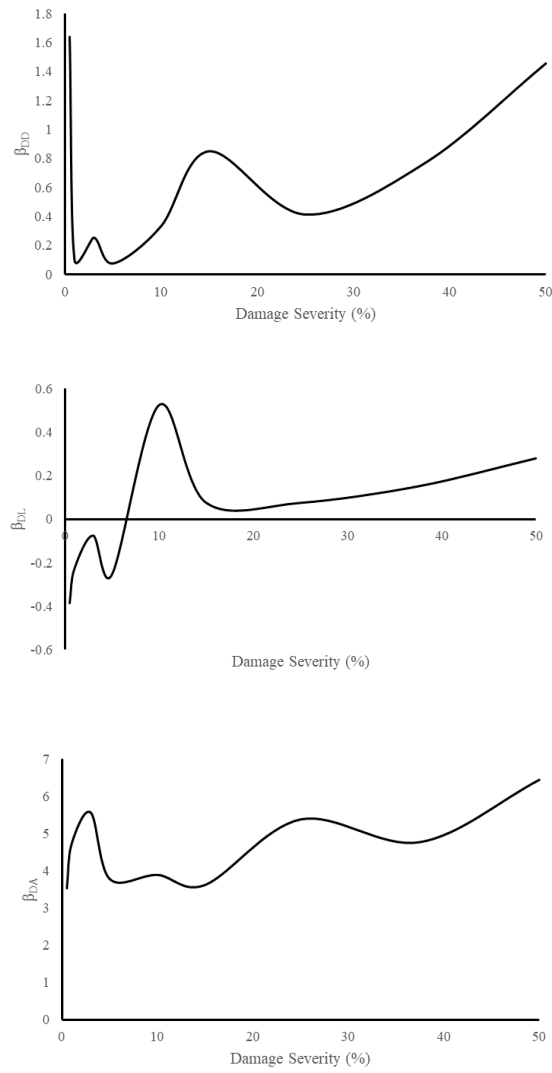


Figure 3-5. The local reliability index attained from element 76 for (Top) Damage detection (Middle) Damage localization (Bottom) Damage assessment. Calculated using equation 3-12 to 3-14.

Local observations of β_{DA} displayed the highest level of reliability across all damage scenarios in comparison to the reliability attained from damage detection, and localization. This was due to the low coefficient of variation across all α values generated for suspected damaged members, and its accuracy in comparison to ADS.

The calculation for local and global β_{SHM} was conducted using weights attained from analytical hierarchical process, with damage detection having an importance

of 7 over localization, and assessment respectively. Damage localization and assessment were deemed to be equally important, thus resulting in values for Ψ_{DD} , Ψ_{DL} , and Ψ_{DA} as 0.778, 0.111, and 0.111 respectively. The resultant curve for β_{SHM} was observed to be strongly dependent on β_{DA} as it compensated for the lower weighted values with its relatively higher reliability index.

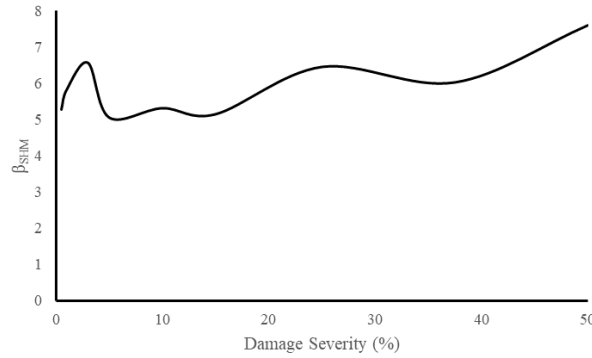


Figure 3-6. Local plot for structure member 76 displaying the combined reliability β_{SHM} across multiple damage severity. Calculated using equation 3-7.

The initial framework for calculating SHM reliability proposed in this chapter, generated two probabilistic performance parameters POAL and POAA, which characterize damage localization, and damage severity performance in the same manner as POD is used for damage detection.

The reliability of damage detection was also calculated for a single member of the fixed offshore platform. Reliability of damage localization, and reliability of damage assessment were also calculated. The proposed equation for merging SHM reliability associated with damage detection, damage localization, and damage assessment was observed to be insufficient due to overcompensation when reliability is combined using equation 3.7. Furthermore, it does not consider any conditional dependencies between these three parameters.

3.5 Improved SHM reliability framework

This section extends the previously described probabilities associated with SHM functions, into a reliability performance metric, where the reliability of damage

detection, damage localization, and damage assessment are attained individually, after which these reliability metrics are combined to generate a single reliability metric that governs the overall SHM performance.

To evaluate the proposed reliability metrics, finite element analysis was employed to simulate a fixed offshore platform in an undamaged and damaged state, where SHM system vibration based modal strain energy was used to detect, localize, and assess damage. Probabilities associated with SHM performance was generated using Hit/miss technique. A limit state function was created for all three SHM outcomes. Reliability analysis was conducted using first order reliability method (FORM).

3.5.1 SHM Conditional Probabilities

The outcome from a SHM system with respect to damage detection may affect the subsequent outcomes for damage localization; furthermore damage assessment outcome could also be affected by prior damage detection and damage localization events [70][63].

For a level 2 SHM system, where damage localization occurs after damage detection, its conditional probability can be expressed using Bayes' theorem as given in equation 3-17. The conditional probability for a level 3 SHM system where damage detection and damage localization are priors to damage assessment is expressed in equation 3-18.

$$P(POAL|POD) = \frac{P(POD|POAL)P(POAL)}{P(POD)} \quad (3-17)$$

$$P(POAA|POAL|POD) = \frac{P(POD|POAL|POAA)P(POAA)}{P(POD|POAL)} \quad (3-18)$$

3.5.2 SHM Uncertainty Network

A framework that calculates the reliability of SHM system outcome based on its ability to detect, localize, assess, and estimate the remaining useful life of a structure in the presence of operational uncertainties is proposed. A flowchart of

the proposed performance function, and the reliability associated with the output for each SHM function is presented in figure 3-6; the undamaged structures behaviour, is attained from sensors mounted on the monitored structure, where signals attained from a time interval when the structure is deemed undamaged are used to infer its damage sensitive parameters. A similar process occurs for the structure in its current state, where its structures damage sensitive parameters, are compared to the undamaged structures damage sensitive parameters to determine if the observed difference exceeds a given damage threshold. Errors and uncertainties associated in the damage detection process arise from the sensor (bond integrity, degradation, communication network), signal processing technique, and damage detection technique. Uncertainties and errors associated with sensor, and signal processing are also present in damage localization and assessment, in addition to further uncertainties in the damage localization and assessment techniques respectively.

Physical uncertainties associated with SHM include environmental loads, operational loads, and geometric dimension. Statistical uncertainties arise from sensor installation, degradation, and limitation, as well as noisy data. Numerical uncertainties arise from signal processing, extraction of damage sensitive features, computation of damage index, selection of damage threshold, damage localization and assessment. Additional numerical uncertainties arise from the resistance and capacity of a structure to withstand a specified damage mechanism.

First order reliability method (FORM) is employed to calculate the reliability index for damage detection, localization, assessment, and structure damage, based on their limit state function and uncertainties associated with their corresponding random variables.

Building on prior limit state functions reported in previous work, the reliability associated with damage detection, damage localization and damage assessment are expressed as

$$R_{DD} = P(D_d + \varepsilon_1 + \varepsilon_2 + \varepsilon_3 - D_{th} > 0) \quad (3-19)$$

$$R_{DL} = P(ALT - |PDL - TDL| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 > 0) \quad (3-20)$$

$$R_{DA} = P(DST - |PDS - ADS| + \varepsilon_1 + \varepsilon_2 + \varepsilon_5 > 0) \quad (3-21)$$

Parameter ε_1 represents uncertainty associated with sensor measurement, ε_2 represents uncertainty from signal processing, ε_3 is the uncertainty associated with damage detection technique, ε_4 represent damage localization uncertainty, and ε_5 is the damage assessment uncertainty. Parameters defined in previous work, include the damage detected D_d , allowable localization tolerance (ALT), predicted location of damage occurrence (PLD), true damage location (TDL), damage severity threshold (DST), predicted damage severity (PDS), and actual damage severity (ADS).

To quantify the SHM reliability performance function for level 3 systems that merges the reliability of damage detection, localization, and assessment, conditional probability of failure associated with the occurrence of each sequential SHM event was attained by updating the SHM probability of failure. Weights ψ were assigned to reliability associated with each SHM outcome to highlight the relative importance of a specific SHM outcome with respect to the attained system reliability.

$$R_{SHM} = 1 - \frac{P[\psi_{DA}(DST - NSD < 0) \cap \psi_{DL}(ALT - NSL < 0) \cap \psi_{DD}(NSD - D_{th} < 0)]}{P[\psi_{DL}(ALT - NSL < 0) \cap \psi_{DD}(NSD - D_{th} < 0)]} \quad (3-22a)$$

$$NSD = D_d + \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \quad (3-23b)$$

$$NSL = |PDL - TDL| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 \quad (3-24c)$$

$$NSD = |PDS - ADS| + \varepsilon_1 + \varepsilon_2 + \varepsilon_5 \quad (3-25d)$$

For a level 2 SHM system, its R_{SHM} is attained by simplifying the conditional probability of failure by excluding the probability of failure associated with damage assessment. Furthermore, the exclusion of probability of failure associated with

damage localization and damage assessment results in R_{SHM} a for a level 1 SHM system.

For a specific type of damage being monitored by a SHM system with the capability of estimating the structures' reliability over its remaining useful life, the estimated structure's reliability is a function of R_{SHM} , the damage limit state function, and its associated uncertainties. The SHM reliability associated with the predicted monitored structure's reliability can then be expressed using a conditional reliability as described in equation 3-23, where the variables E_i and E_{SHM} represent the failure functions for the SHM system and monitored structure respectively.

$$R_{SHM_STRUCTURE}(t) = 1 - P[E_{SHM}|E_i] \quad (3-26)$$

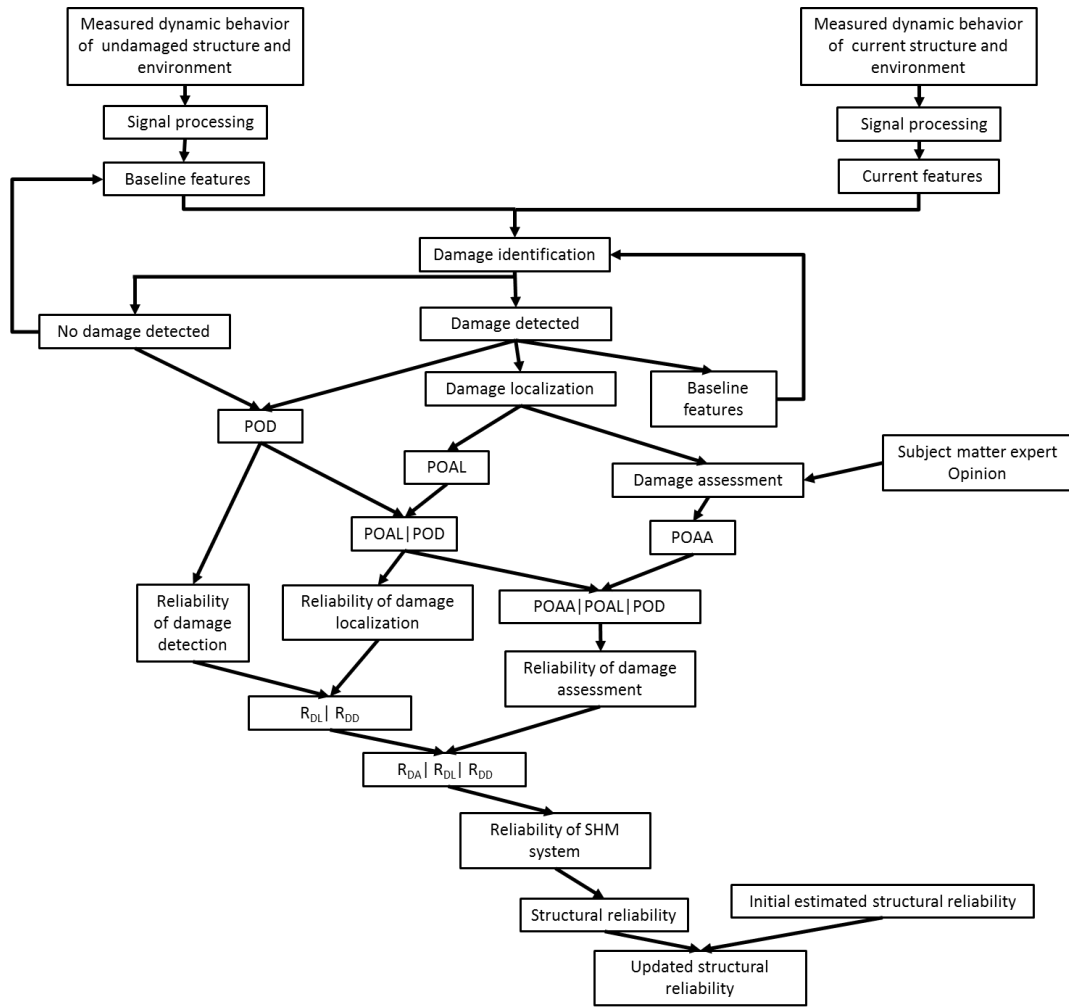


Figure 3-7. A network of SHM displaying the suggested performance reliability metrics associated with damage detection, damage localization, damage assessment, and the monitored structure.

3.5.3 Case Study

The proposed approach was applied to a numerical study to evaluate SHM performance and reliability. Vibration based Modal strain energy (MSE) by Stubbs et al (1995), was employed to assess the integrity of fixed offshore platform with varying degrees of damage at its structure members. The topology and foundation stiffness of the fixed offshore platform used was given in detail by Karadeniz 2001; the operational and environmental loads applied are presented in table 3-3. Finite element model of the fixed offshore platform was constructed using beam elements, where damage was modelled by reducing the stiffness of

a given structure member. Baseline condition was initially attained where no damage was present in the fixed offshore platform. Steel was assigned as the material property of all members in the structure. Eight (8) structure members were chosen to simulate a single occurrence of damage, where each member had 9 levels damage severity.

Table 3-3. Environmental and operational loads applied in the numerical simulation. (Karadeniz 2001.)

Mass of Deck	4800 ton
Water Depth	50 m
Significant wave height	2.5 m
Drag coefficient	1.3
Inertia Coefficient	2.0
Sea spectrum	Pierson-Moskowitz

Level 3 SHM System

Vibration based modal strain energy by Li et al 2007, was implemented in this study to detect, localize, and assess damage. The outcomes from the SHM system with respect to damage detection, damage localization, and damage assessment were substituted into equation 3-17 to 3-19 as D_d , PDL, and PDS respectively. Monte Carlo simulation was implemented to solve equations 3-20 to 3-23 as listed in previous work by Etebu & Shafiee 2018 [87][88], using 500 samples to generate the mean and standard deviation for all SHM outcomes. Uncertainties associated with the noisy mode shapes, and Eigen values were assigned using 0.1% noise, and a random number described by a normal distribution with unit variance and zero mean. Noise level of 0.1% was selected to create variation in the Eigen values, based on the magnitude use by previous researchers [84]. Uncertainties associated with parameters used in the modal strain energy SHM system are given in table 3-4.

Table 3-4. Description of variables in SHM limit state functions and reliability assessment

Variable	Distribution	Mean	COV
Young's Modulus (GPa)	Normal	203.39	0.006
DST	Normal	0.9*ADS	0.1
ALT	Normal	14.64	0.56
D_{th}	Normal	0.1	0.1
Poisson's Ratio	Fixed	0.3	
Ψ_{DD}	Fixed	0.788	
Ψ_{DL}	Fixed	0.111	
Ψ_{DA}	Fixed	0.111	

Hit/Miss technique was applied to attain the relationship for POD, POAL, and POAA based on the output attained from the modal strain energy SHM system. The structural members of the fixed offshore platform were categorized into 4 local groups to attain a local and global SHM performance metric. The structural members were grouped based on orientation and function as horizontal floor brace, diagonal floor brace, legs, and diagonal brace.

To correlate damage severity to crack length, a 3D CAD model of individual members from the fixed offshore platform were created using their actual diameter, thickness, and length. Damaged versions of these members were created by subtracting an ellipsoidal crack from the model at a fixed position on the structural member, where varying crack lengths were simulated at a constant aspect ratio of 0.2. Crack growth was not considered.

The damaged and undamaged models were used to simulate a cantilever beam where a constant load was applied to the end of the cantilever beam and its maximum displacement was recorded [77][89]. The ratio of stiffness reduction

was used to correlate the percent loss of bending stiffness to crack length. The crack length prediction funnels into the limit state function implemented to estimate the fatigue reliability of the structure member as detailed in section 3.5.5.



Figure 3-8a. Schematic of cantilever beam with crack for damage severity to crack length correlation.



Figure 3-9b. Schematic of the finite element model of the fixed offshore platform used in this case study. (Karadeniz, 2001).

3.5.4 Results and Discussion

3.5.4.1 SHM System Probability

The seventy-two (72) scenarios of damage assessed resulted in at least one-member element with a D_d value greater than 0.1 for 71 scenarios, where a false negative was generated on a horizontal floor brace with a 30 mm long crack. The outcome of PDL, was observed to predict more than 1 damaged structure member for all simulations conducted, this prediction typically included the damaged member, and its corresponding load sharing members. As the crack length increased, the inclusion of TDL in the PDL also increased, additional factors that affected the performance of PDL include structure member type and location. The behaviour of PDS displayed similar dependence on structure member type and crack length.

Local values of D_d , PDL and PDS were used to generate curves representing POD, POAL and POAA on a local and global scale. Hit/miss data for POD, POAL and POAA fitted to a logit model are presented in figure 3.3. The dependence of POD, POAL, and POAA on structure member type indicates the modal strain energy SHM method by Li et al displays above an 80% probability at either detecting, localizing, and assessing damage on fixed offshore platform legs. For diagonal floor brace members, the SHM system was able to detect damage; however, it was unsuccessful at accurately localizing the damaged member or its crack size.

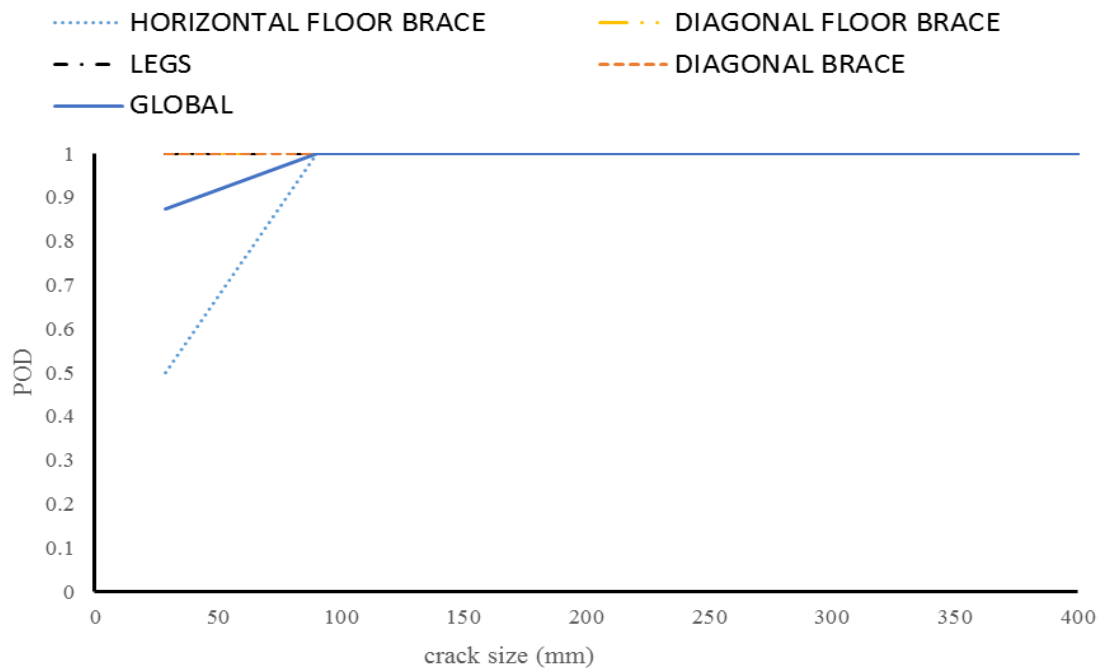


Figure 3-10a. POD Curve for local and global SHM performance. Calculated using equation 3-2.

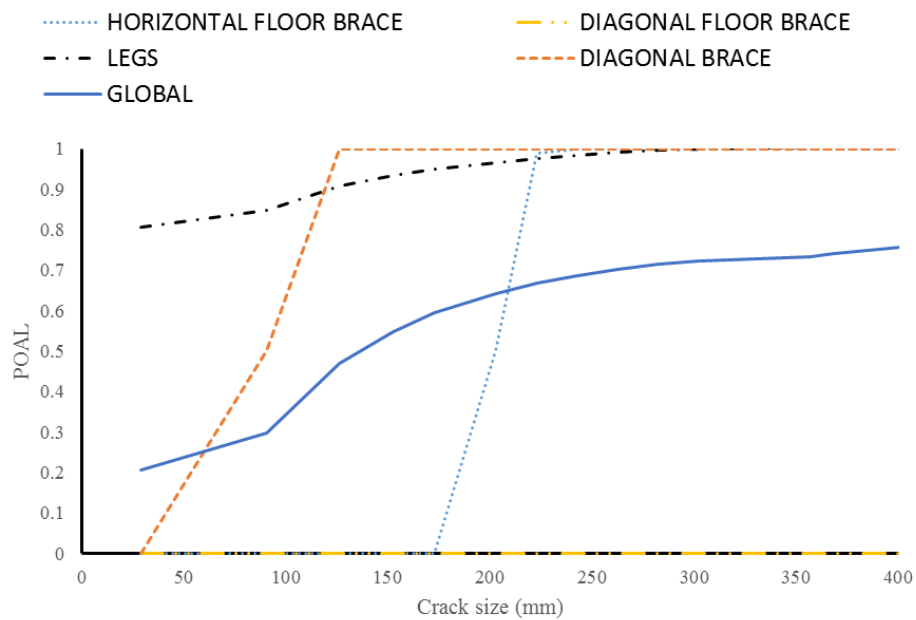


Figure 3-9b. POAL for local and global SHM performance. Calculated using equation 3-5.

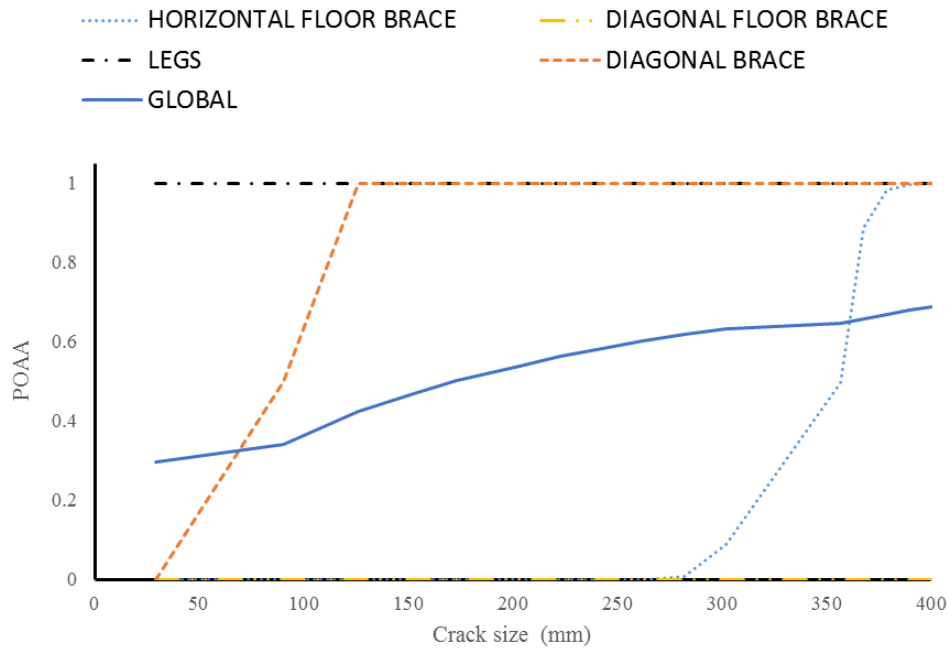
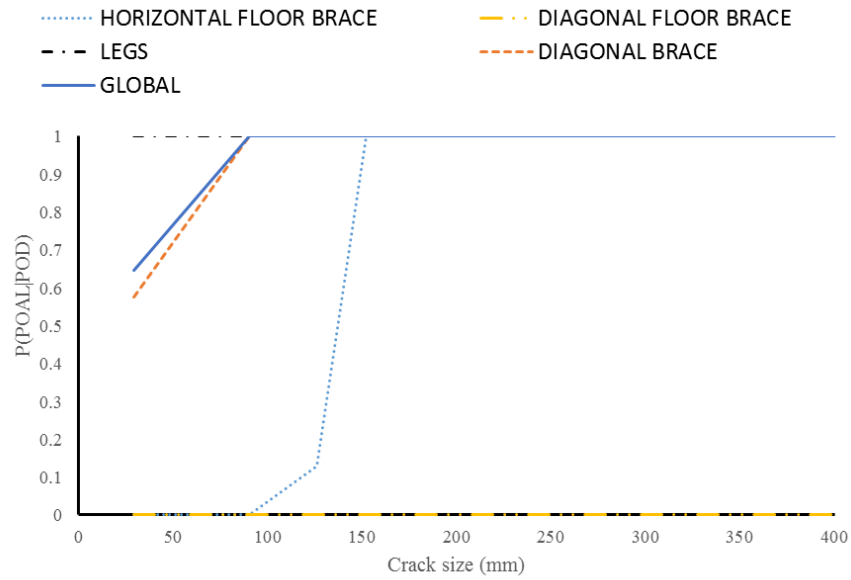


Figure 3-9c. POAA Curve for local and global SHM performance. Calculated using equation 3-6.

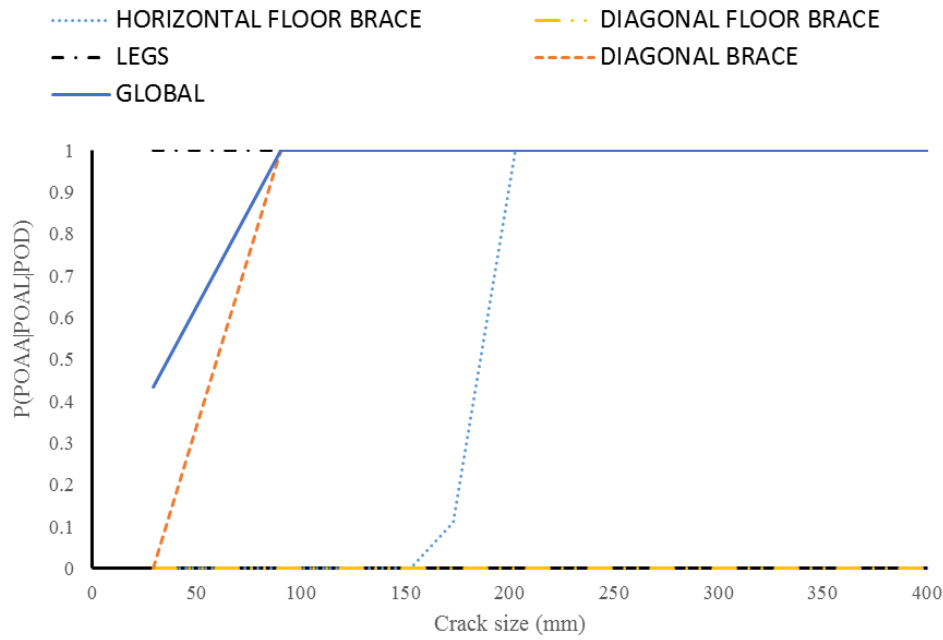
The conditional probabilities for damage localization with damage detection prior, depicts a performance parameter that is highly influenced by the significantly weaker performer at the level 2 stage of the SHM system. For instance, the POAL for diagonal floor brace across all crack sizes simulated was zero; hence its level 2 conditional probability of damage localization after damage detected was also zero. For horizontal floor brace members, the level 2 conditional probability displayed a similar shape as its POAL, however; the crack size at which its probability increased above zero was decreased due to the higher performance of the SHM damage detection system. The global level 2 conditional probability displayed a shape like POD, with a lower probability magnitude for crack size below 75 mm.

The level 3 conditional probability across local members and on a global scale displayed a similar shape to the level 2 conditional probability; however, the

values of level 3 probabilities were visibly lower for crack size below 75 mm on diagonal floor brace members and the global structure.



**Figure 3-9d. Conditional probability associated with Level 2 SHM performance.
Calculated using equation 3-17.**



**Figure 3-9e. Conditional probability associated with Level 3 SHM performance.
Calculated using equation 3-18.**

3.5.4.2 SHM System Reliability

Local reliability index for damage detection R_{DD} for a given member was observed to be highly influenced by the number of structure members displaying D_d values greater than D_{th} , for a specified crack size. This is due to the parallel arrangement for damage detection where a single value of D_d exceeding D_{th} , signals the detection of damage. When the simulated crack size was greater than 152 mm, values of R_{DD} in platform legs, and diagonal brace was observed to increase with crack size (see fig. 3-9), while its corresponding POD across all levels of damage was constant at 100%. The global R_{DD} for crack sizes less than 400 mm in this simulation does not exceed 0.5, whereas the Global POD value for crack sizes greater than 29 mm is over 0.875. This indicates a reduction in value of PFN with increasing crack size; moreover, PFN is also a function of D_{th} . The conjunction of information from R_{DD} and POD could be used to select an appropriate value for D_{th} . This observation also highlights the importance of using reliability as the SHM

systems performance metric rather than the probability associated with its individual functions.

Across all levels of crack size, R_{DL} did not generate a value greater than 0.6 for any local group of structure members. Local curves for R_{DL} were highly dependent on the number of local maxima points generated from D_d . Correspondence of the position for local maxima point generated in comparison to ALT, governed values of observed R_{DL} . Thus the inclusion of a correctly suspected damaged member and members not sharing a node with the damaged member reduced the SHM systems reliability with respect to damage localization. It should be noted that structure members who do not share a node could also share loads due to symmetry, hence increasing the magnitude of ALT beyond the limit prescribed in this work. Nevertheless, it was observed that a specific group of structure members displayed a high frequency of local maxima occurrence independent of crack size, and damaged member. The global R_{DL} was severely affected by the SHM systems inability to localize damage located in diagonal floor brace and diagonal brace members.

The performance of R_{DA} was observed to be independent of ADS for platform legs, as a relatively consistent value was attained across all simulated values of crack size, a similar behaviour was also observed in diagonal brace members. For horizontal floor brace members, R_{DA} was observed to increase when the crack size was between 120 mm to 220 mm, values of R_{DA} observed outside this range were independent of crack size as displayed in figure 3-10. R_{DA} was also observed to display the highest values of reliability across all crack sizes in comparison to R_{DD} and R_{DL} for platform legs, horizontal floor brace, diagonal brace. This was due to the low coefficient of variation across all mean PDS values generated for suspected damaged members, and its accuracy in comparison to ADS. However, R_{DA} was ineffective for diagonal floor brace where its reliability was zero across all crack sizes simulated, which is also reflected in the global value of R_{DA} equaling zero independent of crack size.

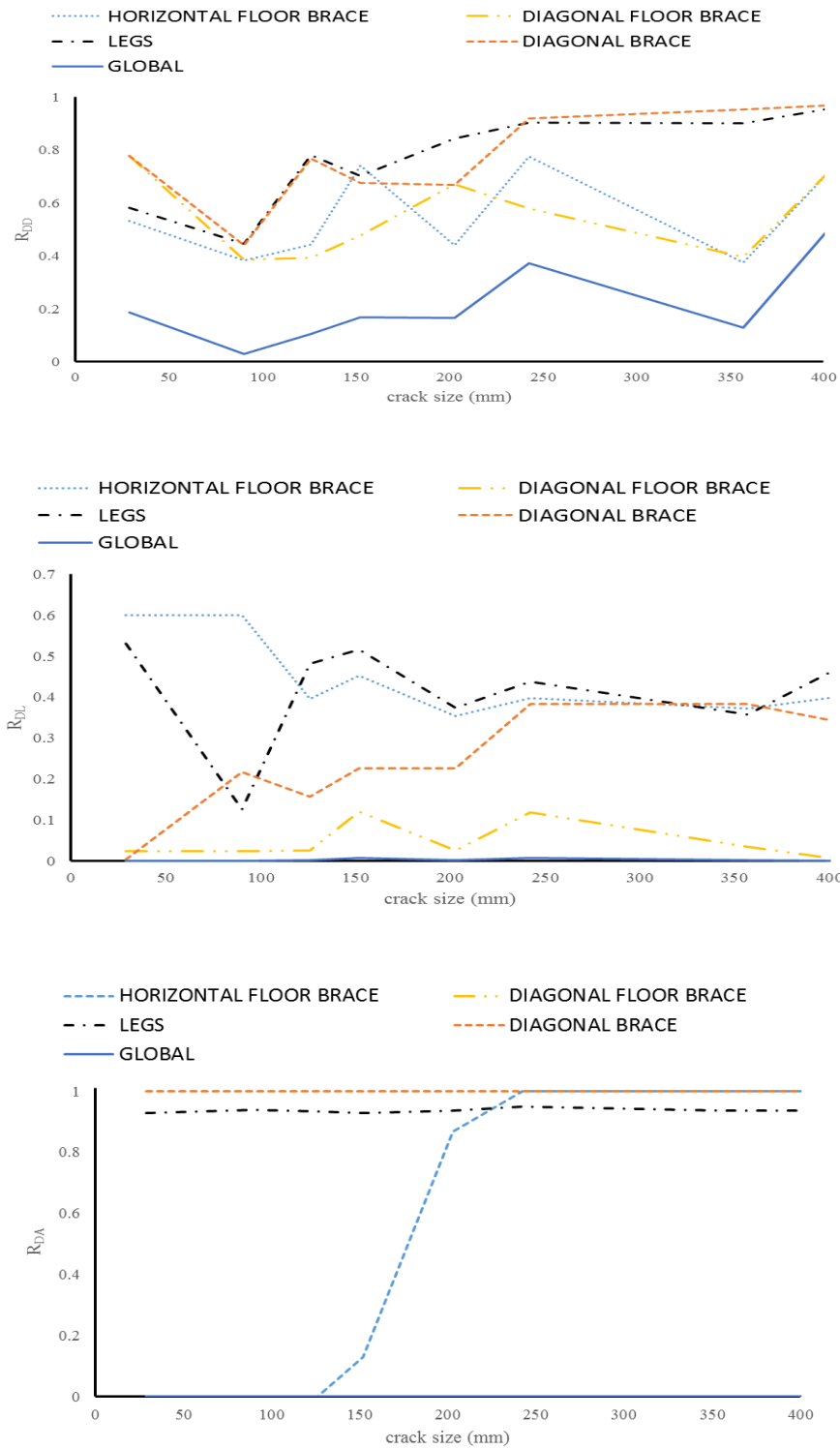


Figure 3-11. The local and global reliability attained for Fig 3.9a (Top) Damage detection Fig 3.9b (Middle) Damage localization Fig 3.9c(Bottom) Damage assessment. Calculated using equation 3-19 to 3-21.

Calculation R_{SHM} was conducted using weights attained from analytical hierarchical process, with damage detection having an importance of 7 over localization, and assessment respectively. Damage localization and assessment were deemed to be equally important, thus resulting in values for Ψ_{DD} , Ψ_{DL} , and Ψ_{DA} as 0.778, 0.111, and 0.111 respectively.

The weighted importance of R_{DD} is reflected in the observed shape of R_{SHM} , for level 2 and level 3 system as displayed in figure 3.5. For local Structure members belonging to the group of horizontal floor brace, the observed level 2 R_{SHM} ranged from 0.830 to 0.954 across all crack size, while a range of 0.491 to 0.744 was observed for diagonal brace structural members. Although structure members belonging to horizontal floor brace and diagonal brace displayed a similar range of R_{DD} values, the SHM systems ability to localize damage after the detection of damage with a higher reliability for horizontal floor brace in comparison to diagonal brace is reflected in a single performance parameter R_{SHM} , for a level 2 SHM system.

At the third level of SHM performance, the observed value for level 3 R_{SHM} for horizontal floor brace members, ranged from 0.07 to 0.999 across all crack size, where a decrease in level 3 R_{SHM} was observed for crack sizes smaller than 230 mm. This observed decrease, coincided with crack sizes where R_{DA} displayed poor performance. For diagonal brace members, where R_{DA} ranged from 0.999 to 1, an increase in level 3 R_{SHM} values in comparison to level 2 R_{SHM} was observed across all crack sizes.

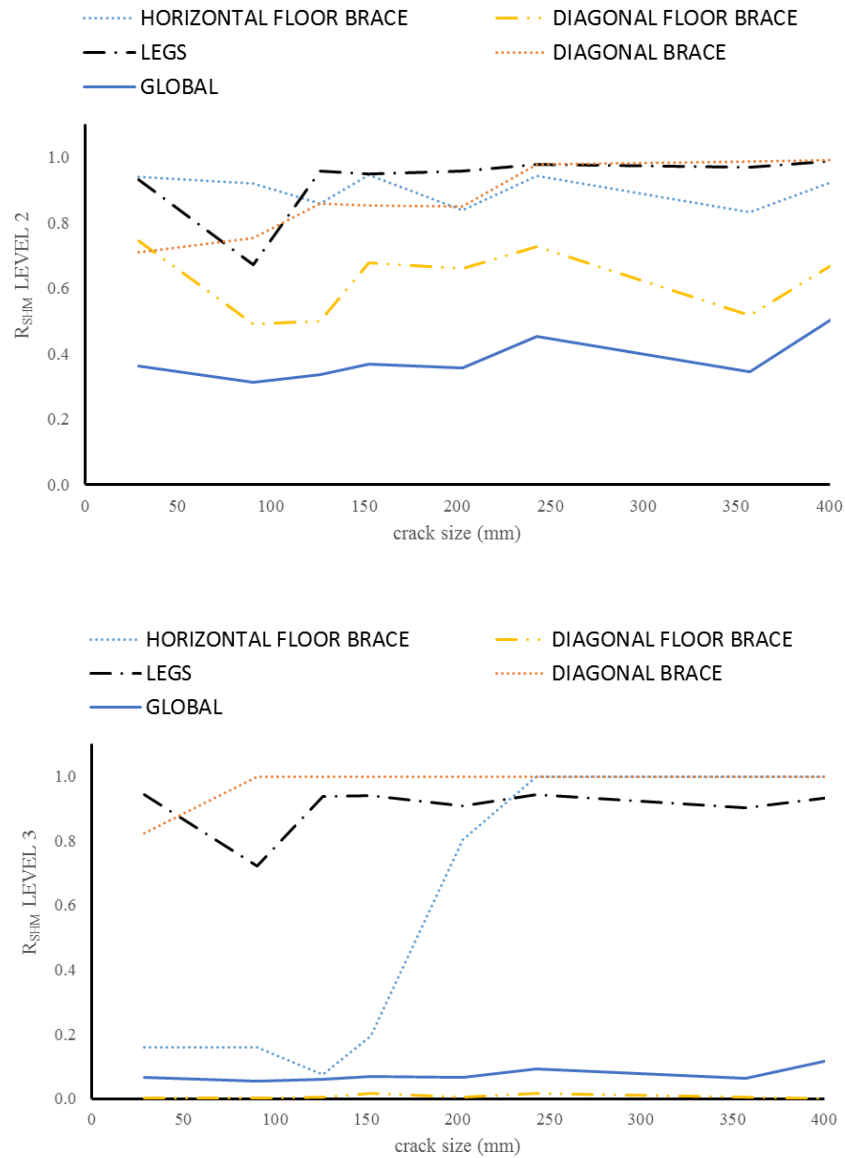


Figure 3-12. Local and global reliability for combined performance of a Fig 3.10a (TOP) Level 2 and Fig 3.10b (Bottom) Level 3 SHM system. Calculated using equation 3-22.

3.5.5 Reliability of Structure estimated from Level 3 SHM output.

To demonstrate the conditional structural reliability of a structure fitted with a level 3 SHM system, the estimated useful life for the fixed offshore platform used in the case study was calculated specifically for fatigue damage.

Fatigue reliability modelling for offshore structures, through inspection is a subject matter that has been covered by previous researchers. Fracture mechanics via the Paris equation is used to model the fatigue limit state, in terms of number of crack size (a_0 , a_T), stress cycles per time period ω , time period T , geometry Y , Paris law constants (C , and m), and stress range expressed a function of the Weibull scale A , and shape B , while Γ is a gamma function [67][68]. Additional terms associated with uncertainties pertaining to variables associated with the Paris equation are also added in the limit state function, for this work the fatigue limit state function is given as:

$$g(\mathbf{X}, \mathbf{T}) = a_0^{[1-0.5m]} - a_T^{[1-0.5m]} + \pi^m \cdot C \cdot Y^m \cdot T \cdot \omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \leq 0 \quad (3-27)$$

The effect of SHM event outcome at a given time on the monitored structures reliability is attained by updating the fatigue reliability [70][68]. Limit state functions for the event where no crack is detected by the SHM system is expressed as

$$h_{nd,i}(\mathbf{X}, \mathbf{T}) = a_d^{[1-0.5m]} - a_0^{[1-0.5m]} - \pi^m \cdot C \cdot Y^m \cdot T \cdot \omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] \leq 0 \quad (3-28)$$

All variables associated with equation 3-25 are the same as equation 3-24 except for the parameter a_d which is the detectable crack size for the inspection system, a_d is typically attained from the POD curve. The updated reliability when no crack is detected is generally written as displayed in equation 3-26 [70][68], where subscript i denotes the specific structure member in the monitored structure.

$$R_{Structure,i}^u(\mathbf{X}, \mathbf{T}) = 1 - \frac{P(g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{nd,i}(\mathbf{X}, \mathbf{T}) \leq 0)}{P(h_{nd,i}(\mathbf{X}, \mathbf{T}) \leq 0)} \quad (3-29)$$

To include the contribution of the total level 3 SHM outcome on the updated fatigue reliability for the monitored structure, an additional event was added to the updating process in the form of a series system as follows.

$$R_{SHM_Structure,i}^u = 1 - \frac{P(E_{SHM3,i}(\mathbf{X}, \mathbf{T}) \geq 0 \cap g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{nd,i}(\mathbf{X}, \mathbf{T}) \leq 0)}{P(g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{nd,i}(\mathbf{X}, \mathbf{T}) \leq 0)} \quad (3-30)$$

The term E_{SHM3_i} is the limit state function associated with the SHM reliability as displayed in equation 3-22 [70][68].

For updating the Structures fatigue reliability in the event where crack is detected by the SHM system [70], the fatigue reliability limit state function is expressed as a function of the SHM predicted crack size a_{pcs} as follows

$$h_{dd_i}(\mathbf{X}, \mathbf{T}) = a_0^{[1-0.5m]} - a_{pcs}^{[1-0.5m]} + \pi^m \cdot C \cdot Y^m \cdot T \cdot \omega \cdot A^m \cdot \Gamma \left[1 + \frac{m}{B} \right] = 0 \quad (3-31)$$

The corresponding updated fatigue reliability for the event of damage detection is expressed in equation 3-29, while the SHM reliability associated with the Structures fatigue reliability is given in equation 3-30.

$$R_{Structure_i}^u = 1 - \frac{P(g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{dd_i}(\mathbf{X}, \mathbf{T}) = 0)}{P(h_{dd_i}(\mathbf{X}, \mathbf{T}) = 0)} \quad (3-32)$$

$$R_{Structure_i}^u = 1 - \frac{P(g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{dd_i}(\mathbf{X}, \mathbf{T}) = 0)}{P(h_{dd_i}(\mathbf{X}, \mathbf{T}) = 0)} \quad (3-33)$$

For continuous events of no damage detected until the event of damage detected, equation 3-31 expresses the updated structures reliability where the superscript associated with the event type, SHM limit state function, and time, denotes the order of events [70][68].

$$\begin{aligned} & R_{SHM_Structure_i}^u \\ &= 1 - \frac{P(E_{SHM3_i}^1(\mathbf{X}, \mathbf{T}^1) \geq 0 \cap g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{nd_i}^1(\mathbf{X}, \mathbf{T}^1) \leq 0 \cap \dots \cap h_{dd_i}^n(\mathbf{X}, \mathbf{T}^n) = 0)}{P(g_i(\mathbf{X}, \mathbf{T}) \leq 0 \cap h_{nd_i}^1(\mathbf{X}, \mathbf{T}^1) \leq 0 \cap \dots \cap h_{dd_i}^n(\mathbf{X}, \mathbf{T}^n) = 0)} \end{aligned} \quad (3-34)$$

3.5.5.1 Numerical Application

The updated fatigue reliability was calculated for simulated fatigue damage on two members of the fixed offshore platform used in the case study from the previous section in this work. The first simulation was conducted on a diagonal brace member 64 where crack size of 30mm occurred at time of 365 days. A second simulation was conducted on a horizontal brace member 92 using the same crack size and time interval as the first simulation. All variables used in calculating the updated fatigue reliability are listed in table 3-5.

3.5.5.1.1 Damage at Diagonal Brace Member 64

The SHM system outcome indicated the event of damage detected on the fixed offshore platform at the 365th day, where the predicted crack size on structure member 64 was 18 mm. The calculated SHM level 3 reliability for the predicted crack size was 0.804. Using the predicted crack size, equations 3-24 to 3-26, the predicted reliable useful life for structure member 64 was attained, and it is displayed in figure 3-11.

The updated estimated fatigue life reliability for structure member 64 as seen in red in figure 3-11, after the detection of damage in year 1, indicates its fatigue reliability will be zero, in less than 0.5 years from the event of crack detection. Reliability calculated for the limit state function h_{dd_64} at detection was 1.0, while its updated fatigue reliability displayed a value of 0.986. The SHM reliability associated with the estimated remaining useful life fatigue reliability for structure member 64 was 0.932 at the event of damage detection.

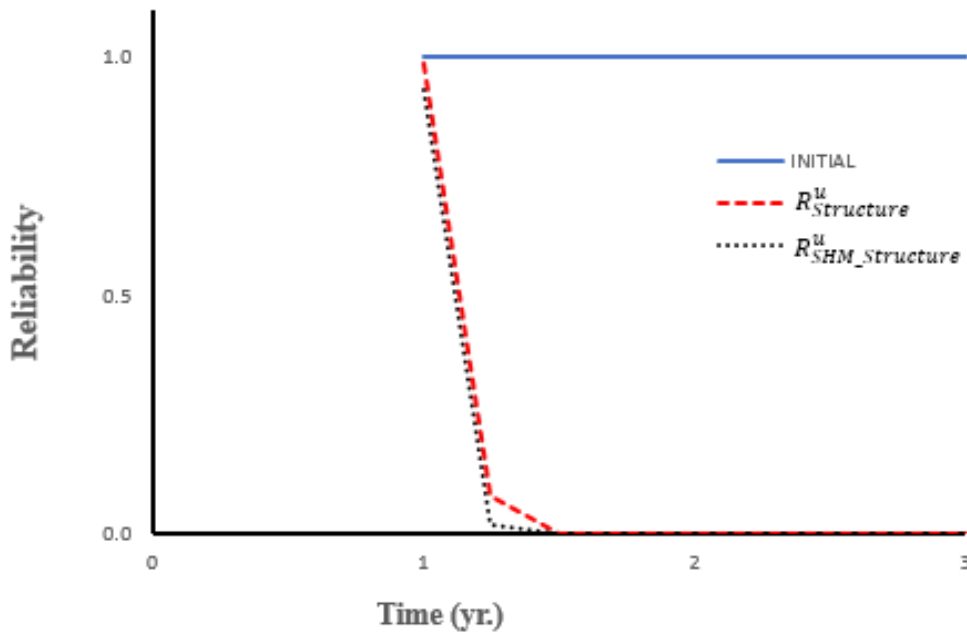


Figure 3-13. Updated Reliability for Structure member 64 with 30 mm crack size damage, at time of 1 year. SHM system detected 18 mm crack damage, which was used to update the structure members fatigue reliability. Calculated using equation 3-22 and 3-23.

3.5.5.1.2 Damage at Horizontal Brace Member 92

At the 365th day, the SHM outcome indicated the event of damage detected, however it did not predict any cracks occurring on structure member 92. The POD diagram for horizontal brace members indicates 90% of cracks above 78 mm are detected, hence it was used as the detectable crack size to predict the remaining useful life via equations 3-22 to 3-29. The calculated SHM level 3 reliability for horizontal brace members when the crack size is below the detectable crack size was 0.15. Reliability calculated for the limit state function h_{nd_92} at the event of no damage detection was 0.5, while a value of 1.0 was attained as the updated fatigue reliability. Subsequently, the calculated SHM reliability associated with the predicted updated fatigue reliability remaining useful life was zero as displayed in figure 3-12.

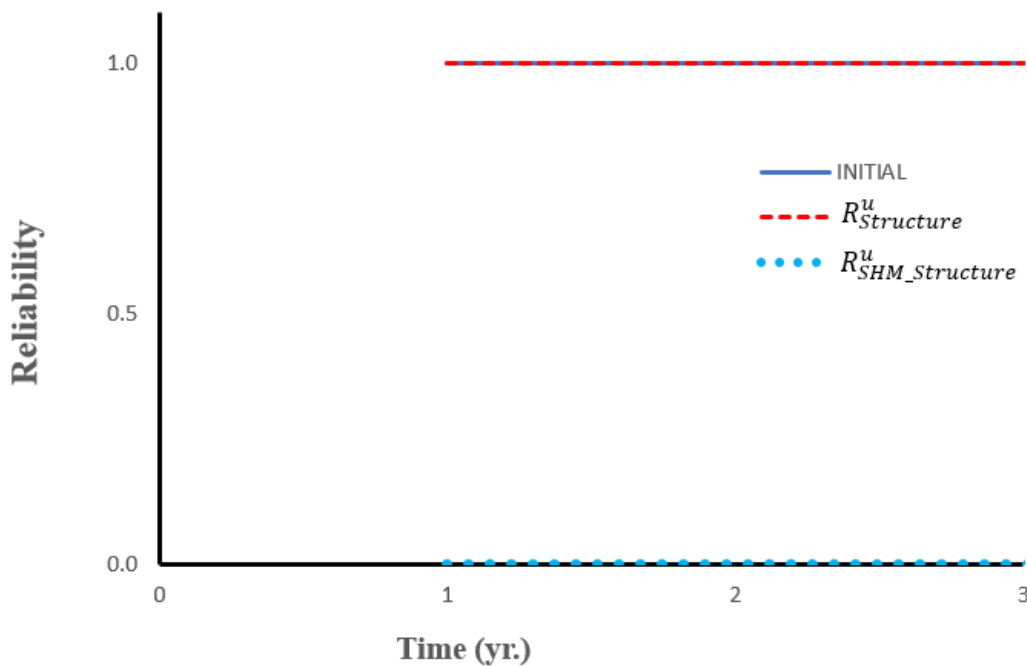


Figure 3-14. Updated Reliability for Structure member 92 with a 30 mm crack size damage at time of 1 year, where the SHM system did not detect damage present in the structure member. Calculated using equation 3-22 and 3-23.

Table 3-5. Descriptions of variables used to calculate the fatigue updated reliability. (Karadeniz, 2001.)

Variable	Distribution	Mean	COV
a_0 (mm)	Exponential	0.1	
a_T (mm)	Normal	125	0.1
$\ln C$	Normal	-29.97	0.014
a_{PCS} (Diagonal Brace) (mm)	Normal	18	0.1
a_d (Horizontal Brace) (mm)	Normal	78	0.1
A	Fixed	11.47	
B	Fixed	1.22	
ω (cycles/ yr.)	Fixed	6×10^6	
Y	Fixed	1	
m	Fixed	3.1	
R_{SHM3} Diagonal Brace #64	Fixed	0.804	
R_{SHM3} Diagonal Brace #64	Fixed	0.15	

3.6 Summary

In this chapter, the reliability of a vibration based modal strain energy SHM system was assessed to determine its performance with respect to detection, localization, and assessment of damage on a fixed offshore platform. A numerical finite element model was employed to simulate loading conditions and response of a fixed offshore platform, with varying degrees of damage. A framework was created which generated limit state functions to capture the uncertainties associated with the SHM process. First order reliability method, Monte Carlo simulation, hit/miss technique was applied via a program written in MATLAB to solve for the SHM systems reliability performance functions, and the probability distribution of SHM performance.

Key developments from this chapter include:

- Reliability of the vibration based Modal Strain Energy SHM systems damage detection process was calculated at varying levels of damage (crack size). The SHM systems performance displayed a dependence on crack size, and type of structure member. Furthermore, a comparison of probability of detection and damage detection reliability across multiple levels of damage provides additional insight on the behaviour of the probability of false negative associated with the damage detection process.
 - A similar conclusion could be drawn about the type 1 error associated with damage localization and assessment when comparing probability of actual localization and the reliability of damage localization, as well as probability of accurate assessment and the reliability of damage assessment.
 - This demonstrates the first objective in this research work, which is the application of a vibration based SHM system to a numerically simulated fixed offshore platform with varying levels of simulated damage.
 - The proposed use of reliability as a performance metric for SHM systems provides a single performance metric that also captures the type1 and type 2 errors associated with the SHM system. This is advantageous in comparison to the widely used POD, which does not capture both types of errors in the SHM system performance.
 - A conditional reliability function that engulfs the SHM systems damage detection, localization, and assessment is also presented.
 - The combined reliability SHM performance parameter provides a single value that can be used to compare the performance of level 3 SHM systems across the global structure that is being monitored as displayed in this work.
 - This addresses an objective of this research work which is to develop a framework that engulfs the

uncertainty associated with the SHM systems process, where the reliability of damage detection, damage localization and damage assessments were outputs from the framework.

- Furthermore, the combined reliability performance parameter can also be used to compare different SHM systems.
- Additionally, the combined reliability performance function is a measure of the level 3 SHM systems reliability that is used to estimate the reliability of the monitored structures useful life.
 - This demonstrates the second objective of this work which is to assess the reliability of a fixed offshore platform and estimate its remaining useful life based on the outcome from the SHM system.
- Thus, an improvement in the combined reliability performance function for a level 3 SHM system is directly related to the improvement in reliability of the monitored structure for a given type of damage.
- The proposed combined reliability SHM performance parameter can also be applied to level 2 SHM systems, where damage assessment is not available.

4 An Improved Slope Change SHM Technique for Jacket Structures

4.1 Introduction

In this chapter, an improved slope change SHM technique is proposed for jacket structures with the capability to detect, localize, and assess damage severity. The proposed SHM technique is based on the detection of damage based on the change in slope measured by the SHM sensor system mounted on the monitored structure. The proposed improved curvature change SHM technique also improves the identification of damage location using a nodal classification algorithm, and a supervised neural network. Additionally, the severity of damage on the structure is also predicted using a supervised neural network.

The probability performance functions of the improved slope change SHM technique was assessed using the probability functions presented in chapter 3. A comparison is probability performance functions between the improved slope change SHM and the vibration based modal strain energy SHM technique from chapter 3 is also conducted.

4.2 Damage Feature Extraction: Slope Change

In this section, the damage feature extraction algorithm for the improved slope change SHM technique is outlined.

The introduction of “curvature mode shape” as a damage sensitive feature to detect and localize damage was proposed by Pandey et al 1991 [90]. They used the difference in the curvature mode shape attained from the undamaged and current state of the structure to infer the presence and location of damage. Pandey et al 1991, applied the curvature mode shape technique to a finite element model of cantilever beam where they were able to detect and locate the presence of damage. Additional modifications to the curvature shape method were made by researchers such as Ho and Ewins 2000 [71], and Wahab and Roeck 1999 [91].

Curvature approximation attained from displacement mode shapes have been reported to be erroneous in comparison of curvature measured from strain gauges [92]. Additionally, the ability for curvature methods to localize damage in complex structures such as jacket structures has been reported to be limited [93].

The proposed SHM technique builds upon the same foundation of the curvature mode change method but implements the slope change as the damage sensitive feature.

The relationship between a beams flexural stiffness and its slope is given by equation 4.1, where φ' is the slope, M represent bending moment, E is the Young's modulus, and I represent the second moment of the cross-sectional area for the specific section of the beam. In the event of damage, the Flexural stiffness (EI) reduces [94][95][96], which in turn increases the magnitude of curvature for the section of the beam where damage occurs.

$$\varphi' = \frac{\int M dx}{EI} \quad (4-1)$$

For dynamic analysis, the eigen value equation for the damaged and undamaged structures are described using equation 4-2 and 4-3 [97][98][99][100]. Where M is the mass matrix, K is the stiffness matrix of the undamaged structure, K' is the stiffness matrix of the damaged structure, λ_j and X_j are the eigen value and eigenvector of the j th member for the intact structure. For the damaged structure K' represents its stiffness matrix while λ_j' and X_j' are the eigen value and eigenvector of the j th member.

$$[K - \lambda_j M]x_j = 0 \quad (4-2)$$

$$[K' - \lambda_j' M]x_j' = 0 \quad (4-3)$$

4.3 Damage Detection

The eigen vectors from each mode shape can be broken down into displacement and rotation components. The magnitude of the displacement eigen vector for each mode shape is used to calculate the displacement slope change as

$$|\varphi_{d,i}'| = \frac{|X_{d,i}| - |X_{d,i+1}|}{h} \quad (4-4)$$

Where h is the length of the element, $|X_{d,i}|$ and $|X_{d,i+1}|$ are the magnitude of the displacement components for eigen vector at each end of the element.

The magnitude of the rotation eigen vector is also used to calculate the rotational slope change as

$$|\varphi_{r,i}'| = \frac{|X_{r,i}| - |X_{r,i+1}|}{h} \quad (4-5)$$

where $|X_{r,i}|$ and $|X_{r,i+1}|$ are the magnitude of the rotation components for eigen vector at each end of the element.

The slope difference for displacement SD_d and rotational SD_r components were calculated using equation 4-5 and 4-6 respectively. The superscript u denotes the undamaged state, while superscript d denotes the damaged or current state.

$$SD_{d,i} = abs \left[|\varphi_{d,i}'|^u - |\varphi_{d,i}'|^d \right] \quad (4-6)$$

$$SD_{r,i} = abs \left[|\varphi_{r,i}'|^u - |\varphi_{r,i}'|^d \right] \quad (4-7)$$

The slope difference is then normalized using its standard deviation and mean as seen in equation 4-7 and 4-8. Parameters σ_{SD_d} and σ_{SD_r} represent the mean of the slope difference for displacement and rotation, respectively. Parameters $\overline{MSD_d}$ and $\overline{MSD_r}$ represent the standard deviation of the slope difference for displacement and rotation, respectively.

$$ZSD_{d,i} = \frac{SD_{d,i} - \sigma_{SD_d}}{\overline{MSD_d}} \quad (4-8)$$

$$ZSD_{r,i} = \frac{SD_{r,i} - \sigma_{SD_r}}{\overline{MSD_r}} \quad (4-9)$$

To compile the normalized displacement slope difference from all modes, the cumulative modal normalized slope difference parameter is used to combine all available modes as follows.

$$CZSD_{d,i} = \frac{1}{N} \sum_{n=1}^N ZSD_{d,n,i} \quad (4-10)$$

$$CZSD_{r,i} = \frac{1}{N} \sum_{n=1}^N ZSD_{r,n,i} \quad (4-11)$$

Where N represent the total number of mode shapes available.

Fusion between the cumulative modal normalized slope difference for the displacement and rotational modes is presented in equation 4-11 as the damage index cumulative slope difference ($DICSD_i$). In the fusion process, the cumulative modal slope difference for the displacement modes is normalized by dividing its value by the maximum value of $CZSD_{d,i}$ across all elements. The rotational cumulative modal slope difference is not normalized to preserve damage sensitive features, that occur in the rotational eigen vector due to the structural behaviour of jacket structures during excitation.

$$DICSD_i = \frac{1}{2} \left[CZSD_{r,i} + \frac{CZSD_{d,i}}{\max[CZSD_d]} \right] \quad (4-12)$$

When the value of $DICSD_i$ exceeds one, it indicates the presence of damage in a structure.

4.4 Damage Localization

The damage localization method consists of a fusion between a numeric algorithm, and a classification neural network.

For complex structures such as a jacket platform where more than three elements can share the same node, the locations where the damage index exceeds the damage threshold ($DICSD_i > 1$), can only be identified as a suspected damage member. To further narrow down the suspected location of damage, a nodal characterization algorithm, was implemented. The process flow of this algorithm is described in figure 4.1.

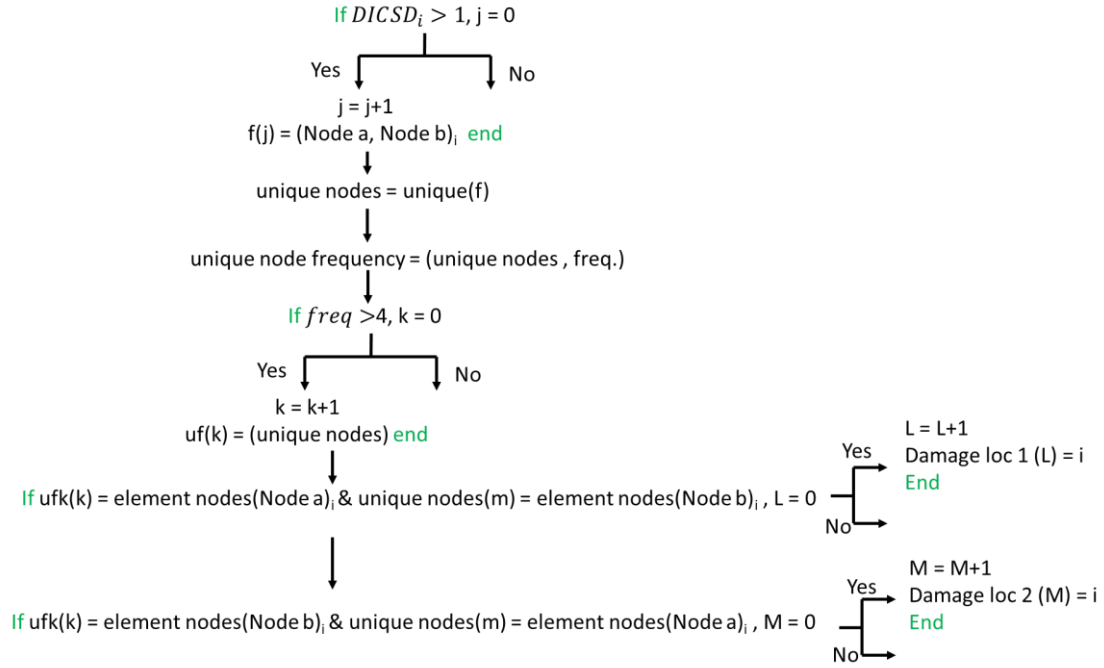


Figure 4-1. Process flow for damage localization scheme

4.4.1 Damage localization: Most likely damaged node

Damage localization begins by grouping nodes on both ends (Node A, Node B) of elements belonging to members of suspected damaged elements $DICSD_i > 1$ in an array. Secondly, the compiled array is sorted to determine the unique nodes, and frequency of each unique node. The frequency of occurrence for each node is determined. If the frequency of a node is greater than the frequency sort threshold, it is placed in a new group of nodes referred to as most likely damaged node. The frequency sort threshold used in this chapter is four. The group of most likely damaged node is used in a for loop to find any element in the group of

suspected damaged elements that contains at least one of the most likely damaged nodes. In the event an element is found to contain a node exceeding the frequency threshold and another node within the nodes of the suspected damaged member, these elements are now classified as the most likely damaged member.

4.4.2 Damage localization: Classification neural network

A classification neural network was trained using the inputs from $DICSD_i$ to classify damage location to specific structural members.

A two-layer feed forward network composed of a sigmoid hidden and output neurons was implemented to classify the inputs from $DICSD_i$ using the “nprtool” in MATLAB [101]. The diagram of the two-layer feed forward network is presented in figure 4.2. In the output layer of this neural network, a sigmoid function is used to limit the output of the target data to its minimum and maximum value. Two-layer feed forward networks have been reported to classify vectors arbitrary, when the numbers of neurons available in its hidden layer is sufficient [102]. The sufficiency of neurons in the hidden layer was assessed based on the performance of the neural network.

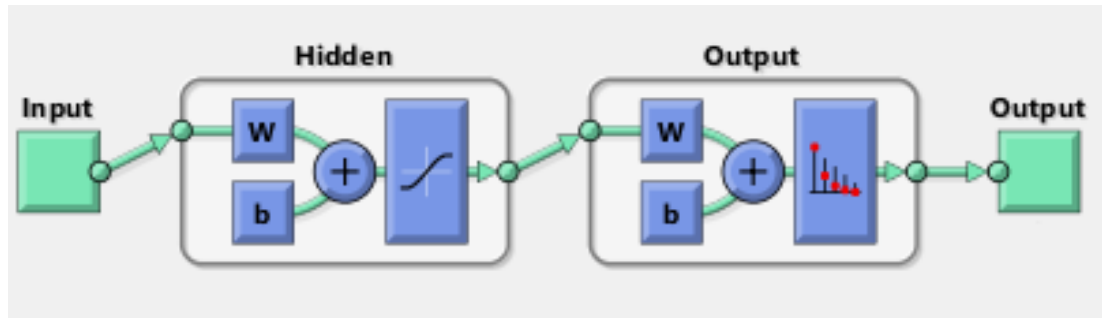


Figure 4-2. Structure of the two-layer feed forward neural network used in this study (MathWorks. 2021).

For validation and testing of the neural network, 70% of the data was used for training, while 15% was used for validation, and 15% for testing. The network is trained using scaled conjugate gradient back propagation, where training is

halted when there is an increase in mean square error of the validation samples [102].

4.5 Damage Assessment

A classification neural network was trained using the inputs from $DICSD_i$ to classify damage location to specific structural members. The target for this neural network were broken down into four damage classes namely very low, low, medium, and high. Very low was set up as a damage class to assess the neural network's ability to properly classify small levels of damage that is quintessential for early detection and asset management decisions. The structure of the neural network is a two-layer feed forward network composed of a sigmoid hidden and output neurons as described in section 4.4. The breakdown of data for training, validation, and testing, as well as when the neural network halts training is the same as in section 4.4.

4.6 Case Study

The improved slope change SHM technique was applied to a Numerical simulation of a fixed offshore jacket platform. SAPOS was implemented as the finite element program used in this numerical simulation. The geometrical properties of the fixed offshore platform as well as the environmental conditions are presented in detail in section 4.5.3. A brief description is given here.

The fixed offshore jacket platform consisted of 118 element members, that make up the legs, vertical bracing, diagonal bracing, horizontal bracing, rigid deck, and piles. The fixed offshore platform extends 12.5 meters above the sea water level, and 50 meters to the seabed. The piles extend 25 meters into the seabed. Steel is used as the material for all elements in the structure, the mass of the deck is set at 4,800 tonnes.

Environmental and operational loads presented in Table 4.3 were applied to the fixed offshore platform and its dynamic modal response was recorded. The first three mode shapes of the fixed offshore platform were recorded along with the

corresponding eigen values. The eigen vector for the end node on each element on the fixed offshore platform was also recorded.

Four levels of damage severity were simulated, namely, very low, low, medium, and High. The corresponding reduction in stiffness for each damage class is presented in table 4.1. For each damage class at least two levels of damage severity that fall within each class was simulated.

Table 4-1. Damage severity class and their corresponding element stiffness reduction

Severity Class	Damage Level in Element
Very Low	Stiffness Reduction $\leq 3\%$
Low	$3\% < \text{Stiffness Reduction} < 10\%$
Medium	$10\% < \text{Stiffness Reduction} \leq 15\%$
High	$15\% < \text{Stiffness Reduction} \leq 50\%$

Damage was simulated on eight different members of the fixed offshore platform as follows: 2 members from the platform legs, 2 members from the vertical bracing, 2 members from the diagonal bracing, and 2 members from the vertical bracing.

Results from the finite element simulation were imported into MATLAB where the improved slope change SHM technique was used to detect, localize and assess damage for all damage scenarios simulated.

4.7 Results

The first three modes shapes of the fixed offshore platform were comprised of the first bending mode shape in the x direction, the first bending mode shape in the y direction, and the first torsional mode shape. The eigen vectors corresponding to each element in the structure was recorded for each mode shape and sent to the SHM program. The mode shape of the fixed offshore jacket can be seen in figure 4.3.1. The damage cumulative slope index for all levels of damage

simulated was observed to display more than one element with a value greater than one. This occurrence satisfied the detection of damage when damage was present in the fixed offshore platform.

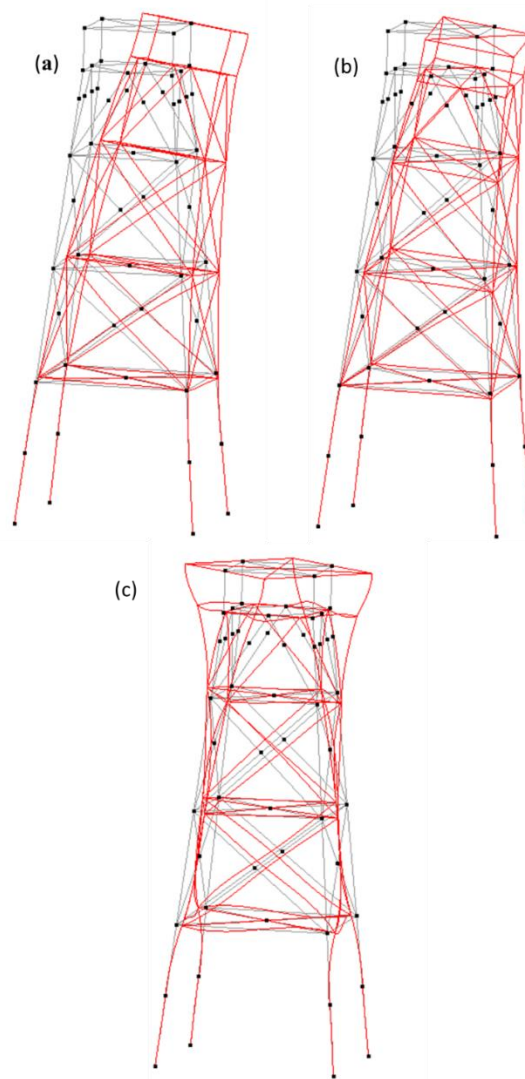


Figure 4-3-1. The first three mode shapes of the fixed offshore platform used in the numerical simulation. 1st bending mode shape in (a) x direction (b) y direction. (c) 1st torsional mode shape.

The $DICSD_i$ index for element 76, when very low damage is given in figure 4.3.2 The vertical dashed line represents the damage threshold. The hit miss technique was implemented to create the probability of detection for all simulated damage

scenarios. The value of POD was constant across all damage scenarios with a value of 1.

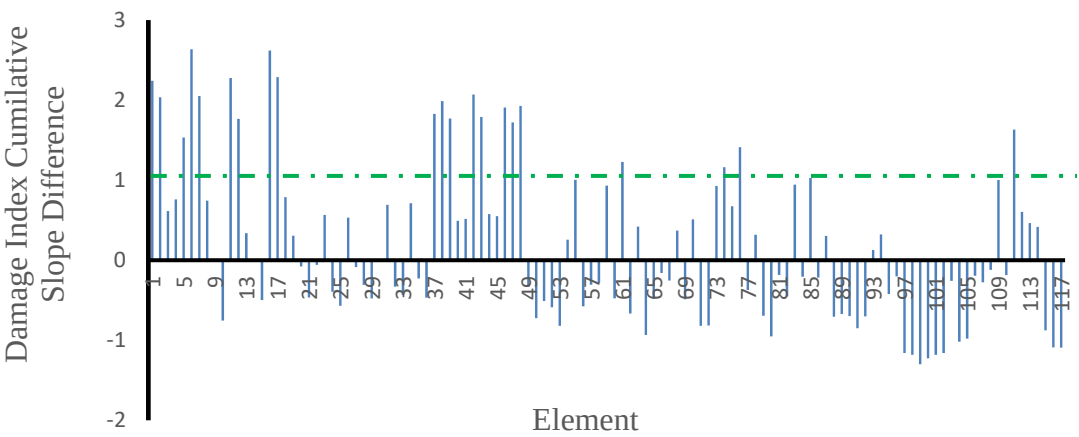


Figure 4-3-2. The damage cumulative slope index for element 76 at very low damage severity. Calculated using equation 4-12.

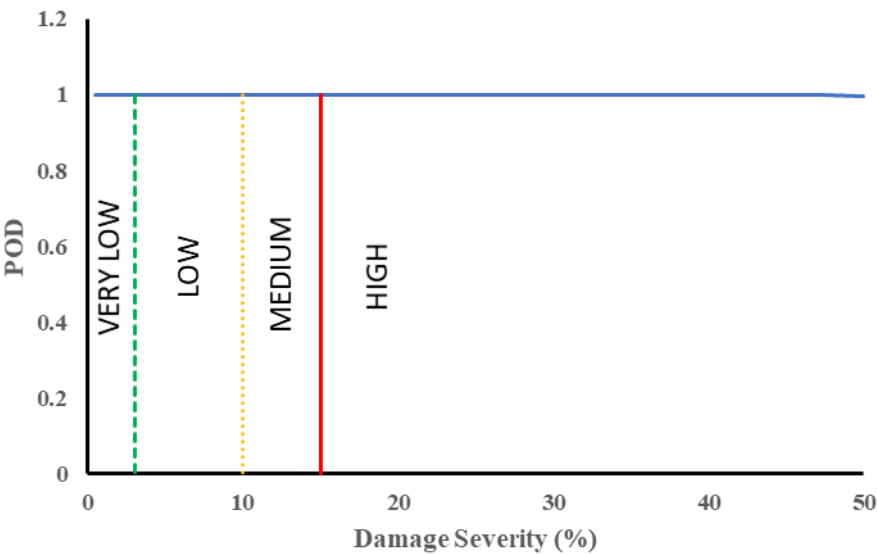


Figure 4-4. The probability of detection curve for the damage cumulative slope index for all levels of damage simulated. Vertical lines on graph delineate regions of classified damage severity used in the neural network.

The plot indicates element 76 along with 20 additional elements are part of the suspected damage members. The application of the damage localization algorithm described in section 4.4.1, was unable to provide a most likely damage

member from the suspected damage member. Further examination of the performance of the damage localization algorithm provided in section 4.4.1 indicated its performance was affected by the type of element in which damage occurred. For instance, damage on diagonal bracing members did not result in an outcome of the most likely damaged member. Outside of diagonal bracing members, the most likely damaged member was reported for all damage elements simulated. The accuracy of the most likely damaged member containing the element member where damage was simulated was used to create the probability of accurate localization PAOL as seen in figure 4.5. The value of POAL is observed to increase with damage severity. The value of POAL increases from 0.29 to 0.53 as damage severity increases from very low to high.

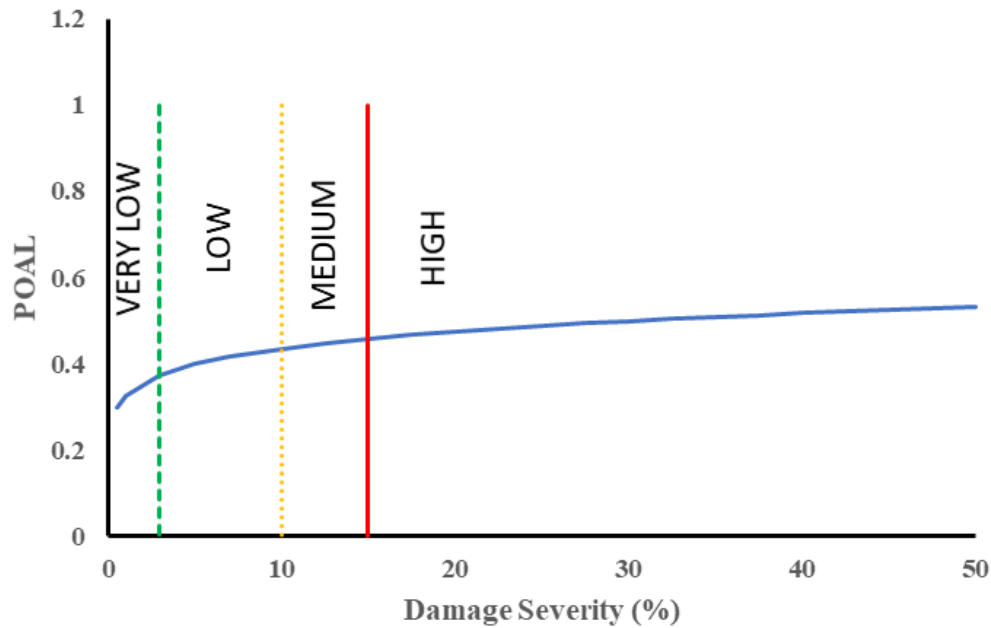


Figure 4-5. The probability of accurate localization curve for the damage cumulative slope index for all levels of damage simulated using the technique described in section 4.4.1. Vertical lines on graph delineate regions of classified damage severity used in the neural network.

The two-layer feed forward network used to localize damage was given 30 neurons in the hidden layers and trained to localize all damage severity levels with a target output of eight corresponding to the eight members where damage

was simulated. Training was halted after 36 iterations. The confusion matrix attained from the neural network was segmented into training, validation, and test as seen in figure 4.8. The overall confusion matrix displayed a classification accuracy of 97.5%. The receiver operating characteristic plot as seen in figure 4.7, displays the rate of true positive and false positive from the training, validation, and test data from the neural network, where two cases of false positive was observed.

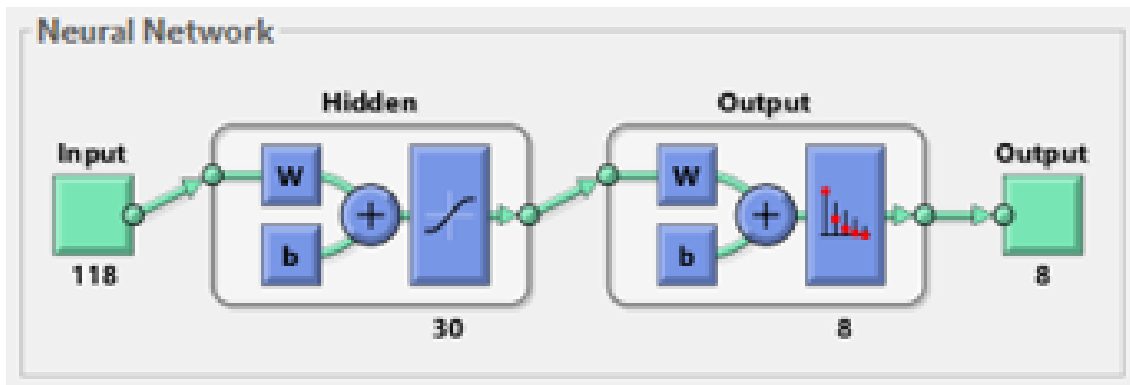


Figure 4-6. The two-layer feed forward network used in damage localization with inputs from the damage cumulative slope index.

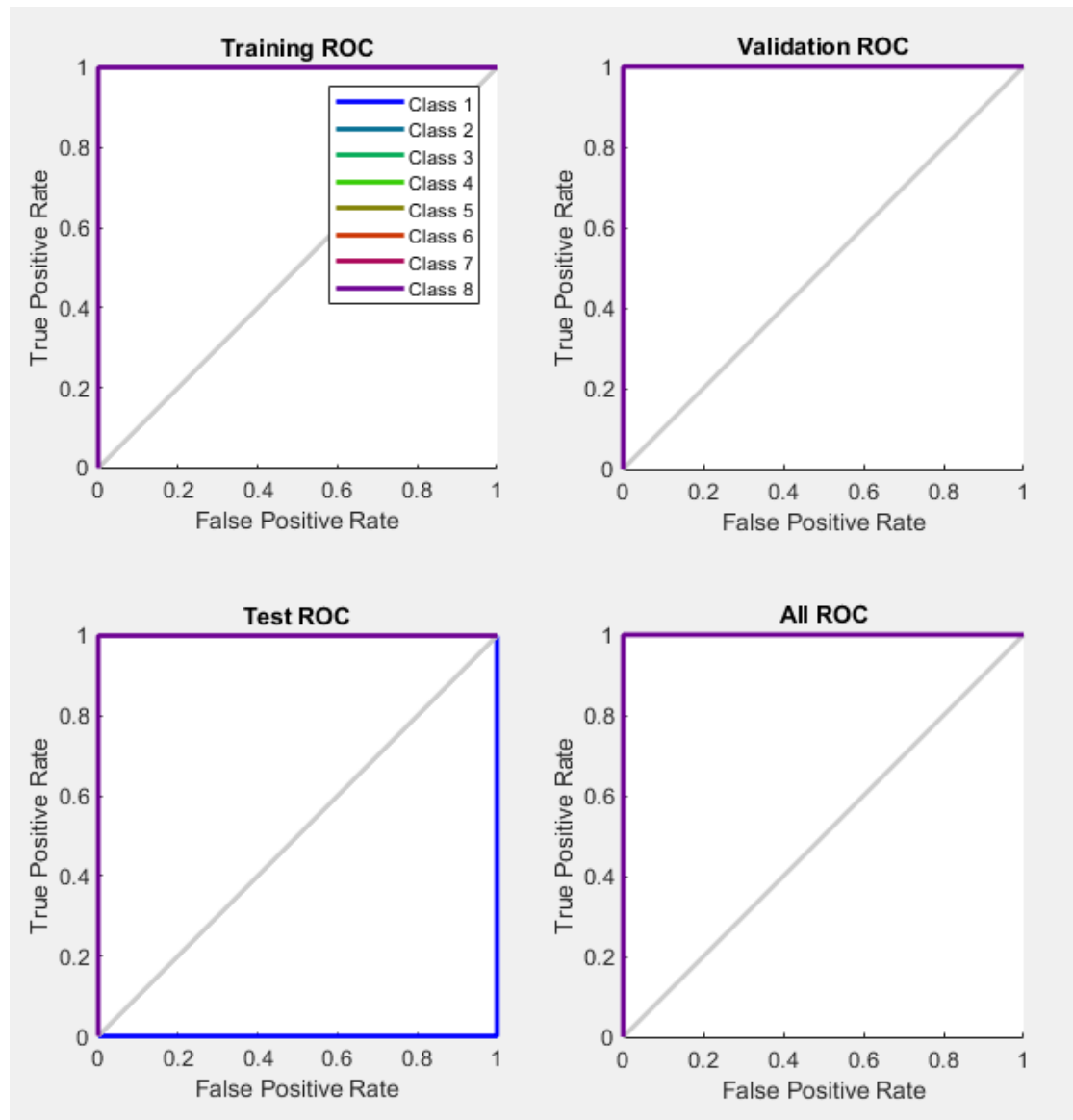


Figure 4-7. The receiver operating characteristics of two-layer feed forward network used in damage localization.

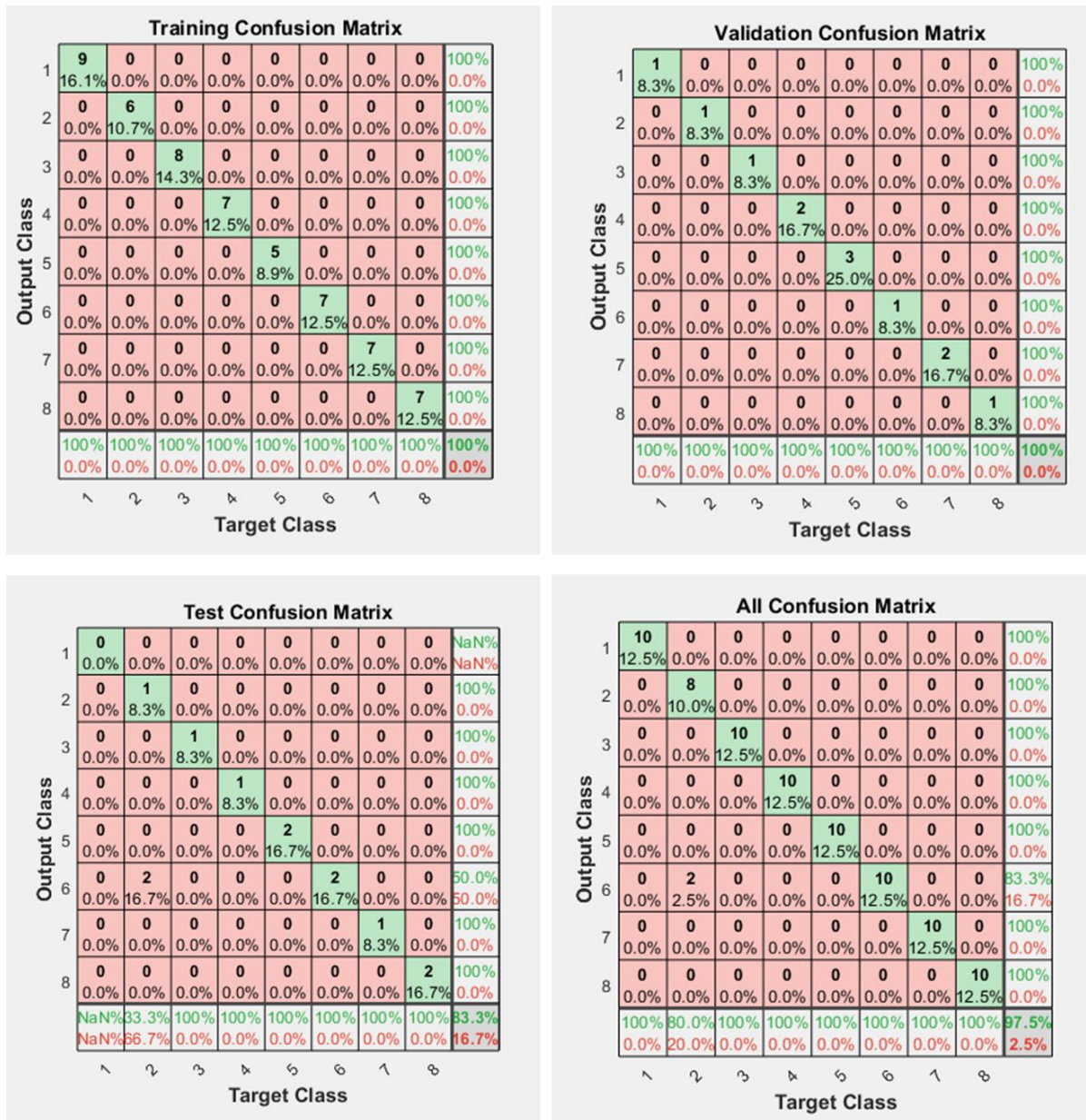


Figure 4-8. The confusion matrix of two-layer feed forward network used in damage localization.

The probability of accurate localization attained from the two-layer feed forward network displayed a constant value of 1 across all levels of damage classification, when the trained network was used to predict the damage location in the SHM program.

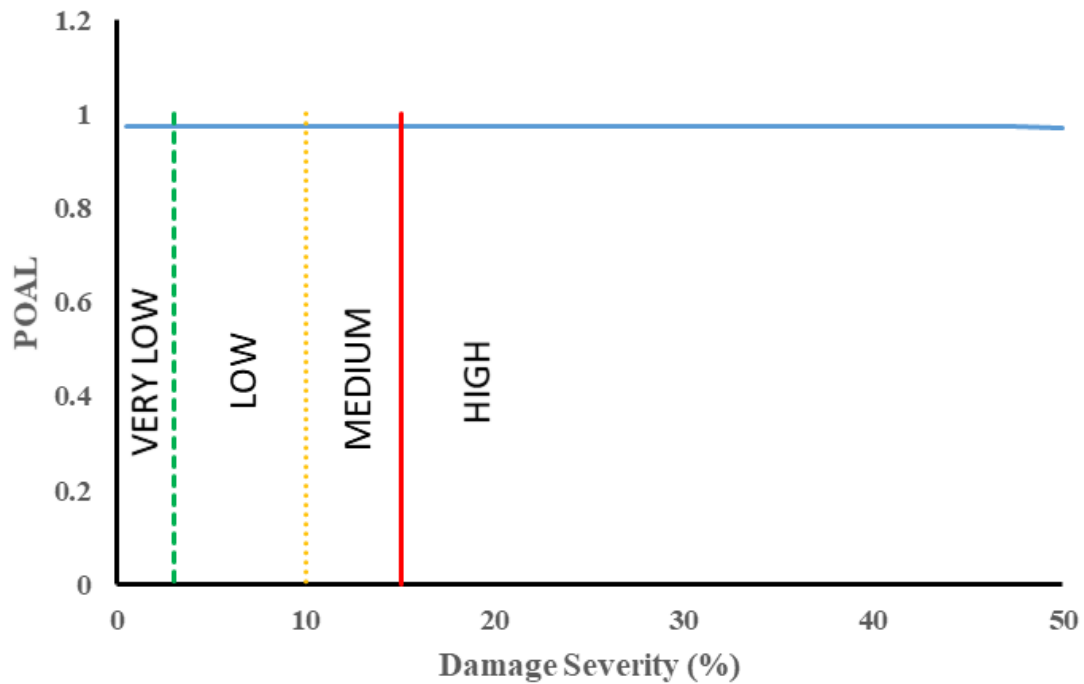


Figure 4-9. The probability of accurate localization curve for the damage cumulative slope index for all levels of damage simulated using the two-layer feed forward network used in damage localization. Vertical lines on graph delineate regions of classified damage severity used in the neural network.

The two-layer feed forward network used to assess the severity of damage was given 10 neurons in the hidden layers and trained to assess all four levels of damage severity levels with a corresponding target output of four. Training was halted after 48 iterations, where a cross-entropy validation performance value of 0.0620 attained (see fig. 4.10). The confusion matrix attained from the neural network was segmented into training, validation, and test as seen in figure 4.11. The overall confusion matrix displayed a classification accuracy of 93.8%. The receiver operating characteristic plot as seen in figure 4.12, displays the rate of true positive and false positive from the training, validation, and test data from the neural network, where five cases of false positive was observed.

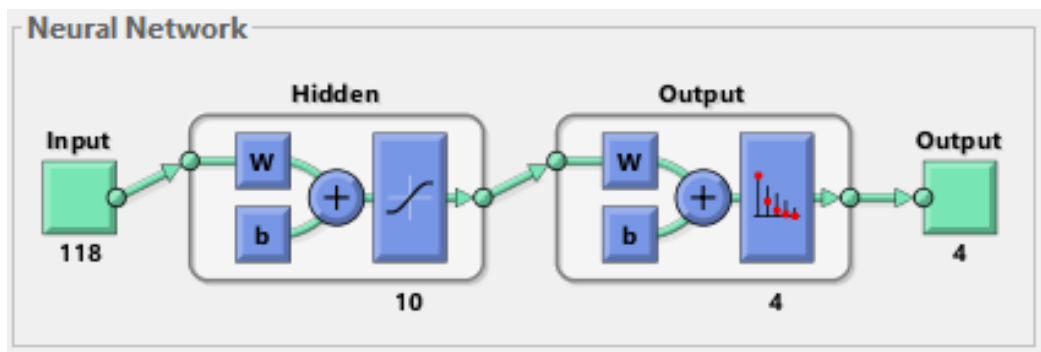


Figure 4-10-1. The two-layer feed forward network used in damage assessment with inputs from the damage cumulative slope index.

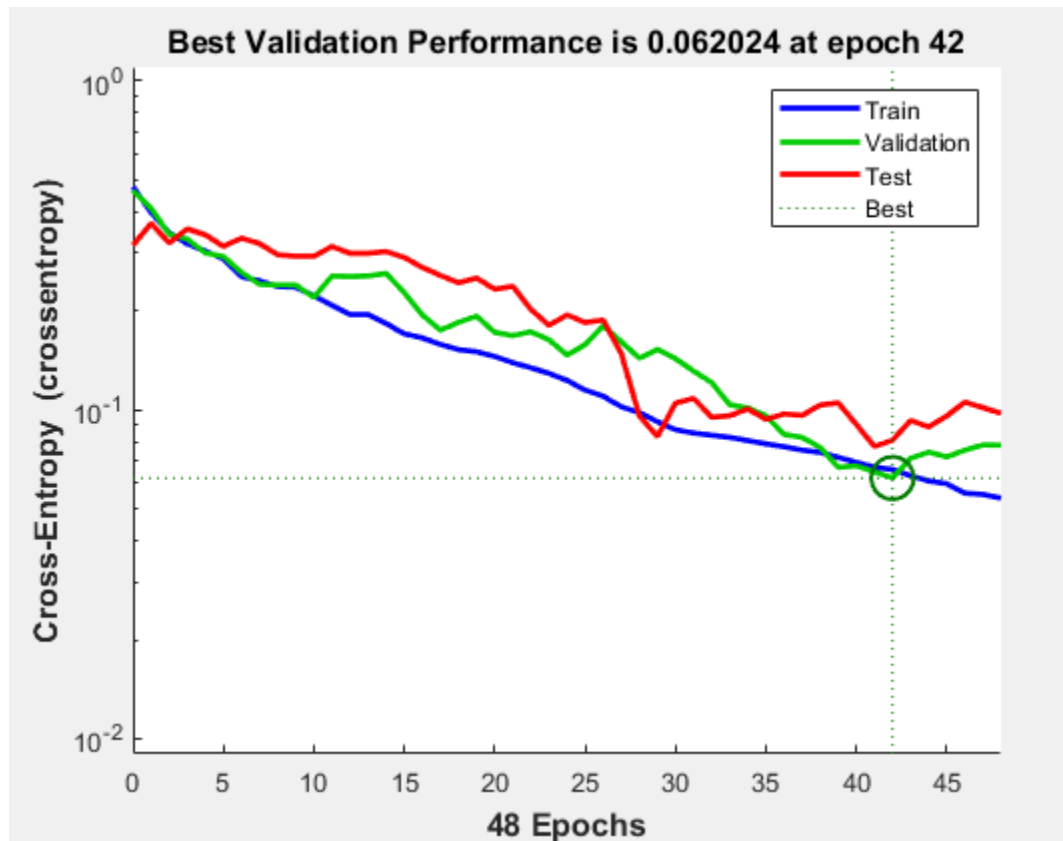


Figure 4-10-2. The variation in cross-entropy of two-layer feed forward network used in damage assessment, displaying the number of training iterations and the best validation performance point at the 42nd iteration.



Figure 4-11. The confusion matrix of two-layer feed forward network used in damage assessment.

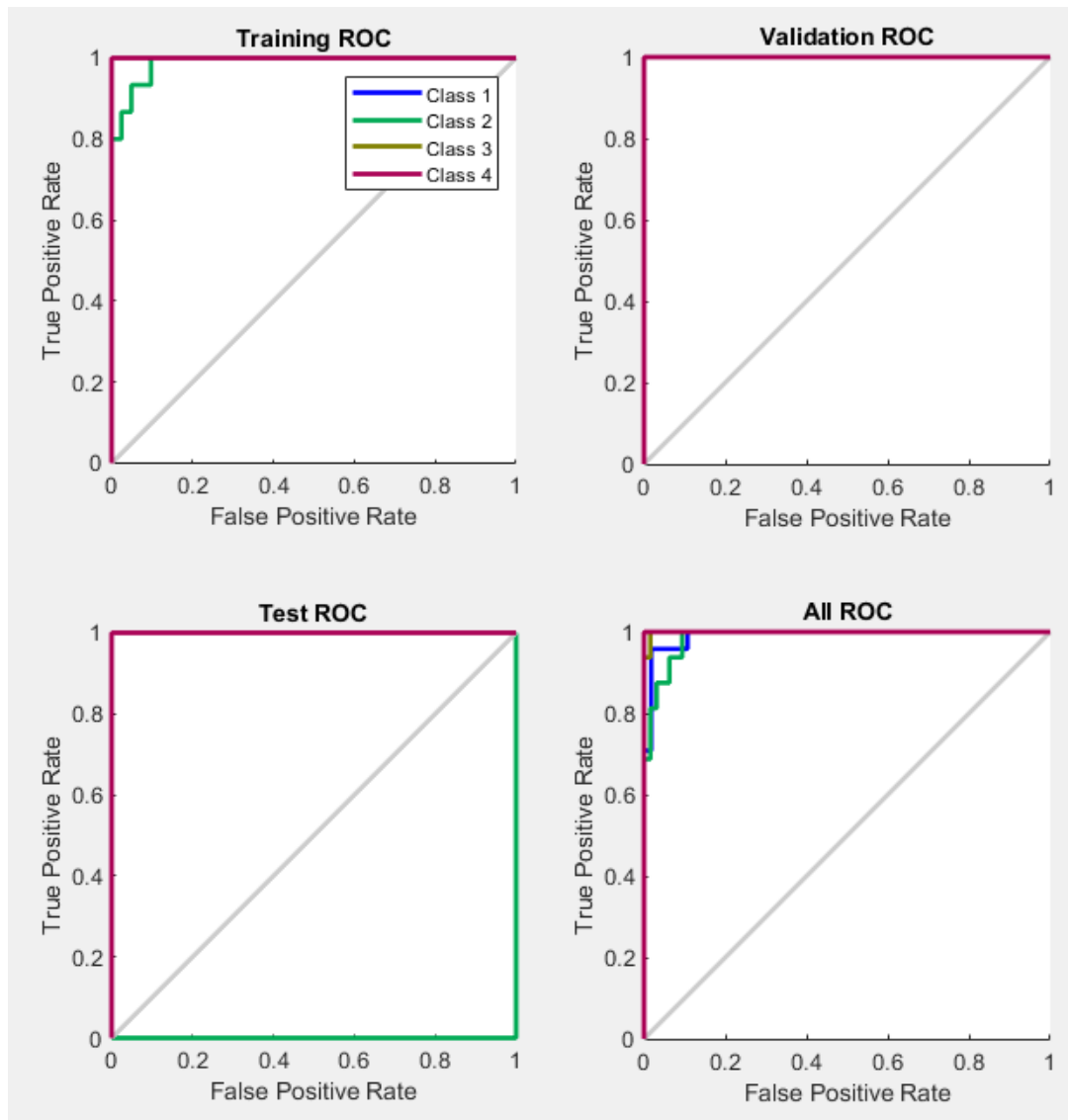


Figure 4-12. The receiver operating characteristics of two-layer feed forward network used in damage assessment.

The probability of accurate assessment attained from the two-layer feed forward network displayed an increase with increasing level of damage severity. Its initial value of 0.9 was displayed at very low damage severity, and it gradually increased to 1 at High damage severity level. The false identification of damage severity occurred in the classification of very low and low damage.

The actual damage severity for very low corresponds to a reduction of stiffness by 3% or less, when the damage severity was 1% or below, the predicted damage severity displayed an accuracy level of 100%. However, when the damage accuracy was closer to 3% the predicted damage severity varied between very low and low where the accuracy level was greater than 90%. A similar observation was made in scenarios where the actual damage in the structure was low, the predicted damage assessment had an accuracy level greater than 90%, and all false identifications were classified as very low.

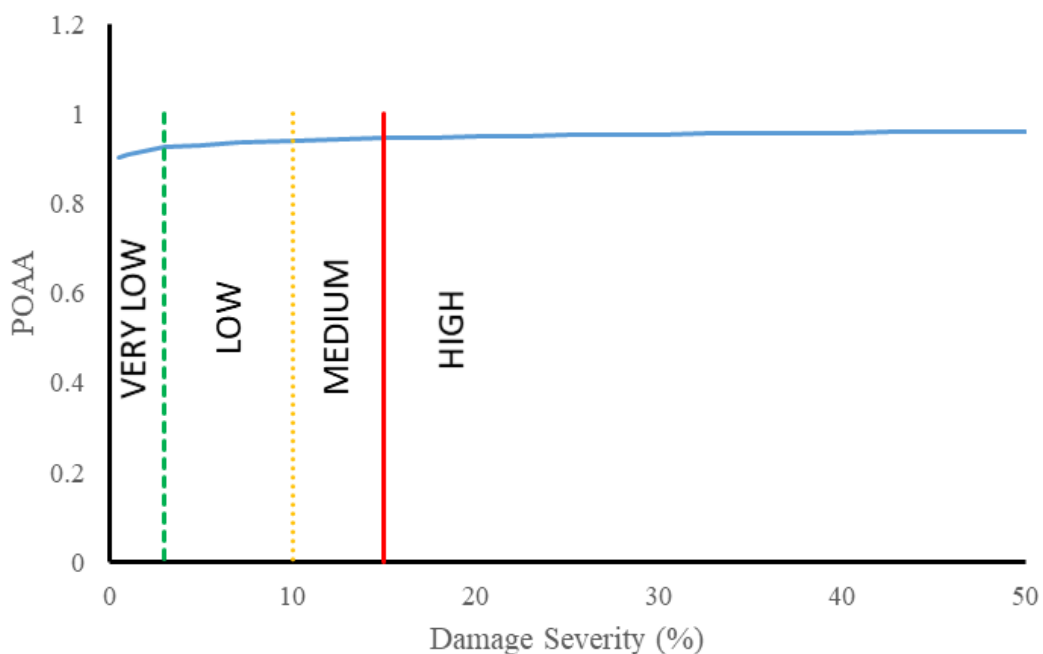


Figure 4-13. The probability of accurate assessment curve for the damage cumulative slope index for all levels of damage simulated using the two-layer feed forward network used in damage assessment. Vertical lines on graph delineate regions of classified damage severity used in the neural network.

4.8 Summary

In this chapter, a new SHM technique was proposed for jacket structures under the vibration based SHM criteria, where the change in slope of the eigen vectors attained from its modal behaviour is used to generate damage sensitive features that are capable of detecting, localizing, and assessing damage severity when coupled with a trained two-layered feed forward neural network.

The key developments in this chapter include:

- A new damage indicator called the damage index cumulative slope difference (DICSD) was used to infer the presence of damage in jacket structures. The values of DICSD are fed into a two-layered feed forward neural network. Two unique two-layered feed forward neural networks are used in this SHM technique, as one network is trained to localize damage in the jacket platform and the other is trained to assess the severity of damage in the jacket platform. The trained neural network classifies damage severity into four criteria: very low, low, medium, and high.
 - The damage index cumulative slope difference (DICSD) was proposed as vibration based SHM technique as it does not require an explicit physics-based model to localize or assess the severity of damage. It is a data driven model that can extend a simplified method of damage detection to damage localization, and damage severity assessment.
 - The proposed SHM technique was tested using numerical finite element model of a fixed offshore jacket platform, loaded with operational and environment loads. Eighty damage scenarios were simulated across eight different member elements of the fixed offshore platform. The attained eigen vectors were fed into the proposed SHM technique.
 - The outcome from the proposed SHM technique was used to calculate the probability performance functions of a SHM system. This includes the commonly used probability of detection POD, and

the two new probability function proposed in chapter four of this thesis, namely the probability of accurate localization POAL, and the probability of accurate assessment POAA.

- The proposal of POAL and POAA as performance metrics for SHM systems is an extension of POD beyond damage detection to damage localization, and damage assessments.

5 Combination of Multiple SHM methods to Improve Reliability Assessment of the Monitored Structure.

5.1 Introduction

In this chapter the reliability of a monitored structure was assessed by combining multiple SHM systems, with the aim of generating an increase in the reliability associated with the SHM predicted outcome. This chapter builds on the SHM reliability framework presented in chapter 4, where the reliability of Damage detection, conditional reliability of damage localization, conditional reliability of damage assessment, and the conditional fatigue reliability of the monitored structure were assessed.

The framework given in chapter 4 is expanded to account for the use of Multiple SHM techniques on the same monitored structure. A numerical case study is conducted using the proposed framework to calculate the improved reliability predicted for the monitored structure which is a fixed offshore platform under fatigue damage. This case study illustrates the level of reliability associated with SHM performance when multiple SHM techniques are used to monitor a single structure for fatigue damage [13][53][14][41]. The predicted fatigue reliability attained from the combining multiple SHM methods is compared to the results obtained from a single SHM technique. Furthermore, the fatigue reliability associated with the simulated damage is also calculated and implemented as the benchmark for reliability performance.

5.2 Fusion of Multiple SHM Techniques

The fusion of outcomes from multiple SHM techniques monitoring the same structure is conducted by combining the reliabilities associated with each outcome of the SHM system. For a SHM technique capable of damage detection, damage localization, damage, assessment, and remaining useful life predictions, the reliability associated with each level of the SHM outcome is combined as a system in parallel.

The reliability of damage detection R_{DD} for a single SHM system is a function of its damage index D_d , damage detection threshold D_{th} , uncertainties associated with the sensor measurement ε_1 , signal processing ε_2 , and damage detection ε_3 technique. These five variables are used to generate equation 4-19, in chapter 4, which was used to calculate the reliability associated with damage detection. The fusion of reliability for damage detection using multiple SHM techniques is conducted as system in parallel, thus the total reliability of damage detection from all SHM techniques is given as

$$Total R_{DD} = 1 - \sum_{j=1}^n (1 - R_{DD,SHM_j}) \quad (5-1)$$

The subscript j represents the number of SHM techniques employed in monitoring a structure.

The conditional reliability of damage localization given damage was detected $R_{DL}|R_{DD}$ and discussed and presented in chapter 4. Modifications were made to the reliability of damage localization. The centre point of a structure member was selected as the point of damage localization for each member. The predicted damage location (PDL), and true damage location (TDL) were then implemented to calculate the magnitude between these two points. The allowable localization tolerance ALT was implemented to create a spherical region of tolerance for damage localization.

$$R_{DL} = 1 - P(\psi_{DL}(ALT - |\overline{PDL}, \overline{TDL}| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 < 0)) \quad (5-2a)$$

$$R_{DL}|R_{DD} = 1 - \frac{P[\psi_{DL}(ALT - |\overline{PDL}, \overline{TDL}| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 < 0) \cap \psi_{DD}(D_d + \varepsilon_1 + \varepsilon_2 + \varepsilon_3 - D_{th} < 0)]}{P[\psi_{DD}(D_d + \varepsilon_1 + \varepsilon_2 + \varepsilon_3 - D_{th} < 0)]} \quad (5-2b)$$

The fusion of conditional reliability of damage localization given damage detection is conducted based on each element member in the monitored structure. The localized fusion of $R_{DL}|R_{DD}$ to attain the total $R_{DL}|R_{DD}$ was conducted as a system in parallel as described in equation 5.3.

$$Total R_{DL}|R_{DD} = \sum_{k=i}^m \left[1 - \sum_{j=1}^n (1 - [R_{DL}|R_{DD}]_{k,SHM_j}) \right] \quad (5-3)$$

The subscript k represents the number of elements members present in the monitored structure, while subscript j represents the number of SHM techniques used in the SHM system.

The conditional reliability for damage assessment given damage was located and detected $R_{DA}|R_{DL}|R_{DD}$ are also combined on a localized basis when attained from a SHM system with multiple damage assessment techniques. It is worthy of note that $R_{DA}|R_{DL}|R_{DD}$ can be calculated using equation 4-22 from chapter 4. In this chapter, modifications were made to the limit state function used in 4-22 as follows; the points for predicted damage severity (PDS) and actual damage severity (ADS) were adopted to calculate the distance between the two points. The damage severity tolerance was implemented to assess if the error in prediction was within the acceptable range of damage severity.

$$R_{DA} = 1 - P(\psi_{DA}(DST - |\overline{PDS}, \overline{ADS}| + \varepsilon_1 + \varepsilon_2 + \varepsilon_5 < 0)) \quad (5-4a)$$

$$R_{DA}|R_{DL}|R_{DD} = 1 - \frac{P[\psi_{DL}(DST - |\overline{PDS}, \overline{ADS}| + \varepsilon_1 + \varepsilon_2 + \varepsilon_5 < 0) \cap \psi_{DL}(ALT - |\overline{PDL}, \overline{TDL}| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 < 0) \cap \psi_{DD}(D_d + \varepsilon_1 + \varepsilon_2 + \varepsilon_2 - D_{th} < 0)]}{P[\psi_{DL}(ALT - |\overline{PDL}, \overline{TDL}| + \varepsilon_1 + \varepsilon_2 + \varepsilon_4 < 0) \cap \psi_{DD}(D_d + \varepsilon_1 + \varepsilon_2 + \varepsilon_2 - D_{th} < 0)]} \quad (5-4b)$$

The total value of $R_{DA}|R_{DL}|R_{DD}$ across all SHM techniques can be calculated as

$$Total R_{DA}|R_{DL}|R_{DD} = \sum_{k=i}^m \left[1 - \sum_{j=1}^n (1 - [R_{DA}|R_{DL}|R_{DD}]_{k,SHM_j}) \right] \quad (5-5)$$

Subscript k represents the represents the number of SHM techniques used in the SHM system. Subscript j represents the number of elements members present in the monitored structure.

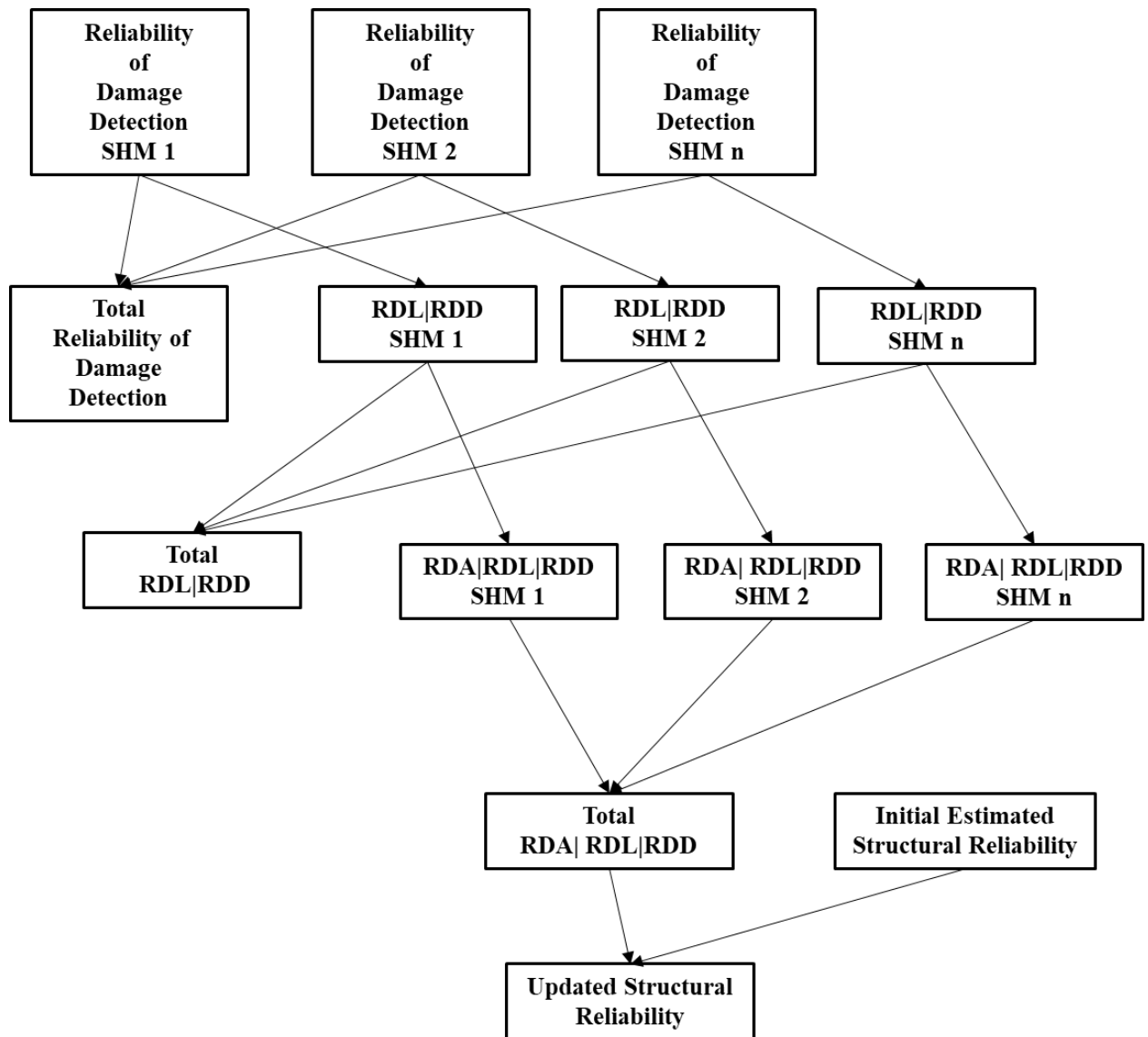


Figure 5-1. Network of Reliability fusion for a SHM system with multiple SHM techniques.

5.3 Numerical Application of Multiple SHM Technique Fusion to Improve Reliability

The proposed multiple technique SHM fusion methodology was applied to a numerical study, where a fixed offshore platform was selected as the monitored

energy structure. The details of the fixed offshore platform and loading conditions were previously provided in chapters 4 and 5.

5.3.1 Damage Simulation

Damage was simulated on eight different members of the fixed offshore platform as follows: two members from the platform legs, two members from the vertical bracing, two members from the diagonal bracing, and two members from the vertical bracing.

Results from the finite element simulation were imported into MATLAB where uncertainties were added as noise to the mode shapes, and eigen values [102]. A value of 0.1% noise, and a random number Ω described by a normal distribution with unit variance and zero mean was used to add noise to the mode shapes and eigen vectors [84][62].

5.3.2 SHM Techniques

Two Vibration based SHM techniques were deployed to monitor the fixed offshore platform. The first SHM technique employed was the modal strain energy; the modal strain energy damage index presented in equation 3-9 was used for damage detection, and damage localization[74][84]. Cross modal strain energy [76] method was implemented to estimate the severity of damage in the structure using 3-10, and 3-11.

The second SHM technique implemented to monitor the fixed offshore platform was the damage index cumulative slope difference DICSM, which was previously presented in chapter 4. The DICSM index was used to infer the presence of damage in the structure. Two trained two-layer feed forward network presented in chapter 4 were implemented to localize damage and predict the severity of damage [102].

5.3.3 Probability Performance Functions

The performance probabilities associated with each SHM performance such as the Probability of detection POD, probability of accurate localization POAL, probability of accurate assessment POAA, were calculated using equations 3-2,

3-5, and 3-6 respectively. The conditional probabilities associated with damage localization given damage was detected, $POAL|POD$, and the probability of damage assessment given damage was localized and detected $POAA|POAL|POD$ was calculated using equation 3-17, and 3-18.

5.3.4 Reliability Performance Functions

Reliability performance functions such as the reliability of damage detection R_{DD} , reliability of damage localization R_{DL} and reliability of damage assessment R_{DA} were calculated using equation 3-19, 5-2 and 5-4 respectively. Conditional reliabilities of the SHM system which include the reliability of localization given damage was detected (SHM level 2), and the reliability of damage assessment given damage was localized and detected were calculated using equation 5-2b and 5-4b respectively.

5.3.5 Fatigue Analysis

Fracture mechanics was used to calculate the fatigue reliability of the fixed offshore platform for the simulated levels of damage severity. Paris equation was used to model the fatigue limit state, with the use of parameters that include crack size (a_0 , a_T), stress cycles per time period ω , time period T , geometry Y , materials fatigue parameters (C , m). Stress range was expressed as a function of the Weibull scale A , and shape B , while Γ is a gamma function [67][68][80].

The initial fatigue reliability, and updated fatigue reliability of the fixed offshore platform member with damage was calculated using equations 4-24 to 4-31. The translation of damage severity to crack length was conducted according to the transformation presented in section 4.5.3 of chapter 4.

The variables associated with SHM reliability and fatigue reliability are given in table 5.1. A detailed description of these variables, and their distributions can be found in chapter 4 of this work. Variables not addressed in chapter 4 are presented as follows.

Table 5-1. Description of variables in SHM limit state functions and reliability assessment

Variable	Distribution	Mean	COV
Young's Modulus (GPa)	Normal	203.39	0.006
DST	Normal	0.5*ADS	0.2
ALT	Normal	30	0.33
$D_{th\ SHM\ 1}$	Normal	0.1	0.1
$D_{th\ SHM\ 2}$	Normal	1	0.1
Poisson's Ratio	Fixed	0.3	
Ψ_{DD}	Fixed	1	
Ψ_{DL}	Fixed	1	
Ψ_{DA}	Fixed	1	
a_0 (mm)	Exponential	0.1	
a_T (mm)	Normal	125	0.1
$\ln C$	Normal	-29.97	0.014
A	Fixed	11.47	
B	Fixed	1.22	
ω (cycles/ yr.)	Fixed	6×10^6	
Y	Fixed	1	
m	Fixed	3.1	

For the DICSM SHM technique, the prediction of damage severity is not a single value, rather the classification provides a maximum and minimum value for the predicted damage severity. The distribution of predicted crack size a_T from the trained two-layer feed forward network used in this study was assumed to be normally disturbed between the maximum and minimum boundaries of crack size.

5.4 Results and Discussions

5.4.1 SHM reliability of the damage index cumulative slope difference (DICSD) technique

The reliability of damage detection for the curvature change method across the four levels of damage severity: very low, low, medium, and high displayed a constant value of one as the DICSD method was able to identify the presence of damage across all damage severity levels as seen in figure 5.2a.

The reliability of damage localization given the detection of damage was observed to increase with increasing damage severity. For each level of damage severity, the values of $|\overline{PDL}, \overline{TDL}|$ were calculated for each damage case, after which the dataset was fit to a distribution. Gamma distribution was observed to display the best fit for very low, low and medium damage severity. A fixed value was used for high damage as there was no variation in the value of $|\overline{PDL}, \overline{TDL}|$.

When the damage present in the system was in the very low category, the value for $R_{DL}|R_{DD}$ was 0.9859. At low and medium damage severity, the DICSD method displayed values of $R_{DL}|R_{DD}$ as 0.992 and 0.998 respectively (see figure 5.2b). At the high damage severity category, $R_{DL}|R_{DD}$ was calculated as one.

The reliability of damage assessment given damage was localized and assessed was observed to display dependence on damage severity level. For each level of damage severity, the values of $|\overline{PDS}, \overline{ADS}|$ were calculated for each damage case, after which the dataset was fit to a distribution. Gamma distribution was observed to display the best fit for all damage severity levels.

At high damage severity the value of $R_{DA}|R_{DL}|R_{DD}$ was 0.874. For medium and low damage severities, the values of $R_{DA}|R_{DL}|R_{DD}$ were 0.804 and 0.831 respectively. At very low damage severity, a value of 0.545 was attained for $R_{DA}|R_{DL}|R_{DD}$.

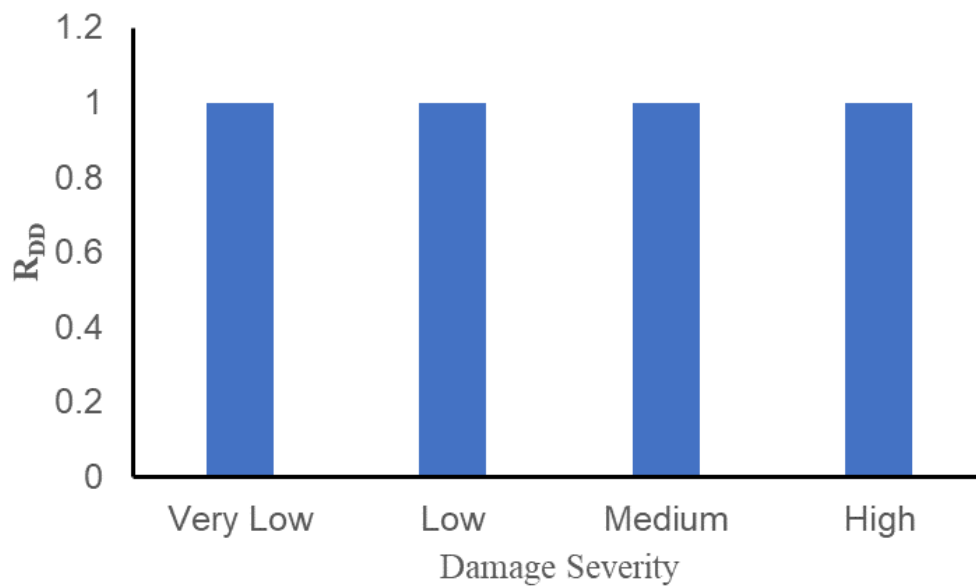


Figure 5-2a. Reliability of damage detection for the damage index cumulative slope difference (DICSD) SHM technique at varying damage severity. Calculated using equation 5-1.

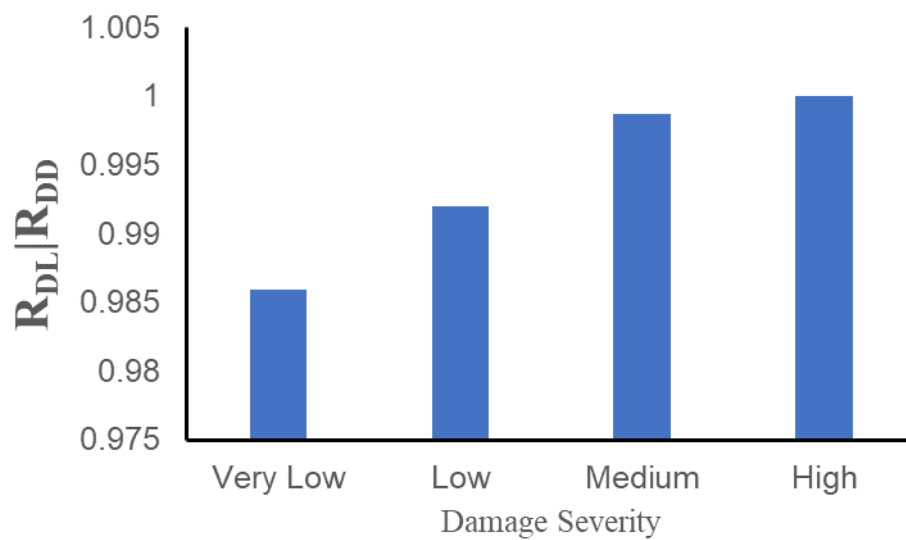


Figure 5-2 b. Reliability of localization given damage detection ($R_{DL|R_{DD}}$) for the damage index cumulative slope difference (DICSD) SHM technique at varying damage severity. Calculated using equation 5-3.

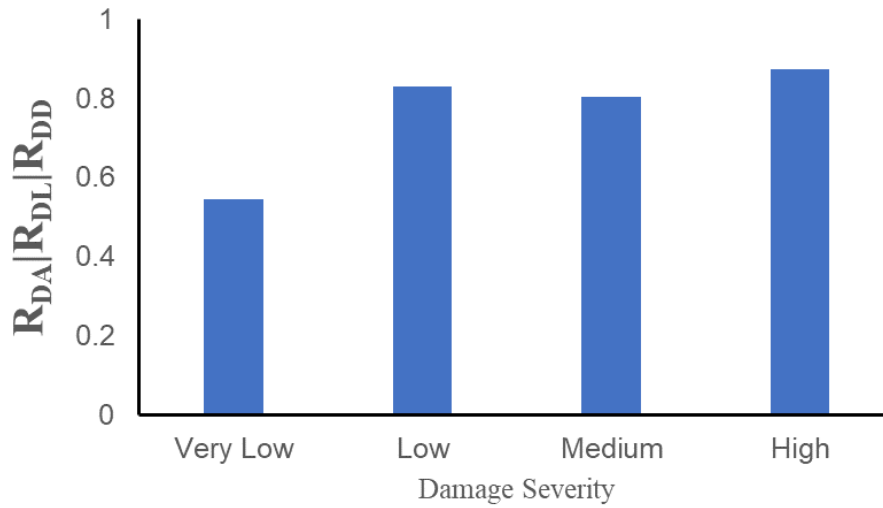


Figure 5-2c. Reliability of damage assessment given damage localization and damage detection ($R_{DA} | R_{DL} | R_{DD}$) for the damage index cumulative slope difference (DICSD) SHM technique at varying damage severity. Calculated using equation 5-4 and 5-5.

Table 5-2a. SHM variable parameters for damage localization and assessment attained from damage index cumulative slope difference (DICSD) SHM technique.

	Distribution	α	β
$ \overline{PDL}, \overline{TDL} $ very low	Gamma	0.249	11.765
$ \overline{PDL}, \overline{TDL} $ low	Gamma	0.134	12.030
$ \overline{PDL}, \overline{TDL} $ medium	Gamma	0.134	12.030
$ \overline{PDL}, \overline{TDL} $ high	Fixed	0	
$ \overline{PDS}, \overline{ADS} $ very low	Gamma	0.140	53.217
$ \overline{PDS}, \overline{ADS} $ low	Gamma	0.07587	81.545
$ \overline{PDS}, \overline{ADS} $ medium	Gamma	0.4248	70.177
$ \overline{PDS}, \overline{ADS} $ high	Gamma	0.251	809.029

5.4.2 SHM reliability of the modal strain energy technique

The reliability of damage detection for the modal strain energy technique was observed to be independent of the level of damage present in the structure. The value of R_{DD} ranged from 0.512 to 0.539 from very low to high damage severity as seen in figure 5.3a.

The reliability of damage assessment given the reliability of damage detection was also observed to be independent of damage severity level. For each level of damage severity simulated, the values of $|\overline{PDL}, \overline{TDL}|$ were calculated for each damage case, after which the dataset was fit to a distribution. Normal distribution was observed to display the best fit for all damage severity levels. The value of $R_{DL}|R_{DD}$ was observed to range from 0.256 to 0.269 from very low to high damage severity as seen in figure 5.3b.

The reliability of damage assessment given damage was localized and detected was also observed to be independent of damage severity levels. For each level of damage severity, the values of $|\overline{PDS}, \overline{ADS}|$ were calculated for each damage case, after which the dataset was fit to a distribution. Normal was observed to display the best fit for all damage severity levels. Across very low, low, medium and high damage severity the value of $R_{DA}|R_{DL}|R_{DD}$ ranged from 0.128 to 0.134 as depicted in figure 5.3c.

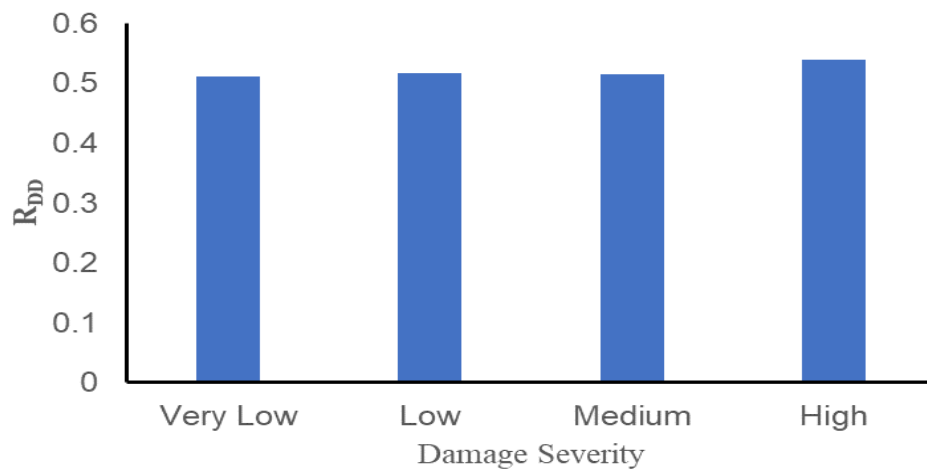


Figure 5-3a. Reliability of damage detection RDD for the modal strain energy SHM technique at varying damage severity. Calculated using equation 5-1.

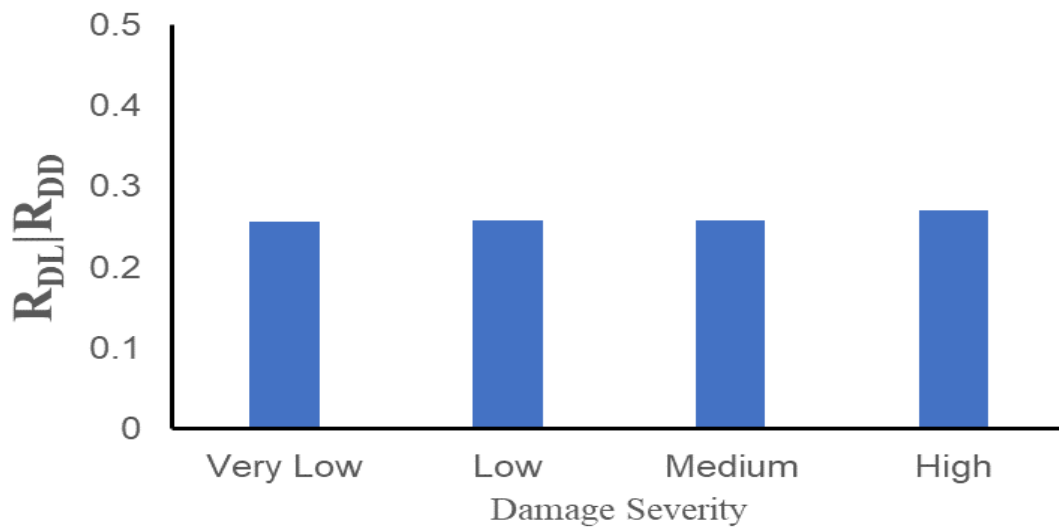


Figure 5-3b. Reliability of localization given damage detection ($R_{DL|R_{DD}}$) for the modal strain energy SHM technique at varying damage severity. Calculated using equation 5-2.

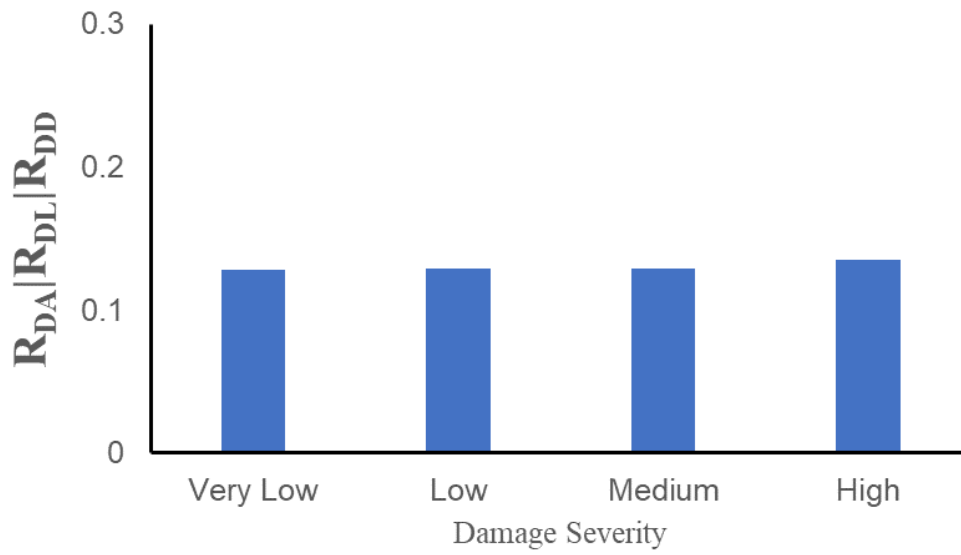


Figure 5-3c. Reliability of damage assessment given damage localization and damage detection ($R_{DA} | R_{DL} | R_{DD}$) for the modal strain energy SHM technique at varying damage severity. Calculated using equation 5-4.

Table 5-3b. SHM variable parameters for damage localization and assessment attained from modal strain energy SHM technique SHM technique.

	Distribution	Mean	Standard Deviation
$ \overline{PDL}, \overline{TDL} $ very low	Normal	44.803	16.097
$ \overline{PDL}, \overline{TDL} $ low	Normal	34.938	16.993
$ \overline{PDL}, \overline{TDL} $ medium	Normal	37.357	20.307
$ \overline{PDL}, \overline{TDL} $ high	Normal	32.890	23.041
$ \overline{PDS}, \overline{ADS} $ very low	Normal	5.500	5.500
$ \overline{PDS}, \overline{ADS} $ low	Normal	8.625	9.259
$ \overline{PDS}, \overline{ADS} $ medium	Normal	44.937	51.290
$ \overline{PDS}, \overline{ADS} $ high	Normal	252.500	437.342

5.4.3 Total reliability of damage detection from multiple SHM systems

The total reliability of damage detection for the SHM system is calculated as a group of systems in parallel, the resultant total reliability is governed by the most reliable SHM technique in the system, as displayed in figure 5.4 which is identical to R_{dd} attained from the DICSD SHM method.

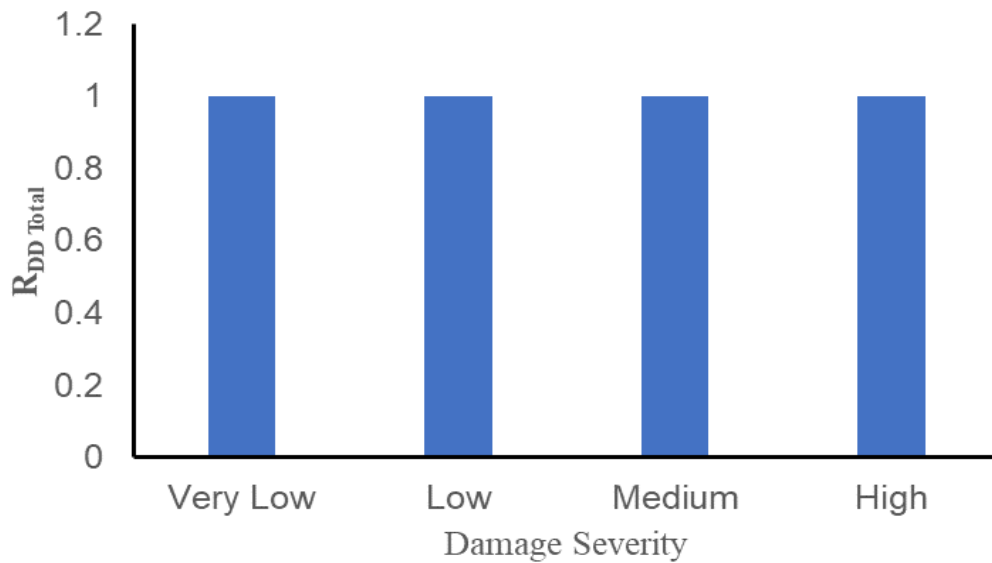


Figure 5-4. The total reliability of damage detection RDD for the SHM system with multiple SHM techniques. Calculated using equation 5-1.

5.4.4 Fatigue reliability of the fixed offshore platform member based on SHM Updating

For the simulation of fatigue, the predicted crack severity a_{pcs} for each damage severity is presented in Table 5.3 along with its distribution. The conversion of damage severity to crack size was conducted as described in section 4.5.3.

Table 5-4. Predicted crack severity at varying levels of simulated damage severity.

Damage Severity	Distribution	Mean	Standard Deviation
$a_{\text{pcs Very low}}$	Normal	51.5	38.5
$a_{\text{d MSE SHM}}$	Normal	30	10

When very low damage was simulated on a structure member, the equivalent crack size in the member was 40 mm. This crack size were implemented to calculate the true simulated reliability of the structure member which was compared to the predicted reliability attained from the SHM output.

5.4.4.1 Very Low Damage in element member 92

When a 40 mm crack was simulated on element number 92 of the fixed offshore platform, the output from the modal strain energy SHM technique indicated there was no damage in the structure. The updated fatigue reliability from the SHM system using the minimum detectable crack size for the modal strain energy technique $a_{\text{d SMH}}$ is as given in Table 5.3. The SHM output from the damage index cumulative slope difference method indicated that there was very low damage in structure member 92, and $a_{\text{pcs Very low}}$ given in Table 5.3 was implemented to calculate the updated fatigue reliability.

The value for total $R_{\text{DL}}|R_{\text{DD}}$ in structure member 92 is 0.985, as the only input in the summation of $R_{\text{DL}}|R_{\text{DD}}$ is from the DICSD technique. The same scenario applies to the Total $R_{\text{DA}}|R_{\text{DL}}|R_{\text{DD}}$ where a value of 0.544 is attained.

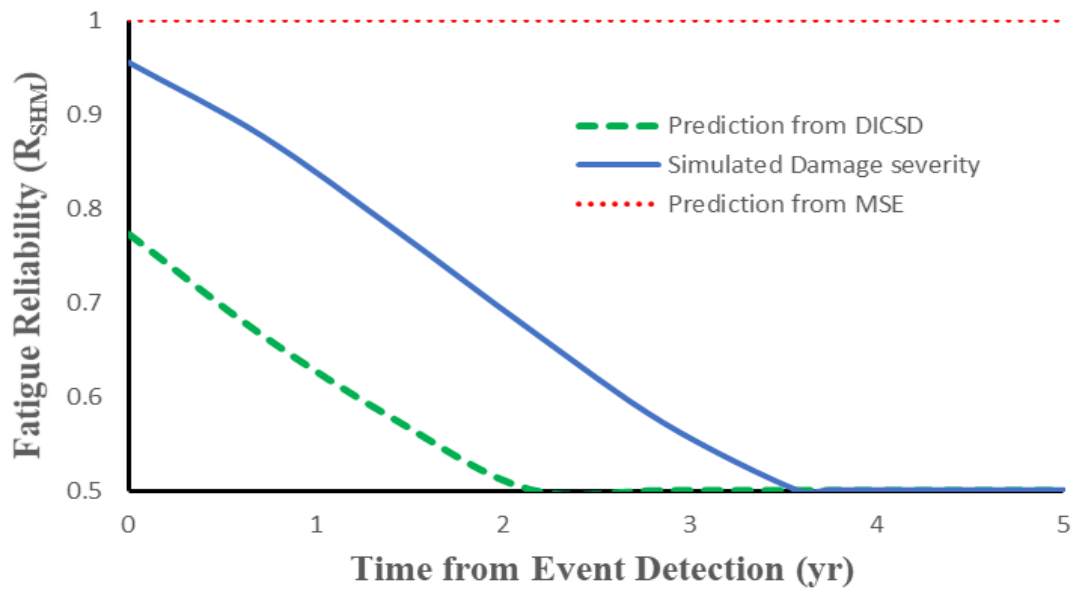


Figure 5-5a. Predicts fatigue reliability for structure member 92 attained from the modal strain energy (MSE), damage index cumulative slope difference (DICSD), and the actual simulated damage in member 92. Calculated using equation 5-1 to 5-5, 3-24 to 3-31.

5.4.4.2 Very Low Damage in element member 14

The observed updated output from the modal strain energy and damage index cumulative slope difference SHM techniques both indicate the presence of very low damage in element member 14, when a 40 mm crack was simulated. The value for total $R_{DL}|R_{DD}$ calculated was 0.985. The alignment between the two techniques used in the SHM system improved the reliability of the SHM outcome beyond the reliability of any of the two systems. The value for total $R_{DA}|R_{DL}|R_{DD}$ was calculated as 0.602, which is also higher than the reliability associated with any of the individual systems.

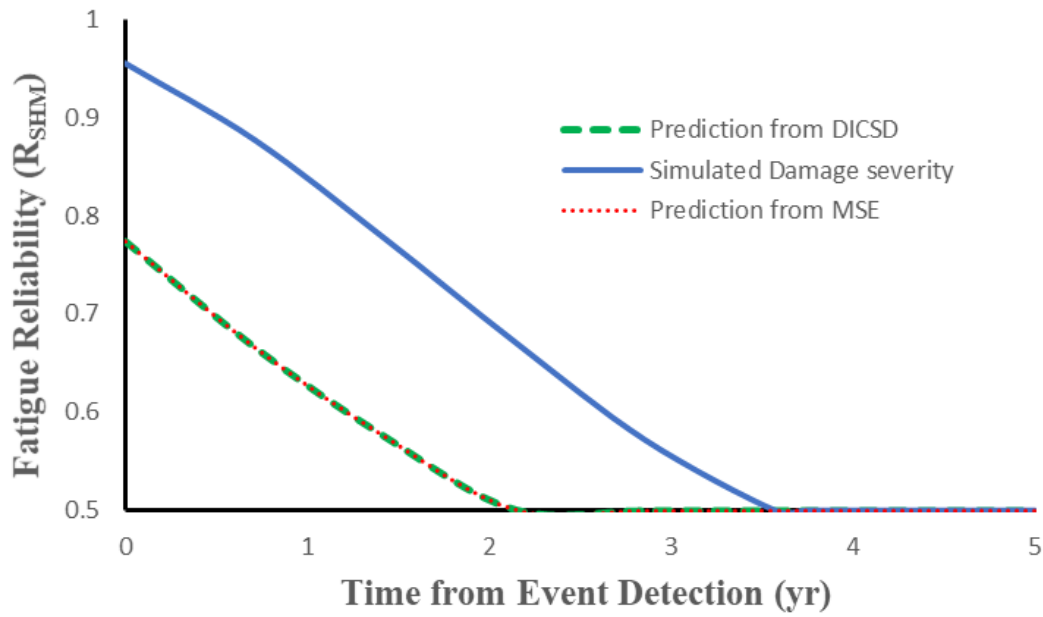


Figure 5-5b. Predicted fatigue reliability for structure member 14 attained from the modal strain energy (MSE), damage index cumulative slope difference (DICSD), and the actual simulated damage in member 14. Calculated using equation 5-1 to 5-5, 3-24 to 3-31.

5.5 Summary

In this chapter a framework was created to calculate the reliability associated with SHM systems that incorporate multiple SHM techniques to detect, localize, and assess damage severity. This framework was tested through numerical simulation of a fixed offshore structure monitored by modal strain energy SHM, and the damage index cumulative slope difference SHM to calculate the updated fatigue reliability index of the damaged structure member.

The key developments in this chapter include:

- The study shows that a single performance metric $total\ R_{DA}|R_{DL}|R_{DD}$ can be implemented to calculate the joint performance of multiple SHM systems monitoring the same structure.

- The Total $R_{DA}|R_{DL}|R_{DD}$ metric provides a means to quantify the potential contribution of multiple SHM systems in parallel to the overall SHM system reliability.
 - This is of importance for making decisions on selecting SHM or upgrading SHM systems currently in use.
- Total $R_{DA}|R_{DL}|R_{DD}$ is used as a metric to quantify the predicted fatigue reliability of the damaged structure member.
 - The development of Total $R_{DA}|R_{DL}|R_{DD}$ is a demonstration of an objective for this research work which include:
 - The use of a single reliability metric as an output from the framework that defines the combined SHM reliability performance.
 - Investigate the effect of the combined SHM reliability performance on the monitored structure's reliability and estimate remaining useful life for fatigue damage.

6 Validation of Reliability based SHM performance metrics using published data from an Experimental Wind turbine Jacket Structure

6.1 Introduction

To validate the use of reliability-based metrics developed from chapter 3 through 5 as a premier performance indicator for SHM systems, the reliability of an experimental wind turbine jacket structure was calculated using data published by a previous researcher [103]. In the work published by Ekhi [104], three SHM algorithms were applied to detect damage on a scaled wind turbine structure. A single level of damage was simulated on the structure, where the researcher varied the location of damage, and simulated wind speed. More details on the experimental procedure are provided later in this chapter.

Results from all three SHM algorithms were compared using the probability of false negative, and the probability of false positive. Additional modifications were made to the best performing SHM algorithm to reduce its bandwidth, increase processing speed, and ability to detect damage. The updated SHM algorithms were also compared based on their probability of false negative, and probability of false positive.

In this chapter, the reliability of damage detection was calculated for the first three SHM algorithms presented by Ekhi. The ranking of these algorithms was compared using both systems. Furthermore, three updated SHM algorithms provided by Ekhi, were also compared to highlight the convenience and additional insights that are provided when using the reliability metrics to compare SHM systems.

6.2 Experimental Laboratory Model

The data used to conduct this case study in this chapter was attained from experimental results from an experimental scaled wind turbine tower with a jacket

foundation published by Ekhi Urigeun [103]. The wind turbine tower was listed as 2.7 m in height, the top mass of the tower was 0.6 m wide, and 1 m long. Sitting on the top mass was a shaker which was implemented to simulate a variation of wind speeds by changing the wave input for the shaker. Change in the nacelle orientation was simulated by experimentally by changing the angle of the top mass from its initial orientation at 0° , to 30° and 90° .

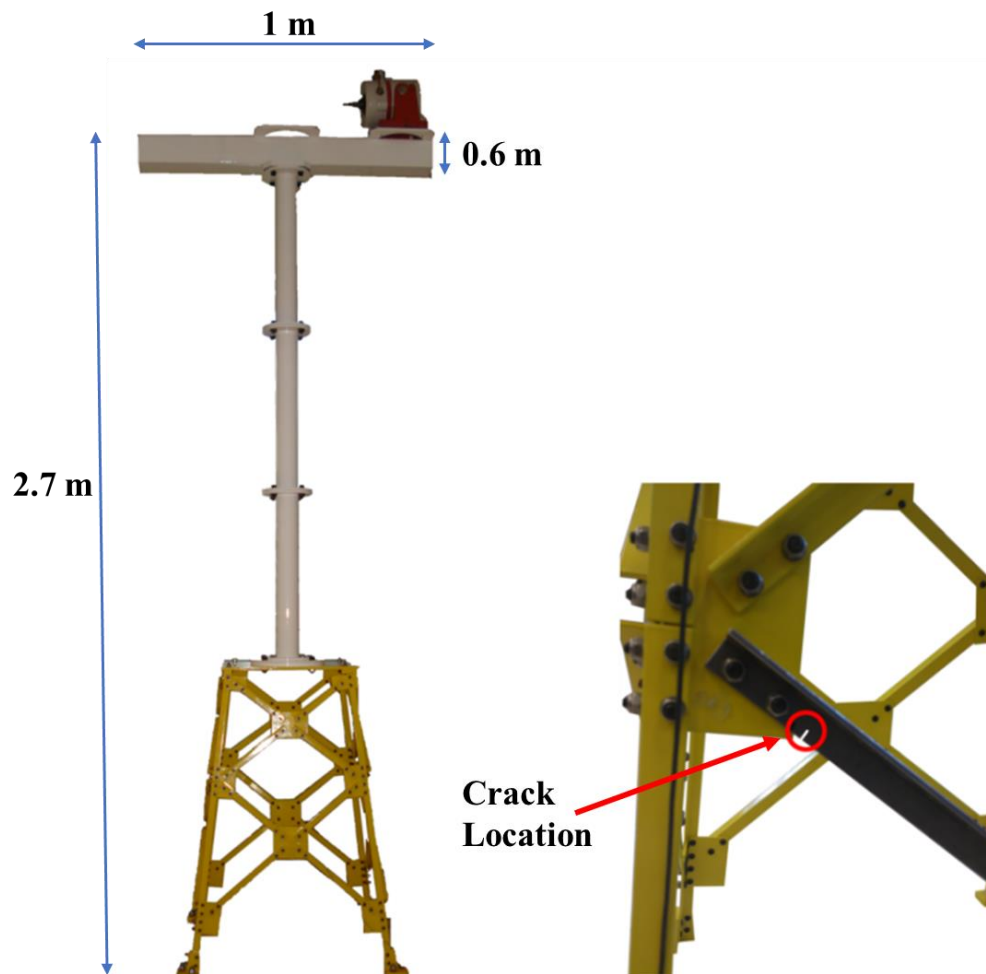


Figure 6-1. Photo of the experimental wind turbine tower with a jacket foundation [103].

The researcher conducted Operational Modal Analysis on the structure using 8 triaxial accelerometers mounted at optimal locations based on the outcome of their sensor placement algorithm [103]. The first 10 modes of the structure were

analysed, the frequency of these 10 modes were reported. The duration of each test conducted lasted 60 seconds, where the sampling frequency was reported as 256 HZ.

Ekhi introduced damage into the experimental wind turbine jacket by replacing an undamaged jacket member with a similar structural member with a 5 mm crack. Damage was simulated at single location for each testing period.

6.3 Comparison of Reliability Based SHM Performance Metrics to Performance Metrics Used by Ekhi.

6.3.1 Damage Detection Algorithms Used on Experimental Laboratory Model

The damage detection algorithm employed by Ekhi [103] was based on the assessment of changes in the structure using time domain data. The time domain data was fed into a two-phase algorithm comprised of a learning phase and detection phase.

In the learning phase, the inputs (nn) for the algorithm are measurements from the accelerometer (YY_a) mounted the healthy structure, where the subscript a has a range from 1 to nn . The value of YY is stored as matrix with i and j dimensions corresponding the number of sensors and number of samples. The learning phase begins with the construction of a Hankel matrix (HH_a) that corresponds to the YY_a input. The first output from the learning phase is the Nullspace (UU_{HH1}) of the first Hankel matrix HH_1 . When a structure is undamaged, the product of the transposed Null space UU_{HH1} and Hankel matrix HH form a residue matrix (RR) with values of zero or approximately zero. This is due to the similarity in Null space. When damage occurs the residue matrix value is expected to deviate from zero. The residual matrix was then vectorized for use in calculating the mean value vector. The variability factor ($\mathcal{E}\mathcal{E}$) was calculated based on the type of damage indicator chosen. See equation 6-1 to 6-6.

In the detection phase, inputs from the accelerometer YY , as well as UU_{HH1} and EE from training were used to calculate the damage indicator as seen in equation 6-1 to 6-6. The threshold (D_{th}) for damage detection was reported to have been attained during the training phase as follows. The mean value for damage indicator from the training phase was calculated and three times the standard deviation was added to the mean value, thus creating a threshold that would be higher than 99% of all values of damage indicators from the training phase.

6.3.1.1 Mean Residual (MR) Damage Indicator

The mean value vector [103] for the mean residual damage indicator was calculated using all the inputs nn in the learning phase and residue matrix RR as follows.

$$\widehat{EE}_{mr} = \left[\frac{1}{nn-1} \right] \sum_{nn} (vec[RR_{i,j}])_{nn} \quad (6-1)$$

The damage indicator for the mean residual was calculated as

$$DI_{mr} = \left[\frac{1}{nn-1} \right] \sum_k \frac{(vec[RR_{i,j}])_{nn+t}}{\widehat{EE}_{mr}} \quad (6-2)$$

Where the residual matrix of the data set being calculated is given as $(vec[RR_{i,j}])_{nn+t}$ and k corresponds to the size of values the dataset.

6.3.1.2 Covariance Matrix Estimate (CME) Damage Indicator

The variability factor for the covariance matrix estimates was calculated using all the inputs nn in the learning phase and residue matrix RR as follows:

$$\widehat{EE}_{cme} = \left[\frac{1}{nn-1} \right] \sum_{nn} (vec[RR_{i,j}])_{nn} (vec[RR_{i,j}])_{nn}^t \quad (6-3)$$

The damage indicator for the covariance matrix estimates was calculated as

$$DI_{cme} = (vec[RR_{i,j}])_{nn+1}^t \widehat{EE}_{cme}^{-1} (vec[RR_{i,j}])_{nn+t} \quad (6-4)$$

6.3.1.3 Scalar Covariance (SC) Damage Indicator

For scalar covariance the variability factor was calculated as follows

$$\widehat{\epsilon\epsilon}_{sc} = \left[\frac{1}{nn-1} \right] \sum_{nn} (vec[RR_{i,j}])_{nn}^t (vec[RR_{i,j}])_{nn} \quad (6-5)$$

The damage indicator for the mean residual was calculated as

$$DI_{sc} = \frac{(vec[RR_{i,j}])_{nn+1}^t (vec[RR_{i,j}])_{nn+t}}{\widehat{\epsilon\epsilon}_{sc}} \quad (6-6)$$

6.3.2 Results from Damage Detection Algorithms Used on Experimental Laboratory Model

The damage index reported for the mean residual DI_{mr} , covariance matrix estimate DI_{cme} , and scalar covariance DI_{sc} are replotted in figure 6.2 to 6.4. It can be visually observed that no false positives were observed for all three damage detection algorithms. There were no false negatives reported for covariance matrix estimate DI_{cme} , while the mean residual DI_{mr} had a false positive rate of 17%, and DI_{sc} had a false positive rate of 63%.

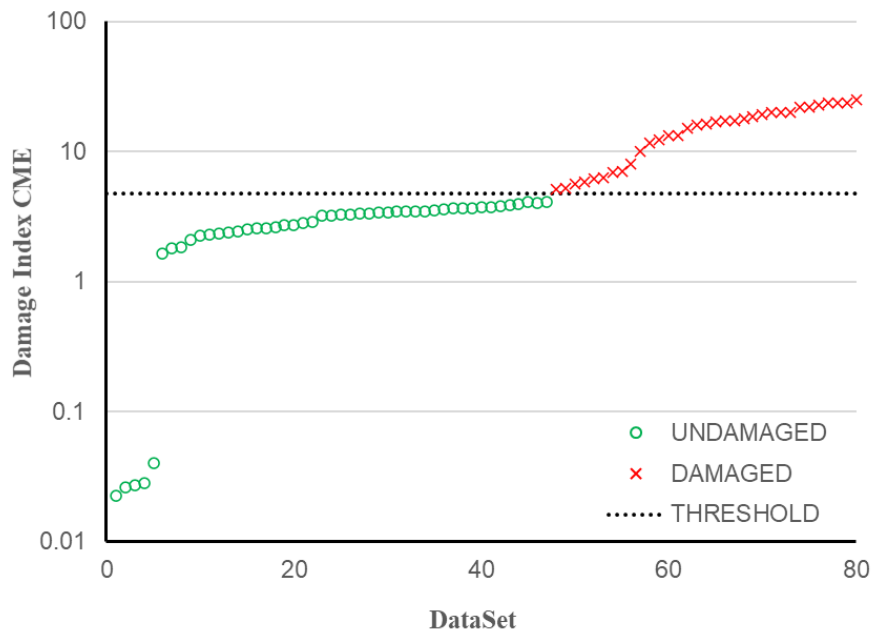


Figure 6-2. The covariance matrix estimate DI_{cme} reported for the experimental wind turbine tower jacket across the damaged and undamaged state [103].

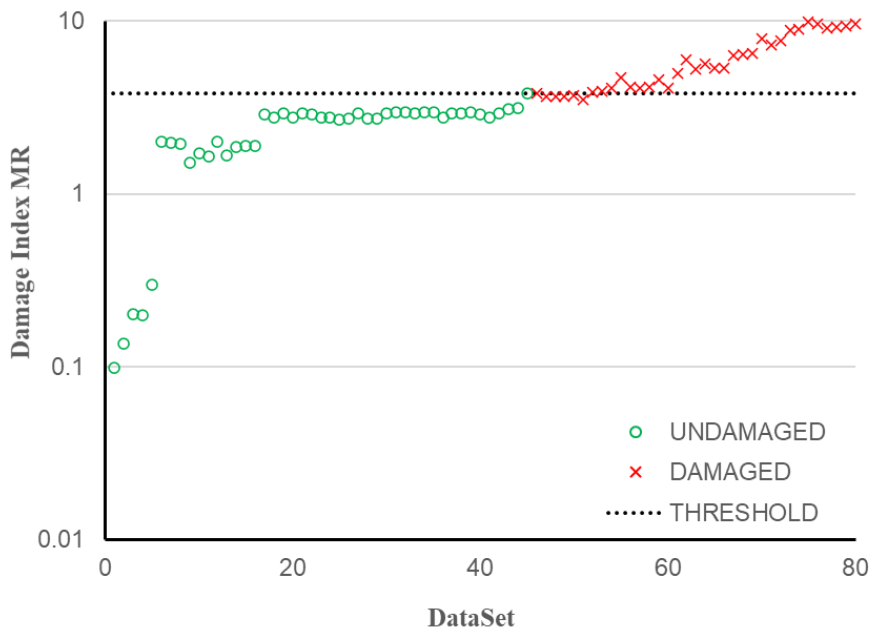


Figure 6-3. The mean residual DI_{mr} reported for the experimental wind turbine tower jacket across the damaged and undamaged state [103].

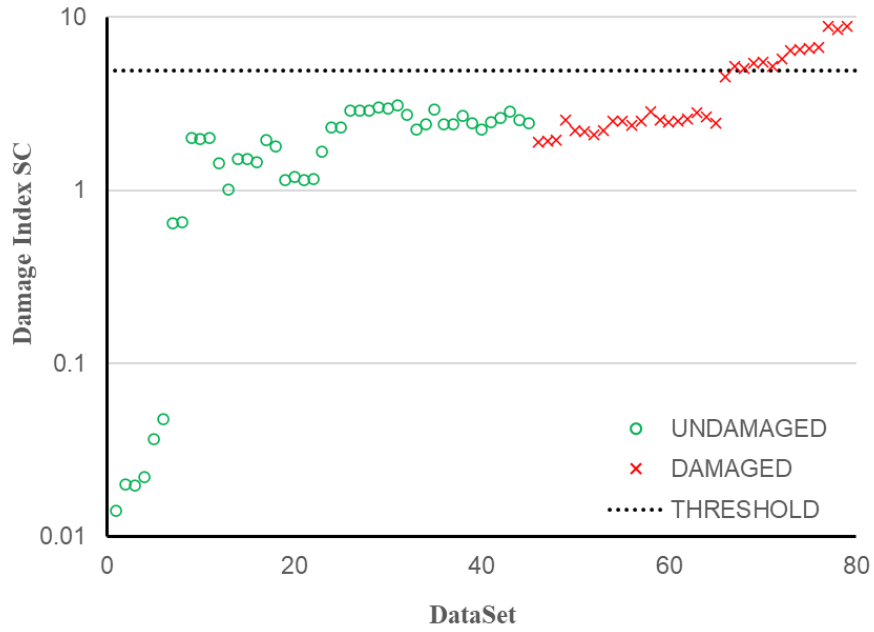


Figure 6-4. The scalar covariance DI_{sc} reported for the experimental wind turbine tower jacket across the damaged and undamaged state [103].

6.3.2.1 Comparison Between Proposed Reliability Metrix for damage detection and probability performance metrics.

To calculate the reliability of the damage index for the DI_{mr} , covariance matrix estimate DI_{cme} , and scalar covariance DI_{sc} algorithm, the values of the damage indicators each of the undamaged and damaged data set were fit to a normal distribution. The mean and standard deviation for each fit is presented in table 6.3. These values were then used in the limit state function to calculate the reliability of damage detection for false positives, and the reliability of damage detection for false negative. A single metric, the reliability of total damage detection was also calculated to account for false positive, and false negative.

$$R_{FP} = 1 - P(DI_{undam} - D_{th} < 0) \quad (6-7)$$

$$R_{FN} = 1 - P(D_{th} - DI_{dam} < 0) \quad (6-8)$$

$$R_{Total} = R_{FP}R_{FN} \quad (6-9)$$

Implementing the values from table 6.3 into equations 6-7 to 6-9, the value for R_{FP} and R_{FN} were calculated for the scalar covariance DI_{sc} algorithm as 0.999 and 0.5 respectively. The value for R_{Total} was 0.4996, since the total reliability is calculated in series, the value of R_{Total} is anchored by the least reliable source of error in the DI_{sc} algorithm. For mean residual DI_{mr} , the calculated values for R_{FP} and R_{FN} were 0.945 and 0.837 respectively. The corresponding value for R_{Total} was 0.798. The highest value of R_{Total} was attained for the covariance matrix estimate as 0.903, where its corresponding values of R_{FP} and R_{FN} were 0.959 and 0.941 respectively. Although the data set did not have any recorded false positives or false negatives for the covariance matrix estimate damage index DI_{cme} , the use of normal distribution contributed to slight variance in the fitted data at the tail of the distribution, where values from the undamaged and damaged dataset are almost at the damage threshold.

6.3.2.2 Discussion.

A comparison of the ranking order of the SHM algorithms based on metrics used by Ekhi, and reliability metrics indicate that both ranking systems agree. The covariance matrix estimate DI_{cme} is ranked first, mean residual DI_{mr} as second, and scalar covariance DI_{sc} placed third position.

To further highlight the advantage of using reliability as premier metric for SHM performance, R_{Total} was calculated and compared to the percent of false positive and false negatives reported by Ekhi for the covariance matrix estimate damage index DI_{cme} with data pre-processing. Data Pre-processing was implemented in the researchers work to transform the original data with the aim of reducing bandwidth and increasing the ease of damage detection.

Table 6-1. Comparison of SHM Algorithms using the performance metrics published by Ekhi, and reliability metrics proposed in this research.

SHM Algorithm	Metrics Used by Ekhi [104]		Proposed Metrics from Reliability		
	% False Negative	% False Positive	R _{TOTAL}	R _{FN}	R _{FP}
Mean Residual DI_{mr}	17.14	0	0.798	0.837	0.954
Scalar Covariance DI_{sc}	62.85	0	0.4996	0.5	0.999
Covariance Matrix Estimate DI_{cme}	0	0	0.903	0.941	0.959

Three datasets are used in this comparison to highlight the advantages of reliability over the percent of false positive and the percent of false negative.

The three data sets for the covariance matrix estimate damage index DI_{cme} used are for data measured from sensors without pre-processing, data pre-processed with principal component analysis **PCA** (100% variance), and feature selected data based on the 10 most informative sensors. The values for all three data sets are presented in figure 6.5 to 6.7.

The mean and standard deviation fitted to damage index DI_{cme} each of the undamaged and damaged data set for the non-pre-processed, pre-processed with PCA and 100% variance, as well as processed using the 10 most informative sensors are provided in table 6.3. The damage index DI_{cme} displayed no false positives or false negatives when no pre-processing was applied. The calculated reliability of false positive and reliability of false negatives were 0.962 and 0.949 respectively; this resulted in a value of 0.914 for R_{Total}.

For the pre-processed PCA with 100% variance, there were no false negatives, and the percent of false positive was 12.5%. The value of R_{Total} corresponding to the pre-processed PCA with 100% variance was 0.829, where its reliability of false positive was 0.829 and its reliability of false negative was 0.999.

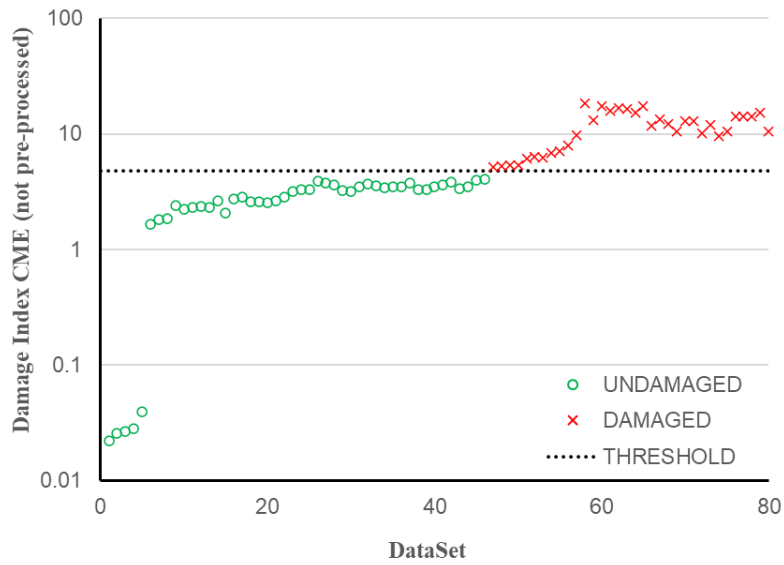


Figure 6-5. The non-pre-processed covariance matrix estimate DI_{cme} reported for the experimental wind turbine tower jacket across the damaged and undamaged state [103].

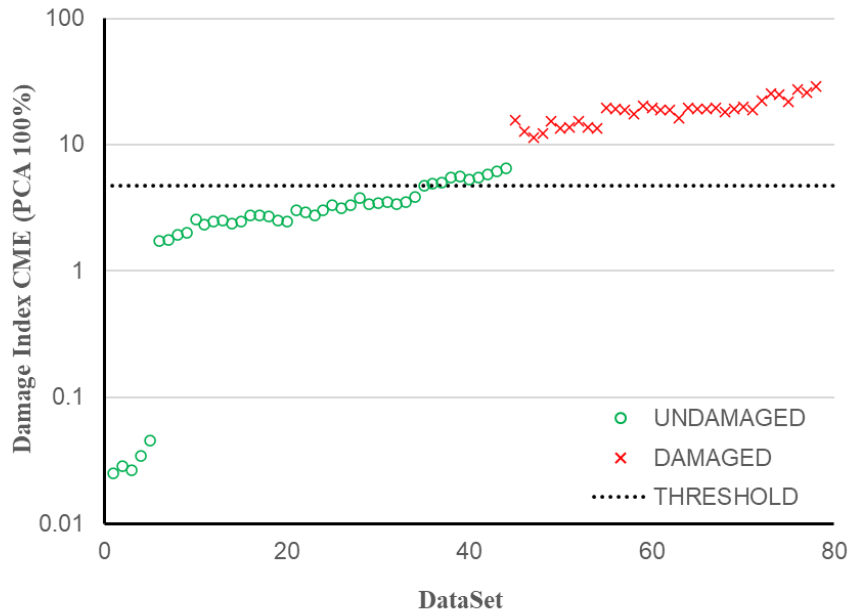


Figure 6-6. The pre-processed principal component analysis with 100% variance covariance matrix estimate DI_{cme} reported for the experimental wind turbine tower jacket across the damaged and undamaged state [103].

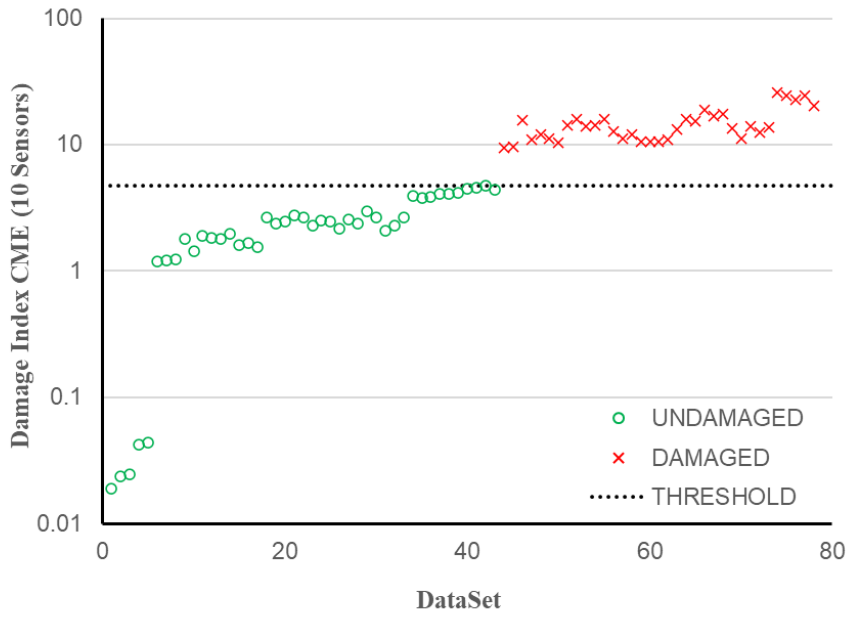


Figure 6-7. The pre-processed covariance matrix estimates DI_{cme} with 10 most informative sensors, reported for the experimental wind turbine tower jacket across the damaged and undamaged state [103].

When pre-processing was conducted using the 10 most informative sensors, there were no false negatives and the percent of false positive was 1.25%. The corresponding reliability of false positive and reliability of false negatives were 0.965 and 0.988 respectively. This resulted in a value of 0.953 for R_{Total} .

Comparing the percent of false positive and percent of false negatives across the non-pre-processed and two pre-processed algorithms, the non-pre-processed algorithm displayed the best performance metric. There were zero false negatives across all three algorithms, hence the false positive was the deciding factor. The damage index DI_{cme} calculated without pre-processing had no false positives while the damage index DI_{cme} calculated with the 10 most informative sensors had 1 false positive. Nevertheless, both algorithms displayed values from the undamaged structure at the vicinity of the damage threshold. The pre-processed PCA with 100% variance was reported to display 10 false positives.

Using the R_{total} metric, the best performing algorithm was the pre-processed with the 10 most informative sensors. Both performance functions R_{total} and percent of false negative rank the pre-processed PCA with 100% variance algorithm third.

The use of reliability as a performance metric provided additional insights on the difference in the reliability of false positive. The non-pre-processed algorithm and pre-processed algorithm using the 10 most informative sensors are almost equivalent, they displayed values of 0.962 and 0.965 respectively. The reliability of false negatives indicates that the non-pre-processed damage index DI_{cme} has a lower reliability of false negative (0.949) than its reliability of false positive (0.962) which reduces its total reliability to 0.914. Whereas the pre-processed algorithm with the 10 most informative sensors had a higher value of reliability of false negative (0.988) than its reliability of false positive (0.965), thus its total reliability is higher with a value of 0.953. It should be noted that an aim of the pre-processing technique by the researchers was to improve the algorithms' ability to easily detect damage through reducing the rate of false positive. This improvement in the algorithm was captured by the reliability metric, whereas the percent of false negative deemed the non-pre-processed and pre-processed damage index DI_{cme} equivalent.

Table 6-2. Comparison of SHM Algorithms using the performance metrics published by Ekhi, and reliability metrics proposed in this research.

SHM Algorithm	Metrics Used by Ekhi [104]		Proposed Metrics from Reliability		
	% False Negative	% False Positive	R_{TOTAL}	R_{FN}	R_{FP}
No Data Pre-Processing DI_{cme}	0	0	0.914	0.949	0.962
Principal Component Analysis (100%) DI_{cme}	0	12.5	0.829	0.999	0.829
10 most informative sensors DI_{cme}	0	1.3	0.952	0.988	0.964

Table 6-3. Mean and standard deviation of damage index fitted to normal distribution for the three damage detection algorithms applied to the experimental wind turbine tower jacket structure.

		Mean	Standard Deviation
DI_{CME}	Undamaged	2.770	1.149
	Damaged	14.998	6.548
DI_{MR}	Undamaged	2.339	2.339
	Damaged	2.339	2.339
DI_{sc}	Undamaged	1.827	0.963
	Damaged	4.015	2.180
DI_{CME}, not pre-processed	Undamaged	2.728	1.131
	Damaged	11.359	4.036
DI_{CME}, pre-processed with PCA 100% variance	Undamaged	3.110	1.666
	Damaged	18.696	4.340
DI_{CME}, pre-processed with 10 most informative sensors	Undamaged	2.355	1.299
	Damaged	14.634	4.399

6.4 Summary

In this chapter, the use reliability of damage detection was validated by applying it as performance metric to experimental results published by previous researchers.

The key developments in this chapter include:

- Multiple SHM systems used to monitor the same structure with the same level of damage severity, and experimental conditions were ranked using the proposed reliability metrics from this work.

- The ranking of the SHM algorithms from the reliability-based metrics and the percent of false positive and false negative used by previous researchers were in the same order for the first three algorithms the previous researcher implemented.
- The reliability-based metric was able to produce a single metric to rank these SHM systems while the previous researchers used two metrics to convey the overall ranking of their SHM systems.
- This is also a demonstration of an objective for this research which is to investigate the use of a single reliability metric as an output that defines the combined SHM reliability performance.
- Additional rankings of three SHM algorithms implemented by the previous researcher to reduce the bandwidth of the algorithm, increase its speed, and ease of damage detection highlighted to advantage of using reliability as a SHM performance metric.
 - The reliability of damage detection can be used to differentiate SHM systems that display an equivalent percentage of false positive or false negative as it considers the distribution of variables rather than a single outcome.
 - Although this was evident in the results presented by previous research, their use of percent of false positive and false negative as metrics could not quantify the improvements made on their SHM techniques.

7 Summary, and Recommendations.

The final chapter will summarize the work presented in the previous chapters of this this Thesis. It will also identify the contribution of the research that was conducted. The aim of this Thesis is to demonstrate numerically the application of reliability-based techniques to quantify the performance of vibration based SHM systems when applied to a fixed offshore platform. The methodology and its application to a numerical model of a fixed offshore platform under theoretical loading and damage conditions provided useful results and conclusions. Recommendations for future work are presented in this chapter to state areas in which the current methods established can be improved and extended.

7.1 Summary

In the first chapter of this thesis, the background and motivation for the study is presented. The statement of purpose, scope of research, aim and objectives for this thesis are outlined herewith. Furthermore, the proposed methodology to be implemented to accomplish the aim and objectives are also stated.

The second chapter of this work presents a review of SHM technologies, where commonly used local and global SHM methodologies are reviewed. The SHM methodologies reported by previous researchers to have been applied in monitoring fixed offshore platform energy structures were also reviewed. These SHM methods provide background for the development of a stochastic framework presented in later chapters of this thesis. A review of reliability analysis, and fatigue reliability was also presented which will provide the background for the development of methodology employed in the next chapters.

In the third chapter, a stochastic framework for calculating the reliability of damage detection associated with a SHM system is introduced. First order reliability method, Bayes method, Monte Carlo simulation, and Hit/Miss technique are implemented in codes developed for the scope of this assessing the framework. Numerical simulations were performed on fixed offshore platform under theoretical loading and damage scenarios via FEA simulations. Outputs

from the FEA simulations were used as inputs for a vibration based SHM system. The Outputs from the vibration based SHM system were used as inputs for the stochastic framework used to calculate the reliability of the SHM systems output. The results from this chapter demonstrate the reliability of damage detection for a vibration based SHM system on a numerically simulated fixed offshore platform with varying levels of damage. This is of importance as it provides a single metric that is more comprehensive to evaluate the damage detection performance of SHM systems in comparison to the widely used POD. Additionally, it also demonstrates the reliability of damage localization as well as the reliability of damage assessment for the same SHM system. These are the main findings from this chapter which is of importance to quantifying the performance of SHM systems beyond damage detection. Furthermore, the conditional reliability of SHM systems presented in this chapter presents a single metric that can be used to quantify the overall SHM system performance, this is also another main finding from this chapter.

In the fourth chapter, a vibration based SHM technique for fixed offshore jacket platforms is proposed based on the difference in the change in slope of mode shapes measured from the monitored structure. The damage index cumulative slope difference (DICSD) was presented for a numerically simulated fixed offshore platform with varying levels of damage. Two trained neural networks were implemented to localize and assess damage severity. The use of DICSD in conjunction with neural networks was demonstrate the extension of data-based vibration SHM techniques beyond damage detection, onto damage localization and damage severity. This is a key achievement in this chapter. The performance of the DICSD SHM system were assessed by computing its probability of detection (POD), probability of accurate localization (PAOL), and probability of accurate assessment (POAA). The metrics POAA and POAL are key achievements in this chapter, they provide an extension of POD which provide probability metrics to quantify SHM performance.

In Chapter five, a framework was presented to calculate the reliability associated with SHM systems that incorporate multiple SHM techniques to detect, localize,

and assess damage severity. This framework was tested through numerical simulation of a fixed offshore platform monitored by modal strain energy SHM system, and the damage index cumulative slope difference SHM system. The updated fatigue reliability index of the damaged structure member monitored by both systems was demonstrated in this chapter. Results from study shows that the reliability of the total SHM system outcome $total\ R_{DA}|R_{DL}|R_{DD}$ could be calculated using the reliability of damage assessment given damage was localized and detected. Total $R_{DA}|R_{DL}|R_{DD}$ is used as a metric to quantify the predicted fatigue reliability of the damaged structure member. This variable is a key finding from this chapter as it can be implemented as a performance metric to judge SHM systems with multiple techniques that function in parallel.

Chapter six demonstrates the application of reliability as a performance metric for SHM systems using data attained from an experimental structure. The reliability of damage detection was calculated using experimental data from a scaled wind turbine jacket structure published in the work of previous researchers. The previous researcher compared the performance of three-time based SHM techniques using the percent of false positive and false negative as performance metrics. The reliability of damage detection was calculated for the three-time based SHM techniques and compared to the percent of false positive and percent of false negative to display its effectiveness as metric for SHM performance. The reliability of damage detection can be used to differentiate SHM systems that display an equivalent percentage of false positive or false negative as it considers the distribution of variables rather than a single outcome.

7.2 Contributions to knowledge

The contributions of knowledge from this PhD research work are summarized as follows:

- A generic stochastic framework was proposed which could be used to calculate the probability of accurate localization (POAL) based on the output from a SHM system. The justification for proposing POAL performance metric is an extension of POD to the second-tier level of SHM

outputs which is damage localization. The limit state function provided in the framework, was generated using the uncertainties associated with damage localization in the SHM process. This limit state function can be solved using FORM. (See chapter; Section 3.2.1).

- Another probability metric associated with SHM performance named the probability of accurate assessment (POAA) was also proposed in this research work. POAA was proposed as a metric to characterizes the performance of the SHM systems ability to assess damage severity, a limit state function was also provided to characterize the variables associated with damage assessment in a SHM system. The techniques implemented to solve for POAL are also used to solve for POAA. (See chapter; Section 3.2.2)
- Conditional probabilities were also proposed to calculate the dependence of sequential SHM outcomes. These conditional probabilities proposed are used as a single probability metric to judge the performance of a SHM system for damage localization given damage was detected $POAL|POD$. A second conditional probability was proposed as a performance metric for damage assessment, given damage was localized, and detected $POAA|POAL|POD$. This metric provides a single value that can be used to compare probabilities associated with SHM systems capable of damage detection, localization, and assessment. (See chapter; Section 3.5.1)
- Reliability performance metrics were also proposed as measure for judging SHM performance as an alternate to probability as it provides a single metric that could be used to judge the overall performance of a SHM output. Three reliability performance metrics were presented: the reliability of damage detection R_{dd} , reliability of damage localization R_{dl} , and reliability of damage assessment R_{da} . (See chapter; Section 3.5.2)
- Conditional reliabilities were also proposed as performance metrics that provide a single value for judging multiple levels of SHM performance. The reliability of damage localization given damage was detected $R_{Dl}|R_{DD}$ is a single metric that can be used to judge the overall behaviour of a SHM

system capable of detecting and localizing damage. The reliability of damage assessment, given damage was localized and detected $R_{DA}|R_{DL}|R_{DD}$ is a single metric that can be implemented to judge the overall SHM performance for a system capable of damage assessment, localization, and detection. (See chapter Section 3.5)

- The conditional reliability of a monitored structure attained from SHM outputs was also proposed in this work as metric that characterizes the confidence in the estimated useful life of the structure given the reliability of the SHM system. This parameter establishes a direct relationship with the monitored asset management and the reliability of the SHM system. (See chapter Section 3.5)
- A vibration based SHM technique titled damage index cumulative slope difference (DICSD) was proposed in this thesis for platform structures. This SHM technique incorporates the change in slope of mode shapes to infer the presence of damage in a structure. The DICSD index was used to train two unique two-layer feed forward neural networks, one for damage localization and the other for damage assessment. The trained neural networks were implemented to localize and assess damage. (See chapter 4)
- A framework was created to calculate the reliability associated with SHM systems that incorporate multiple SHM techniques to detect, localize, and assess damage severity. This framework was designed to combine the reliability associated with multiple techniques operating in parallel, with the goal of improving the overall reliability of the monitored structure. (See chapter 5).

7.3 Future Recommendations

This thesis has presented some useful insights and conclusions on the reliability of SHM systems implemented on fixed offshore platforms, which might instigate further investigation. Topics of interests that could be furthered include:

- This work was highly dependent on numerical simulation to provide the initial presentations of the reliability performance metrics proposed. Although there was experimental data available by previous researchers on damage detection, which enabled the calculation of the reliability of damage detection for an energy structure, the reliability of damage localization and reliability of damage assessment, as well as the conditional reliabilities and probabilities were not validated through experimentation.
- The damage index cumulative slope difference (DICSD) vibration based SHM method proposed in this study was also not validated via experimentation.
- The errors associated with damage detection, damage localization, and damage assessment were proposed as a linear function. Future work is required to extend these error functions to encapsulate the potential non-linearities and dependence of errors associated with SHM operations.

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APPENDICES

Appendix A: Fixed Offshore platform properties, loading conditions, and modal outputs for FEA.

In this appendix, the details of the simulate fixed offshore platform, as well as its operational and environmental loads used in the finite element simulation are presented.

The SAPOS input file is given below.

JOINT COORDINATES

1	X	0.0	Y	0.0	Z	62.5
2	X	16.0	Y	0.0	Z	62.5
3	X	0.0	Y	16.0	Z	62.5
4	X	16.0	Y	16.0	Z	62.5
5	X	0.0	Y	0.0	Z	55.0
6	X	8.0	Y	0.0	Z	55.0
7	X	16.0	Y	0.0	Z	55.0
8	X	0.0	Y	8.0	Z	55.0
9	X	16.0	Y	8.0	Z	55.0
10	X	0.0	Y	16.0	Z	55.0
11	X	8.0	Y	16.0	Z	55.0
12	X	16.0	Y	16.0	Z	55.0
13	X	-0.5	Y	-0.5	Z	50.0
14	X	4.8333	Y	-0.5	Z	50.0
15	X	11.1667	Y	-0.5	Z	50.0

16 X 16.5 Y -0.5 Z 50.0
17 X -0.5 Y 4.8333 Z 50.0
18 X 16.5 Y 4.8333 Z 50.0
19 X -0.5 Y 11.1667 Z 50.0
20 X 16.5 Y 11.1667 Z 50.0
21 X -0.5 Y 16.5 Z 50.0
22 X 4.8333 Y 16.5 Z 50.0
23 X 11.1667 Y 16.5 Z 50.0
24 X 16.5 Y 16.5 Z 50.0
25 X -1.5 Y -1.5 Z 40.0
26 X 17.5 Y -1.5 Z 40.0
27 X 8.0 Y 8.0 Z 40.0
28 X -1.5 Y 17.5 Z 40.0
29 X 17.5 Y 17.5 Z 40.0
30 X 8.0 Y -2.4048 Z 30.9524
31 X -2.4048 Y 8.0 Z 30.9524
32 X 18.4048 Y 8.0 Z 30.9524
33 X 8.0 Y 18.4048 Z 30.9524
34 X -3.5 Y -3.5 Z 20.0
35 X 19.5 Y -3.5 Z 20.0
36 X 8.0 Y 8.0 Z 20.0
37 X -3.5 Y 19.5 Z 20.0

38 X 19.5 Y 19.5 Z 20.0

39 X 8.0 Y -4.42 Z 10.8

40 X -4.42 Y 8.0 Z 10.8

41 X 20.42 Y 8.0 Z 10.8

42 X 8.0 Y 20.42 Z 10.8

43 X -5.5 Y -5.5 Z 0.0

44 X 21.5 Y -5.5 Z 0.0

45 X -5.5 Y 21.5 Z 0.0

46 X 21.5 Y 21.5 Z 0.0

47 X 8.0 Y 8.0 Z 0.0

\$..... Piles

48 X -6.75 Y -6.75 Z -12.5

49 X 22.75 Y -6.75 Z -12.5

50 X -6.75 Y 22.75 Z -12.5

51 X 22.75 Y 22.75 Z -12.5

\$.....

52 X -8.0 Y -8.0 Z -25.0

53 X 24.0 Y -8.0 Z -25.0

54 X -8.0 Y 24.0 Z -25.0

55 X 24.0 Y 24.0 Z -25.0

\$.....

MEMBER PROPERTIES

\$..... Top legs : D = 2.00 t = 0.050

1,6,11,16 AX 0.314160 IX 0.31416 IY 0.15710 IZ 0.15710

\$ Jacket Legs & Vertical diagonals, L -30 hor. diagonals : D = 1.20 t = 0.016

2 to 5, 7 to 10, 12 to 15 AX 0.06030 IX 0.02170 IY 0.01090 IZ 0.01090

17 to 36, 53 to 88 AX 0.06030 IX 0.02170 IY 0.01090 IZ 0.01090

\$..... Level +5 bracings & hor. diagonals : D = 0.80 t = 0.008

37 to 48 AX 0.020106 IX 0.003217 IY 0.0016085 IZ 0.0016085

\$...Level -10 bracings & hor. diagonals, L -30 bracings : D = 1.20 t = 0.014

49 to 52, 89 to 96 AX 0.05278 IX 0.019 IY 0.0095 IZ 0.0095

103 to 110 AX 0.05278 IX 0.019 IY 0.0095 IZ 0.0095

\$..... Rigid deck

97 to 102 AX 1.0E+6 IX 1.0E+9 IY 1.0E+9 IZ 1.0E+9

\$..... Piles : D = 1.20 t = 0.016

111 to 118 AX 0.06030 IX 0.02170 IY 0.01090 IZ 0.01090

\$.....

JOINT MASSES

1 to 4 UX 1.75E+6 UY 1.75E+6 UZ 1.75E+6

\$.....

TYPE SPACE FRAME

MEMBER INCIDENCES

1 5 1

2 13 5

3 25 13
4 34 25
5 43 34
6 7 2
7 16 7
8 26 16
9 35 26
10 44 35
11 10 3
12 21 10
13 28 21
14 37 28
15 45 37
16 12 4
17 24 12
18 29 24
19 38 29
20 46 38
21 25 14
22 14 6
23 15 6
24 26 15

25 28 22

26 22 11

27 23 11

28 29 23

29 26 18

30 18 9

31 20 9

32 29 20

33 25 17

34 17 8

35 19 8

36 28 19

37 5 6

38 6 7

39 5 8

40 6 8

41 6 9

42 7 9

43 8 10

44 8 11

45 9 11

46 9 12

47 10 11

48 11 12

49 25 27

50 26 27

51 27 28

52 27 29

53 36 37

54 36 38

55 34 36

56 35 36

57 30 25

58 30 26

59 34 30

60 35 30

61 39 34

62 39 35

63 43 39

64 44 39

65 33 28

66 33 29

67 37 33

68 38 33

69 42 37

70 42 38

71 45 42

72 46 42

73 32 26

74 32 29

75 35 32

76 38 32

77 41 35

78 41 38

79 44 41

80 46 41

81 31 25

82 31 28

83 34 31

84 37 31

85 40 34

86 40 37

87 43 40

88 45 40

89 25 26

90 25 28

91 26 29

92 28 29

93 34 35

94 34 37

95 35 38

96 37 38

97 1 2

98 1 3

99 1 4

100 2 3

101 2 4

102 3 4

103 43 44

104 44 46

105 45 46

106 43 45

107 47 45

108 47 46

109 43 47

110 44 47

\$..... Piles

111 48 43

112 49 44

113 50 45

114 51 46

115 52 48

116 53 49

117 54 50

118 55 51

\$.....

RAYLEIGH LOADING 1 'EIGENMODE : 1'

JOINT LOADS

1 FX 100.0

2 FX 100.0

3 FX 100.0

4 FX 100.0

RAYLEIGH LOADING 2 'EIGENMODE : 2'

JOINT LOADS

1 FY 100.0

2 FY 100.0

3 FY 100.0

4 FY 100.0

RAYLEIGH LOADING 3 'EIGENMODE : 3'

JOINT LOADS

1 FX 100.0

2 FX 100.0

3 FX -100.0

4 FX -100.0

\$.....

MATERIAL CONSTANTS

E 20.5E10 1 to 109, 111 to 118

E 18.45E10 110

POISSON 0.25 ALL

\$ Densities.....

DENSITY 7.8E+3 37 to 48,1,2,6,7,11,12,16,17,22,23,26,27,30,31,34,35

DENSITY 27.085E+3 49 to 52, 89 to 96, 103 to 110

DENSITY 43.436E+3 3 to 5, 8 to 10, 13 to 15, 18 to 20

DENSITY 24.680E+3 21,24,25,28,29,32,33,36, 53 to 88

DENSITY 1.0E-9 97 to 102

\$..... Piles

DENSITY 7.8E+3 111 to 118

END of material constatnts

\$.....

WAVE DATA

WAVE HEIght 2.5

WAVE PERiod 6.5

WAVE DIRection 0.0

WATER depth 50.0

STILL water surface 50.0

UNI-directional wave

MAIn wave numbers 1

DRAG force coefficient cd 1.3 ALL

INERtia force coefficient cm 1.6 ALL

MARine growth thickness 0.20 ALL

DENSity of water ro 1024.0

WATER-STRUcture interaction 1

SEA STATE PROPERTIES

P.M spectrum HS 5, ALPHA 0.0081

LONG TERM DISTRIBUTION OF SEA STATES

HS WEIBULL A 0.60, B 1.67, C 1.20

END of wave data

\$.....

RESPONSE ANALYSIS

GAUSS POINTS FOR FREQUENCY INTEGRATION 3

DYNamic and STATic contributions

DAMPING RATIOS 0.01 0.01 0.01 0.01

\$.....

SPECTRAL analyis

FATIGUE ANALYSIS,

NUMBER OF S-N LINES 2

*.....API Basic Design S-N curve

70.18 3.0

106.22 5.0

STRESS LOCATIONS

\$..... member: 5

5 6

0.0 2.0 2.0 2.0

15.0 2.0 2.0 2.0

30.0 2.0 2.0 2.0

45.0 2.0 2.0 2.0

60.0 2.0 2.0 2.0

90.0 2.0 2.0 2.0

END of stress locations

END of response analysis

\$.....

EIGENVALUE SOLUTION

subspace ITERATION, BASE VECTORS 6

CONSISTENT MASS MATRIX

NATURAL MODE 3

MAXIMUM ITERATION NUMBER 50

NORMALIZE EIGENVECTORS TO VALUE 1.0

dump intermediate results

END OF EIGENVALUE SOLUTION

\$.....

FOUNDATION MEMBERS

111 TO 118 KX 1.0E8 KY 1.0E8 KZ 1.0E8

\$.....LIST COMMANDS.....

LISt GLObal LOAd vector

LISt JOInt LOAdS

LISt MASs matrix

LISt STIffness matrix

LISt DEComposed stiffness matrix

LISt FLExibility matrix

LISt LOCal coordinates 4 to 8

LISt REActions

LISt DISplacements 1 5 13

LISt EIGenVALues

LISt EIGenVEctors

LISt FORces 5 8

LISt QUAsi-static RESponse

LISt TRAnsfer functions of GENeralized DISplacemments

LISt EARthquake SPEctrum

LISt TRAnsfer functions of RELative DISplacements

LISt SPEctra of DISplacements

LISt TRAnsfer functions of FORces

LISt SPEctra of FORces

LISt SPEctral MOMents of FORces

LISt SPEctral MOMents of DISplacements

LISt STRESS SPEctral MOMents of DISplacements

LISt STRESS TRAnsfer functions

LISt STRESS SPEctrum

LISt STRESS SPEctral MOMents

\$.....PLOT COMMANDS.....

PLOt TOPology

PLOt DISplacements

PLOt MODE shapes

PLOt STOchastic results

*-----

END OF INPUT

An example of the raw topology, eigne value, and eigen vector data of the fixed offshore platform is provided below:

118 55 0 3 : Nr.MEM. - Nr.JOIN. - Nr.LOAD. - Nr.MOD.

1 0.000000E+00 0.000000E+00 0.125000E+02

2 0.160000E+02 0.000000E+00 0.125000E+02

3	0.000000E+00	0.160000E+02	0.125000E+02
4	0.160000E+02	0.160000E+02	0.125000E+02
5	0.000000E+00	0.000000E+00	0.500000E+01
6	0.800000E+01	0.000000E+00	0.500000E+01
7	0.160000E+02	0.000000E+00	0.500000E+01
8	0.000000E+00	0.800000E+01	0.500000E+01
9	0.160000E+02	0.800000E+01	0.500000E+01
10	0.000000E+00	0.160000E+02	0.500000E+01
11	0.800000E+01	0.160000E+02	0.500000E+01
12	0.160000E+02	0.160000E+02	0.500000E+01
13	-.500000E+00	-.500000E+00	0.000000E+00
14	0.483330E+01	-.500000E+00	0.000000E+00
15	0.111667E+02	-.500000E+00	0.000000E+00
16	0.165000E+02	-.500000E+00	0.000000E+00
17	-.500000E+00	0.483330E+01	0.000000E+00
18	0.165000E+02	0.483330E+01	0.000000E+00
19	-.500000E+00	0.111667E+02	0.000000E+00
20	0.165000E+02	0.111667E+02	0.000000E+00
21	-.500000E+00	0.165000E+02	0.000000E+00
22	0.483330E+01	0.165000E+02	0.000000E+00
23	0.111667E+02	0.165000E+02	0.000000E+00
24	0.165000E+02	0.165000E+02	0.000000E+00

25 -.150000E+01 -.150000E+01 -.100000E+02
26 0.175000E+02 -.150000E+01 -.100000E+02
27 0.800000E+01 0.800000E+01 -.100000E+02
28 -.150000E+01 0.175000E+02 -.100000E+02
29 0.175000E+02 0.175000E+02 -.100000E+02
30 0.800000E+01 -.240480E+01 -.190476E+02
31 -.240480E+01 0.800000E+01 -.190476E+02
32 0.184048E+02 0.800000E+01 -.190476E+02
33 0.800000E+01 0.184048E+02 -.190476E+02
34 -.350000E+01 -.350000E+01 -.300000E+02
35 0.195000E+02 -.350000E+01 -.300000E+02
36 0.800000E+01 0.800000E+01 -.300000E+02
37 -.350000E+01 0.195000E+02 -.300000E+02
38 0.195000E+02 0.195000E+02 -.300000E+02
39 0.800000E+01 -.442000E+01 -.392000E+02
40 -.442000E+01 0.800000E+01 -.392000E+02
41 0.204200E+02 0.800000E+01 -.392000E+02
42 0.800000E+01 0.204200E+02 -.392000E+02
43 -.550000E+01 -.550000E+01 -.500000E+02
44 0.215000E+02 -.550000E+01 -.500000E+02
45 -.550000E+01 0.215000E+02 -.500000E+02
46 0.215000E+02 0.215000E+02 -.500000E+02

47 0.800000E+01 0.800000E+01 -.500000E+02
 48 -.675000E+01 -.675000E+01 -.625000E+02
 49 0.227500E+02 -.675000E+01 -.625000E+02
 50 -.675000E+01 0.227500E+02 -.625000E+02
 51 0.227500E+02 0.227500E+02 -.625000E+02
 52 -.800000E+01 -.800000E+01 -.750000E+02
 53 0.240000E+02 -.800000E+01 -.750000E+02
 54 -.800000E+01 0.240000E+02 -.750000E+02
 55 0.240000E+02 0.240000E+02 -.750000E+02

 1 5 1
 2 13 5
 3 25 13
 4 34 25
 5 43 34
 6 7 2
 7 16 7
 8 26 16
 9 35 26
 10 44 35
 11 10 3
 12 21 10
 13 28 21

14	37	28
15	45	37
16	12	4
17	24	12
18	29	24
19	38	29
20	46	38
21	25	14
22	14	6
23	15	6
24	26	15
25	28	22
26	22	11
27	23	11
28	29	23
29	26	18
30	18	9
31	20	9
32	29	20
33	25	17
34	17	8
35	19	8

36	28	19
37	5	6
38	6	7
39	5	8
40	6	8
41	6	9
42	7	9
43	8	10
44	8	11
45	9	11
46	9	12
47	10	11
48	11	12
49	25	27
50	26	27
51	27	28
52	27	29
53	36	37
54	36	38
55	34	36
56	35	36
57	30	25

58	30	26
59	34	30
60	35	30
61	39	34
62	39	35
63	43	39
64	44	39
65	33	28
66	33	29
67	37	33
68	38	33
69	42	37
70	42	38
71	45	42
72	46	42
73	32	26
74	32	29
75	35	32
76	38	32
77	41	35
78	41	38
79	44	41

80	46	41
81	31	25
82	31	28
83	34	31
84	37	31
85	40	34
86	40	37
87	43	40
88	45	40
89	25	26
90	25	28
91	26	29
92	28	29
93	34	35
94	34	37
95	35	38
96	37	38
97	1	2
98	1	3
99	1	4
100	2	3
101	2	4

102	3	4
103	43	44
104	44	46
105	45	46
106	43	45
107	47	45
108	47	46
109	43	47
110	44	47
111	48	43
112	49	44
113	50	45
114	51	46
115	52	48
116	53	49
117	54	50
118	55	51

1 : EIGEN MODE

1 -.9651E+00 0.1000E+01 0.4662E-02 -.1672E-01 -.1613E-01 0.1464E-06

2 -.9651E+00 0.1000E+01 0.2628E+00 -.1672E-01 -.1613E-01 0.1464E-06

3 -.9651E+00 0.1000E+01 -.2628E+00 -.1672E-01 -.1613E-01 0.1464E-06

4 -.9651E+00 0.1000E+01 -.4662E-02 -.1672E-01 -.1613E-01 0.1464E-06

5 -.7952E+00 0.8238E+00 0.4608E-02 -.2663E-01 -.2568E-01 -.3687E-03

6 -.7719E+00 0.8005E+00 0.1212E+00 -.1943E-01 -.1591E-01 0.4778E-03

7 -.7921E+00 0.8208E+00 0.2598E+00 -.2718E-01 -.2626E-01 0.6684E-05

8 -.7726E+00 0.7998E+00 -.1170E+00 -.1648E-01 -.1875E-01 0.4951E-03

9 -.7726E+00 0.7998E+00 0.1170E+00 -.1648E-01 -.1875E-01 -.4950E-03

10 -.7921E+00 0.8208E+00 -.2598E+00 -.2718E-01 -.2626E-01 -.6401E-05

11 -.7719E+00 0.8005E+00 -.1212E+00 -.1943E-01 -.1591E-01 -.4777E-03

12 -.7952E+00 0.8238E+00 -.4608E-02 -.2663E-01 -.2568E-01 0.3690E-03

13 -.6768E+00 0.7012E+00 0.4833E-02 -.2265E-01 -.2191E-01 0.2588E-03

14 -.6798E+00 0.7006E+00 0.8488E-01 -.1941E-01 -.1826E-01 0.1662E-02

15 -.6826E+00 0.7033E+00 0.1753E+00 -.1933E-01 -.1738E-01 -.1319E-04

16 -.6759E+00 0.7003E+00 0.2724E+00 -.2110E-01 -.2031E-01 -.4481E-05

17 -.6761E+00 0.7044E+00 -.7872E-01 -.1889E-01 -.1874E-01 0.1663E-02

18 -.6789E+00 0.7072E+00 0.1724E+00 -.1803E-01 -.1865E-01 -.4568E-04

19 -.6789E+00 0.7072E+00 -.1724E+00 -.1803E-01 -.1865E-01 0.4581E-04

20 -.6761E+00 0.7044E+00 0.7872E-01 -.1889E-01 -.1874E-01 -.1663E-02

21 -.6759E+00 0.7003E+00 -.2724E+00 -.2110E-01 -.2031E-01 0.4697E-05

22 -.6827E+00 0.7033E+00 -.1753E+00 -.1933E-01 -.1738E-01 0.1329E-04

23 -.6798E+00 0.7006E+00 -.8488E-01 -.1941E-01 -.1826E-01 -.1662E-02

24 -.6768E+00 0.7012E+00 -.4833E-02 -.2265E-01 -.2191E-01 -.2586E-03

25 -.4845E+00 0.5025E+00 0.5086E-02 -.1715E-01 -.1655E-01 0.1979E-02

26 -.4979E+00 0.5154E+00 0.2867E+00 -.1699E-01 -.1639E-01 -.3506E-04

27 -.4977E+00 0.5157E+00 -.3900E-06 -.1499E-01 -.1447E-01 0.4002E-07

28 -.4979E+00 0.5154E+00 -.2867E+00 -.1699E-01 -.1639E-01 0.3514E-04

29 -.4845E+00 0.5025E+00 -.5085E-02 -.1715E-01 -.1655E-01 -.1979E-02

30 -.3380E+00 0.3703E+00 0.1376E+00 -.1455E-01 -.1344E-01 0.1104E-02

31 -.3574E+00 0.3502E+00 -.1328E+00 -.1393E-01 -.1405E-01 0.1144E-02

32 -.3574E+00 0.3502E+00 0.1328E+00 -.1393E-01 -.1405E-01 -.1144E-02

33 -.3380E+00 0.3703E+00 -.1376E+00 -.1455E-01 -.1344E-01 -.1104E-02

34 -.1890E+00 0.1970E+00 0.4091E-02 -.1078E-01 -.1040E-01 0.3279E-02

35 -.2226E+00 0.2294E+00 0.2304E+00 -.1092E-01 -.1054E-01 -.5812E-04

36 -.2219E+00 0.2299E+00 0.5991E-05 -.1002E-01 -.9667E-02 0.1656E-07

37 -.2226E+00 0.2294E+00 -.2305E+00 -.1092E-01 -.1054E-01 0.5816E-04

38 -.1890E+00 0.1970E+00 -.4085E-02 -.1078E-01 -.1040E-01 -.3279E-02

39 -.9824E-01 0.1353E+00 0.8153E-01 -.8385E-02 -.6892E-02 0.1064E-02

40 -.1305E+00 0.1018E+00 -.7869E-01 -.7148E-02 -.8094E-02 0.1096E-02

41 -.1306E+00 0.1018E+00 0.7869E-01 -.7142E-02 -.8093E-02 -.1103E-02

42 -0.9823E-01 0.1353E+00 -0.8153E-01 -0.8386E-02 -0.6899E-02 -0.1058E-02
 43 -0.2855E-01 0.3019E-01 0.1856E-02 -0.8384E-02 -0.8097E-02 0.1718E-02
 44 -0.4620E-01 0.4724E-01 0.1044E+00 -0.8694E-02 -0.8402E-02 -0.3053E-04
 45 -0.4618E-01 0.4722E-01 -0.1044E+00 -0.8663E-02 -0.8371E-02 0.3037E-04
 46 -0.2854E-01 0.3021E-01 -0.1848E-02 -0.8398E-02 -0.8083E-02 -0.1718E-02
 47 -0.4586E-01 0.4752E-01 0.1190E-02 -0.2766E-02 -0.2669E-02 0.5157E-06
 48 0.9929E-03 -0.9341E-03 0.6473E-03 0.6118E-03 0.5718E-03 -0.4869E-04
 49 -0.1783E-02 0.1749E-02 0.3642E-01 0.1079E-02 0.1058E-02 0.7340E-06
 50 -0.1773E-02 0.1739E-02 -0.3643E-01 0.1084E-02 0.1063E-02 -0.9329E-06
 51 0.9964E-03 -0.9306E-03 -0.6450E-03 0.6099E-03 0.5737E-03 0.4860E-04
 52 0.1085E-03 -0.4310E-04 0.3521E-03 0.7515E-04 0.7131E-04 0.5503E-04
 53 -0.1849E-02 0.1847E-02 0.1982E-01 0.1061E-03 0.1035E-03 -0.1111E-05
 54 -0.1849E-02 0.1846E-02 -0.1983E-01 0.1064E-03 0.1038E-03 0.9024E-06
 55 0.1086E-03 -0.4297E-04 -0.3512E-03 0.7505E-04 0.7143E-04 -0.5512E-04

2 : EIGEN MODE

1 0.1000E+01 0.9651E+00 0.2628E+00 -.1613E-01 0.1672E-01 -.1021E-05

2 0.1000E+01 0.9651E+00 -.4662E-02 -.1613E-01 0.1672E-01 -.1021E-05

3 0.1000E+01 0.9651E+00 0.4662E-02 -.1613E-01 0.1672E-01 -.1021E-05

4 0.1000E+01 0.9651E+00 -.2628E+00 -.1613E-01 0.1672E-01 -.1021E-05

5 0.8208E+00 0.7921E+00 0.2598E+00 -.2626E-01 0.2718E-01 0.5527E-05

6 0.7997E+00 0.7726E+00 0.1170E+00 -.1875E-01 0.1648E-01 -.4960E-03

7 0.8238E+00 0.7952E+00 -.4608E-02 -.2568E-01 0.2663E-01 0.3678E-03

8 0.8005E+00 0.7719E+00 0.1212E+00 -.1591E-01 0.1943E-01 0.4768E-03

9 0.8005E+00 0.7719E+00 -.1212E+00 -.1591E-01 0.1943E-01 -.4787E-03

10 0.8238E+00 0.7952E+00 0.4608E-02 -.2568E-01 0.2663E-01 -.3699E-03

11 0.7998E+00 0.7726E+00 -.1170E+00 -.1875E-01 0.1648E-01 0.4941E-03

12 0.8208E+00 0.7921E+00 -.2598E+00 -.2626E-01 0.2718E-01 -.7558E-05

13 0.7003E+00 0.6759E+00 0.2724E+00 -.2031E-01 0.2110E-01 -.5562E-05

14 0.7072E+00 0.6789E+00 0.1724E+00 -.1865E-01 0.1804E-01 -.4663E-04

15 0.7044E+00 0.6761E+00 0.7872E-01 -.1874E-01 0.1889E-01 -.1664E-02

16 0.7011E+00 0.6767E+00 -.4832E-02 -.2191E-01 0.2265E-01 -.2597E-03

17 0.7033E+00 0.6826E+00 0.1753E+00 -.1738E-01 0.1933E-01 -.1419E-04

18 0.7006E+00 0.6797E+00 -.8489E-01 -.1826E-01 0.1941E-01 -.1663E-02

19 0.7006E+00 0.6797E+00 0.8489E-01 -.1826E-01 0.1941E-01 0.1661E-02

20 0.7033E+00 0.6826E+00 -.1753E+00 -.1738E-01 0.1933E-01 0.1235E-04

21 0.7012E+00 0.6768E+00 0.4832E-02 -.2191E-01 0.2265E-01 0.2577E-03

22 0.7044E+00 0.6761E+00 -.7872E-01 -.1874E-01 0.1889E-01 0.1662E-02

23 0.7072E+00 0.6789E+00 -.1724E+00 -.1865E-01 0.1804E-01 0.4479E-04

24 0.7003E+00 0.6759E+00 -.2724E+00 -.2031E-01 0.2110E-01 0.3617E-05

25 0.5154E+00 0.4979E+00 0.2867E+00 -.1639E-01 0.1699E-01 -.3600E-04

26 0.5025E+00 0.4845E+00 -.5085E-02 -.1655E-01 0.1715E-01 -.1980E-02
 27 0.5156E+00 0.4977E+00 -.1799E-07 -.1447E-01 0.1500E-01 -.9049E-06
 28 0.5025E+00 0.4845E+00 0.5085E-02 -.1655E-01 0.1715E-01 0.1978E-02
 29 0.5154E+00 0.4978E+00 -.2867E+00 -.1639E-01 0.1699E-01 0.3420E-04
 30 0.3502E+00 0.3574E+00 0.1328E+00 -.1405E-01 0.1393E-01 -.1145E-02
 31 0.3703E+00 0.3380E+00 0.1376E+00 -.1344E-01 0.1455E-01 0.1104E-02
 32 0.3703E+00 0.3380E+00 -.1376E+00 -.1344E-01 0.1455E-01 -.1105E-02
 33 0.3502E+00 0.3574E+00 -.1328E+00 -.1405E-01 0.1393E-01 0.1144E-02
 34 0.2294E+00 0.2225E+00 0.2305E+00 -.1055E-01 0.1092E-01 -.5938E-04
 35 0.1969E+00 0.1889E+00 -.4088E-02 -.1040E-01 0.1078E-01 -.3278E-02
 36 0.2299E+00 0.2219E+00 -.1254E-06 -.9667E-02 0.1002E-01 -.8352E-06
 37 0.1969E+00 0.1889E+00 0.4088E-02 -.1040E-01 0.1078E-01 0.3277E-02
 38 0.2294E+00 0.2225E+00 -.2305E+00 -.1055E-01 0.1092E-01 0.5694E-04

39 0.1017E+00 0.1305E+00 0.7870E-01 -.8096E-02 0.7151E-02 -.1100E-
 02
 40 0.1352E+00 0.9821E-01 0.8154E-01 -.6900E-02 0.8389E-02 0.1058E-
 02
 41 0.1352E+00 0.9819E-01 -.8155E-01 -.6902E-02 0.8389E-02 -.1061E-
 02
 42 0.1018E+00 0.1305E+00 -.7870E-01 -.8096E-02 0.7149E-02 0.1096E-
 02
 43 0.4718E-01 0.4616E-01 0.1044E+00 -.8359E-02 0.8648E-02 -.3400E-
 04
 44 0.3015E-01 0.2850E-01 -.1852E-02 -.8064E-02 0.8367E-02 -.1722E-
 02
 45 0.3018E-01 0.2852E-01 0.1852E-02 -.8086E-02 0.8388E-02 0.1711E-
 02
 46 0.4720E-01 0.4614E-01 -.1044E+00 -.8356E-02 0.8651E-02 0.2694E-
 04
 47 0.4748E-01 0.4583E-01 -.2110E-04 -.2684E-02 0.2781E-02 0.2839E-
 04
 48 0.1739E-02 0.1772E-02 0.3643E-01 0.1063E-02 -.1084E-02 -.2977E-
 05
 49 -.9349E-03 -.9975E-03 -.6461E-03 0.5749E-03 -.6128E-03 0.4008E-04
 50 -.9306E-03 -.9929E-03 0.6461E-03 0.5712E-03 -.6093E-03 -.5394E-04
 51 0.1738E-02 0.1773E-02 -.3643E-01 0.1063E-02 -.1084E-02 -.4703E-
 05
 52 0.1846E-02 0.1849E-02 0.1983E-01 0.1034E-03 -.1067E-03 -.4747E-
 05

53 -0.4316E-04 -0.1087E-03 -0.3517E-03 0.7229E-04 -0.7601E-04 -0.6387E-04

54 -0.4291E-04 -0.1085E-03 0.3517E-03 0.7074E-04 -0.7446E-04 0.4960E-04

55 0.1846E-02 0.1849E-02 -0.1983E-01 0.1041E-03 -0.1060E-03 -0.2794E-05

3 : EIGEN MODE

1 0.1000E+01 -0.1000E+01 0.2820E-04 -0.1739E-05 0.1785E-05
0.1250E+00

2 0.1000E+01 0.1000E+01 -0.3606E-06 -0.1739E-05 0.1785E-05
0.1250E+00

3 -0.1000E+01 -0.1000E+01 0.3742E-06 -0.1739E-05 0.1785E-05
0.1250E+00

4 -0.1000E+01 0.1000E+01 -0.2818E-04 -0.1739E-05 0.1785E-05
0.1250E+00

5 0.7604E+00 -0.7604E+00 0.2787E-04 0.4714E-01 0.4714E-01
0.1212E+00

6 0.6482E+00 -0.7710E-05 0.1238E-04 -0.1842E-05 0.5661E-02 0.6920E-01

7 0.7604E+00 0.7604E+00 -0.3557E-06 -0.4714E-01 0.4714E-01
0.1212E+00

8 -0.4607E-05 -0.6482E+00 0.1264E-04 0.5658E-02 0.1852E-05 0.6920E-01

9 -0.5612E-05 0.6482E+00 -0.1269E-04 -0.5661E-02 0.1888E-05 0.6920E-01

10 -0.7604E+00 -0.7604E+00 0.3690E-06 0.4714E-01 -0.4714E-01
0.1212E+00

11 -.6482E+00 -.6705E-05 -.1231E-04 -.1807E-05 -.5658E-02 0.6920E-01
 12 -.7604E+00 0.7604E+00 -.2786E-04 -.4714E-01 -.4714E-01
 0.1212E+00
 13 0.6034E+00 -.6035E+00 0.2876E-04 0.3715E-01 0.3716E-01 0.9568E-
 01
 14 0.5946E+00 -.1884E+00 -.8420E-02 0.6577E-02 0.1621E-01 0.5855E-
 01
 15 0.5946E+00 0.1884E+00 0.8446E-02 -.6580E-02 0.1621E-01 0.5855E-
 01
 16 0.6034E+00 0.6034E+00 -.3670E-06 -.3716E-01 0.3716E-01 0.9568E-
 01
 17 0.1884E+00 -.5947E+00 0.8457E-02 0.1620E-01 0.6580E-02 0.5855E-
 01
 18 0.1884E+00 0.5946E+00 -.8446E-02 -.1621E-01 0.6580E-02 0.5855E-
 01
 19 -.1884E+00 -.5947E+00 -.8430E-02 0.1620E-01 -.6576E-02 0.5855E-
 01
 20 -.1884E+00 0.5946E+00 0.8420E-02 -.1621E-01 -.6577E-02 0.5855E-
 01
 21 -.6035E+00 -.6035E+00 0.3792E-06 0.3715E-01 -.3715E-01 0.9568E-
 01
 22 -.5947E+00 -.1884E+00 0.8430E-02 0.6577E-02 -.1620E-01 0.5855E-
 01
 23 -.5947E+00 0.1884E+00 -.8457E-02 -.6580E-02 -.1620E-01 0.5855E-
 01

24 -.6035E+00 0.6034E+00 -.2875E-04 -.3716E-01 -.3715E-01 0.9568E-01
 25 0.4253E+00 -.4253E+00 0.2963E-04 0.9997E-02 0.1000E-01 0.4610E-01
 26 0.4253E+00 0.4253E+00 -.3776E-06 -.9999E-02 0.9999E-02 0.4610E-01
 27 -.3100E-04 -.3239E-04 0.4919E-08 -.1516E-05 0.1556E-05 0.4440E-01
 28 -.4253E+00 -.4253E+00 0.3874E-06 0.9996E-02 -.9996E-02 0.4610E-01
 29 -.4253E+00 0.4253E+00 -.2962E-04 -.1000E-01 -.9997E-02 0.4610E-01
 30 0.3710E+00 -.4118E-04 0.1382E-04 -.1565E-05 0.3602E-02 0.3313E-01
 31 -.4833E-04 -.3711E+00 0.1538E-04 0.3600E-02 0.1509E-05 0.3313E-01
 32 -.4012E-04 0.3710E+00 -.1417E-04 -.3602E-02 0.1602E-05 0.3313E-01
 33 -.3711E+00 -.4938E-04 -.1502E-04 -.1471E-05 -.3600E-02 0.3313E-01
 34 0.2835E+00 -.2836E+00 0.2893E-04 0.3851E-02 0.3857E-02 0.2385E-01
 35 0.2835E+00 0.2835E+00 -.3069E-06 -.3866E-02 0.3866E-02 0.2386E-01
 36 -.6109E-04 -.6173E-04 0.1470E-07 -.1321E-05 0.1347E-05 0.2538E-01

37 -.2836E+00 -.2836E+00 0.3134E-06 0.3854E-02 -.3854E-02 0.2385E-01

38 -.2836E+00 0.2835E+00 -.2892E-04 -.3857E-02 -.3851E-02 0.2385E-01

39 0.2259E+00 -.2217E-03 0.3639E-04 -.3762E-05 -.2370E-02 0.2401E-01

40 -.1176E-03 -.2260E+00 0.1485E-04 -.2388E-02 0.3582E-05 0.2401E-01

41 -.2213E-03 0.2259E+00 -.3660E-04 0.2370E-02 0.3785E-05 0.2401E-01

42 -.2260E+00 -.1180E-03 -.1463E-04 -.3561E-05 0.2388E-02 0.2401E-01

43 0.1407E+00 -.1408E+00 0.2029E-04 0.3068E-01 0.3062E-01 0.1167E-01

44 0.1407E+00 0.1407E+00 -.1408E-06 -.3055E-01 0.3055E-01 0.1166E-01

45 -.1408E+00 -.1408E+00 0.1431E-06 0.3065E-01 -.3065E-01 0.1167E-01

46 -.1408E+00 0.1407E+00 -.2029E-04 -.3062E-01 -.3068E-01 0.1167E-01

47 -.6410E-04 -.6424E-04 -.3676E-07 -.3213E-03 0.3213E-03 0.1009E-01

48 -.9068E-02 0.9065E-02 0.2565E-05 -.3299E-02 -.3301E-02 0.1848E-01

49 -.9092E-02 -.9092E-02 -.4962E-07 0.3316E-02 -.3316E-02 0.1845E-01

50 0.9074E-02 0.9074E-02 0.5036E-07 -.3305E-02 0.3305E-02 0.1847E-01

```

51 0.9065E-02 -.9068E-02 -.2565E-05 0.3301E-02 0.3299E-02 0.1848E-
01
52 -.6273E-03 0.6274E-03 0.1249E-05 0.1281E-02 0.1281E-02 0.1756E-
01
53 -.6288E-03 -.6288E-03 -.2697E-07 -.1277E-02 0.1277E-02 0.1753E-01
54 0.6278E-03 0.6278E-03 0.2740E-07 0.1280E-02 -.1280E-02 0.1756E-
01
55 0.6274E-03 -.6273E-03 -.1248E-05 -.1281E-02 -.1281E-02 0.1756E-01

END OF DATA

```

Appendix B : Vibration Based SHM and FORM codes.

In this appendix, the MATLAB codes for vibration based SHM techniques are presented. Also presented are MATLAB codes used for calculating first order reliability, and conditional reliability. Artificial Neural network codes for the proposed damage index cumulative slope difference method are also presented.

B.1 Vibration Based SHM Codes

Coordinate Modal assurance criterion

```

%CODE TO calculate COMAC (Coordinate Modal assurance criterion)
clear all
close all
clc

%NUMBER OF ELEMENTS
nelm=55;
%IMPORT VALUES FROM FINITE ELEMENT ANALYSIS

load('macv.mat');

%undamaged modes
ev1=m1;
ev2=m2;
ev3=m3;

%damaged modes

Dev1=m1;
Dev2=m2;

```

```

Dev3=m3;

%eigen mode vector multiplication between damaged and undamaged
structure for all three
%modes
for i=1:1:nelm
    m11dot=(abs(ev1(i,:)*Dev1(i,:)'))^2;
    m12dot=(abs(ev1(i,:)*Dev2(i,:)'))^2;
    m13dot=(abs(ev1(i,:)*Dev3(i,:)'))^2;
    m21dot=(abs(ev2(i,:)*Dev1(i,:)'))^2;
    m22dot=(abs(ev2(i,:)*Dev2(i,:)'))^2;
    m23dot=(abs(ev2(i,:)*Dev3(i,:)'))^2;
    m31dot=(abs(ev3(i,:)*Dev1(i,:)'))^2;
    m32dot=(abs(ev3(i,:)*Dev2(i,:)'))^2;
    m33dot=(abs(ev3(i,:)*Dev3(i,:)'))^2;

    m11dotV{i}=m11dot;
    m12dotV{i}=m12dot;
    m13dotV{i}=m13dot;
    m21dotV{i}=m21dot;
    m22dotV{i}=m22dot;
    m23dotV{i}=m23dot;
    m31dotV{i}=m31dot;
    m32dotV{i}=m32dot;
    m33dotV{i}=m33dot;

end

for i=1:1:nelm

mNUMdot=m11dotV{i}+m12dotV{i}+m13dotV{i}+m21dotV{i}+m22dotV{i}+m23dotV
{i}+m31dotV{i}+m32dotV{i}+m33dotV{i};

    mNUMdotv{i}=mNUMdot;

end

%denominator of comac
for i=1:1:nelm

    denom_undamaged1=((ev1(i,:))*(ev1(i,:))');
    denom_damaged1=(Dev1(i,:)*Dev1(i,:));

    denom_undamaged2=((ev2(i,:))*(ev2(i,:))');
    denom_damaged2=((Dev2(i,:))*(Dev2(i,:))');

```

```

denom_undamaged3=((ev2(i,:))*(ev2(i,:))');
denom_damaged3=((Dev3(i,:))*(Dev3(i,:))');

denom_undamaged1V{i}=denom_undamaged1;
denom_undamaged2V{i}=denom_undamaged2;
denom_undamaged3V{i}=denom_undamaged3;

denom_damaged1V{i}=denom_damaged1;
denom_damaged2V{i}=denom_damaged2;
denom_damaged3V{i}=denom_damaged3;

end

for i=1:1:nelm

denomNUM=(denom_undamaged1V{i}+denom_undamaged2V{i}+denom_undamaged3V{
i})*(denom_damaged1V{i}+denom_damaged2V{i}+denom_damaged3V{i})';

denomNUMV{i}=denomNUM;
end

for i=1:1:nelm

COMAC=mNUMdotv{i}/denomNUMV{i};
%comac index
COMACV{i}=COMAC;
end

```

Modal strain Energy and Cross Modal Strain Energy

```

%CODE TO CALCULATE GLOBAL STIFFNESS MATRIX
clear all
close all
clc

%IMPORT VALUES FROM FINITE ELEMENT ANALYSIS
load('undamagedmodelnewMSEUSE.mat');

nsamples=500;
for i=1:1:nsamples

E=20.0e10+(rand(1)*1.5e10);
v=0.25;

J=Iy+Iz; G=E/(2*(1+v));

```

```

% generation of coordinates and connectivities
xx=nodeCoordinates(:,1);
yy=nodeCoordinates(:,2);
zz=nodeCoordinates(:,3);
numberNodes=size(nodeCoordinates,1);
numberElements=size(elementNodes,1);

% for structure:
% stiffness: stiffness matrix
% GDof: global number of degrees of freedom

GDof=6*numberNodes;
stiffness=zeros(GDof,GDof);

% Global stiffness matrix
[stiffness]=
formStiffness3Dframe(GDof,numberElements,elementNodes,numberNodes,
deCoordinates,E,A,Iz,Iy,G,J);

%individual stiffness matrix global
kstiffness =
formStiffness3Dframeindividual(GDof,numberElements,elementNodes,
numberNodes,nodeCoordinates,E,A,Iz,Iy,G,J);

%individual stiffness matrix local
kstiffnessl=
formStiffness3Dframeindividuallocal(GDof,numberElements,elementNodes,
numberNodes,nodeCoordinates,E,A,Iz,Iy,G,J);

%IMPORT VALUES OF FIRST 3 MODE SHAPES FROM FINITE ELEMENT ANALYSIS

%undamaged platform
load('undamagedmodelnewAUG17Pu.mat')

%damaged platform in element 5
%load('damageplatformELEMENT5stiffness0_5_reduced.mat')
%load('damageplatformELEMENT5stiffness_50_reduced.mat')

%damaged platform in element 14
%load('damageplatformELEMENT14stiffness0_5_reduced.mat')
%load('damageplatformELEMENT14stiffness_50_reduced.mat')

%damaged platform in element 104
%load('damageplatformELEMENT104stiffness_50_reduced.mat')

%damaged platform in element 52
%load('damageplatformELEMENT52stiffness_50_reduced.mat')

```

```

%damaged platform in element 76
load('damageplatformELEMENT76stiffness_50_reduced.mat')

%damaged platform in element 36
%load('damageplatformELEMENT36stiffness_05_reduced.mat')

%damaged platform in element 109
%load('damageplatformELEMENT109stiffness_50_reduced.mat')

%damaged platform in element 94
%load('damageplatformELEMENT94stiffness_05_reduced.mat')

%damaged platform in element 92
%load('damageplatformELEMENT92stiffness0_5_reduced.mat')

%damaged platform in element 64
%load('damageplatformELEMENT64stiffness_38_reduced.mat')

%damaged platform in element 109
%load('damageplatformELEMENT109stiffness_50_reduced.mat')

%add a percent noise to undamaged mode shape and natural frequency
n_oise=0.001/100;
m1=m1.*(1+rand(55,6)*(n_oise));
m2=m2.*(1+rand(55,6)*(n_oise));
m3=m3.*(1+rand(55,6)*(n_oise));
W1=W1*(1+rand(1)*(n_oise));
W2=W2*(1+rand(1)*(n_oise));
W3=W3*(1+rand(1)*(n_oise));

%add a percent noise to damaged mode shape
dm1=dm1.*(1+rand(55,6)*(n_oise));
dm2=dm2.*(1+rand(55,6)*(n_oise));
dm3=dm3.*(1+rand(55,6)*(n_oise));
W1D=W1D*(1+rand(1)*(n_oise));
W2D=W2D*(1+rand(1)*(n_oise));
W3D=W3D*(1+rand(1)*(n_oise));

%damaged element for severity
de=76;
%damage detection via stubbs index
zMse(:,i)=formzMSE2(m1,m2,m3,dm1,dm2,dm3,kstiffness,stiffness,numberEl
ements, elementNodes, GDof);
%damage detection via modal strain energy change ratio
zMseCR(:,i)=formzMSECR(m1,m2,m3,dm1,dm2,dm3,kstiffness,stiffness,numbe
rElements,elementNodes, GDof, E);

```

```

%crack severity response via cross modal strain energy
zE(:,i)=crackseverityzMSE(m1,m2,m3,dm1,dm2,dm3,kstiffness,stiffness,numberElements,elementNodes, GDof, E, W1, W2, W3, W1D, W2D, W3D, de);

end

%mean and standard deviation of stubb index
m_zMse=funcm_zMse(zMse,zMseCR,numberElements);
std__zMse=funcstd__zMse(zMse,zMseCR,numberElements);

%mean and standard deviation of modal strain energy change ratio
m_zMseCR=funcm_zMseCR(zMse,zMseCR,numberElements);
std__zMseCR=funcstd__zMseCR(zMse,zMseCR,numberElements);

%mean and standard deviation of crack severity estimation
m_zE=mean(zE(1,:));
std__zE=std(zE(1,:));
%plot damage detection functions

subplot(1,2,1);
plot (m_zMse);
subplot(1,2,2);
plot(m_zMseCR)

```

Functions used in the code:

Function 1

```

function [stiffness]=
formStiffness3Dframe(GDof,numberElements,elementNodes,numberNodes,no
deCoordinates,E,A,Iz,Iy,G,J);

stiffness=zeros(GDof);
% computation of the system stiffness matrix

for e=1:numberElements
% elementDof: element degrees of freedom (Dof)
indice=elementNodes(e,:);
elementDof=[6*indice(1)-5 6*indice(1)-4 6*indice(1)-3 ...
6*indice(1)-2 6*indice(1)-1 6*indice(1)...
6*indice(2)-5 6*indice(2)-4 6*indice(2)-3 ...
6*indice(2)-2 6*indice(2)-1 6*indice(2)] ;
x1=nodeCoordinates(indice(1),1);
y1=nodeCoordinates(indice(1),2);
z1=nodeCoordinates(indice(1),3);
x2=nodeCoordinates(indice(2),1);

y2=nodeCoordinates(indice(2),2);
z2=nodeCoordinates(indice(2),3);
L = sqrt((x2-x1)*(x2-x1) + (y2-y1)*(y2-y1) + (z2-z1)*(z2-z1));
k1 = E*A(e,1)/L;
k2 = 12*E*Iz(e,1)/(L*L*L);
k3 = 6*E*Iz(e,1)/(L*L);
k4 = 4*E*Iz(e,1)/L;

```

```

k5 = 2*E*Iz(e,1)/L;
k6 = 12*E*Iy(e,1)/(L*L*L);
k7 = 6*E*Iy(e,1)/(L*L);
k8 = 4*E*Iy(e,1)/L;
k9 = 2*E*Iy(e,1)/L;
k10 = G*J(e,1)/L;

a=[k1 0 0; 0 k2 0; 0 0 k6];
b=[ 0 0 0;0 0 k3; 0 -k7 0];
c=[k10 0 0;0 k8 0; 0 0 k4];
d=[-k10 0 0;0 k9 0;0 0 k5];
k = [a b -a b;b' c b d; (-a)' b' a -b;b' d' (-b)' c];

```

```

if x1 == x2 & y1 == y2
if z2 > z1
Lambda = [0 0 1 ; 0 1 0 ; -1 0 0];
else
Lambda = [0 0 -1 ; 0 1 0 ; 1 0 0];
end
else
CXx = (x2-x1)/L;
CYx = (y2-y1)/L;
CZx = (z2-z1)/L;
D = sqrt(CXx*CXx + CYx*CYx);
CXy = -CYx/D;
CYy = CXx/D;
CZy = 0;
CXz = -CXx*CZx/D;
CYz = -CYx*CZx/D;
CZz = D;
Lambda = [CXx CYx CZx ;CXy CYy CZy ;CXz CYz CZz];
end

```

```

R = [Lambda zeros(3,9); zeros(3) Lambda zeros(3,6); zeros(3,6) Lambda
zeros(3);zeros(3,9) Lambda];
stiffness(elementDof,elementDof)=
stiffness(elementDof,elementDof)+R'*k*R;
end

```

Function 2

```

function kstiffness=
formStiffness3Dframeindividualte(GDof,numberElements,elementNodes,numb
erNodes,nodeCoordinates,E,A,Iz,Iy,G,J);

```

```

% computation of the system stiffness matrix

```

```

for e=1:numberElements
% elementDof: element degrees of freedom (Dof)
indice=elementNodes(e,:);
elementDof=[6*indice(1)-5 6*indice(1)-4 6*indice(1)-3 ...
6*indice(1)-2 6*indice(1)-1 6*indice(1) ...
6*indice(2)-5 6*indice(2)-4 6*indice(2)-3 ...

```

```

6*indice(2)-2 6*indice(2)-1 6*indice(2)] ;
x1=nodeCoordinates(indice(1),1);
y1=nodeCoordinates(indice(1),2);
z1=nodeCoordinates(indice(1),3);
x2=nodeCoordinates(indice(2),1);

y2=nodeCoordinates(indice(2),2);
z2=nodeCoordinates(indice(2),3);
L = sqrt((x2-x1)*(x2-x1) + (y2-y1)*(y2-y1) + (z2-z1)*(z2-z1));
k1 = E*A(e,1)/L;
k2 = 12*E*Iz(e,1)/(L*L*L);
k3 = 6*E*Iz(e,1)/(L*L);
k4 = 4*E*Iz(e,1)/L;
k5 = 2*E*Iz(e,1)/L;
k6 = 12*E*Iy(e,1)/(L*L*L);
k7 = 6*E*Iy(e,1)/(L*L);
k8 = 4*E*Iy(e,1)/L;
k9 = 2*E*Iy(e,1)/L;
k10 = G*J(e,1)/L;

a=[k1 0 0; 0 k2 0; 0 0 k6];
b=[ 0 0 0;0 0 k3; 0 -k7 0];
c=[k10 0 0;0 k8 0; 0 0 k4];
d=[-k10 0 0;0 k9 0;0 0 k5];
k = [a b -a b;b' c b d; (-a)' b' a -b;b' d' (-b)' c];

if x1 == x2 & y1 == y2
if z2 > z1
Lambda = [0 0 1 ; 0 1 0 ; -1 0 0];
else
Lambda = [0 0 -1 ; 0 1 0 ; 1 0 0];
end
else
CXx = (x2-x1)/L;
CYx = (y2-y1)/L;
CZx = (z2-z1)/L;
D = sqrt(CXx*CXx + CYx*CYx);
CXy = -CYx/D;
CYy = CXx/D;
CZy = 0;
CXz = -CXx*CZx/D;
CYz = -CYx*CZx/D;
CZz = D;
Lambda = [CXx CYx CZx ;CXy CYy CZy ;CXz CYz CZz];
end

R = [Lambda zeros(3,9); zeros(3) Lambda zeros(3,6); zeros(3,6) Lambda
zeros(3);zeros(3,9) Lambda];
stiffnessv= R'*k*R;
kstiffness{e}=stiffnessv/E;
end

```

Function 3

```

function kstiffnessl=
formStiffness3Dframeindividuallocalte (GDof,numberElements,elementNodes,
numberNodes,nodeCoordinates,E,A,Iz,Iy,G,J);

% computation of the system stiffness matrix

for e=1:numberElements
% elementDof: element degrees of freedom (Dof)
indice=elementNodes(e,:);
elementDof=[6*indice(1)-5 6*indice(1)-4 6*indice(1)-3 ...
6*indice(1)-2 6*indice(1)-1 6*indice(1)...
6*indice(2)-5 6*indice(2)-4 6*indice(2)-3 ...
6*indice(2)-2 6*indice(2)-1 6*indice(2)] ;
x1=nodeCoordinates(indice(1),1);
y1=nodeCoordinates(indice(1),2);
z1=nodeCoordinates(indice(1),3);
x2=nodeCoordinates(indice(2),1);

y2=nodeCoordinates(indice(2),2);
z2=nodeCoordinates(indice(2),3);
L = sqrt((x2-x1)*(x2-x1) + (y2-y1)*(y2-y1) + (z2-z1)*(z2-z1));
k1 = E*A(e,1)/L;
k2 = 12*E*Iz(e,1)/(L*L*L);
k3 = 6*E*Iz(e,1)/(L*L);
k4 = 4*E*Iz(e,1)/L;
k5 = 2*E*Iz(e,1)/L;
k6 = 12*E*Iy(e,1)/(L*L*L);
k7 = 6*E*Iy(e,1)/(L*L);
k8 = 4*E*Iy(e,1)/L;
k9 = 2*E*Iy(e,1)/L;
k10 = G*J(e,1)/L;

a=[k1 0 0; 0 k2 0; 0 0 k6];
b=[ 0 0 0;0 0 k3; 0 -k7 0];
c=[k10 0 0;0 k8 0; 0 0 k4];
d=[-k10 0 0;0 k9 0;0 0 k5];
k = [a b -a b;b' c b d; (-a)' b' a -b;b' d' (-b)' c];

if x1 == x2 & y1 == y2
if z2 > z1
Lambda = [0 0 1 ; 0 1 0 ; -1 0 0];
else
Lambda = [0 0 -1 ; 0 1 0 ; 1 0 0];
end
else
CXx = (x2-x1)/L;
CYx = (y2-y1)/L;
CZx = (z2-z1)/L;
D = sqrt(CXx*CXx + CYx*CYx);
CXy = -CYx/D;
CYy = CXx/D;
CZy = 0;
CXz = -CXx*CZx/D;

```

```

CYz = -CYx*CZx/D;
CZz = D;
Lambda = [CXx CYx CZx ;CXy CYy CZy ;CXz CYz CZz];
end

```

```

R = [Lambda zeros(3,9); zeros(3) Lambda zeros(3,6); zeros(3,6) Lambda
zeros(3);zeros(3,9) Lambda];
stiffnessv= R'*k*R;
kstiffness1{e}=k/E;
end

```

Function 4

```

function
zMse2=formzMSE2(m1,m2,m3,dm1,dm2,dm3,kstiffness,stiffness,numberElemen
ts,elementNodes, GDof);

%global mode shape arrangement per mode
%undamaged
tev1 = reshape(m1',GDof,1);
tev2 = reshape(m2',GDof,1);
tev3 = reshape(m3',GDof,1);
%damaged
Dtev1 = reshape(dm1',GDof,1);
Dtev2 = reshape(dm2',GDof,1);
Dtev3 = reshape(dm3',GDof,1);

%setup mode shapes per element for undamaged and damaged per modes
for i=1:numberElements

    %undamaged 3 modes
    rm1=(horzcat(m1(elementNodes(i,1),:),m1(elementNodes(i,2),:)))';
    rmm1{i}=rm1;

    rm2=(horzcat(m2(elementNodes(i,1),:),m2(elementNodes(i,2),:)))';
    rmm2{i}=rm2;

    rm3=(horzcat(m3(elementNodes(i,1),:),m3(elementNodes(i,2),:)))';
    rmm3{i}=rm3;

    %damaged 3 modes

    drml=(horzcat(dm1(elementNodes(i,1),:),dm1(elementNodes(i,2),:)))';
    drmm1{i}=drml;

    drm2=(horzcat(dm2(elementNodes(i,1),:),dm2(elementNodes(i,2),:)))';
    drmm2{i}=drm2;

    drm3=(horzcat(dm3(elementNodes(i,1),:),dm3(elementNodes(i,2),:)))';
    drmm3{i}=drm3;

end

```

```

for e=1:numberElements

    %mode 1
    b1num =
    ((drmm1{e}'*kstiffness{e}*drmm1{e})+(Dtev1'*stiffness*Dtev1))*((tev1'*
    stiffness*tev1));
    b1denom =
    ((rmm1{e}'*kstiffness{e}*rmm1{e})+(tev1'*stiffness*tev1))*((Dtev1'*sti
    ffness*Dtev1));

    %mode 2
    b2num =
    ((drmm2{e}'*kstiffness{e}*drmm2{e})+(Dtev2'*stiffness*Dtev2))*((tev2'*
    stiffness*tev2));
    b2denom =
    ((rmm2{e}'*kstiffness{e}*rmm2{e})+(tev2'*stiffness*tev2))*((Dtev2'*sti
    ffness*Dtev2));

    %mode 3

    b3num =
    ((drmm3{e}'*kstiffness{e}*drmm3{e})+(Dtev3'*stiffness*Dtev3))*((tev3'*
    stiffness*tev3));
    b3denom =
    ((rmm3{e}'*kstiffness{e}*rmm3{e})+(tev3'*stiffness*tev3))*((Dtev3'*sti
    ffness*Dtev3));

    beta = ((b1num/b1denom)+(b2num/b2denom)+(b3num/b3denom));

    beta_j{e}=beta;

end

for u=1:1:numberElements
    be_j(u,1)=beta_j{u};
end

%damage index

stddev_beta=std(be_j);

```

```

mean_beta=mean (be_j) ;

for i=1:1:numberElements

    z=(be_j (i,1)-mean_beta)/stdev_beta;
    z_j{i}=z;
end

zMse2=z_j';

end

```

Function 5

```

function
zMseCR=formzMSECR(m1,m2,m3,dm1,dm2,dm3,kstiffness,stiffness,numberElem
ents,elementNodes, GDof, E);

%global mode shape arrangement per mode
%undamaged
%tev1 = reshape(m1',GDof,1);
%tev2 = reshape(m2',GDof,1);
%tev3 = reshape(m3',GDof,1);
%damaged
%Dtev1 = reshape(dm1',GDof,1);
%Dtev2 = reshape(dm2',GDof,1);
%Dtev3 = reshape(dm3',GDof,1);

%setup mode shapes per element for undamaged and damaged per modes
for i=1:1:numberElements

    %undamaged 3 modes
    rm1=(horzcat(m1(elementNodes(i,1),:),m1(elementNodes(i,2),:)))';
    rmm1{i}=rm1;

    rm2=(horzcat(m2(elementNodes(i,1),:),m2(elementNodes(i,2),:)))';
    rmm2{i}=rm2;

    rm3=(horzcat(m3(elementNodes(i,1),:),m3(elementNodes(i,2),:)))';
    rmm3{i}=rm3;

    %damaged 3 modes

    drml=(horzcat(dm1(elementNodes(i,1),:),dm1(elementNodes(i,2),:)))';
    drmm1{i}=drml;

    drm2=(horzcat(dm2(elementNodes(i,1),:),dm2(elementNodes(i,2),:)))';
    drmm2{i}=drm2;

```

```

drmm3{e}=(horzcat(dm3(elementNodes(i,1),:),dm3(elementNodes(i,2),:)))';
drmm3{i}=drmm3{e};

end

for e=1:numberElements

    %mode 1
    b1num = ((drmm1{e}'*(E*kstiffness{e})*drmm1{e}));
    b1denom = ((rmm1{e}'*(E*kstiffness{e})*rmm1{e}));

    %mode 2
    b2num = ((drmm2{e}'*(E*kstiffness{e})*drmm2{e}));
    b2denom = ((rmm2{e}'*(E*kstiffness{e})*rmm2{e}));

    %mode 3
    b3num = ((drmm3{e}'*(E*kstiffness{e})*drmm3{e}));
    b3denom = ((rmm3{e}'*(E*kstiffness{e})*rmm3{e}));

    MSECRJ1=(abs(b1num-b1denom))/b1denom;
    MSECRJ2=(abs(b2num-b2denom))/b2denom;
    MSECRJ3=(abs(b3num-b3denom))/b3denom;

    MSECRJ1v{e}=MSECRJ1;
    MSECRJ2v{e}=MSECRJ2;
    MSECRJ3v{e}=MSECRJ3;

end

%find maximum VALUE OF MSECR IN EACH MODE
tt=zeros(1,numberElements);
rr=zeros(1,numberElements);
ss=zeros(1,numberElements);

for i=1:1:numberElements
    tt(1,i)=MSECRJ1v{i};
    rr(1,i)=MSECRJ2v{i};
    ss(1,i)=MSECRJ3v{i};

end

ntt=max(tt(:));
nrr=max(rr(:));

```

```

nss=max(ss(:));

for i=1:1:numberElements

MSECRJV=(1/3)*(MSECRJ1v{i}/ntt)+(MSECRJ2v{i}/nrr)+(MSECRJ3v{i}/nss);
MSECRJVn{i}=MSECRJV;

end

zMseCR=MSECRJVn';

end

```

Function 6

```

function
zE=crackseverityzMSE(m1,m2,m3,dm1,dm2,dm3,kstiffness,stiffness,numberE
lements,elementNodes, GDof, E, W1, W2, W3, W1D, W2D, W3D, de);

%global mode shape arrangement per mode
%undamaged
tev1 = reshape(m1',GDof,1);
tev2 = reshape(m2',GDof,1);
tev3 = reshape(m3',GDof,1);
%damaged
Dtev1 = reshape(dm1',GDof,1);
Dtev2 = reshape(dm2',GDof,1);
Dtev3 = reshape(dm3',GDof,1);

%setup mode shapes per element for undamaged and damaged per modes
for i=1:1:numberElements

%undamaged 3 modes
rm1=(horzcat(m1(elementNodes(i,1),:),m1(elementNodes(i,2),:)))';
rmm1{i}=rm1;

rm2=(horzcat(m2(elementNodes(i,1),:),m2(elementNodes(i,2),:)))';
rmm2{i}=rm2;

rm3=(horzcat(m3(elementNodes(i,1),:),m3(elementNodes(i,2),:)))';
rmm3{i}=rm3;

%damaged 3 modes
drml=(horzcat(dm1(elementNodes(i,1),:),dm1(elementNodes(i,2),:)))';
drmm1{i}=drml;

```

```

drm2=(horzcat(dm2(elementNodes(i,1),:),dm2(elementNodes(i,2),:)))';
drmm2{i}=drm2;

drm3=(horzcat(dm3(elementNodes(i,1),:),dm3(elementNodes(i,2),:)))';
drmm3{i}=drm3;

end

for e=1:numberElements

    %mode 1
    b1num =
    ((drmm1{e}'*kstiffness{e}*drmm1{e})+(Dtev1'*stiffness*Dtev1))*((tev1'*
stiffness*tev1));
    b1denom =
    ((rmm1{e}'*kstiffness{e}*rmm1{e})+(tev1'*stiffness*tev1))*((Dtev1'*sti
ffness*Dtev1));

    %mode 2
    b2num =
    ((drmm2{e}'*kstiffness{e}*drmm2{e})+(Dtev2'*stiffness*Dtev2))*((tev2'*
stiffness*tev2));
    b2denom =
    ((rmm2{e}'*kstiffness{e}*rmm2{e})+(tev2'*stiffness*tev2))*((Dtev2'*sti
ffness*Dtev2));

    %mode 3

    b3num =
    ((drmm3{e}'*kstiffness{e}*drmm3{e})+(Dtev3'*stiffness*Dtev3))*((tev3'*
stiffness*tev3));
    b3denom =
    ((rmm3{e}'*kstiffness{e}*rmm3{e})+(tev3'*stiffness*tev3))*((Dtev3'*sti
ffness*Dtev3));

    beta = ((b1num/b1denom)+(b2num/b2denom)+(b3num/b3denom));

    beta_j{e}=beta;

end

```

```

for u=1:1:numberElements
    be_j(u,1)=beta_j{u};

end

%MODE 1 DAMAGE ASSESSMENT
EE1=(tev1'*stiffness*Dtev1);
EE2=(tev2'*stiffness*Dtev2);
EE3=(tev3'*stiffness*Dtev3);

%EE4=(tev2'*stiffness*Dtev1);
%EE5=(tev2'*stiffness*Dtev2);
%EE6=(tev2'*stiffness*Dtev3);

%EE7=(tev3'*stiffness*Dtev1);
%EE8=(tev3'*stiffness*Dtev2);
%EE9=(tev3'*stiffness*Dtev3);

%EIGEN VALUE FREQUENCY FOR UNDAMAGED MODES
%W1=7.3282E+00;
%W2=77.3282E+00;
%W3=3.3193E+01;

%EIGEN VALUE FREQUENCY FOR DAMAGED MODES
%W1D=7.3279E+00;
%W2D=7.3282E+00;
%W3D=3.3193E+01;

BB1=((W1D/W1)-1)*EE1;
BB2=((W2D/W2)-1)*EE2;
BB3=((W3D/W3)-1)*EE3;

BB=[BB1; BB2; BB3];

%damaged element
%de=5;
EN1=(rmm1{de}*(E*kstiffness{de})*drmm1{de});
EN2=(rmm2{de}*(E*kstiffness{de})*drmm2{de});
EN3=(rmm3{de}*(E*kstiffness{de})*drmm3{de});

EN=[EN1; EN2; EN3];

```

```
ALPH=inv (EN'*EN) *EN'*BB;
```

```
zE=ALPH*100;
```

```
end
```

Function 7

```
function m_zMse=funcm_zMse(zMse,zMseCR,numberElements)
```

```
%convert to matrix
```

```
zMse_M=cell2mat(zMse);
```

```
zMseCR_M=cell2mat(zMseCR);
```

```
for i=1:numberElements
```

```
%mean and standard deviation of stubb index
```

```
    m_zMse(i)=(mean(zMse_M(i,:)));
```

```
    std__zMse(i)=std(zMse_M(i,:));
```

```
%mean and standard deviation of modal strain energy ratio
```

```
    m_zMseCR(i)=mean(zMseCR_M(i,:));
```

```
    std__zMseCR(i)=std(zMseCR_M(i,:));
```

```
end
```

```
m_zMse=m_zMse';
```

```
std__zMse=std__zMse';
```

```
m_zMseCR=m_zMseCR';
```

```
std__zMseCR=std__zMseCR';
```

```
end
```

Function 8

```
function std__zMse=funcstd__zMse(zMse,zMseCR,numberElements)
```

```
%convert to matrix
```

```
zMse_M=cell2mat(zMse);
```

```
zMseCR_M=cell2mat(zMseCR);
```

```
for i=1:numberElements
```

```
%mean and standard deviation of stubb index
```

```
    m_zMse(i)=(mean(zMse_M(i,:)));
```

```
    std__zMse(i)=std(zMse_M(i,:));
```

```
%mean and standard deviation of modal strain energy ratio
```

```
    m_zMseCR(i)=mean(zMseCR_M(i,:));
```

```

std__zMseCR(i)=std(zMseCR_M(i,:));

end

m_zMse=m_zMse';
std__zMse=std__zMse';
m_zMseCR=m_zMseCR';
std__zMseCR=std__zMseCR';

end

```

Function 9

```

function m_zMseCR=funcm_zMseCR(zMse,zMseCR,numberElements)

%convert to matrix

zMse_M=cell2mat(zMse);
zMseCR_M=cell2mat(zMseCR);

for i=1:1:numberElements
%mean and standard deviation of stubb index
    m_zMse(i)=(mean(zMse_M(i,:)));
    std__zMse(i)=std(zMse_M(i,:));

    %mean and standard deviation of modal strain energy ratio
    m_zMseCR(i)=mean(zMseCR_M(i,:));
    std__zMseCR(i)=std(zMseCR_M(i,:));

end

m_zMse=m_zMse';
std__zMse=std__zMse';
m_zMseCR=m_zMseCR';
std__zMseCR=std__zMseCR';

end

```

Function 10

```

function std__zMseCR=funcstd__zMseCR(zMse,zMseCR,numberElements)

%convert to matrix

zMse_M=cell2mat(zMse);
zMseCR_M=cell2mat(zMseCR);

for i=1:1:numberElements
%mean and standard deviation of stubb index
    m_zMse(i)=(mean(zMse_M(i,:)));
    std__zMse(i)=std(zMse_M(i,:));

    %mean and standard deviation of modal strain energy ratio

```

```

m_zMseCR(i)=mean(zMseCR_M(i,:));
std__zMseCR(i)=std(zMseCR_M(i,:));

end

m_zMse=m_zMse';
std__zMse=std__zMse';
m_zMseCR=m_zMseCR';
std__zMseCR=std__zMseCR';

end

```

Damage Index Cumulative Slope Difference

This is the MATLAB code for the Damage index cumulative slope difference SHM technique developed in this thesis.

```

clear all
close all
clc

%MATLAB code for the Damage index cumulative slope difference SHM
technique developed in this thesis.

load('undamagedmodelnewMSEUSE.mat');

%undamaged platform
load('undamagedmodelnewAUG17Pu.mat')

%damaged platform in element 5
load('damageplatformELEMENT109stiffness_5_reduced.mat')
true_d_elem=109;
true_d_sever=1; %(very low =1 (0.5,1,3), low =10 (5,7), medium = 100
(10,15), high = 1,000 (25-50))

nsamples=500;
for iit=1:1:nsamples
% generation of coordinates and connectivities
xx=nodeCoordinates(:,1);
yy=nodeCoordinates(:,2);
zz=nodeCoordinates(:,3);
numberNodes=size(nodeCoordinates,1);
numberElements=size(elementNodes,1);
GDof=6*numberNodes;

%add a percent noise to undamaged mode shape and natural frequency
n_oise=0.001/100;

```

```

m1=m1.*(1+rand(55,6)*(n_oise));
m2=m2.*(1+rand(55,6)*(n_oise));
m3=m3.*(1+rand(55,6)*(n_oise));

%add a percent noise to damaged mode shape
dm1=dm1.*(1+rand(55,6)*(n_oise));
dm2=dm2.*(1+rand(55,6)*(n_oise));
dm3=dm3.*(1+rand(55,6)*(n_oise));

%global mode shape arrangement per mode
%undamaged
tev1 = reshape(m1',GDof,1);
tev2 = reshape(m2',GDof,1);
tev3 = reshape(m3',GDof,1);
%damaged
Dtev1 = reshape(dm1',GDof,1);
Dtev2 = reshape(dm2',GDof,1);
Dtev3 = reshape(dm3',GDof,1);

%setup mode shapes per element for undamaged and damaged per modes
for i=1:numberElements

    %undamaged 3 modes
    rm1=(horzcat(m1(elementNodes(i,1),:),m1(elementNodes(i,2),:)))';
    rmm1{i}=rm1;

    rm2=(horzcat(m2(elementNodes(i,1),:),m2(elementNodes(i,2),:)))';
    rmm2{i}=rm2;

    rm3=(horzcat(m3(elementNodes(i,1),:),m3(elementNodes(i,2),:)))';
    rmm3{i}=rm3;

    %damaged 3 modes

    drml=(horzcat(dm1(elementNodes(i,1),:),dm1(elementNodes(i,2),:)))';
    drmm1{i}=drml;

    drmm2=(horzcat(dm2(elementNodes(i,1),:),dm2(elementNodes(i,2),:)))';
    drmm2{i}=drmm2;

    drmm3=(horzcat(dm3(elementNodes(i,1),:),dm3(elementNodes(i,2),:)))';
    drmm3{i}=drmm3;

end

```

```

for i=1:1:numberElements

    %undamaged modes per element for modes 1,2,3
    zutt1=cell2mat(rmm1);
    undm1=zutt1';

    zutt2=cell2mat(rmm2);
    undm2=zutt2';

    zutt3=cell2mat(rmm3);
    undm3=zutt3';

    %damaged modes per element for modes 1,2,3
    dzutt1=cell2mat(drmm1);
    dundm1=dzutt1';

    dzutt2=cell2mat(drmm2);
    dundm2=dzutt2';

    dzutt3=cell2mat(drmm3);
    dundm3=dzutt3';

end

%axial resultant modes and torsional resultant modes

for i=1:1:numberElements
zap(i,:)=[sqrt((undm1(i,1)^2)+(undm1(i,2)^2)+(undm1(i,3)^2)),sqrt((undm1(i,4)^2)+(undm1(i,5)^2)+(undm1(i,6)^2)),sqrt((undm1(i,7)^2)+(undm1(i,8)^2)+(undm1(i,9)^2)),sqrt((undm1(i,10)^2)+(undm1(i,11)^2)+(undm1(i,12)^2))];
zap2(i,:)=[sqrt((undm2(i,1)^2)+(undm2(i,2)^2)+(undm2(i,3)^2)),sqrt((undm2(i,4)^2)+(undm2(i,5)^2)+(undm2(i,6)^2)),sqrt((undm2(i,7)^2)+(undm2(i,8)^2)+(undm2(i,9)^2)),sqrt((undm2(i,10)^2)+(undm2(i,11)^2)+(undm2(i,12)^2))];
zap3(i,:)=[sqrt((undm3(i,1)^2)+(undm3(i,2)^2)+(undm3(i,3)^2)),sqrt((undm3(i,4)^2)+(undm3(i,5)^2)+(undm3(i,6)^2)),sqrt((undm3(i,7)^2)+(undm3(i,8)^2)+(undm3(i,9)^2)),sqrt((undm3(i,10)^2)+(undm3(i,11)^2)+(undm3(i,12)^2))];

dzap(i,:)=[sqrt((dundm1(i,1)^2)+(dundm1(i,2)^2)+(dundm1(i,3)^2)),sqrt((dundm1(i,4)^2)+(dundm1(i,5)^2)+(dundm1(i,6)^2)),sqrt((dundm1(i,7)^2)+(dundm1(i,8)^2)+(dundm1(i,9)^2)),sqrt((dundm1(i,10)^2)+(dundm1(i,11)^2)+(dundm1(i,12)^2))];
dzap2(i,:)=[sqrt((dundm2(i,1)^2)+(dundm2(i,2)^2)+(dundm2(i,3)^2)),sqrt((dundm2(i,4)^2)+(dundm2(i,5)^2)+(dundm2(i,6)^2)),sqrt((dundm2(i,7)^2)+(dundm2(i,8)^2)+(dundm2(i,9)^2)),sqrt((dundm2(i,10)^2)+(dundm2(i,11)^2)+(dundm2(i,12)^2))];
dzap3(i,:)=[sqrt((dundm3(i,1)^2)+(dundm3(i,2)^2)+(dundm3(i,3)^2)),sqrt((dundm3(i,4)^2)+(dundm3(i,5)^2)+(dundm3(i,6)^2)),sqrt((dundm3(i,7)^2)+(dundm3(i,8)^2)+(dundm3(i,9)^2)),sqrt((dundm3(i,10)^2)+(dundm3(i,11)^2)+(dundm3(i,12)^2))];

```

end

%curvature damaged and undamaged modes for axial and torsional
for i=1:1:numberElements

 %axial curvature

 %undamaged

 undcurv(i,:)=[(zap(i,1)-zap(i,3))/L(i)];

 undcurv2(i,:)=[(zap2(i,1)-zap2(i,3))/L(i)];

 undcurv3(i,:)=[(zap3(i,1)-zap3(i,3))/L(i)];

 %damaged

 dundcurv(i,:)=[(dzap(i,1)-dzap(i,3))/L(i)];

 dundcurv2(i,:)=[(dzap2(i,1)-dzap2(i,3))/L(i)];

 dundcurv3(i,:)=[(dzap3(i,1)-dzap3(i,3))/L(i)];

 %torsional curvature

 undcurvT(i,:)=[(zap(i,2)-zap(i,4))/L(i)];

 undcurvT2(i,:)=[(zap2(i,2)-zap2(i,4))/L(i)];

 undcurvT3(i,:)=[(zap3(i,2)-zap3(i,4))/L(i)];

 %damaged

 dundcurvT(i,:)=[(dzap(i,2)-dzap(i,4))/L(i)];

 dundcurvT2(i,:)=[(dzap2(i,2)-dzap2(i,4))/L(i)];

 dundcurvT3(i,:)=[(dzap3(i,2)-dzap3(i,4))/L(i)];

end

%curvature difference

for i=1:1:numberElements

 %curvature difference

 cdiff_axial(i,:)=abs(-dundcurv(i,:)+undcurv(i,:));

 cdiff_torsional(i,:)=abs(-dundcurvT(i,:)+undcurvT(i,:));

 cdiff_axial2(i,:)=abs(-dundcurv2(i,:)+undcurv2(i,:));

 cdiff_torsional2(i,:)=abs(-dundcurvT2(i,:)+undcurvT2(i,:));

 cdiff_axial3(i,:)=abs(-dundcurv3(i,:)+undcurv3(i,:));

 cdiff_torsional3(i,:)=abs(-dundcurvT3(i,:)+undcurvT3(i,:));

end

stdev_cdiff_axial=std(cdiff_axial);

mean_cdiff_axial=mean(cdiff_axial);

stdev_cdiff_axial2=std(cdiff_axial2);

mean_cdiff_axial2=mean(cdiff_axial2);

stdev_cdiff_axial3=std(cdiff_axial3);

mean_cdiff_axial3=mean(cdiff_axial3);

```

stdev_cdiff_torsional=std(cdiff_torsional);
mean_cdiff_torsional=mean(cdiff_torsional);

stdev_cdiff_torsional2=std(cdiff_torsional2);
mean_cdiff_torsional2=mean(cdiff_torsional2);

stdev_cdiff_torsional3=std(cdiff_torsional3);
mean_cdiff_torsional3=mean(cdiff_torsional3);

for i=1:1:numberElements

index_axial(i,:)= (cdiff_axial(i,1)-
mean_cdiff_axial)/stdev_cdiff_axial;
index_axial2(i,:)= (cdiff_axial2(i,1)-
mean_cdiff_axial2)/stdev_cdiff_axial2;
index_axial3(i,:)= (cdiff_axial3(i,1)-
mean_cdiff_axial3)/stdev_cdiff_axial3;

index_torsional(i,:)=(cdiff_torsional(i,1)-
mean_cdiff_torsional)/stdev_cdiff_torsional;
index_torsional2(i,:)=(cdiff_torsional2(i,1)-
mean_cdiff_torsional2)/stdev_cdiff_torsional2;
index_torsional3(i,:)=(cdiff_torsional3(i,1)-
mean_cdiff_torsional3)/stdev_cdiff_torsional3;

end

max_a1=max(index_axial);
max_a2=max(index_axial2);
max_a3=max(index_axial3);

max_t1=max(index_torsional);
max_t2=max(index_torsional2);
max_t3=max(index_torsional3);

%normindex
%axial
n_a1=index_axial;
n_a2=index_axial2;
n_a3=index_axial3;

%torsional
n_t1=index_torsional;
n_t2=index_torsional2;
n_t3=index_torsional3;

```

```

%damage index for all modes
for i=1:1:numberElements

    index_axial_all_modes(i,:)=((1/3)+(n_a1(i,1)+n_a2(i,1)+n_a3(i,1)));
    index_torsional_all_modes(i,:)=((1/3)+(n_t1(i,1)+n_t2(i,1)+n_t3(i,1)));
;

end

max_index_axial_all_modes=max(index_axial_all_modes);
max_index_torsional_all_modes=max(index_torsional_all_modes);

for i=1:1:numberElements

    cumulative_index(i,:)=(index_axial_all_modes(i,1)/max_index_axial_all_
    modes+index_torsional_all_modes(i,1))*0.5;

end

utp=0;
for i=1:1:numberElements

    if    cumulative_index(i)>1
        utp=utp+1;
        zzzatt(utp)=i;
    end

end

for i=1:1:length(zzzatt)

    suspected_nodes(i,:)=(elementNodes(zzzatt(i),:));

end

%data_end=suspected_nodes;
data_end=suspected_nodes;

unique_data=unique(data_end);
%disp("series_no "+"frequency");
for i=1:length(unique_data)
    [~,indices]=find(data_end==unique_data(i));
    freq(i)=length(indices);
    %disp(unique_data(i)+" "+freq(i))

    node_freq(i,:)=[unique_data(i),freq(i)];
end

```

```

%sortrows for most frequently damaged nodes
zzzzz=sortrows (node_freq,2,'descend');

utp=0;
for i=1:1:length (zzzzz)

    if    zzzzz (i,2)>2
        utp=utp+1;
        nzzzatt (utp)=zzzzz (i,1);
    end

end

utp=0;
most_likely_damaged_member=[];
for i=1:1:length (nzzzatt)
    for j=1:1:length (nzzzatt)
        for k=1:1:numberElements

            if elementNodes (k,1) == nzzzatt (i) && elementNodes (k,2) ==
nzzzatt (j)
                utp=utp+1;
                most_likely_damaged_member (utp)= k;

            end

        end
    end
end

suspected_damaged_members=zzzzatt;
na_damage_dey=most_likely_damaged_member;

%SECOND LEVEL DAMAGE MEMBER SEARCH

utp=0;
Anzzzatt=[];
for i=1:1:length (zzzzz)

    if    zzzzz (i,2)>4
        utp=utp+1;
        Anzzzatt (utp)=zzzzz (i,1);
    end

end

utp=0;
most_likely_damaged_member_G2=[];
for i=1:1:length (Anzzzatt)
    for j=1:1:length (zzzzz)

```

```

        for k=1:1:numberElements

            if elementNodes(k,1) == Anzzzatt(i) && elementNodes(k,2)
== zzzzz(j,1)
                utp=utp+1;
                most_likely_damaged_member_G2(utp)= k;

            end

            if elementNodes(k,2) == Anzzzatt(i) &&
elementNodes(k,1) == zzzzz(j,1)
                utp=utp+1;
                most_likely_damaged_member_G2(utp)= k;

            end

        end
    end
end

```

```

na_damage_dey2=most_likely_damaged_member_G2;

%call neural network for predictions
%severity_predicted=[];
severity_predicted=myNeuralNetworkFunction(cumilative_index);
%damaged_member_predicted
location_predicted=myNeuralNetworkFunction_id_damage_member_strainshm(
cumilative_index);

%SEVERITY PREDICTION 3 STAGE CLASSIFICATION

    if severity_predicted(1)> severity_predicted(2) &&
severity_predicted(1)> severity_predicted(3)
        predicted_damage_sevrity_1 ='LOW';

    end

    if severity_predicted(2)> severity_predicted(1) &&
severity_predicted(2)> severity_predicted(3)
        predicted_damage_sevrity_1 ='MEDIUM';

    end

```

```

        if severity_predicted(3)> severity_predicted(1) &&
severity_predicted(3)> severity_predicted(2)
            predicted_damage_sevritiy_1 ='HIGH';

        end

%SEVERITY PREDICTION 4 STAGE CLASSIFICATION

severity_predicted2=myNeuralNetworkFunction_4output(cumilative_index);

        if severity_predicted2(1)> severity_predicted2(2) &&
severity_predicted2(1)> severity_predicted2(3)&&
severity_predicted2(1)> severity_predicted2(4)
            predicted_damage_sevritiy ='VERY LOW';

        end

        if severity_predicted2(2)> severity_predicted2(1) &&
severity_predicted2(2)> severity_predicted2(3)&&
severity_predicted2(2)> severity_predicted2(4)
            predicted_damage_sevritiy ='LOW';

        end

        if severity_predicted2(3)> severity_predicted2(1) &&
severity_predicted2(3)> severity_predicted2(2)&&
severity_predicted2(3)> severity_predicted2(4)
            predicted_damage_sevritiy ='MEDIUM';

        end

        if severity_predicted2(4)> severity_predicted2(1) &&
severity_predicted2(4)> severity_predicted2(2)&&
severity_predicted2(4)> severity_predicted2(3)
            predicted_damage_sevritiy ='HIGH';

        end

%LOCATION PREDICTION 8 MEMBERS STAGE CLASSIFICATION

        if location_predicted(1)> location_predicted(2) &&
location_predicted(1)> location_predicted(3)&& location_predicted(1)>
location_predicted(4)&& location_predicted(1)> location_predicted(5)&&
location_predicted(1)> location_predicted(6)&& location_predicted(1)>
location_predicted(7)&& location_predicted(1)> location_predicted(8)
            predicted_damage_location='MEMBER 76';
        end

        if location_predicted(2)> location_predicted(1) &&
location_predicted(2)> location_predicted(3)&& location_predicted(2)>
location_predicted(4)&& location_predicted(2)> location_predicted(5)&&
location_predicted(2)> location_predicted(6)&& location_predicted(2)>
location_predicted(7)&& location_predicted(2)> location_predicted(8)
            predicted_damage_location='MEMBER 64';
        end

```

```

        if location_predicted(3)> location_predicted(1) &&
location_predicted(3)> location_predicted(2)&& location_predicted(3)>
location_predicted(4)&& location_predicted(3)> location_predicted(5)&&
location_predicted(3)> location_predicted(6)&& location_predicted(3)>
location_predicted(7)&& location_predicted(3)> location_predicted(8)
            predicted_damage_location='MEMBER 14';
        end

        if location_predicted(4)> location_predicted(1) &&
location_predicted(4)> location_predicted(2)&& location_predicted(4)>
location_predicted(3)&& location_predicted(4)> location_predicted(5)&&
location_predicted(4)> location_predicted(6)&& location_predicted(4)>
location_predicted(7)&& location_predicted(4)> location_predicted(8)
            predicted_damage_location='MEMBER 5';
        end

        if location_predicted(5)> location_predicted(1) &&
location_predicted(5)> location_predicted(2)&& location_predicted(5)>
location_predicted(3)&& location_predicted(5)> location_predicted(4)&&
location_predicted(5)> location_predicted(6)&& location_predicted(5)>
location_predicted(7)&& location_predicted(5)> location_predicted(8)
            predicted_damage_location='MEMBER 52';
        end

        if location_predicted(6)> location_predicted(1) &&
location_predicted(6)> location_predicted(2)&& location_predicted(6)>
location_predicted(3)&& location_predicted(6)> location_predicted(4)&&
location_predicted(6)> location_predicted(5)&& location_predicted(6)>
location_predicted(7)&& location_predicted(6)> location_predicted(8)
            predicted_damage_location='MEMBER 109';
        end

        if location_predicted(7)> location_predicted(1) &&
location_predicted(7)> location_predicted(2)&& location_predicted(7)>
location_predicted(3)&& location_predicted(7)> location_predicted(4)&&
location_predicted(7)> location_predicted(5)&& location_predicted(7)>
location_predicted(6)&& location_predicted(7)> location_predicted(8)
            predicted_damage_location='MEMBER 92';
        end

        if location_predicted(8)> location_predicted(1) &&
location_predicted(8)> location_predicted(2)&& location_predicted(8)>
location_predicted(3)&& location_predicted(8)> location_predicted(4)&&
location_predicted(8)> location_predicted(5)&& location_predicted(8)>
location_predicted(6)&& location_predicted(8)> location_predicted(7)
            predicted_damage_location='MEMBER 104';
        end

pdl=predicted_damage_location;

tft1=strcmp(predicted_damage_sevrity,'VERY LOW');
tft12=strcmp(predicted_damage_sevrity,'LOW');
tft13=strcmp(predicted_damage_sevrity,'MEDIUM');
tft14=strcmp(predicted_damage_sevrity,'HIGH');

```

```

if tft1 == 1
    yttrs=1;
end
if tft12 == 1
    yttrs=10;
end
if tft13 == 1
    yttrs=100;
end

if tft14 == 1
    yttrs=1000;
end

%distribution of output with noise.
All_cumulative_index(:,iit)=cumulative_index;
ALL_NN_predicted_damage_assesment(:,iit)= yttrs;

end

for i=1:1:numberElements
    %mean and standard deviation of damage cumulative index
    m_cumulative_index(i)=(mean(All_cumulative_index(i,:)));
    std__cumulative_index(i)=std(All_cumulative_index(i,:));

end

utp=0;
for i=1:1:numberElements

    if m_cumulative_index(i)>1
        utp=utp+1;
        mean_suspected_cum_index(utp)=m_cumulative_index(i);
        std_suspected_cum_index(utp)=std__cumulative_index(i);

        m_suspected_nodes(utp)=i;

    end

end

%mean and standard deviation of damage severity
m_severity_index=mean(ALL_NN_predicted_damage_assesment);
std__severity_index=std(ALL_NN_predicted_damage_assesment);

```

```
location_predicted_mean=myNeuralNetworkFunction_id_damage_member_strai
nshm(cumilative_index);
```

%LOCATION PREDICTION 8 MEMBERS STAGE CLASSIFICATION

```
if location_predicted_mean(1)> location_predicted_mean(2) &&
location_predicted_mean(1)> location_predicted_mean(3) &&
location_predicted_mean(1)> location_predicted_mean(4) &&
location_predicted_mean(1)> location_predicted_mean(5) &&
location_predicted_mean(1)> location_predicted_mean(6) &&
location_predicted_mean(1)> location_predicted_mean(7) &&
location_predicted_mean(1)> location_predicted_mean(8)
    predicted_damage_location_mean='MEMBER 76';
end

if location_predicted_mean(2)> location_predicted_mean(1) &&
location_predicted_mean(2)> location_predicted_mean(3) &&
location_predicted_mean(2)> location_predicted_mean(4) &&
location_predicted_mean(2)> location_predicted_mean(5) &&
location_predicted_mean(2)> location_predicted_mean(6) &&
location_predicted_mean(2)> location_predicted_mean(7) &&
location_predicted_mean(2)> location_predicted_mean(8)
    predicted_damage_location_mean='MEMBER 64';
end

if location_predicted_mean(3)> location_predicted_mean(1) &&
location_predicted_mean(3)> location_predicted_mean(2) &&
location_predicted_mean(3)> location_predicted_mean(4) &&
location_predicted_mean(3)> location_predicted_mean(5) &&
location_predicted_mean(3)> location_predicted_mean(6) &&
location_predicted_mean(3)> location_predicted_mean(7) &&
location_predicted_mean(3)> location_predicted_mean(8)
    predicted_damage_location_mean='MEMBER 14';
end

if location_predicted_mean(4)> location_predicted_mean(1) &&
location_predicted_mean(4)> location_predicted_mean(2) &&
location_predicted_mean(4)> location_predicted_mean(3) &&
location_predicted_mean(4)> location_predicted_mean(5) &&
location_predicted_mean(4)> location_predicted_mean(6) &&
location_predicted_mean(4)> location_predicted_mean(7) &&
location_predicted_mean(4)> location_predicted_mean(8)
    predicted_damage_location_mean='MEMBER 5';
end

if location_predicted_mean(5)> location_predicted_mean(1) &&
location_predicted_mean(5)> location_predicted_mean(2) &&
location_predicted_mean(5)> location_predicted_mean(3) &&
location_predicted_mean(5)> location_predicted_mean(4) &&
location_predicted_mean(5)> location_predicted_mean(6) &&
```

```

location_predicted_mean(5)> location_predicted_mean(7) &&
location_predicted_mean(5)> location_predicted_mean(8)
    predicted_damage_location_mean='MEMBER 52';
end

    if location_predicted_mean(6)> location_predicted_mean(1) &&
location_predicted_mean(6)> location_predicted_mean(2) &&
location_predicted_mean(6)> location_predicted_mean(3) &&
location_predicted_mean(6)> location_predicted_mean(4) &&
location_predicted_mean(6)> location_predicted_mean(5) &&
location_predicted_mean(6)> location_predicted_mean(7) &&
location_predicted_mean(6)> location_predicted_mean(8)
        predicted_damage_location_mean='MEMBER 109';
    end

    if location_predicted_mean(7)> location_predicted_mean(1) &&
location_predicted_mean(7)> location_predicted_mean(2) &&
location_predicted_mean(7)> location_predicted_mean(3) &&
location_predicted_mean(7)> location_predicted_mean(4) &&
location_predicted_mean(7)> location_predicted_mean(5) &&
location_predicted_mean(7)> location_predicted_mean(6) &&
location_predicted_mean(7)> location_predicted_mean(8)
        predicted_damage_location_mean='MEMBER 92';
    end

    if location_predicted_mean(8)> location_predicted_mean(1) &&
location_predicted_mean(8)> location_predicted_mean(2) &&
location_predicted_mean(8)> location_predicted_mean(3) &&
location_predicted_mean(8)> location_predicted_mean(4) &&
location_predicted_mean(8)> location_predicted_mean(5) &&
location_predicted_mean(8)> location_predicted_mean(6) &&
location_predicted_mean(8)> location_predicted_mean(7)
        predicted_damage_location_mean='MEMBER 104';
    end

figure(1)
bar(m_cumulative_index);

%RELIABILITY DAMAGE DETECTION
for i=1:1:length(mean_suspected_cum_index)

mn=mean_suspected_cum_index(i);
stdv=std_suspected_cum_index(i);
%reliability calculation for data detection
%number of random variables, m;
m=2;
%initial guess for z0 =0;

z0 = ones(1,m);
%minimize objective function

```

```

%exitflag = 1 for normal termination
options = optimset('LargeScale','off');
funj=@(z)pfunDICSD(z,mn,stdv);
[z,fval,exitflag,output]=fmincon(@objfun,z0,[],[],[],[],[],[],funj,options);

%first order reliability index
beta1_dd=fval;
pfl_dd=normcdf(-beta1_dd);
Reliability=normcdf(beta1_dd);

pof_i(i)=pfl_dd;
reliability_i(i)=Reliability;

end

%reliability in parallel FOR DAMAGE DETECTION
RELIABILITY_DD=1-prod(1-reliability_i);

%RELIABILITY FOR DAMAGE LOCALIZATION

%calculate mid point for each element
Predicted_Damage_member_number=str2double(regexpi(predicted_damage_location_mean, '[\d.]+', 'match'));

%node coordinates per element
for i=1:length(elementNodes)

    nodecord_elem=(horzcat(nodeCoordinates(elementNodes(i,1),:),nodeCoordinates(elementNodes(i,2),:)))';

    nodecord_elem1(i,:)=nodecord_elem;

    %midpoint
    midpoint_elem_nodes(i,:)
    =[ (0.5*(nodecord_elem1(i,1)+nodecord_elem1(i,4))), (0.5*(nodecord_elem1(i,2)+nodecord_elem1(i,5))), (0.5*(nodecord_elem1(i,3)+nodecord_elem1(i,6)))];
end

%mean and std of damage localization sphere
mean_d_loc_sphere=30;
std_d_loc_sphere=10;

%distance from damage location
d_from_d_loc=sqrt(((midpoint_elem_nodes(Predicted_Damage_member_number,1)-midpoint_elem_nodes(true_d_elem,1))^2)+((midpoint_elem_nodes(Predicted

```

```

_Damage_member_number,2)-
midpoint_elem_nodes(true_d_elem,2))^2)+((midpoint_elem_nodes(Predicted
_Damage_member_number,3)-midpoint_elem_nodes(true_d_elem,3))^2))

```

```

%reliability calculation for data detection
%number of random variables, m;
m=1;
%initial guess for z0 =0;

```

```

z0 = ones(1,m);
%minimize objective function
%exitflag = 1 for normal termination
options = optimset('LargeScale','off');
funj=@(z)pfundICSD_loc(z,mean_d_loc_sphere,std_d_loc_sphere,d_from_d_loc);
[z,fval,exitflag,output]=fmincon(@objfun,z0,[],[],[],[],[],[],funj,options);

```

```

%first order reliability index
beta1_dl=fval;
pfl_dl=normcdf(-beta1_dl);
Reliability_dl=normcdf(beta1_dl);

```

```

%RELIABILITY FOR DAMAGE ASSESSMENT

```

```

Predicted_damage_severity=yttrs;
mean_damageseverity=true_d_sever*0.5;
std_damage_severity=mean_damageseverity*0.1;

```

```

%reliability calculation for data detection
%number of random variables, m;
m=1;
%initial guess for z0 =0;

```

```

Damage_assessment_difference = sqrt((Predicted_damage_severity-
true_d_sever)^2)

```

```

z0 = ones(1,m);
%minimize objective function
%exitflag = 1 for normal termination
options = optimset('LargeScale','off');
funj=@(z)pfundICSD_assessment(z,mean_damageseverity,std_damage_severity,
Damage_assessment_difference);
[z,fval,exitflag,output]=fmincon(@objfun,z0,[],[],[],[],[],[],funj,options);

```

```

%first order reliability index
beta1_da=fval;

```

```
pfl_da=normcdf(-betal_da);
Reliability_da=normcdf(betal_da);
```

Here are the functions required to run the code give above.

Function 1:

```
function [Y,Xf,Af] = myNeuralNetworkFunction(X,~,~)
%MYNEURALNETWORKFUNCTION neural network simulation function.
%
% Auto-generated by MATLAB, 25-Jun-2021 11:24:23.
%
% [Y] = myNeuralNetworkFunction(X,~,~) takes these arguments:
%
%   X = 1xTS cell, 1 inputs over TS timesteps
%   Each X{1,ts} = 118xQ matrix, input #1 at timestep ts.
%
% and returns:
%   Y = 1xTS cell of 1 outputs over TS timesteps.
%   Each Y{1,ts} = 3xQ matrix, output #1 at timestep ts.
%
% where Q is number of samples (or series) and TS is the number of
timesteps.

%#ok<*RPMT0>

% ===== NEURAL NETWORK CONSTANTS =====

% Input 1
x1_step1.xoffset = [-0.440995171;0.142578823;-0.570376533;-
0.717292369;-0.716880313;-0.442699642;0.096137188;-0.572708469;-
0.788166554;-0.82330037;-0.446231292;0.109877303;-0.632566026;-
0.851508534;-0.929282469;-0.441493958;0.067120209;-0.636504124;-
0.86594001;-0.871638304;-0.579146065;-0.774478946;-0.617238034;-
0.671373862;-0.634007971;-0.52131042;-0.222904383;-0.581919882;-
0.608811028;-0.704350837;-0.516115756;-0.615358856;-0.546557231;-
0.59408886;-0.29021768;-
0.552927543;0.642887961;0.571391032;0.691624142;0.054691696;0.05293438
4;0.759061592;0.703233996;0.184602146;0.196920402;0.644093808;0.670545
231;0.728224905;-0.699281849;-0.831861352;-0.716674004;-0.871770431;-
0.936622656;-0.885218406;-0.648135277;-0.903113898;-0.702799875;-
0.631622242;-0.511681134;-0.4757868;-0.526668674;-0.66585132;-
0.968630295;-1.048287556;-0.483468094;-0.617587651;-0.543569568;-
0.647740608;-0.691901352;-0.506228099;-1.003975525;-0.980057222;-
0.474890749;-0.43634993;-0.545018027;-0.457919351;-0.496305005;-
0.553281036;-0.964480341;-1.031467904;-0.461767522;-0.461685774;-
0.70746065;-0.648494944;-0.434108003;-0.559458914;-0.795329566;-
0.904956045;-0.953999423;-0.953960081;-1.047941564;-0.987172875;-
1.036510684;-0.926430838;-0.991686918;-1.012974362;-1.253852466;-
1.262420432;-1.368323708;-1.384544237;-1.265970204;-1.245258859;-
1.142755854;-1.121017549;-1.102875381;-1.033492097;-0.643410587;-
0.399126707;-0.677911679;-0.463078146;-0.647689348;-0.326175349;-
```

```

0.5926082;-0.081080411;-1.196490133;-1.163123544;-1.180921166;-
1.212432348];
x1_step1.gain =
[0.556464033016645;0.593817012834437;0.969741823253679;0.9798069690716
57;0.614183149740155;0.517489461170583;0.572004424298637;0.68350877700
9854;1.90874493735826;1.1363736984362;0.62408911443855;0.5105690166984
62;0.646079252228907;0.57214297693938;1.23893623361533;0.5129091789042
09;0.461857279415738;0.566912996836049;1.00284273523619;1.099715160631
8;5.34581924258909;0.793352370693511;0.989338757430559;3.4252457556885
;0.947981581576741;0.870448430380232;0.866999409162011;0.8749542083418
68;2.58619123671789;0.796811480772165;0.733685299535406;1.196055432387
46;4.29443009539359;0.983806205040951;0.917368650421591;1.195934450256
34;0.729480587543332;0.573914378912143;0.776439880631763;0.67520081857
35;0.676905839526287;0.68288315765784;0.922193887953344;0.706160868187
643;0.711594684798722;0.68406385969396;1.00039462166483;0.721994585592
212;4.58901564084067;2.20836932998345;0.932959184730855;1.014716454042
02;1.04659498104351;1.75147427566689;1.08878661878676;2.49286188008709
;3.52959374640698;3.87576537185375;0.983159316592195;2.68970072935902;
0.969022722981575;0.612831281381008;0.639591617579801;0.48351365777765
4;0.98220471358942;0.752946490253141;0.912922580022828;1.7317200493125
3;0.833611147447063;1.96817556357485;1.15040131560079;0.74225882856540
2;1.4261330731017;0.807757805479588;1.63936621098991;1.0037005395043;1
.58938100095482;1.08797845221249;0.714245469614553;0.657684554704412;2
.83759418838804;1.02932244328304;0.902459895899419;0.918736850900379;0
.968347750704705;0.956999589163904;0.714161270409058;2.07704713719108;
3.39430095240826;1.14599818439622;1.13720518435354;1.17882121876685;1.
23494744327343;1.00073139855287;1.9378679498913;1.19418817443206;5.279
31519721913;5.81695852238085;4.87940304095035;4.69409005870422;5.75773
055503411;5.37648435156084;0.947813129485647;1.62753820819073;1.105409
54684468;0.999637091750211;1.93510633484295;1.0804313359564;0.58559668
3988037;0.907209593505577;0.409950338306505;0.531586502379312;1.328517
78230218;1.41600650195635;3.33736768801387;4.31064879335748;5.38409744
686584;3.63606114252066];
x1_step1.ymin = -1;

% Layer 1
b1 = [1.4424518386589098018;1.3300569876183385709;-
1.2202868198716043668;-1.1403544092909443375;-
1.0264727353512086427;0.90990262272747468586;-
0.84742824986634102125;0.73301943964190341418;-
0.6249701309287001294;0.56972614404150956346;-
0.45635856574179978207;0.3424804411361928036;0.2166264259372245593;-
0.14406443742849700529;0.073888340347828582177;0.044883516493654039559
;0.16516707097843047469;0.22428997281866880353;0.37126525335954940754;
-
0.44431543867416173343;0.53968736350188761808;0.66705392002638863591;-
0.77167528853998135219;-0.82131427390328393123;-
0.91233406030848962498;0.99330179227913140139;1.2049973908752102947;-
1.2557671888232753155;-1.3322899033520312351;-1.4707331394133116298];
IW1_1 = [-0.10246227147815759051 -0.061247470008307304534
0.19728724462103836013 0.091581911476924890425 -
0.037750165237538581275 -0.1082840475504569383 0.10650896202685759817
0.17160747116041738525 0.18340616527954434201 -0.099670888150727637855
-0.18324847072518857249 0.025725476369957898243 -
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-0.13704746744834356287 -0.14814327674223240483 -
0.20369031885668384407 -0.015181897630637139485 -
0.19262785018946365634 0.16004252301851668028 -0.053006730730686381359
-0.037409382897067175455;0.010213788595793225206 -
0.19618493546373694247 -0.00709532720499122041 0.15069423136283288667
0.15449924474452536582 -0.14858167890548285017 -0.1856216064364416829
-0.053570886623600710852 0.17691181655305154852 0.17806699090633157367
0.22124632058772455978 -0.17404586838577840169 0.13104453758751108405
0.084003031697690286328 0.18334648562758529278 0.21521841595329041508

```

-0.044115385224890210636 -0.17593039121749637355
0.06622737183055639465 0.14420337883342301821 -0.15576071040294842129
0.20763878499315149839 -0.066899217441049096955 -
0.01023680631204092889 -0.15869850620044559375 -
0.013296779603642587195 -0.14974360292760410807 0.19964934336928638614
-0.21076556543752714146 -0.14190081261823808689 -
0.093549467728275492728 -0.21709479862435412945 0.17897965622203848568
0.028424203072431743211 -0.038153531948541534458
0.18188795297057644418 0.050139849416051048003 -0.17159274587610587326
0.10713683960143075002 0.036192560053410149923 0.10329470466817054775
0.13660044512331742661 0.081569324764357742374 0.1934933330708906718
0.0046548043310240495504 0.21691813368274415197 -
0.23939882211951438173 -0.048198507137423615698 -
0.075460981541479621448 0.1729083252010620575 -0.097493513959820241044
0.20887044622747780176 -0.15815754054203007284
0.0029764493945426762425 0.035870737860810186781 -
0.067971306973768325088 -0.010968019375586038691
0.017084452525819471269 -0.2137171880388585854 -0.1564550652766192318
0.14369376952270535019 0.048560492686664444295 -0.14128590950499275714
-0.093255947070539649268 0.017557138241077026308
0.22809616268523430493 -0.21304704860844925207 0.021632005201266096828
0.05846350840453477804 0.10581281952340870767 0.2233626346866514345
0.17797162581272124582 -0.087850258924883795064 0.11119100294318436106
-0.083275205668173521434 0.06935375795824924583 0.15226695919312821514
-0.079464428151395830047 -0.10194701627361102414 -
0.031456706142390308822 0.0095914917694166264978
0.061214721894432749805 0.09638507498718731914 0.062519238421217149249
0.0016778308659358403404 0.11594303926857843501
0.010692886372041694731 0.075755239329933915515 -
0.034330936346860511932 -0.10045465126406090406 0.22283786553555165466
-0.16190186860694064097 -0.12100991528684792997 -
0.19136368376102239064 0.14575370337649951047 0.093306569776481856904
-0.013869578682788400933 -0.08763069011797031127 -
0.17335943378128837455 0.083556200516259615529 0.10753740950035892143
0.028005949464963989654 0.077990052841093684965 -
0.11238112193738279687 -0.032006411724119693263 -
0.089672668781701186935 0.10911103540836637749 -0.19809752654115195258
-0.15940004234530089078 0.075303752084750055773 0.15633326226393876035
-0.001061888391300933477 -0.17192347718595282768
0.039139761194198229022 0.13214882119442200592 -
0.011197125337123586472 -0.15422635983932445058
0.11692742267615396923];

```

```
% Layer 2
```

```

b2 = [0.44342664323318142783;-0.57146225446164022888;-
0.46252228431176944934];
LW2_1 = [-0.88841796753072488357 0.92629750869130977886 -
0.35446576105565796855 0.070085081305189200762 0.92814727299493382517
-0.19767718340413489853 -0.2294502893093294249 0.79629705173058551448
0.25751752594652371764 -0.25045340968529439252 0.27285771682319787113
-0.26051927017424775235 0.90889922277396462125 -0.47284486931538538546
0.46195291331952803571 -0.94287316415904742772 -0.18958160463384612915
-0.25125219294080791688 0.59703419189531925504 -0.61101495341822975593
-0.2761066155958850632 -0.84492771700589242023 0.71748905957140474143
-0.33650836133822786822 -0.78332924755265220806 -
0.63766179801104150293 0.91601550457215452639 0.38146558458541740544 -
0.65349684288143494726 -0.69060486454571312631;-0.64634990767544031609

```

```

-0.71803561923487557728 0.6375378283243643418 -0.23106515750437120471
0.98501379755811402372 0.34445674369358170175 -0.70704643309841819221
0.36430772848933029584 -0.71485492702153397016 0.42081823130236989394
0.51496311275092720994 0.98647334547662679505 0.79863534983386130772 -
0.86156000042622027379 -0.21162555413957007122 0.34319352289505861142
0.607762722267527231552 0.7261978743202103237 -0.45909778496504372036 -
0.50561947107025362325 -0.93380919211219903797 0.68825430042644952788
-0.68636822033181343894 0.36743294027256578893 0.92645559187878789853
0.1579061246120441464 -0.48929296325513960131 -0.11699040568323069988
-0.94162355852725687644 0.9489071622581803922;-0.42742488054411903464
-0.26373586537155074838 -0.66692700531548854137 0.86968854108569793038
-0.26709488264219910514 -0.79412027485526859305
0.039648936689180333537 0.11597882309715588922 -0.79753790558139803224
0.50489410132628009809 0.11905135741142025552 0.25821659063227359043 -
0.92435574220280758428 -0.69098504524744686073 0.4483210121540643911 -
0.12251559758536734179 -0.35850820654204618165 0.86170624717105448465
-0.91525187713383127086 -0.091628344073736059383 1.0339053843704648639
0.91203393187015358023 -0.65815840493248856102 0.89327877580595382856
0.66152005777386491125 -0.89109238917849764583 0.76073376676328241519
-0.33299910960228756851 -0.88614570891659416585 -
0.65808062384025878266];

```

```

% ===== SIMULATION =====

```

```

% Format Input Arguments

```

```

isCellX = iscell(X);

```

```

if ~isCellX
    X = {X};
end

```

```

% Dimensions

```

```

TS = size(X,2); % timesteps

```

```

if ~isempty(X)

```

```

    Q = size(X{1},2); % samples/series

```

```

else

```

```

    Q = 0;

```

```

end

```

```

% Allocate Outputs

```

```

Y = cell(1,TS);

```

```

% Time loop

```

```

for ts=1:TS

```

```

    % Input 1

```

```

    Xp1 = mapminmax_apply(X{1,ts},x1_step1);

```

```

    % Layer 1

```

```

    a1 = tansig_apply(repmat(b1,1,Q) + IW1_1*Xp1);

```

```

    % Layer 2

```

```

    a2 = softmax_apply(repmat(b2,1,Q) + LW2_1*a1);

```

```

    % Output 1

```

```

    Y{1,ts} = a2;

```

```

end

```

```

% Final Delay States
Xf = cell(1,0);
Af = cell(2,0);

% Format Output Arguments
if ~isCellX
    Y = cell2mat(Y);
end
end

% ===== MODULE FUNCTIONS =====

% Map Minimum and Maximum Input Processing Function
function y = mapminmax_apply(x,settings)
y = bsxfun(@minus,x,settings.xoffset);
y = bsxfun(@times,y,settings.gain);
y = bsxfun(@plus,y,settings.ymin);
end

% Competitive Soft Transfer Function
function a = softmax_apply(n,~)
if isa(n,'gpuArray')
    a = iSoftmaxApplyGPU(n);
else
    a = iSoftmaxApplyCPU(n);
end
end
function a = iSoftmaxApplyCPU(n)
nmax = max(n,[],1);
n = bsxfun(@minus,n,nmax);
numerator = exp(n);
denominator = sum(numerator,1);
denominator(denominator == 0) = 1;
a = bsxfun(@rdivide,numerator,denominator);
end
function a = iSoftmaxApplyGPU(n)
nmax = max(n,[],1);
numerator = arrayfun(@iSoftmaxApplyGPUHelper1,n,nmax);
denominator = sum(numerator,1);
a = arrayfun(@iSoftmaxApplyGPUHelper2,numerator,denominator);
end
function numerator = iSoftmaxApplyGPUHelper1(n,nmax)
numerator = exp(n - nmax);
end
function a = iSoftmaxApplyGPUHelper2(numerator,denominator)
if (denominator == 0)
    a = numerator;
else
    a = numerator ./ denominator;
end
end

% Sigmoid Symmetric Transfer Function
function a = tansig_apply(n,~)
a = 2 ./ (1 + exp(-2*n)) - 1;

```

end

Function 2:

```
function [Y,Xf,Af] =  
myNeuralNetworkFunction_id_damage_member_strainshm(X,~,~)  
%MYNEURALNETWORKFUNCTION neural network simulation function.  
%  
% Auto-generated by MATLAB, 26-Jun-2021 10:18:16.  
%  
% [Y] = myNeuralNetworkFunction(X,~,~) takes these arguments:  
%  
% X = 1xTS cell, 1 inputs over TS timesteps  
% Each X{1,ts} = 118xQ matrix, input #1 at timestep ts.  
%  
% and returns:  
% Y = 1xTS cell of 1 outputs over TS timesteps.  
% Each Y{1,ts} = 8xQ matrix, output #1 at timestep ts.  
%  
% where Q is number of samples (or series) and TS is the number of  
timesteps.  
  
%#ok<*RPMT0>  
  
% ===== NEURAL NETWORK CONSTANTS =====  
  
% Input 1  
x1_step1.xoffset = [-0.440995171;0.142578823;-0.570376533;-  
0.717292369;-0.716880313;-0.442699642;0.096137188;-0.572708469;-  
0.788166554;-0.82330037;-0.446231292;0.109877303;-0.632566026;-  
0.851508534;-0.929282469;-0.441493958;0.067120209;-0.636504124;-  
0.86594001;-0.871638304;-0.579146065;-0.774478946;-0.617238034;-  
0.671373862;-0.634007971;-0.52131042;-0.222904383;-0.581919882;-  
0.608811028;-0.704350837;-0.516115756;-0.615358856;-0.546557231;-  
0.59408886;-0.29021768;-  
0.552927543;0.642887961;0.571391032;0.691624142;0.054691696;0.05293438  
4;0.759061592;0.703233996;0.184602146;0.196920402;0.644093808;0.670545  
231;0.728224905;-0.699281849;-0.831861352;-0.716674004;-0.871770431;-  
0.936622656;-0.885218406;-0.648135277;-0.903113898;-0.702799875;-  
0.631622242;-0.511681134;-0.4757868;-0.526668674;-0.66585132;-  
0.968630295;-1.048287556;-0.483468094;-0.617587651;-0.543569568;-  
0.647740608;-0.691901352;-0.506228099;-1.003975525;-0.980057222;-  
0.474890749;-0.43634993;-0.545018027;-0.457919351;-0.496305005;-  
0.553281036;-0.964480341;-1.031467904;-0.461767522;-0.461685774;-  
0.70746065;-0.648494944;-0.434108003;-0.559458914;-0.795329566;-  
0.904956045;-0.953999423;-0.953960081;-1.047941564;-0.987172875;-  
1.036510684;-0.926430838;-0.991686918;-1.012974362;-1.253852466;-  
1.262420432;-1.368323708;-1.384544237;-1.265970204;-1.245258859;-  
1.142755854;-1.121017549;-1.102875381;-1.033492097;-0.643410587;-  
0.399126707;-0.677911679;-0.463078146;-0.647689348;-0.326175349;-  
0.5926082;-0.081080411;-1.196490133;-1.163123544;-1.180921166;-  
1.212432348];  
x1_step1.gain =  
[0.556464033016645;0.593817012834437;0.969741823253679;0.9798069690716  
57;0.614183149740155;0.517489461170583;0.572004424298637;0.68350877700  
9854;1.90874493735826;1.1363736984362;0.62408911443855;0.5105690166984  
62;0.646079252228907;0.57214297693938;1.23893623361533;0.5129091789042
```

```

09;0.461857279415738;0.566912996836049;1.00284273523619;1.099715160631
8;5.34581924258909;0.793352370693511;0.989338757430559;3.4252457556885
;0.947981581576741;0.870448430380232;0.866999409162011;0.8749542083418
68;2.58619123671789;0.796811480772165;0.733685299535406;1.196055432387
46;4.29443009539359;0.983806205040951;0.917368650421591;1.195934450256
34;0.729480587543332;0.573914378912143;0.776439880631763;0.67520081857
35;0.676905839526287;0.68288315765784;0.922193887953344;0.706160868187
643;0.711594684798722;0.68406385969396;1.00039462166483;0.721994585592
212;4.58901564084067;2.20836932998345;0.932959184730855;1.014716454042
02;1.04659498104351;1.75147427566689;1.08878661878676;2.49286188008709
;3.52959374640698;3.87576537185375;0.983159316592195;2.68970072935902;
0.969022722981575;0.612831281381008;0.639591617579801;0.48351365777765
4;0.98220471358942;0.752946490253141;0.912922580022828;1.7317200493125
3;0.833611147447063;1.96817556357485;1.15040131560079;0.74225882856540
2;1.4261330731017;0.807757805479588;1.63936621098991;1.0037005395043;1
.58938100095482;1.08797845221249;0.714245469614553;0.657684554704412;2
.83759418838804;1.02932244328304;0.902459895899419;0.918736850900379;0
.968347750704705;0.956999589163904;0.714161270409058;2.07704713719108;
3.39430095240826;1.14599818439622;1.13720518435354;1.17882121876685;1.
23494744327343;1.00073139855287;1.9378679498913;1.19418817443206;5.279
31519721913;5.81695852238085;4.87940304095035;4.69409005870422;5.75773
055503411;5.37648435156084;0.947813129485647;1.62753820819073;1.105409
54684468;0.999637091750211;1.93510633484295;1.0804313359564;0.58559668
3988037;0.907209593505577;0.409950338306505;0.531586502379312;1.328517
78230218;1.41600650195635;3.33736768801387;4.31064879335748;5.38409744
686584;3.63606114252066];
x1_step1.ymin = -1;

```

```

% Layer 1
b1 = [-
1.3370712814443517225;1.2539271827583122754;1.1655470129825979964;1.04
70301283246463697;0.98248118777905968368;-
0.90404942158650225537;0.87596926437426092527;-
0.7192373222498432344;0.60862134373949738908;-
0.47297678097001039088;0.44118775656658998363;0.31365938292918643659;0
.2616800393293288729;0.17794957921756279773;-0.11627668887625144944;-
0.0070235625594164876467;0.12395210453969389419;0.18232900754483011285
;-0.36496501651414509082;0.41483295362281630281;-
0.54626776035595125958;-
0.54657853570610515082;0.68246116830766778705;-
0.79291741520680936173;-0.84350936828836464709;-
0.9784979200604262406;-
1.071651424091699889;1.1699072923401152568;1.3862935458770964114;1.418
085653388975409];
IW1_1 = [0.26090193334698091876 -0.096016336187031273153 -
0.1054041825240251834 0.16152784921029969545 0.036522759966488231587 -
0.091108440464191725594 0.10621139471913733365 0.095246678687689767528
0.14269981544088775061 -0.10551299506123003324
0.0035713789610641115922 0.22594646112852739828 0.27891881879897784113
0.19023605102966459346 0.17049715997707445836 -0.18425967058332076709
-0.10332861615185742754 -0.036599790975362943291 -
0.10932372162081144262 0.13778279691776115778 -0.19764750783061985073
0.21505901806713351165 -0.20134098049105850214 0.12298570790210112957
-0.20942635719537724959 -0.18029938079390928074 -
0.033799580903668031973 0.010404346328949442418 -
0.27037402985370989628 0.1771602597894775255 -0.089601747418385377375
-0.11934374962838766032 -0.12818357817394426812 -

```

0.019709624462565505237 0.021237476035020075305 -
0.048065146553458282241 0.17494637723883374458 0.21427698006097292693
0.26346095746842868035 -0.22277230307085496563 0.03351461173307071495
0.079259446626074869791 -0.18057356139307792486 -
0.076066918661092428056 -0.20714228803275630542
0.099014385141112229438 -0.13233968319661840174 -
0.12652949273198835223 0.052510138554324972682 -
0.071278402939078583378 0.014602247073852221704 -
0.30990970063997791417 -0.12410335526473757761 0.024782569760521087898
0.019141178304548908673 0.064842567959399091682 0.23877045876513686151
-0.21356067144599399921 0.18888407387949751604 0.11921539010384038515
0.082171943706750669167 -0.15011034996618685677 -0.1644454762624855404
-0.086837114978624410644 0.12783451590150471389
0.0057768963894421496499 -0.15211145821136951017 -
0.074605958235634373121 0.15762913280244189584 -0.13557494134752418047
-0.051462209849346074453 0.053157339421402008406
0.035701974349152690302 -0.10493192596847673859 -
0.21287700312054119722 0.015598982808521543938 -0.08420415915022257114
-0.24795947443263116616 -0.050610527857040038535
0.13064719621373740988 0.23633620672447527844 0.0010799510911820877062
0.20882581696509958102 0.060412887474274361288 0.1731889664762167047 -
0.16620996778948002315 -0.10000225690670608292 0.042360452422558564356
0.044691510317326703372 0.24007773413815328145 -0.11353528020257830367
0.059920628187781647955 -0.18573260442667532955
0.014129660722589910266 0.078476613904889233608 -
0.18232687301097494359 0.13457735607402035449 -0.23221357630755060097
-0.011083056000748863629 -0.095852671363194669185 -
0.090072817771828100897 0.085927802503975234116 -
0.32509753489140452709 0.14649575714143500682 -0.26649492522562195918
-0.20174938545604659268 0.010394182322404578803 -
0.0092535286074704667381 0.079433397246848391759 -
0.1805765246589597639 0.095996596698123423663 0.096038793281088857823
0.10936792275519599538 0.043853376276755985652 -0.18633066488062827171
-0.14164977482734644743 -0.20590092194762912858 -
0.17025746298339947127;-0.056710917623855182368 -
0.20718119404965090746 -0.091734664237335741821 -
0.19044024709503623582 0.11742224315554047887 0.19971420589787247657 -
0.24080003644792102868 0.11822727445747206743 0.3000359523986163568
0.20794845669034092706 0.051029049945726032145 -0.38710111245438133531
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-0.053199528578312567373 0.35055733122966031834 -
0.009672854109522356289 -0.1079687827004170847 0.16909552318346768307
-0.0044072825018970796657 0.26955030467065904665
0.28521212319444572136 0.15100281730011796966];

```

```

% Layer 2

```

```

b2 = [-0.49369678091157181976;-
0.17038152727634930939;0.74217440638952725251;-
0.60000508762232152016;-0.11750334307220221264;-
0.13458175697495691758;-0.01105767900120578108;-
0.19681516333662771312];
LW2_1 = [0.41635410825707108717 1.3209149996285767248 -
0.37265054667852992587 -1.1628481197516642442 0.44617478851628039616
1.37461337236210146 0.79518933283166404191 0.87689586232982796865 -
0.57664250948850270806 0.077359095628194859962 -
0.019998558958453812456 -0.19268037484476185917 -
0.45597826954209719208 0.06247182681835721646 0.34834575624749097855
0.81219624725807559873 -1.2358130368124800036 0.46024264179537410779
0.9996445572982423089 -0.49354783054367518114 -0.49761128678641419754
0.89160013429725470946 1.2017944998267546808 1.405144371155085059
0.27030827980521238141 1.0239329335212787875 0.77233846188003107969
0.98502980604069390047 -0.3835215624819779956 -

```

0.97666358765005245601;1.1433089825084181701 -1.1558664549372299479 -
0.65916821261451985503 0.58214649240710059086 0.63036524570728991179
0.046067073390812680878 0.48187833789160744447 0.4831488459982284378 -
0.53568737735670868272 0.40596287043850964871 -0.58608649436440041214
0.82557038301457619234 0.057778422836810748586 0.39144227609507337151
0.95272247859521841384 0.42756689193553421013 0.73528319156293453496 -
0.22406402185670276639 0.024829340727631973862 -0.68996128104306941875
-0.76279976965239981723 0.30685580515003219038 0.72878527595435349529
-0.81224965301944540563 0.41081374038389545378 0.30251416069885400661
0.088855568978905924427 0.53968941577622464578 -0.64516900238057772743
0.11578354857765452146;0.83012416819424983405 -0.85815173749720197183
0.029790603058475622483 0.079339561167723227086 0.64904667579403729771
0.6997135495483088885 -0.75348705630424561708 -0.53832140072959477894
0.36175139425813934713 0.029575580697220472948 -0.17435389352482255632
-1.0394822930922216209 -0.3622026190235976828 -0.052484941213467653509
-0.9939586850369367399 0.071606200090838664774 0.043289544293219635318
-0.97255061331521341916 1.1110507203088761941 0.057783895587734557253
0.61022249418858842684 -0.07915828195682544921 0.90541737338943806268
0.3653200071919814329 -0.57627797226086707738 -0.028993984918221023944
-0.73431569226344550749 -1.0985714855462018757 -0.25674044708905258139
0.99909531876668178363;-0.39232728167782632278 -
0.0013004148611647885214 0.53084430284203176775 -0.3125257778640478934
-0.61760947639274399457 0.18662290086807739597 -1.1773764449377057684
0.24458436545587372568 -0.053140741647576032747 -
0.57321161278707477571 -0.75087061502650032097 1.4811950284066828232 -
0.38826371961085559548 0.026361545214143050631 0.81463123364736322873
-1.0771264965261988511 0.51209245110244927535 -1.379547619401095826 -
0.40423860882593587451 -1.0360918693256657708 1.1305167467464307673 -
1.0749773790132863827 0.88792288228278970497 0.15706087266846971429 -
0.69998522072599544952 0.92164645355034269247 0.44641776226615370593
0.90372546649794660567 -0.25621724383880994935
0.78226058697265099529;-0.33791563818118935947 0.060218077525793570204
0.73114858042300301388 -0.40310191298024722339 -0.89552151590825046501
0.49139688403017622864 0.75830946461541293147 1.1929469138591899391
1.0247350513609858602 -0.87584963740915255936 -0.47463749056333270904
0.00076976927760196789743 -0.28675650022518572868 -1.2033802579890438
0.57361155891993209632 -0.53224316394028003963 0.78777586502828089721
0.62764018530470722101 -0.5908676309294949025 0.48205080732442351366 -
0.019310370533084344341 0.94294535955817937456 0.29652650687929715811
0.75963701998421617745 -0.80136667212359358192 -0.34790141752617881332
1.1173521978861704618 0.51317602867816802803 0.17160108325726960987
0.71409787369667498957;-0.1342240839177564482 0.79010941171840798347
0.29768343827341858798 1.0245166917246999461 0.51382487625817974131 -
0.012087956310982375663 -0.80820365993014053885 0.34195300188070676395
-0.99772379099068708719 -0.93709753607651702367 -1.1315040727872254234
-1.3151924764413129854 0.1595554988053350387 -0.47431053224525021594
0.19254895024094734191 0.07942143721602261397 -0.73573173933457514106
0.31824967072477194918 1.2530606311584151502 1.0907567915225839794 -
0.073075006775070908138 -1.0964615068817995525 -0.95685993905578992091
0.1711942427671524769 -0.36225067341413813571 0.54937935632930712249
0.36927532197273160719 0.70623101604774396467 -0.59601503765367469523
-1.2713618117013754105;-0.48715604145703256256 -0.95810337485055874218
-0.4333130883517867793 -0.89779088637706438991 -0.31175296894950310644
0.81953243126707520094 0.79942620486370319366 1.0034147690397126063
0.5526248158323983084 1.309497660309231204 0.1677439455874399632
0.27443331111867408367 -0.45380439910893288769 0.23457272592047107018
0.39192167978605590983 -0.14593719167506788437 -0.61266492123079041576

```

-0.75831816083150438423 0.2214031742275950343 -0.56227677604859704896
-0.65200877983882365996 -0.4313069818959601176 0.22619902619919751707
0.37042557257566260942 -0.51810515041236560041 1.1380704718020968613
0.74336138260682327328 -0.84307167222757051217 0.085064168427725808663
-1.0604285436377975937;-0.57397152413699903395 0.29289158837678375136
0.16156897517497778582 -0.86924906129503465291 0.97661845802571745079
0.40647980427185848029 0.80834996729127706061 -0.69416444402150423443
-0.84643777146460186245 0.54067472537795313592 -0.96538287303637870806
-0.51814628488770264614 -0.73734055357543870635 -
0.60645788091669228237 -0.98377953674921880811 -0.19182883591525573541
-0.72737401288669345512 -0.49788004851689582342 -
0.73086162078150729293 1.0398191068886506461 -0.40350213427578418557
0.87677189807853106451 -0.67407885622526952929 0.86164333405695714418
0.9395831573505839529 -0.55903788355739969518 0.79933133810551626475 -
0.010954172402579216358 0.4729028578959720841 0.35552115204183681874];

```

```

% ===== SIMULATION =====

```

```

% Format Input Arguments

```

```

isCellX = iscell(X);

```

```

if ~isCellX
    X = {X};
end

```

```

% Dimensions

```

```

TS = size(X,2); % timesteps

```

```

if ~isempty(X)
    Q = size(X{1},2); % samples/series
else
    Q = 0;
end

```

```

% Allocate Outputs

```

```

Y = cell(1,TS);

```

```

% Time loop

```

```

for ts=1:TS

```

```

    % Input 1

```

```

    Xp1 = mapminmax_apply(X{1,ts},x1_step1);

```

```

    % Layer 1

```

```

    a1 = tansig_apply(repmat(b1,1,Q) + IW1_1*Xp1);

```

```

    % Layer 2

```

```

    a2 = softmax_apply(repmat(b2,1,Q) + LW2_1*a1);

```

```

    % Output 1

```

```

    Y{1,ts} = a2;

```

```

end

```

```

% Final Delay States

```

```

Xf = cell(1,0);

```

```

Af = cell(2,0);

```

```

% Format Output Arguments
if ~isCellX
    Y = cell2mat(Y);
end
end

% ===== MODULE FUNCTIONS =====

% Map Minimum and Maximum Input Processing Function
function y = mapminmax_apply(x, settings)
y = bsxfun(@minus, x, settings.xoffset);
y = bsxfun(@times, y, settings.gain);
y = bsxfun(@plus, y, settings.ymin);
end

% Competitive Soft Transfer Function
function a = softmax_apply(n, ~)
if isa(n, 'gpuArray')
    a = iSoftmaxApplyGPU(n);
else
    a = iSoftmaxApplyCPU(n);
end
end
function a = iSoftmaxApplyCPU(n)
nmax = max(n, [], 1);
n = bsxfun(@minus, n, nmax);
numerator = exp(n);
denominator = sum(numerator, 1);
denominator(denominator == 0) = 1;
a = bsxfun(@rdivide, numerator, denominator);
end
function a = iSoftmaxApplyGPU(n)
nmax = max(n, [], 1);
numerator = arrayfun(@iSoftmaxApplyGPUHelper1, n, nmax);
denominator = sum(numerator, 1);
a = arrayfun(@iSoftmaxApplyGPUHelper2, numerator, denominator);
end
function numerator = iSoftmaxApplyGPUHelper1(n, nmax)
numerator = exp(n - nmax);
end
function a = iSoftmaxApplyGPUHelper2(numerator, denominator)
if (denominator == 0)
    a = numerator;
else
    a = numerator ./ denominator;
end
end

% Sigmoid Symmetric Transfer Function
function a = tansig_apply(n, ~)
a = 2 ./ (1 + exp(-2*n)) - 1;
end

```

Function 3:

```

%define the fatigue limit state function, p

```

```

function [c, ceq] = pfunDICSD(z,mn,stdv)

%convert standard normal random variables to physical variables

%define uncertain variables based on distribution

%uniform distribution y(1) = 2+6*normcdf(z(1));
%mn=5;
%stdv=0.1;

%normal distribution
y(1) = mn + z(1)*stdv;
y(2) = 1 + z(2)*0.1;

c = y(1)-y(2);
%nonlinear equality constraints
ceq = [];
end

```

Function4:

```

%define the fatigue limit state function, p

function [c, ceq] =
pfunDICSD_loc(z,mean_d_loc_sphere,std_d_loc_sphere,d_from_d_loc)

%convert standard normal random variables to physical variables

%define uncertain variables based on distribution

%normal distribution
y(1) = mean_d_loc_sphere + z(1)*std_d_loc_sphere;

c = -d_from_d_loc+y(1);
%nonlinear equality constraints
ceq = [];
end

```

Function5:

```

%define the fatigue limit state function, p

function [c, ceq] =
pfunDICSD_assessment(z,mean_damageseverity,std_damage_severity,Damage_
assessment_difference)

%convert standard normal random variables to physical variables

```

```

%define uncertain variables based on distribution

%normal distribution
y(1) = mean_damageseverity + z(1)*std_damage_severity;

c = -Damage_assessment_difference+y(1);
%nonlinear equality constraints
ceq = [];
end

```

B.1 Reliability Analysis Codes

Fatigue Initial reliability

```

%calculate initial reliability
for t=1:1:7;
%number of random variables, m;

m=7;
tc=t_use(t);
%initial guess for z0 =0;
z0 = ones(1,m);
%minimize objective function
%exitflag = 1 for normal termination
options = optimset('LargeScale','off');
funj=@(z)pfunexampuse_tc(z,tc);
[z,fval,exitflag,output]=fmincon(@objfun,z0,[],[],[],[],[],[],funj,options);

%first order reliability index
betal=fval;
pfl=normcdf(-betal);
Reliability=1-pfl;

zini(t,:)=z;
betaini(t,1)=betal;

time(t)=t;
end

```

Function required to run the program above:

```

%define the fatigue limit state function, p

function [c, ceq] = pfunexampuse_tc(z,tc)

```

```

%convert standard normal random variables to physical variables

%define uncertain variables based on distribution

%ac normal distribution mean = 8.0 cov 0.04
y(1) = 155 + z(1)*(155*0.1);

%ln(Ca) is normal w mean=-29.84 stdev=0.55, where Ca is lognormal
mutwo = exp(-29.97+((0.4178^2)/2));
stdtwo = (exp((2*-29.97)+(0.4178^2))*(exp((0.4178^2))-1))^0.5;
xtwo=sqrt(log(1+(mutwo*stdtwo)^2));
lamtwo= log(mutwo)-0.5*xtwo^2;
y(2) = exp(lamtwo+xtwo*z(2));

%delta y is normal mean =1, cov = 0.1
y(3) = 1 + z(3)*(0.1*1);

%lognormal distribution delta tf mean =1.5, cov = 0.5
%xphi = sqrt(log(1+0.50^2));
%lamphi = log(1.5)-0.5*xphi^2;
%y(4) = exp(lamphi+xphi*z(4));

%lognormal distribution delta f mean =1.0, cov = 0.1
xbeta = sqrt(log(1+0.1^2));
lambeta = log(1)-0.5*xbeta^2;
y(4) = exp(lambeta+xbeta*z(4));

%lognormal distribution delta s mean =1.0, cov = 0.15
xbeta2 = sqrt(log(1+0.15^2));
lambeta2 = log(1)-0.5*xbeta2^2;
y(5) = exp(lambeta2+xbeta2*z(5));

%lognormal distribution delta scf mean =1.0, cov = 0.1
xbeta3 = sqrt(log(1+0.1^2));
lambeta3 = log(1)-0.5*xbeta3^2;
y(6) = exp(lambeta3+xbeta3*z(6));

%exponential a0 mean =0.11, cov = 1.0
y(7)=-0.1*log(1-normcdf(z(7)));

%fixed variables note yc was not given so i guessed.
yc=1.0;
ac=11.47;
bc=1.22;
vc=6.277e6;
mc=3.10;

%terms from the integral solution were grouped to simplify equation
dd=y(2)*yc*y(3);
vv=(1-0.5*mc);

```

```

ppp=pi^(-0.5*mc);
aac=(y(1))^vv;
aao=(y(7))^vv;

%log of non linear constrain for stability
uc = (((2*ppp*(aac-aao))/((2*dd)-
(dd*mc))))+(vc*tc*((y(4))^mc)*((y(5))^mc)*((y(6))^mc)*(ac^mc)*gamma(1+
(mc/bc)));

%nonlinear inequality constraints, c<0
c = [];
%nonlinear equality constraints
ceq = [uc];
end

Function 2:
%objective function for FORMfatiguereliab
function f =objfun(z)

%objective function =distance from the origin
% z= vector of uncorrelated standard normal random
%variables
f = norm(z);

end

```

Fatigue damage detected reliability

```

%calculate event reliability_damage_Detection

for t=1:1:7;
%number of random variables, m;
m=7;
tc=t_use(t);
%initial guess for z0 =0;
z0 = ones(1,m);
%minimize objective function
%exitflag = 1 for normal termination
options = optimset('LargeScale','off');
funj=@(z)pfundetection_tc(z,tc)
[z,fval,exitflag,output]=fmincon(@objfun,z0,[],[],[],[],[],[],funj,options);

%first order reliability index
betal=fval;
pfl=normcdf(-betal);

zevent(t,:)=z;
betadetection(t,1)=betal;

```

end

Function required to run the program above:

%define the fatigue limit state function, p

function [c, ceq] = pfundetection_tc(z,tc);

%convert standard normal random variables to physical variables

%define uncertain variables based on distribution

%ac normal distribution mean = 5.0 cov 0.04

y(1) = 155 + z(1)*(155*0.1);

%ln(Ca) is normal w mean=-29.84 stdev=0.55, where Ca is lognormal

mutwo = exp(-29.97+((0.4178^2)/2));

stdtwo = (exp((2*-29.97)+(0.4178^2))*(exp((0.4178^2))-1))^0.5;

xtwo=sqrt(log(1+(mutwo*stdtwo)^2));

lamtwo= log(mutwo)-0.5*xtwo^2;

y(2) = exp(lamtwo+xtwo*z(2));

%delta y is normal mean =1, cov = 0.1

y(3) = 1 + z(3)*(0.1*1);

%lognormal distribution delta tf mean =1.5, cov = 0.5

%xphi = sqrt(log(1+0.50^2));

%lamphi = log(1.5)-0.5*xphi^2;

%y(4) = exp(lamphi+xphi*z(4));

%lognormal distribution delta f mean =1.0, cov = 0.1

xbeta = sqrt(log(1+0.1^2));

lambeta = log(1)-0.5*xbeta^2;

y(4) = exp(lambeta+xbeta*z(4));

%lognormal distribution delta s mean =1.0, cov = 0.15

xbeta2 = sqrt(log(1+0.15^2));

lambeta2 = log(1)-0.5*xbeta2^2;

y(5) = exp(lambeta2+xbeta2*z(5));

%lognormal distribution delta scf mean =1.0, cov = 0.1

xbeta3 = sqrt(log(1+0.1^2));

lambeta3 = log(1)-0.5*xbeta3^2;

y(6) = exp(lambeta3+xbeta3*z(6));

%exponential a0 mean =0.11, cov = 1.0

y(7)=30 + z(7)*(10);

%fixed variables note yc was not given so i guessed.

yc=1.0;

ac=11.47;

bc=1.22;

```

vc=6.277e6;
mc=3.10;

%terms from the integral solution were grouped to simplify equation
dd=y(2)*yc*y(3);
vv=(1-0.5*mc);
ppp=pi^(-0.5*mc);
aac=(y(1))^vv;
aao=(y(7))^vv;
%aao=(40)^vv;
%log of non linear constrain for stability
uc = log((2*ppp*(aac-aao))/((2*dd)-
(dd*mc)))+log(vc*tc*((y(4))^mc)*((y(5))^mc)*((y(6))^mc)*(ac^mc)*gamma(
1+(mc/bc)));

%nonlinear inequality constraints, c<0
c = (uc);
%nonlinear equality constraints
ceq = [];

end

```