

CRANFIELD UNIVERSITY

M COLIN DE VERDIERE

Damage and strain rate optical characterisation of standard and tufted non  
crimp fabric carbon composites for Meso-scale impact models

SCHOOL OF APPLIED SCIENCE

PhD THESIS

Academic Year 2005-2009

Supervisor: A Walton, J Chubb

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## **Abstract**

As global warming is a prime concern to the wellbeing of the planet, lighter planes are a requirement to reduce CO<sub>2</sub> emissions. Light structures made of carbon epoxy composite materials are of particular interest but are sensitive to impacts such as hail or bird strikes. Static and dynamic testing of composite specimens and structures (from aeronautical standard) through novel testing methods was the first aim of this PhD research. Subsequently it led to novel material characterisation and material parameters calibration for which numerical simulations of impact responses could be developed. In this research further investigation under static, dynamic and impact loading of two certified aeronautical materials occurred. Carbon non crimp fabric epoxy (tufted and untufted) response was investigated. Novel tests and testing methods were developed for in-plane and for delamination focussing on the use of optical analysis using digital image correlation (DIC) and high speed cameras. A novel damage detection method was proposed using DIC. The experimental data set was used to calibrate a damage model with imposed strain rate laws and added delamination Mode I and II interface prior to a punch validation study. A novel compression apparatus designed for DIC usage worked well in static and dynamic. A novel intermediate strain rate tensile test worked better on bias direction lay-up than on axial one. Dynamic DIC method proved of interest to record strains up to strain rate achieved with a Split Hopkinson pressure bar apparatus. In quasi static tufting reduced axial properties considerably but had little effect in shear loading, in addition it increased significantly the resistance to delamination and reduced the crack speed in dynamic. The damage fields generated allowed for the detection of damage progression for various load cases. More damage occurred in compression and shear than in tension as the tufted laminate showed more pronounced damage than the

untufted one. The dynamic effect of tufting on in-plane and impact response was reduced as it increased considerably delamination resistance in Mode I and II. For both tufted and untufted NCF composites, strong strain rate effects were detected from a low speed on the in-plane strength and failure strain as no or little effects were recorded on the material stiffness. Novel dynamic delamination Mode I and II tests combined with optical analysis provided possibilities to detect rate effects and crack speed propagation while loaded in pure mode I and II. No strain rate effects were recorded in delamination Mode I apart from a slight effect during crack initiation which was stronger for the tufted material. In Mode II a slight rate effect was detected for the tufted interface during crack propagation. During out-of-plane impact loading at intermediate speed, a minor negative loading rate effect was detected.

The model calibrated in damage, delamination and strain rate prove useful for dynamic DCB representation and assessment of possible mix mode crack loading. Modelling tufts as P-link was of interest but requires further investigation. Damage and strain rate was well modelled in tension, compression and bias direction loading, even if the strain rate shear law would require some modification. A Meso-scale model was validated successfully by means that the model responses would follow the experimental trends in quasi static loading but with the modification of 4 parameters among  $\pm 50$ . Further research could extend its use for impact modelling. This research showed the complexity of the failure mechanism occurring in composite materials, modelling them at high speed in the plane and in out of plane impact remains a difficult challenge. Carbon composites damage sensitivity is significant and invisible to the naked eye for some load cases and lay-ups necessitating regular non destructive testing on aging airframe.

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## Notation

|            |                                                                     |
|------------|---------------------------------------------------------------------|
| $A$        | Cross-sectional area                                                |
| $A$        | Crack length                                                        |
| $[A]$      | Matrix defining the in plane stiffness                              |
| $B$        | Width of DCB sample                                                 |
| $[B]$      | Coupling matrix which relate curvature to in plane force            |
| $C$        | Compliance                                                          |
| $[D]$      | Bending stiffness matrix                                            |
| DCB        | Double cantilever beam                                              |
| DIC        | Digital image correlation                                           |
| DICM       | Digital image correlation method                                    |
| $D_R$      | First Parameter of yield stress law                                 |
| $d$        | Damage in Ladeveze model                                            |
| $d_{max}$  | Maximum allowed damage value for shear damage and transverse damage |
| $d_{12}$   | Shear damage                                                        |
| $d_{22}$   | Transverse matrix damage                                            |
| $d_u^{fc}$ | Compressive fiber ultimate damage                                   |
| $d_u$      | Tensile fiber ultimate damage                                       |
| $D_{11}$   | First parameter of longitudinal Young's Modulus law                 |
| $D_{11}^R$ | First parameter of fibre ultimate law                               |
| $D_{22}$   | First parameter of transverse Young's Modulus law                   |
| $D_{12}$   | First parameter of shear Modulus law                                |
| $E$        | Young's Modulus                                                     |
| EADS       | European Aeronautic Defence and Space Company                       |
| $E_f$      | Young's Modulus of matrix                                           |

|               |                                                     |
|---------------|-----------------------------------------------------|
| $E_{fl}$      | Flexural Modulus                                    |
| $E_m$         | Young's Modulus of resin                            |
| $E_1^{0\ c}$  | Compressive initial Young's Modulus                 |
| $E_1^{'}$     | Overall Young's Modulus in compression              |
| $E_2^o$       | Initial transverse Young's Modulus                  |
| $E_1^o$       | Initial axial Young's Modulus                       |
| $ELS$         | End loaded split specimen                           |
| $E_{PSi\_ft}$ | Tensile strain                                      |
| $E_{PSu\_ft}$ | Tensile ultimate strain                             |
| $FE$          | Finite element                                      |
| $FEA$         | Finite element analyses                             |
| $FEM$         | Finite element method                               |
| $G$           | Shear modulus                                       |
| $G_{12}^o$    | Initial shear modulus                               |
| $G_{IC}$      | Mode-I strain energy release rate                   |
| $G_{IIC}$     | Mode-II strain energy release rate                  |
| $G_u^n$       | Shear stress to start and continue delamination     |
| $G_u^i$       | Mode I fracture energy                              |
| $H$           | DCB Thickness of DCB Sample                         |
| $H_{cont}$    | Distance for kinematic                              |
| $I$           | Second moment of inertia                            |
| $IITRI$       | Illinois Institute of Technology Research Institute |
| $ITool$       | Framework IV EU project                             |
| $K$           | Mid plane curvature of the laminate                 |
| $L$           | Sample width                                        |

*Limess* Measuring and testing system, messtechnik und Software GmbH

$M$  Moments

$M$  Mass

$N$  Loads

$\nu_{12}$  Poisson's ratio in 1,2 plane

$NCF$  Non Crimp Fabric

$P$  Plastic Strain

$R$  Plastic hardening function

$RAE$  Royal Aircraft Establishment

$R(p)$  Plastic hardening function

$\tau_c$  Shear strength

$SHPB$  Split Hopkinson pressure bar

$SPH$  Smoothed particle hydrodynamic

$[S]$  Compliance matrix

$[S]^{-1}$  Inverse of compliance matrix or  $[Q]$  stiffness matrix

$t_n^{max}$  First parameter of yield stress law

$t_i^{max}$  Normal stress to start and continue delamination

$UD$  Unidirectional

$VCCT$  Virtual crack closure technique

$V_f$  Fibre volume fraction

$V_m$  Volume percentage of resin

$Y$  Damage limitation

$Y^t$  Fibre strength in tension in the second direction

$Y^c$  Fibre strength in compression in the second direction

$Y_{22}^0$  Initial transverse damage limit

|                      |                                                                             |
|----------------------|-----------------------------------------------------------------------------|
| $Y_{12}^0$           | Initial shear damage limit                                                  |
| $Y_{22}^c$           | Critical transverse damage limit                                            |
| $Y_{12}^c$           | Brittle transverse damage limit of fibre matrix interface                   |
| $Y_{22}^u$           | Brittle transverse damage limit of fibre matrix interface                   |
| $Y_{12}^u$           | Elementary shear damage fracture limit                                      |
| $\beta_1$            | Fabric type correction factor for rules of mixture                          |
| $\beta_2$            | Length correction factor for rules of mixture                               |
| $\varepsilon^0$      | Mid planes strains of the laminate                                          |
| $\varepsilon_e$      | Elastic strain                                                              |
| $\varepsilon_p$      | Inelastic strain                                                            |
| $\varepsilon_u^{ft}$ | Compressive fiber ultimate strain                                           |
| $\varepsilon_i^{ft}$ | Tensile fiber initial strain                                                |
| $\varepsilon_u^{ft}$ | Tensile fiber ultimate strain                                               |
| $\dot{\varepsilon}$  | Strain rate                                                                 |
| $\delta$             | Fibres angle relative to loading                                            |
| $\nu$                | Poisson's ratio                                                             |
| $\rho$               | Density                                                                     |
| $\sigma_{11}$        | Stress of the composite in the fibre direction                              |
| $\sigma_{22}$        | Stress of the composite in the transverse fibre direction                   |
| $\sigma_{12}$        | Shear stress                                                                |
| $\tau$               | Shear stress                                                                |
| 1,2                  | Axial and transverse fibres directions respectively computation; used in FE |
| 2D                   | 2 dimensions                                                                |
| 3D                   | 3 dimensions                                                                |
| %                    | Percent of                                                                  |

*A la pointe de Corbiere (Channel Islands)...*

# Chapter – 1 Introduction

## ***1.1 Background information***

By definition composites are a physical, rather than a chemical combination of two or more separate components which act together to give unique properties not found in either of the materials in isolation. In this research fibrous reinforcements and polymeric matrices were specially considered.

High stiffness, high strength, low density and design freedom are the advantages of composite materials over classic materials such as metals<sup>1-2</sup>. Their usage is of considerable benefit to the transportation industry. The design stage of composite structures is complex and often requires the use of advanced software due to the complexity of the material stiffness matrix and of the failure mechanisms occurring<sup>1-2</sup>. In addition the mechanical properties are much influenced by the manufacturing process and the volume fibre fraction. Therefore design should also take into account manufacturing processes characteristics such as change of draping fibre angles in the mould. Predicting manufacturing conditions and mechanical properties is relatively complex and as a result extensive coupon testing is usually required before design can occur<sup>1-3</sup>.

How could these barriers be overcome? How to further develop composite knowledge and take full advantage of their capacity? An answer was proposed through a large European project ITOOL involving thirteen industrial, researcher and academic universities for three years. Through this large synergy a software friendly environment dealing with numerous simulation aspects of composites was implemented in SYSPLY<sup>TM</sup> 4 in 2009.

The European project ITOOL was a Framework VI project that focuses on linking softwares on a multiscale approach to create a user-friendly software environment for composite material modelling in term of structural response and manufacturing leading to faster composite designs. At the lower end of the spectrum, Micro-scale was considered which dealt with the unit cell mechanical modelling as such as fibre weaves. In the middle of the spectrum, Meso-scale models are considered which are typically made from a pile of shells or solid elements representing the individual reinforced textile composite plies individually linked with delamination interface such as cohesive elements. At the upper end of the spectrum was the Macro-scale which dealt with the laminate representation integrated in a shell element. The Macro-scale representation is commonly used for structural response to load or flow progression on large components or structures as it is relatively fast to implement and run.

Shouten<sup>5</sup> stated that “the scientific objective of ITOOL is to close the gap between missing knowledge and the proven advantages of dry fibre textiles by the development of an adequate integrated simulation tool for textile preforming technologies including braiding, advanced engineering textiles, weaving and stitching”. Figure 1 gives an example of ITOOL exchange database between the different modelling tools. The multi-scale approach in ITOOL makes possible the exchange of data's between different modelling software ranging from micro to macro structures, from fabric draping to infusion and structural simulation. The exchange of such data on several scales leads to virtual testing and reduction time in components design.

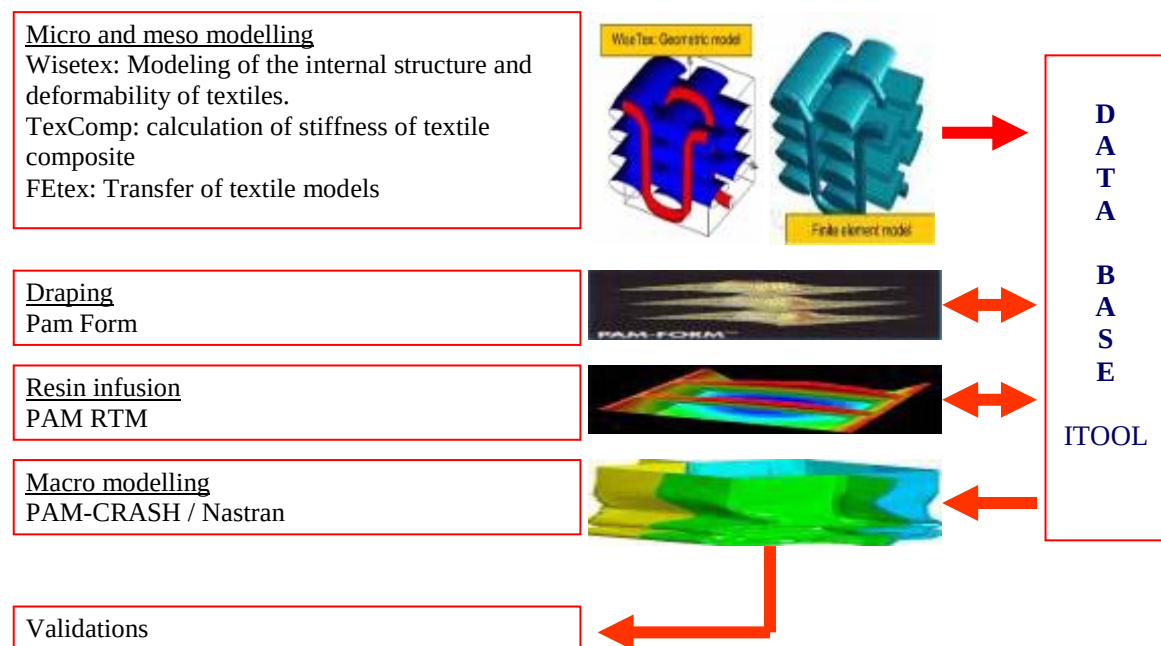


**Figure 1: ITOOL possibilities**

The large number of academic partners (Cranfield University, University of Stuttgart, University of Aachen, Katholieke Universiteit Leuven, ENSAM University Paris, University of Zaragoza) and industrial partners (EADS Germany, Alenia Aeronautica S.p.A, Dassault Aviation, German Aerospace Center, EADS Corporate Research Center France, ESI Software) involved in the project required the work to be split into seven work packages. In-plane failure and delamination at various loading rates were the focus of this research thesis and occurred in work package 4. This aspect is important in order to attempt to accurately predict the crash and impact behaviour of textile composite materials and structures. The interactions with other work packages are shown in Figure 2. This research took place within ITOOL but is not directly connected to Multi-scale modelling.

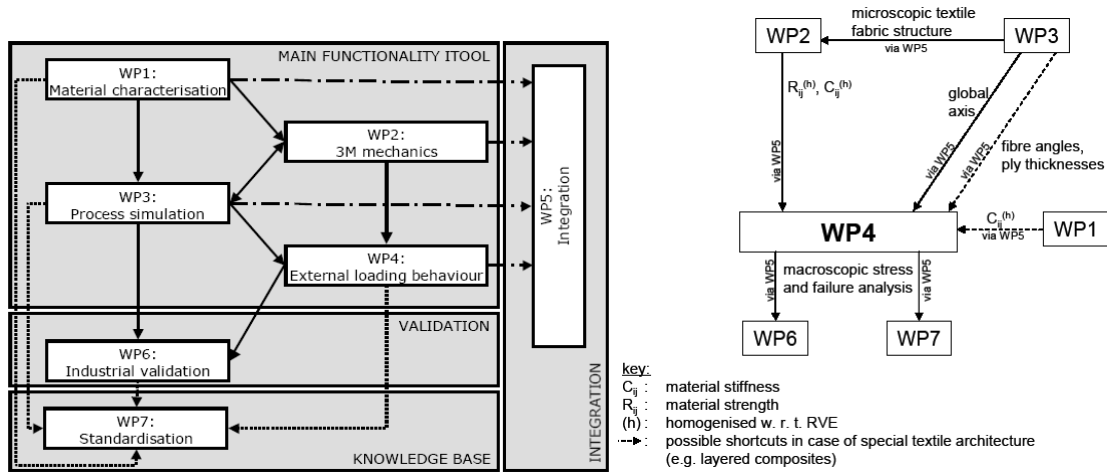


Figure 2: WP4 interactions<sup>5</sup>: left general diagram, right in details diagram

## 1.2 Objectives of the research

### 1.2.1 Context of the research

The research was not linked to Multi-scale modelling or data software exchange and was a little separated from the rest of the ITOOL project. The background to this PhD research was bird strikes on the airframe, which occurred 7666 times worldwide in commercial aviation in 2007 according to the Federal Aviation Administration<sup>6</sup> and represents a substantial safety risk and cost to the airline industry. From 1990 to 2007 there were 82,057 bird strikes<sup>6</sup>. The trends in the collisions are disturbing as well: in 1990, the industry saw 1,738 bird strikes; in 2007, the number had increased to 7,666. Whilst current leading edge wing designs absorb much of the bird energy the modelling of the composite large deformation at high strain rate is still difficult to model. It is due to complex failure mechanisms of the laminate and its complex strain rate dependency. As airframes incorporate more and more composite structures (50% by weight for the Boeing Dream Liner<sup>7</sup>) the risk of other accidental impact on composites at low, intermediate or high speed are increasingly possible either during maintenance (a tool falling on a wing), or during bad weather conditions (hail). Further bird strikes problems are also possible on

recently designed composite engine fan blades. Impact damage is then becoming a threat to the aircraft safety as it can lead to catastrophic structural failure or invisible damage. The Federal Aviation Administration database<sup>6</sup> lists 32 occurrences of bird strikes into both engines within the last 18 years, not yet including the accident of US Airways US-1549, which successfully ditched in the Hudson River at New York. To address those high speed impact problems composite failure mechanisms requires a good understanding at various strain rates. Then material models can be improved in order to reduce structural testing cost and improve design performances while reducing structural safety factors.

### **1.2.2 Research objectives and tasks**

The aim of this PhD research was the static and dynamic testing of composite specimens and structures (from aeronautical standard) through novel testing methods leading to novel material characterisation, for novel material parameters estimation and therefore numerical simulations.

In this PhD research work, in order to better understand dynamic failure of composites, a full testing program, was performed with in plane and delamination loading. This required the manufacture of samples and often the designing of new tests. Secondly, a FE software PAM-CRASH<sup>TM 8</sup> was used to model those samples and improve or better understand the material models limitation. PAM-CRASH<sup>TM 8</sup> is an industry-standard software from ESI-GROUP<sup>9</sup> which is used for the analysis of transport vehicles and aircraft structures under impact. It includes a library of 300 solids, shells and link material models, 15 of which are related to modelling composite material behaviour in the plane and in delamination. However the material models were not used in a combination of damage, delamination, strain rates and

through the thickness reinforcements which is what this thesis has aimed for. This is with regard to addressing the problem of bird strikes on the leading edge of commercial aircraft wings.

However one of the main difficulties for using or modifying complex models is to obtain good material data in the first instance to work with. As to obtain good material data, one must first of course make and prepare specimens, but essentially find often new testing methods to extract specific test data required by the model. Such novel testing methods were made possible by the use of novel DIC and dynamic DIC equipment mainly.

Therefore the PhD objectives were relatively large as the means to fulfil the objectives became secondary objectives:

- Characterization of the biaxial tufted and untufted non crimp fabric (540g/m<sup>2</sup>) reinforced with RTM6 in static and dynamic testing via (secondary objectives):
  - The development of a new compression static test.
  - The development of a new intermediate strain rate compressive test.
  - The development of a new intermediate strain rate tensile test.
  - The development of a new dynamic delamination test in mode I.
  - The development of a new dynamic delamination test in mode II.
  - The use of the SHBP for high rate testing in tension shear and compression.
- Damage analysis of the tufted and standard NCF under tension, compression, shear, and shear compression.
- Calibration of the damage model in tension, compression and shear.
- Calibration of delamination models in mode I and II for the untufted and tufted interface.

- Calibration and validation of strain rate law for the PAM-CRASH<sup>TM 8</sup> damage model (Ladeveze<sup>10</sup>) in tension, compression and shear via the data collected experimentally.
- Static and dynamic validation of the FE models on small structures made of the above tufted and standard NCF.
- Discussion and conclusion on the material behaviour, testing procedure, damage detection, and on the possibility to model composite damage, strain rate and delamination all together.

### 1.2.3 Methodology of the research

The research methodology was rather complex due to the many research areas it covered. A flow chart illustrates how the research articulated itself, broadly (Figure 3) and in details (Figure 4).

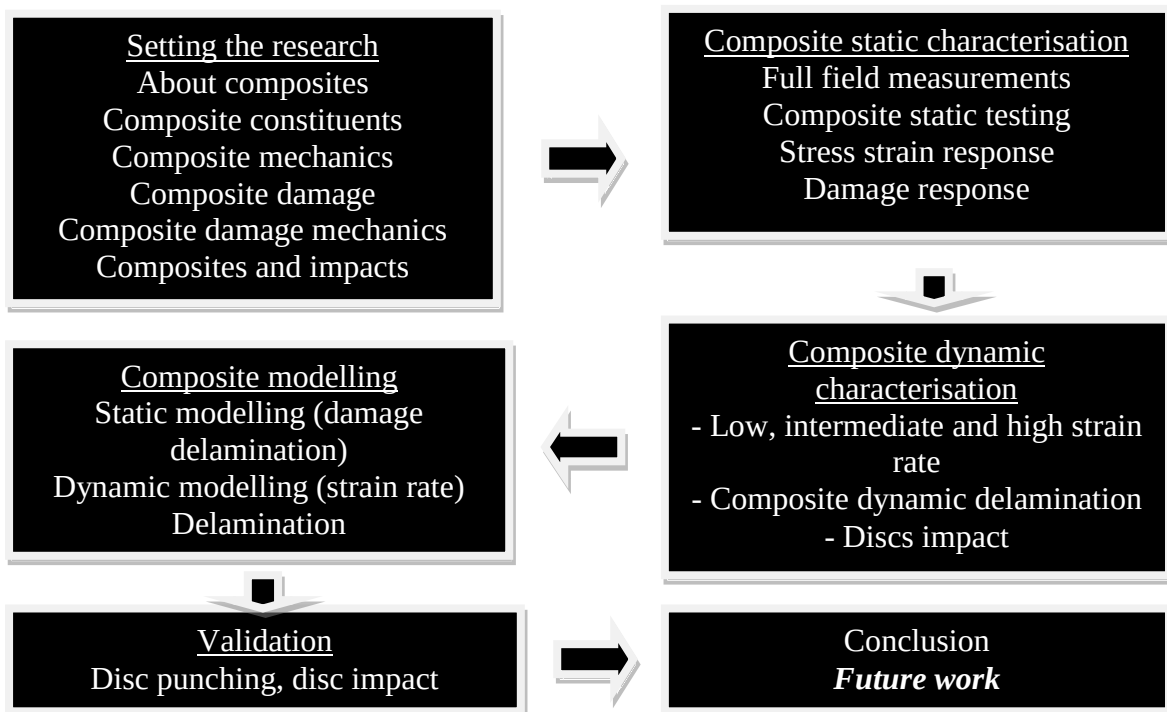
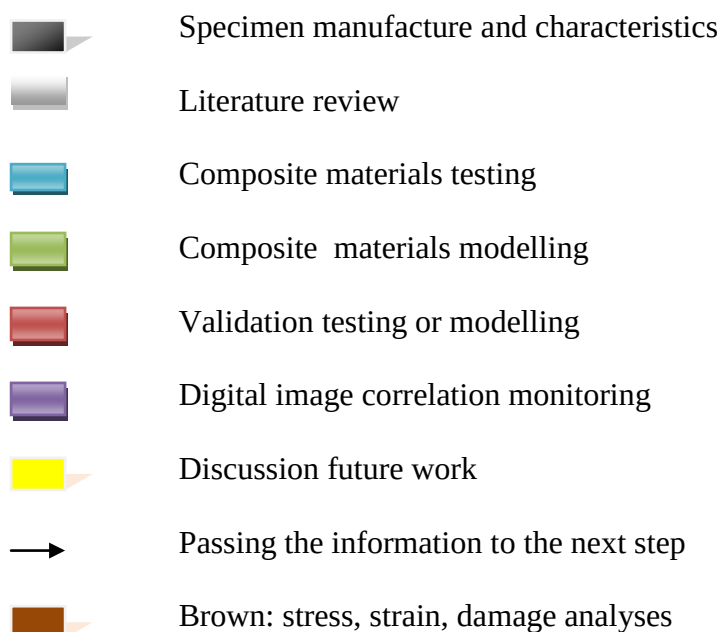


Figure 3: Research methodology

A more detailed analysis of how the work was completed is shown in Figure 4. The complexity of the flow chart illustrates the difficulty of finding a way to predict damage, delamination and strain rate effects within a dynamically loaded composite structure. The splitting and separation of the different failure mechanism was required to better understand the effect of each of them on the structure and their modelling. Each failure modes, mechanical characteristics and models can then be put back together to intend impact modelling on composite structure mixing all effects occurrence. One had the choice of big simplifications or in detail modelling of most of the physical effects occurring. This latter solution was the path chosen. Figure 4 presents the flow diagram of the whole research undertaken. The legend is as follow:





The research described in Figure 4 is relatively difficult to organize and lay in a thesis format. Yet the organization of the research thesis is as follow.

- Chapter one introduces the research and plants the ITOOL and PhD objectives.
- Chapter two revises the literature relevant to the research.
- Chapter three reviews the preparation of specimens and testing procedures.
- Chapter four assess the test results in quasi static and dynamic loading in tension, compression, shear, shear compression, delamination Mode I and II and in impact.
- Chapter five calibrates the damage ply model in tension, compression and shear with enforced strain rate laws. In addition the delamination model is calibrated in delamination mode I and II with added tuft “spring” in Mode I.
- Chapter six attempts to validate in mix loadings the models calibrated previously. For this purpose it compares a mix mode loaded composites structure response to its model.
- Chapter seven and eight discuss some aspect of the finding such as novelties, difficulties and limitations. Finally conclusions are undertaken.
- Chapter eight describes potential further work relevance.

## **Chapter – 2 Literature review and important concepts**

The area of research was relatively wide and dealt with the investigation of the dynamic behaviour of composites while including damage, through-thickness reinforcement, strain rate and delamination considerations. To do so, one often required new test procedures. Once the material behaviour would be acquired it could be inputted in a Meso-scale composite model to attempt to predict such materials response (damage, delamination, strain rate and through-thickness). The literature review describes first some important concepts needed for the global understanding of the work but secondly contained paragraphs that really reviews the literature that concerned some novel aspects of the research.

It reviews first the behaviour of carbon composites to providing a global understanding

- Mechanical response of long fibre polymeric composites
- Composite failure and damage
- Dynamic response or strain rate effects
- Impact response of composites

Then secondly, it reviews ways to test carbon composites to assess their properties:

- Experimental techniques for static characterisation of polymeric composites.
- Experimental techniques for dynamic characterisation of polymeric composites.
- Experimental techniques for dynamic delamination of polymeric composites.

Finally, it reviews some of the methods used to model the responses of carbon composites in terms of damage, delamination, through-thickness reinforcement and strain rate.

- Dynamic common models used to model composite laminated structures.
- Dynamic delamination models commonly used.
- Presentation of a through-thickness reinforcement model.

## 2.1 About carbon composites

### 2.1.1 Composite constituent characteristics

A wide range of fibres are used in polymeric composites to add strength and stiffness to the matrix. Figure 5 provides some typical information on the strength and weight of various fibrous reinforcements, it is noted that carbon fibres exhibit excellent properties.

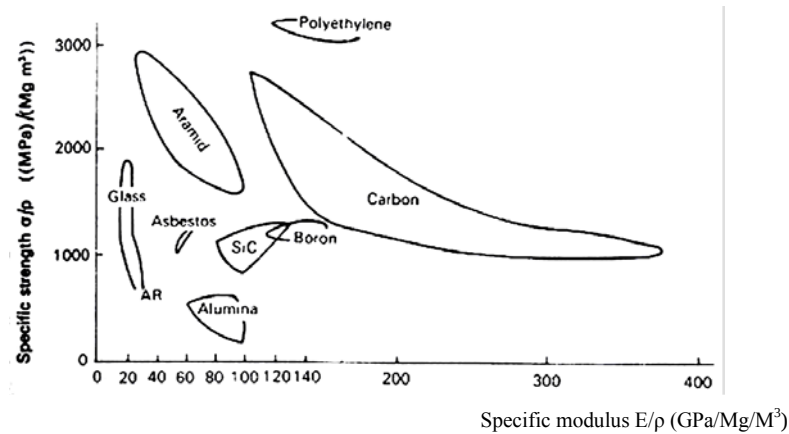


Figure 5: Specific strength against specific modulus for different types of fibers<sup>1</sup>

Different carbon fibres grades exist within which high stiffness grades would have a slight reduction in strength. Different matrix system can be used for binding fibrous materials. Metallic, carbon, or polymeric matrices are the different families of available matrices. The polymer category is subdivided in various categories (Figure 6) such as rubber, thermoplastic and thermoset within which many molecular arrangements are possible to provide matrices with specific properties.

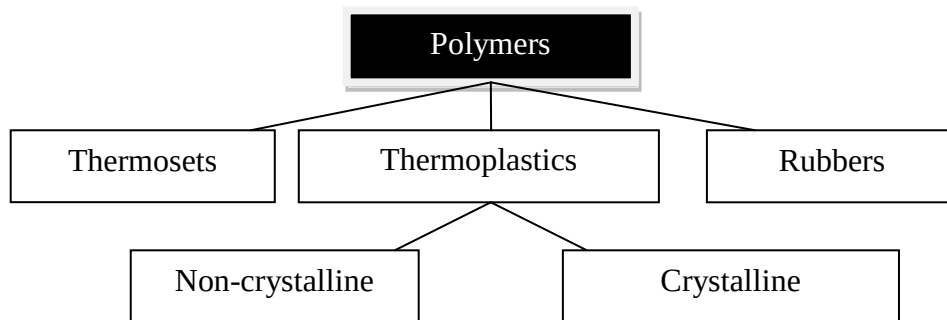


Figure 6: Simple classification of resin for composites<sup>1</sup>

Table 1 exhibits some of the mechanical properties of thermosets. In general epoxy is seen to be of special interests because of its high mechanical properties and ease of processing.

|                  |                      | Epoxy   | Polyester | Phenolics | Polyimides |
|------------------|----------------------|---------|-----------|-----------|------------|
| Density          | (Mg/m <sup>3</sup> ) | 1.1-1.4 | 1.1-1.5   | 1.3       | 1.2-1.9    |
| Young' Modulus   | (Gpa)                | 2.1-6   | 1.3-4.5   | 4.4       | 3-3.1      |
| Tensile strenght | (MPa)                | 35-90   | 45-85     | 50-60     | 80-190     |

**Table 1: Mechanical properties for some thermoset matrices<sup>1</sup>**

The epoxy group is a three member ring containing one oxygen and two carbon atoms (Figure 7). The curing mechanism can be complex and is called ring opening mechanism which means that on a polymer chain a water molecule has been removed.

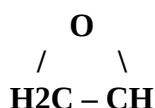


**Figure 7: Epoxy group**

### **2.1.2 Ply definitions**

Composite materials possess specific definitions due to their layered nature. It is required to clarify them at the start of the literature review to avoid any misunderstanding. Several plies composing a structure are called a laminate. But one composite ply constituting the laminate is called a lamina. The plies in the laminate can be of different natures, thicknesses and orientations. In some case one layer from the laminate can get debonded due to normal or shear stresses. This mechanism is called delamination. Matrix cracking can lead to delamination but it is often limited and consists in the degradation of the matrix mechanical properties. It occurs mainly during the shearing of the laminate plies.

### 2.1.3 Architecture of the fibrous reinforcements

The manner in which carbon fibres are processed in actual textile plies influences their strength and stiffness since it affects the fibres orientation and the fabric crimp. Some different fibres architecture are considered in Figure 8. They consist essentially of UD plies and different weave architectures. The primary purpose of the weave fabric is to make a structure that has good in-plane properties but also a low bending stiffness. Often composite reinforcements in the form of fabrics are chosen over UD laminates for their ability to drape.

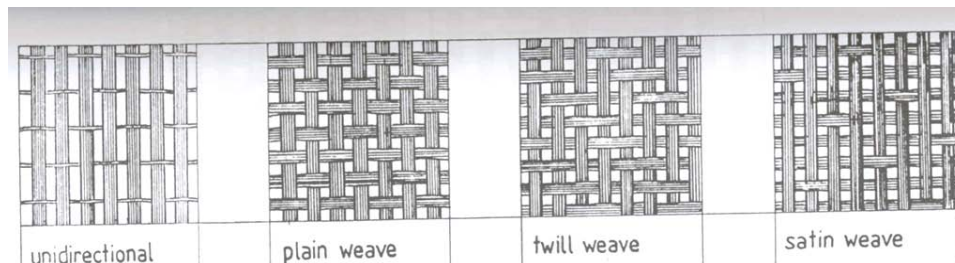


**Figure 8: Different fiber's weave<sup>2</sup>**

In this PhD special interests were given to NCF composites that are, by definition, UD layers none structurally stitched together. Several layers of carbon fibres are stitched together and can be laid in the mould at the same time which reduces processing time. It has the advantage of possessing little crimp and thus has high in-plane mechanical properties while fast drapability is achievable.

### 2.1.4 Through the thickness reinforcements of advanced composites

As with other classes of continuous fibre/thermosetting matrix composites the superior in-plane performance of NCF is accompanied by susceptibility to delamination. A number of methodologies have been developed to address the issue of low delamination resistance of continuous fibre composites which focused on the use of toughened resin systems, 3D weaving/braiding or through-thickness

reinforcements. 3 D fabric consists of several plies weaved or braided together for which constitutive yarns belong to several layers. This type of reinforcement is also called “interlock” since the plies are locked together (Figure 9). These reinforcements possess high out of plane properties (delamination resistance), but have weaker in-plane properties due to the high crimp and numerous resin rich areas.

Through-thickness reinforcements consist of 2D fabrics reinforced through the thickness after the weaving process, usually by a needle. Different needles path lead to different techniques such as stitching and tufting. The nature, size, density of the reinforcements can vary to obtain the adequate response of the laminate. Also there are two kinds of through the thickness reinforcements, one is called structural in which the stitching yarn (for example) adds through the thickness strength and prevent further delamination. The other type is called non structural and is made from a very thin low strength thread that is only used to attach numerous fabric layers together to allow faster laying of the fabric in the mould. For example, non-structural stitching is commonly used to produce NCF and to attach the UD plies together.

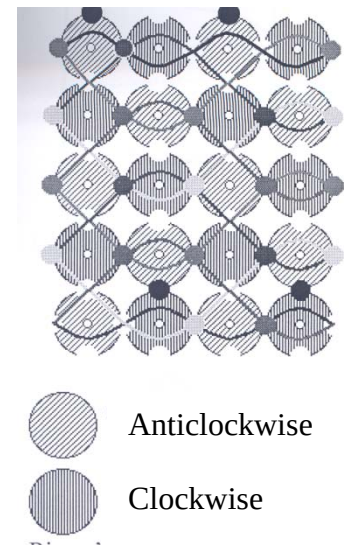


**Figure 9: Braiding process of a 3D interlock braid<sup>11</sup>**

In stitching, a needle is used to perforate the fabric and to insert a high strength yarn which is locked by a second thread. Stitching affects delamination properties positively with notable improvements to both mode I and mode II toughness<sup>12;13;14</sup>. In-plane mechanical behaviour is also influenced with potential enhancement (or degradation) of properties depending on laminate type, manufacturing route, stitching condition and loading<sup>15</sup>. Stitching also enhances the impact response of laminates with significant improvements under impact conditions and prevents the formation of

large delaminations<sup>16</sup>. The final set of properties obtained is influenced to a large extent by damage, such as resin pockets, broken fibres, fibres kinking and misalignment, introduced during stitching<sup>15; 17</sup>. Tufting (Figure 10) is performed using a needle that carries the tuft through a dry fabric and retracts, allowing the action of friction to hold the thread in place. Tufting increases the load carrying capacity of structures prone to delamination damage<sup>18</sup> and improves both the delamination<sup>19</sup> and compression after impact (CAI) response<sup>17</sup>.

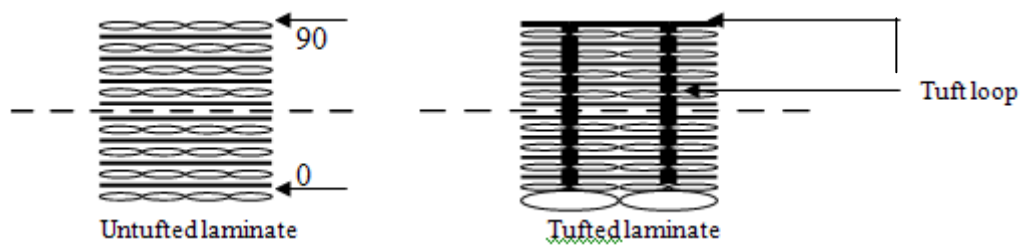


**Figure 10: Tufted and untufted material**

In z-pinning, pultruded carbon pins incorporated in crushable foam are inserted in pre-impregnated textiles using an ultrasonic hammer. The inserted z-pins significantly improve delamination response of composite laminates<sup>20-21</sup>. Similarly to stitching, z-pins induce crimping and distortion of fibres as well as resin rich pockets which degrade the in-plane response of laminates<sup>22; 23</sup>.

## **2.2 Mechanical response of long fibre polymeric composites**

After defining the various constituents and particularities of the NCF polymeric composites used in this research, their mechanical response are reviewed. As such responses are different from isotropic solid materials, it requires special attention.

### 2.2.1 Scale considerations

To understand the behaviour of composite structures there is a need for two considerations. One based on mechanics at the unit cell scale of a single ply called Micro-mechanics and one called Macro-mechanics based on the laminate (composed from multiple plies) response. The unit cell level and laminate level are illustrated in Figure 11.

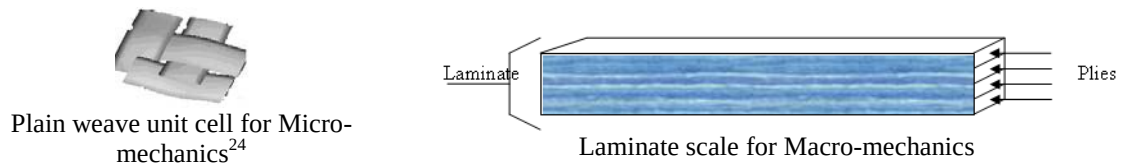


**Figure 11: Unit cell and laminate scales**

Micro-mechanics permits the calculation and estimation of the mechanical properties of the plies, such as the ply stiffness or strength. Micro-mechanics requires basic properties often provided by resin or fibre manufacturers such as the resin and fibres stiffness on their own. Classical Micro-mechanics equations can be observed in Appendix 1, nevertheless the important rules of mixture (Equation 1) is presented. It illustrates well how the individual properties of the fibres and resin can be used to predict the mechanical characteristics of a single ply.

$$E_{11} = \beta_1 * \beta_2 * E_f * V_f + E_m * (1 - V_f) \quad \text{Equation 1: rules of mixtures from Micro-mechanics}^{1-2}$$

- $E_{11}$  Longitudinal stiffness which is the elastic modulus in the longitudinal direction.
- $V_f$  Fibers percentage in volume of the composites, depends on the manufacturing process.
- $1 - V_f = V_m$   $V_m$  matrix percentage in the composites.
- $E_f$  The Young's Modulus of the fibres.
- $E_m$  The Young's Modulus of the resin.
- $\beta_1$  Depends of the fabrics type:
  - $\beta_1 = 1$  unidirectional layer
  - $\beta_1 = 0.5$  woven fabric 0/90
  - $\beta_1 = 3/8$  random in plane
- $\beta_2$  Lengths correction factor for short discontinuous fibres, (if continuous  $\beta_2 = 1$ )

The data obtained from Micro-mechanics is often used to supply the Macro-mechanics calculation (the response of the laminate). For which the ply (lamina) stiffness, Poisson's Ratio and strength is required. Also in many cases, specific testing (tension, compression and shear) is preferred to Micro-mechanics calculations as they are often more reliable. Recently some software such as Wisetex (modelling of the internal structure and deformability of textiles)<sup>25</sup> combined with FEtex (transfer of textile models to FE packages)<sup>25</sup> have been developed to model the response of composite unit cell into which fibres architecture and constituents can be chosen and for which numerical data such as stiffness, strength and damage are calculated from FE analysis. This area of research or engineering is known as virtual testing and is under current intense development. Some research on this topic occurred within the framework of ITOOL in Katholieke Universiteit Leuven and EADS partners.

Macro-mechanics applies to the composite mechanics on a larger scale: the laminate scale rather than the unit scale. The response of such laminates to force and moment allows the calculation of strains and stresses on each ply composing the laminate. Since Macro-mechanics in composite materials uses rather complex matrix calculations it benefits from numerical computer power such as FE analysis. Added complexity of the calculation occurs on curved surfaces, on complex layup sequences or intricate loading. Some of the basic mechanical response of composites occurring at scales such as a specimen or a panel length is reviewed below.

### **2.2.2 Mechanical behaviour**

The mechanical behaviour of solids is reviewed before expanding to the one of composites and therefore of NCF composites.

### 2.2.2.1 Mechanical behaviour of solids

The Stress - strain relationship for an isotropic material can be simply described by Hooke's law<sup>1</sup>:  $\sigma = E\varepsilon$       **Equation 2: Hooke's law<sup>1</sup>**

This equation 2 is only true in the elastic region as shown on (Figure 12). E characterized the stiffness of the part and can be seen as the slope of the curve on the Figure 12.

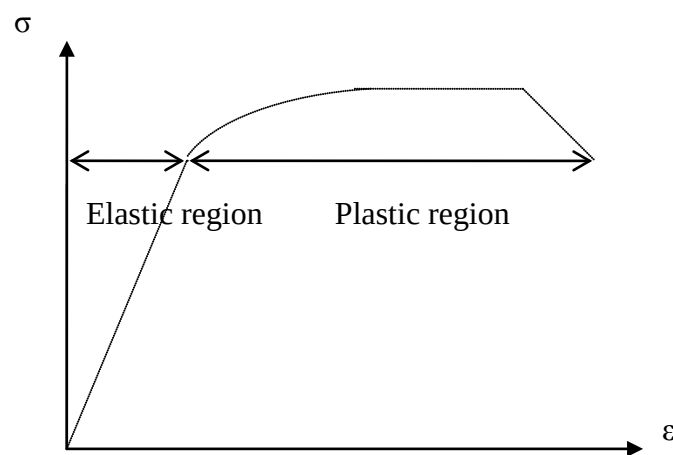


**Figure 12: Stress versus strain**

The material will only recover to its initial state if the stresses and strains are limited to the elastic region, if not the material will be deformed permanently which is then called damage. The mechanics of the elastic response is rather straightforward. Nevertheless, the progressive damage mechanics which occurs in the plastic region is rather complex.

### 2.2.2.2 Mechanical analysis of composite laminate

A laminate is composed of a sequence of plies (Figure 11), which are characterized by a thin woven or unidirectional fabric reinforced by a polymeric matrix which bonds the plies together to form the laminate. The laminate is often thin compared to the composite structure itself, in analysis this allows it to be modelled as a 2D shell with a 2D stress system. It is assumed that the plies are bonded together perfectly (the bond will be very thin). The mechanical properties of the different plies

will dictate the behaviour of the whole laminate. Firstly the mechanical behaviour of one ply only is considered in plane stress (2D).

The stress strain relationship is then:

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{12}}{E_1} & 0 \\ \frac{-\nu_{12}}{E_2} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [S] \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} \quad \text{Equation 3}^{1,2}$$

and

$$\nu_{12} / E_1 = \nu_{21} / E_2 \quad \text{Equation 4}^{1,2}$$

So that orthotropic materials are defined with four constants.

To define the stresses in term of strains, it is needed to take the inverse of [S] which is:

$$[S]^{-1} = [Q] = \begin{pmatrix} \frac{E_1}{J} & \frac{\nu_{12} * E_2}{J} & 0 \\ \frac{\nu_{12} * E_2}{J} & \frac{E_2}{J} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \quad \text{Equation 5}^{1,2}$$

Where  $J = (1 - \nu_{12}\nu_{21})$

$$\text{So that } \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [S]^{-1} \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{pmatrix} \quad \text{Equation 6}^{1,2}$$

To find the stresses while the material axis and the loading axis differ from an angle  $\theta$ , a transformation matrix is required: T will be the transformation matrix which is defined as follow.

$$[T] = \begin{vmatrix} \cos^2 \theta & \sin^2 \theta & 2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & -2 \sin \theta \cos \theta \\ -\sin \theta \cos \theta & \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{vmatrix} \quad \text{Equation 7}^{1,2}$$

$$\text{Then } \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [T] \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{bmatrix} \text{ and } \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \frac{\gamma_{12}}{2} \end{pmatrix} = [T] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \frac{\gamma_{xy}}{2} \end{bmatrix} \quad \text{Equation 8}^{1,2}$$

Combining those equations with the Hooke's law<sup>1</sup> for orthotropic materials gives:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} = [T]^{-1}[Q][T] \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \frac{\gamma_{xy}}{2} \end{bmatrix} \quad \text{Equation 9}^{1,2}$$

The formula above will explain the behaviour of one ply but it is all more complicated when a sequence of plies is stuck together with different orientations, thickness and nature.

To obtain the complete response of the laminate to forces or moment, further calculations must be used. The equation 9 is known as the constitutive equation and can be written as:

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ k \end{bmatrix} \quad \text{Equation 10}^{1,2}$$

Where N is the loads, M the moments, k the mid plane curvature of the laminate,  $\varepsilon^0$  mid planes strains of the laminate, [A] is a matrix defining the in plane stiffness, [B] is a coupling matrix which relates curvature to in-plane force and [D] is the bending stiffness matrix<sup>26</sup>. Because of the complexity of the calculations involved, FE software are used when the loading and the ply sequence are not simple. A laminate design guide can be seen in Appendix 2. It shows that the plies need to be checked individually for failure with adequate failure criteria. If a ply, fails first it is advised to

reduce its stiffness if possible, so that loads are carried by other plies. This often means changing the orientation of the materials.

### **2.3 *Composite failure and damage***

It is noticed that the previous approach deals with the elastic response of the laminate; no damage of the materials is taken in account. The response is perfectly elastic and is not able to predict delamination or damage. Predicting damage and failure is rather complex in composite materials and they can be dealt separately or in combination. It is important to differentiate the two approaches; “damage” relates to the degradation of the composite stiffness (matrix cracking mainly) as “failure” deals more with ultimate failure such as fibres failure and delamination.

#### **2.3.1 Failure criteria**

Failure criteria are based on the material elastic response to which failure stresses and strains are compared to the material stress state. If the strength is reached the materials has failed. Failure criteria are applied to each ply individually and checked against the elastic strain or stress calculated with the stiffness matrix described previously. In some cases, where certain plies fail and others do not, the laminate is also said to have failed, although it can often still bear considerable loading. More than 20 failure criteria have been developed over the years to predict laminate failure, some being rather simple other being complex. Recently, a world failure exercise<sup>27</sup> have taken place to compare the accuracy of the failure criteria on different lay ups and boundary conditions. The correct prediction of failure is important for many applications but, in the case of structural impact it defined the energy absorbed. A few of the basic failure criteria will be reviewed to provide an understanding of their applications.

The simplest failure criteria are known to be the maximum failure stress criteria and its counterpart the maximum failure strain criteria<sup>1, 2, 26, 27</sup>. In the first one, failure is said to have occurred if the stress in the ply is greater than the tensile or compressive or shear strength. Similarly, in the case of the maximum strain failure criteria, failure is said to have occurred if the strain in one of the plies is said to have exceeded the tensile, compressive or shear failure strain of the ply. More advanced failure criteria exists such as the one of Tsai Hill<sup>28</sup>. In this case, no distinction is made between tension and compression, so depending on the loading, the appropriate tensile or compressive strength must be chosen adequately. Also Tsai Hill<sup>28</sup> criteria do not identify the failure mode. Differently, Tsai Wu<sup>29</sup> failure criteria can account for differences between tensile and compressive strength.

Numerous more failure criterias exists in the literature with some capable of even degrading the stiffness once failure has occurred. The lists and performance of the failure criterias reviewed by the World Failure exercise<sup>27</sup> is illustrated in Table 2. Prediction of the laminate strength, non-linear response, large deformations, capturing feature and Micro-mechanics, were all assessed and provided a useful insight of the best failure criteria for a particular design. The list of theories is exhibited and their performance is shown (# means the theory attempted to consider the characteristics and • means the theory performed well in that respect).

|                | Laminar strenght prediction | Non linear analyses | Elastic laminate constants | Laminate strenght prediction | Large deformation prediction | Capturing features | Crack density prediction | Initial strenght prediction | Micro-mechanics | Fibre failure prediction | 3 D stress analyses | Computer code availability | Linkage to FE code |
|----------------|-----------------------------|---------------------|----------------------------|------------------------------|------------------------------|--------------------|--------------------------|-----------------------------|-----------------|--------------------------|---------------------|----------------------------|--------------------|
| Chamis         | #                           |                     | #                          | #                            |                              | #                  |                          | #                           | •               | #                        | #                   | #                          | #                  |
| Eckold         | #                           |                     | #                          |                              |                              |                    |                          |                             |                 |                          |                     |                            |                    |
| Edge           | #                           | #                   | #                          | #                            | #                            | #                  |                          | #                           |                 | #                        |                     | #                          |                    |
| Hart-Smith(1)  | #                           |                     | #                          | #                            |                              | #                  |                          |                             |                 | #                        |                     |                            |                    |
| Hart-Smith(2)  | #                           |                     | #                          | #                            |                              |                    |                          |                             |                 | #                        |                     |                            |                    |
| Hart-smith (3) | #                           |                     |                            | #                            |                              |                    |                          |                             |                 | #                        |                     |                            |                    |
| McCartney (A)  |                             |                     | #                          |                              |                              |                    | #                        | #                           | #               |                          | #                   | #                          |                    |
| McCartney(B)   |                             |                     | #                          | #                            |                              |                    | •                        | #                           | #               | #                        | #                   | #                          |                    |
| Puck           | •                           | #                   | #                          | #                            | #                            | #                  |                          | #                           |                 | #                        | #                   | #                          | #                  |
| Rotem          | #                           | #                   | #                          | #                            |                              |                    |                          | #                           |                 |                          |                     |                            |                    |
| Sun(L)         | #                           |                     | #                          | #                            |                              | #                  |                          | #                           |                 | #                        |                     |                            |                    |
| Sun(NL)        |                             |                     | #                          |                              |                              |                    | •                        | #                           |                 |                          | #                   | #                          |                    |
| Tsai (A)       | #                           |                     | #                          | #                            |                              | #                  |                          | #                           |                 |                          |                     | #                          |                    |
| Tsai (B)       | #                           |                     | #                          | #                            | #                            | •                  |                          | #                           |                 |                          |                     | #                          |                    |
| Wolfe          | #                           | #                   | #                          | #                            |                              | #                  |                          | #                           |                 |                          |                     |                            |                    |
| Wolfe (B)      | #                           | #                   | #                          | #                            |                              | #                  |                          | #                           |                 |                          |                     | #                          |                    |
| Zinoviev       | #                           |                     | #                          | •                            | #                            | •                  |                          | #                           |                 | #                        |                     | #                          |                    |
| Bogetti        | #                           | #                   | #                          | #                            |                              | #                  |                          | #                           |                 | #                        | #                   | #                          |                    |
| Mayes          | #                           | #                   | #                          | #                            |                              | #                  |                          | #                           | #               | #                        | #                   | #                          | #                  |
| Mayes (B)      | #                           | #                   | #                          | #                            |                              | #                  |                          | #                           | #               | #                        | #                   | #                          | #                  |
| Cuntze (A)     | #                           | #                   | #                          | #                            |                              | #                  |                          | #                           |                 |                          |                     |                            |                    |
| Cuntze (B)     | •                           | #                   | #                          | #                            | #                            | #                  |                          | #                           |                 | #                        | #                   | #                          |                    |
| Huang          | #                           | #                   | #                          | #                            | #                            | #                  |                          | #                           | •               |                          | #                   | #                          |                    |

**Table 2: List of failure criteria recommendations<sup>27</sup>**

According to Soden<sup>27</sup> five leading theories were found to provide best results<sup>30-34</sup>. But in the case of the prediction of the ultimate strength of multi-loaded laminates, none of the theory were said to be successful. But all of the failure criteria were capable of predicting the linear elastic deformations of laminates at low strains. Puck<sup>33</sup>, Cuntze<sup>32</sup> and Bogetti<sup>31</sup> could also predict the nonlinear behavior that can

occur at moderate strains before initial failure (Figure 13). In the case of large deformation failure theories would all under predict the failure of the laminate.

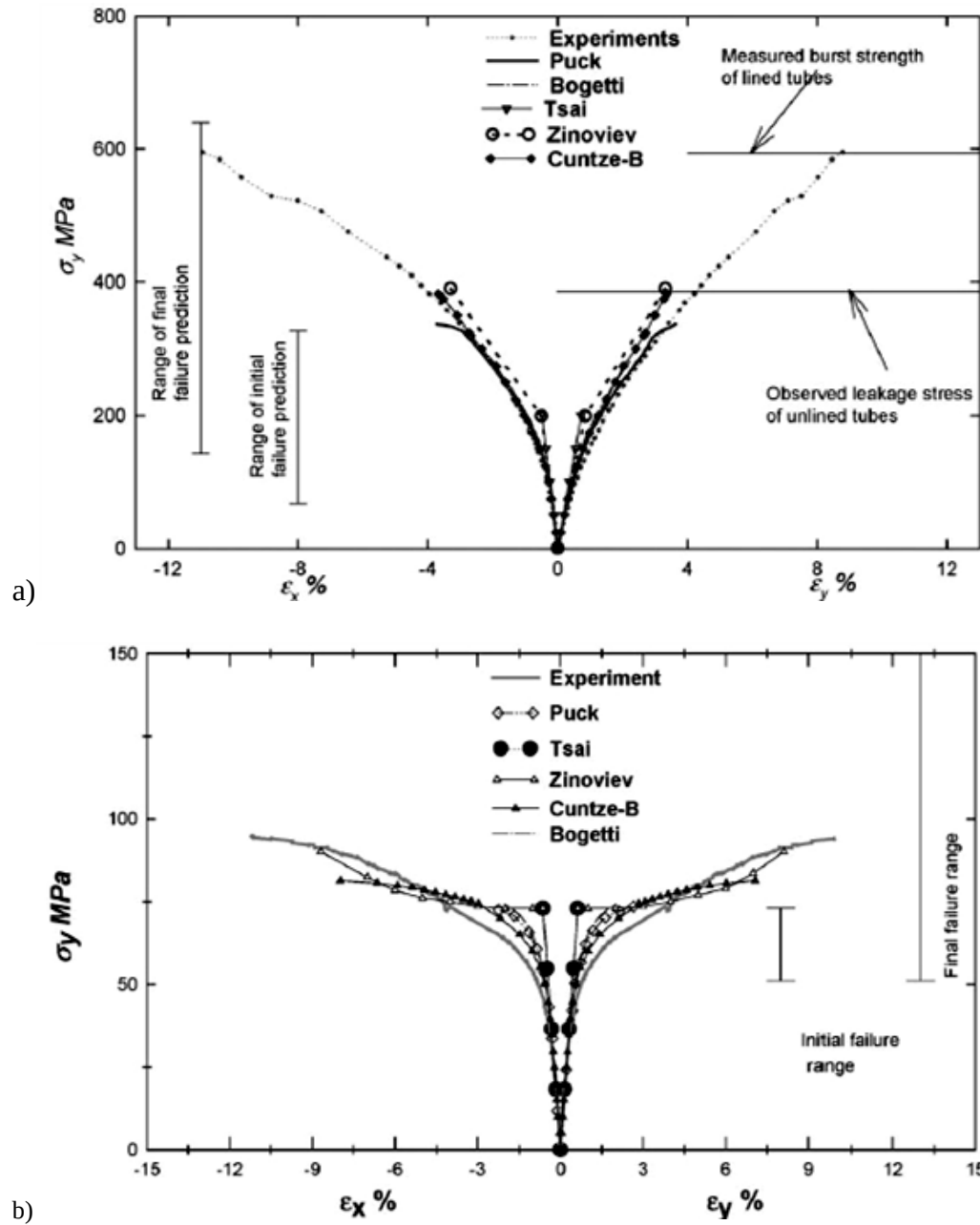


Figure 13: Various failure theories assessed on [+45] laminates<sup>27</sup>; a) Comparison between the predicted and measured stress strain curves for +- 55 Eglass laminate My750 under uniaxial tension, b) comparison between the predicted and measured stress strain curves for +-45 Eglass / My750 filament wound tube

The theories used by Puck<sup>33</sup> and Cuntze<sup>32</sup> considered three-dimensional failure mechanisms in some details and applied non-linear analysis to predict progressive failure<sup>27</sup>. The theory of Puck<sup>33</sup> best predicted the response of the laminate and experimental feature under the variety of loading and lay-up used in the world-wide

failure exercise<sup>27</sup>. It also acknowledged that work still remains in order to predict well failure.

At impact large non-linear deformations of the material with extensive fibre failure, ply delamination and matrix cracking occur so that mechanical damage considerations are of interests to better understand and represent such event.

### **2.3.2 Damage**

It is important to differentiate between failure criteria and damage progression as their mechanics are different. Damage is a loss of stiffness throughout loading that starts occurring at an early stage of deformation<sup>10</sup>. Failure criteria's are applied once a strain or stress threshold is reached on often a purely elastic model. But what is exactly damage and how can it be detected?

#### **2.3.2.1 Experimental approach to damage detection**

According to Kolsky<sup>35</sup> solids are not perfectly elastics under loading and some energy is propagated in heat through internal friction in the Micro-structure but in minute amounts at quasi static loading speed. Damage in a composites structure can occur in various ways such as, fibre failure, fibre Micro-buckling, matrix cracking, or delamination. Several experimental techniques are available to experimentally examine composites. These include the Xray technique<sup>36-38</sup>, ultrasonics<sup>36</sup>, microscopy observations, thermal deply procedure<sup>39</sup>, optical techniques and real time modulus assessment via cyclic loading of structures<sup>10</sup>. X-ray tomography consists of acquiring tomographic images during a test and usually requires the load to be brought to a standstill during the acquisition time. Electrons are sent at high velocity at a target that allows the generation of Xrays to be directed on to a specimen<sup>37</sup>. Acoustic emissions deal with the recording of acoustic material damage during loading by the means of sensors<sup>36;38</sup>. Thermal imaging requires thermal image capture of a structure via

vibrations that are imposed on the structure to generate heat while the damaged area experience a greater temperature gradient and are captured with the thermal camera<sup>34</sup>. Further options consist of optical methods (digital image correlation) that allow the monitoring of the strain field<sup>36</sup> throughout loading. Finally, a pragmatic mechanical approach may be used to estimate a damaged evolution by monitoring the reduction of modulus from a structure during cyclic loading<sup>10</sup>. With this method, damage is directly linked to the ratio of the initial specimen stiffness and subsequent specimen stiffness during loading. This method requires the specimen to be loaded cyclically to determine the elastic modulus of the material for each cycle. The first cycle corresponds to the undamaged stiffness of the specimen, and subsequent cycle corresponds to the reduced response of the specimen stiffness. But how can general mechanics represent damage?

### 2.3.2.2 Mechanistic approach to damage

Because of different damage types that can occur (matrix cracking, delamination, etc...) damage mechanics is complex. A convenient approach regards the material non-linearity as a loss of stiffness as a whole, which can be assessed through cyclic loading (Figure 14). All damaging modes such as matrix cracking, delamination or Micro-buckling are taken into account under the “umbrella” called “stiffness reduction”.

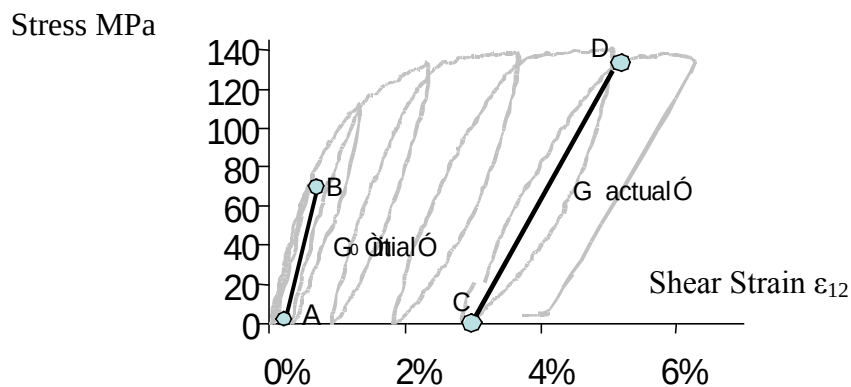


Figure 14: Example of stiffness reduction on [+45] lay ups<sup>10</sup>

The stress strain response of the laminate while taking in account damage is described in Equation 11.

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E_1(1-d_1)} & -\frac{\nu_{12}}{E_1} & 0 \\ -\frac{\nu_{21}}{E_1} & \frac{1}{E_2(1-d_2)} & 0 \\ 0 & 0 & \frac{1}{G_{12}(1-d_{12})} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = [S]\{\sigma\} \quad \text{Equation 11}^{10}$$

$E_1$  and  $E_2$  are the material elastic constant in the 0 and 90 directions.  $d_1$ ,  $d_2$  and  $d_{12}$  are the damage in the fibre principal direction and shear direction respectively. As one can foresee, this approach is considerably different from the failure-criteria approach. Several damage models have been developed but the work of Ladeveze<sup>10</sup> (section 2.9.2) has received considerable attention and would be used in this PhD research.

## 2.4 *Dynamic response or strain rate effects*

Commonly, materials are characterised under quasi-static loading conditions and design-loads are chosen based on these data sets. In reality, loads are often applied dynamically, rather than quasi-statically. Examples for this dynamic loading are all types of impact events such as a mechanic dropping a tool on to a composite structure. The understanding of composites static response is relatively complex due to the fibrous and orthotropic nature of the composites and the difference response to particular loading. In dynamic loading the response of the composite is even more complex due to stress wave propagation, depending on time and location in the inhomogeneous orthotropic material.

Often, when one thinks of dynamics of solids, one thinks of stress waves, strain rates, and sometimes even shock waves. Dynamic characterisation of composite materials is challenging as the non-homogeneity and possible difference in layup or ply drop offs, affect the stress wave propagation. If the stress wave reaches certain

conditions it can then be called a shock wave. According to Krehl<sup>40</sup> a shock wave describes a mechanical wave characterised by a surface or sheet of discontinuity in which, within a narrow region, the pressure, density, particle velocity and temperature change abruptly. In gas or liquids, shock waves can be observed in certain conditions but in a solid it is more difficult as the molecular or atomic displacements are relatively limited prior to failure of the material.

Several authors studied shock loading on composites in the literature. It was found that dynamic characterisation of composite materials was challenging as the non-homogeneity and possible difference in layup or ply drop off affect the stress waves propagation. Holmes<sup>41</sup> investigated shock wave propagation by planar impact on UD composites made from Aluminium fibres and epoxy matrix. Single, steady state-shock waves were observed. Shock pressures were many times greater than the materials strength so that it behaved as a compressible fluid. A study by Millet<sup>42</sup> attempted to determine the effect of fibre orientation on the propagation of shock waves in carbon epoxy composites. Results showed that if impacted in the through-thickness direction, the material would behave as a simple polymer. But if loaded in-plane the fibre orientations would only play a role at low stress loading. In dynamic conditions the stress in the specimen becomes a function of time and position on the sample.

## **2.5 *Impact response of composites***

Hancox<sup>43</sup> remarked that composite impact resistance is low because the laminate has low transverse and inter-laminar shear strength, as well as limited ability to absorb plastic deformations. The laminar construction and the anisotropy also reduce impact strength.

### 2.5.1 Matrix effect

In composite structures, the ply layup can often be designed so that the main load is in the fibre direction. But, in the case of accidental impact on a composite structure, the loading could be in the out-of-plane direction and may cause cracking and failure<sup>43</sup>. In this direction the mechanical properties of the structure are similar to that of the matrix. Consequently, increasing the matrix toughness will increase the impact resistance. Hancox<sup>43</sup> has suggested that up to 20% of a toughening agent could be added to the resin to make the composite tougher. It could consist of:

- Reactive liquid rubbers
- Functionally terminated engineering thermoplastics
- Reactive ductile diluents and inorganic/ hybrid particles.

But, it was found that despite a rapid increase in strain release energy rate (related to the energy to crack the matrix) after a low amount of additive that the rate of increase then diminished rapidly with additional additives.

### 2.5.2 Impact energy

In order to estimate the dissipation characteristics before impact some simple formulas can be found in the literature (Appendix 3). For example Hancox<sup>43</sup> specified two ways of predicting impact energy:

- The first technique is to predict impact energy dissipation characteristics via the use of Micro-mechanics where the following failure modes are considered: fibres failure {Uf}, resin cracking {Um}, fibre resin debonding {Ud}, fibre pull out from the matrix across a failure surface {Up}, fibre relaxation {Ur}, multiple fibre failure {Umf}, multiple matrix failure {Umm}. The total energy is then:

$$U_{Tot} = U_f + U_m + U_d + U_p + U_r + U_{mf} + U_{mm} \quad \text{Source: Hancox}^{43}.$$

The second technique is to evaluate the bulk strain energy in the laminate which is commonly the area under a stress strain curve under various possible loads. This can only be done after the test as the force displacement load trace is required.

### 2.5.3 Impact response

Sierakowski<sup>44</sup> states that an impact between two masses ( $m_1$  and  $m_2$ ) can be defined using a mass-spring system. The author differentiated between low and high speed impacts with two different spring set up as shown in Figure 15. In this research impact loading would be used by the mean of a drop tower and SHPB apparatus at intermediate and high speed. The difference between such impacts speed consists in the change of spring position and constraint of the systems as observed in Figure 15.

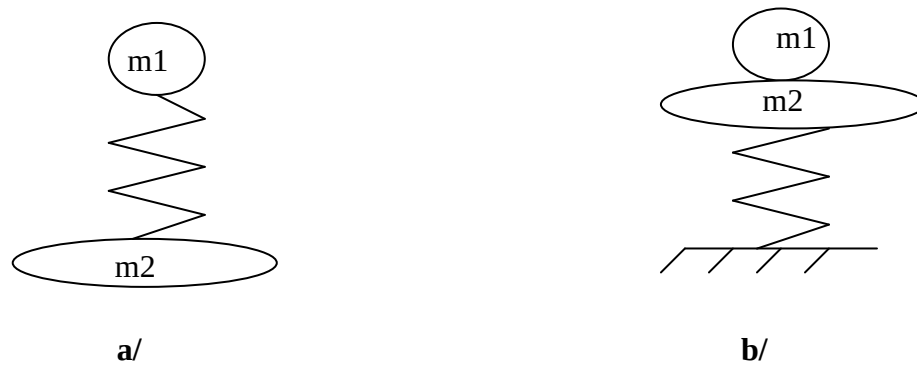


Figure 15: Low and high velocity impact spring set up<sup>44</sup>, a) low velocity, b) high velocity

The literature reviews has covered some aspects of the material response to various loading. It can now cover ways of characterising the material in-plane and in delamination at high or low speed.

## 2.6 *Experimental techniques for static characterisation of composites*

Composite structures undergo complex loading depending on the laminate design, part geometry and the loading itself. Such structures are subjected to tension,

shear, compression and out-of-plane stresses. To predict the response of such structures engineers and researchers require experimental data that can be used by analytical or FE material models. In Chapter 2.1, it has been observed that some data required by laminates mechanics theory can be obtained from Micro-mechanics at the unit cell level or even by modelling at that scale. This sort of modelling is also called virtual testing. But experimental testing remains the most accurate way to assess a composite material at the present time as the numerical tools are still being developed. Therefore tension, shear compression and delamination tests are still used to assess the characteristics such as stiffness and strength of a material. This data can be used by laminate Macro-mechanics calculations to predict the response of a structure. To monitor the response, several apparatus can be used, such as strain gauges, extensometers, lasers and full-field optical measurements. Special attention is given to full field measurements as it was made available for this research.

### **2.6.1 Strain acquisition with digital image correlation**

The usage of optical full-field measurements techniques have been increasing recently as it allows the monitoring of structure deformation through time. If DICM is combined with the use of high speed cameras, ultra-high speed deformation such as impact can also be monitored. The technique emerged in 1982<sup>45</sup>. The method involves the spraying of a specimen with a stochastic pattern. The tracking of a speckle pattern deformation through time and loading, monitored by camera(s), is the foundation of the method. Subsequently, a post processor calculates the normalized cross section via a small subset of an undeformed image while no load is applied. This calculation is repeated for a large number of subsets allowing full field acquisition<sup>46</sup>. Displacement and strain movements over two sequential images are calculated via this image

correlation algorithm for every pixel. Two possible methods can be used to acquire the field information of this pattern. If the field information is planar, only one camera can be used with 2 D post processing. But if out-of-plane movement are added or, if the pattern is in three dimensions then 2 cameras must be used to acquire the deformation through loading. In addition, the two cameras used must be synchronised in time; for pure in-plane motion (2D), only one camera is used which must be perpendicular to the surface analysed to obtain correlation results representative of the specimen deformation. The 3D analysis requires the positioning of the two cameras in space relative to one another. This is achieved through the capture of several images of a calibration target (Figure 16 (b)) being rotated around all axes. Subsequently, positions and angles of the cameras are interpreted by the software (Figure 16 (a and b)). Lichtenberger<sup>46</sup> state that “Commonly, a pin-hole camera model with Seidel lens distortions is used to allow the calibration calculation ‘ ‘ in addition 3D parameters are now the base to the mapping function.

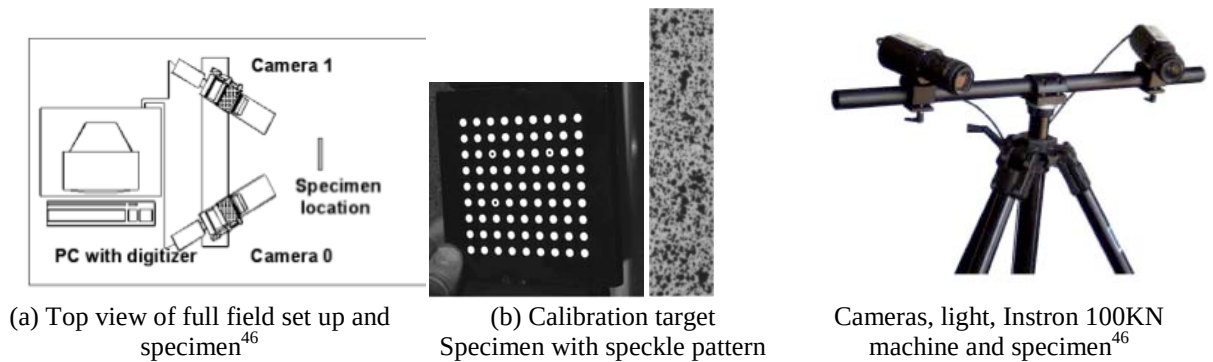


**Figure 16: 3D digital image correlation set up**

Many different algorithms have been used over the years<sup>45; 47-51</sup>. An optimized digital correlation method (DCM) was proposed by Sutton<sup>47</sup> in 1986 to improve the existent correlation algorithm for better image processing. The “optimised method” used by Sutton<sup>47</sup> has greater accuracy and faster image analysed speed. According to Sutton<sup>47</sup> the “optimized correlation” routine employs the Newton-Raphson method

with differential corrections to minimize search time. The tracking of points from an undeformed image to a deformed image is based on the recognition of small subsets in deformed images. The random speckle pattern allows subsets to be identified by x and y coordinates (in pixels) and light intensity ranging from 0 to 256, with 0 being black and 256 white. The algorithm assumes that the light intensity of a distinct point does not vary when moving and thus, a subset from an undeformed image can be correlated to a subset from a deformed image. The displacement of the centre of the subset can be written as follows

$$(x')_i = (x)_i + (u)_i + \frac{(\partial(u_i(x))}{\partial x_j} dx_j$$

**Equation 12**<sup>47</sup>

i: coordinate axis direction 1  
j: coordinate axis direction 2  
x': deformed position of the subset centre  
x: original position of the subset centre  
u: displacement vector  
 $\frac{\partial u_i}{\partial x_j}$ ; component of the deformation gradient of the subset.

The displacements for subsets are calculated using a least square error minimisation technique. The difference of the light intensity between points in the undeformed subset and all deformed subsets of the same size is compared. Upon this work, Schreier<sup>49</sup> reduced systematic errors caused by the deformed coordinates not falling onto the sampling grid of the image, by using a grey-value interpolation technique to achieve optimal sub-pixel accuracy without bias<sup>51</sup> which allowed better recognition of the stochastic pattern and easier handling of the tool. A LIMESS "Measurement Technique and Software" optical strain measurement system allowed recording of two<sup>52</sup> or three dimensional<sup>52</sup> strain and displacement fields over the full area of the tension and compression specimens use. This equipment uses algorithms from Sutton<sup>47</sup> with modification of Schreier<sup>49</sup>. In the 3D case the algorithms vary slightly with according to Lichtenberger<sup>46</sup> 3D calibration parameters being the base to the mapping function. This tool permits measurement field sizes in the range of 1 cm<sup>2</sup> to 10 m<sup>2</sup>. Typical accuracy for displacements is around 1µm with a one mega pixel-

camera and 100mm measurement field width, as the accuracy for the strain is 200  $\mu$ strains ( $=0.02\%$ ). High speed measurement is possible and is only limited by the acquisition rate of the camera. The progress of optical devices allows the usage of high frame rate recordings which are ideal to monitor high speed events such as impact. This method can be coupled with full field measurements analysis of speckle pattern of dynamically loaded specimen. Revilock<sup>53</sup> used 27000 images per second with a 256\*256 resolution to monitor dynamic impact with a slightly larger speckle pattern. This type of measurement provides additional information such as displacement and strain field corresponding to many strain gauge and extensometer.

### **2.6.2 Tensile testing**

Tensile quasi testing is straight forward via a standard testing machine. In ISO standard 527-4<sup>54</sup> it is recommended that the specimen should be 25 mm wide, 250 mm long and 2 to 10 mm thick with 50 mm end tabs (preferably made from glass).

### **2.6.3 Compression testing**

The existing compressive apparatus are classified in three different categories depending on the manner in which the load is introduced in the specimen (Figure 17). The first category is called the end loading method and introduces the load directly at the end of the specimen; it is described in standard D695-91<sup>55</sup>. It recommends a long specimen gage length and anti buckling guides. This set up is cheap and versatile to use but has the main disadvantages that complete stress strain curves are not obtainable and that specimen's geometry is extremely sensitive<sup>56</sup>. Westberg<sup>57</sup> recommends the adding of an end cap at the specimen top to prevent brooming (damage of the specimen end). The second category of compressive apparatus is called the shear loading method which introduced the load in shear by clamping the

short tabbed specimen in grips and is described in standard D34109/D34010M-03<sup>58</sup>. The set ups use the Celanese or the IITRI rig which are similar heavy rigs. However, the Celanese set up requires constant specimen thickness. Finally, more recently, a new category of apparatus emerged (combined loading) as it was found that combinations of end and shear loading methods were reducing stress concentrations at the tab tip and at the loaded end<sup>59</sup>. The RAE rig used this method in the early eighties apparatus<sup>60</sup> but in recent times new advanced compressive apparatus (Wyoming CLC<sup>61</sup> and ICSTM<sup>62; 63</sup> using combined loading were developed and led to standard D6641/D6641M<sup>64</sup>.

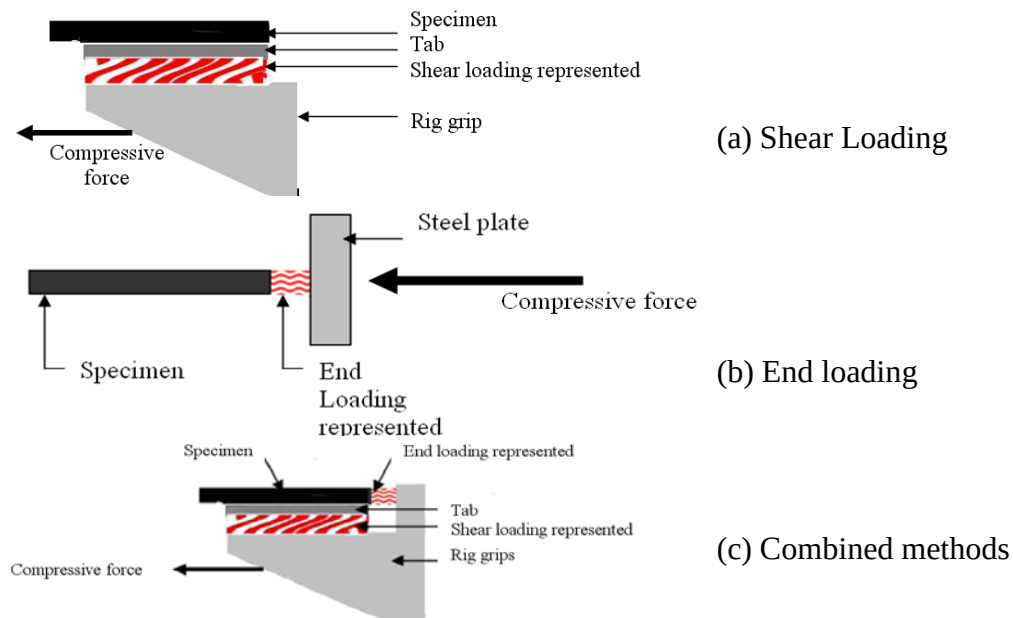
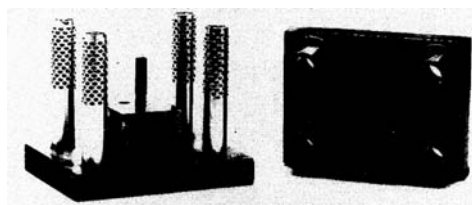


**Figure 17: End loading methods**

Comparison of compressive methods via Round Robin test programmes or more limited research occurred more than 15 years ago<sup>56; 57; 60; 62; 63; 65; 66</sup> and showed some contradicting trends. Tan<sup>67</sup> established that the Celanese apparatus provided lower compressive strength than other testing methods, which opposed the finding of Aoki<sup>68</sup>. Woolstencroft<sup>60</sup> illustrated that the RAE apparatus conferred a compressive strength near the true value of the material. The end loading method was said to be superior to others and yielded at higher compressive strength<sup>59</sup> for thick specimen.

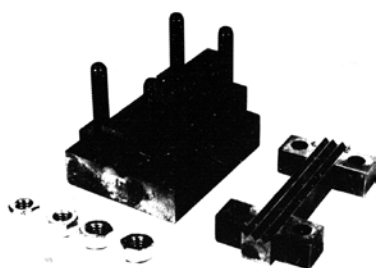
Westeberg<sup>57</sup> found that the differences between shear loading and end loading methods were small in their optimum configuration, as long as the end did not crush and that in either case, the tabs did not debond<sup>56</sup>. Finally, specimen preparation was critical to optimum compressive testing<sup>56; 57; 68; 69</sup>. Some of the apparatus used are illustrated in Figure 18.



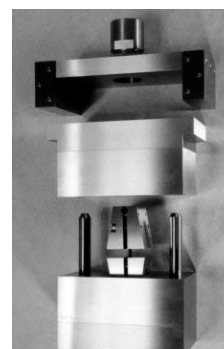
Imperial college (ICSTM apparatus)



Crag apparatus source



ASTMD695 modified



IITRI<sup>74</sup>

Figure 18: Different compressive set ups<sup>62,74</sup>

### 2.6.3.1 Different experimental techniques to measure compressive properties of polymeric materials

The load on all the various compressive apparatus is acquired through a load cell but the amount of displacement is acquired with more difficulty. Testing standards<sup>55; 58; 64</sup> recommend such a small specimen gauge length (+/-10mm) to obtain pure compression that it is difficult to apply a strain gauge. Then, often the weave architecture would be of the same dimensional order as the strain gauge on such short specimen influencing, the readings. Furthermore, the strain reading would often be influenced by stress concentrations due to load introduction (Figure 19) putting together a reduced environment for strain measurements. In addition, strain gauges are

limited by the amount of strain they can detect before failure (a few percents (+3%), as DICM can capture up to 100% of deformation. Most compressive apparatus have been designed specifically to reduce the squatter in ultimate strength of the material, and only in secondary for compressive elastic modulus or strain measurements accuracy. Many researchers would prefer to use an extension-meter, to characterise the specimen compressive displacement from which they will compute an overall strain rather than the use of a strain gauge.

#### **2.6.3.2 Notes on experimental compressive testing**

In compression testing, the introduction of load can lead to stress concentrations that affect strain reading on small specimen leading to poor material characterization. Adams<sup>56</sup> found that shear loaded specimens had more stress concentrations at the tab tip while end loaded specimen had more stress at the end loaded tip. As the tested specimen became thicker, stress concentrations occurred at the end tabs making the interpretation of the elastic modulus difficult and lowering the overall measured compressive strength<sup>67</sup>. Bogetti<sup>70</sup> found that end effect on the IITRI rig could make the Young's Modulus only 30% of its true value. Therefore Harper<sup>65</sup> recommended the use of longer specimen. Adams<sup>56</sup> acknowledged that specimen gauge length had little influence on compressive strength, but that the failure may occur away from the strain gage location. Hence, the use of full field optical techniques on the specimen surface could resolve this problem.

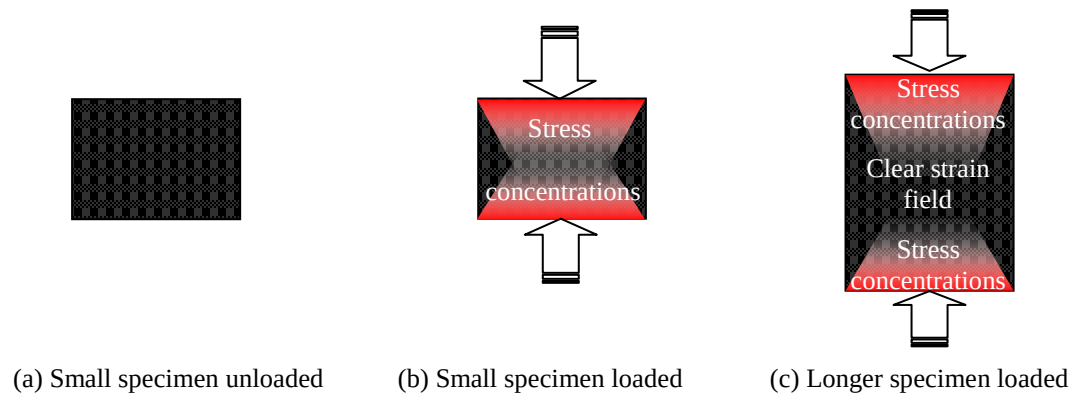


**Figure 19: Stress concentration in compression**

Nisitani<sup>71</sup> using a Celanese rig found that strength was constant 3.2 to 12.7 mm specimen gage length. Small gage length specimens can provide a close to realistic measure value of the true strength but more difficulty of the strain. Salvi<sup>72</sup> compressed off-axis composite specimens and recommended long specimen gage lengths with anti-buckling guides for proper characterization. It is understood that a longer gage length provides a clear uni-axial strain field in the middle of the specimen (Figure 19).

According to Harper<sup>65</sup>, misalignment creates a bending moment in the specimen that makes the strain recording on both sides of the composite vary, giving improper stress-strain curves and modulus. Similarly, Woolstencroft<sup>60</sup> with the RAE rig, found that in-plane misalignments reduced by 50% the compressive strength.

It has previously been noted an important effect in the testing of composites are the tab effect and fiber waviness. Some authors<sup>56; 59</sup> showed that with the use of the Boeing Modified D695 apparatus, that un-tabbbed specimens were crushing under load. Westeberg<sup>57</sup> found that a glass tab at 90 degrees provided good results. Hsiao<sup>73</sup> found that compressive strength and modulus decreased rapidly when fiber waviness increased and that a fiber misalignment of 1.5 to 2 degrees reduced considerably the compressive strength. Finally Aoki<sup>68</sup> established that standard deviation was far less on quasi-isotropic laminates than on UD materials.

#### 2.6.4 Shear testing

In-plane laminate shear data can be revealed by testing coupon specimens following standard procedures<sup>75</sup>. These procedure allow for the characterisation of shear stress versus shear strain via a tensile test on 200 to 300 mm long specimens having a [+45/-45] layup.

#### 2.6.5 Delamination testing

Delaminations are an important failure mode and specialised testing methods have been developed to characterize them. Delamination is carried out through testing of a double cantilever beam having a pre-crack which is a non adhesive film placed at one end of the beam mid plane. The two side of the beam can be pulled apart which corresponds to Mode I loading. The two sides can be sheared apart longitudinally which corresponds to Mode II, and also sideways which corresponds to mode III. Figure 20 illustrates the response of the composite to delamination in Mode I, II and III. But in order for a crack to develop, a pre crack needs to be made in the sample.

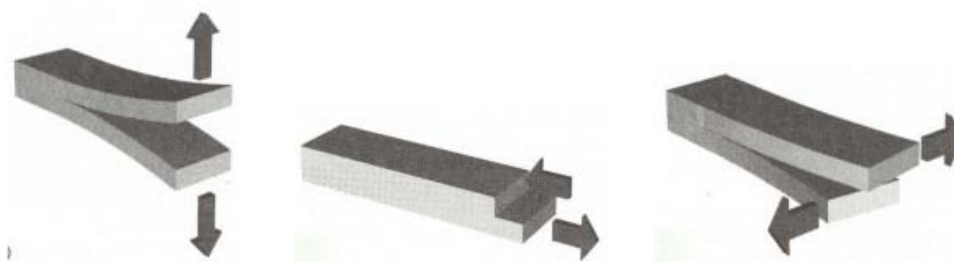


**Figure 20: Figure of delamination failure mode, I, II, and III from left to right**<sup>76</sup>

Rodopoulos<sup>76</sup> added that during delamination the strain release energy is the sum of the strain release energy in Mode I, II and III.

##### 2.6.5.1 Delamination Mode I

Different international standards have defined a procedure to determine the properties of the delamination in Mode I so that results are comparable between

different test site<sup>77; 78; 79</sup>. A standardized Mode I delamination specimen is illustrated in Figure 21.

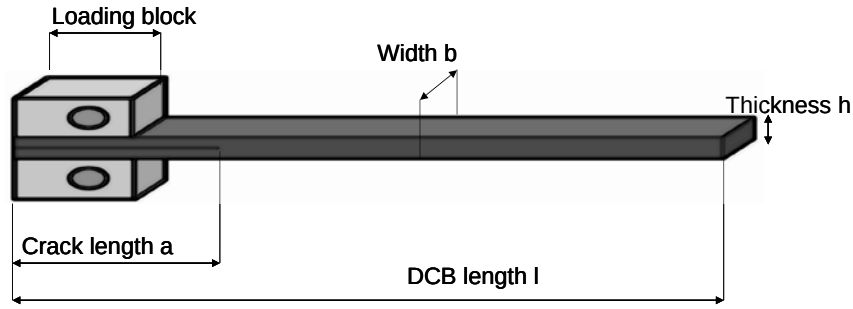


**Figure 21: Delamination Mode I specimen**

An analytical solution was determined by Williams<sup>79</sup> (Equation 13) for the strain release energy rate characterisation during the DCB delamination.

$$G_{IC} = \frac{12P^2 a^2 \phi}{B^2 h^3 E_{11}} \quad \text{Equation 13}$$

P the applied force, B the beam width, a the delamination length, h the beam thickness, E the flexural modulus of the beam and ‘φ’ relating to the beam thickness.

The compliance C of the beam is described as:

$$C = \frac{\delta}{P} = \frac{8a^3 \phi}{Bh^3 E_{11}} \quad \text{Equation 14}$$

So that  $G_{IC}$  can also be written as:

$$G_{IC} = \frac{3P\delta}{2Ba} \quad \text{Equation 15}$$

A modified beam theory has been developed to represent better the compliance at the crack tip. The standard formula above pre-supposes that the compliance at the crack tip is null but in reality some deflection and rotation exists. Hashemi<sup>80</sup> and Williams<sup>79</sup> developed a modified formula with extended crack length ( $\chi h$ ) in the form of

$$G_{IC} = \frac{12P^2 (a + \chi h)^2 \phi}{B^2 h^3 E_{11}} \quad \text{Equation 16}$$

$$\text{or } G_{IC} = \frac{3}{2} \frac{P\delta}{B(a + \chi h)} \quad \text{Equation 17}$$

$\chi h$  can be determined by plotting  $C^{1/3}$  (C being the compliance) versus crack length a.  $\chi h$  is the crack length value when  $C^{1/3}$  is null.

Furthermore, some specimens with high toughness and reduced stiffness can encounter large bending of the specimen arm plus local stiffening, due to the bonding of adhesive loading blocks. Correction factors F and N account, for those modifications respectively.

$$F = 1 - \theta_1 \left( \frac{\delta}{a} \right)^2 - \theta_2 \left( \frac{\delta l_1}{a^2} \right)^2 \text{ with } \theta_1 = \frac{3}{10} \text{ and } \theta_2 = \frac{3}{2} \quad \text{Equation 18}^{81}$$

$$N = 1 - \theta_3 \left( \frac{l_2}{a} \right)^3 - \theta_4 \left( \frac{\delta l_1}{a^2} \right) - \theta_5 \left( \frac{\delta}{a} \right)^2 \quad \text{Equation 19}^{81}$$

$$\text{with } \theta_3 = 1 \text{ and } \theta_4 = \frac{9}{8} \left[ 1 - \left( \frac{l_2}{a} \right)^2 \right] \text{ and } \theta_5 = \frac{9}{35} \quad \text{Equation 20}^{81}$$

Using those correction factors in the modified beam theory provides the corrected modified beam theory as follow:

$$G_{IC} = \frac{3}{2} \frac{P\delta}{B(a + \chi h)} \cdot \frac{F}{N} \quad \text{Equation 21}^{81}$$

Brunner<sup>82, 83</sup> identified that mode I data are safe limits that can be used for mode 2 and 3.

#### 2.6.5.2 Delamination Mode II

In Mode II delamination similar assumptions and correction factor can be used to those used in mode I. Several methods have been used to define the Mode II fracture energy but none are standardized so far. The methods are similar in terms of specimen and crack length size requirement. But, the specimen loading and boundary conditions to propagate Mode II cracks differ. The different tests configuration are the end notch flexure tests which are close to a 3-point bending test, the 4 point end notch flexure tests (4 point ENF) which correspond to a 4 points bending test, and finally the End Loaded Split (ELS) configuration (Figure 22) which uses a cantilever beam with particular boundary conditions.

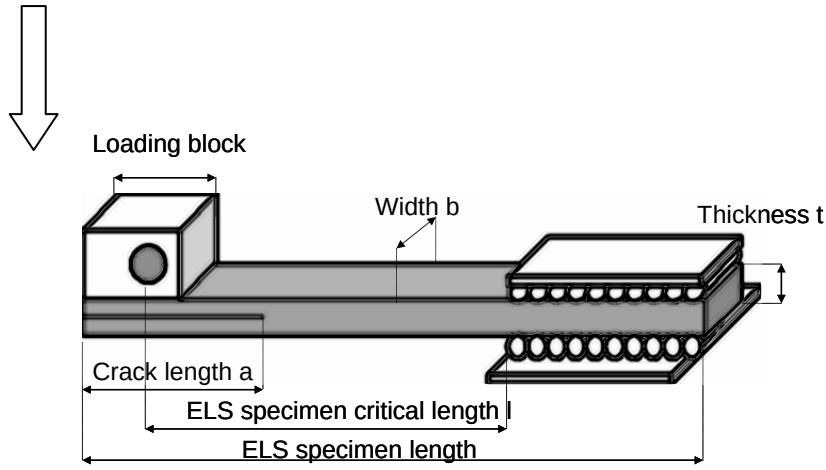


Figure 22: ELS specimen

Mode II end loaded specimen testing follows the ELS protocol analysis developed by the ESIS TC committee<sup>78</sup>. The strain release energy in Mode II is computed via equation (22) for standard and tufted interfaces with ( $P$ ) the load, ( $a$ ) the crack length, ( $b$ ) the ELS specimen width, ( $t$ ) the ELS specimen thickness, ( $Ef$ ) the flexural modulus.

$G_{IIC}$  in the ELS configuration is defined as:

$$G_{IIC} = \frac{(9 * P^2 * a^2)}{4b^2t^3Ef} \quad \text{Equation 22}^{81, 78}$$

$$P = \frac{d}{C} \quad \text{with } C \text{ compliance} \quad \text{Equation 23}^{81, 78}$$

A modified expression of the  $G_{IIC}$  expression has been rewritten to take in account the clamping of the specimen.

$$\text{With } C = \frac{(3a^3) + (L + \Delta)^3}{2bt^3Ef} \quad \text{Equation 24}^{81, 78}$$

$$G_{IIC} = \frac{\left( 9 * \left( d \frac{2bt^3Ef}{(3a^3) + (L + \Delta)^3} \right) a^2 \right)}{4b^2t^3Ef} \quad \text{Equation 25}^{81, 78}$$

$\Delta$ : correction factor taking in account the compliance of the specimen clamping in the ELS apparatus.

## 2.7 Experimental methods for dynamic characterisation of composites

Hamouda<sup>84</sup> stated that dynamic testing occurred at the beginning of the 19<sup>th</sup> century but got seriously investigated during and after World War two. Currently several testing methods are employed to characterise dynamic properties of composites.

### 2.7.1 Dynamic in-plane characterisation

The choice of the method depends on the loading speed target, the loading style, the specimen geometry and of course of the equipment availability. These different methods achieve different loading which are summarised in Table 3.

|                    |                                                  |                                       |
|--------------------|--------------------------------------------------|---------------------------------------|
| <b>Compression</b> | 0.1 s <sup>-1</sup>                              | Conventional testing machine          |
|                    | 0.1–100 s <sup>-1</sup>                          | Servo-hydraulic machine               |
|                    | 0.1–500 s <sup>-1</sup>                          | Cam plastometer and drop test         |
|                    | 200–10 <sup>4</sup> s <sup>-1</sup>              | Hopkinson pressure bar                |
|                    | 10 <sup>4</sup> –10 <sup>5</sup> s <sup>-1</sup> | Direct impact using air gun apparatus |
| <b>Tension</b>     | 0.1 s <sup>-1</sup>                              | Conventional testing machine          |
|                    | 0.1–100 s <sup>-1</sup>                          | Servo-hydraulic machine               |
|                    | 100–10 <sup>4</sup> s <sup>-1</sup>              | Hopkinson pressure bar in tension     |
|                    | 10 <sup>4</sup> s <sup>-1</sup>                  | Expanding ring                        |
|                    | 10 <sup>5</sup> s <sup>-1</sup>                  | Flyer plate                           |
| <b>Shear</b>       | 0.1 s <sup>-1</sup>                              | Conventional testing machine          |
|                    | 0.1–100 s <sup>-1</sup>                          | Servo-hydraulic machine               |
|                    | 10–10 <sup>3</sup> s <sup>-1</sup>               | Torsional impact                      |
|                    | 100–10 <sup>4</sup> s <sup>-1</sup>              | Hopkinson pressure bar in torsion     |
|                    | 10 <sup>3</sup> –10 <sup>4</sup> s <sup>-1</sup> | Double-notch shear and punch          |
|                    | 10 <sup>4</sup> –10 <sup>7</sup> s <sup>-1</sup> | Pressure-shear plate impact           |

**Table 3: Experimental techniques for high strain rates testing<sup>84</sup>**

In addition Hamouda<sup>84</sup> stated a few important issues while designing such experiments.

- Launch mechanism design to achieve the required stress strain state.
- Grip design to introduce the load correctly in the specimen.
- Adequate specimen geometry to monitor the material behaviour correctly
- Adequate test duration and equilibrium time to also monitor the material behaviour correctly

- Requirement of the understanding of the composite materials complex failure mode.
- Measurement of transient parameters accurately.
- Finally data collection and analysis.

Groves<sup>26</sup> added that dynamic testing required correct specimen configuration, fabrication method and machining tolerances.

### 2.7.2 Intermediate strain rate measurements

Intermediate strain rate testing allows the understanding of the behaviour of the material during an event such as an impact. This loading speed can be achieved at intermediate strain rate through the use of hydraulic tensile test machines and drop weight apparatus to achieve a loading speed between 1 to 25 m/s. A drop weight apparatus would have to be tall to achieve this upper

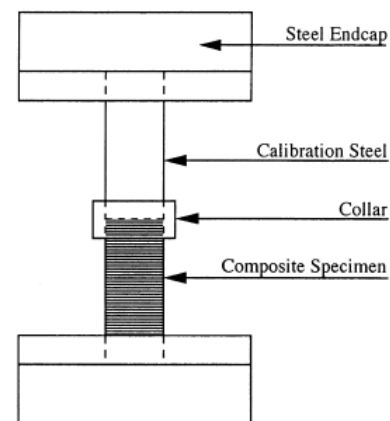


**Figure 23: Impact specimen configuration (a) source Hsiao<sup>85</sup>**

range of velocities. Therefore, in some case, they are fitted with an elastic bungee that accelerates the impactor providing reduced total drop height requirement. The drop weight apparatus has the benefit that it is relatively inexpensive to run but the results are strongly dependent on the specimen impactor interface and on the load cell locations. In some cases the load acquisition can be challenging. Hsiao<sup>85</sup> proposed to use a steel specimen mounted above the composites specimen for which strain would be recorded (Figure 23). Then, assuming the high strength steel would be loaded only in its elastic region providing constant stiffness, Hsiao<sup>85</sup> used the strain recording on

the steel as a load cell and obtain similar results for both load acquisition with a slightly better reading for the calibrated steel prior to failure.

Hsiao<sup>85</sup> used an hydraulic machine (Figure 24) for strain below  $10\text{s}^{-1}$  and a drop tower for strain rate above  $10\text{s}^{-1}$  (Figure 25 and 26.a) to test thick composite laminates at various orientations achieving strain rates up of to  $60\text{s}^{-1}$ . The shear response showed non-linearity with a plateau region at a stress level that increased significantly with loading rate. Unidirectional and cross ply laminate showed higher strength and strain to failure, with stiffness slightly increased over static values. Non linearity would occur in this latter load case if the specimen was made from high fibre waviness plies. Higher strength (42%) and strain to failure (25%) were also recorded by Montiel<sup>86</sup> using a drop tower apparatus at strain rates of up to  $8\text{s}^{-1}$  strain rate. Groves<sup>26</sup> investigated the response of a continuous fibre polymer with a drop tower (with a different set up to Hsiao<sup>85</sup>) and achieved high strain with this setup (up to  $1000\text{s}^{-1}$  for unidirectional composites) for relatively thick composites. Geometry included tapered cube, a one inch (25.4mm) cube and solid rods. The load cell in this case was placed below the apparatus holding the specimen vertically.

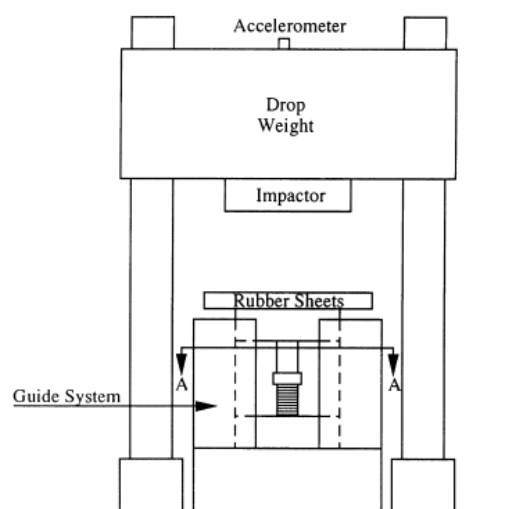


**Figure 24 : Specimen holder configuration**  
source Hsiao<sup>85</sup>

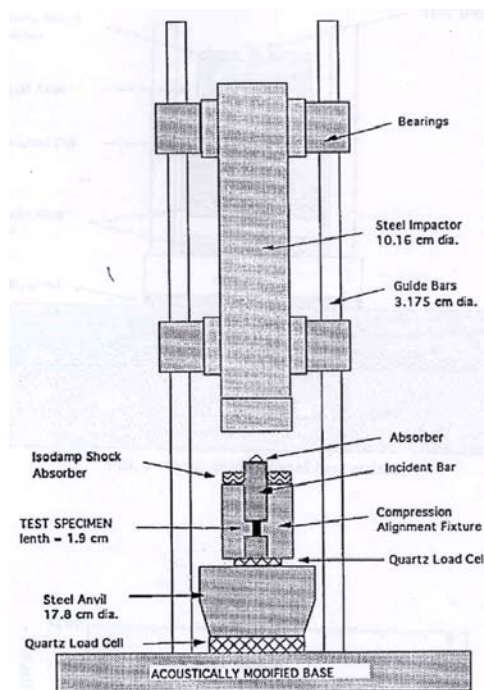


**Figure 25 : Drop tower for impact compression (a) and drop tower impact tension device (b)**  
source: Groves<sup>26</sup>

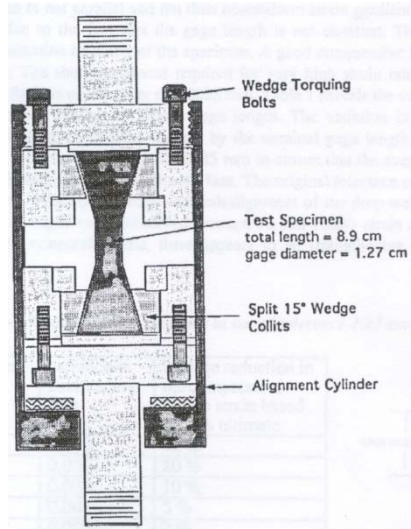
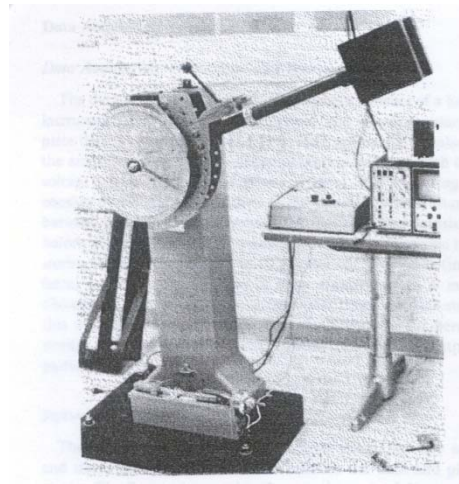


**Figure 26: Drop tower impact tension device source (a) <sup>26</sup> and pendulum impact tester (b) <sup>87</sup>**

In addition, an acoustically damped base system above the load cell and around the specimen would become loaded after specimen failure (Figure 25). The damped base would then absorb the residual load and reduced shock wave reflections on the load cell to enable accurate dynamic load measurement. Additionally, Groves<sup>26</sup> used a dynamic tensile test set up (Figure 26 (a)) with the same drop tower which was successfully used at a high strain rates ( $1000\text{s}^{-1}$ ) for tube-like specimens.

Hayes<sup>87</sup> differently used an instrumented tensile impact test system (Figure 26 (b)) with partial loading capability made from a pendulum type impact tester. The system was said to be a simple and convenient way to test composite materials and to assess strain rate properties. Also, mixed trends were obtain (sic) for a glass epoxy and carbon epoxy material with increasing modulus and strength for the first material and decreasing modulus and strength for the second one.

### **2.7.3 High strain rates measurements**

High strain tests characterise the response of the material when subjected to high speed impact / crash or blast loads. To characterise the material at such high speed the SHPB is a common tool providing measurement capability. At high strain

rates while using the SHPB to compress carbon epoxy composites, an increase in strength is observed on several lay-up configurations compared to quasi static loading force recordings<sup>26; 88-90</sup>. The same effect occurred in tension and shear<sup>26; 91-94</sup>. Also Groves<sup>26</sup> found that strength and modulus would increase exponentially with loading rate on carbon composites. Additionally, Weeks<sup>95</sup> noted that unidirectional laminates would be linearly elastic but that off-axis laminate and angled ply laminate would be subjected to strong strain rate effects. Additionally, Wang<sup>94</sup> noted that the material response depended strongly on the layup as one would expect from quasi static response. Ferrero<sup>96</sup> added that [+45] laminates had strong non linearity which was not observed on the [0/90] laminate. Nevertheless, some authors found the amount of strain would increase with loading<sup>96-98</sup> but other authors found that the amount of strain would decrease during the dynamic event or would remain comparable<sup>98,94</sup>. Stiffening of the material was observed by some authors<sup>94</sup> or not<sup>96</sup>.

### 2.7.3.1 Tensile measurements

A typical SHPB set up is illustrated in Figure 27 but its use is described later in the research. The literature reviewed what author found using such device and composite materials.

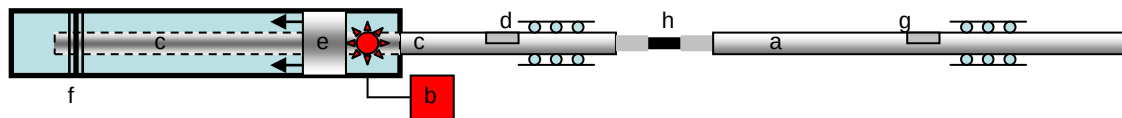


**Figure 27: SHPB bar set up in tension, (c) incident bar, (b) gas gun, (a) transmitted bar, (e) impactor, (d and g) strain gauge, (f) the impacted area of c, (h) the tensile composites specimen**

Two different methods of strain acquisition were carried out by Gilat<sup>92</sup> that measured the strain rate pulse reflection in the incident bar to compute the strain on the specimen and additionally also measured the strain on the specimen itself with a strain gauge. The failure strain recorded on the specimen would be lower (7% strain)

that the failure strain on the bar (9.6%). Examination of the fractured specimens shows that when a strain gage is glued to the specimen, the specimen fractures at the boundary of the strain gage foil so that Gilat<sup>92</sup> wondered if the strain gauge was not inducing a stress concentration. Wang<sup>94</sup> used 60mm long specimen with a gauge length of 9 mm. In a similar study on carbon T300 epoxy, Zhao<sup>99</sup> used similar specimen geometry epoxy to determine its dynamic tensile response and found that modulus and strength would increase with rising strain rate. Harding<sup>100</sup> using a tensile Hopkinson bar and gluing composite specimen in steel slots attached to the incident and transmitted bar investigated the high strain rates response of carbon epoxy and glass epoxy. The carbon epoxy composite was found to have little strain rate effect but the glass epoxy exhibited a strong increase in strain and strength.

### 2.7.3.2 Compressive measurements

Figure 28 presents a representation of a compressive Hopkinson bar setup for loading composite specimens. A gas gun (b) send a striker (g) on to an incident bar (a) which compressed the specimen (h) on to the transmitted bar (c). Meanwhile, the strain in the bar at (e) and (f) are recorded during the impact and are related to the stresses and strains on the specimen.

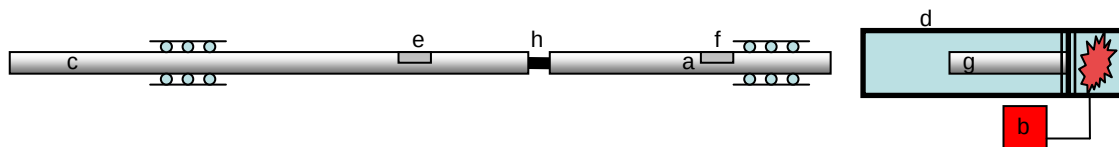


**Figure 28: SHPB bar set up in compression, (a) incident bar, (b) gas gun, (c) transmitted bar, (d) gas gun chamber, (e and f) strain gauge, (g) striker bar and (h) the compressive composites specimen**

While using UD carbon epoxy cubic specimen with different fibre orientations at strain rates in between 250 to 1100s<sup>-1</sup>. Vinson<sup>98</sup> found that the material strength would decrease non linearly while increasing fibre angle. The strength reduction would occur mainly from 0 to 20 degrees of axis plies; above this value the strength

would remain alike with a stress plateau. A comparable response was noted for the strain at failure that would increase regularly as fibre orientation was increased up to 30 degrees. Above this value no significant increase in strength was noted. Tsai<sup>101</sup> compared the response of the material depending on the specimen shape. Coupon specimen response used in quasi static testing and small cubic specimen's response used in fast dynamic loading were compared in quasi static loading and results prove to be of different magnitude. Failure stress was similar but strain development was slightly different with coupon specimen being stiffer than small specimen block which could be due to the relatively short length (6mm) of the fibre in the block specimen. Ferrero<sup>96</sup> added that compression results would depend upon specimen size and shape. Ferrero<sup>96</sup> used specimen blocks of 10 mm long and 15 mm wide with thickness in between 4 and 11 mm.

#### **2.7.3.3 Bias direction measurements**

In plane shear can be achieved through the Hopkinson bar apparatus in tension and compression by loading a [+45] laminates specimen<sup>90</sup>.

#### **2.7.3.4 Other high strain rates considerations**

The stress equilibrium of the sample during loading is an important assumption used to integrate the strain rate in the incident bar. The stress equilibrium depends considerably on the loading pulse transmitted to the incident bar by the impactor (also called striker bar) and subsequently to the specimen. The loading pulse itself depends considerably on the striker length and material. Frew<sup>102</sup> added copper rings between the striker and the incident bar to shape the loading pulse to achieve better dynamic stress equilibrium of the specimen. The copper (C11000) pulse shaper (thin disk) creates a longer duration pulse in the bar. Frew<sup>102</sup> added that for some rock

or ceramic material disc shaping is required to obtain stress equilibrium in the sample. Ellwood<sup>103</sup> rather than copper rings used an additional 1 meter long bar called a “preloading bar” for pulse shaping. In additions a dummy specimen was placed between the preloaded bar and the incident bar. The dummy specimen was identical to the actual tested specimen. The dummy specimen provided yield and flow stress properties that shaped the loading pulse for the second “real” specimen ideally. This method proved to be successful on many different type of metals. More recently, Parry<sup>104</sup> used the same method but without the dummy specimens. To achieve constant strain rate Parry<sup>104</sup> used a pre loaded bar similar to Ellwood<sup>103</sup> configuration but with lower strength than the transmitted and incident bar, this attenuated the noise of the pulse providing a clearer pulse with longer rise time.

## **2.8    *Dynamic delamination***

As impacts loading are by definition a dynamic event and as polymeric composite materials in plane response is rate dependent it is a necessity to also investigate the delamination rate dependency of the composite that would influence the damage response and failure of the structure as a whole.

### **2.8.1    Dynamic delamination Mode I measurements**

Commonly, materials are characterised under quasi-static loading conditions and design-loads are chosen based on these data sets. In reality, loads are often applied dynamically, rather than quasi-statically. Examples of these dynamic loadings are all types of impact events such as dropping a tool on a composite structure. Jadhav<sup>105</sup> specified that delamination and matrix cracking are the principle modes of failure of the composite specimens when loaded dynamically. Several researchers have reported that the interlaminar fracture toughness  $G_{IC}$  of composite materials is

dependent on the rate of loading<sup>106-108</sup> whilst other studies showed little or no rate effects<sup>111; 112</sup>. Researchers have used several experimental set ups ranging from screw driven test machines<sup>106; 110; 111; 113; 114</sup> modified Charpy and Izod impact tests<sup>107</sup>, hydraulic test machines<sup>112</sup>, drop weight impact tower<sup>115; 116</sup> and SHPB apparatus<sup>117</sup> in which boundary condition and loading proved to be different in many cases.

Several test methods have been proposed recently to determine the Mode I fracture toughness under dynamic loading of long fibre polymeric composite materials. Smiley and Pipes<sup>106</sup> used an Instron 1322 machine for experimental investigations and reported a significant decrease of  $G_{IC}$  for both, graphite/PEEK and graphite/epoxy laminates over a range of loading rate from  $4.2 \times 10^{-6} \text{ ms}^{-1}$  to  $6.7 \times 10^{-1} \text{ ms}^{-1}$ . Similarly, Mall<sup>110</sup>, using a screw driven machine and graphite/PEEK specimen, found a decrease in fracture toughness while increasing loading speed up to 1m/min. Blackman et al<sup>111</sup> also reported a slight decrease for carbon/PEEK composites if the loading rate exceeded  $5 \text{ ms}^{-1}$ . But unidirectional carbon/epoxy materials did not show any change in fracture toughness. A servo-hydraulic machine (Instron 1343) allowing test rates of up to  $25 \text{ ms}^{-1}$  and high-speed cameras were used to follow the crack propagation. Hug<sup>112</sup> mounted a DCB with symmetric displacement to obtain symmetric displacement of the arm in pure Mode I and attained arm speed of up to  $1.6 \text{ ms}^{-1}$  and observed an insignificant rate effect. You<sup>113</sup> with a screw driven tests machine at low speed, detected increasing fracture energy with increasing loading speed of carbon epoxy DCB. Other authors<sup>107</sup> used modified Charpy and Izod impact tests to measure fracture toughness. The interlaminar fracture toughness at high rates of loading ( $1\text{-}10\text{ms}^{-1}$ ) was about half of the quasi-static value. Drop weight loading was also used to load DCB dynamically. Benmedakhene<sup>116</sup> mounted a single cantilever beam specimen in a drop tower using an acoustic emission system to detect

crack initiation and follow subsequent crack growth. Their results indicated that  $G_{IC}$  is a function of velocity and brittleness of the resin system with observations that the fracture toughness increases for brittle resin systems with increasing test rate and decreases for toughened resin systems<sup>108</sup>. Sridhar<sup>115</sup> mounted double cantilever beam (DCB) specimens in a drop tower but placed them vertically and introduced the load with a falling wedge whilst recording the displacement with high-speed camera systems. Kusaka<sup>109</sup> used DCB specimen at quasi static speed and a split Hopkinson bar with “wedge-insert-fracture” specimen and to investigate rate effect up to  $25\text{ms}^{-1}$ . Kusaka<sup>109</sup> observed a decrease in  $G_{IC}$  with increasing test speed.

Finally through-thickness reinforcement was also investigated under dynamic conditions. Sridar<sup>115</sup> investigated through-thickness reinforced DCB specimens loaded with a flying wedge. From high to moderate loading rates crack propagation due to kinetic energy and bridging mechanism was important. At lower loading rates bridging mechanisms enhanced the delamination resistance. Similarly, Liu<sup>115</sup> investigated z pin behaviour during dynamic delamination at low loading rates with pull out and double cantilever beam set ups, in screw driven test machines. Positive strain energy release rate was detected at increased loading rates. The failure mode of the pins varied from pin pull out to failure, depending on the loading rate and pin density used. Kilic<sup>118</sup> also investigated carbon composites with Z pins responses to dynamic delamination. A universal testing machine and a loaded spring were used to achieve a loading rate up to  $5\text{ m/s}$  on carbon epoxy specimens. An electronic crack locator strip was used to monitor crack growth.  $G_{IC}$  was found to increase particularly with loading rate.

All dynamic delamination studies<sup>114; 115; 118</sup> with through-thickness reinforced DCB, detected a positive rate effect. But DCB's with standard resin interface,

according to the literature, provide inconsistent trends. Comparisons of test results by different configurations and materials are extremely complex. To make sense of the trends in the literature, it is proposed to assess for each test set up the dynamic load capture, the possible inertia effects, and whether or not pure mode I crack loading is achieved. Results from Hug<sup>112</sup> and Blackman<sup>111</sup> provide strong arguments (both arms are loaded at the same speed providing pure Mode I crack propagation) and their trend showed no significant rate effects with increasing loading speed which agrees with Cantwell<sup>119</sup>.

### **2.8.2 Dynamic delamination Mode II measurements**

The delamination rate dependency of a composite shell is a possibility that would influence the damage response and failure of the structure as a whole. But some load cases will subject the interface layers to Mode II shear loading, predominantly. For example, resin interface shear mechanisms occurring in bending take place in large amount during out-of-plane loading events such as impacts. Therefore, delamination Mode II response at high loading rate is of interest to predict impact damage. In this PhD research dynamic delamination Mode II and subsequent possible rate effects are studied for the tufted and standard NCF.

Different apparatus can provide delamination Mode II measurement, however none are standardized. End notch flexural (ENF) specimen<sup>120</sup>, End loaded split (ELS), or short length specimens are all possible test configurations to quantify delamination in Mode II. These experiments can be carried in dynamic conditions via hydraulic tests machines, drop towers or SHPB apparatus. Smiley<sup>120</sup> investigated Mode II fracture toughness dependency to strain via a screw driven and a hydraulic testing machine (up to  $0.092 \text{ ms}^{-1}$ ) with ENF type specimen. It was found that crack growth

changed from ductile to brittle mode with higher rates of loading. This change resulted in considerable drop in  $G_{IIC}$ . Nwsosu<sup>121</sup> investigated mode II delamination in graphite epoxy specimens at high rates with a SHPB and ENF and CNF specimen configuration. Results showed that delamination and energy absorbed in fracture increased with increased impact energy. Wu<sup>122</sup> with a SHPB used a three-point-bending and compact shearing test configuration but found no significant rate effect in Mode II. Cairn<sup>123</sup> used a modified ENF set up in a drop tower apparatus and registered superior fracture initiation and higher resistance to propagation under dynamic conditions. Tsai<sup>124</sup> similarly used a modified ENF test in a drop weight tower but used a special insert film that delayed crack initiation, allowing a high crack speed to be reached. Using FE analysis and experimental results, it was concluded that no significant rate effect was achieved until a 1100 m/s crack speed threshold. Cantwell<sup>125</sup> with similar methods (ENF and drop tower as well screw driven machine) detected positive rate sensitivity for increasing loading rate. It was also noticed that offsetting a few degrees the interface would increase the rate sensitivity. Using CNF and FE analysis Maikuma<sup>126</sup> and Caimini<sup>127</sup> came across decreasing fracture energy for an increasing loading on carbon composites with screw driven or drop tower test devices. Also Caimini<sup>127</sup> with a new specimen set up called ECNF (compact edge-notched shear specimen) but with the same material and test methods that were used with the CNF tests configuration above, found increasing fracture energy with loading rates. Again, with ENF apparatus and drop weight loading on glass-fibre / vinyl-ester specimen, Compston<sup>128</sup> came across no significant rate effect.

Through thickness reinforcement by the means of stitching were investigated in Mode II static delamination in carbon epoxy laminates by Wood<sup>129</sup>. It was found

that the stitch effect could be measured but did not play a significant improvement in the delamination resistance.

Ways to characterise the material have been reviewed so that a closer look can be given to ways to model the composites. This will be of use once the material data has been collected.

## ***2.9 Explicit models used to model composite structures***

The responses of composite structures are heavily based on the plies constituting the laminate. It is useful to compute stiffness and stress strain response of a composites structure via FE analysis as the calculation can be complex. It permits the appliance of failure criteria as shown in Chapter 2.3. This proves to give satisfactory results in static codes to evaluate the failure of a structure and its design but it possesses limitations in computing large post failure deformation of a laminate. In the case of impact, this scale of large deformation is the mechanism of energy dissipation. To represent those failure mechanisms it is often better to use damage mechanics, energy function and material experimental calibration that prove to better represent impact responses. These damage models do not focus on the first detection of failure but on the accuracy of the large deformation response and can be strain rate dependent. Often, strain rate parameters can be added to reproduce better the deformation. But what governs “explicit” finite element analysis?

Non linear FE programs used are based on updated Lagrangean formulation. The governing equations for updated Lagrange formulation are:

- Conservation of mass
- Conservation of linear momentum
- Conservation of angular momentum
- Conservation of energy
- Constitutive equations
- Rate of deformation
- Boundary condition
- Initial conditions
- Interior continuity conditions

Source: Belytschko<sup>130</sup>

The explicit FE code PAM-CRASH<sup>TM 8</sup> includes a composite model that allows damage and strain rate modelling via continuum damage mechanics treating strength degradation and failure. The orthotropic homogenous model called Ladeveze<sup>10</sup> model is used for UD composite modelling. The model can represent fibre failure and matrix micro-cracking by its calibration via coupon testing. To calibrate the model completely, a series of tests are required in tension, compression, and shear bias directions. The numerous parameters extracted from the tests then feed into the model that then represents the material response. The models do not represent delamination.

### **2.9.1 Impact modelling**

#### **2.9.1.1 The impactor**

There are different solutions to model an impactor. Solid elements, or shell elements, can model well an impactor until a certain speed. If the impactor deforms too much then the mesh is highly distorted which will affect the mechanical response of the part and cause problems with the software time step. To avoid this problem in high speed impact a Smoothed Particle Hydrodynamic (SPH) mesh has been developed that can model soft body impact such as gelatine or birds, to represent bird strikes on a plane Johnson<sup>131</sup> acknowledged that the impactor can “flow over the structure on impact, spreading the impact load over a significant surface area which

limits local impact damage”. The SPH method, instead of using elements, uses discrete interacting particles (Figure 29) which are independent from each other.

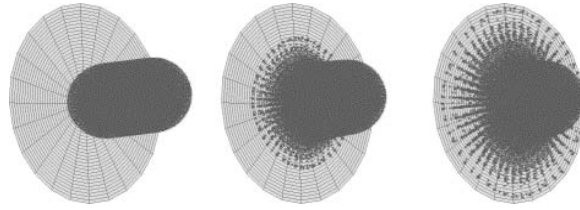


Figure 29: SPH simulation of bird impact on rigid plate ( $M=1.82$  kg,  $V_0=225$  m/s)<sup>132</sup>

### 2.9.1.2 Failure modelling

According to Sierakowski<sup>44</sup> FE codes that have the analytical capability to predict failure are available, but no constitutive model with matrix cracking and fibres breaking and delamination are yet available. According to Goldeberg<sup>133</sup>, matrices are strain rate sensitive as fibres may or may not be strain rate reliant depending on their kind. Therefore, Goldeberg<sup>133</sup> stated, that matrix and fibres must be separated when creating a strain rate model of a composite laminate. Goldeberg<sup>133</sup> added that in carbon fibre composites the matrix can only be considered strain rate sensitive and not the carbon fibres. Furthermore, he added that simple failure models can predict well the onset of failure, but not the post failure damage for which complex damage models must be developed. Failure must be modelled as a graduate loss of stiffness to provide a stable solution in the FE method.

Most advanced commercial FE codes require accurate data to model an impact on a composite structure. But the material might be applied to various loading cases and at various strain rates which make the required data set large. It is common to need up to 20 numerical values when using Ls Dyna<sup>134</sup> with the Chang Chang<sup>135</sup> failure criteria and up to 50 in the Ladaveze<sup>5</sup> failure model from PAM-CRASH<sup>TM 8</sup>.

### 2.9.1.3 Relevant composite models for impact

A few models that can be used for the representation of composites fibres during impacts are reviewed in this section. Also in the last years more models have been developed but it is not really the scope of this to review all of them.

- Chang Chang<sup>135</sup> progressive damage model / source LS Dyna user's manual<sup>134</sup> which is a basic model that is simple and fast to obtain early results however it does not predict well shear damage.
  - Lately Ianucci<sup>132; 136</sup> has used Ls Dyna and Dyna 3 D<sup>134</sup> to produce energy based damage mechanics approached for modelling impact onto woven composite materials.
  - The Ladeveze<sup>10</sup> model assumes plane stress and uses a damaging model based on continuum damage mechanics theory but can only model cases with minimal delamination effect.
  - Relatively recently Alix<sup>137</sup> used a delamination damage Meso-model for composite laminates defined previously. This Meso-model included interlaminar interfacial deterioration as well as the main inner-layer damage mechanisms.
- In this research the Ladeveze<sup>10</sup> code is reviewed in more detail as it was chosen to model the composite response to various loading.

### 2.9.2 Details on Ladeveze<sup>10</sup> damage ply model

Unidirectional ply damage and inter-ply delamination are implemented in the explicit code PAM-CRASH<sup>TM 8</sup> via the use of the Ladeveze damage model<sup>10</sup> and cohesive elements. In the UD ply damage model knock down factors ( $d_1$ ,  $d_2$  and  $d_{12}$ ) are used to degrade the Young's Modulus ( $E_1$  and  $E_2$ ) and the shear modulus ( $G_{12}$ ) of the ply.

So that:

$$E_1 = E_1^0 (1 - d_1) \quad \text{Equation 26}$$

$$E_2 = E_2^0 (1 - d_2) \quad \text{Equation 27}$$

$$G_{12} = G_{12}^0 (1 - d_{12}) \quad \text{Equation 28}$$

The strain-stress laws are given by the following expression:

$$\sigma = S * \varepsilon \quad \text{Equation 29}$$

$$\text{with } S = \begin{bmatrix} 1/E_1(1-d_1) & -\nu_{12}/E_1 & 0 \\ -\nu_{12}/E_1 & 1/E_2(1-d_2) & 0 \\ 0 & 0 & 1/G_{12}(1-d_{12}) \end{bmatrix} \quad \text{Equation 30}$$

Damage mechanism constant  $Y_1$ ,  $Y_2$ ,  $Y_{12}$ , characterize damage mechanism<sup>131; 139; 140</sup>

$$Y_1 = \sigma_{11}^2 / (2E_1(1-d_1)^2) \quad \text{Equation 31}$$

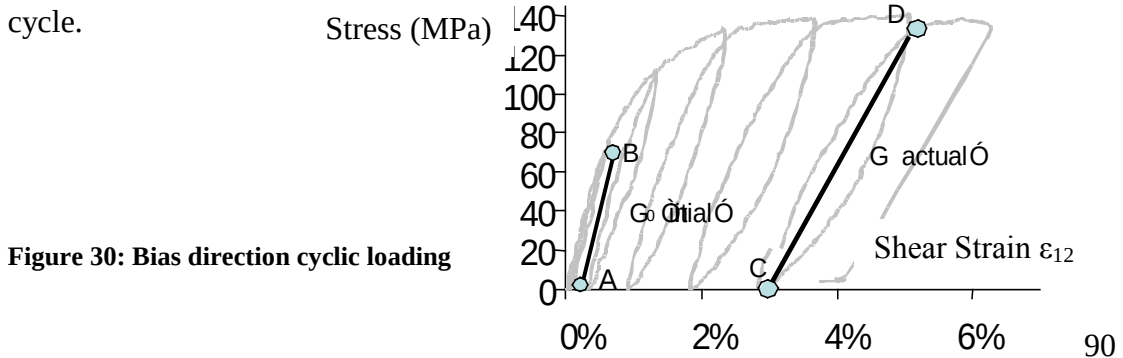
$$Y_2 = \sigma_{22}^2 / (2E_2(1-d_2)^2) \quad \text{Equation 32}$$

$$Y_{12} = \sigma_{12}^2 / (2G_{12}(1-d_{12})^2) \quad \text{Equation 33}$$

To define large non linear response due to matrix plasticity in shear, a hardening law is defined. Its parameters are found through cyclic shear loading of the material and the decrease of modulus. The model implemented in PAM-CRASH<sup>TM</sup> 8 has further requirements (Appendix 4) but overall, the model defines a tensile damage response, a compressive non linear damage response and a shear non linear response with large plasticity.

$$\left\{ \begin{array}{l} \sigma_{12} = \frac{\sigma_x}{2} \\ \gamma_{12} = 2\varepsilon_{12} = (\varepsilon_x - \varepsilon_y) \end{array} \right\} \quad \text{Equation 34}$$

The damage law is described by the degradation of the shear modulus through cyclic loading as illustrated in Figure 30.  $G_{12}^0$  being the initial shear modulus of the first



$$d_{12} = 1 - \frac{G_{12}}{G_{12}^0} \quad \text{Equation 35}$$

The elastic strain is used  $\varepsilon_{12}^e$  to compute the conjugate shear forces  $Y_{12}$  for each cycle that drives the damage propagation.

$$Y_{12} = \sqrt{\frac{1}{2} G_{12}^0 (2\varepsilon_{12}^e)^2} \quad \text{Equation 36}$$

$$Y_{12}(d_i) = Y_{12c} d_i + Y_{12} \quad \text{Equation 37}$$

The plastic strain at each cycle gives parameters for the plasticity law for shear modelling.  $R_0$  is the yield stress.

$$\begin{aligned} f_p(\sigma, R) &= \frac{\sigma_{12}}{1 - d_{12}} - R(p) - R_0 = 0 & R_{(p)} &= \frac{\sigma_{12}'}{1 - d_{12}} - R_0 \\ p &= \int_0^{2\varepsilon_{12}^p} 2(1 - d_{12}) d\varepsilon_{12}^p & \text{or} & \\ & & \varepsilon^p &= 2(1 - d_{12})\varepsilon_{12}^p \end{aligned}$$

The relationship above provide the experimental law below for which parameters  $a$  and  $m$  are obtained from experimental results.

$$R_{(p)} = a(p)^m \quad \text{Equation 38}$$

The Ladeveze<sup>10</sup> model requires calibration tests for strain parameters which require 3 kinds of tests.

The tests are:

- Simple tensile and cyclic test on 0 degrees to find  $E_{11}$ ,  $\varepsilon_{12}$ ,  $Y_{110}$  and  $Y_{11R}$
- Cyclic tests on 45 degrees to find:  $G_{12}$ ,  $Y_{120}$ ,  $Y_{12C}$ ,  $Y_{12R}$ ,  $R_0$ ,  $m$  and  $a$ .
- Compression test on 0 degrees to find:  $E_{11}^c$ ,  $V_{12}^c$ ,  $Y_{110}^c$ ,  $Y_{11C}^c$  and  $Y_{11R}^c$

Using this calibration method the plies response is accurate at low loading speed.

### 2.9.3 Strain rate effects for the damage ply model

Dynamic responses of material are often unlike the static response as illustrated in Figure 31.

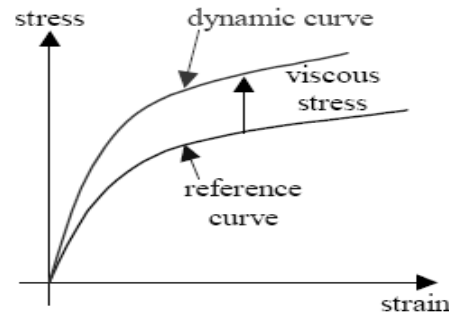


Figure 31: Rate dependent stress strain curve  
source PAM-CRASH<sup>TM8</sup>

The strain rate laws are additional functions built upon the static calibrated model. Zhao<sup>91</sup> determined the strain rate properties of carbon epoxy laminate using MTS machines and the SHPB technique. Subsequently, strain rate was modelled based on “one dimensional damage mechanics” theory. The model results fitted the experimental results well for both the  $[+45]_{4s}$  and  $[0/45/90/-45]_{2s}$  lay ups under dynamic loading conditions. Fiber-Reinforced Epoxy was model by Haque<sup>93</sup> at high strain rates and obtain satisfactory results. Tsai<sup>101</sup> used a visco-elastic model in compression and found a good agreement between the model and the test response. In PAM-CRASH<sup>TM 8</sup> the strain rate laws developed by Rozecky<sup>140</sup> are functions extracted from dynamic stress-strain response of coupon specimens for specified load cases which are:

- a) Dynamic tensile test at 0 degrees
- b) Dynamic compression test at 0 degrees
- c) Dynamic tensile and compression test at 45 degrees

The strain rate laws implemented in the model act on the material modulus rupture strain and yield strain and are described below.

$F_{11}(\dot{\epsilon})$  acts upon the longitudinal Young's Modulus

$F_{22}(\dot{\epsilon})$  acts upon the transverse Young's Modulus

$F_{12}(\dot{\epsilon})$  acts upon the transverse shear modulus

$F_{11}^R(\dot{\epsilon})$  acts upon the longitudinal rupture strain

$F_R(\dot{\epsilon})$  acts upon yield stress

Those functions are then used to modify the static parameters in shear and in axial tension and compression (more information in Appendix 4):

The shear response is then defined as:

$$f(\boldsymbol{\sigma}, R) = \sqrt{\left[ \frac{\sigma_{12}}{(1-d)} \right]^2 + a^2 \left[ \frac{\sigma_{22}}{(1-d)} + (\sigma_{22}) \right]^2} - (R_0 + \beta(\epsilon^p)^m) \quad \text{Equation 39}$$

$$\text{With } R_0 = R_0(1 + F_R(\dot{\epsilon})) \quad \text{Equation 40}$$

So that in tension the strain is given by

$$\epsilon_{i,u}^{ft} = \epsilon_{i,u}^{ft} (1 + F_{11}^R(\dot{\epsilon})) \quad \text{Equation 41}$$

and in compression

$$\epsilon_{i,u}^{fc} = \epsilon_{i,u}^{fc} (1 + F_{11}^R(\dot{\epsilon})) \quad \text{Equation 42}$$

#### 2.9.4 Delamination modelling

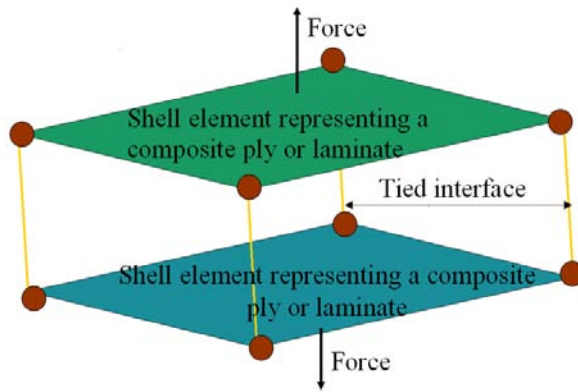


**Figure 32: Delamination interface using cohesive elements**

According to May<sup>141</sup> modelling progressive damage with interface elements has become a widely accepted technique offering some advantages over traditional methods such as the Virtual Crack Closure Technique (VCCT).

Interface elements are implemented into the mesh at locations of possible crack paths, in this case the mid-plane of the DCB. Unlike VCCT, modelling with interface elements does not require complex re-meshing algorithms and therefore allows modelling of complex 3D crack fronts. Interface elements are characterised by independently defined traction displacement curves for both Mode I and Mode II. The shape of these traction-displacement curves may vary from bi-linear as proposed by Johnson et al<sup>131</sup> or Jiang et al<sup>142</sup> to high-order polynomials as used by Pinho et al<sup>143</sup>. Despite the difference in shape, all interface models have in common that the area enclosed by the traction displacement curve is equivalent to the fracture toughness of the material (Figure 33). Meo<sup>144</sup> found that the main difficulties are to predict delamination initiation, crack size and propagation.

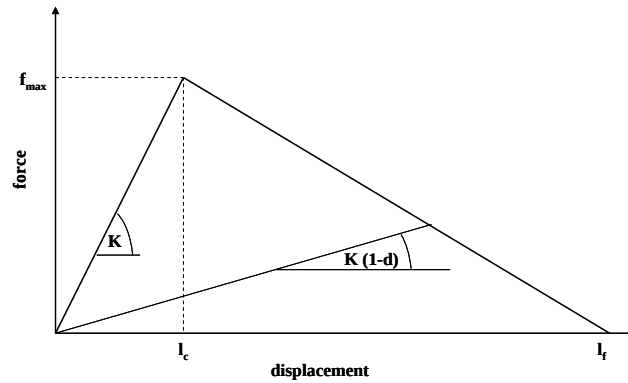


**Figure 33: Force-displacement curve of the cohesive interface**

The behaviour of the interface is elastic up to a maximum force after which damage occurs. The area under the force-displacement curve corresponds to the fracture toughness ( $G_{IC}$  or  $G_{IIC}$ ). The stiffness of the interfacial link  $K$  is reduced due to damage to  $K(1-d)$  with factor  $d$  depending on accumulated damage as follows.

$$d = \begin{cases} \frac{d - d_f}{d_c - d_f}, & d > d_c \\ 0, & d \leq d_c \end{cases} \quad \text{Equation 43}$$

For mixed mode loading the initiation and completion of damage are calculated using a linear law (more information in Appendix 5):

$$\frac{G^n}{G_u^n} + \frac{G^s}{G_u^s} = 1 \quad \text{Equation 44}$$

Iannucci<sup>131</sup> used a stress threshold for damage to begin, and secondly, a critical energy release rate for the particular delamination mode. The PAM-CRASH<sup>TM 8</sup> delamination model uses the same idea. Practically delaminations are often in a mixed mode state and take a form of multiple delaminations, in particular, in an impact problem. It is essential that an appropriate mixed mode criterion is employed in the prediction of delamination propagation and it is applicable to a multiple delamination scenario<sup>145</sup>.

In mixed mode loading conditions Modes I and II need to be coupled (Equation 44). Linear coupling is used in the present model for this purpose. Furthermore, the numerical instability associated with a characteristic quick growth of delamination in many practical delamination problems remains as a challenge yet to be resolved<sup>147</sup>. The PAM-CRASH<sup>TM 8</sup> model can take delamination strain rates in account and the law is as follow.

$$\sigma_{ss} = \sigma_s \left( 1 + \left( \frac{\dot{\varepsilon}}{D} \right)^{\frac{1}{p}} \right)$$

D: First strain rate parameter.  
P: Second strain rate parameter.  
 $\sigma_n$ : stress in the node at the interface.  
 $\dot{\varepsilon}_{\text{filt}}$ : is the filtered strain rate calculated by the program.

### 2.9.5 Tuft modelling: P-Links

P links, which are spot weld connections in PAM-CRASH<sup>TM 8</sup> attach a master and a slave part. Connecting nodes are created on the master and slave segment. The mechanical response of the P link is like one of a spring that can be activated for all 6 degrees of freedom and that generate a penalty force between the connecting nodes<sup>4</sup>.

Stiffness and strength of the P links can be user defined for tension and shear loads. P links could be useful for the representation of tufts.

### ***2.10 Brief summary of gaps between the aims of the research and the present literature.***

By comparing the objectives and aim of the research and the literature some gaps were spotted that would require to be filled.

- Compression for DIC
- Intermediate strain rate tests for DIC.
- SHPB for DIC in tension and compression.
- Full in plane characterisation at quasi static, low intermediate and high strain rates of carbon composites in tension, compression and bias direction. Comparison of impact response of tufted and untufted NCF.
- Dynamic delamination of untufted and tufted carbon NCF composites.
- Reliable method to determine loading rate on dynamic delamination due to wavy load signal.
- Full in plane and out of plane untufted and tufted material characterization.
- Strain rate modelling of Carbon NCF.
- Effect of tufting to some extent.
- Tufts modelling.
- Impact modelling with damage, delamination and strain rate.

Further gaps were spotted during the research which turned out to be of interest. It consisted of Photo-mechanics (mechanics on images) which has not been much used to this day.

- DIC for damage detection.

- DIC for velocity, acceleration and force field generation.

To meet the research aims and objectives the above gaps would require special attention and focussed investigation.

## Chapter – 3    **Materials and experimental methods**

Part 3 of the thesis reviews the experimental methods used to manufacture, characterise and simulate the NCF and tufted NCF composites in quasi-static and dynamic conditions. Firstly the experimental approach is reviewed; secondly details on the specimen preparations are presented. Then testing methods used to achieve inplane and out of plane static and dynamic characterisation are illustrated. Finally modelling methods used to reproduce such responses are introduced.

### ***3.1    Experimental approach***

Static and dynamic characterisation of tufted and untufted carbon NCF was undertaken. For this purpose adequate testing method needed selection or invention in order to characterise the material appropriately. Recent experimental developments in full field measurements have been reviewed and were of particular interest for improved material characterisation. A LIMESS optical strain measurement system allowed recording of the three dimensional strain and displacement fields over the full area of the tension and compression specimens (in the axial and the bias directions). Briefly, the technique involved spraying the specimen with a speckle pattern; which was then monitored via two cameras. An image analysis algorithm was used to compute the displacement vector of each point over two sequential images. It allows the tracking of large deformation up to 100% which was necessary in the case of tensile or compressive loading in the bias direction, for which large shearing of specimens was observed (up to 8% strain).

#### **3.1.1    Selection**

Standard test methods were used with DICM to allow adequate materials characterisation. Standard testing methods were used in accordance with ASTM

standards<sup>55, 58, 64, 75, 77, 86</sup> when possible (tension, tension bias direction, compression and delamination mode I) or ESIS committee recommendation<sup>78</sup> (delamination mode II). In some case full field measurements required new test methods (static compression) to be proposed.

Carbon epoxy composite structure responses rely primarily on the constitutive plies characteristics and sequences. Secondly the responses are dictated by the applied loads. The literature<sup>98; 133; 132</sup> suggests that strong and low strain rate effects are overlaid on the static response at high loading speed, adding to the complexity of the response. To be able to characterise the material response at high speed, some tests development are required. Standard procedures have only been developed for quasi-static testing but none have been specifically designed for DICM usage. Furthermore, none exists for dynamic testing. Nevertheless, extensive dynamic testing of composites has already been carried out over the years by several authors at intermediate ( $1-80\text{s}^{-1}$ ) and high strain rates ( $80-1000\text{s}^{-1}$ ). All dynamic experiments in this study would be filmed with high-speed cameras for better understanding of the dynamic events and images post processing via DICM for strain mapping. Only one camera meaning two-dimension, was used during dynamic recordings to avoid complex calibration and synchronization used in 3D representation. The high cost of such a camera and the difficulty of storing a large amount of images in the reduced time also enforced the use of only one camera. The use of only one camera meant that perpendicularity between the specimen and the camera became decisive to obtain strain and displacement readings representative of the loading. Misalignment would affect the images size and would impinge on the displacements and strain calculations. Images would be post-processed and analysed through Vic 2D software

from Limes<sup>52</sup> with strain readings being extracted from the strain field and the speckle pattern movement.

Dynamic tests had load acquisition obtained through a load cell or a strain measurement combined with a material Young's Modulus in the case of the SHPB. This load would require to be interpolated with the strain measurement from the high speed camera in a time consuming process to obtain a stress strain material characterizations.

Therefore many test methods used in dynamics testing would be made from existing static tests apparatus which needed improvement to allow for dynamic full field measurements monitoring. This was the case of intermediate rate compression and delamination mode II tests that were a mix of the static tests combined with a drop tower usage. For the intermediate speed compression a steel specimen permitted a better load introduction into the carbon composites that avoided carbon splitting and delamination during impact initiation or excessive deformation of the aluminium cap (Hsiao<sup>85</sup>). The steel chosen was EN24 steel which is a high strength tool steel.

The low rate tensile tests used the static tensile and tensile bias direction standard recommendations.

High speed testing was achieved with the HSPB use and small modification of the grips was required to allow proper load introduction. Finally the dynamic mode I test used in a drop tower was completely novel and was modified to allow for dynamic intermediate tensile tests to be performed within the Hopkinson bar apparatus.

Out of plane punching or impacting was carried out on small discs so that multi loading at various speed could be achieved. Such test combined supposedly all the loading define previously and was ideal for the validation case.

### **3.1.2 A novel damage detection method.**

The previous section described the characterisation of the material in term of stress strain responses and force displacement responses. Additionally the cyclic response in term of stress strain could provide damage factor as presented by Ladeveze<sup>10</sup>. Results could then be analysed and inputted in complex material models to attempt to predict such responses. While carrying such cyclic experiments with DICM monitoring, a novel damage detection method was discovered in the form of novel damage field maps that fit the description of Photo-mechanics.

#### **3.1.2.1 The method itself**

The DIC tool can provide two types of information, it is important to differentiate them. Firstly the DIC tool allows parameters (strain and displacement) extraction for any selected area of the strain field. The parameters are averaged over a particular chosen area and are obtained for each image during the duration of the test. This technique (DICM technique A)<sup>155</sup> was used to acquire strain measurement during loading for the in-plane tension and compression tests. The choice of the area was of moderate importance. The tool can also be used in a second manner (DICM technique B)<sup>155</sup>. The DICM tool can provide for any image a map of the displacement or strain in terms of x and y coordinates. This is not a strain or displacement parameter averaged over a selected area during time as “DICM technique A”, but a field of strain or displacements with corresponding x and y coordinates at any image time; it is the actual planar strain or displacement distribution for a particular image. The “DICM technique A and B” can be used to compute damage fields during cyclic loading which has an analogy with in-time, regression point-by-point method for damage threshold detection, proposed by Ivanov<sup>36; 146</sup>.

Classical measurements of damage for in-plane tests follow the procedure of Ladeveze<sup>10</sup> that defined damage  $d$  through cyclic loading (Figure 30, page 85) as:

$$d = 1 - \frac{E_o}{E} \quad \text{Equation 45}$$

$E_0$  denotes the initial Young's Modulus of the material and  $E$  the Young's Modulus of a subsequent cycle. Figure 30 plots stress versus strain using "DICM technique A" (the extracted strain is a strain average from the failure area). It is possible to use the stress and strain at time A, B, C and D (Figure 30) of a loading cycle to compute  $E_o$ ,  $E$  and subsequently  $d$  using Equation 45. Where  $d$  is in fact an average of the damage over the area to which the strain was extracted.

Equation 45 can also be modified for use with "DICM technique B" to obtain a damage field map. "DICM technique B" can provide a strain field map at time moment A, B, C, and D to which corresponds images A, B, C and D. Those images in time (Figure 30) correspond to a specific state of the strain field defined through  $x$  and  $y$  coordinates. Using a standard spreadsheet software, it is possible to calculate from the strain field, the modulus field in terms of  $x$  and  $y$  coordinates using Equation 46 and 47 (page 96). It allows the initial modulus field ( $E_0$ ) and subsequent modulus field ( $E$ ) to be computed for each cycle. It must be understood that these operations are not carried out on the averaged strain (extracted in some area of the sample through time "DICM technique A") but on the whole strain field defined by  $x$  and  $y$  coordinate of the specimen surface at time moment A, B or C, D.

The traditional assumption of homogeneity of load and stress during quasi-static experiments is made. The stress used is a section averaged stress obtained from load intensity and specimen geometry (Figure 30).  $E(x,y)$  calculations are best for specimens with nearly constant geometry with good load introduction to avoid stress concentrations and so errors on  $E(x,y)$  calculations. A further limitation of the method

is defined: as damage initiates, it redistributes the stresses through the specimen which affects the strain reading and also the state of stress in the material. In this study the strain redistribution due to damage is taken into account but the state of stress redistribution in the material due to damage is assumed to be limited.

The calculations of the modulus field are as follows:

$$E_0(x, y) = \frac{\sigma_B - \sigma_A}{\varepsilon_B(x, y) - \varepsilon_A(x, y)} \quad \text{Equation 46}$$

$$E(x, y) = \frac{\sigma_D - \sigma_C}{\varepsilon_D(x, y) - \varepsilon_C(x, y)} \quad \text{Equation 47}$$

With:

$E_0(x, y)$ : initial modulus field

$\sigma_A$ : stress at time A

$\sigma_B$ : stress at time B

$\varepsilon_A(x, y)$ : strain field at time A

$\varepsilon_B(x, y)$ : strain field at time B

and

$E_{(x,y)}$ : actual modulus field

$\sigma_C$ : stress at point C

$\sigma_D$ : stress at point D

$\varepsilon_C(x, y)$ : strain field at moment C

$\varepsilon_D(x, y)$ : strain field at moment D

Subsequently the damage parameter  $d(x, y)$  (Equation 48) can be computed combining (Equations: 45, 46 and 47). Following this procedure a damage field can be created for each cycle following the initial cycle to allow monitoring of the distribution and evolution of damage prior to failure.  $d(x, y)$  being the spatial damage field representation.

$$d(x, y) = 1 - \frac{E_o(x, y)}{E(x, y)} \quad \text{Equation 48}$$

In contrast to the case of the modulus field calculation, the damage field  $d(x, y)$  can be computed for specimens with irregular geometries. Effectively,  $E_0(x, y)$  and  $E(x, y)$  are maps obtained from the same sample and therefore the same geometry. If the cross section area of the sample is halved, the initial computed modulus  $E_o(x, y)$  and subsequent computed modulus  $E(x, y)$  in this area would be twice the reality inducing an error on the modulus fields reading. But  $d(x, y)$  is a ratio of modulus field at a specific spatial coordinate so that the increase of stress due to change in the geometry

is annulled by the modulus ratio at that location. So, for irregular geometries, the modulus field is not representative of the actual stiffness but the damage field is representative of the actual damage.

### **3.1.3 Modelling of the experimental response.**

As shown in the literature review there are principally two ways to model composite failure which are with either failure criteria or continuum damage mechanics. As for fracture mechanics the cohesive elements or VVTC methods are the main methods used. Impact is a time dependent process and as large deformation can be obtained the need to use a time dependent model with large deformation capacity and interply delamination is required. The PAM-CRASH<sup>TM 8</sup> is listed as only one of the 3 to 4 main stream software capable of bearing such simulation. As PAM-CRASH<sup>8</sup> mother company<sup>9</sup> was part of ITOOL it was preferred over other solutions and permitted the use of continuum damage mechanics with inter ply delamination.

## **3.2 Material and specimen characterisations**

The material used in this study was an NCF carbon/epoxy composite. The carbon fibres used were HTA 6 K from Tenax aligned by Saertex in a bidiagonal outline ( $\pm 45^\circ$ ). The resulting NCF fabric had an areal density of 540g/m<sup>2</sup>. Tufted specimens were produced using HTA 1k Tenax thread. A 5 mm  $\times$  5 mm pattern was used and tufting was aligned to the 0° direction of the NCF material (Figure 34).

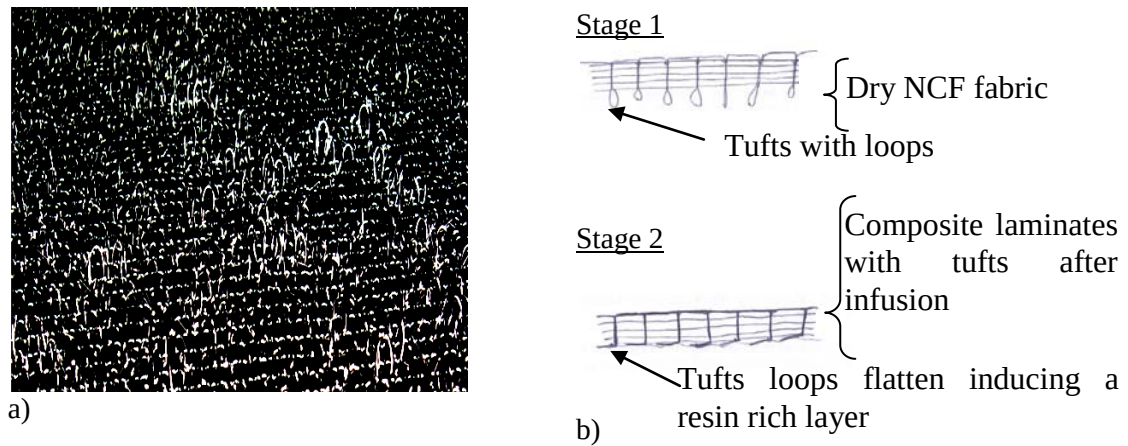


**Figure 34: Tufts loops on the back of the NCF dry fabric (a and b, stage 1), tufts in the consolidated laminate (b, stage 2).**

Panels with dimensions of 700 mm × 300 mm and layup sequences of  $[0/90]_3$  or  $[0/90]_4$  were infused under vacuum at 120°Cm (Figure 35). The epoxy resin used was RTM6 (from Hexcel). After completion of filling, the material was cured at 160°C for 3 hours. Panels for delamination tests incorporated a 60 mm wide 13 µm thick PTFE film inserted along the length of the panels at mid-thickness.



**Figure 35: Resin infusion of the textile laminate**

Aluminium tabs were bonded to specimens used for in-plane experiments and steel loading blocks were attached to delamination specimens (Figure 21 and 22). The specimen layup, size and tabs for the various static tests are summarised in Table 4 from which it can be observed that  $[0/90]_{3s}$ ,  $[\pm 45]_{3s}$ ,  $[0/90]_{4s}$  and  $[\pm 45]_{4s}$  lay ups were tested in quasi-static conditions with a 100 KN Instron machine.

| Test                                       | Layup           | Dimensions(mm) | Tabs (mm) |
|--------------------------------------------|-----------------|----------------|-----------|
| Compression – untufted                     | $[0/90]_{3s}$   | 80×25×3.3      | 13×25×1.5 |
| Cycling compression $[\pm 45]$ – untufted  | $[\pm 45]_{3s}$ | 80×25×3.3      | 13×25×1.5 |
| Tension- untufted                          | $[0/90]_{3s}$   | 250×25×3.3     | 50×25×1.5 |
| Cycling tension $[\pm 45]$ – untufted      | $[\pm 45]_{3s}$ | 250×25×3.3     | 50×25×1.5 |
| Compression- tufted                        | $[0/90]_{4s}$   | 80×25×4.4      | 13×25×1.5 |
| Cycling compression $[\pm 45]$ – tufted    | $[\pm 45]_{4s}$ | 80×25×4.4      | 13×25×1.5 |
| Tension- tufted                            | $[0/90]_{4s}$   | 250×25×4.4     | 50×25×1.5 |
| Cycling tension $[\pm 45]$ – tufted        | $[\pm 45]_{4s}$ | 250×25×4.4     | 50×25×1.5 |
| Delamination Mode I double cantilever beam | $[90/0]_{4s}$   | 200×20×4.4     | 20×20×10  |
| Delamination Mode II end loaded specimen   | $[90/0]_{4s}$   | 200×20×4.4     | 20×20×10  |

**Table 4: Geometry and layup of specimens for static testing**

$[0/90]_{3s}$  and  $[\pm 45]_{3s}$  lay ups were used at low loading rate with aluminium tabs bonded to the specimens for proper gripping and load introduction. In these cases, an Instron hydraulic 200KN test machine was used. At intermediate and high strain rates tests, the specimens required adequate gripping in tension as this can affect the stress wave propagation into the specimen and produce inertia effects. In compression, this problem is less apparent as the specimen can be end loaded (no gripping) with relatively good load introduction. Therefore in tension, the specimen thickness would be reduced to limit the failure stress allowing for a minimalist gripping design. In these cases, the specimens were bonded into a steel slot with a strong polymeric adhesive. Differently at intermediate and high rates in compression,  $[0/90]_{4s}$  layup would be used as a certain thickness is required to avoid any buckling and specimens can be end loaded.

### ***3.3 Description of testing methods used in static***

#### ***characterisation***

This section reviews the different test procedures used in quasi-static conditions to characterise the composites. It uses conventional as well as new tests procedures. A LIMESS optical strain measurement system allowed recording of the three dimensional strain and displacement fields over the full area of the tension and compression specimens.

##### **3.3.1 Tension**

Tension tests were carried out on an Instron testing machine with a 100 kN load cell. The loading speed was 0.7 mm/min for axial tension tests and increased to 1.5 mm/min for cyclic [ $\pm 45$ ] tests to reduce testing time as the cycles would increase it significantly.

##### **3.3.2 Compression**

Several types of apparatus were used in order to characterise the materials in compression. The research aimed to first enhance the author understanding of compression testing using a standard apparatus. The first apparatus used was a IITRI apparatus. With this set up it was noticed that the strain field was subjected to strain concentrations due to load introduction. To reduce this problem a slight modification was made which consisted of the addition of 2 anti-buckling pins that permitted the increase of the strain gauge length. Also the anti-buckling pins led to stress concentration occurring half way through loading. After considering those results and reviewing the literature, it was decided to improve the compressive strain reading with a new experimental set up that was designed in the form of a long gauge length compressive apparatus. It permitted strain recording with little loading introduction

effects in the specimen centre. This feature combined with strain field recording permitted the difficult characterisation of the material modulus in compression.

### 3.3.2.1 IITRI apparatus

The IITRI apparatus was first used to attempt the characterisation of the chosen material in compression. This apparatus introduced the compressive load by shear in the specimen. Usually, strain gages and extensometers are used to record specimen deformation in the compressive case. In the present case, optical strain field recording apparatus was chosen with a slight increase to the recommended gage length, to increase the optical field size and reduce loading introduction effects. The set up with the optical cameras is presented in Figure 36.

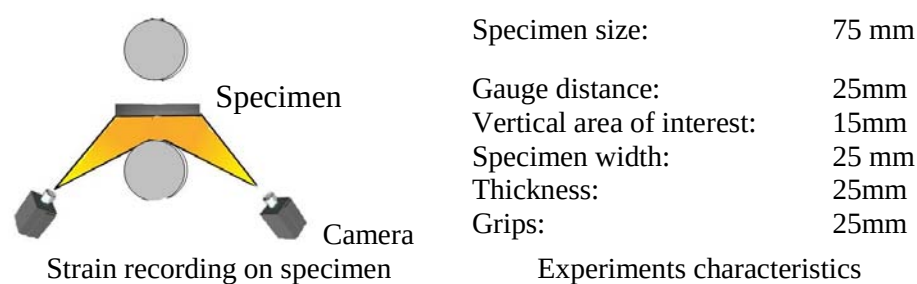


**Figure 36: IITRI specimen set-up**

Secondly, the IITRI apparatus was modified to allow a longer specimen with a longer gauge length which was maintained by an anti buckling pin. Figure 37 illustrates the modified setup characterised by the IITRI longer columns with an anti-buckling pins passing through.

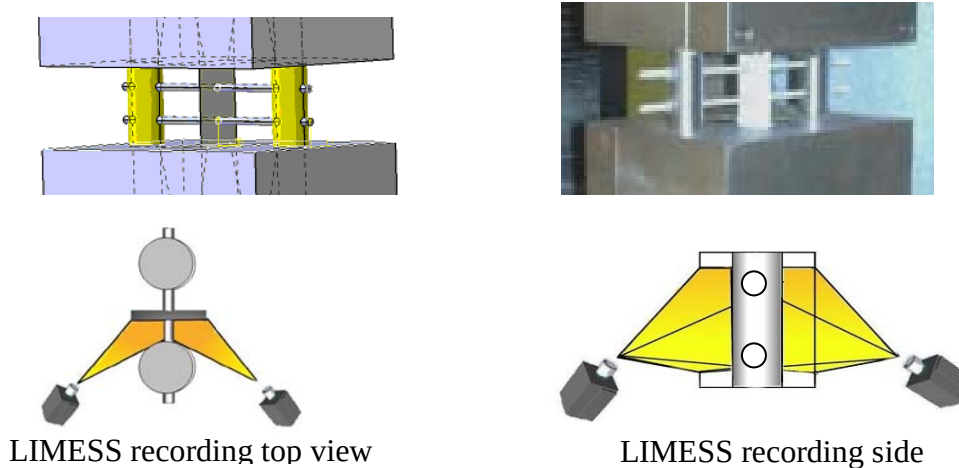


**Figure 37: Modified IITRI apparatus**

After mixed results from the above configuration further compressive investigation were decided.

### **3.3.2.2 New long gauge length apparatus**

A second investigation led to the design of a novel compression test that was designed so that it could be used in quasi-static and intermediate strain rate conditions via drop tower loading. The specimen characteristics can be viewed in Table 4 and 5 for this apparatus.

Long specimen gage length with an anti-buckling guide recommended by Salvi<sup>72</sup> suits the use of optical strain field measurements and provides a stress concentration free zone in the middle of the specimen. Effectively the contact between the test machine and the specimen is commonly under higher stress due to specimen gripping (squeezing) and contacts. Therefore, a new apparatus was designed to provide maximum and regular enlightenment of the sample with long gauge lengths (Figure 38). The specimen was loaded via end and shear loading at the bottom of the sample, as the specimen top end was loaded directly by the testing machine. The loading speed was reduced to 0.5 mm per minute in the axial condition as failure occurred rapidly. In the bias direction, faster speeds were used (1.5-2.5mm/min) as

failure strain was larger. To allow for a clear filming of the specimen in compression, only the side of the specimen would be maintained by anti buckling guides to avoid any stress concentration as the one created by anti-buckling pins in the middle of the specimen.

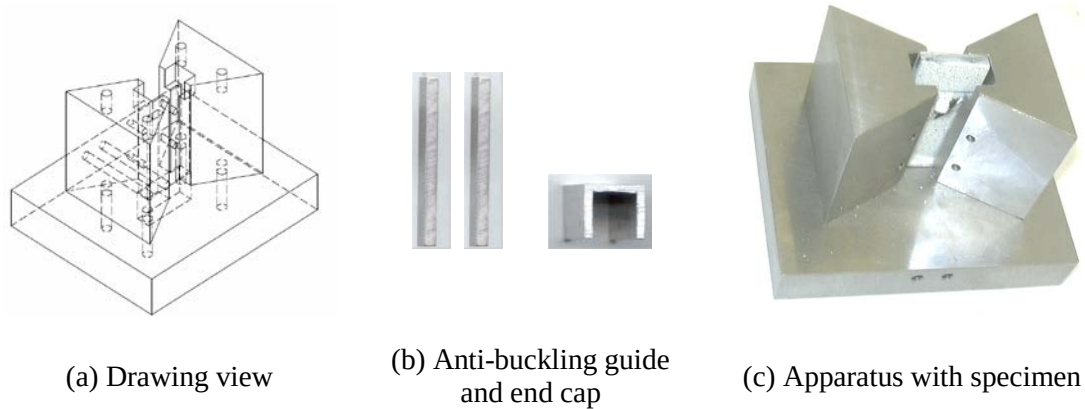


**Figure 38: Long gauge length compressive apparatus**

In order to improve the end load introduction in the specimen, 1.5 mm aluminium tabs were glued at the specimen extremity to reinforce the specimen locally. To prevent any delamination, a cap was added at the upper end of the specimen. Anti-buckling guides were composed of two steel struts that held the side of the specimen (Figure 38 b). The anti-buckling guide required a gentle tightening of the specimen side to allow vertical specimen displacement. While the lower constrained of the specimen required a strong tightening to avoid any movement of the specimen bottom.

### **3.3.3 Bias direction loading or shear**

Shear or bias direction loading was carried out following a standard procedure<sup>75</sup> in tension. Also, shear could be well assessed in compression because of the long gauge length allowance of the new compressive rig that suited particularly well the monitoring of shearing mechanisms. Eventually, cyclic shear testing was performed and consisted of gradually loading and unloading the [+45] specimen in

tension or compression until failure. The loading speed was increased to 1.5 - 2.5 mm/min to reduce the test time due to the large specimen plasticity and the cyclic loading required to monitor damage progression.

### **3.3.4 Delamination**

Delamination tests were carried out on a Zwick test machine equipped with a 2 KN load cell. Mode I double cantilever beam delamination tests followed the ASTM D 5528 protocol<sup>77</sup>. The loading speed was 3 mm/min and the crack interface was located between 0° plies. One specimen side was painted and marked every 2 mm to permit monitoring and recording of the crack length as a function of time. Simultaneous recording of load and crosshead displacement allowed the calculation of strain energy release rate<sup>18</sup>. Mode II end loaded specimen tests were carried out following the ELS protocol analysis developed by the ESIS TC committee<sup>78</sup>. Similar to Mode I testing, the crack interface was located between 0° plies and crack length, load and displacement were recorded. The strain release energy in shear was calculated according to the procedure outlined in<sup>78</sup>.

### **3.3.5 A novel damage measurement method**

The principal behind the method has been reviewed. Technically it consisted of cyclic loading on axial and bias direction tests in tension and compression monitored with the DIC tool at quasi static speed following the testing procedure reviewed above.

### **3.3.6 Multi loading of the composites via a simple disc punch**

Tests reviewed previously characterized the material for a specific loading case to extract valuable data from each ones. But those tests do not reflect on the material response as a whole. To better understand the global response, tri-axial in

plane and delamination loading was achieved through loading a simply supported disc at its centre with a punch (Figure 39). The disc diameter was 120 mm and the thickness varied between 4.1 and 4.4 mm for the untufted and tufted composites respectively.



**Figure 39: Punched discs**

The loading speed was constant at 1mm/min with force and displacement was recorded by a 100KN Newton load cell. The layup of the discs were [0/90] with untufted, fully tufted and partially tufted fibres.

### ***3.4 Testing methods used in in-plane dynamic characterisation***

All strains were acquired optically through DIC measurements as load were acquired from various load cells. Samplings of both were required as they could be sometimes of different nature. The start of the loading and strain increase would be the starting points of sampling with load and strain drop off being the end points. The different specimen layup, size, speckle pattern and tabs used for the various tests are summarised in Table 5.

From Table 5 it is observed that some of the speckle patterns are relatively coarse (large dots  $\pm 0.7\text{mm}$ ) which was due to the requirements of the high speed camera and the DICM software. As the image frame rate increases, the resolution of images decreases for memory storage purpose mainly. As the pixel gets larger, the

speckle pattern needs to enlarge to allow sufficient contrast between pixels so that the DICM algorithm can calculate displacement and strain fields.

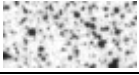
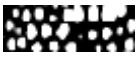
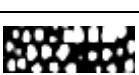
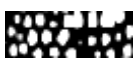
| Tests                            | Pixels    | Speckle pattern                                                                    | Image frame rate | Layup                                                                                | Specimen (mm)                        | Tab (mm)             |
|----------------------------------|-----------|------------------------------------------------------------------------------------|------------------|--------------------------------------------------------------------------------------|--------------------------------------|----------------------|
| <b>Tension quasi static</b>      | 1392*1040 |   | 1/2s             | [0/90] <sub>3s</sub> [0/90] <sub>4s</sub><br>[±45] <sub>3s</sub> [±45] <sub>4s</sub> | 250×25×3.3 or<br>250×25×4.1          | 2 tabs<br>50×25×1.5  |
| <b>Tension low rate</b>          | 256*256   |   | 10000/s          | [0/90] <sub>3s</sub><br>[±45] <sub>3s</sub>                                          | 250×25×3.3                           | 2 tabs<br>50×25×1.5  |
| <b>Tension intermediate rate</b> | ≥64*144   |   | 50000-200000/s   | [0/90] <sub>1s</sub><br>[±45] <sub>1s</sub>                                          | 100×6×1.1<br>Dog bone<br>Rectangular | No tab               |
| <b>Tension high rate</b>         | 64*32     |   | 500000/s         | [0/90] <sub>1s</sub><br>[±45] <sub>1s</sub>                                          | ±15×6×1.1<br>Dog bone<br>Rectangular | No tab               |
| <b>Compression quasi static</b>  | 1392*1040 |   | 1/2s             | [0/90] <sub>3s</sub> [0/90] <sub>4s</sub><br>[±45] <sub>3s</sub> [±45] <sub>4s</sub> | 80×25×3.3 or<br>80×25×4.1            | 2 tabs<br>10×25×1.5  |
| <b>Compression intermediate</b>  | ≥64*144   |   | 50000-200000/s   | [0/90] <sub>4s</sub> [±45] <sub>4s</sub>                                             | 65×25×4.1                            | One tab<br>10×25×1.5 |
| <b>Compression high rate</b>     | 64*32     |  | 500000 /s        | [0/90] <sub>4s</sub> [±45] <sub>4s</sub>                                             | ±8×±6×4.1                            | No tab               |

Table 5: Tufted and untufted NCF composites specimen characteristics and optical settings used

### 3.4.1 Low rate of loading

Tension tests at low rates were carried out on an Instron 8032 Servo hydraulic machine, with Instron 8500 controlling electronics that permitted 100 KN actuator, 109 KN stall force, 45 minute manifold, 1 litre pressure line accumulator and 40 litres / min servo valves. Speed used for testing was 40 mm/s and the maximum capacity of the system of 80mm/s.

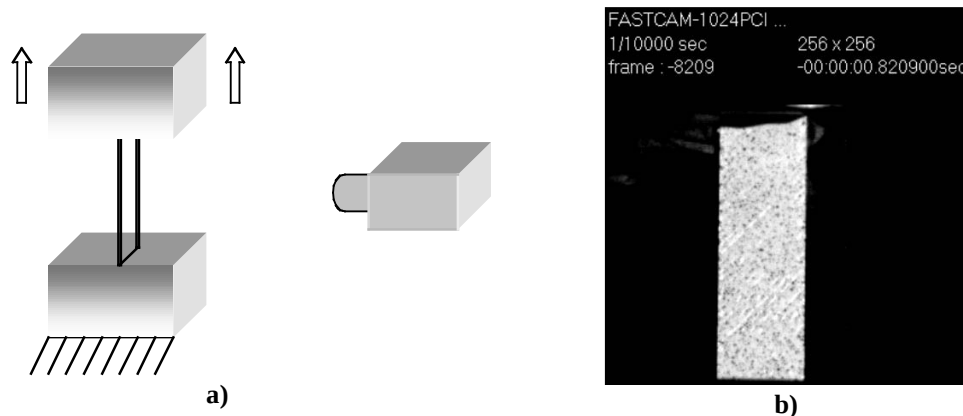


Figure 40: Low strain rate tensile tests with hydraulic test machine and high speed optical acquisition; a) schematic of set up, b) tensile set up.

For this loading rate, only untufted specimens with [0/90] and [+45] lay ups were tested in tension. Tufted specimens were not available at the time of this test. The set up and specimen characteristics are briefly illustrated in Figure 40.

### 3.4.2 Intermediate rate of loading

The tensile machine speed capability being reached at low loading speeds, another apparatus was used for higher strain rate characterisation: the drop tower. The drop tower does not generate a continuous loading but an impact pulse load with the speed  $v$  varying with time ( $t$ ) as shown in Equation 49.

$$v(t) = v_o - \int \frac{F(t)}{m} dt, \quad \text{Equation 49}$$

$F$  is the recorded load,  $t$  is the time,  $v_o$  is the initial velocity from the velocity versus time curve where  $v_o$  is the initial velocity measured by the flag at impact. The displacement ( $\delta$ ) of the impactor over time is found by:

$$\delta(t) = \int v(t) dt. \quad \text{Equation 50}$$

As shown previously in Chapter 3 (Page 100) the test setups were different whether the specimen would be under tension or compression. In tension the test has a special set up (Figure 42) with an improved load cell location that remained static throughout the test. The material thickness was reduced in order to weaken the specimen failure load to enable a light test setup to be used (Figure 42). Lighter grips and loading designs would have reduced inertia which combined with the static load cell setup should improve the dynamic load recordings. Images acquired at high frame rate between 45000 and 200000 would allow the DIC analysis tool to be used and the generation of displacement and strain field data at those speeds. At such frame rates, images would possess reduced resolution and for the DIC algorithms to differentiate

between pixel contrast and compute strain and displacement the speckle would need to be relatively outsized to avoid a grey area without any contrast to be acquired.

### 3.4.2.1 Tensile intermediate rate measurements

The intermediate setup is based on the modification of an apparatus designed to monitor the load during dynamic delamination (see chapter 3.4.1) in a drop weight apparatus (Figure 41). It is characterised by a static load cell mounted (d) above the specimen (e). During loading, the bottom of the specimen is pulled down (h) by the dropping weight (a) loading the pin (b) at the top of the specimen (h and i) acting on to a moving block (m) that compress the static load cell (d) on to a constraint block (l).



**Figure 41: Drop tower apparatus**

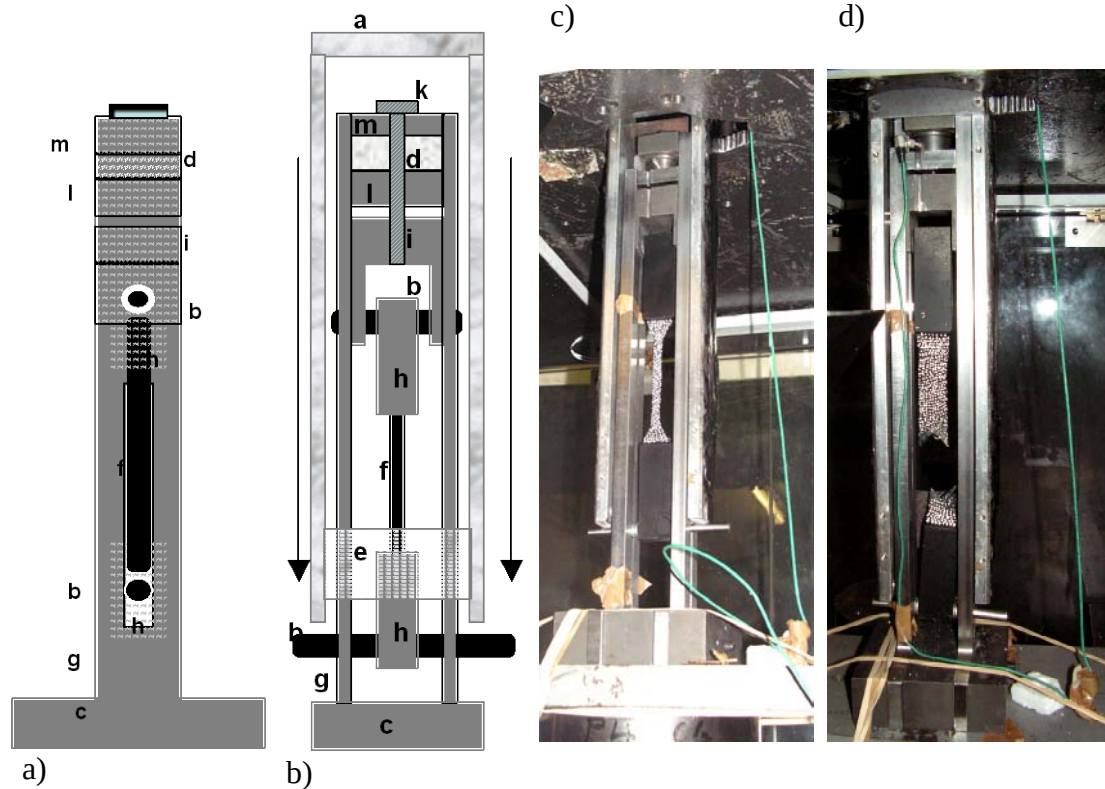


**Figure 42: View of tensile apparatus; a) side view, b) front view with impactor, c) set up with [0/90] specimen, d) set up with [+45]**

Identically to other tests, the strain was calculated via high speed filming. Load readings were recorded through the new load cell setup which directly measured the load applied on the specimen. With this setup, little inertia effects and stress waves spurious reflection were introduced during load recordings. Unlike conventional tensile apparatus generating linear loading, drop weight loading generate pulse loading in the form of a cosine waves. Figure 42 (c and d) illustrates the specimen geometry for a 0/90 and a bias direction layup. The dog bone shape for the [0/90] layup is used to reduce the specimen failure load to ensure specimen failure occurred before possible tab specimen debonding or loading pin plastic damage. For the bias direction layup the failure stress was much reduced and such specimen geometry was not necessary.

#### **3.4.2.2 Compressive intermediate loading rate**

##### **measurements**

Dynamic characterisation of specimens in compression at those rates (0.5-6m/s) was achieved with a specimen holder already used successfully during static characterisation (Figure 43 (a)). A cap was placed on top of the specimen to avoid composite crushing (Figure 43 (b)). This set up was used for dynamically testing the bias direction layup. In the [0/90] dynamic case the load to reach failure would be considerable so that a tool steel specimen with a collar (Figure 43 (d)) was placed above the carbon fibres specimen for improved load introduction. In this case, the compressive apparatus was double its initial height (Figure 43 (c)).

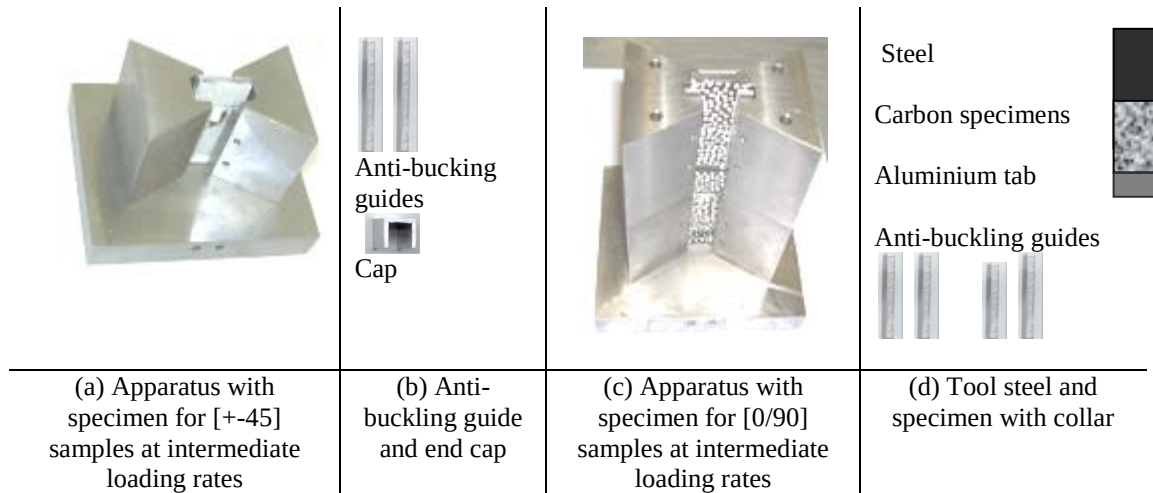


**Figure 43: Long gauge length compressive apparatus**

### 3.4.3 High rate of loading

High rate of loading was achieved through the use of a SHPB. The bar can be used in tension, compression or torsion via two separate gas gun. In the present study the bar was solely used in tension, compression and shear. The basic visible features of the bar are shown in Figure 44; its functioning is described in Figure 45 and 46 in tension and compression. The strain is calculated by the Hopkinson bar response but direct strain monitoring was preferred as the literature showed that bar and specimen density as well as specimen gripping could affect the calculated strain from the apparatus. To monitor strain on the specimen, full field DICM was used with ultra-high speed camera monitoring.

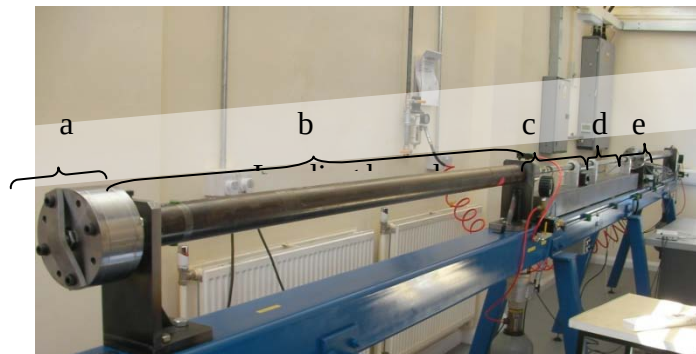


**Figure 44: Hopkinson bar apparatus: a) shock absorber, b) tensile loading bar, c) incident (tension) or transmitted (compression) bar, d) specimen, e) incident compression or transmitted (tension) bar.**

### 3.4.3.1 Tensile high rate measurements

Step one the specimen was attached between bar A and C. A sudden pressure release from the gas gun b (Figure 45) in the pressure chamber p (Figure 45) occurred. Step 2 the impactor e (Figure 45) pushed by the extra air pressure slid at high speed toward the extremity of the bar c (Figure 45). The impactor contacted the end of the bar g (Figure 45) pulling the bar c (Figure 45) and a (Figure 45). The stress wave propagated through c and loaded the specimen g (Figure 45) which transmitted the stress in the bar a (Figure 45). Meanwhile part of the stress had been reflected at the bar specimen interface and moved backwards in bar c (Figure 45).

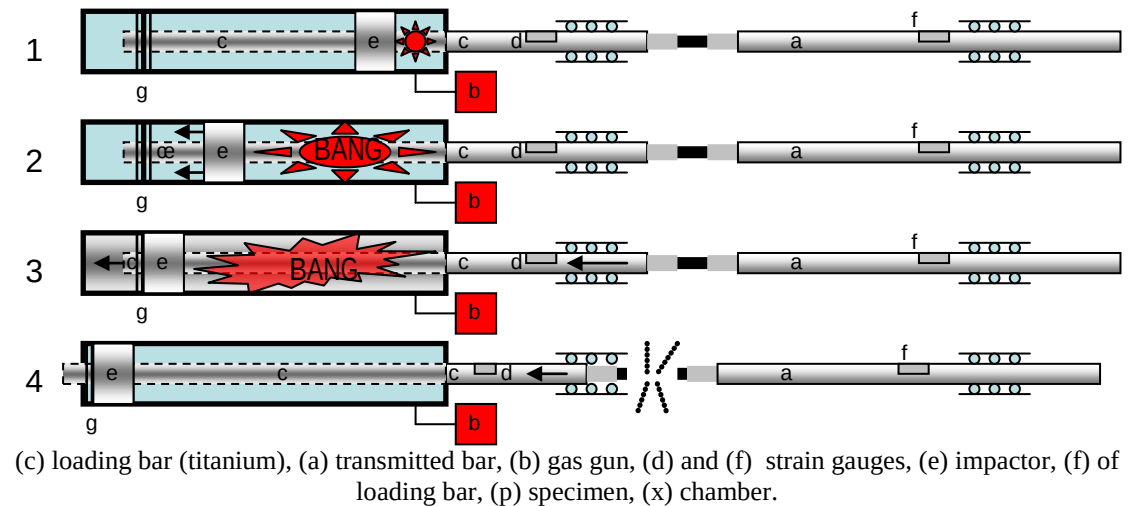


**Figure 45: Hopkinson bar kinematics**

Strains in bar a and c (Figure 45) were recorded by strain gauge at d and f (Figure 45). The load on the specimen was directly linked to the stress transmitted through the specimen to bar a and strain recordings at f (Figure 45). As the strain observed by the specimen was linked to the strain rate in the bar c (Figure 45).

The stress waves propagating in the bars needed to remain relatively small so they remained in the elastic region of the bar material. It would avoid plastic deformation that would affect the energy transmitted to the specimen. The bars used in these experiments are made from titanium with high strength. If the bar

deformation remains elastic only then the incident bar deformation  $\varepsilon_r$  during the pulse reflection allows the calculation of the strain rate measurement on the specimen.

$$\dot{\varepsilon} = 2 \frac{C}{L_s} \varepsilon_r(t) \quad \text{Equation 51}$$

So that the strain on the specimen is given by:

$$\varepsilon = \int_0^t \dot{\varepsilon}(t) dt \quad \text{Equation 52}$$

Differently the strain deformation in the transmitted bar is:

$$\sigma(t) = E \frac{A_0}{A} \varepsilon_T(t) \quad \text{Equation 53}$$

C is the elastic wave speed in the bar,  $L_s$  the specimen gauge length,  $A_0$  is the area of the bar, A is the area of the specimen and T and R correspond to transmitted and reflected subscript.

### 3.4.3.2 Compressive high rate measurements

In compression, the behaviour would be slightly different and can be observed in Figure 46. Basically the strain gauge purposes are inverted from the tensile case in the compressive one. The gas gun b (Figure 46) sent a sudden release of compressed air that pushed g (Figure 46) toward a (Figure 46). After impact, a stress wave propagates and compressed the specimen h (Figure 46) before being partly reflected in a (Figure 46) and transmitted to c (Figure 46). The reflected stress wave was captured by f (Figure 46) and was directly related to the specimen strain state through time. As the transmitted stress wave was captured by e (Figure 46) in terms of strains which were directly related to stress in the sample during loading.

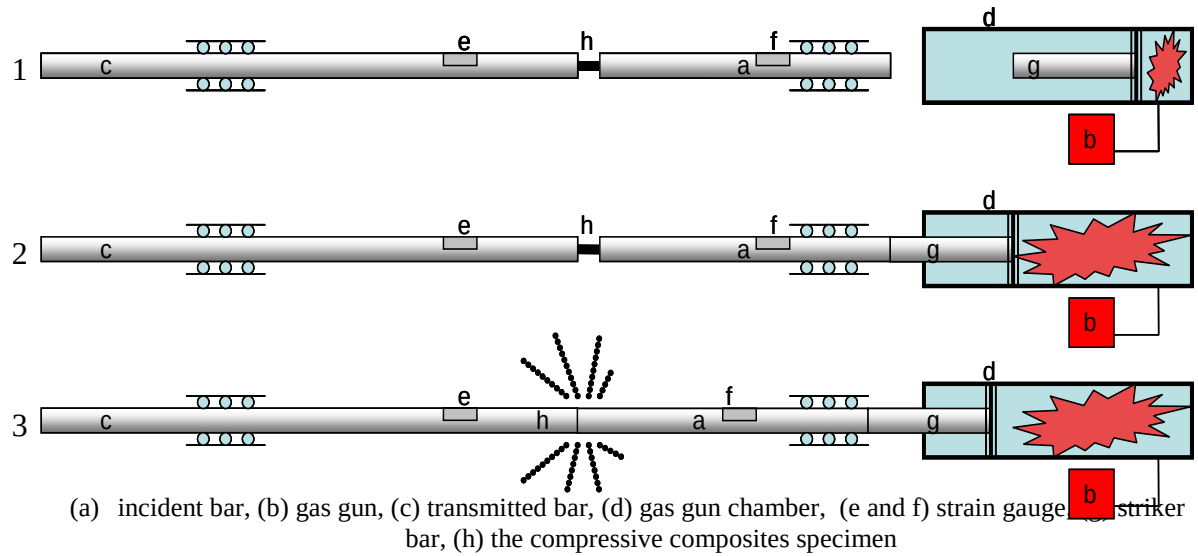


**Figure 46: Hopkinson bar set up in compression**

### 3.5 *Dynamic delamination measurement methods*

According to the literature, dynamic out of plane monitoring of potential delamination loading rate effects were particularly difficult at high speed due to unsteady load signals. With this information in mind two new delamination tests were designed.

#### 3.5.1 **Dynamic delamination Mode I measurements**

The dynamic setup was similar to the static one. Effectively, 2 pins were used to mount the DCB specimen horizontally into the experimental apparatus placed inside the drop weight impact tower. The experimental apparatus allowed rotation around the pin axis for both arms. Only vertical displacement of the lower cantilever arms was permitted, as the upper arm had all displacements constrained (Figure 47). Delamination occurs when the lower pin is struck by an aluminium impactor featuring side grooves. This design has been chosen as previous investigations<sup>148</sup> have shown that the quality of the signal recorded by the load cell is strongly dependent on the mass of the impactor. High masses result in significant oscillations in the load signal.

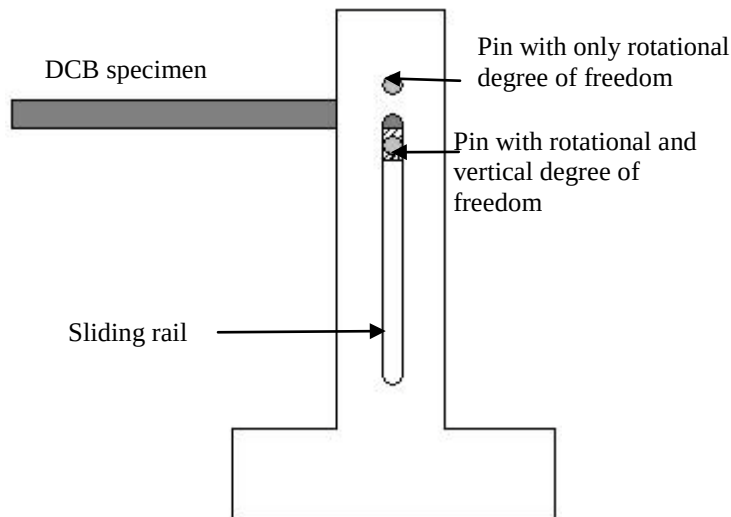


**Figure 47: Sketch of dynamic delamination apparatus**

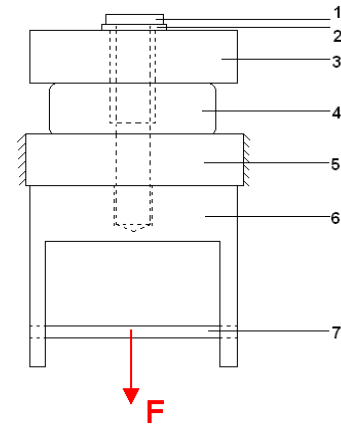


**Figure 48: Load cell set up**

Furthermore, this work indicated<sup>148</sup> that the load cell should be located as close to the specimen as possible as stress waves travelling in the rig and mass effects, lead to unrealistic loads signals. The load cell was therefore placed above the specimen (see Figure 48). When the impactor strikes the lower pin, a reaction force is created in the upper pin (7), the load cell (4) is compressed between a free block (3) and a fixed block (5). Once struck by the impactor, the lower pin slides down a rail tearing the DCB specimen apart. When the impactor strikes the lower pin, a reaction force is created in the upper pin (7), the load cell (4) is compressed between a free block (3) and a fixed block (5). The force measured corresponds to the force at the crack tip allowing calculation of fracture toughness. Once struck by the impactor, the lower pin slides down a rail tearing the DCB specimen apart. The rig was mounted into a Rosand drop tower with variable load and impact speed. Tests were carried out at various loading rates between 0.8m/s and 8.7 m/s for 3D reinforced as well as plain NCF specimens. The opening of the crack during delamination was monitored using a Photron 1024PCI high-speed camera with a frame rate of 2000 frames per second. Movies were saved every frame as JPEG images. Post-processing of the images was

completed with a in-house software which allowed accurate crack and lower arm displacement measurements throughout the complete delamination of the beam.

The pre-crack length was measured using digital callipers from the extremity of the pre-crack to the centre of the loading pin. Additionally, specimen geometry dimensions for width, length and thickness were measured at 3 different locations using a digital calliper and averaged. After delamination, one arm of each specimen was loaded in a three point bending tests that allowed the calculation of the flexural modulus from the beam dimension and load displacement experimental curves as it was required in some part of the delamination analysis.

### **3.5.2 Dynamic delamination Mode II measurements**

The dynamic set up for delamination mode II used a modified ELS apparatus to allow for the dynamic specimen loading in a drop weight impact tower. The detailed setup is described in Figure 49. Added elements to the conventional setup are a fork acting as an impactor, a guided pin transmitting the impact load to the specimen and two crash absorbers to decelerate the pin and the impactor at the end of the experiments. Two Photron high speed cameras were used. The Photron 1024PCI high-speed camera used a standard resolution of 256\*256 pixels for 6000 to 10000 image/s acquisition. Differently, the Photron SA1 used an ultra-high resolution of 1024\*896 pixels for 6250 images/s. Their usage depended on their availability and allowed the monitoring of arm and crack displacements versus time. The impactor (*e*) (Figure 49) impacted the pin (*g*) (Figure 49) guided by the apparatus (*b*) (Figure 49) at a specified speed. The beam (*f*) (Figure 49) bent downwards, moving the ELS clamp (*d*) (Figure 49) and the right end of the specimen (*f*) (Figure 49) to the left. After a certain amount of beam bending, the crack started to propagate. Once it had propagated through all

the specimen length ( $f$ ) the beam continued to deflect until the loaded pin ( $g$ ) (Figure 49) and the impactor ( $e$ ) reached the aluminium honeycomb crash absorber ( $c$ ) (Figure 49) that brought them to a halt. During this entire event the load had been recorded by the load cell ( $h$ ) (Figure 49) and a high speed camera ( $j$ ) (Figure 49) recorded the deflection and the crack propagation of the specimen ( $f$ ) (Figure 49).

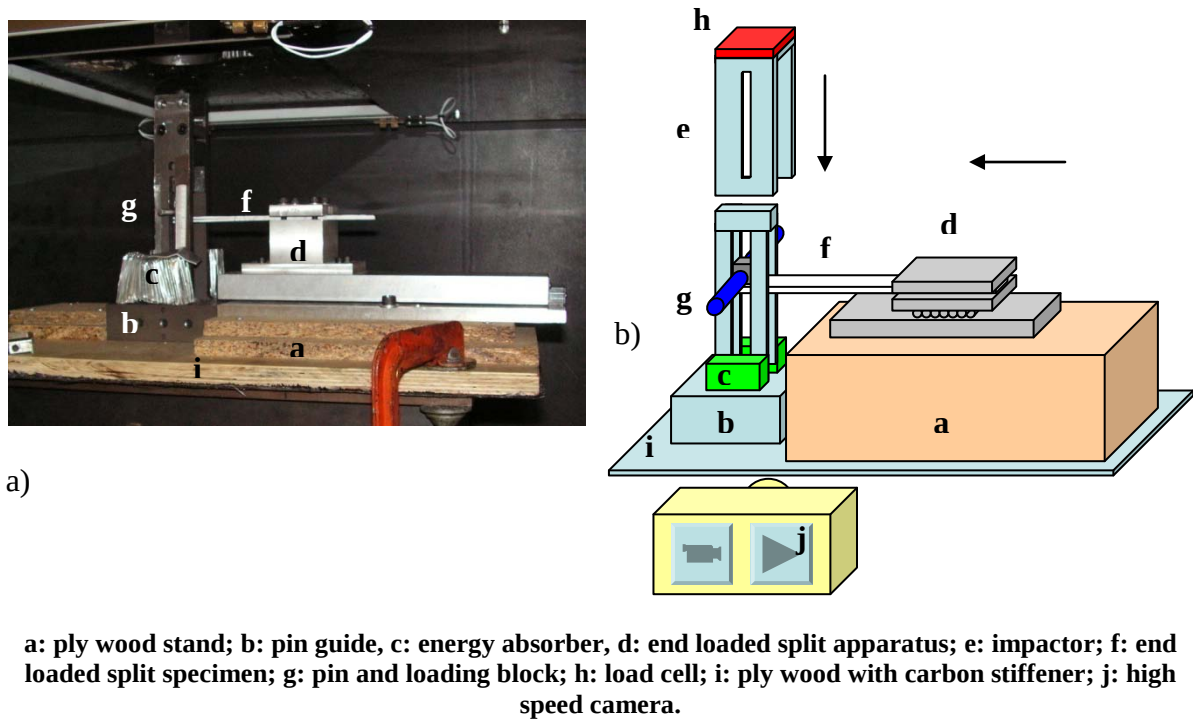


**Figure 49: Dynamic modified end load split (ELS) set up; a) picture, b) diagram.**

### 3.5.3 Optical measurements of dynamic mode I and II events

The images acquired via high speed filming of Mode I and II dynamic delamination provided information on the specimen response to dynamic loads. Such observations of the DCB and ELS sample arms could permit the observance or not of pure Mode I and II crack loading which are required to use successfully Equation 15 and 22 to determine  $G_{IC}$  and  $G_{IIC}$  and assess rate effect. The images could also be used to measure the crack propagation and specimen arm displacement evolution through time and loading with the in house software. An object in the image with known length could be used to calibrate the pixel sizes to physical object length. Once

calibrate the software could load each image in a row and allowed the user to measure crack length and displacement evolution. Finally an excel file could be exported containing all measurement. Such file permitted the calculation of dynamic  $G_{IC}$  and  $G_{IIC}$  through loading.

### **3.6 Impact responses**

Tests reviewed previously characterized the material for a specific loading type to extract valuable strain rate effect for each load cases in dynamic conditions (for example, tension, compression, shear, delamination Mode I and II...). But these tests did not reflect the behaviour of the material as a whole. To better understand this, a dynamic global response (tensile, compression, shear and delamination Mode I and II) was achieved through loading a simply-supported disc at its centre with a falling punch within a drop tower apparatus. This loading type was comparable to a low speed out of plane impact. The disc diameter was 120 mm and the thickness was 4.1 to 4,4 mm for the tufted and untufted composites. The impact speed was of 5m/s and the loading mass of 12.3kg.

### **3.7 Finite element materials model used**

The damage, strain rate and delamination models that were used have been reviewed in the literature review and consisted of the Ladeveze<sup>10</sup> model and cohesive elements built within PAM-CRASH<sup>TM 8</sup>.

The method to successfully simulate ply damage, delamination and strain rates with tufts reinforcements in carbon NCF composites is relatively complex. It consists first of identifying the damage parameters from tensile, compressive and tensile bias direction tests following the Ladeveze<sup>10</sup> and PAM-CRASH<sup>TM 8</sup> recommendations ( $\pm 34$  parameters). The delamination parameters and tufts parameters can be identified

from mode I and mode II delamination tests using the DCB and ELS tests procedure ( $\pm 14$  parameters). Strain rate parameters are to be identified from tensile, compressive, tensile bias directions and delamination mode I and II tests with varying loading speed ( $\pm 10$  parameters). Stress strain curves response from in plane tests with increasing strain rate allows the definition of strain rate parameters. The delamination mode I and II in dynamic tests allow for the comparison of  $G_{IC}$  and  $G_{IIC}$  for various crack speeds and the possible detection of loading rate effect from which parameters can be identified. In order to check that the model is representative of the materials response the model is run on coupon tests (tensile, compression and bias direction test) and delamination mode I and II (DCB and ELS) tests at various speed. Such method permit to gain confidence in the model but also allows to detect possible weakness in the testing procedure. The model calibration allows for structural simulations to be undertaken at various loading speeds with tufts, damage delamination and strain dependency.

**Chapter – 4     Results: Characterization of tufted and untufted NCF composites**

This section is split between quasi-static and dynamic events. The first part reviews the static material characterization in term of stress strain response and damage monitoring. More specifically, it compares tufted and untufted materials in tension, compression, shear, damage and delamination (mode I and II). For compression characterization, a novel compression apparatus was specially developed. A second section deals with low, intermediate and high speeds testing for which tests or parts of tests were developed.

**4.1     *Static measurements of tufted and untufted composites***

**4.1.1     Measurements of tensile properties**

Tensile static tests are relatively straight forward to perform. Also, some care must be taken during failure as the [0/90] specimen tends to dissipate the energy rapidly in a large fragmenting process. In the case of the tufted specimens, the tufts hold the specimen together better, preventing catastrophic delamination and broken piece of laminate to fly around (Table 6).

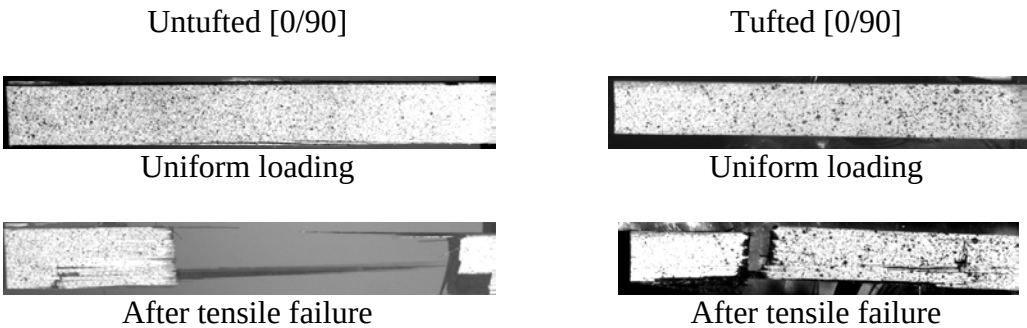


**Table 6: [0/90] specimens after and before failure; (a) untufted, (b) tufted**

Table 6 shows that for [0/90] lay ups, the untufted specimen failure is very different from the tufted one in tension. Effectively, a good part of the untufted

specimen explodes in dust or debris during the catastrophic failure as the internal energy is suddenly released.

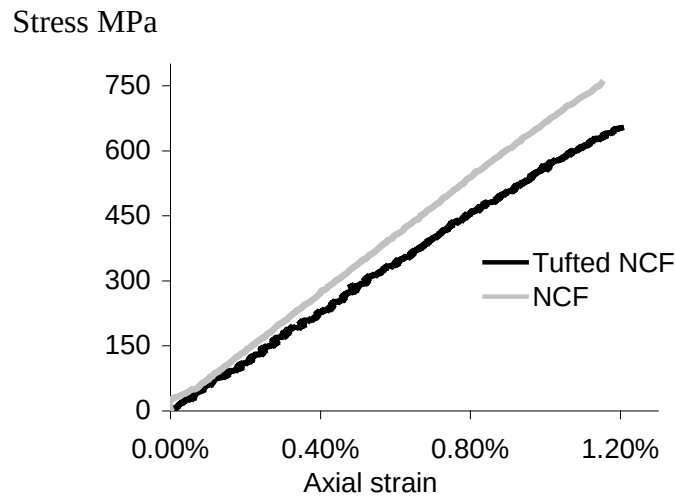


**Figure 50 : Tensile stress strain response for standard and tufted NCF**

From Figure 50 and Table 7 it is observed that tufted NCF composites have lower stiffness than untufted composites (10-15%). So that the strength is also reduced as the failure strain is similar for both composites. The scatter in Table 7 illustrates the variability of the measured properties for 5 tufted and untufted specimens.

|                             | Untufted | Tufted | Scatter |
|-----------------------------|----------|--------|---------|
| Tensile modulus (GPa)       | 63       | 55     | 1%      |
| Tensile ultimate strain (%) | 1.26     | 1.20   | 3%      |
| Tensile strength (MPa)      | 755      | 654    | 3%      |

**Table 7: Material parameters obtained from axial tension of [0/90] NCF composites**

#### **4.1.2 Measurements of tensile properties in the bias direction**

Shear or bias direction response is characterized by matrix cracking and delamination during the fibre shearing mechanism. In the case of tension in the bias directions, the cracks open and propagate with little frictional resistance, causing increased damage and ultimate failure at 5-6% strain.

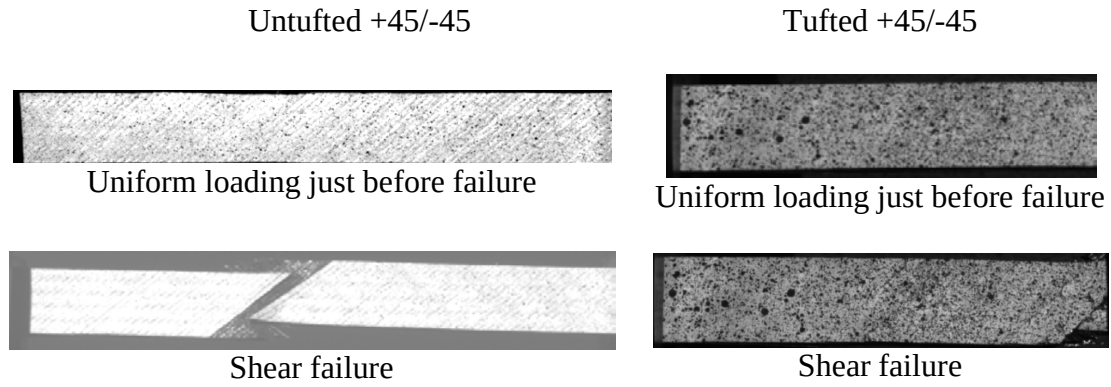


**Table 8: Bias direction failure of untufted and tufted NCF composites**

According to Table 8, the failure seems more limited on the tufted material than on the untufted material. The failure process on this layup and load case is slow. The material is elastic at first but rapidly, the fibres shear and realign in the loading direction, causing matrix cracking and permanent damage. The damage increases as the stress reaches a peak at 2.3 % strain and remains close to 135MPa as the shearing mechanism continues and strain increases (Figure 51). Load cycles can be added to allow the calculation of the amount of damage of the materials for each cycle via Equation 45.

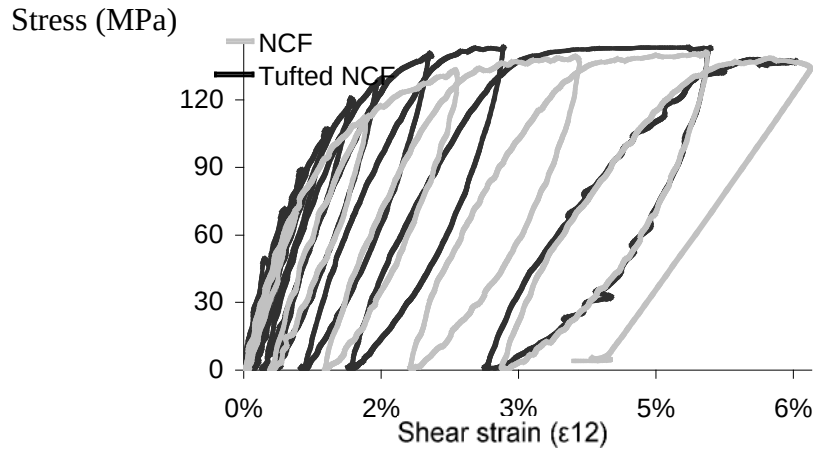


**Figure 51: Bias direction testing for the untufted and tufted materials**

From Figure 51 and Table 9, it can be observed that standard and tufted composites behaved in a similar pattern on this [+45] layup. The initial shear modulus of the tufted NCF was slightly stiffer than the one of the standard NCF. The tufts reduced slightly the shearing effect and kept the layers all together preventing

extensive delamination. This also had the effect that the tensile strength was slightly higher for the tufted reinforcements.

|                                     | Untufted | Tufted | Scatter |
|-------------------------------------|----------|--------|---------|
| Initial tensile shear modulus (GPa) | 6.6      | 7.4    | 1%      |
| Tensile ultimate strain (%)         | 6.25     | 6.09   | 2%      |
| Tensile strength (MPa)              | 139      | 143    | 2%      |
| Damage factor average in tension    | 0.28     | 0.32   |         |

**Table 9: Material parameters obtained from tension and compression tests in bias direction for NCF composites**

#### 4.1.3 Measurements of compressive properties

In this study, emphasis was given to the recording of representative compressive strain rather than ultimate compressive strength. This was because the stress-strain response characterisation, in terms of elasticity and damage, was essential for modelling purposes and the damage monitoring, even if the ultimate strength was slightly under predicted. With this in mind the work could begin with the use of IITRI and IITRI modified apparatus

##### 4.1.3.1 Measurements with IITRI and IITRI modified

##### apparatus

The specimen used in this test had a gauge length of 25\*10\*3.3 mm (Figure 52). The strain field was affected by stress concentrations due to grips loading and/or slight misalignments.

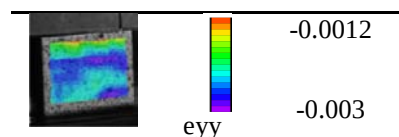


**Figure 52: Strain recording on the IITRI specimen**

The strain increased non linearly throughout loading and reached large values before failure. On the IITRI modified apparatus, longer specimen gauge lengths were used (50\*25\*3.3mm). Stress concentrations occurred at the anti-buckling pin

locations half way into the compressive loading phase due to slight misalignment. As a result, the measured stiffness on the specimen was not representative of the material stiffness.



**Figure 53: Strain field recording on the IITRI modified rig**

Strain concentrations therefore would not allow for the true characterisation of Young's Modulus, strain and strength in compression. The specimen failure is shown in Figure 54 (a) and the influenced strain field in Figure 54 (b).



**Figure 54: Failure and loading of the composite specimen in compression**

#### **4.1.3.2 Measurements with the novel long gauge length apparatus**

The results from the IITRI and modified IITRI apparatus were rather mixed in terms of material strain monitoring and loading. Consequently, a complete new apparatus was designed. This new compressive apparatus provided a long “area of interest” (+55 mm) (Figure 55) that allowed for the characterisation of [0/90] and [+45/-45] tufted and unfted specimens. The strain field allowed for maximum strain recognition which was in agreement with specimen failure localisation.

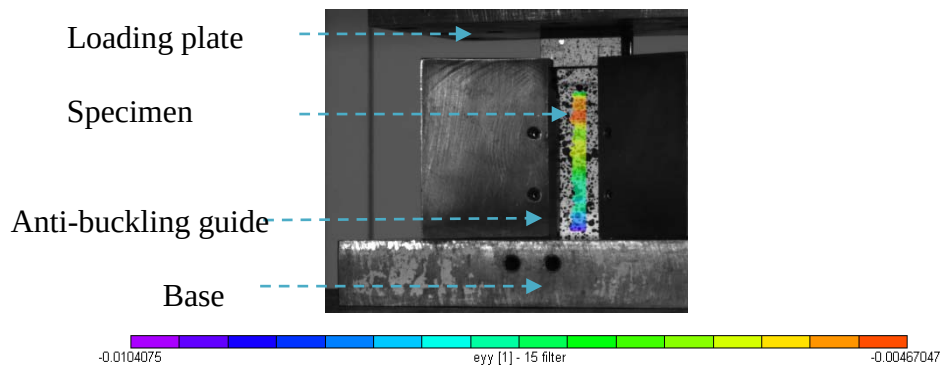


**Figure 55 :  $\epsilon_{yy}$  strain field on 0/90 untufted in compression**

The large strain field permitted the analysis of the specimen failure in compression throughout loading using several strain extraction methods. This permitted the gain of useful information on the validity of the specimen response in term of bending or strain concentrations. These strain extraction methods consisted of:

- “Failure”: the strains were extracted on the failure area.
- “Average centre”: the strains were averaged over the whole specimen.
- “Average displacement”: the strains were calculated from the displacement at the top and bottom of the sample.
- “Local central point”: the strains were extracted in the middle of the sample and were assumed to be similar to a strain gauge.

#### **4.1.3.3 Measurements of axial properties**

##### **a) Untufted specimen**

Figure 56 shows the behaviour of the untufted [0/90] specimen in compression. It is observed that the strain at the failure point was higher than the strain averaged on the sample area which meant that the failure was relatively localised.

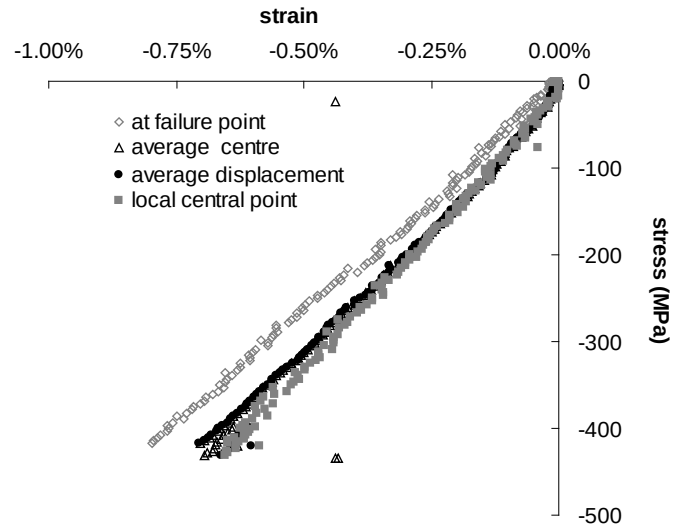


**Figure 56: Stress strain response of [0/90] untufted specimen**

The “average displacement” and the “average centre” strain were close. It can be deduced that the specimen was not bending and that the test was therefore not valid. The specimen was observed with an optical microscope. The identified failure models were delamination, kink bands, matrices cracking and fibre breaking (Figure 57). The [0] plies can be observed in white and the [90] plies in dark grey. It can be observed that the non-crimp plies have some waviness throughout the thickness of the materials.

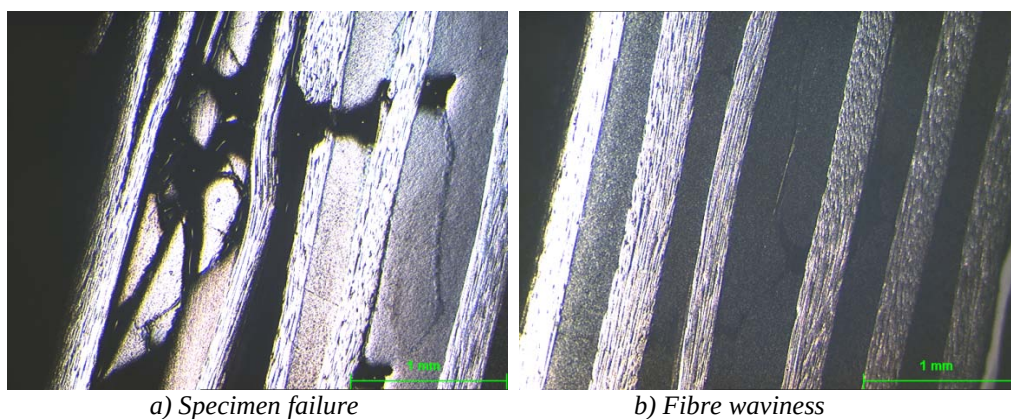


**Figure 57: Optical microscope images**

It is also noted that little damage occurred away from the failed area. Finally it was noticed that the supposedly 0 degrees fibres were rarely perfectly at a strict 0 degrees from the specimen axis as shown in Figure 57.

## b) Tufted specimens

The results of tufted specimen in compression were monitored with the optical strain field apparatus. It allowed failure monitoring localisation near the top of the specimen (Figure 58). In effect according to the DIC scale (Figure 58) in that area maximal compressive strains of 1.1285 % were occurring.

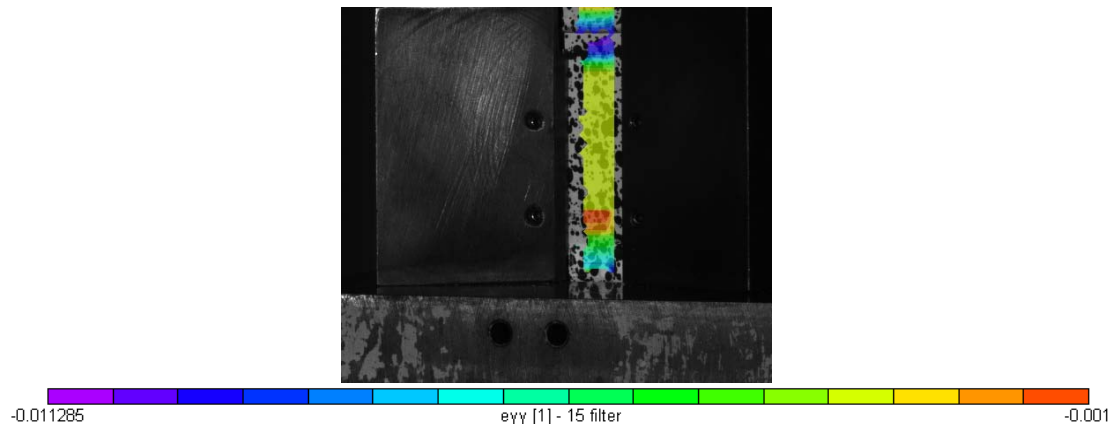


**Figure 58: Strain field on the tufted specimen**

The specimen behaviour during compression is shown in Figure 59.

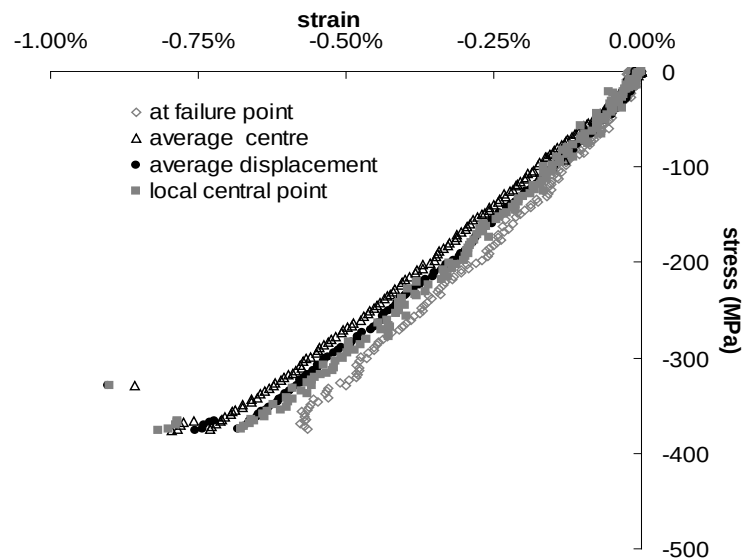


**Figure 59: Tufted specimen in compression**

The failure was localised mainly on the unmonitored side and occurred near the top tabs on the monitored side. The tabs stiffened up the material reading in this area, explaining the low strain at failure in this area. Results also showed that the specimen was not bending, as the average displacement strain recording and the

average center strains were close. The specimen was observed under a stereoscope.

Figure 60 (a and b) showed the resin rich area caused by the through thickness tufts.

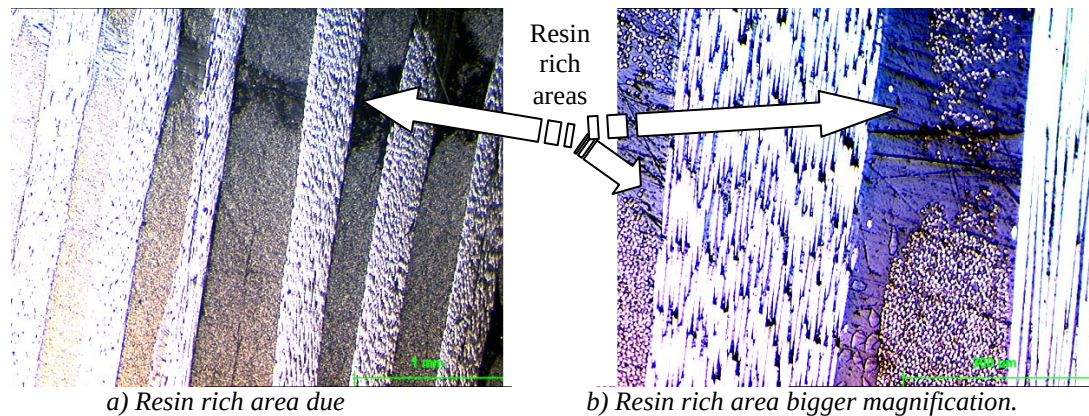


**Figure 60: Through the thickness resin rich area due to the tuft**

### **c) Comparison of tufted and untufted [0/90]**

Global strain was used to compare and analyse the results. Global strain is the average of the strain on the specimen area. This strain is preferred to the use of failure strain because the tufted specimen failure showed that failure could, in some cases, be localised on one side of the specimen mainly because of the tuft holding the material together. Therefore, if the recordings were done on the opposite side to failure, then the recordings were not totally representative of the material behaviour. The response of the tufted and untufted composites in compression is observed in Figure 60 using the global measurement method.

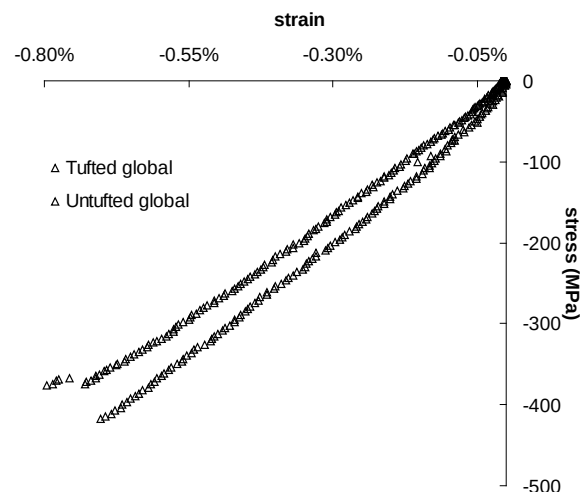


**Figure 61: Tufted and untufted composite material response in compression**

Untufted materials showed a stiffer and stronger response than the tufted NCF composites. This is partly explained by the resin rich area at the tuft site which lowered the volume fibre fraction. Also, the tuft tows fitted into the NCF fabric thickness created some local misalignment on the 0 degrees fibres.

|                                 | Untufted | Tufted |
|---------------------------------|----------|--------|
| Compressive modulus (GPa)       | 63       | 56     |
| Compressive ultimate strain (%) | 0.70     | 0.71   |
| Compressive strength (MPa)      | 418      | 374    |

**Table 10: Mechanical compressive characteristics of the composite materials**

Micrographs at failure of [0/90] compressive specimens are observed in Figure 62 (a and b). Both tufted and untufted specimens show kink bands, large delamination, fibre failure, kinking. The tufted specimen showed that the damage was smaller on the specimen surface but had propagated through the specimen thickness. The untufted specimen showed more Micro-delamination and a more concentrated damage area.

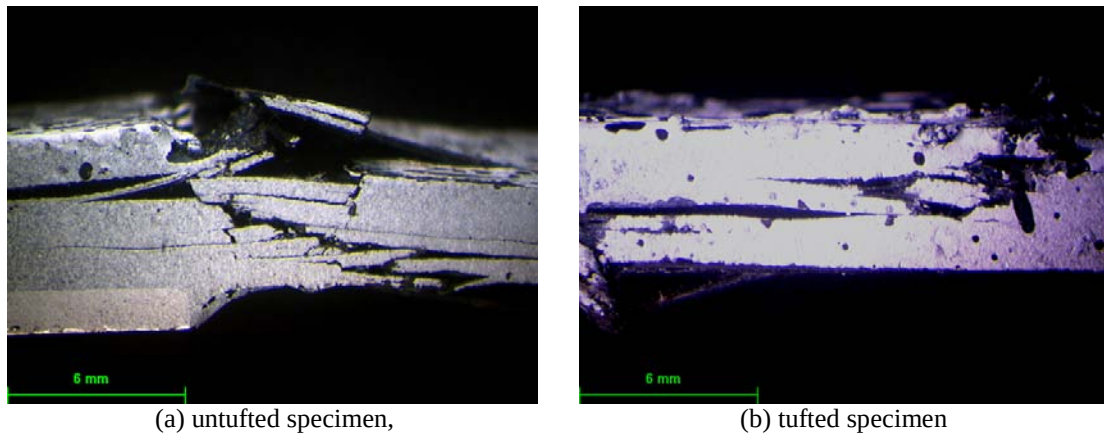


**Figure 62: Axial compressive failure (a) untufted specimen, (b) tufted specimen**

#### 4.1.3.3 Measurements of bias direction properties

In-plane shear tests are commonly performed in tension following standard procedures with a laminate at [+45/-45]. The new long gauge length allows for compressive shear testing since the specimen gauge length is twice as long as its width. Effectively, the [+45] tows need to slide freely relative to one another to allow

shear behaviour. It is then completely allowed by the long specimen gauge length. Again, data is extracted from the strain field to follow the specimen compressive shear response monitoring. Several methods of strain extraction were used:

- “middle” the strain was extracted in the middle of the specimen.
- “failure” the strain was extracted at the shear failure location.
- “global extensometer” the strain was computed from the displacement extracted at the top and bottom of the specimen.

#### a) Untufted specimen

The untufted specimen response can be observed in Figure 63. The strains recorded in the middle of the specimen and at failure are close because failure occurred in the specimen middle. Less strain was witnessed overall before ultimate failure as the specimen tended to relax when part of it was failing. This difference is explained by the fact that failure was localised to a specific area of the specimen.

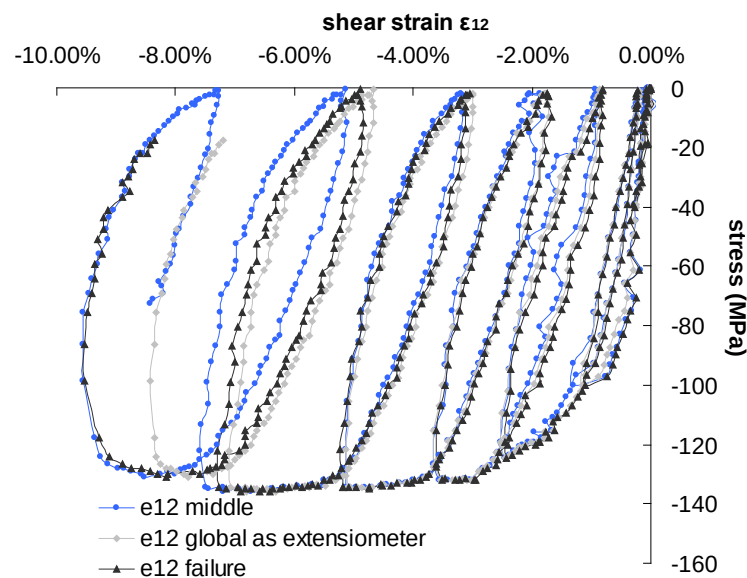


**Figure 63: Compressive bias direction response for untufted specimen with strains extracted at different location**

### b) Tufted specimen

The strain recording on the tufted specimen was similar to the untufted specimen and can be observed in Figure 64. The difference between the middle strain and the failure strain indicates that the shear failure did not take place in the middle. Large strains at “failure” are observed compared to “overall strain” which highlights the localisation of the damage area.

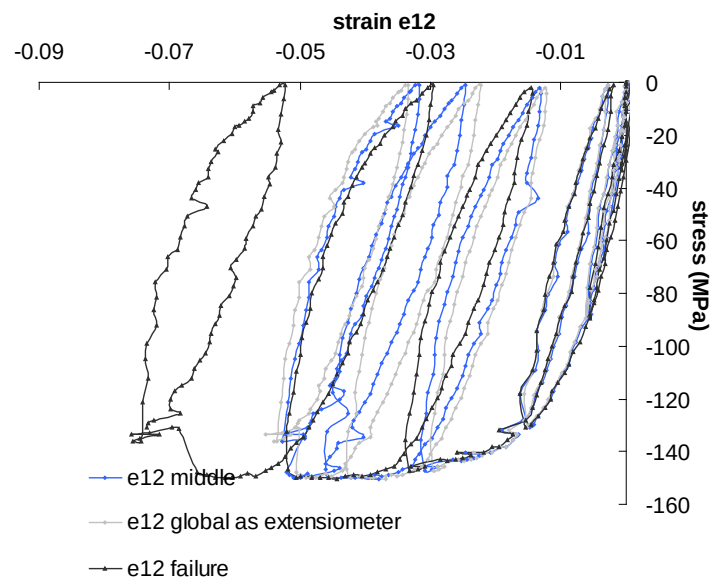


**Figure 64: Compressive bias direction response for tufted composite with strains extracted at different location**

### c) Comparisons between tufted and untufted

Comparison of the tufted and untufted material can be seen in Figure 65. The tufted material shows a stronger response meaning that the specimen absorbed considerably more energy during plastic failure. The strain at failure was considered to be similar.

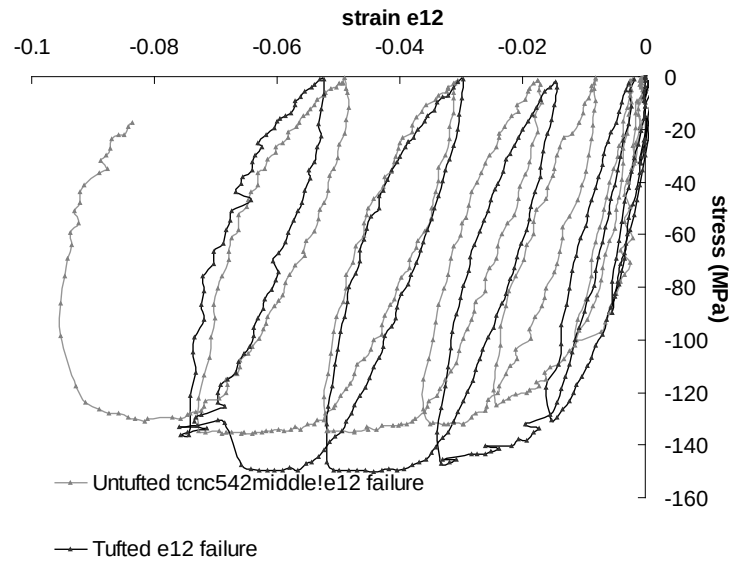
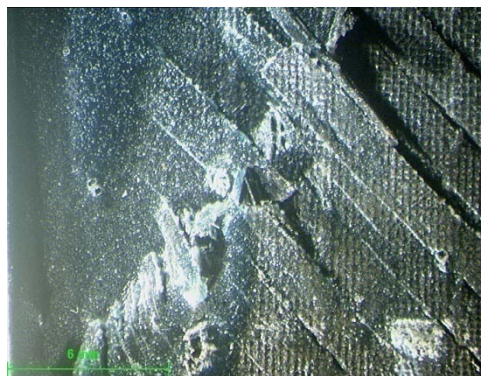
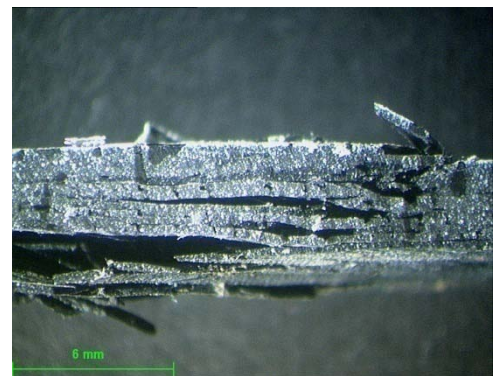


**Figure 65: Tufted and untufted response in shear compression**

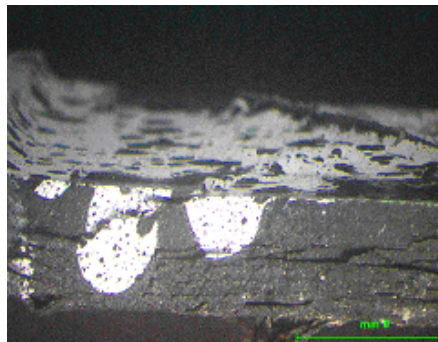
The untufted specimen showed large shear delamination of the layers through the thickness with some shear failure and delamination of the tows on the surface. Tufted specimens showed less severe delamination on the surface and through the thickness. Nevertheless, delamination was well spread through the thickness (Figure 66).



a) Untufted



b) Untufted



c) Tufted

**Figure 66: (a) Untufted specimen shear failure/ a) on the surface, b) through the thickness c) tufted specimen shear failure through the thickness.**

#### **d) Conclusion on measurements of the [0/90] tests**

The scatter in strength recording was relatively high (15%) on the [0/90] layup. This was explained by the possible slight misalignment of the 0 degrees layer and the parallel and flat specimen end requirements which were difficult to achieve perfectly. A few degrees of misalignment in the layup during specimen preparation, or inexact specimen cutting, could cause premature failure. This would respectively reduce the specimen mechanical properties or induce stress concentrations. In addition, any slight out-of-plane misalignment would also lead to premature failure. If the ultimate compressive strength was slightly under-estimated by this test, it captured well the response of the materials and could be used for possible misalignment checking.

#### **e) Conclusion on measurements of [+45] tests**

Low standard deviation was observed on the stress strain shear response; the stress and plasticity was highly reproducible from test to test. To verify this, the new long gauge length apparatus provided a clear strain field that allowed for characterisation of the material in compression (shear modulus) with repeatable results in term of modulus and strength on the +-45 laminate. Characterisations of Young's Modulus prove to be successful on the [0/90] specimens with negligible specimen misalignments; but some variance was observed on the strength of the specimen. Figure 67 recapitulates the strain field behaviour in compression on the various apparatus tested.

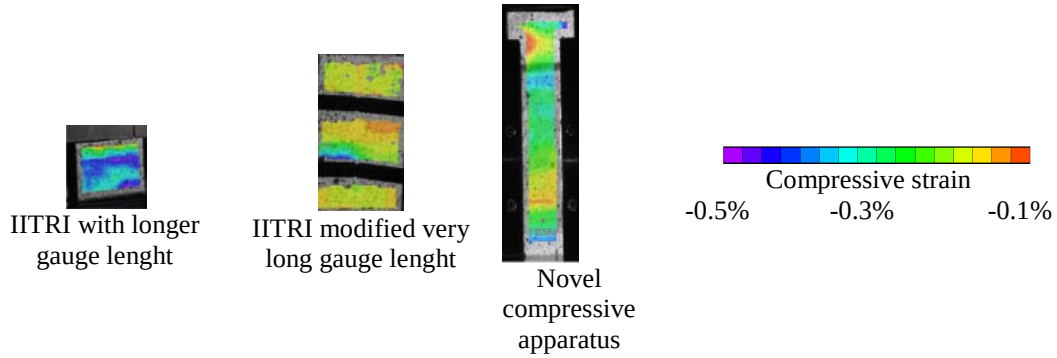


**Figure 67: Full field strain recording on the various compressive set ups**

#### **f) Comparison between tension and compression loading**

Comparison of the axial tension and compression behaviour indicated significant variations induced by the dominance of different failure mechanisms, such as Micro-buckling in compression and fibre fracture in tension. Strength and ultimate strains were significantly lower in compression in the axial direction, whilst non linearity tended to be more pronounced in compression than in tension. The initial axial compressive Young's Modulus was identical to the tensile Young's Modulus until non-linearity occurred. This was observed for both the tufted and untufted composites.

The material response differed for shear loading in the bias direction in the case of large deformations. The cyclic behaviour of  $[\pm 45]$  NCF composites under tension and compression is illustrated in Figure 68.

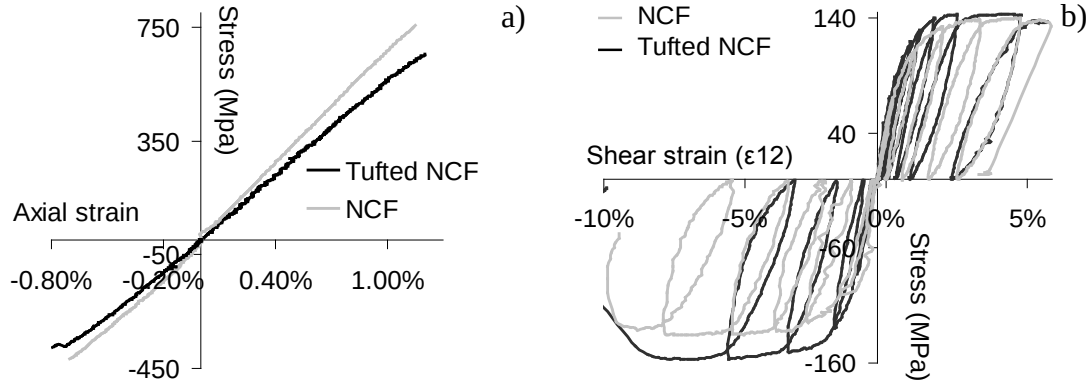


**Figure 68: In plane response of NCF and tufted NCF composites: (a) Axial tension and compression experimental behaviour, (b) Cyclic [ $\pm 45^\circ$ ] tension and compression experimental behaviour**

Shear response in the bias direction was characterized by matrix cracking and delamination during fibre shearing mechanism. Compression and tension of tufted and untufted NCF composites in this bias direction exhibited comparable strength (Figure 68 b). However, the compressive failure shear strain was larger by 20 % than the tensile failure shear strain for both materials. The compressive shear failure strain was characterized by a sudden and total loss of stress occurring at 5 % strain in tension and 10% strain in compression (Figure 68 b). This result is understood to be due to the closure of cracks and localised friction around the cracks during the compressive loading in the bias direction. In the case of tension in the bias direction, the cracks opened and propagated with little friction resistance, causing increased damage and ultimate failure at a lower strain value. This is characterized on the Macro-scale by extensive fibre shearing and matrix cracking in tension and limited fibre shearing in compression.

#### **4.1.4 A novel real time damage detection method**

Figure 69 to 70 illustrates the damage distributions calculated from Equation 48 for NCF and Tufted NCF composites under different loading types. Damage fields were compared with the results of ultrasonic C-scanning after failure in the case of

[ $\pm 45$ ] specimens under cyclic loading in Figures 71 and 72. It can be observed that there is a close correspondence between the damage fields calculated using optical strain measurements and the results of C-scans.

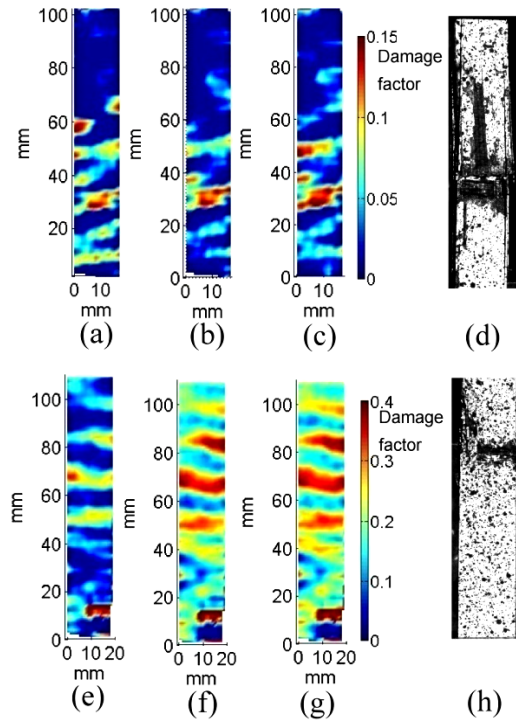


**Figure 69: Damage field on [0/90] specimen in tension on untufted specimen (a) 0.34% strain; (b) 0.7% strain; (c) 1.02% strain; (d) damaged specimen; and on tufted specimen: (e) 0.36% strain; (f) 0.7% strain; (g) 1.01% strain; (h) damaged specimen.**

For tension of [0/90] specimens, the damage at 0.35% strain was comparable for both tufted and untufted composites (Figure 69.e and 69.a). As the specimen loading was increased to 1% strain, the tufted specimen showed a greater amount of damage than the untufted specimen (Figure 69.c and 69.g). This observation is in accordance with the reduction of Young's Modulus for the tufted material shown in Figure 69.a.

In compression, the [0/90] composites behaved non-linearly as the axial fibres

underwent Micro-buckling. This effect is characterised by a slight reduction of stiffness at the Macro-scale throughout loading until final failure. Damage recorded in axial compression was believed to correspond to some extent to Micro-buckling of the axial fibres which increased regularly, but not uniformly, with loading (Figure 70.c and 71.g). This implied that Micro-buckling could be non uniform and concentrated locally in parts of the compressed specimen. The tufted and untufted composites behaved differently in compression. The untufted specimen had large concentrated

damage at the failure location (Figure 70.c); likewise, the tufted specimen showed damage concentration at the failure location (Figure 70.g) but in a smaller amount.

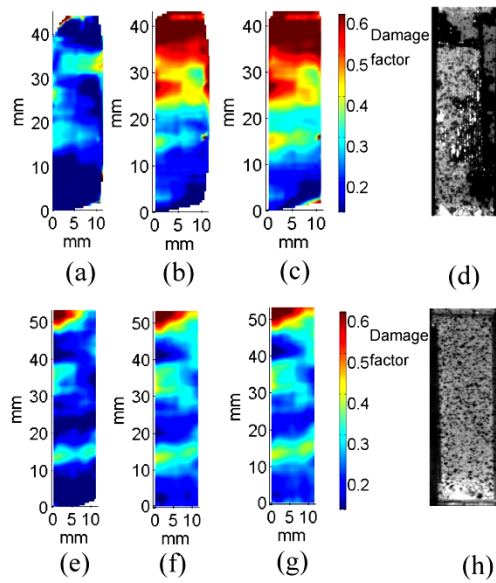


**Figure 70: Damage field on [0/90] specimen in compression on untufted specimen :(a) 0.3% strain; (b) 0.71% strain; (c) 0.8% strain; (d) damaged specimen; and on tufted specimen :(e) 0.28 % strain; (f) 0.49% strain; (g) 0.8% strain; (h) damaged specimen.**

The large non-linear behaviour of  $[\pm 45]$  specimens in tension and compression allowed easier monitoring of damage than in the  $[0/90]$  case. Tufted and untufted damage response appeared to be comparable in intensity and extent (Figure 71.a, 71.b, 71.e and 71.f). The shear failure in tension occurred with large  $\pm 45$  failure patterns for the untufted specimen Figure 71.d) and limited  $\pm 45$  patterns for the tufted specimen (Figure 71.g). Failure was similar in both tension and compression in

the bias direction for the tufted material. However, for the untufted material, the failure pattern was reduced from a double  $[\pm 45]$  degree shear failure to a simple  $[+45]$  failure in compression with a more homogenous damage field.

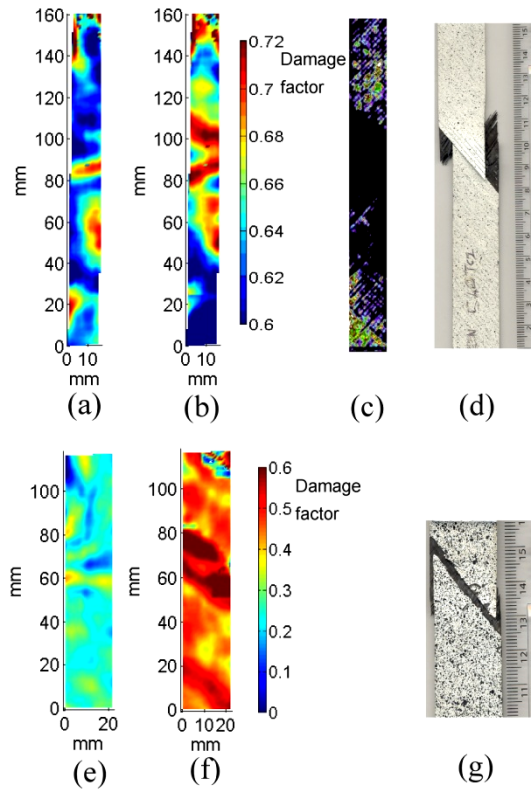


**Figure 71 : Damage field of  $[\pm 45^\circ]$  untufted composites in tension on untufted specimen: (a) 1.3% strain; (b) 4.7% strain; (c) C-scan (in black damage area); (d) damaged specimen; and tufted specimen (e) 1.5% strain; (f) 4.5% strain; (g) damaged specimen.**

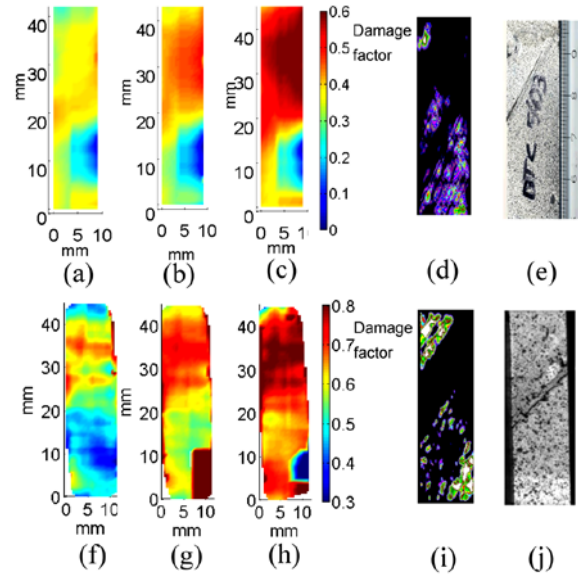


**Figure 72 : Damage field of  $[\pm 45^\circ]$  untufted composites in compression on untufted specimen (a) 1.5% strain; (b) 4.0% strain; (c) 6.7% strain (d) C-scan (in black damage area); (e) damaged specimen and on tufted specimen: (f) 1.5% strain; (g) 4.5% strain; (h) 6.9% strain, (i) C-scan (in black damage area), (j) damaged specimen.**

Compressive damage in the bias direction showed similar results for the tufted and untufted specimens in terms of damage progression and intensity. Nevertheless, slightly more damage appeared in the tufted specimen (Figure 72.h) in which damage was seemingly guided by line patterns that corresponded to tufts sequences. These observations are in accordance with the similar stress strain response of the material from Figure 68.b.

All cases predicted well the localization of failure. Damage intensity was the lowest on the  $[0/90]$  specimen in tension. In axial compression, more damage was recorded in the range of shear damage recorded earlier on. The occurrence of the first damage cycle proved to be of extreme importance and would influence the intensity of the damage factor. Nevertheless, if the initial cycle was carried too early in the loading

phase, the specimen could not be under uniform strain and stress and therefore the Modulus field could be inappropriate (below 6 KN). Satisfactory results were given with initial cycle unloading between 6 and 9 KN. The first cycle unloading must occur at a consistent load for all specimens, to allow the comparison of the damage fields together. The damage maps created are reproducible because previous tests without cyclic loading have shown good quality in ultimate stress and strain reproducibility's as well as in the amount of non linear response for at least 5 specimens tested for each load cases. Only a little of squatter in ultimate compressive stress and strain (Figure 68) measurements were found. If the ultimate stresses and strains were alike with comparable amount of non linearity in the same loading conditions, then it is understood that the amount of damage leading to the failure was of the same magnitude. The damage maps are therefore reproducible in term of amount of damage occurrence. But the location of damage could be different from specimen to specimen as damage initiate from a tiny defect in the material that could be localized differently on different specimens.

#### **4.1.5 Measurements of delamination in Mode I**

The response to delamination of the standard and tufted NCF composites showed large differences. Tests on the plain NCF material were reproducible and smooth crack propagation could be recorded visually. Tufted NCF showed early resin crack propagation at 35 Newtons like the response of the standard NCF DCB, but further delamination was stopped by the tuft reinforcements until tuft failure would occur at 90 N. This behaviour was evidenced by a noticeable change of the loading slope in the tufted NCF at 38 N (Figure 73.a).

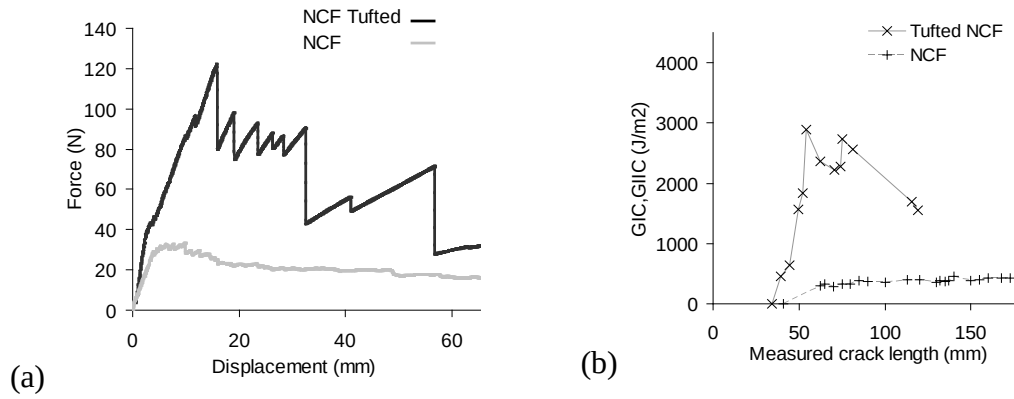


**Figure 73: Delamination mode I in term of force versus displacement (a) and  $G_{IC}$  versus measured crack (b) for tufted and untufted materials**

Figure 73 (a) shows that the crack propagation was highly influenced by the tufts. The low density of the tufting (5\*5) meant that after the tufted reinforcement failed there was 5 mm with a pure resin interface. Therefore, at that point, the load in this area was twice higher than the necessary load to propagate the crack, inducing high crack speed in this zone. The cracks propagated through several tufted reinforcements before the force and speed reduced enough to be stopped by the next tufts. This behaviour, known as stick slip, was exacerbated in tufted DCB specimens and gave unsteady loads. Tufting enhanced by 3 orders of magnitude the delamination resistance while the energy release rate increased 10 times.

#### 4.1.6 Measurements of delamination in Mode II

The response of the tufted and standard NCF are shown in Figure 74, a. The responses of both materials were characterized by similar loading behaviour until cracking was initiated due to similar bending stiffness. Once the crack initiated, it propagated with little extra bending and force requirement in the standard interface. In the case of the tufted NCF, the specimen retained high strength during the crack initiation and propagation as the tufts failed at shear force and at specimen bending higher than the untufted samples.

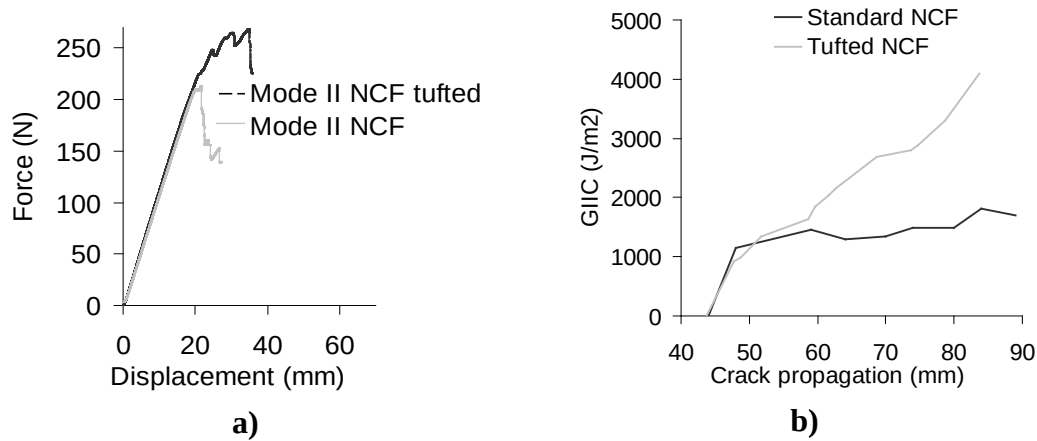


**Figure 74: Standard and tufted NCF response to delamination: (a) force versus crack displacement, (b) strain energy release rate**

The strain release energy in Mode II is computed via Equation 22 (Page 68) for standard and tufted interfaces with ( $P$ ) the load, ( $a$ ) the crack length, ( $b$ ) the DCB width, ( $t$ ) the DCB thickness, ( $E_f$ ) the flexural modulus.

The strain release energy rate for both materials was presented in Figure 74, b and illustrates the strong benefits of the tufts with one third more energy absorption during delamination.

#### 4.1.7 Effect of tufting on punched discs

Tri-axial loading was achieved through loading a simply supported disc with a punch at its centre. The results are illustrated in Figure 75 for untufted, semi-tufted and tufted discs. These results show that tufted discs absorbed more energy than untufted or semi-tufted discs because of the higher delamination toughness (Figure 75 b)). However, in this case it appeared that untufted discs could carry higher maximum loads. Effectively, in-plane and out-of-plane coupon testing results showed higher maximum load for the untufted materials. Figure 75 illustrates that the energy absorbed by the tufted specimen was 30 % higher than in the case of the untufted composite disc.

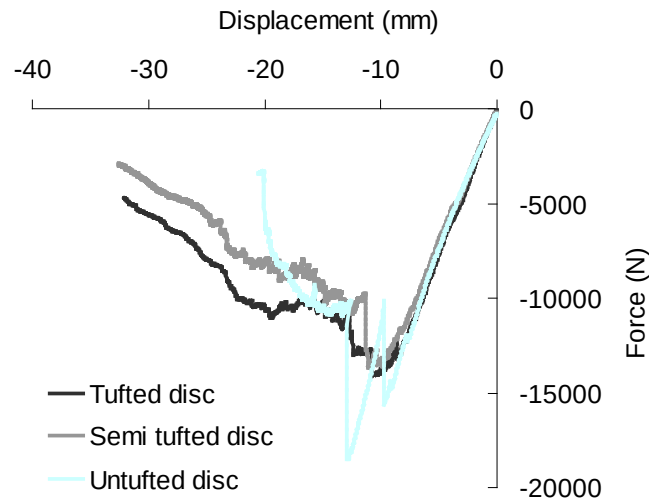


**Figure 75: Punch discs force versus displacement**

This would indicate that tufted materials may be superior for crash and impact applications but would be less advantageous for critically stiff composite structures due to their slightly diminished in plane properties.

#### **4.1.8 Measurements of open hole effect**

Open hole specimens are often used as stress concentration methods and consist in this case of 3 mm hole in the center of the specimen. The testing of an open hole specimen followed the procedure used to test specimens without a hole, which meant the use of an 100KN Instron machine and DICM full field acquisition. The response of untufted and tufted NCF composites to a stress concentration was studied in tension and compression. The response to the stress concentrations resulting from a 3 mm open hole in the laminate in terms of damage factor distribution is illustrated in Figure 76. In [0/90] layups, the presence of the hole reduces the strength of the laminates by 19% for the tufted material and by 23% for the untufted material.

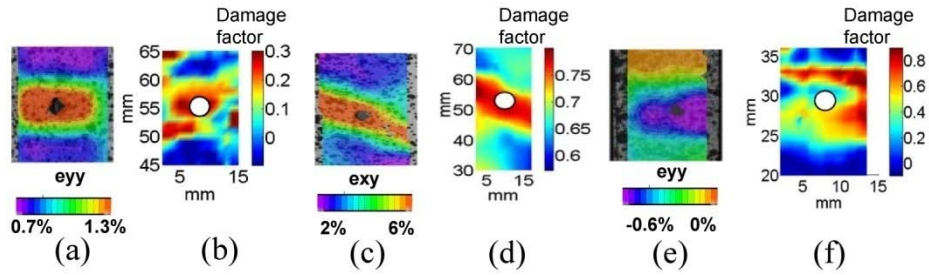


**Figure 76: Strain and damage field in tension and compression on open hole tufted specimen just before failure; (a) tensile strain field; (b) tensile damage field; (c) tensile shear strain field; (d) tensile shear damage field; (e) compressive strain field; (f) compressive damage field.**

In compression, the strength was reduced by approximately 25% in both cases. Damage field intensities were found to be comparable with, and without, holes with more damage occurring around the hole. The strain and damage fields around the hole were slightly different in tension and compression. In compression, the strain field indicated that one side of the hole was more loaded which induced more damage on that side (Figure 76 e). In tension the same strains on both sides of the hole (Figure 76.a) were recorded and the damage in that case was concentrated around the hole (Figure 76.b). For  $[\pm 45]$  layups, the reduction of strength due to the hole was only 4.2%. The strain (Figure 76.c) and damage fields (Figure 76.d) were comparable between each other but also comparable to damage intensity for specimen without a hole.

## 4.2 *Dynamic characterisation of NCF composites*

Static monitoring of the two composites (untufted and tufted) materials for various load case and layups have illustrated different damage, strains, strengths, delamination and stiffness responses. According to the literature review, these responses would also be subjected to strain rate effects. Therefore, it is of interest to assess the strain rate sensitivity of different load cases and layup. This section deals with stress strain acquisition for various loading speeds, load cases and layups. More

specifically, this section describes the in-plane response of the material at low, intermediate and high strain rates.

#### 4.2.1 Tensile measurements at low rate of loading

Low rate tensile testing of carbon NCF composites through the use of hydraulic machines at 40 and 80 mm/s was studied. The response of the [0/90] consisted of small rapid deformation until tensile failure occurred. The high speed recording of the specimen deformation at 10000 images per second permitted the capture of speckle movement during loading that generated full strain and displacement fields. As the high speed camera frame rate was increased the resolution of the images was reduced. At 10000 images per second the images were 256 pixels by 256 pixels.

##### 4.2.1.1 Measurements of the axial response

Figure 77 shows the failure of the [0/90] specimen in tension at the low rate (40mm/s). The image frame number can be seen on the top of the specimen. It is observed that unlike quasi-static testing, the specimen did not fragment in numerous pieces and that rupture (failure) occurred rapidly (1 milli-second).

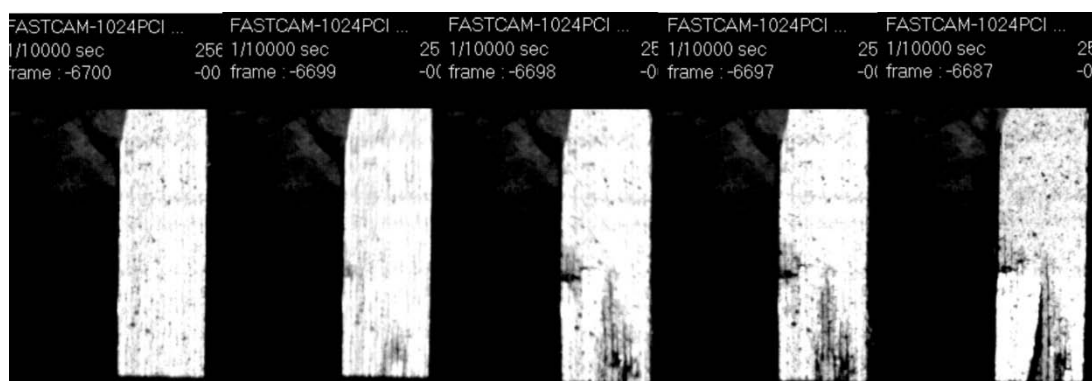


**Figure 77: Tensile failure of [0/90] untufted specimens at low rate**

Figure 77 presents the results of the speckle pattern movements just prior to failure and Figure 78 the strain and displacement field obtained from the speckled pattern.

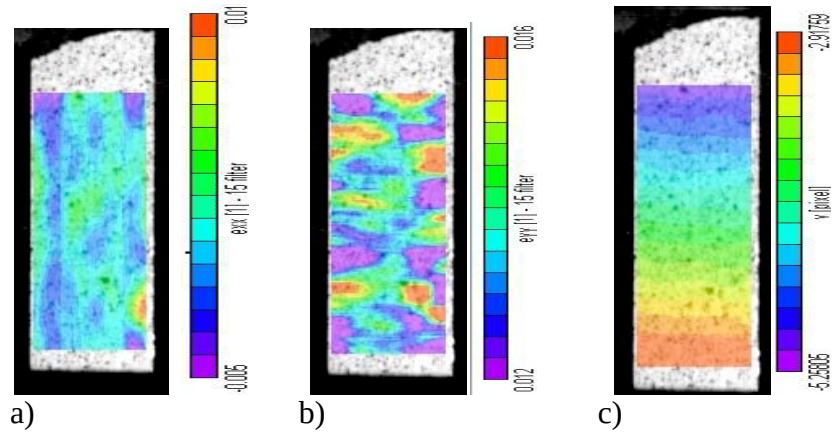


**Figure 78: Low speed tensile loading on [0/90] NCF composites; full field measurement acquired at 10000 images /second just before failure. a) exx, b) eyy, c) vertical displacement in pixels.**

The axial strain extracted from the specimen surface displacement was sampled with the stress obtained from the load cell and the specimen geometry, Figure 79. In this case, the strains were calculated from the specimen displacement fields manually as the strain algorithm struggled to compute the strain with a large noise signal. Previously in the static section (Chapter 3) on compressive testing it was possible to calculate strains from the full field displacement measurements which were less sensitive to speckle pattern size and contrast. In this case, this method was also preferred. The force readings were linear up to failure and were sampled with the calculated strain from displacement readings in Figure 79.

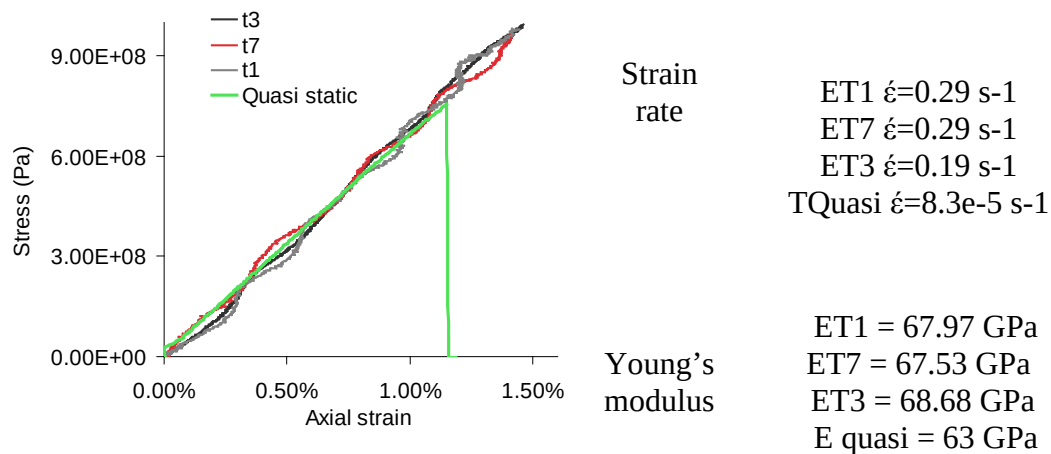


**Figure 79: Low strain rate tensile loading of [0/90] NCF composites**

It can be observed that the strains and stresses increased significantly (from 1 to 1.40 % in strain and from 750 to 920 MPa in stress) with the increase in loading speed from 1 mm/min to 40 and 80 mm/s (2.4 m/min and 5.6 m/min). The measured stiffness remained close to the static experimental value of E (63 GPa). The responses of dynamic tensile tests in the bias direction at low strain rate are illustrated in the next paragraph.

#### 4.2.1.2 Measurements of the bias direction response

The bias direction failure of the untufted specimen at low rate is presented in Figure 80 with the corresponding frame number at the beginning and towards the end of the test.

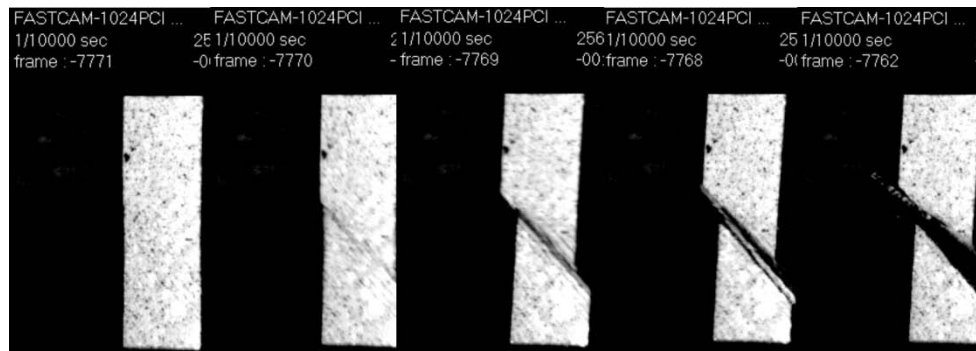


**Figure 80: Tensile failure in the bias direction at low strain rate (80 mm/s or 0.54 s<sup>-1</sup>) for T2 specimen through hydraulic machine loading.**

The specimen failed in classical shear failure deformation. The full field measurements are presented in Figure 81 just prior to failure.

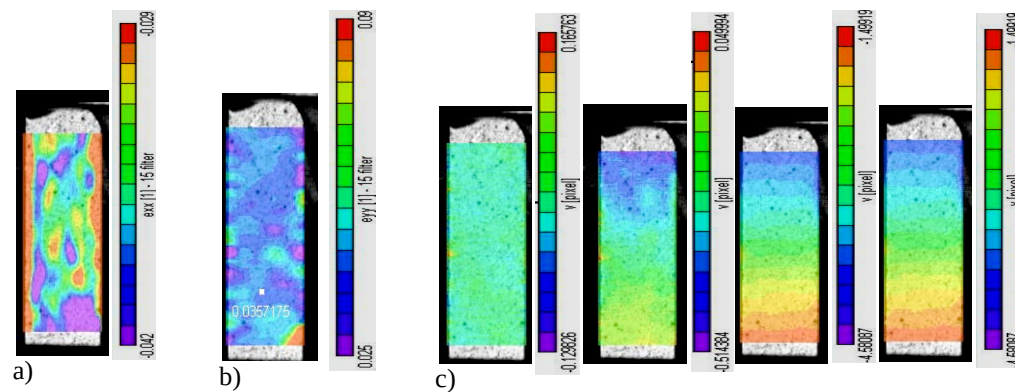


**Figure 81: Tensile failure in the bias direction at low strain rate (80 mm/s or 0.54 s<sup>-1</sup>) for T2 specimen through hydraulic machine loading: a) exx, b) eyy, c) displacement loading**

Strain measurements were extracted and resampled in time with the force from the load cell. Stress strain responses of such tests were presented in Figure 82.

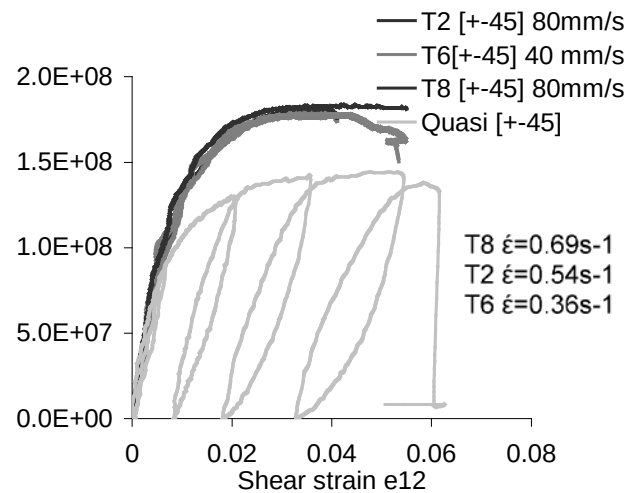


**Figure 82: Bias direction for untufted material at quasi static and low rate**

Failure stresses were found to be much higher and failure strains decreased slightly at low strain rate rather than in quasi static condition. If this response was expected from the literature it was surprising to see such an increase in strength for such a small increase in loading speed. The specimen could bear more energy absorption even so the failure strain was slightly reduced.

#### **4.2.2 Measurements at intermediate loading rate**

As explained before, the intermediate rate was achieved within a drop tower apparatus on the tufted and untufted composites.

##### **4.2.2.1 Tensile measurements**

###### **a) Measurements of tensile bias direction responses**

The responses of the tufted and untufted specimens to loading in the bias directions are illustrated in Figure 83 and 84 in tension. The failure pattern is shown to be slightly different for both. A diagonal shear pattern is observed for the untufted specimen and a double failure pattern for the tufted specimen.

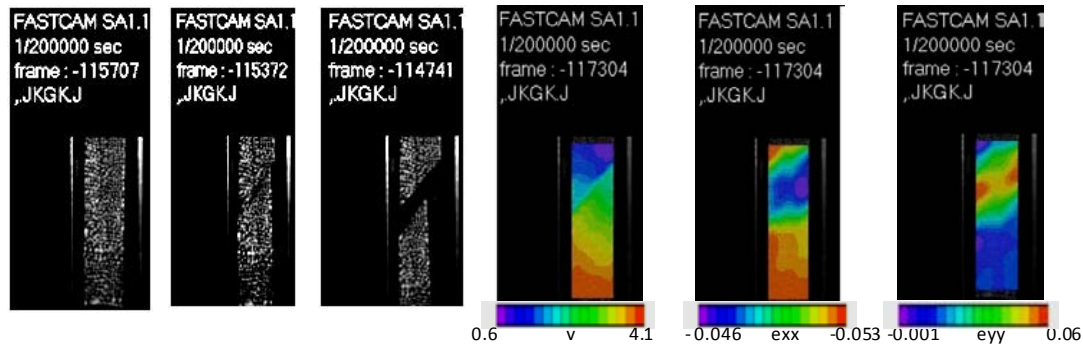


**Figure 83: Tensile test in the bias direction through drop weight loading of standard epoxy NCF composites at [+45]**

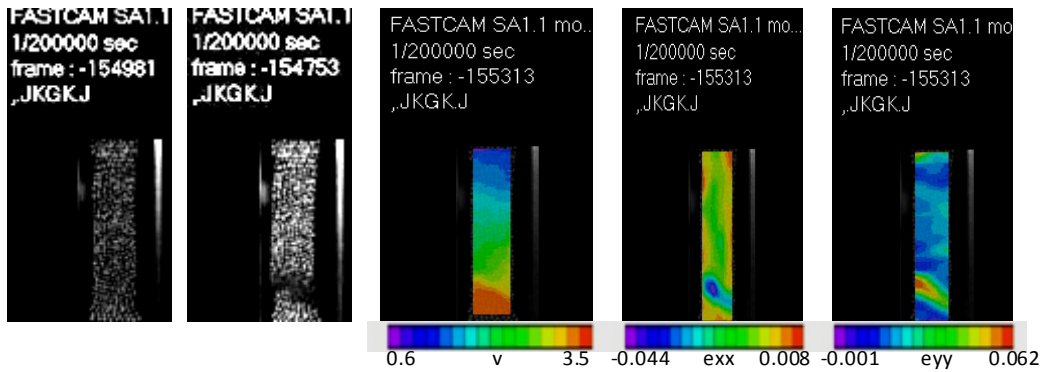


**Figure 84: Tensile tests in the bia direction through drop weight loading of tufted epoxy NCF composites at [+45]**

The dynamic strain versus time is shown in Figure 85 for several samples. It is observed that for similar loading speeds of (2.4 and 3 m/s), strain responses versus times followed the same increase for both the tufted and untufted composites. While this loading speed was halved, the deformation occurred at the same speed but with slightly less ultimate deformation. It seems that with this apparatus that halving the loading speed made only a small reduction in the strain rate. This response is characteristic of a positive strain rate effect. The amount of strain per unit of time can also be plotted and is illustrated in Figure 85.

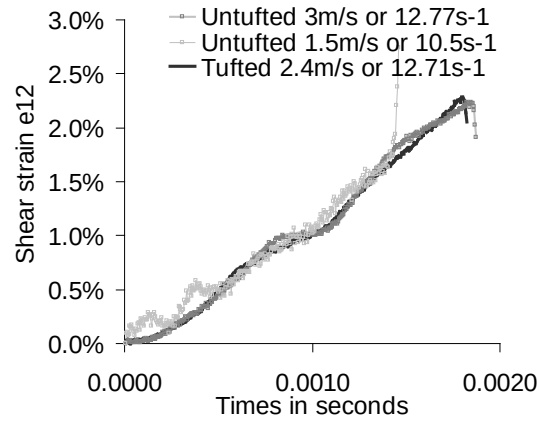


**Figure 85: Shear strain versus time at intermediate strain rate for tufted and untufted composites.**

The strain rate was filtered and plotted versus time in Figure 86. The filtering method used was an average of the last 5 readings. It was observed that for specimens loaded at similar speeds, the strain rate evolved in a similar manner for the tufted and untufted case.

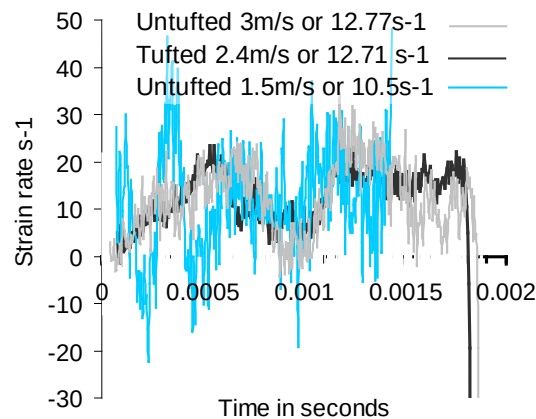


**Figure 86: Strain rate versus time for tufted and untufted specimens at intermediate strain rate**

At the lower loading speed, the strain rate response to time was slightly different with slightly more fluctuation (Figure 86). The load capture was performed with the novel load cell setup (Figure 42) and an example of the load acquisition for the tufted material is shown in Figure 87. It is noted that the load has a pulse form meaning a sharp load increase soon followed by a sharp decrease.

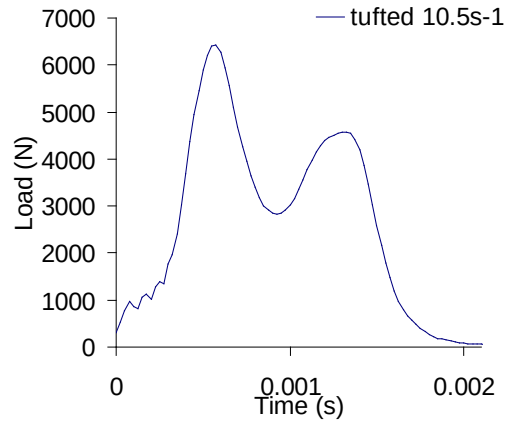


**Figure 87: Load trace versus time for the tufted specimen**

From the load cell recording and the strain acquisition, it was possible to sample both curves to obtain stress strain curves. The stress strain responses at the intermediate strain rate are compared to the quasi-static response in tension in Figure 88.

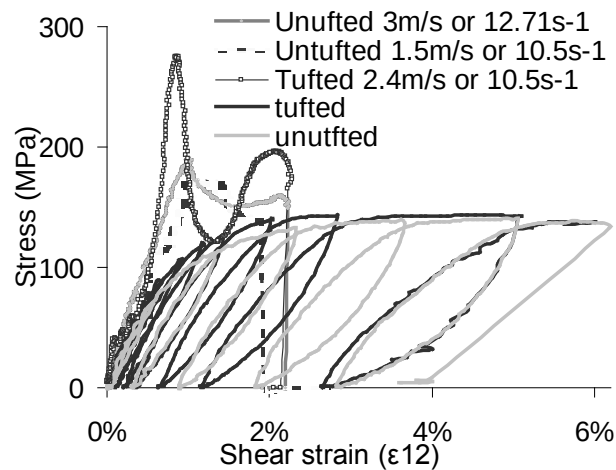


**Figure 88: Stress strain response at intermediate and quasi static rate**

It was observed that the tufted material required a much larger force to initiate damage than the untufted material. This sharp peak load was understood to correspond to extra forces required to damage the tufts and to allow the subsequent shearing of the ply with interface matrix cracking. Once tufts were damaged, the load dropped to a value comparable to the force required to shear untufted specimens. Indication of the dynamic shear stiffness measured is shown in Table 11.

|                                            |             |
|--------------------------------------------|-------------|
| $G_{12}$ untufted: 3 m/s or $12.71s^{-1}$  | 19873.4 MPa |
| $G_{12}$ untufted: 1.5m/s or $10.5 s^{-1}$ | 16842.1 MPa |
| $G_{12}$ tufted: 2.4m/s or $10.5s^{-1}$    | 12500 MPa   |

**Table 11: Intermediate loading on [0/90] specimens in tension through drop tower loading.**

### b) Measurements of axial tensile response

Typical specimen failures of the axial composites are illustrated in Figure 89 and 90. It is observed that the DIC method still produced a reasonable correlation at frame rate (200000 images/second) and resolution (64\*144) pixels.

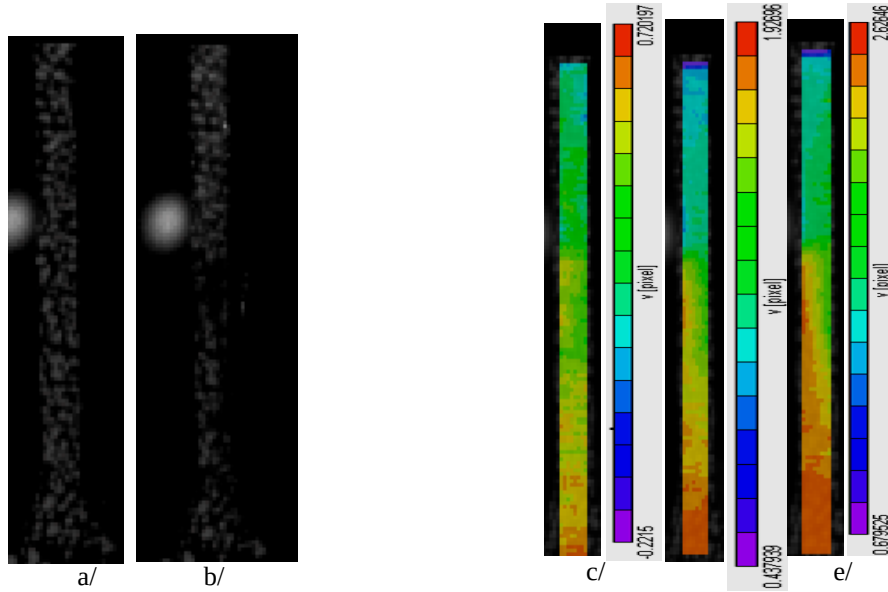


**Figure 89: Image of the speckle pattern: a/ during initial loading, b/ after failure**

**Figure 90: DIC vertical displacement in Pixel: a/ early loading, b/ halfway through loading, c/ just before failure.**

From the displacement measurement, the strain can be computed by the DIC tool which is plotted versus time in Figure 92. Only a few specimens were tested in this configuration and good results were obtained for the tufted and untufted specimens, but for a different strain rate, which made any comparison difficult. Nevertheless, the results can still complement the strain rate database.

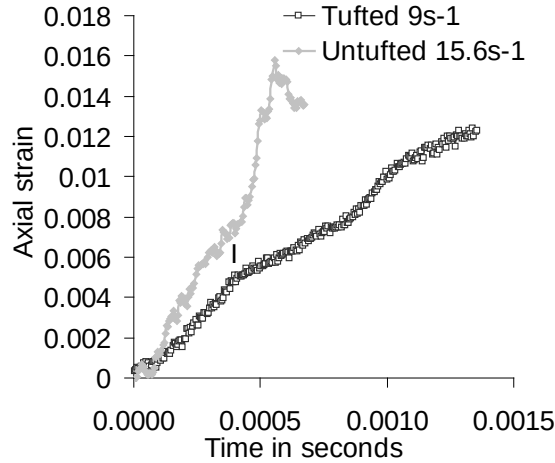


**Figure 91: Tufted and untufted composites in axial tension ([0/90]) at intermediate loading rate**

The strains versus time are plotted in Figure 91. An oscillation in the response was observed which is common in dynamic testing when stresses and strains have to be plotted versus each other. Effectively in dynamics often stresses and strains are acquired with different methods or technique. Also, it is noted that the untufted specimen breaks at a reduced time because the strain rate was higher than the one measured in the tufted case.

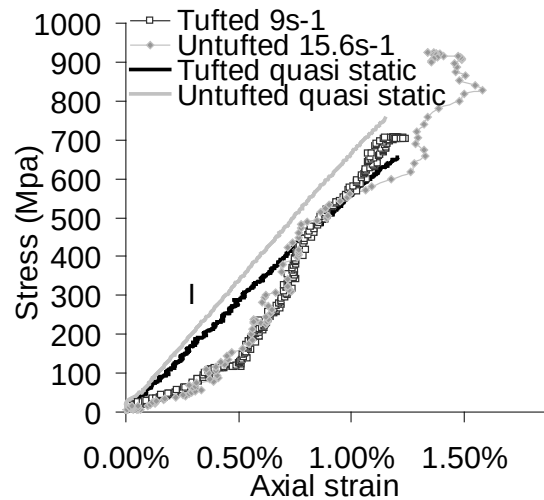


**Figure 92: Stresses versus strain in static and intermediate tensile strain rate conditions**

Figure 92 plots stresses versus strains at static and intermediate tensile strain rate conditions. As in static tests, tufted material was failing at lower stresses than the untufted material. Positive strain rate effects (higher stresses and strains at higher loading speed) were noticed for both materials but were more significant for the

untufted composites. The dynamic curves are shown to be non-linear. This is understood to be due to the difficulty of sampling the impact dynamic load pulse from the load cell with the strains on the samples. Effectively, unlike low strain rate loading which uses a tensile hydraulic machine, in the impact case of a drop weight tower, the stresses generated are alike a tensile stress pulse, with stresses rising slowly before increasing steeply as shown in Figure 93.

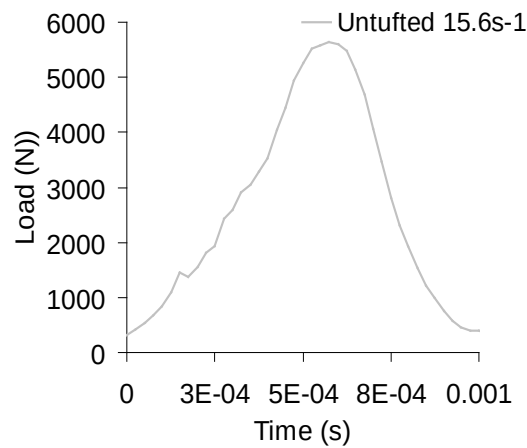


**Figure 93: Tensile pulse load**

From Figure 92, it was possible to obtain the Young's Modulus using different methods by either running a straight average through the curve or using the ultimate loading and strains before failure. The first method provided an unrealistic measure of Young's Modulus because strain and stress capture through time do not match during loading. The second method was preferred as the first method was sensitive to the sampling of strains and stresses. Effectively in this load case, it was preferred to use the maximum strains and stresses to compute stiffness for which failure stresses and strains were synchronized as the failure provided a time indication (Table 12).

| Materials and strain rates |                     | E "averaged" | E "final failure point" |
|----------------------------|---------------------|--------------|-------------------------|
| Untufted                   | 15.6s <sup>-1</sup> | 56.6 GPa     | 65714.2 MPa             |
| Tufted                     | 9s <sup>-1</sup>    | 53 GPa       | 61391.3 MPa             |

**Table 12: Dynamic Young's Modulus at intermediate strain rate**

#### 4.2.2.2 Compressive measurements

Similar apparatus and methods used for the quasi-static compression characterisation were used at the intermediate strain rate loading speed in compression.

##### a) Measurements in the axial direction

For the intermediate strain rate tests, the strain versus time and load versus time results are plotted in Figure 94 and 95 respectively. From them both it is seen that the pulse load is not regular. The loads and strains for the tufted and untufted materials contained a similar pattern through time. Nevertheless, the strain oscillations did not match completely the load oscillations apart from the initial and final increase. On both it was observed that the specimen and tool steel were loaded initially until rupture of the specimen at 0.0004 seconds (red area on Figure 94) then the specimen was compressed further and became jammed (blocked) in the compressive apparatus which corresponded to the load

plateau on Figure 94. Finally, the load rose further as the specimen was completely jammed and all the energy of the impactor was absorbed.

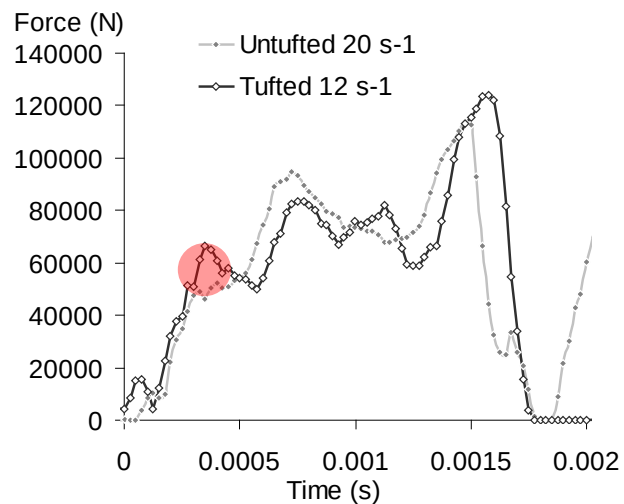


**Figure 94: Intermediate frame rate compression strain versus time and load versus time for tufted and untufted specimen: red area initial rupture of the sample.**

Sampling load and strains provide results that can be observed in Figure 95.

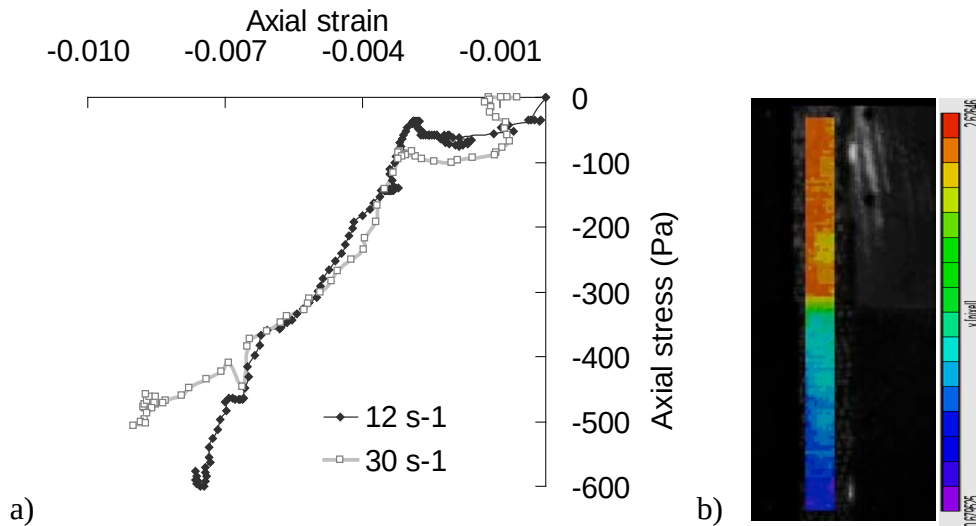


**Figure 95: Intermediate strain rate in axial compression for tufted and untufted specimen: (a) stress strain response, (b) example of dynamic displacement field**

Finding the sampling start and end was difficult in term of stress and strain as the results were not so precise, Figure 95 shows similar stiffness for the untufted and tufted response during loading except while approaching the failure load for which the tufted composite stiffened up. Table 13 plots different information for this loading. Different shear strain rates were achieved for the two different materials due to experimental uncertainties.

| Tests type  | Time (s) | Material | Lay up | Max strain | Max stress MPa | E "trend line" GPa | E "from max" GPa | Strain rate s <sup>-1</sup> |
|-------------|----------|----------|--------|------------|----------------|--------------------|------------------|-----------------------------|
| Compression | 0.00029  | Untufted | [0/90] | 0.00872    | 503            | 60.94              | 57.68            | 30.06                       |
| Compression | 0.000721 | Tufted   | [0/90] | 0.0087     | 590            | 60.4               | 67.              | 12.06                       |

**Table 13: axial [0/90] testing data table.**

In the bias direction, case Figure 96 illustrates the loading versus time for the [+45] layup. These responses proved to be different to the one of the [0/90] layup shown in Figure 94. The signal was understood to be better in the [+45] case (Figure 96) rather than in the [0/90] case. In that latter case, the specimen had the tool steel placed above the specimen as a load introduction. The energy to break the specimen was high in the [0/90] cases for which the material response was that of a stiff spring. Once failure occurred, little load could be carried by the specimen. In the [+45] case,

failure was not catastrophic and the response was similar to a loose spring absorbing most of the impact energy as the damage progressed. This behaviour and the fact that no load introduction was required is an explanation for the current better results.

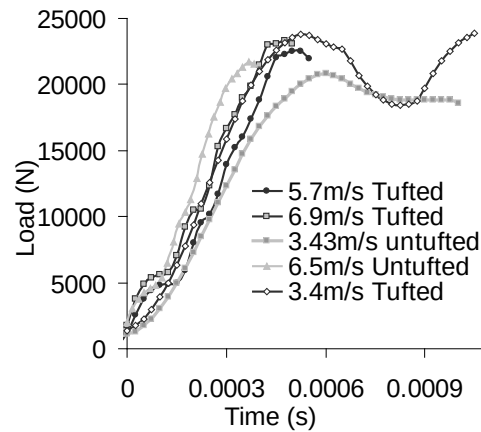


**Figure 96: Load traces bias direction in compression at intermediate strain rate**

In the  $[+/-45]$  case, failure occurred in a much shorter time at much lower load than the  $[0/90]$  layup. Furthermore, for 3 m/s impact speed, the impact load increased and peaked at around 22 KN before holding and reducing slightly from this value until failure. If the speed was doubled to 6 m/s, the load increased to a slightly higher peak value but the specimen did not hold the load any longer, unlike the little load plateau for 3m/s impact speed specimens. The difference between the tufted and the untufted specimens seems to be small in terms of loading and responses; the tufted specimen carrying a bit more load than the untufted specimen. Also, failure seemed to diminish with increasing strain rate for the untufted laminate. Sampling of load and strains for both composites is presented in Figure 97. Strong strain rate effects were observed so that the quasi-static and intermediate strain rate responses have little in common.

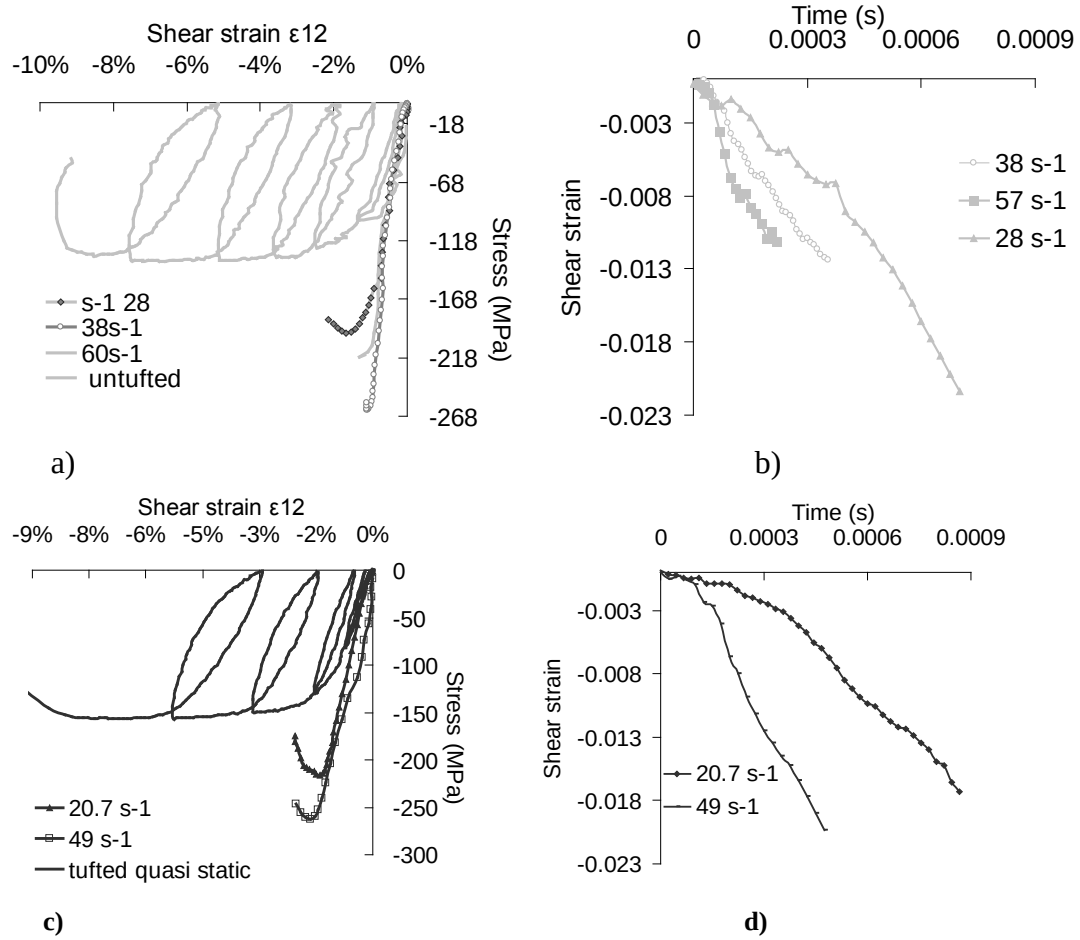


**Figure 97: Tufted (c.d) and untufted (a.b) composites response in the bias direction**

The material response evolved from a large non-linear deformation at high failure strain in quasi-static loading to one of a nearly-linear material response at intermediate strain rates. The maximum load was doubled while the failure strain was extremely reduced.

#### 4.2.3 Measurements at high rates of loading

High strain rates testing was achieved in tension and compression with two different SHPB set ups reviewed previously on 2 types of materials and with two layup configurations. In the literature, some researchers have shown that correction factors were often needed for the bar apparatus specimen strain measurements. This is understood to be due to the difference of density and stiffness between the bar and the specimen that affect the reflected wave characteristic used to compute the specimen

strain during impact. Strain gauging high strain rates specimens prove to be extremely technical, time consuming and difficult because of their reduced size. Therefore, the dynamic DIC method was of particular interest to monitor strains independently from the bar apparatus measurement. Unlike the specimen strain measurement, the failure stress was understood to be better-measured by the bar apparatus. This stress is directly related to the transmitted wave and so is directly linked to the strains in the bar behind the specimen; no integration through time is required. In general SHPB apparatus the strain in the sample is based on the integration of the reflected strain in the striker bar through time. A difference of stiffness, density and different grip design will affect the pulse reflection shape providing a constant error on the strain results. A correction factor from the DIC results can be applied for any specific setup and lay up configuration to obtain realistic strain values from the SHPB bar directly.

#### **4.2.3.1 Measurements at high strain rates in axial tension**

Figure 98 (a) illustrates the strains recording in the bars with Channel B directly linked to the load in the specimen. Figure 98 (b) shows the failure of the samples at high strain rates ( $\pm 300\text{s}^{-1}$ ) in tension. The [0/90] specimen had a slight dog bone shape to ensure failure of the composite rather than debonding from the grips.

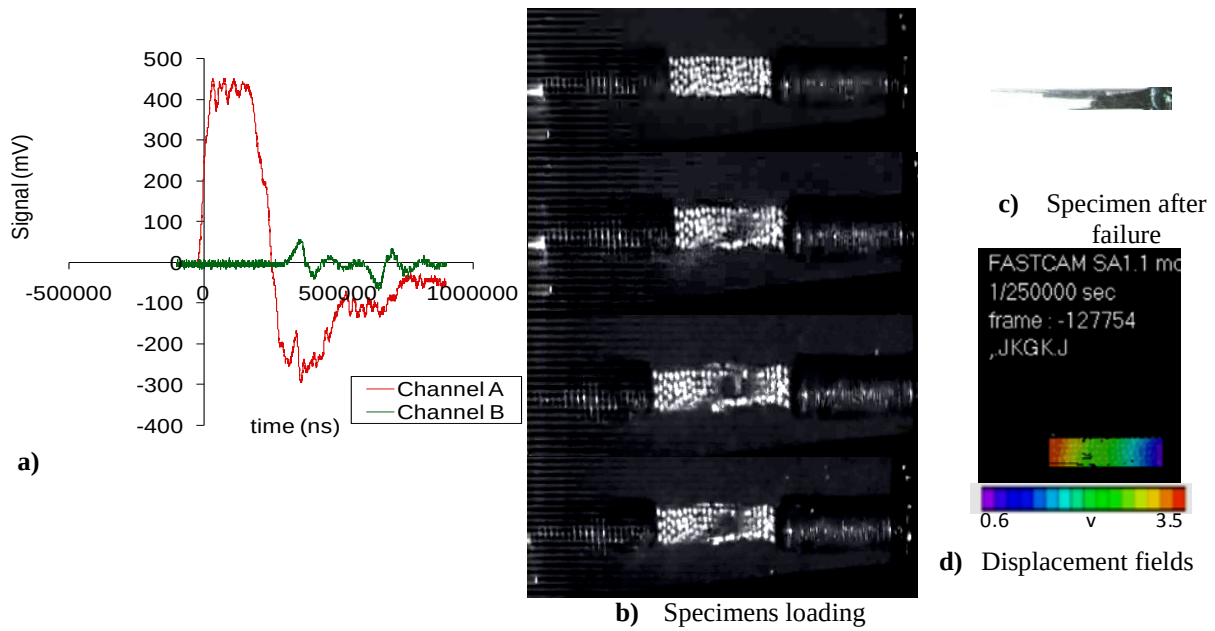


**Figure 98: High strain rates tensile [0/90] test: (a) strains recording in the bars for such lay-up, (b) specimen loading with SHPB apparatus, (c) failed specimen, (d) displacement field.**

The untufted and tufted composite response to such fast tensile load was illustrated in Figure 99 and 100 with the strain acquired optically.

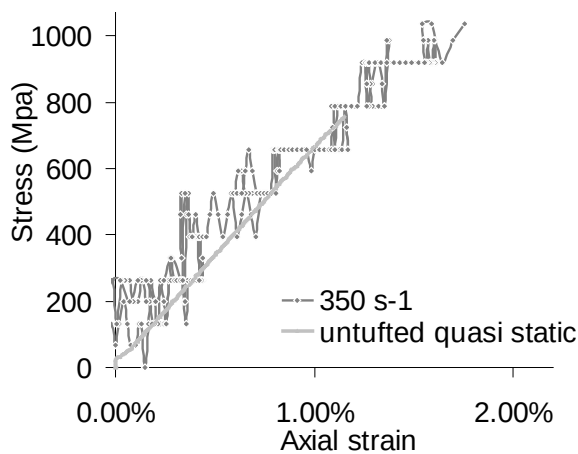


**Figure 99: Stress strain response at 350 s<sup>-1</sup> for the untufted specimen**

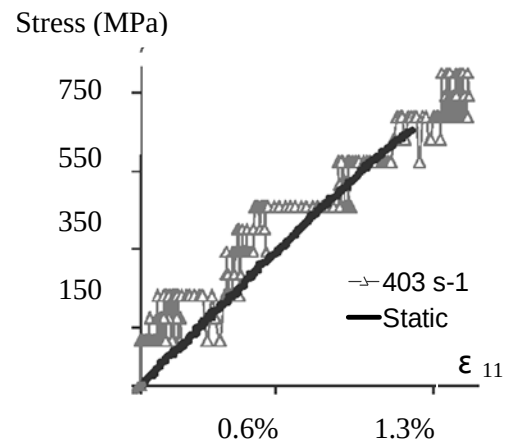


**Figure 100: Stress strain response at high strain rates for tufted composites**

It was observed that the stiffness was similar to the quasi static stiffness value but that the failure stress and strain had increased significantly for both the tufted and untufted specimens. The load trace was noisy due to the setting on the oscilloscope.

#### 4.2.3.2 Measurements at high strain rates in tensile bias

##### direction

Tensile failure of specimens (Figure 101) in the bias direction at this strain rate is illustrated in Figure 102 (459, 4512, 4511 4510 were the sample names). From the dynamic DIC, the strain through time was plotted for various specimens at strain rate in between 168 and 290s<sup>-1</sup>.

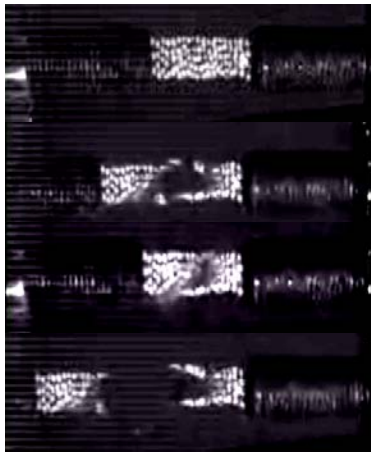


**Figure 101: [+45] specimens**

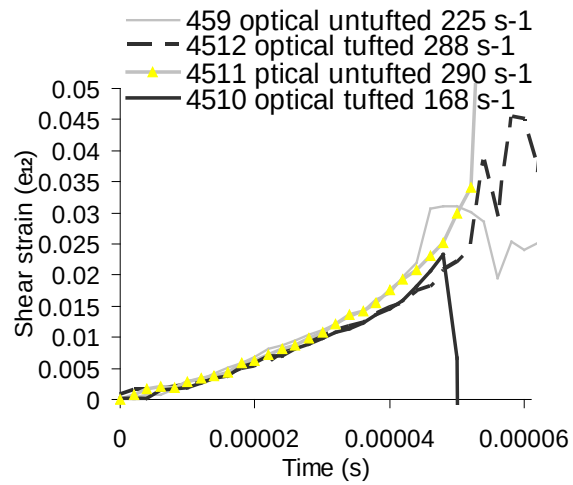


**Figure 102: Strain versus time at high strain rates**

The optical strain (Figure 102) was sampled with the stress from the SHPB (Figure 103.a Channel B) and stress strain curves were obtained at high strain rates. Channel A correspond to strain gauge reading on the pulling bar (which could also be related strain on the sample) as channel B correspond to strain gauge reading on the transmitted bar directly linked to the load in the specimen. The results are compared to quasi-static tensile behaviour in Figure 103.b.

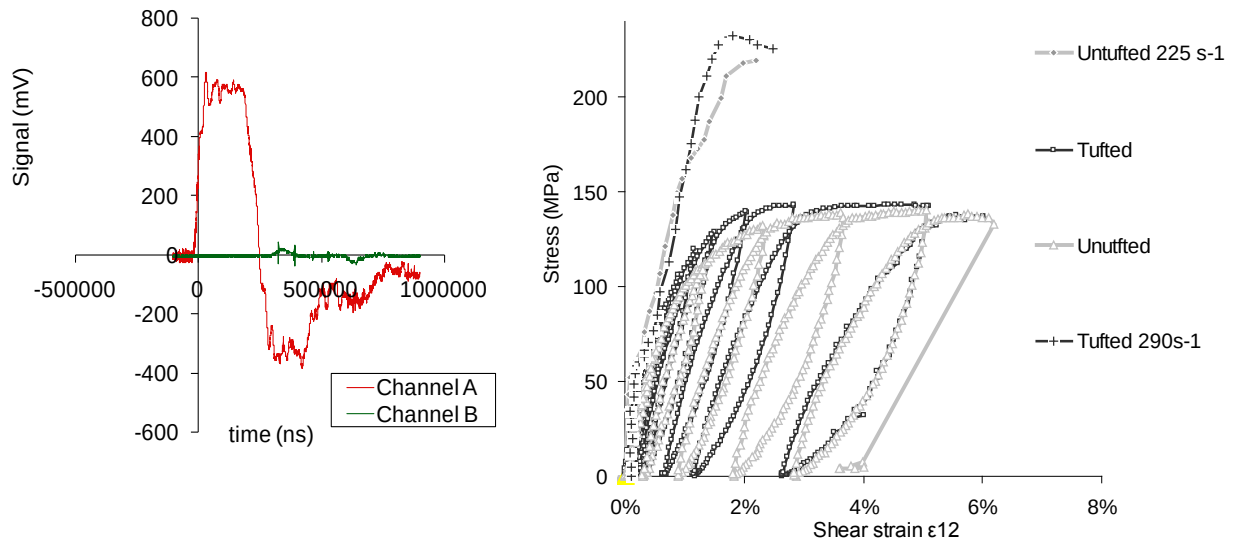


**Figure 103: (a) examples of strains and stresses responses acquired from SHPB for such layup, (b) high strain rates for the tufted and untufted composites in the bias direction**

As with previous results on such lay-ups while the strain rate was increased, the failure strain is reduced and the failure stress is increased. Such behaviour was also observed on high strain rates ( $\pm 300\text{s}^{-1}$ ) lay-ups for both the tufted and untufted composites. Untufted specimens exhibited slightly less failure stress than the tufted specimens as previously observed for quasi static rates.

#### **4.2.3.3 Measurements at high strain rates in axial compression**

High strain rates experiments were also carried out in compression using the SHPB apparatus but with a different set up. Tests were once again carried in the axial and bias direction. The strains were computed from the optical measurements and sampled with the stress acquired from the SHPB apparatus (Figure 104).

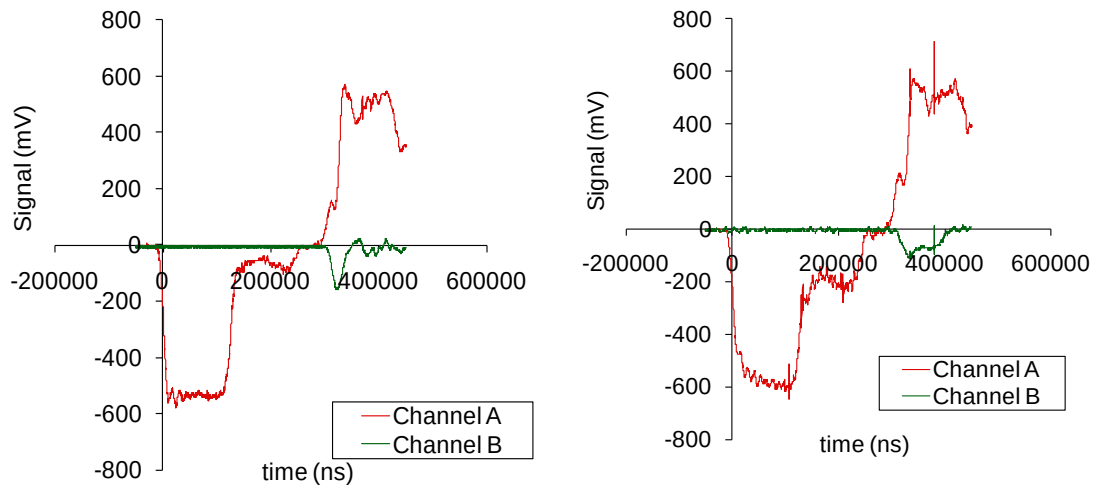


**Figure 104: Strain in the SHPB at high strain rates in compression: (a) axial direction, (b) bias direction**

Figure 105 (a) illustrates the specimens failure and a DICM dynamic displacement field image and images of specimens after failure. Figure 105 (b) illustrates the dynamic DIC field at  $250\,000\text{ s}^{-1}$ .

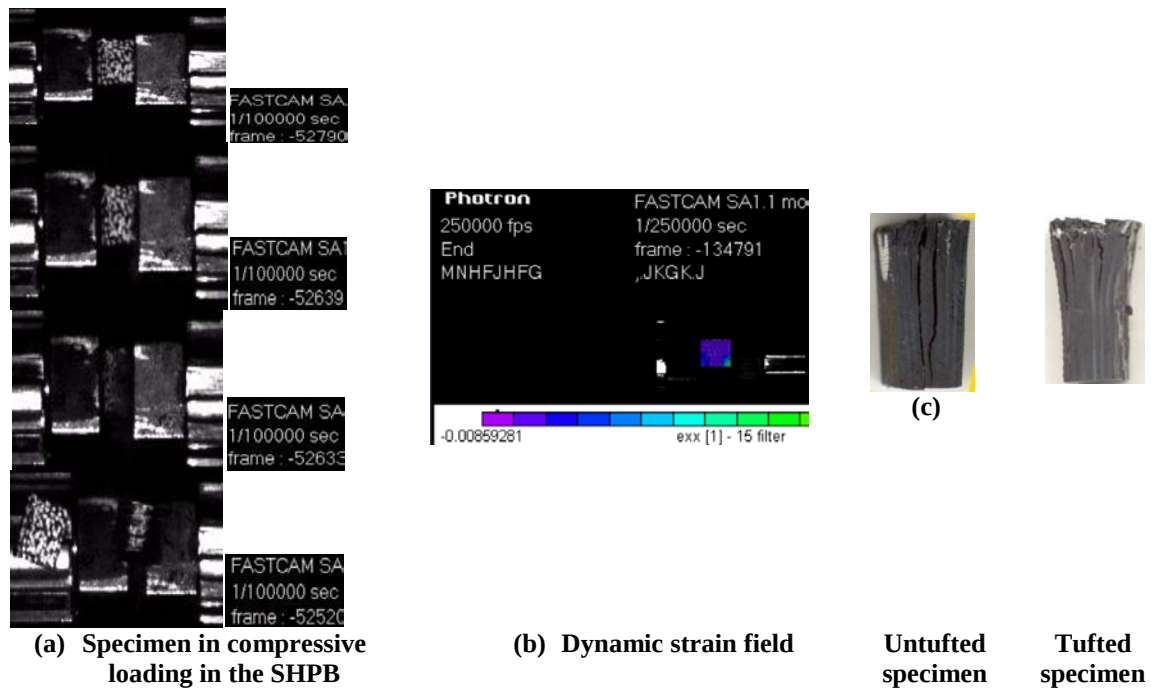


**Figure 105: SHPB strain capture in compression, (a) specimen failure, (b) dynamic strain field and (c) untufted and tufted specimen after failure**

The quasi-static and high strain rates response ( $\pm 300\text{ s}^{-1}$ ) is shown in Figure 106 for untufted composites (a) and tufted composites (b).

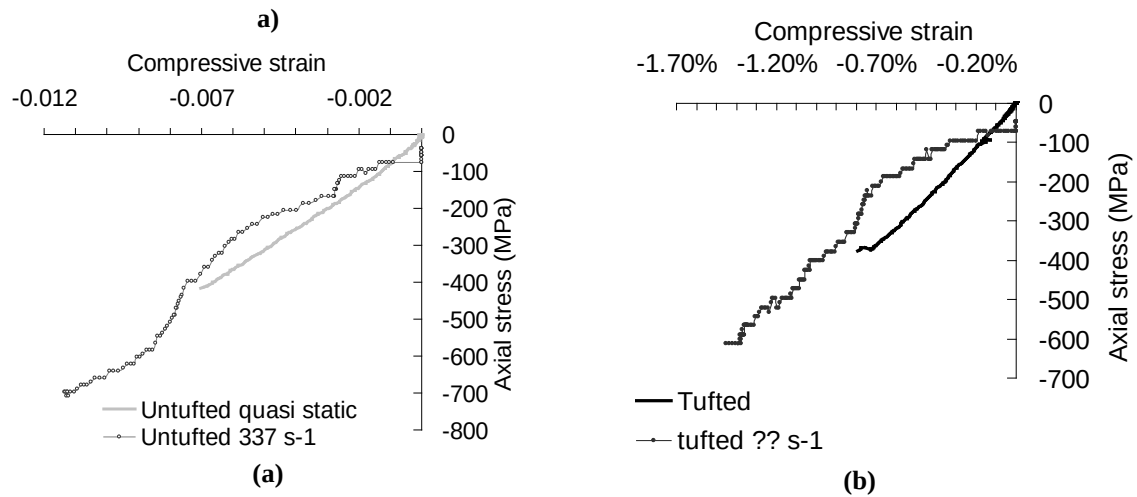


**Figure 106: High rate of loading in compression (a) untufted, (b) tufted response compared to quasi static response**

It is observed that the failure strain and stress increased was considerable (about doubled the static value) while strain rate increased from virtually zero to about  $300 \text{ s}^{-1}$ . Therefore, a positive strong rate effect was seen on such laminate layup at high strain rates. Such laminates can absorb considerable energy at high rates. In quasi-static conditions, consideration of the modulus is difficult to assess as it depends on the sampling of the stress and strain in time. Also, no significant Young's Modulus increase or decrease was observed with the current sampling method (beginning of sampling when time or strain rose, end of sampling when load and strain dropped).

#### 4.2.3.4 Measurements at high strain rates in bias direction

##### compression

As for other stress strain responses, reduced failure strain and increased failure stress was observed in the bias direction at high strain rates. In Figure 107, the high strain rates response is plotted with the intermediate rate response and quasi static response for tufted and untufted laminates.

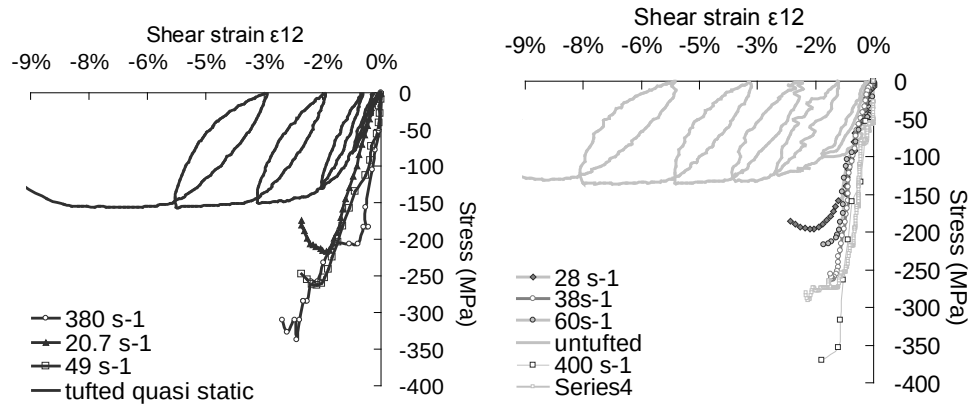


**Figure 107: Tufted (right) and untufted (left) bias direction laminate response at quasi static, intermediate and high strain rates.**

#### 4.2.4 Overall strain rate in-plane laminate sensitivity

The results in the axial direction in tension for various strain rates are observed in Figure 108 and 110 for the untufted and tufted laminate, correspondingly. It is observed that the strain rate effects occurred from a low strain rate threshold. Effectively, at  $0.29\text{s}^{-1}$ , a sharp increase in strength was observed for the axial and bias direction specimens characterizing an already significant positive strain rate effect. Overall in the axial direction, the strain rate effect was found to be slightly more important in compression than in tension. As observed from Figure 108 and 110, the modulus seems to be reasonably constant and no significant increase was observed. Some of the non-linearities were due to the sampling of loads and strains which, for some experimental set up, and load cases were difficult to synchronize. The strain was captured on the specimen itself as the load was captured from a distance.

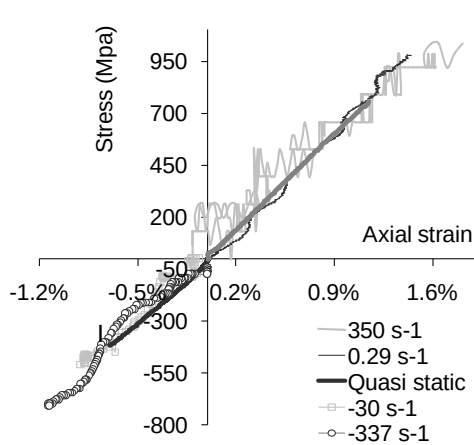


**Figure 108: Axial response of the untufted laminate**

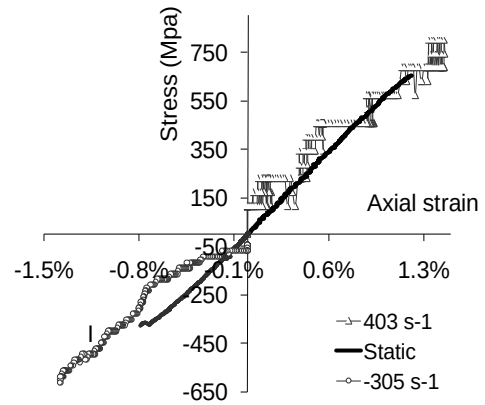


**Figure 109 : Axial response of the tufted laminate**

A similar strain rate range was used for the tufted and untufted materials in the axial direction (Figure 108 and 109). The tufts did not influence the strain rate effects. Also, the tufts seemed to be more beneficial in compression than in tension in term of material strength. Results of loading at various strain rate the untufted and tufted composites in tension are presented in Table 14 and Table 15.

| Test setup        | Name | Material | Lay up | max strain | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate s <sup>-1</sup> |
|-------------------|------|----------|--------|------------|------------------|-----------------------|-----------------------|-----------------------------|
| Quasi static      |      | untufted | [0/90] | 0.0115     | 755.8            | 65.4                  | 65721.74              | 8.30E-05                    |
| Low rate          | t3   | untufted | [0/90] | 0.01461    | 993              | 68.6                  | 67967.15              | 0.19                        |
| Low rate          | t1   | untufted | [0/90] | 0.013985   | 945              | 66.4                  | 67572.4               | 0.29                        |
| Intermediate rate | u2   | untufted | [0/90] | 0.01472    | 914              | 65.2                  | 62092.39              | 15.6                        |
| High rate         | u12  | untufted | [0/90] | 0.0176     | 1035             | 67                    | 58806.82              | 207                         |
| High rate         | u11  | untufted | [0/90] | 0.0164     | 986              | 62.9                  | 60121.95              | 305                         |
| High rate         | u11  | untufted | [0/90] | 0.0164     | 986              | 62.9                  | 60121.95              | 305                         |

**Table 14: [0/90] untufted composite response in axial tension at various strain rate**

Similar material responses were also observed for the tufted composites.

| Test setup        | Name | Material | Lay up | Max strain | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate s <sup>-1</sup> |
|-------------------|------|----------|--------|------------|------------------|-----------------------|-----------------------|-----------------------------|
| Quasi static      |      | tufted   | [0/90] | 0.012      | 653              | 56.18                 | 54416.6               | 8.3E-05                     |
| intermediate rate |      | tufted   | [0/90] | 0.0123     | 701              | 63.2                  | 57024.3               | 9                           |
| high rate         | t902 | tufted   | [0/90] | 0.0142     | 844              | 67                    | 59436.6               | 354                         |
| high rate         | t901 | tufted   | [0/90] | 0.0174     | 1023             | 56                    | 58793.1               | 402                         |

**Table 15: [0/90] tufted composite response in axial tension at various strain rate**

Experiments in axial compression were carried out and some results at various strain rates are presented in Table 16 and 17 for the untufted and tufted materials.

| Test set up                          | Name | Material | Lay up | Max strain | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate $s^{-1}$ |
|--------------------------------------|------|----------|--------|------------|------------------|-----------------------|-----------------------|----------------------|
| quasi static<br>intermediate<br>rate | o10  | untufted | [0/90] | -0.00709   | -411             | 60.4                  | 57.9                  | -8.3E-05             |
|                                      |      | untufted | [0/90] | -0.00872   | -503             | 60.945                | 57.683                | -30.069              |
| high rate                            | 9011 | untufted | [0/90] | -0.01133   | -698             | 60.928                | 61.606                | -298.16              |

**Table 16: [0/90] untufted composite response in axial compression at various strain rates**

The responses were also investigated on tufted composite materials.

| Test set up       | Name  | Material | Lay up | Max strain | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate $s^{-1}$ |
|-------------------|-------|----------|--------|------------|------------------|-----------------------|-----------------------|----------------------|
| Quasi static      | 92    | tufted   | [0/90] | -0.00728   | -374             | 51.5                  | 51.3                  | 8.30E-05             |
| Intermediate rate |       | tufted   | [0/90] | -0.0087    | -590             | 60.4                  | 67.1                  | -12.0666             |
| High rate         | tc904 | tufted   | [0/90] | -0.01386   | -612             | 41                    | 44.1                  | -400                 |

**Table 17: [0/90] tufted composite response in axial compression at various strain rates**

These results permits to plot Figure 110 and 111 which plot failure strain and strength versus strain rate respectively.

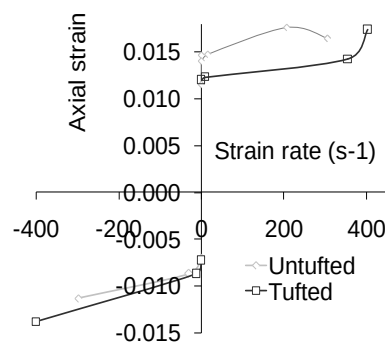
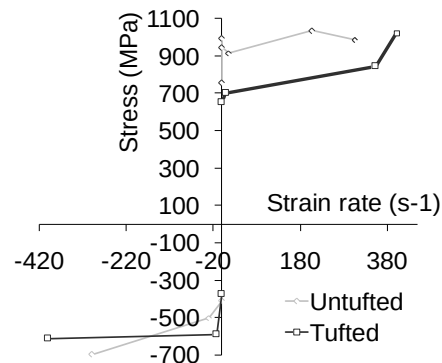


**Figure 110: Axial strain versus strain rate (s-1)      Figure 111: Axial stress versus strain rate (s-1)**

Axial strain and axial stress evolution was show to be non linear with strain rate increase. Slightly different behaviours were observed in tension and compression. Tufting had less effect in compression than in tension. Strain rate effects were monitored from a low strain rate increase.

In the bias direction, strain rate effects were more pronounced than in the axial direction; however, the responses of the tufted and untufted materials were alike

(nearly the same). Figure 112 and 113 plot the stress versus strain for the untufted and tufted materials at different strain rates. It is observed that the increase in compressive failure strain over tensile failure strain which occurred at quasi-static loading rate, seemed to disappear rapidly when the loading speed was increased. Furthermore, a slight increase in strain rate produced a significant increase in the strength of the material (20 %). At high strain rates, the strength of the material increased further but the failure strain was reduced considerably, providing a nearly linear response. This effect is particularly well observed in Figure 112 and 113 that plot strains versus strain rate. For this layup sequence, the failure strain dropped from approximately  $\pm 6.5\%$  in tension and  $\pm 9\%$  in compression in static conditions to  $\pm 2\%$  at intermediate loading rate for both load cases and nearly stabilizes around this value even with an increasing loading rate.

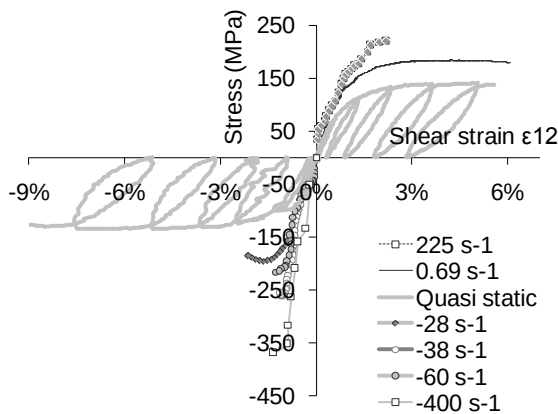


**Figure 112: Stress versus strain in the bias direction for the untufted material.**

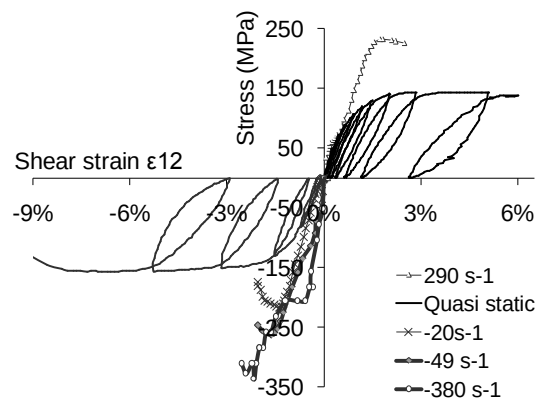


**Figure 113: Stress versus strain in the bias direction for the tufted material.**

The data in Figure 112 and 113 can be post processed in term of failure strain and failure strength versus strain rate and was recorded into Table 18 to 22 for model calibration purpose (Chapter 5).

From the composite materials experimental responses observed at different speed (Figure 112 and 113) some basic information were retrieve for different layup and load cases that provided indication of the stiffness, strength and plasticity versus

strain rate. These data were key elements to the estimation of dynamic parameters to simulate strain rate effects. The first sets of results are presented in Table 18 which was the [+45] response in tension for untufted and tufted NCF composites.

| Test setup           | Name    | Material | Lay up | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate s <sup>-1</sup> | Ro    |
|----------------------|---------|----------|--------|------------------|-----------------------|-----------------------|-----------------------------|-------|
| Quasi static Tension | missing | untufted | [±45]  | 0.061            | 136                   | 6.6                   | 0.000083                    | 0.02  |
| Low rate             | t6      | untufted | [±45]  | 0.054            | 165                   | 9.5                   | 0.36                        |       |
| Low rate             | t2      | untufted | [±45]  | 0.061            | 179                   | 7.9                   | 0.69                        | 0.12  |
| Low rate             | t4      | untufted | [±45]  | 0.064            | 175                   | 9.7                   | 0.54                        |       |
| Intermediate rate    | 3m/s    | untufted | [±45]  | 0.021            | 159                   | 11.2                  | 12.7                        |       |
| Intermediate rate    | 1.5m/s  | untufted | [±45]  | 0.018            | 138                   | 9.9                   | 10.5                        |       |
| High rate            | 459     | untufted | [±45]  | 0.022            | 219                   | 11.6                  | 225                         | 0.149 |

**Table 18: [+45] untufted composites response in bias direction tension at various strain rate; units (GPa) for stresses and modulus.**

From Table 18 results it was observed that the yield stress parameter increased with strain rate. Also shear modulus increased and failure strain decreased with strain rate.

Similar trends were observed for the tufted material in Table 19.

| Test setup        | Name    | Material | Lay up | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate s <sup>-1</sup> | Ro     |
|-------------------|---------|----------|--------|------------------|-----------------------|-----------------------|-----------------------------|--------|
| Quasi static      | missing | tufted   | [±45]  | 0.061            | 136                   | 7.4                   | 8.30E-05                    | 0.02   |
| Intermediate rate | 2.4 m/s | tufted   | [±45]  | 0.020            | 194                   | 9.92                  | 10.5                        | rising |
| High rate         | 4512    | tufted   | [±45]  | 0.024            | 225                   | 14.47                 | 290                         | rising |

**Table 19: [+45] tufted composites response in bias direction tension at various strain rate; units (GPa) for stresses and modulus.**

In the same way results were gathered in bias direction compression and are presented in Table 20 and 21 for the untufted and tufted material respectively.

| Test setup        | Material | Lay up | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate s <sup>-1</sup> | Ro       |
|-------------------|----------|--------|------------------|-----------------------|-----------------------|-----------------------------|----------|
| Quasi static      | untufted | [±45]  | -0.0927          | -124                  | 8                     | -8.30E-05                   | -0.02    |
| Intermediate rate | untufted | [±45]  | -0.0214          | -185                  | 9.03                  | -28                         | Dropping |
| Intermediate rate | untufted | [±45]  | -0.011           | -256                  | 10.6                  | -38                         | Dropping |
| Intermediate rate | untufted | [±45]  | -0.0128          | -217                  | 11.02                 | -60                         | Dropping |
| High rate         | untufted | [±45]  | -0.013           | -370                  | 15.6                  | -400                        | Dropping |

**Table 20: [+45] untufted composites response in bias direction compression at various strain rate; units (GPa) for stresses and modulus.**

| Test setup               | Material | Lay up       | Max stress (MPa) | Young's Modulus (Gpa) | Young's Modulus (Mpa) | Strain rate $s^{-1}$ | Ro       |
|--------------------------|----------|--------------|------------------|-----------------------|-----------------------|----------------------|----------|
| quasi static compression | tufted   | [ $\pm 45$ ] | -0.0858          | -152                  | 7.6                   | -8.30E-05            | -0.02    |
| compression drop         | tufted   | [ $\pm 45$ ] | -0.02            | -174                  | 7.6                   | -20                  | Dropping |
| compression drop         | tufted   | [ $\pm 45$ ] | -0.02            | -246.9                | 9.8                   | -49                  | Dropping |

**Table 21: [ $\pm 45$ ] tufted composites response in bias direction compression at various strain rate; units (GPa) for stresses and modulus.**

Using data from Table (18-21), Figure 114 plots strain rate versus shear strain for various bias direction specimen sizes loaded at various speed. Figure 115 plots strain rate versus shear strength for the same specimen and loading speed. The response of the failure shear strain to strain rate was strongly nonlinear with a sharp shear strain reduction at low strain rate (Figure 114). However from intermediate to high strain rates loading no significant change of the failure strain was observed. As a significant increase in strength was observed (Figure 115) from low strain rate loading ( $0.69s^{-1}$ ) which persisted but more softly as the strain rate was increased further. This outcome is also witnessed by the tufted composite.

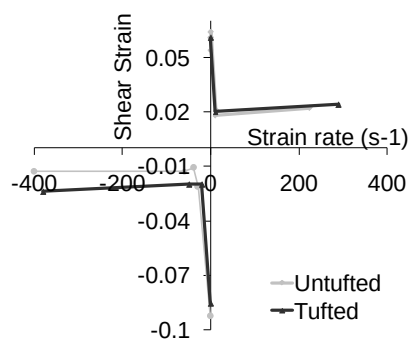


**Figure 114: Shear strain versus strain rate (s-1)**

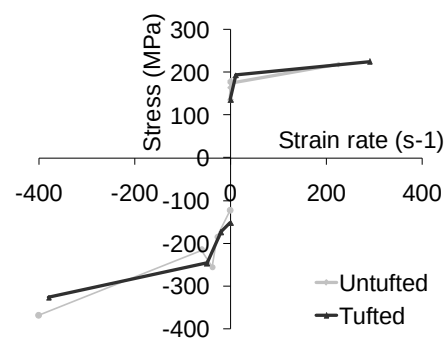


**Figure 115: Shear stress versus strain rate (s-1)**

Both the strain and strength increased in a non-linear manner with the higher strain rate (Figure 114 and 115). As with the quasi-static response, the compressive strength at high speed was slightly superior to the tensile strength at high speed for the bias direction layup.

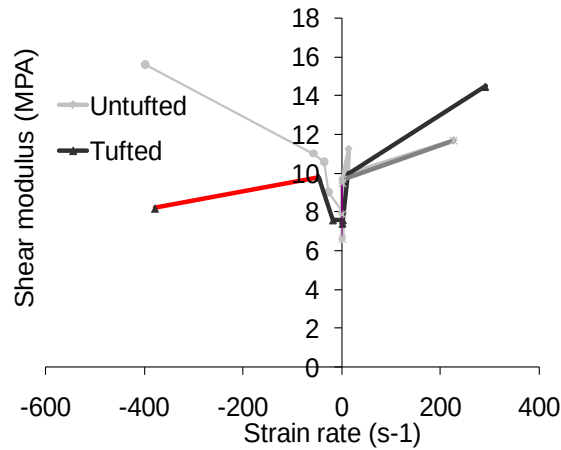


**Figure 116: Shear modulus in the bias direction with strain rate**

Figure 116 illustrates the evolution of shear modulus with strain rate. Globally the shear modulus evolved with strain rate positively and also non-linearly. One measurement in high speed compression was not fitting the trends and must be taken with care (red).

The material would now be characterised in high speed delamination.

#### **4.2.5 Measurements of dynamic delamination in Mode I**

After measuring strain rate effect in the plane, delamination was considered at intermediate speed to foresee if any loading rate effect and crack speed would affect  $G_{IC}$  and  $G_{IIC}$  values. Such high speed loading of the crack was achieved with a drop tower and the specialized delamination test apparatus (Figure: 47, 48).

##### **4.2.5.1 Simple image analyses**

Figures 117 and 118 illustrate the response of the DCB specimen under various dynamic loading cases for the standard and tufted NCF, in the set up described in Figure 47 and 48. Image analyses of the DCB arms bending during loading showed appropriate bending and crack loading in pure Mode I (Figure 117 (a, b, d)). But asymmetric DCB arm bending was observed above 4m/s. This

phenomenon was more pronounced with increasing loading rate (Figure 117 (f, h, I, k, l)) and meant that the crack would not be loaded in pure Mode I but in a combination of Mode I and II.

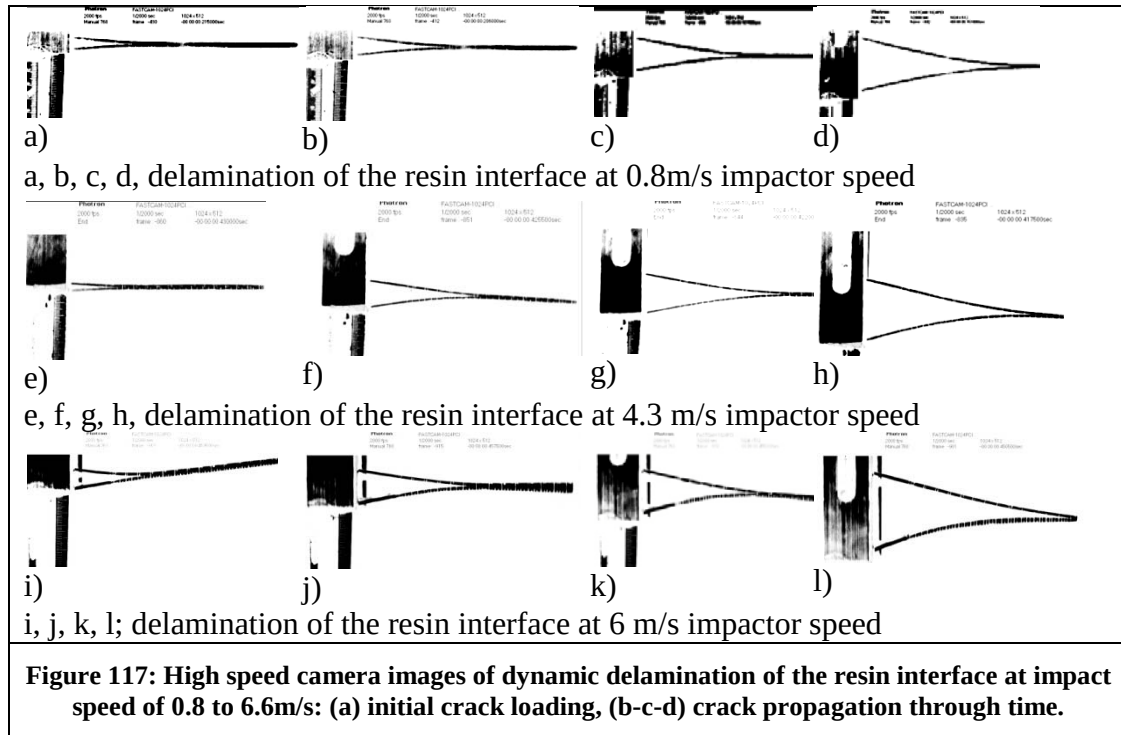
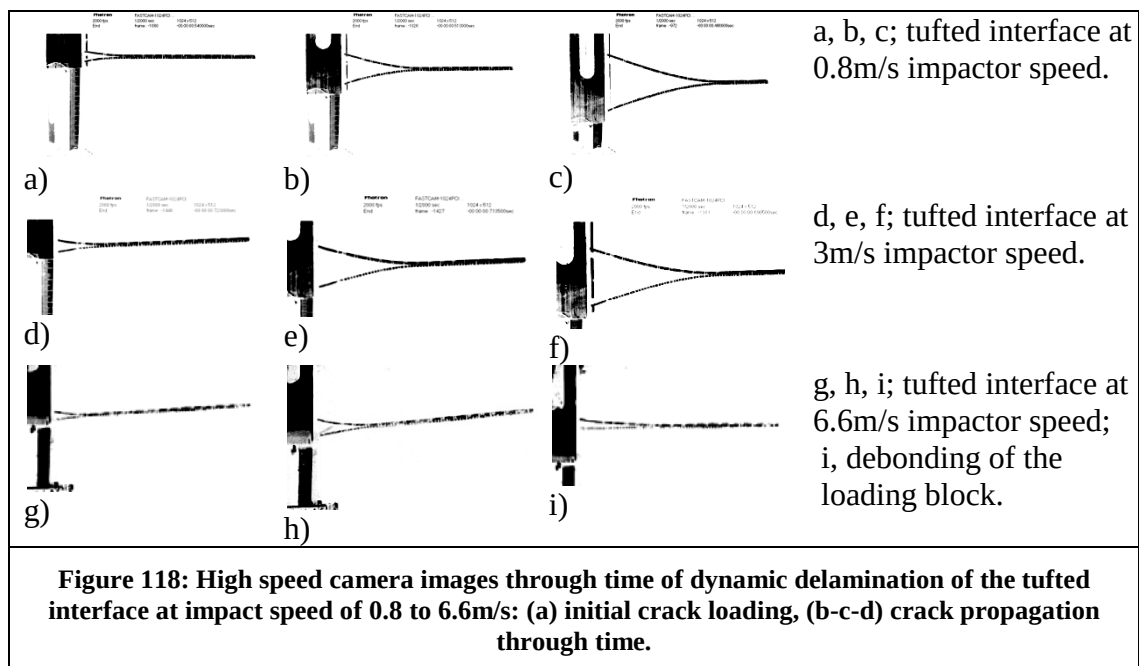


Figure 118 illustrates the delamination under different rate of loading for a resin interface reinforced with tufts.



For the tufted specimens, less asymmetry of the two DCB arm bending was observed (Figure 118 (d, e, f)) than for the plain NCF specimens. The likely reason is that the tufts reduced the crack speed and required a higher force to fail than the resin, allowing slightly more time for the resin and tuft interface to load both DCB arms symmetrically. Tab debonding for the tufted composites above 3 m/s loading speed (Figure 118 g, h, i) made further investigation difficult at higher velocities.

Figure 119 illustrates the differences between the tufted and untufted crack propagations. The untufted interface revealed no bridging but light reflection disparity (in lines patterns (Figure 119 a)) probably due to interface roughness differences being caused by crack speed variation (or more precisely a stick slip response). The tufted interface show strong bridging effect and tuft failure (Figure 119, d, e, f).

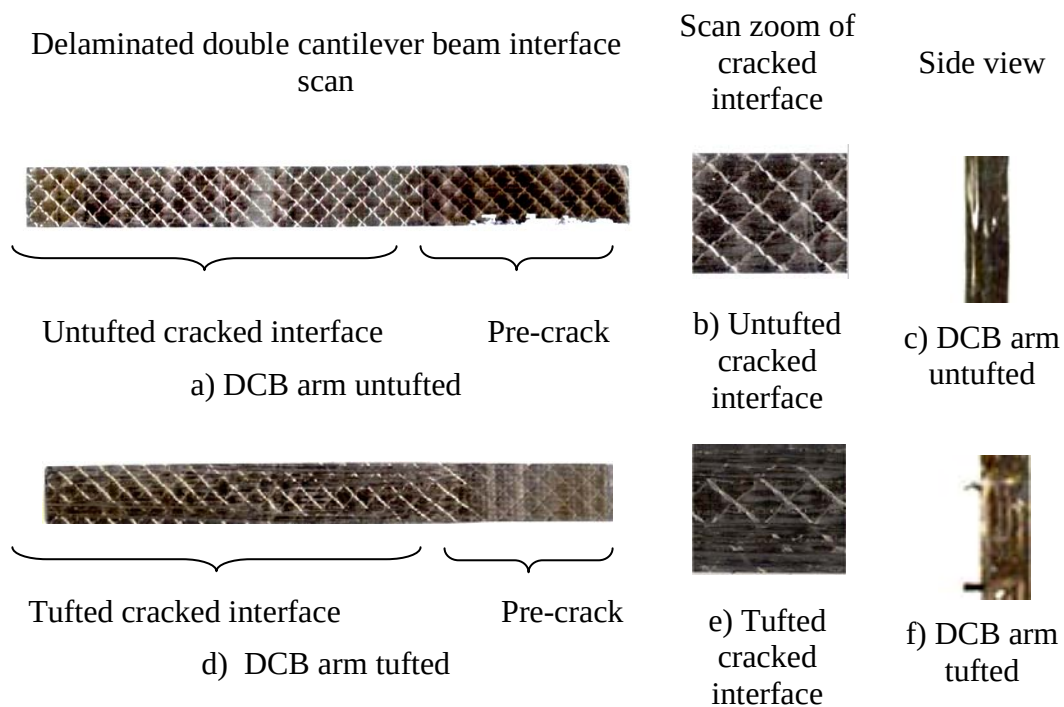


**Figure 119: Crack interfaces differences between tufted and untufted NCF after dynamic mode I loading**

#### **4.2.5.2 Dynamic analyses using a static load cell set up**

The conventional setup in the drop tower apparatus used forces acquired by a load cell mounted above a moving impactor. The new set up (Figure 47 and 48) used a static load cell to reduce noises and inertia effects during delamination that would occur with the standard load acquisition (Silberman<sup>148</sup>). The results for both set ups are presented in Figure 120. The static load cell setup (Figure 120(h)) provided, improved results as the standard load cell mounted above the impactor Figure 120 (g)) recorded additional forces due to friction between the lower loading pin and its guiding rail. The force signal was critical to the investigation of rate effects, in term of its reproducibility and accuracy. The dynamic delamination of the untufted material Figure 120 (a, e, f) illustrated that the noise in the force signal increased with loading speed. These load signals correspond to the dynamic delamination response of DCB specimens as shown in Figure 117 for various loading speed of the DCB lower arm and so for various DCB crack speed response.

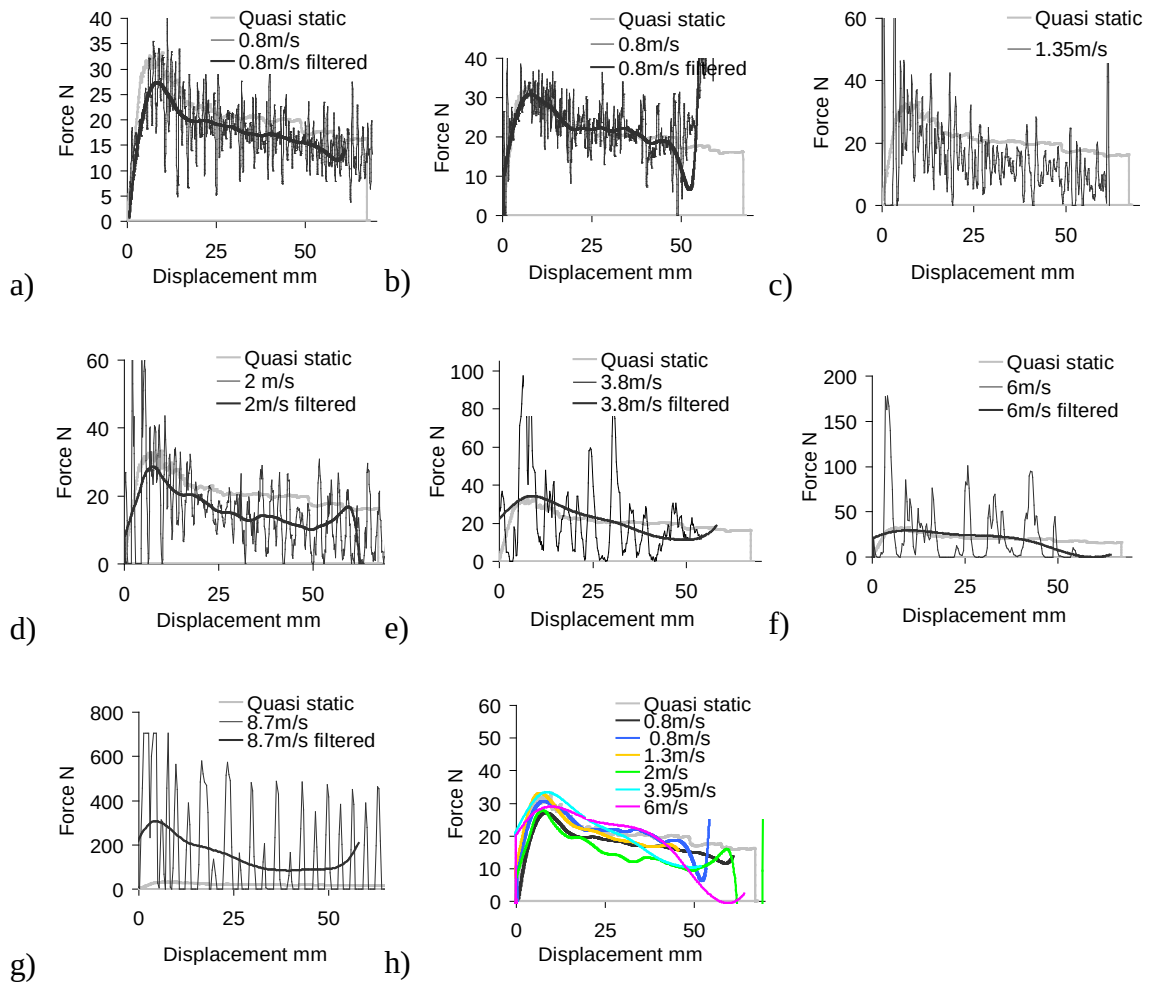


**Figure 120: Load response versus displacement at various delamination speeds for the tufted NCF; (a-b) 0.8m/s, (c) 1.35m/s, (d) 2m/s, (e) 3.8m/s, (f) 6m/s, (g) 8.7m/s with load recording standard load cell set up, (h) all speed with force reading filtered.**

From Figure 120 (a, b and h), it was observed that the reproducibility of the force recording was not sufficient to provide information about rate effects for that material. Effectively, in Figure 120 (h) which correspond to filtered load traces for various loading speed it was observed that no trend was observed with up to 25 % crack load initiation variation unrelated to loading speed. Such a high number do not permit any analyses to be undertaken. Nevertheless, the force seen by the upper pin was comparable within certain limits for all loadings and provided results comparable to the quasi-static test results (Figure 120 (h)). The poor reproducibility was understood to be linked to pre-crack minute differences between specimens, rather than to the experimental set-up. This variation in load was not observed for quasi-

static loading with specimen from the same plate, implying it could be a dynamic effect.

Tufted DCB were delaminated successfully up to 3 m/s. Above this speed, the force seen by the lower block increased dramatically and ultimately caused the debonding of the loading block from the DCB arm. Figure 121 illustrates the load measurement during delamination of tufted specimens for various delamination speeds. Similar to the untufted specimen, the noise in the force signal increased until filtering became necessary.

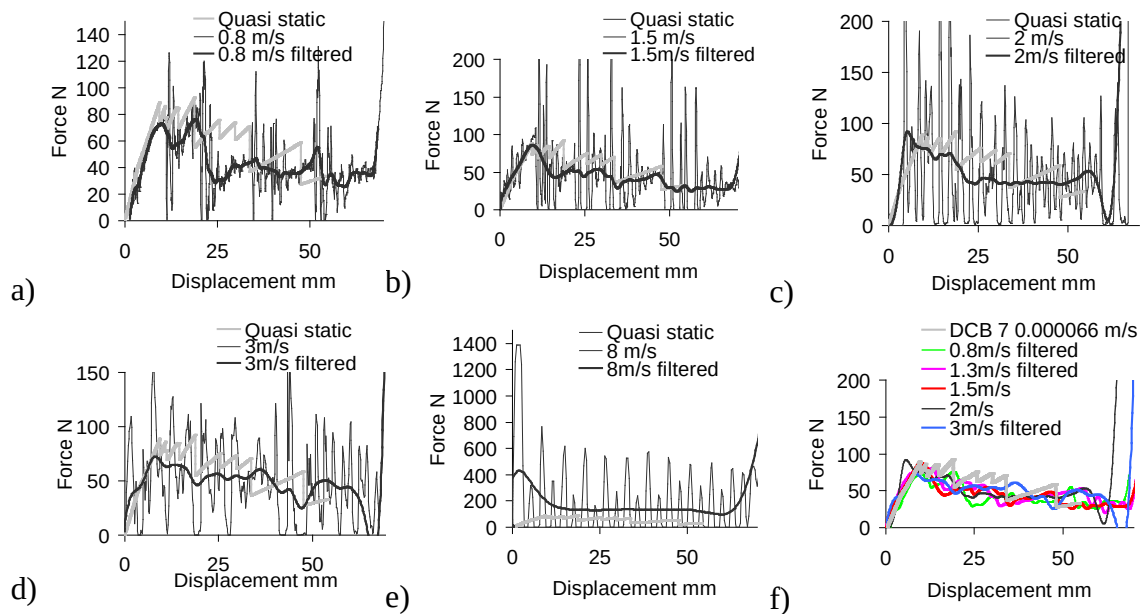


**Figure 121: Load response versus displacement at various delamination speeds for the tufted NCF; (a) 0.8m/s, (b)1.5m/s, (c) 2m/s, (d) 3m/s, (e) 8m/s, (f) all speed filtered.**

Even if the signal were noisier than for the untufted one, the accuracy and consistency of the results had considerably improved. In that case, the crack speed was lower and the force threshold was higher. The tufts enhanced the load and energy transfer to the upper DCB arm and therefore to the load cell. Consequently, the strong and regular nature of the tufts provides a more reproducible outcome at diverse delamination speed.

#### 4.2.5.3 Optical analyses of crack and displacement

Signals from the load cell were difficult to analyse to investigate rate effects as they were neither that repetitive nor accurate but readings from the high-speed images were accurate (Figure 122), due to the fact that acquisition at 1000 or 2000 images per second were sufficient to monitor crack propagation and DCB arm displacement. Effectively at such image frame rate the picture retains reasonably high resolutions which meant that the crack propagation and arm displacements could be monitored by the in house software. This meant that the crack opening of the DCB was much more consistent and easy to measure than the dynamic loading of the DCB arms.

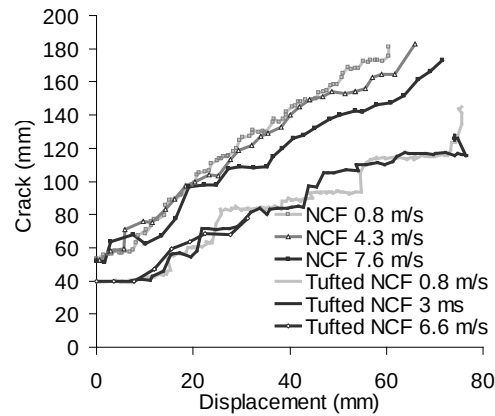


**Figure 122: Crack versus displacement at various speed for the standard and tufted NCF**

Steps in the crack versus displacement response for the tufted NCF characterised the strong stick-slip response of the sample. The steps were due to the crack speed reaching a value of zero while the tufts held the load. Subsequently, after a row of tufts failed, the crack propagated at high speed until the load decreased enough so that tufts held the load and the crack stopped again. This behaviour was not seen in standard NCF at low loading speeds but occurred at high speed (Figure 122). For this material, the crack appeared to propagate further for a reduced displacement while the speed increased as observed in Figure 122. This type of behaviour is indicative of rate effects. To quantify or detect rate effects the strain energy release

rate ( $G_{IC}$ ) during delamination was used. This took into account the initial crack length as well as the specimen width and thickness that influenced the response to delamination. Therefore, variation of  $G_{IC}$  with loading speed was the most accurate approach to assess possible rate effects.

#### 4.2.5.4 Optical investigation of rate effect through $G_{IC}$ calculations

The basic  $G_{IC}$  expression is shown in Equation 54 (also 15) and relies on accurate reading of load  $P$ . In the case of the dynamic delamination, the load readings to delaminate the resin interface were difficult to use because of their reduced accuracy and consistency.

Here,  $a$  is the crack length,  $b$  the width of the sample and

$$G_{IC} = \frac{3Pd}{2ba} \quad \text{Equation 54} \quad d \text{ the arm displacement.}$$

An alternative method to Equation 54 consisted of investigating rate effects using optical readings of the crack displacement through delamination, without load recordings but with specimen geometry and flexural modulus characteristics. The compliance  $C$  of the beam could then be defined by the displacement of the arm and the flexural modulus of the arm (equation 55). The load  $P$  (Equation 56) could then be calculated from the compliance (Equation 54 and 55).

$$C = \frac{d}{P} = \frac{8a^3}{E_f h^3 b} \quad \text{Equation 55} \quad \text{or} \quad P = \frac{d * E_f * h^3 * b}{8a^3} \quad \text{Equation 56}$$

Here  $E_f$  is the flexural modulus and  $h$  is the thickness of the specimen.

Combining Equation 56 with Equation 58 yields a new expression of  $G_{IC}$  without load requirement:

$$G_{IC} = \frac{3}{16} \left( \frac{d^2 h^3 E_f}{a^4} \right) \quad \text{Equation 57}$$

The flexural modulus was measured after delamination by a 3 point bending test on the delaminated DCB arm in the same bending conditions as in Mode I. The results of Equation 59 were compared to the experimental static signal (Figure 123) and showed good agreement.

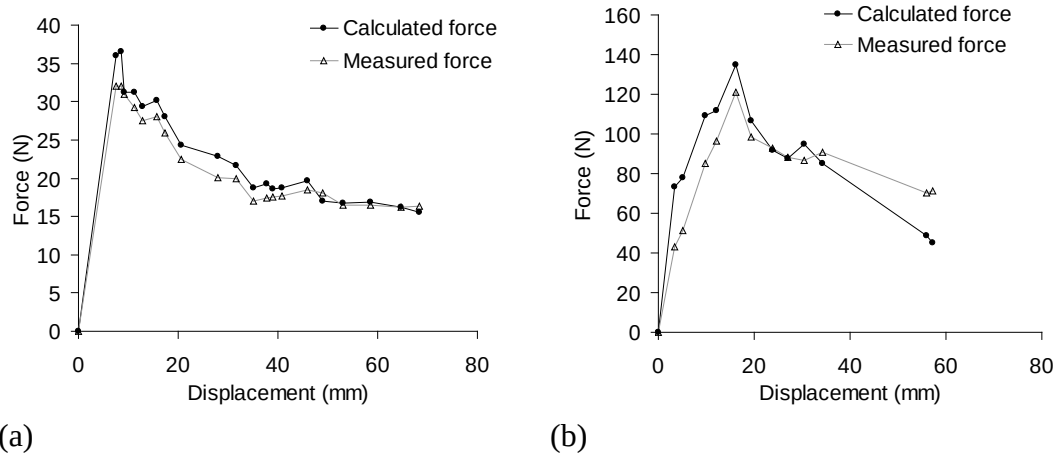


**Figure 123: Calculated force and measured force in mode I; (a) NCF, (b) Tufted NCF**

Figure 123 (a and b) illustrates the dynamic response of the NCF and tufted NCF DCB's respectively at various loading speeds using the calculated force from Equations 56. The dynamic calculated force results for both materials proved to be relatively noisy. A slight force increase during the crack initiation time for the tufted interface (Figure 124 (b)) was noticed.

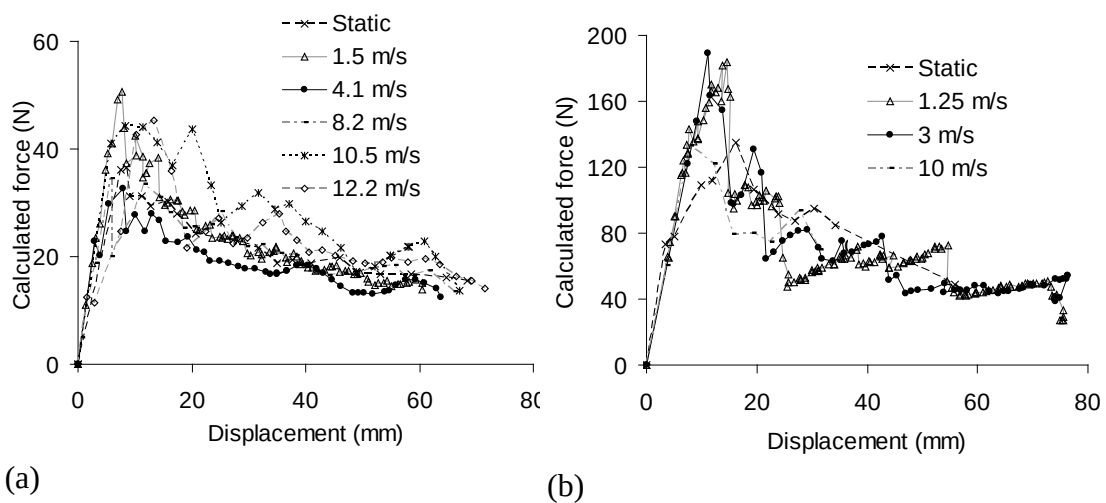


**Figure 124: Calculated force versus displacement at different rates; (a) NCF, (b) Tufted NCF**

The load signal for the standard interface slightly increased during crack propagation (Figure (125 a)) at higher loading speed.

Similarly, to assess the validity of Equation 57, the results of Equations 54 and 57 were compared in static conditions for which all test characteristics were available. As for the load calculation, the good agreement allowed the use of Equation 57 to compute  $G_{IC}$  dynamic for which results are presented in Figure 125.b.

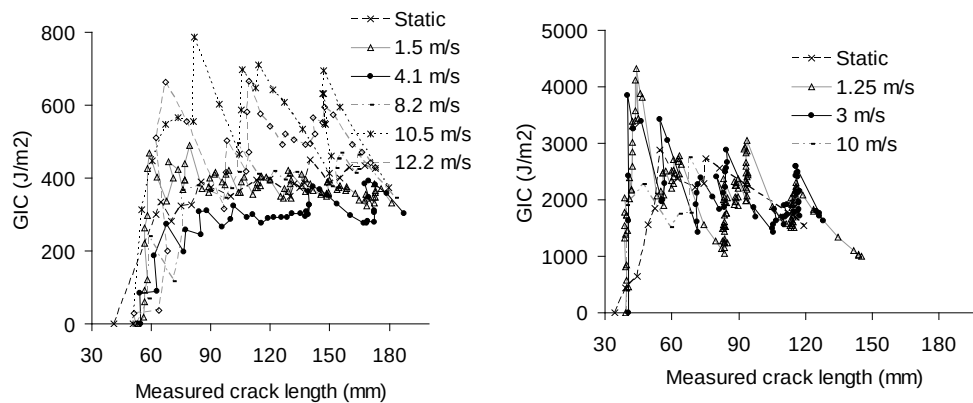


**Figure 125: Strain energy release rate versus crack length for the NCF at different rates; (a) NCF, (b) Tufted NCF**

Figures 125 (a) shows that the strain release energy rate was more unsteady while crack speed increased for the standard interface than for the tufted interface. As the crack speed increased significantly above a threshold of 6 m/s an increase in  $G_{IC}$  was observed (Figure 125 a and b). During dynamic loading the tufted material absorbed considerably larger energy during the crack initiation part before rapid reduction to quasi-static  $G_{IC}$  levels (Figure 125 b). The signal was unstable from low to high speed because of the tuft presence.

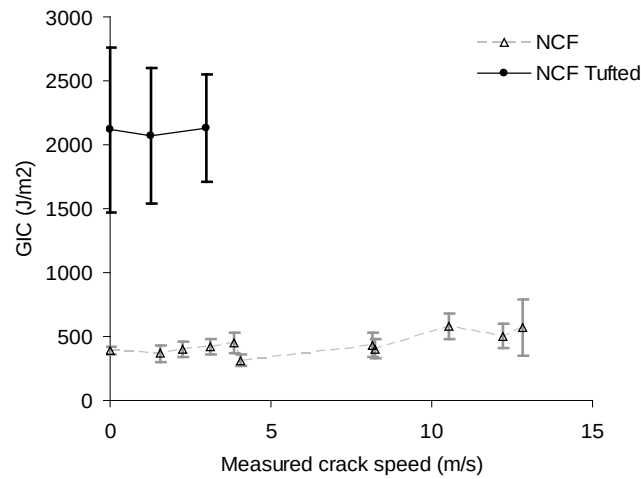


**Figure 126:  $G_{IC}$  versus crack speed for the NCF and tufted material**

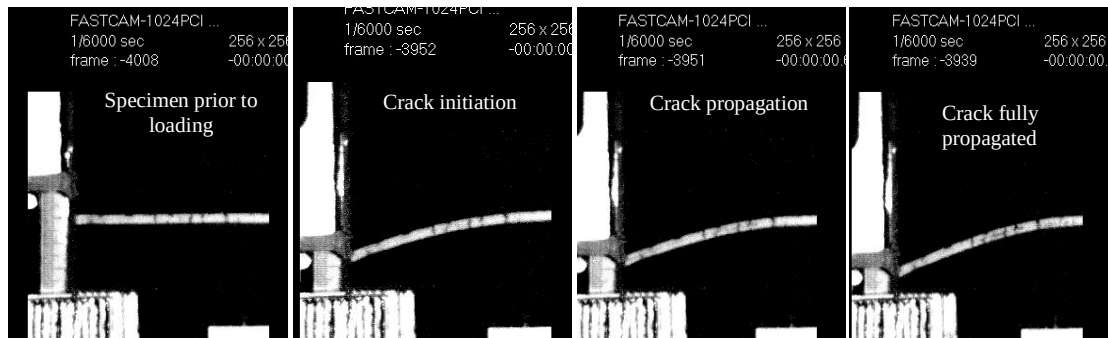
The average of  $G_{IC}$  throughout delamination is plotted against crack speed in Figure 126 with a standard variation of 66%. Figure 126 illustrates the increase in  $G_{IC}$  for the standard NCF from a 6m/s crack speed onwards and no significant changes in the tufted interface response were seen despite a noisy signal. The error bar was linked to the importance of the oscillations in the signal (Figure 126). The optical analyses therefore identified no rate effect for both materials at low speed but, above 6m/s crack propagation; a significant rate effect was spotted for the standard NCF. Questions arose on this increase in  $G_{IC}$  detected (Figure 126). It could be a default in the test setup as the simple image analyses could suggest (Figure 117 (asymmetric arm loading)) rather than a true rate effect of the material. This possibility was investigated through dynamic models using parameters extracted from static tests that would investigate the specimen arms response through the dynamic loading with the Finite Element code PAM-CRASH<sup>TM 8</sup>.

#### 4.2.6 Measurements of dynamic delamination in mode II

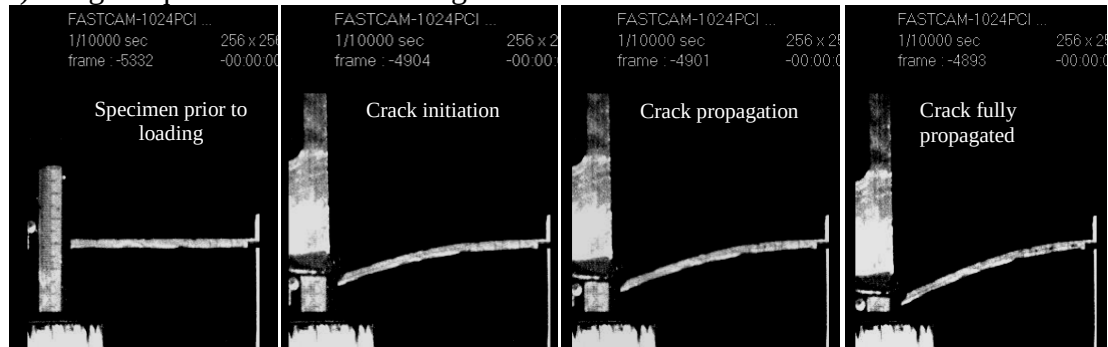
This research on dynamic Mode II was inspired from the quasi static mode II measurement (Chapter 4.1.6) and the dynamic mode I measurements (Chapter 4.2.5).

#### **4.2.6.1 Image analysis**

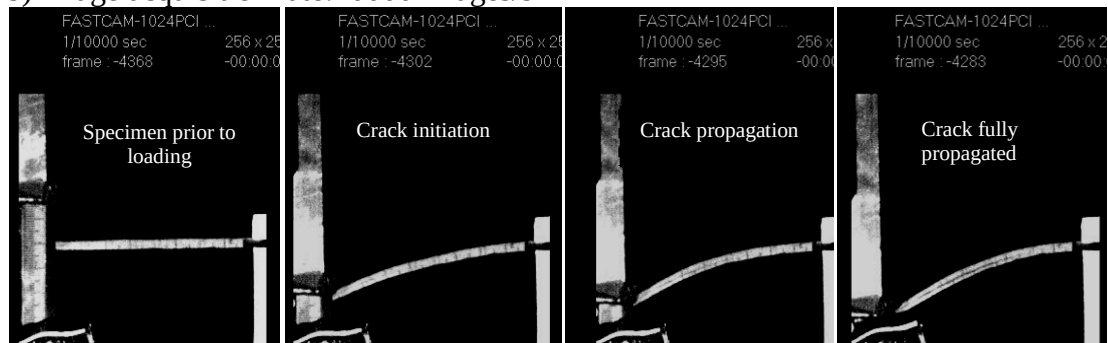
The response of the beam during loading is presented in Figure 127 for the standard and tufted NCF at various loading speeds. Images illustrate comparable pure Mode II loading behaviour for both material specimens at various loading speeds. High-speed camera with a frame rate of 6000 to 10000 images/s monitored the crack propagation at high speed in shear. The Photron 1024PCI camera provided 256 by 256 pixels resolution for such a rate which made crack propagation detection difficult (Figure 127 (a, b, c)). The Photron SA1 provided 1024 by 896 pixels resolution for that range of speed (Figure 127 (d)), which allowed better crack propagation detection.



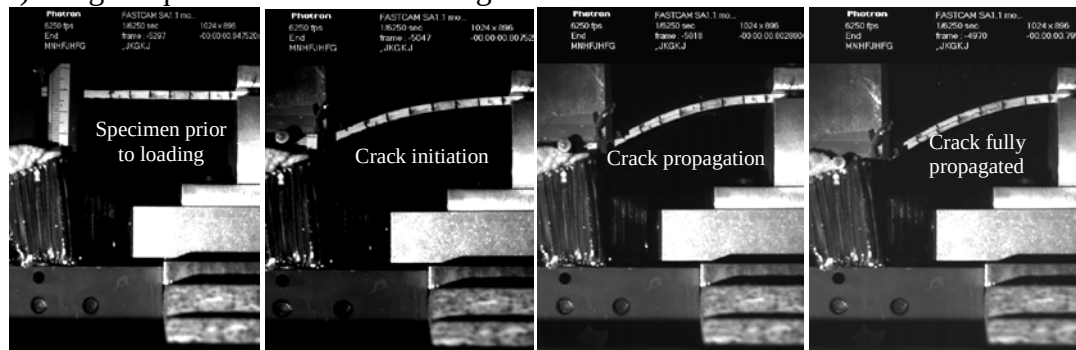
a) Image acquisition rate 6000 images/s



b) Image acquisition rate:10000 images/s



c) Image acquisition rate: 10000 images/s



d) Image acquisition rate: 6250 images/s

**Figure 127: Response of standard and tufted NCF ELS specimen to dynamic delamination; (a) standard NCF specimen loaded at 2.5m/s, (b) standard NCF specimen loaded at 6.3 m/s, (c) tufted NCF specimen loaded at 5.7m/s, (d) tufted standard NCF specimen loaded at 0.8m/s.**

#### 4.2.6.2 Load cell analysis

The load versus displacement chart presented in Figure 128 and 129 were acquired during shear delamination of the standard and tufted interface. Various loading rate were used to attempt to observe the sensitivity of delamination in mode II to loading rate.

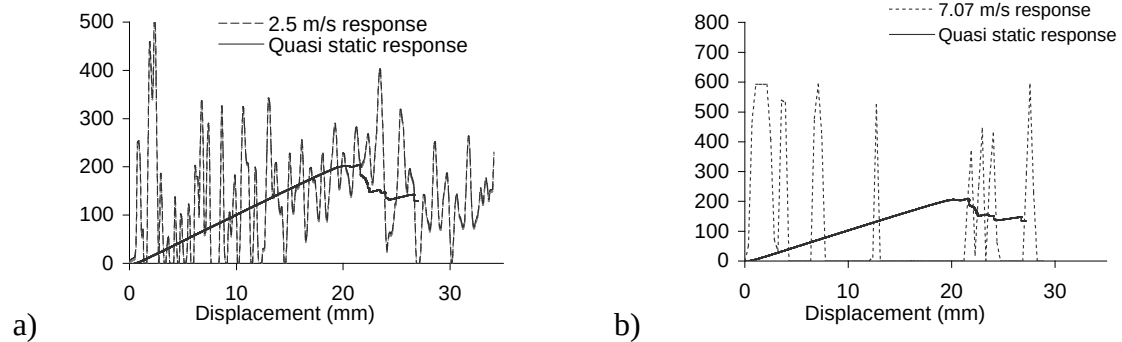


**Figure 128: Load versus displacement response in dynamic mode II for the standard NCF composite material at 2.5m/s loading speed (a) and 7.07m/s loading speed (b).**

The dynamic load readings have a noisy response as the delamination velocity increased. The dynamic responses were characterised by a large initial force peak (at approximately 2 mm arm displacement) corresponding to the force increase required to initiate the delamination crack. This peak was more intense for the tufted specimens. Above 3 m/s, the amount of noise in the signal made any analysis of the crack propagation difficult. Filtering degraded the signal during crack propagation and could not be applied successfully.

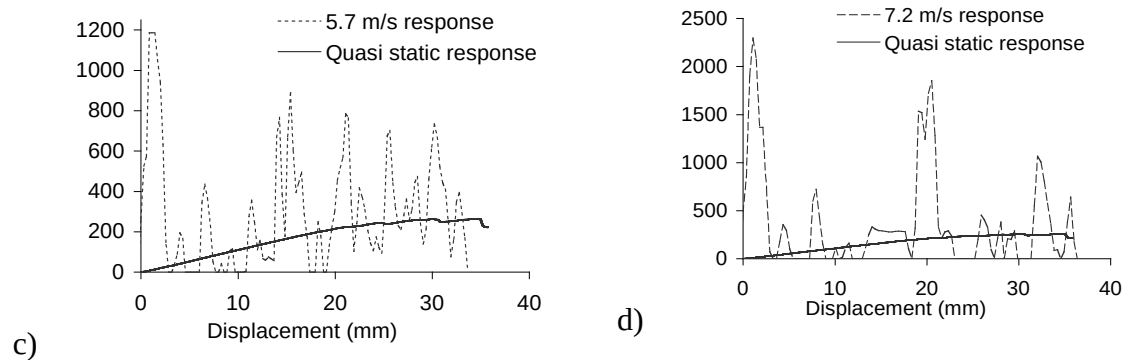


**Figure 129: Load versus displacement response in dynamic mode II for tufted NCF composite material at 5.7 m/s loading speed (c) and 7.2m/s loading speed (d).**

Nevertheless, the dynamic results for both interfaces showed a similar response to the quasi-static response but little beam information could be extracted from the load readings during crack propagation at high speed. Consequently, the loading rate effect on delamination Mode II could not be investigated using the loading response.

The previous section on dynamic delamination Mode I of the tufted and standard interface demonstrated the benefit of using full optical analyses over load recordings to investigate rate effect. A similar analysis for Mode II is developed in this section.

#### 4.2.6.3 Crack versus displacement response

Measurement on images acquired by the high speed camera were made possible by the use of the in-house code that allowed the plotting of crack versus displacement of standard and tufted interface through time (Figure 130).

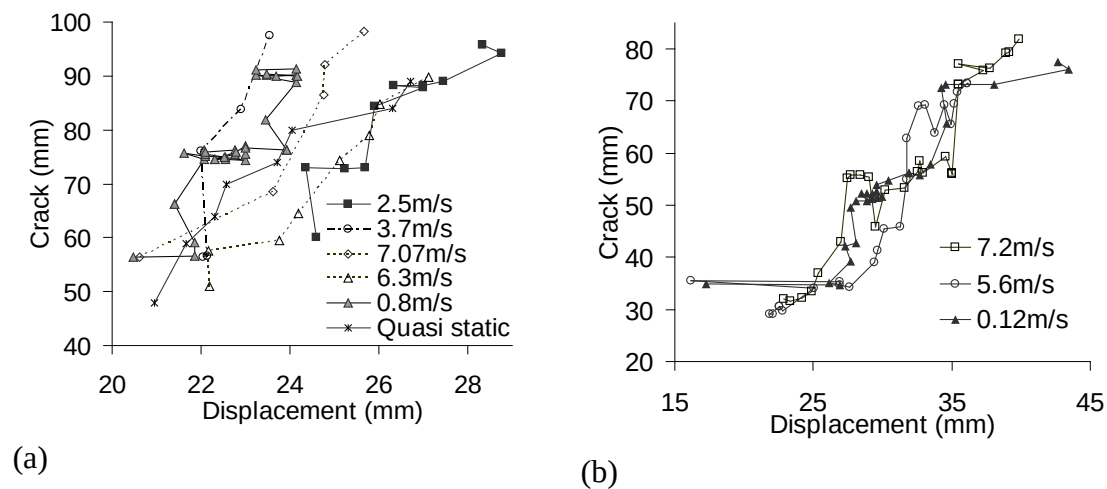


**Figure 130: Crack versus displacement for the tufted (b) and standard (a) interface at various loading speed.**

It is observed in Figure 130 (a) that the crack propagation varies with displacement and loading speed but that no trends were observed. The response occurred for some loading speed in steps that characterized stick-slip behaviour. If, in some cases, the displacement was reduced during loading, it was due to low accuracy of the measurement on low resolution images rather than to any physical effects. In

contrast, for the tufted interface response (Figure 131 (b)), the crack versus displacements results showed a comparable trend for various loading speeds. In this case, strong stick-slip behaviour was observed. Tufts changed the catastrophic resin crack propagation into steady crack propagation through a range of loading speeds for the carbon NCF composites.

#### 4.2.6.4 Rate effect investigations in mode II

##### a) The optical approach

Rate investigation through  $G_{IIC}$  calculation (Equation 58) is simplest as it takes into account specimen thickness ( $t$ ), specimen width ( $b$ ), loading ( $P$ ), arm flexural modulus ( $Ef$ ), arms displacement ( $d$ ) and crack propagation ( $a$ ) throughout the beam delamination. But in dynamic cases, it has been impossible to use load acquisition at high speed because of poor signal quality during crack propagation. Dynamic delamination analysis in Mode I (Chapter 4.2.5) for the same materials has shown that full optical displacement and crack propagation recordings combined with beam compliance, permitted successful investigation of rate effects in Mode I. In this study, similar analysis will be performed in Mode II to prevent the use of the load signal reduced quality.

$G_{IIC}$  in the ELS configuration is defined as:

$$G_{IIC} = \frac{(9 * P^2 * a^2)}{4b^2t^3Ef} \quad \text{Equation 58}$$

$$P = \frac{d}{C} \quad \text{Equation 59} \quad \text{with } C = \frac{(3a^3) + (L + \Delta)^3}{2bt^3Ef} \quad \text{Equation 60}$$

$$G_{IIC} = \frac{\left( 9 * \left( d \frac{2bt^3Ef}{(3a^3) + (L + \Delta)^3} \right) a^2 \right)}{4b^2t^3Ef} \quad \text{Equation 61}$$

$\Delta$ : correction factor taking in account the compliance of the specimen clamping in the ELS apparatus.

Combining Equation 58 and 60 allowed the numerical analysis of  $G_{IIC}$  (Equation 61) without requirement for the load signal.

#### 4.2.6.5 Static verification of the optical approach

The static tests benefit from the fact that all parameters are known to compare with measured load recordings to calculated load readings through the beam compliance (Equation 58 and 60). The results, Figure 131, show good correlations between the 2 methods that validate the optical approach free from load signal (Equation 61).

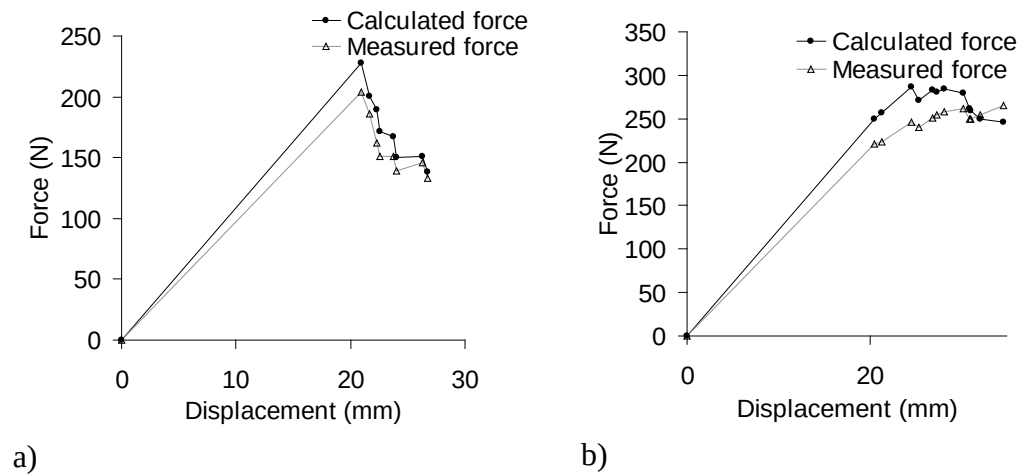


**Figure 131: Calculated and measured force versus displacement for the standard (a) and tufted interface (b)**

#### 4.2.6.6 Mode II dynamic delamination

In dynamic tests, the optical approach provided sensible results for the tufted and untufted interface. Figure 132 illustrates the load response according to the specimen compliance for different crack speeds.

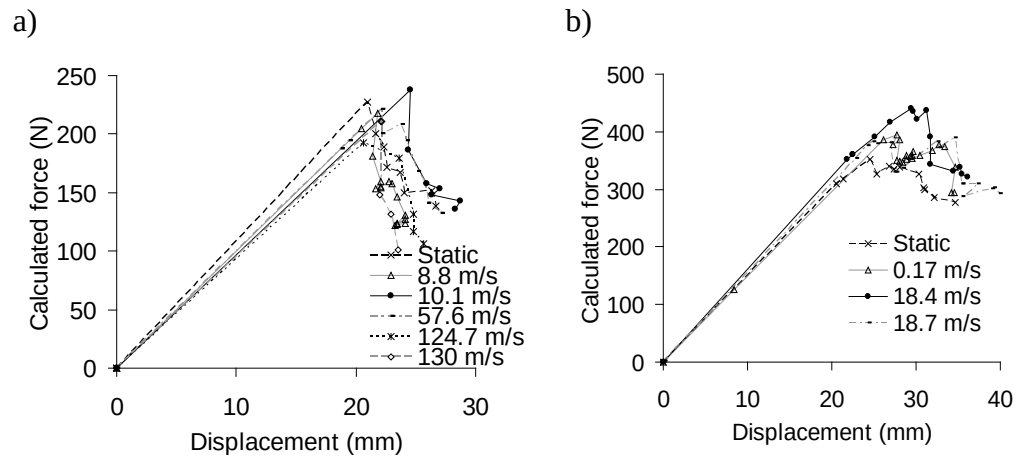


**Figure 132: Calculated force through beam compliance versus displacement for various delamination mode II crack speed: (a) standard interface, (b) tufted interface**

From Figure 132 it is noted that the tufts would reduce by 80% the crack speed during the Mode II delamination events. The force required to delaminate the tufted ELS would be considerably higher than the one for the untufted specimen as in quasi-static loading. But in dynamic (Figure 132), it can be observed that the load dropped during crack propagation of the untufted material as it stabilized or increased for the tufted one. Nevertheless, no significant increase in the force was noted while the crack speed increased which provided indications of little rate effect. More precise investigation of possible rate effects was carried out through  $G_{IIC}$  calculation that took into account specimen geometries and crack lengths during dynamic delamination events.

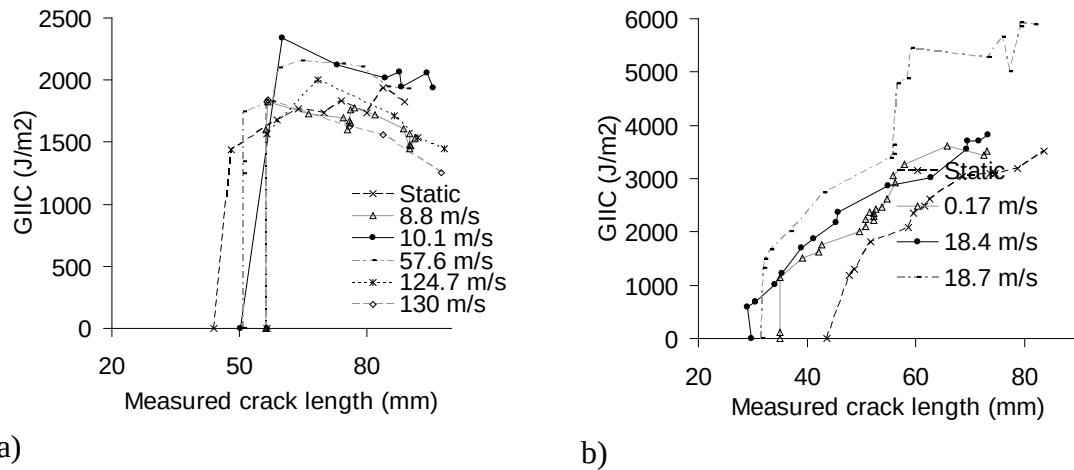


**Figure 133: Calculated  $G_{IIC}$  versus crack length from calculated load for various crack speed: (a) Standard interface, (b) reinforced interface**

Results from Figure 133 show no significant increase of  $G_{IIC}$  while crack speed was increased for both the standard and reinforced resin. For the standard interface,  $G_{IIC}$  will decrease as the crack progresses unlike the tufted interface, for which  $G_{IIC}$  would raise as the crack propagates attaining significant large values. No trends indicating a possible rate effect could be seen for both the standard and tufted interface. To search out a global rate effect,  $G_{IIC}$  values would be averaged during crack propagation (Figure 134). An error bar would provide indications on how concentrated were the measurements around the mean value.

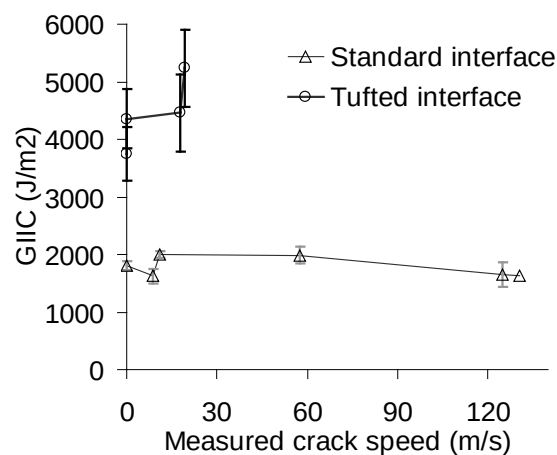


**Figure 134:  $G_{IIC}$  versus crack speed for the standard and tufted interface**

In keeping with previous findings, no  $G_{IIC}$  rate effect was seen for increasing crack speed for the standard resin interface. The crack speed of the standard interface

would be extremely high, reaching values up to 120m/s while the specimen upper arm loading velocity was 7m/s. In contrast the tufts interface limited crack speed of 18.8m/s for the 7m/s upper arm loading velocity. So that the tufts influence was beneficial and reduced 7 times the crack speed propagation in shear. The  $G_{IIC}$  readings increased with increasing crack speed for the tufted interface which characterised a rate effect of the tufted interface in Mode II. Further investigations in this thesis will use a dynamic FE model to investigate the shear delamination response of the standard and tufted interface.

#### 4.2.7 Measurements of impacts

The dynamic disc test was similar to the static disc test (Chapter 4.1.7) apart from that the load is applied dynamically with a falling punch, enabling dynamic multi loading of the sample (Figure 135).



**Figure 135: Punched impacted discs in the drop tower apparatus**

At intermediate loading speeds, during out-of-plane impact only little strain rate effects were observed (Figure 136) compared to in-plane impact (Figure 108-117) which demonstrated strong strain rate effects. In the literature review, Hancox<sup>39</sup> stated that the response of a composite material during out-of-plane impact would be determined by the one of the matrix. Study of the matrix response to delamination Mode I and II has shown in Chapter 4.2.5 and 4.2.6 that no strain rate effects existed in mode I and II for the untufted interface up to 3m/s loading speed. Those findings are consistent with the undetection of strain rate effects in out-of-plane impact in

Figure 136. For such loading the material is loaded in various directions. It is understood that mode II delamination occurs rapidly degrading the structural stiffness before any rate effects due to the fibres could occur. Effectively, the rate effect due to the fibres is not related to the elastic modulus but to the failure strength and strains of the fibres. It is understood that only if fibres failure would occur would strain rate effects be recorded. If no positive strain rate effect was recorded the tests results showed a slight negative strain rate effect for both tufted and untufted material that behaved comparably in dynamic while loaded at 5 m/s. This negative strain rate effect could be due to a difference of contact between the punch and the disc in static and dynamic conditions. The effect of the lay-up influence on such loading seems to be negligible with a similar response for the [0/90] and the [0/45/90/135].

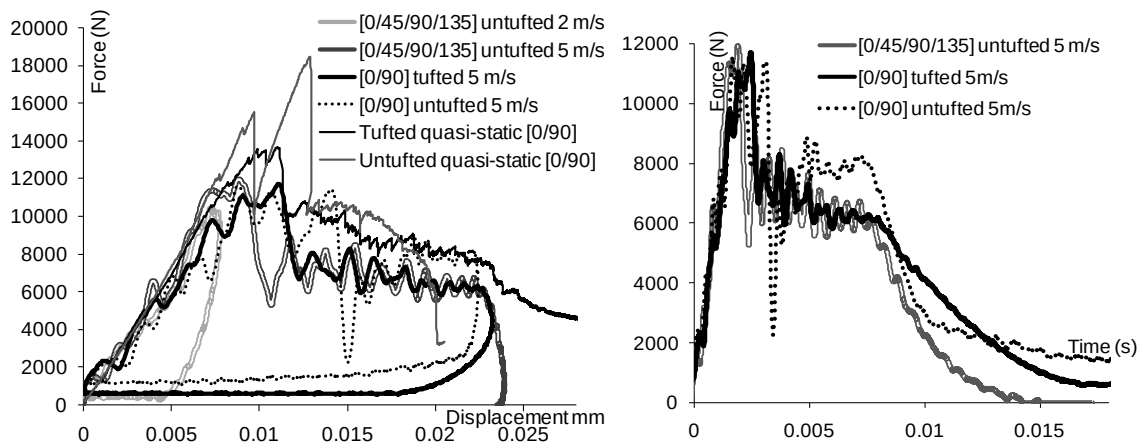


**Figure 136: Impact response of tufted and untufted discs: (a) quasi-static and dynamic response in term of force and displacement, (b) dynamic response in term of force versus time**

## **Chapter – 5 Results: Calibration of the tufted and untufted composites damage model**

This part of the thesis dealt with the calibration of the FE model on the experimental results acquired previously. Ultimately, it could allow the FE code to model the composite responses accurately during damage, delamination and strain rate. The calibration occurred in static firstly and then dynamically. The model used to simulate the plies was the damage Ladeveze<sup>10</sup> model reviewed previously (Chapter 2.2.2.2). The model differentiated between tensile, compressive and bias direction parameters with possibility to superimpose strain rate effects to adjust to different dynamic responses. The laminate model was made from 12 plies. The delamination parameters were estimated from delamination mode I and II experiments. The tufts were represented by links that followed a linear behaviour until failure. The failure was governed by a limit load which was independently defined for the shear and normal components of the link.

### ***5.1 In-plane parameter calibration***

Tensile specimens were represented by a layer of 320 shell elements and compression specimens by a layer of 180 shells. Uni-axial boundary conditions were applied, whilst in the case of the compression model additional out of plane constraints were used to represent the anti-buckling guides. The dimensions and layups of the models were identical to the experimental coupons in static.

#### **5.1.1 Parameters estimation in static axial tension**

The recommended procedure<sup>10</sup> for calibration of in plane parameters was used. However specimens tested were NCF plies (UD lamina stitched) with [0/90] and [+/-45] layup. But the FE model used Ladeveze<sup>10</sup> UD ply model designed for UD plies

calibration only so that some assumptions were needed to extrapolate the responses from a [0/90] lay up to the one of a UD layup. This was difficult and was not an ideal case for parameters estimation. It was compulsory due to the nature of the NCF composites in which NCF single plies were stitched at 90 degrees angles 2 by 2. No such models existed within PAM-CRASH<sup>TM 8</sup> library so the choice had to be made between a UD damage model and a woven damage model. According to Greve<sup>138</sup> the UD model could be successfully used to model NCF materials.

To use this UD material model some assumptions were essential:

- The stiffness, strength, of UD laminates would be twice the one of a cross ply laminate [0/90] in axial tension and compression. But the failure strain would remain the same. These assumptions meant that the influence of the 90 degrees fibres would be assumed as negligible on such lay-up.
- The transverse Young's Modulus would have to be estimated either from micromechanics or copied from comparable data available in the literature.

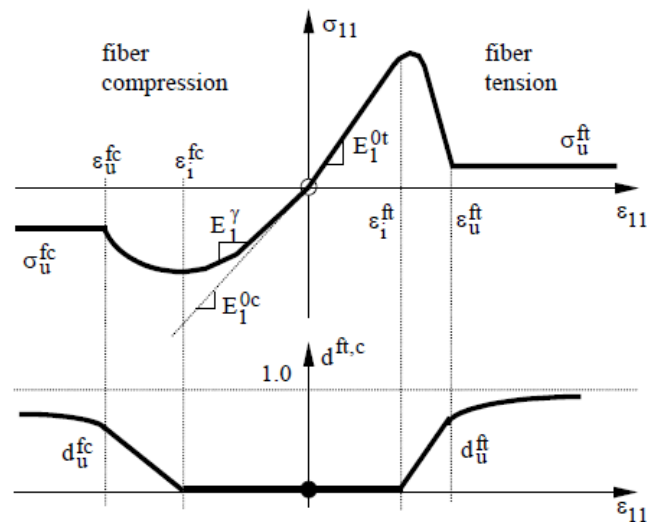


**Figure 137: Axial tension and compression parameter visualization source PAM-CRASH manual<sup>8</sup>**

Figure 137 provides a good understanding of how the material parameters were obtained from an experimental stress-strain response point of view. However a few of the parameters had to be chosen according to previous literature<sup>139, 149</sup> which included

the Poisson's ratio and the transverse Young's Modulus  $E_2$ . The remaining axial parameters were calibrated from Figure 50. The tensile elastic data from the experimental tests (Figure 50) and extraction parameter method (Figure 137) supply tensile PAM-CRASH<sup>TM</sup> <sup>8</sup> parameters which are both presented in Table 22 for the untufted and tufted materials.

| Unidirectional ply elastic properties | Symbol     | Unit | NCF test data | UD ply model | Tufted NCF test data | UD ply model |
|---------------------------------------|------------|------|---------------|--------------|----------------------|--------------|
| Young's Modulus in first direction    | $E_{1_0t}$ | GPa  | 65.0          | 130          | 55.5                 | 111          |
| Young's Modulus in 2 direction        | $E_{2_0}$  | GPa  | 65.0          | 8.00         | 55.5                 | 8            |
| Poisson's ratio in 1,2 plane          | NU12_0     | ...  | ...           | 0.33         | ...                  | 0.33         |
| Tensile strain                        | EPSi_ft    |      | 0.01256       | 0.01256      | 0.0120               | 0.012        |
| Tensile ultimate strain               | EPSu_ft    |      | 0.01260       | 0.01260      | 0.0121               | 0.01205      |
| Tensile ultimate damage               | Du_ft      |      |               | 1            |                      | 1            |

**Table 22: Untufted and tufted tensile Ladeveze<sup>10</sup> parameters extracted from experimental test**

Using the calibrated model in tension, the simulation was run in axial tension. The experimental (Figure 138 (a)) and the simulation responses Figure 138 (c and d) are compared for the untufted material. The simulation showed uniform stress loading and constant displacement (Figure 138 (c and d)) which was expected as the loading was uni axial tensile stress.

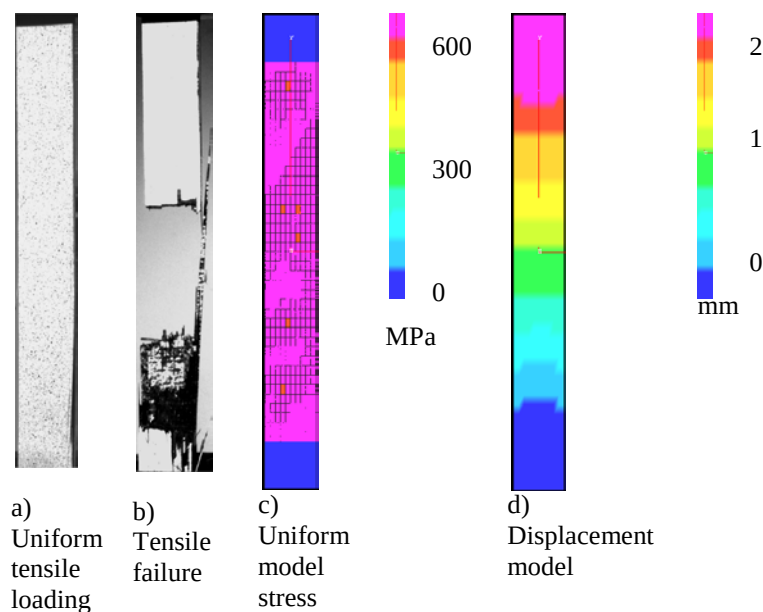


**Figure 138: NCF specimen tests and simulations**

The stress strain response of such simulations with parameters used from Table 22 was compared to experimental responses in tension in Figure 139. It can be observed that the model followed the experimental behaviour closely with respect to both stiffness and strength of coupon specimens. These results were a verification of the implementation of the model and not of its predictive capabilities as the experimental curves were directly related to the material properties used in the models.

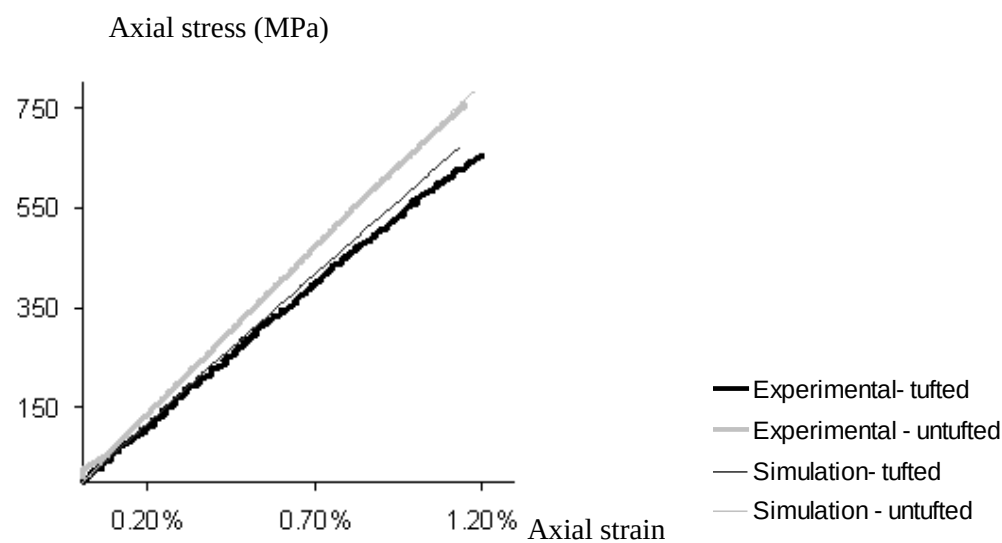


**Figure 139: Axial tension and compression experimental and simulation behaviour of tufted and untufted NCF composites.**

### 5.1.2 Parameters estimation in static bias direction tension

The model parameters extraction from the tensile bias direction tests was more complex since the response was strongly non linear. An energy function was used to reduce the material stiffness ( $G_{12}$ ). Table 23 summarises the material data obtained from the experimental bias direction response (Figure 51).

|                                     | Untufted | Tufted |
|-------------------------------------|----------|--------|
| Initial tensile shear modulus (GPa) | 6.6      | 7.4    |
| Tensile ultimate strain (%)         | 6.25     | 6.09   |
| Tensile strength (MPa)              | 139      | 143    |

**Table 23: Tensile bias direction data from the cyclic tensile shear test**

Data from Table 24 could be directly inputed in the material ply model but such data was not sufficient to predict the non linear response. To be able to model the non linearity a method recommended by Ladeveze<sup>10</sup> based on cyclic loading was used. This damage model was assessed in the literature review in section 2.9.2. For each loading cycle the shear modulus, shear stress, elastic and plastic strains were recorded (Table 24).  $R_0$  which is the stress value at damage initiation was also recorded. Damage  $d$  was then computed for each cycle and was directly linked to the material stiffness degradation due to the debonding between fibers and matrix. Energy function  $Y_c$  and  $Y_o$  were also computed for each cycle. All parameters measured or calculated for the bias direction model are illustrated in Table 24.

| $d_i$  | $G_{12}$ | $\epsilon_{ie12}$ | $Y_{(ii)}$ | $Y_r$ | $Y_C$               | $Y_o$  | $R_0$ | $\sigma_{12}$ | $R_i$  | $p$    | $\epsilon_{p12}$ | Beta | m    |
|--------|----------|-------------------|------------|-------|---------------------|--------|-------|---------------|--------|--------|------------------|------|------|
| 0.0000 | 7        | 0.0056            | 0.0210     |       | 8.25E-02            | 0.0198 | 0.02  | 0.0340        | 0.0010 | 0.0000 |                  | 1.6  | 0.64 |
| 0.2086 | 5.54     | 0.0102            | 0.0382     |       | 1.05E-01            |        | 0.02  | 0.0565        | 0.0514 | 0.0046 | 0.0029           |      |      |
| 0.3986 | 4.21     | 0.0155            | 0.0581     |       | 1.45E-01            |        | 0.02  | 0.0654        | 0.0887 | 0.0108 | 0.0090           |      |      |
| 0.5114 | 3.42     | 0.0199            | 0.0745     |       | 1.71E-01            |        | 0.02  | 0.0680        | 0.1192 | 0.0178 | 0.0182           |      |      |
| 0.5880 | 2.88     | 0.0234            | 0.0876     | 0.087 | 1.49E-01            |        | 0.02  | 0.0675        | 0.1438 | 0.0232 | 0.0282           |      |      |
|        |          |                   |            |       | Yc average<br>0.142 |        |       |               |        |        |                  |      |      |

**Table 24: damage parameters extraction from the untufted materials (unit system GPa, mm, Kg, ms)**

In Table 24 the Plastic hardening ( $R_i$ ) and the Plastic strain  $P$  were calculated and plotted versus each other in Figure 140. The slope in Figure 140 provided Beta and  $m$  parameters for a power law solution of the damage shear energy function (section 2.9.2 for details).

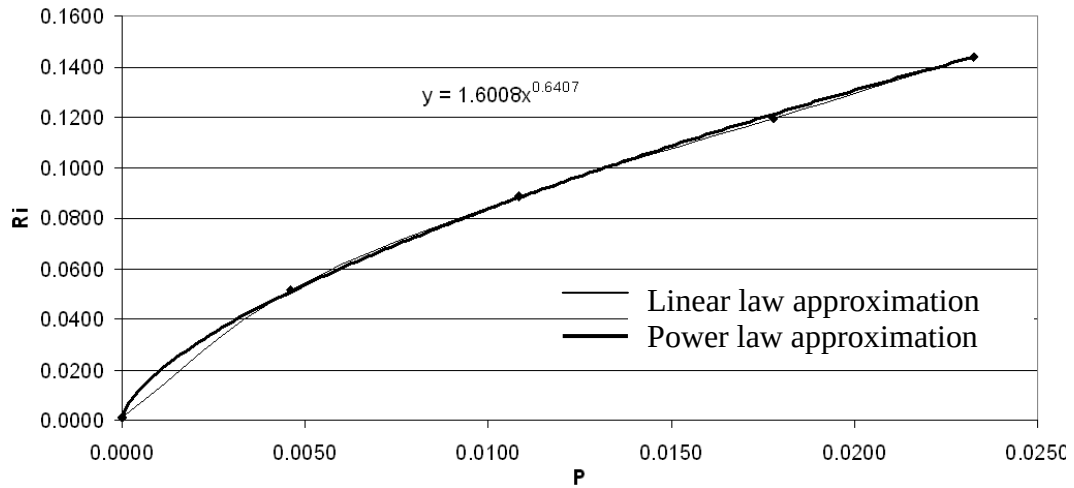


**Figure 140: Provide hardening coefficient for the shear damage law**

The power shear law was known to not represent well the bias direction responses of composite materials from previous research<sup>138; 139; 149</sup>. In order to improve the accuracy of the shear plasticity a modification from a power law (Figure 141) to a polynomial law of second order (Figure 141) was preferred.

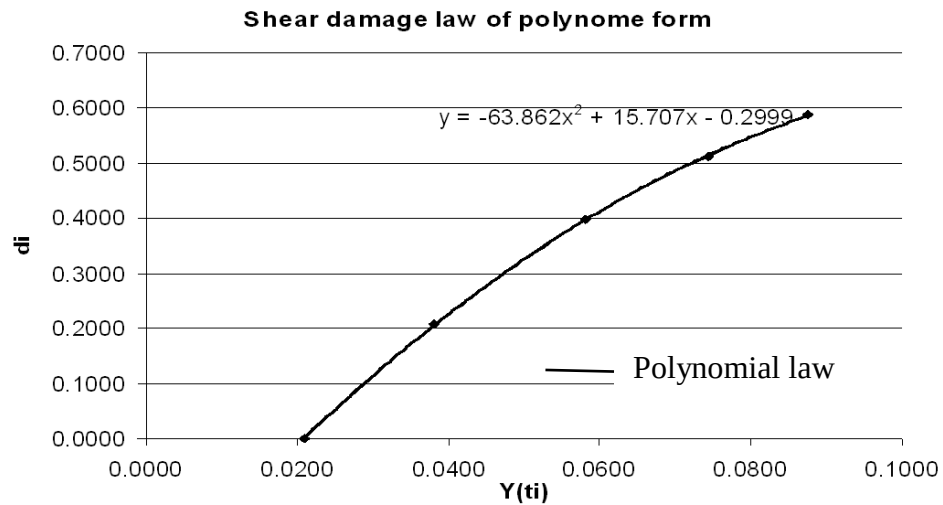


**Figure 141: polynomial damage shear law**

The polynomial damage shear law was of the form  $(-63.862 y(ti)^2 + 15.707 y(ti) - 0.299)$ . From Table 23 and 24 as well as from Figure 140 and 141 all the bias direction damage parameters could be measured and calculated and are presented in Table 25.

| Unidirectional Ply Elastic                                                     | Symbol     | Untufted NCF | Tufted NCF |
|--------------------------------------------------------------------------------|------------|--------------|------------|
| Tensile matrix shear modulus in 1,2-plane                                      | G12        | 6.6          | 7.4        |
| Tensile matrix shear modulus in 2,3-plane                                      | G23        | 4            | 4          |
| Poisson's ratio in 1, 2-plane                                                  | $\nu_{12}$ | 0.33         | 0.33       |
| Shear correction factor in 2, 3-plane                                          | k23        | 0            | 0          |
| Shear correction factor in 1, 3-plane                                          | k13        | 0            | 0          |
| <b>Damage Properties of Ply</b>                                                |            |              |            |
| Critical shear damage (d) limit                                                | $Y_c$      | 0.142        | 0.142      |
| Initial shear damage (d) limit                                                 | $Y_o$      | 0.0198       | 0.0198     |
| Critical transverse damage (d') limit                                          | $Y_{c'}$   | 0.1          | 0.1        |
| Initial transverse damage (d') limit                                           | $Y_{o'}$   | 0.02         | 0.02       |
| Coupling factor between shear and transverse damage (default: = $E_2/G_{12}$ ) | b          | 0.6          | 0.6        |
| Brittle transverse damage limit of fiber-matrix interface                      | $Y_{s'}$   | 0.1          | 0.1        |
| Elementary shear damage fracture limit                                         | $Y_r$      | 0.087        | 0.087      |
| Maximum allowed damage value for shear damage (d) and transverse damage (d' )  | dmax       | 1            | 1          |

**Table 25: Damage shear properties for the Ladeveze model unit system (GPa, mm, Kg. ms)**

Both polynomial and power shear laws were included in the simulation and their responses were compared to the physical test in Figure 142. The power law was implemented in the commercial PAM-CRASH<sup>TM8</sup> software as the shear law was implemented in the PAM-CRASH<sup>TM8</sup> development tool: PAM-MODE<sup>8</sup>.

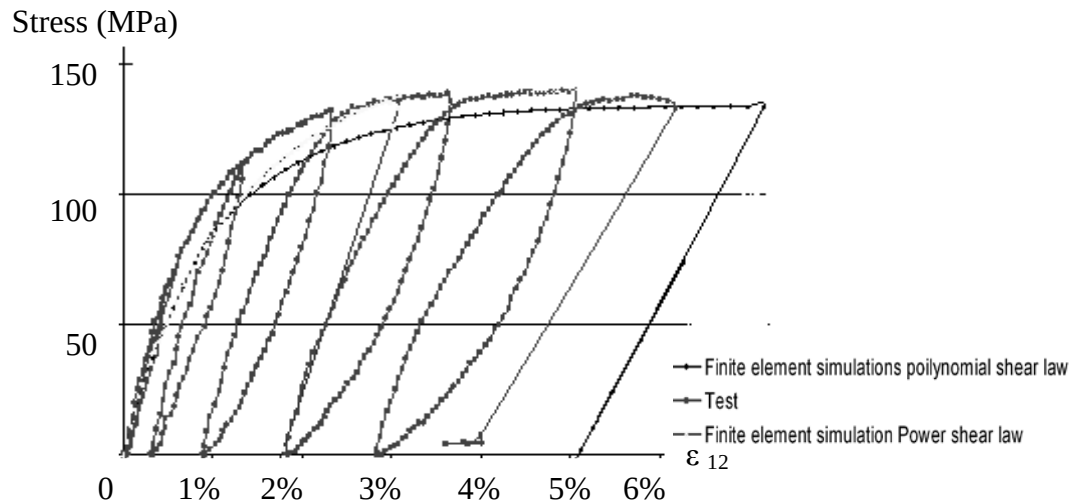


**Figure 142: Comparison of shear test and simulation using a power law and polynomials law**

From Figure 142, it was observed that the response with the power shear law power could not predict well the shear damage behaviour, the simulation stopped at a

relatively low strain but nevertheless at the correct stress. To avoid this problem  $Y_r$  was increased, but then the failure occurred at the correct strain but over estimated the stress; this was a known problem for this law. Therefore a modified shear law fitted better to the experimental trends, but for the non crimp fabric it seems to over predict the damage behaviour at the beginning of the test. Figure 143 plots the polynomial shear law implemented in PAM-MODE 2005<sup>8</sup> Fortran subroutine and in PAM-CRASH 2008 commercial code in which a recent modification could allow it. The results were similar but not exactly the same. This could be due to either small loading speed differences or slight differences between the two softwares version<sup>4</sup>.

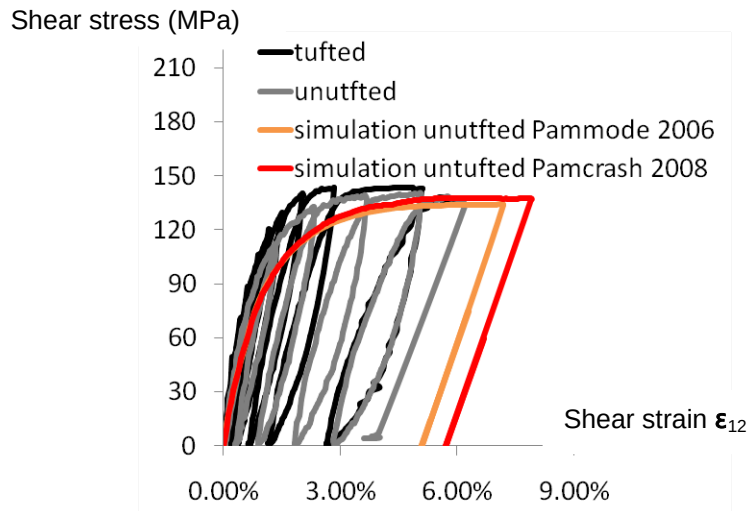


**Figure 143: Comparison of the polynomial shear law within PAM-CRASH<sup>8</sup> 2008 and PAM-MODE<sup>8</sup> 2006**

From Figure 143, it was observed that the model accuracy was slightly limited compared to the experimental response. The responses of the tufted and untufted specimens were comparable (Figure 143). Therefore the untufted parameters could be used to also replicate the tufted NCF response in shear with reasonable accuracy. This assumption saved considerable parameters estimation time.

### 5.1.3 Parameters estimation in axial compression

As in axial tension the parameter estimations are relatively straight forward in axial compression and follow Ladeveze<sup>10</sup> recommendations. As in tension assumptions were required since the model was an UD model and the experiments used a [0/90] lay-up. Unlike the axial tensile behaviour the axial compressive response was non linear in term of stiffness due to Micro-buckling of the fibres principally. From the experimental response (Figure 68) the initial compressive Young's Modulus was defined and was degraded by the use of a gamma knock down factor ( $\gamma$ ) taking in account Micro-buckling effects. Ultimate and initial failure strains as well as the knock down factor were among the model parameters to be identified from Figure 61, 68 and Equation 62.

$$E_1^\gamma = \frac{E_1^{0c}}{1 + \gamma E_1^{0c} |\epsilon_{11}|}.$$

**Equation 62**

$E_1^{0c}$  was the compressive initial Young's Modulus and  $E_1^\gamma$  was the overall Young's Modulus in compression. These calculations led to new compressive parameters illustrated in Table 26 for tufted and untufted composites.

| Compressive properties                     | Parameter | Unit | Untufted | Tufted |
|--------------------------------------------|-----------|------|----------|--------|
| Compressive Young's Modulus in 1-direction | E_OC      | GPa  | 126.610  | 112    |
| Compressive factor of modulus correction   | GAMMA     | none | 0.090    | 0.14   |
| Compressive ultimate strain                | EPSi_fc   | none | 0.008    | 0.008  |
| Compressive ultimate strain                | EPSu_fc   | none | 0.0073   | 0.0078 |
| Compressive ultimate damage                | Du_fc     | none | 1.00     | 1      |

**Table 26: Compressive parameter estimation**

These parameters permitted the modelling of the axial compressive response with a [0/90] layup model. A relatively close correspondence was observed for the experimental and model responses (Figure 144).

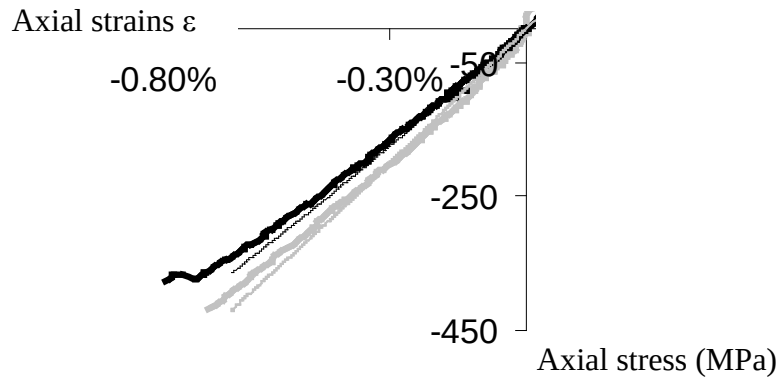


Figure 144: Axial compressive response of tufted and untufted [0/90] lay up

#### 5.1.4 Parameters estimation in the bias direction

From the experimental results it was noticed that the bias direction response was significantly different in tension and compression in term of failure strain (Figure 68) in quasi static loading. The current Ladeveze<sup>10</sup> model implemented in PAM-CRASH<sup>TM8</sup> did not allow for the differentiation of tensile and compressive bias direction parameters. It would double the number of shear parameters which will add to the complexity of the model. As a result the tensile bias direction parameters were used in the modelling response in compression bias direction to foresee inaccuracies that could take place. From Figure 145 it was observed that the tensile shear parameters fitted well the compressive response of untufted NCF. The parameters would only under predicted slightly  $\epsilon_{12}$  in compression. From these results it was concluded that no differentiation of tensile and compressive bias direction model response was necessary due to the slightly limited accuracy of the model. Especially as the experimentally measured  $\epsilon_{12}$  in tension and compression tend to be the same at higher loading rate.

Bias direction strain

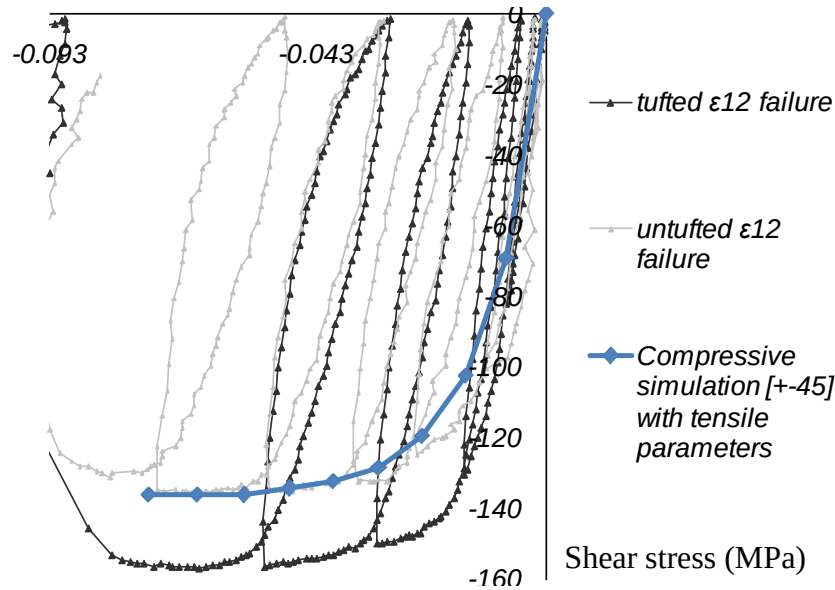


**Figure 145: Bias direction response in compression/ comparison experimental against model with tensile bias direction parameters.**

The model was able to reproduce both the tensile and compressive bias direction response of the untufted materials and in a less extent the one of the tufted composite. Effectively in this latter case the increase in compressive strength could not be modelled fully with the untufted tensile shear model parameters used.

#### 5.1.5 Parameters estimation to represent Micro-cracks

The UD Ladeveze<sup>10</sup> model recommends as well the calibration of the model on a [+45] response. The parameter  $d'$  is related to damage due to the Micro-cracks of the matrix parallel to the fiber direction. The  $d'$  parameter is applied to the transverse Young's Modulus to degrade its propriety. Unfortunately it was not possible to carry this test due to the impossibility to stack up this layup sequence. The effect of Micro-cracks would then be neglected in this modelling approach but the effect of fibres matrix debonding would still be taken in account through the bias direction damage parameter  $d$ .

## 5.2 Out of plane response: delamination mode I and II models

Once the in plane parameters were calibrated it was necessary to calibrate the delamination model in mode I and II. No such calibration guide exists for such loading and calibrating the initiation and propagation stress of the crack in mode I and II is particularly difficult. Often such parameters are defined arbitrarily until the model and the curve experimental fits. In this research material parameters could be extracted from the following expressions, based on beam theory (used to calculate the crack opening<sup>148</sup>):

Mode I:

$$\Delta_{\alpha_0} = \frac{3d}{\alpha^3} \left[ \frac{\alpha(\alpha - \alpha_0)^2}{2} - \frac{(\alpha - \alpha_0)^3}{6} \right] \quad \text{Equation 63}^{150}$$

Mode II:

$$\Delta_{\alpha_0} = \frac{2d\alpha^3 h}{3\alpha^3 + L^3} \left[ \frac{3\alpha_0^2}{\alpha^3} - \frac{3}{\alpha} \right] \quad \text{Equation 64}^{150}$$

Where  $d$  is the displacement,  $\alpha$  the crack length,  $\alpha_0$  the initial crack length,  $h$  the half thickness of the ELS specimen and  $L$  the length of the specimen.

Initiation and propagation crack stress parameters were difficult to obtain. Equation 63 and 64 could be used in visual basic in combination with the experimental curve. From such combination a fitting and model parameters could be assigned. Using this sequence the delamination parameters were estimated in mode I and mode II that appeared as calibrated in Table 27. Those parameters would prove to have limitation in the validation study (Figure 161) so that defined parameters were also used for comparison (Table 27).

| Parameter definitions                  | Parameters name and unit      | Untufted interface                      | Tufted interface                        |
|----------------------------------------|-------------------------------|-----------------------------------------|-----------------------------------------|
| Distance for kinematics computation    | Hcont (mm)                    | 0.025                                   | 0.025                                   |
| Normal Modulus                         | $E_0$ (GPa)                   | 2.89                                    | 2.89                                    |
| Shear Modulus                          | $G_0$ (GPa)                   | 1.1                                     | 1.1                                     |
| Normal stress to continue delamination | $\sigma$ propage (GPa)        | 0.00056                                 | 0.00056                                 |
| Shear stress to continue delamination  | $\gamma$ propage (GPa)        | 0.03 (defined)<br>0.000065 (calibrated) | 0.03 (defined)<br>0.000065 (calibrated) |
| Mode I Fracture Energy                 | $G_{IC}$ (J/m <sup>2</sup> )  | 429                                     | 429                                     |
| Mode II Fracture Energy                | $G_{IIC}$ (J/m <sup>2</sup> ) | 1200                                    | 1200                                    |
| Normal stress to initiate delamination | $\sigma$ start (GPa)          | 0.0003                                  | 0.8                                     |
| Shear stress to initiate delamination  | $\gamma$ start (GPa)          | 0.035 (defined)<br>0.00007 (calibrated) | 0.035 (defined)<br>0.00007 (calibrated) |
| Tufts normal strength                  | GPa                           | None                                    | 0.29                                    |
| Tufts shear strength                   | GPa                           | None                                    | 0.15                                    |

**Table 27: parameter data for the resin interface properties with tufts and no tufts (units system: GPa, mm, kg)**

With the above parameter the PAM-CRASH<sup>TM4</sup> simulation of a double cantilever beam and End loaded split specimen were ran. It permitted the checking of the model parameters validity as the DCB and ELS model responses were compared to the experimental curves. Figure 146 illustrates the response of a double cantilever beam specimen with an untufted interface.

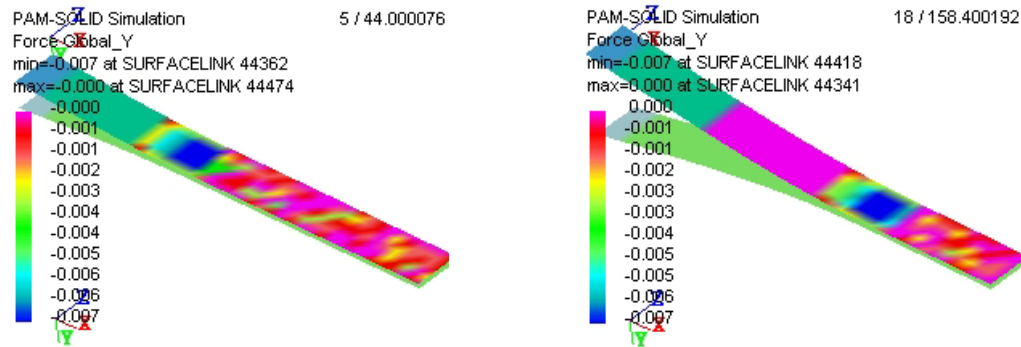


**Figure 146: Delamination mode I of double cantilever beam specimen**

The crack loading was observed. A load concentration was spotted at the crack tip location over the specimen width and up to 20 mm away from the crack tip. After which the interface was not much loaded. The force versus displacement of the Mode I and mode II simulations are presented in Figure 147 and 148.

It was observed that mode I experimental results were reproduced closely by the model. But mode II results were only nearly reproduced in the case of the untufted material and not reproduced in the tufted case.

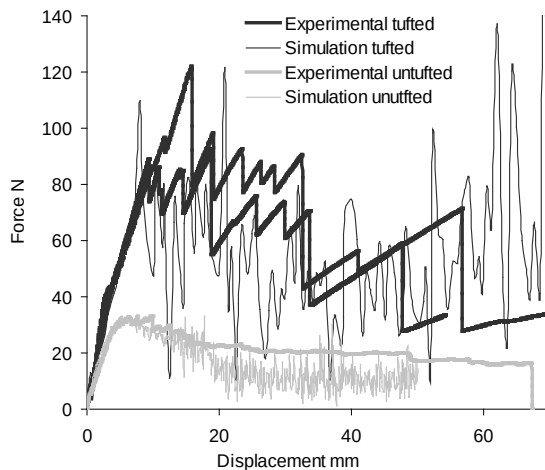


**Figure 147: Mode I delamination model**

**Figure 148: Mode II delamination model**

Lower apparent stiffness of the model response could be related to discrepancies between the model and the experiments boundary condition application. In other words the problem could be related to the clamping of the specimen in the

ELS apparatus. If not the problem could be that delamination occurred earlier than thought leading to a loss of stiffness in the ELS model.

### **5.3 *Dynamic in plane model calibration***

The model had been calibrated in quasi static conditions so that the strain rate calibration can take place.

From the experimental responses (Figure 110, 111 and 114, 115) and Tables 14 to 21 some functions were defined that supplied the finite element explicit code and provided a modification of the stiffness, failure strains and stresses to allow a strain rate sensitive response. Strain rate effects on axial Young's Modulus, failure shear and axial strains, transverse Young's Modulus, shear modulus and yield stress were considered. Also assessing strain rate effects on  $E_2$  is impossible as they require [UD] layups and NCF plies are stitched 2 by 2 at [0/90]. The parameters of the strain rate functions are found by plotting for example strain rate increase versus failure strain increase for different strain rate. This way another 12 parameters were defined for the model. Some of the parameters were kept at a minimum as in the case of the axial Young's Modulus that did not show any significant increase versus strain rate. The laws used are all power laws that fitted well the experimental data (Figure 149 for axial layup and 150 for bias direction ones).

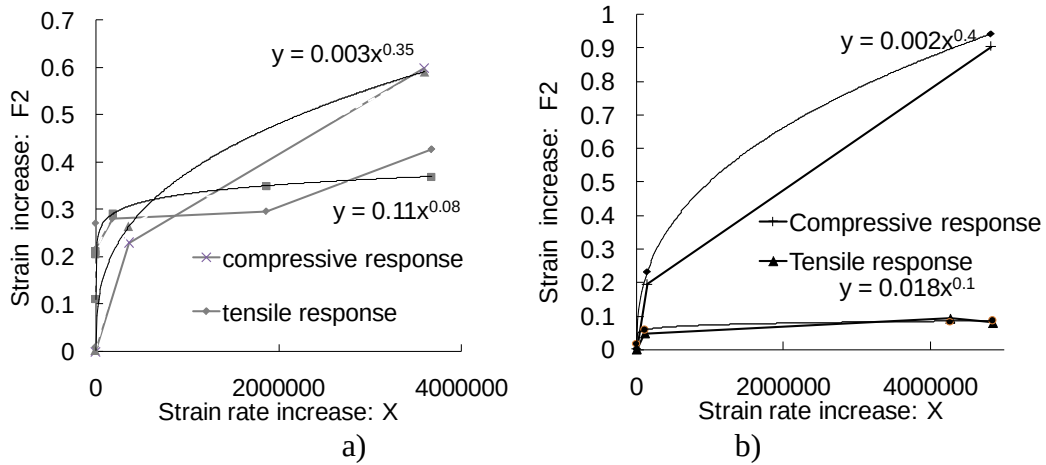


**Figure 149: Compressive and tensile strain increase versus strain rate increase for [0/90] laminate (a) untufted, (b) tufted**

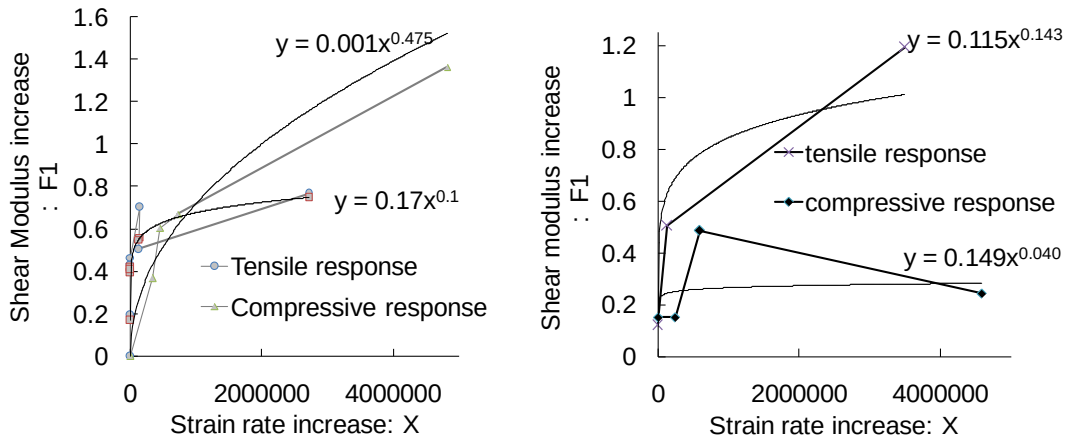


**Figure 150 : Compressive and tensile shear modulus increase versus strain rate increase for bias direction laminate (a) untufted, (b) tufted.**

Appendix 5 describes the additional in plane strain rate laws parameters retrieved from the experiments in tension and compression. Much of the parameters are from Figure 149 and 150 strain rate laws.

It is understood that a slight modification on the yield stress parameters law would be required. On a different note the model can use either tensile or compressive strain rate parameters but it is not possible to use them both on the same simulation run as it would double the number of strain rate parameters required. The PAM-CRASH<sup>TM8</sup> strain rate model is therefore slightly less accurate on multi-loaded structures combining tension and compression.

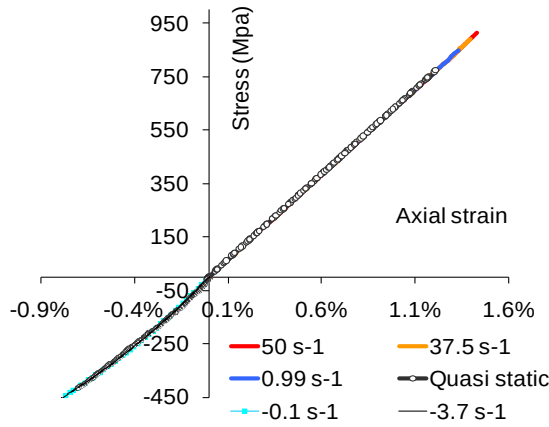


**Figure 151: Model response in the axial direction**

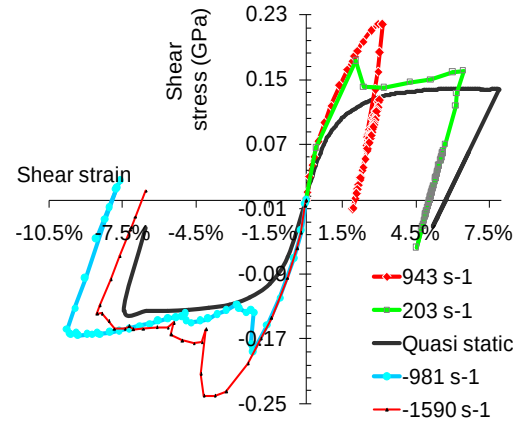


**Figure 152: Model response in the bias direction**

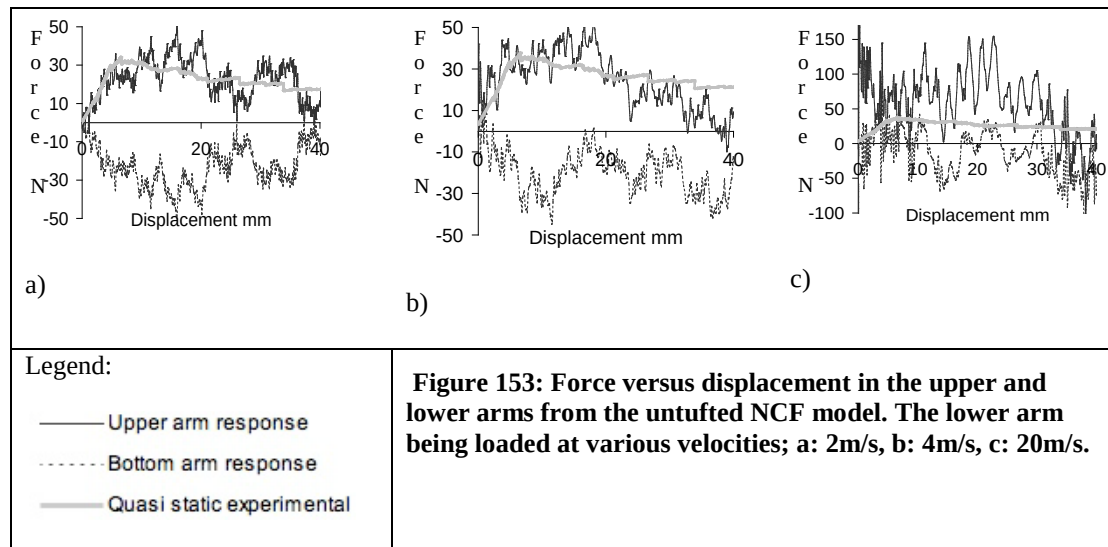
In axial tension and compression the model responded identically to the tests (Figure 151). Also in rapid compression less strength was observed from the model than from the experiments. In dynamic the tensile or compressive strain rate parameters must be used solely by the material model. In this case the tensile strain rate parameters were used which can explain the results. The other explanation is that the compressive model has the static and intermediate loading rate specimen's dimensions which are not ideal at high loading speed. In reality at high speed small cubes were tested. A specimen finite element model of this reduced size could be used at high modelling speed with the compressive strain rate parameters for better compressive validation of the material model in the axial direction.

Strain rate effects in shear on the  $R_0$  parameter (yield stress; the stress at which damage start to occurs in the bias direction) was positive from the experimental response (Table 18, 19, 20 and 21) also the current material model strain rate laws in PAM-CRASH<sup>8</sup> supposed it decreased with strain rate (Equation 39 and 40), therefore its effect was kept to a minimum, which might be one of the reasons for the mixed results of the simulation on that model layup at high speed (Figure 152). In the future this material model law will require some improvements.

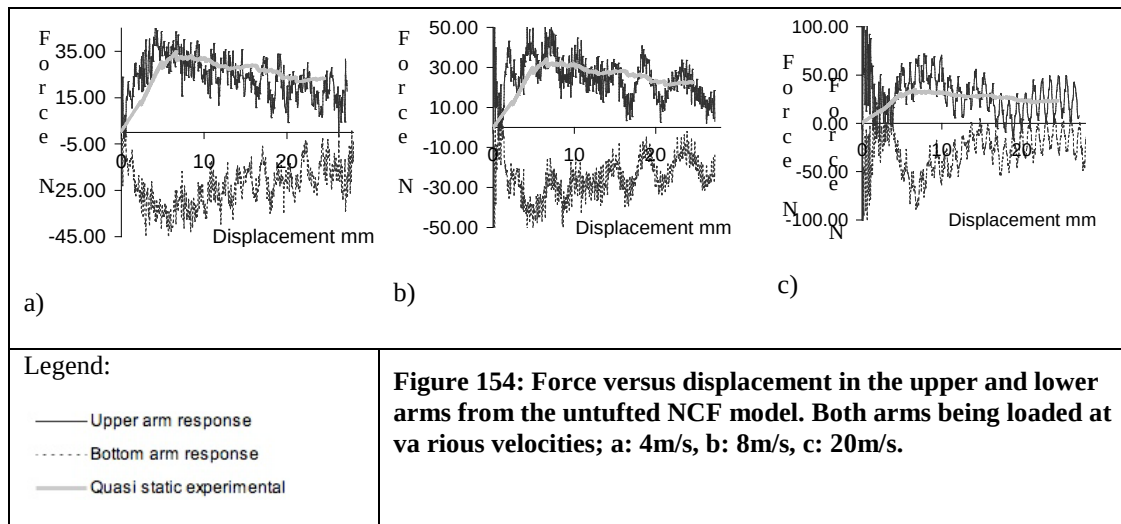
### 5.3.1 Dynamic delamination mode I models

Dynamic out of plane experimental response showed no strain effect in mode I while the crack was loaded in pure mode I. In mode II a slight strain effect was noted for the tufted materials. As no strain rate effects, were uncovered on the Young's Modulus and in some extent on the shear modulus in the axial direction the static models could be used at higher speeds to predict DCB and ELS responses.

Results obtained from model (b) representing the more accurate boundary conditions applied to the beam in dynamic loading are presented in Figure 153 and 154 which meant only one arm was loaded at high speed. For that loading case, comparison of the force in both arm with the model showed that from 4 m/s impact speed the force seen by the upper arm would differ from the force seen in the lower arm. For this range of speeds the interface would not transfer the energy in the upper arm appropriately. This effect was also observed on the delamination images and rate analysis by asymmetric arm bending (Figure 117 i, j, k and l) and rate effect characterisation for the untufted NCF (Figure 124 a and 125). Physically the stresses cause the resin interface to fail before they fully propagates in the upper arm.



It is of interest to know if this mix mode effect and asymmetric DCB arm loading would occur in the case of double arms loading. Figure 154 shows results for a new model with simultaneous loading of both arms. The results for the untufted NCF material with both arm loaded showed good force comparison between both arms until large speed (higher than 20 m/s).



These results suggested pure mode I loading at elevated loading rate as the force readings were comparable and synchronized in both arms. Also no significant force increase was observed implicating no significant rate effects occurred with standard parameters. However simulation showed that tufted DCB would fail in bending above

4 m/s loading speed due to the large force increase required to initiate the crack dynamically which caused the debonding of the loading block experimentally.

It seems the mode II interface would be damaged significantly in mode II if the speed is not extremely low. This effect can either be due to the ELS model set up or to the algorithms itself. This effect is analogue to a positive finite element strain rate effect.

## Chapter – 6 Results: Validations of the calibrated model

This chapter deals with attempts to validate all the model parameters calibrated previously. It also permits the verification that the loads, while acting together in large amount, do not generate unrealistic model results. In other words, that some unrealistic coupling does occur between the various pure loads cases. If the model was to be validated, it could be used on larger structures in quasi-static and dynamic cases without any further checking. Such simulations could be used in the modelling of bird strike impacts on wings, and could predict the response of the composite structure in term of stress, strain, damage and delamination.

The structure chosen for validation to generate compression, tension and shear loading with delamination damage and potentially strain rate effects was a 12 cm radius disc punched in its centre (Figure 155).

### 6.1 *Quasi static model validation*

In this section, punched discs with boundary conditions comparable to the experimental punched discs set up were modelled at quasi-static loading speed.

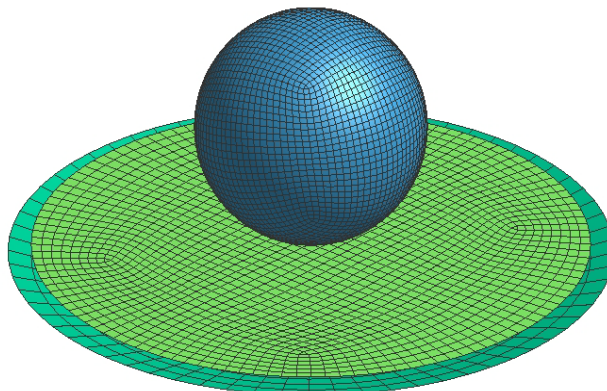


**Figure 155: Punched discs**

Two types of disc models were generated.

- The first type constituted of a single shell layer into which the stacking sequence was built up; this type of model can be also called a Macro-scale model.
- The second model constituted of several stacked layers of shell elements representing a layer of [0/90] NCF plies each; the shells were then linked by interface elements representing the resin in-between the plies. The nature of the second model was called a Meso-scale model in opposition to a Macro-scale model made from only one shell layer.

The first disc model could validate the stiffness, first onset of failure and damage progression of the model. The meso-model in addition, attempted to predict the amount of delamination in Mode I and II. Both could potentially predict strain rate effect.

#### **6.1.1 Multi-ply shell model validation**

The multi ply model used the parameters defined previously during coupon calibration. In this section, delamination was not modelled and therefore not taken into account. The model was composed of a punch stressing the centre of the composite disc, as shown in Figure 156. It had a rigid body ball representing the punch. A disc shell was used to represent the composite material. Finally, a support inclined at eleven degrees was represented by shell elements. The boundary conditions were as follows:

- Constant speed was applied to the punch.
- A contact algorithm was used between the punch and the disc and in between the discs and the support. The disc was simply supported on its edges by the support.

The damage progression is illustrated in Figure 156 and started at the contact point between the shell and the punch and propagated throughout the structure.

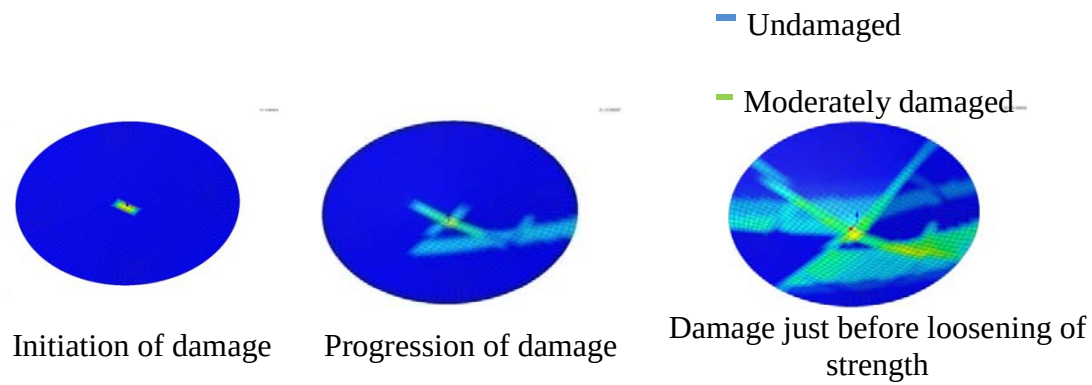


**Figure 156: Progression of damage on punched untufted disc.**

One problem in this simulation was found to be the difference of contact between the real test and the simulation. Effectively, the contact interface was localised in the simulation while it was more diffused in the experimental test due to a small dent occurring during the crushing of the top plies and of the resin. This effect led to a greater contact area in the physical test. Therefore stresses in the experimental tests were more spread and less sharp in the disc centre reducing the amount of damage. In the simulation the contact lead to a sharp stress concentration (Figure 157(a)) which led to premature damage of the shell elements in contact with the punch and to loss of stiffness of the disc structure (Figure 157 (c)).

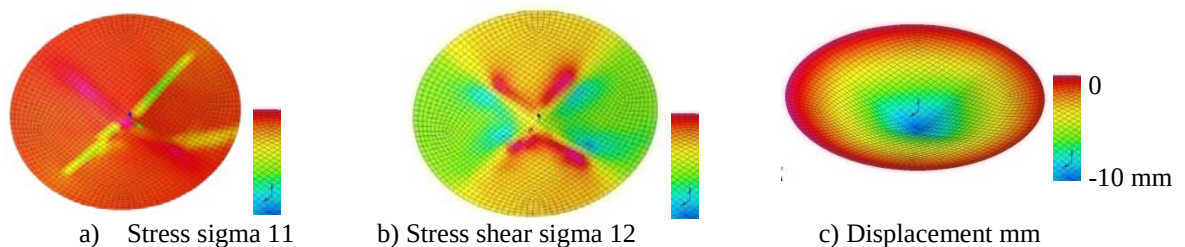


**Figure 157: Stress and displacement before complete stiffness reduction**

Therefore, although this test introduced tension, shear and compression loading for model validation, it had the disadvantage to introduce further modelling difficulties due to the contact interface. Therefore, this set up was not ideal to validate the material models. In order to reduce the stress concentrations, a larger punch model was introduced and benefited the model in reducing the stress concentrations. Even so, the matching of experimental tests and simulation response were still underestimated. Ultimately, the compressive axial failure strain parameter was

increased as it could possibly have been slightly underestimated due to inherent slight misalignment leading to premature failure known to occur in axial compression testing. With a large impactor spreading the stresses on a large area and a higher compression ultimate failure strain, the discs showed similar force value to the tests, as shown in Figure 158. The assumptions made were required to delay the occurrence of damage during out-of-plane loading of the single shell elements with this model. Greve<sup>134</sup> used an unusually high tensile strength while performing such validations on a similar model. This seemed to be required on out-of-plane loading of composite single shell elements with this current model. It is understood that no such increase would be required if the load and boundary condition would be spread and applied in the plane.

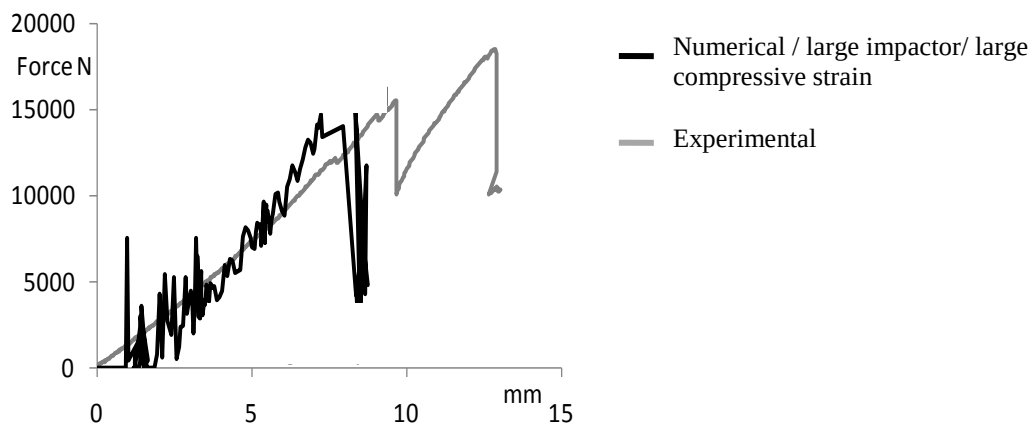


**Figure 158: Force versus displacement untufted discs**

If one wanted to use this model for further out of plane punching or impact simulation, such procedures should be implemented (larger impactor and larger failure strain).

### **6.1.2 Multi-layered shell model validation**

The model used a Meso-scale representation of the discs. This model was not made of a single shell but of several layers of shells linked by delamination interfaces. Technically, it could reproduce the crushing of the top layers and delamination.

Unfortunately, the model provided excessive delamination throughout the loading. This problem was understood with difficulty as great efforts were given to produce accurate delamination parameters that were validated by the DCB and ELS models. It must be understood that the validation of the ELS specimen was not that accurate in regards to the matching of experiments and models (Chapter 5.2). Nevertheless, it did provide much better matching between the simulation and the experimental test than in the case of the punched disc.

The fact that the delamination progressed too rapidly in the multi layered discs model (Figure 159) puts questions on the validity of the parameters, on the coding of the delamination itself or on the FE model and the contact interface. But the delamination parameters had been validated relatively well on ELS and DCB specimens. In which it was found that the delamination Mode II was quite unstable during initiation of loading on the ELS specimen model. But could that be the reasons for such difference between the poor disc model response and the relatively good ELS and DCB delamination responses. Alternatively the problem could come from mix mode delamination loading and poor interaction of both delamination mode I and II propagation. Or again the problem could come from the crushing of the disc by the punch as in the single shell problem. It could create more delamination damage than in reality due to more stress concentration and less contact area.

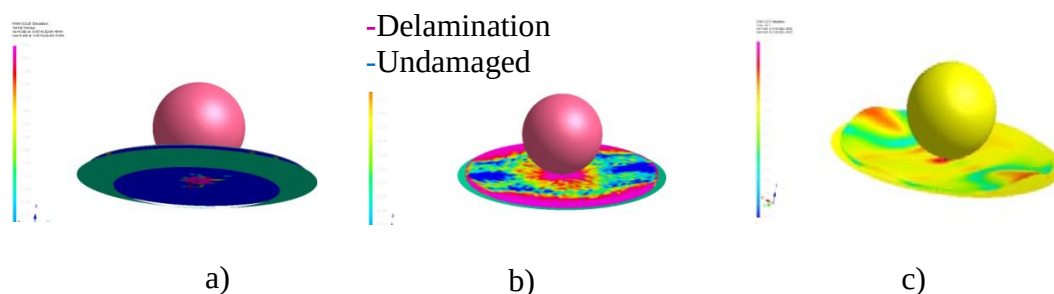


**Figure 159: Initiation of delamination mode I; b) wide spread delamination before complete disc failure, c) axial stresses and physical response of the discs.**

### 6.1.3 Modified Multi-layered shell validation

In order to see how delamination influenced the disc response, the initiation and propagation stress delamination parameters in Mode I and II were increased until experiment and model matched. The reason for such action is that attempt to calculate the stress intensity factor via crack opening of ELS and DCB specimen have proved limited results on the ELS specimens (Mode II). Obtaining them by other means such as thermographic analyses could be of interest. The response to delamination was better with the modified parameters, in terms of physical response and load deflection curves which were comparable to the test. The simulation response can be observed in Figure 160.

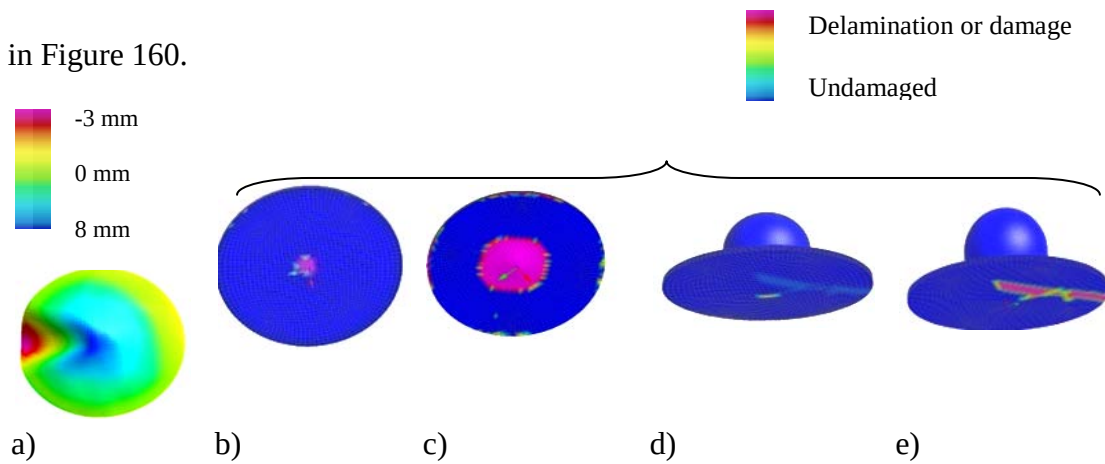


**Figure 160: Disc behaviour with modified parameters; a) displacement after failure, b) delamination mode II initiation, c) delamination mode II propagation, d) damage initiation, e) damage propagation.**

The load deflection response with such parameter can be observed in Figure 161. It plots the experimental response against the model ones with defined and calibrated initiation and propagation stresses. The calibrated delamination interface under predict considerably the material response as a whole as the defined one is too stiff. Further investigation on the initiation and propagation delamination stresses is understood to be required to better under the model response and the parameters calibration.

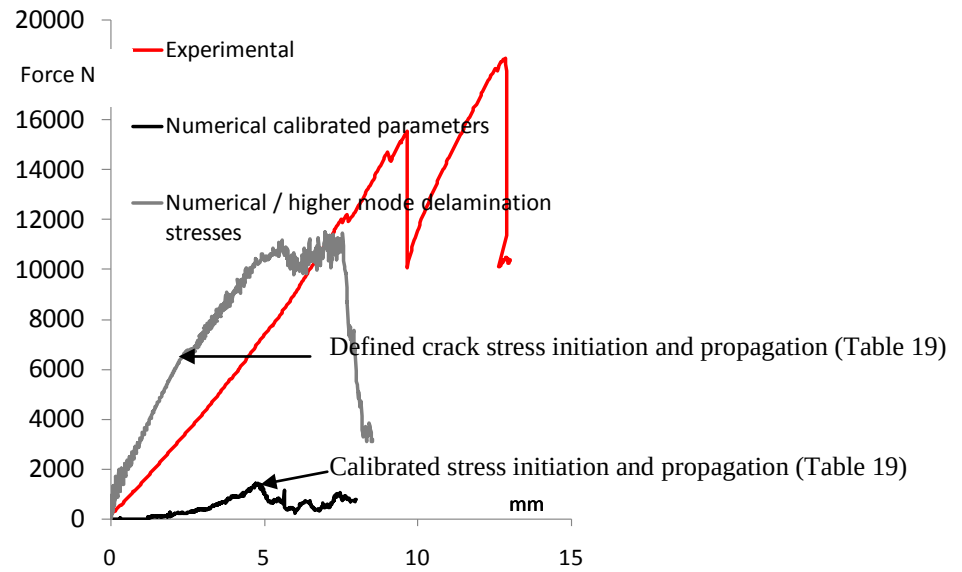


**Figure 161: Numerical experimental comparison of the disc response in quasi-static**

## **6.2 Impact model validation**

The FE discs models could also be used at higher speed by a simple increase of the punch speed and the addition of strain rate parameters defined previously. But, as difficulty was observed in the quasi static-modelling and that the strain rate effects were only partially modelled on the coupon tests, such simulation were not conducted in this thesis. Such simulation would have a reduced value at the present time but could still be performed, if required with the data set proposed.

## Chapter – 7 Discussions

In this section, some of the important findings will be reviewed and considered further.

### **7.1 *Static characterisation of tufted and untufted composites***

The static characterisation results of tufted and untufted NCF are reviewed in Table 28. The in-plane compressive response of both tufted and untufted laminates were found to be non-linear, while tufting reduced the modulus and strength of the laminates by 10 to 15% in both tension and compression. The responses of  $[\pm 45]$  NCF were different in compression and tension, with a 20% higher strain to failure under compressive loading. This measurement was made possible by the use of DCIM that allowed for large displacement monitoring and was previously underestimated by strain gauges (that failed before 7% strain). For this lay-up, the influence of tufting was more significant in compression. These results are of importance to damage modelling. FE models should ideally differentiate between tension and compression damage properties in the bias direction. Not taking this effect into account for compression in the bias direction could under estimate the energy absorbed by 20% in quasi static loading. In dynamics this difference between tensile and compressive failure strains was not observed and can be ignored.

|                                                                                                            | NCF composites                                                                                     | NCF Tufted composites                                                                                 |
|------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|
| <u>Tension</u><br>Modulus<br>Strength<br>Bias direction<br>Tensile Damage<br>Shear damage                  | High<br>High<br>Highly non linear<br>Low<br>Spread and high                                        | Lower- non linear<br>13% lower<br>Similar to untufted<br>Higher and spread<br>Spread and high         |
| <u>Compression</u><br>Modulus<br>Strength<br>Damage<br>Bias direction                                      | Non linear<br>53% of tension<br>High and spread<br>20% more strain than tension                    | Non linear<br>50% of tension<br>More localized<br>Higher strength and<br>20% more strain than tension |
| <u>Delamination</u><br>Mode I<br>Mode II                                                                   | Low force<br>Unsteady crack                                                                        | Ten fold increase<br>Three fold increase                                                              |
| <u>Specimens with a hole (3mm)</u><br>Strength of [0/90]<br>Strength on [45/-45]<br>Strain field with hole | Reduction by 25% in compression; 23% in tension<br>Reduction of 4%<br>Non symmetric in compression | Reduction by 25% in compression; 19% in tension<br>Reduction of 4%<br>Non symmetric in compression    |
| <u>Response to multi loading</u><br>Elastic response<br>Plastic response                                   | High peak loading<br>Medium energy absorption                                                      | Lower peak loading<br>Higher energy absorption (+30%)                                                 |

**Table 28: Conclusive tufted and untufted NCF properties**

Delamination resistance increased significantly with tufting. Tufted specimens reached higher loads under Mode I, and crack propagation occurred with an increase force in Mode II. The strain energy release rate in Mode I and II was also much higher for the tufted material than for the untufted one. Those findings follow the same trends as the ones using stitching reinforcements<sup>12-14</sup>. Consequently in quasi static the tufted multi loaded discs could absorb 30% more energy as the crack and delamination were progressing with difficulty in the tufted structure compared to the untufted disc. Comparable trends were found by Cartié<sup>18</sup> and Dell'Anno<sup>19</sup>.

## **7.2 Novel damage detection method**

Damage field (see Chapter 3.2.5 and 4.1.4) predicted a good localisation of failure and intensity in all cases. Damage was seen to vary considerably with loading conditions and lay ups. Also, through the thickness reinforcement was observed to affect considerably damage field intensity and localisations. For example, it was observed that the two materials behaved differently when comparing damage in tension and compression for the [0/90] lay ups. Damage intensity was the lowest for the untufted [0/90] specimen in tension while the tufted specimen displayed more damage progression after 0.3% strain. While using this method to detect damage, it was found that the occurrence of the first damage cycle was of extreme importance and this influenced the intensity of the damage factor (Equation 48).

The first unloading cycle, which is the reference in the damage calculation (Chapter 3.2.5) needs to occur at a load consistent for all specimens, to allow comparison of damage fields for various load cases and materials. Effectively, damage must not have yet initiated but nevertheless the specimen must be under an uniform state of stress. If the first unloading cycle occurs at a large loading, the damage would be already initiated which would influence the subsequent damage maps and factors to be computed. On the contrary, if the first unloading cycle occurs before the specimen is homogeneously loaded, then the state of strain is not representative of the actual stress leading to an error in modulus  $E(x,y)$  and damage  $d(x,y)$  computation. Unloading of the specimen occurring between 6 and 9 KN during the first cycle, provided the best results in terms of damage detection.

Stress concentrations were investigated in both tufted and standard NCF. It was found that a 3 mm open hole had little effect on the strength in the bias direction (reduction by 4.2% only) but had more effect on [0/90] laminates (reduction by 19 to

25%) with further effects in compression. Overall, it was found that the effect of tufting proved to be small in the response of the open hole specimens. Strain and damage fields around the hole are likely to be of interest in the design of complex parts.

### ***7.3 Novel compression test in static conditions***

The new compressive apparatus developed in this PhD research (Chapter 3.2.2.2) provided information that was not obtainable previously in compression with standard apparatus and strain gauges or extensometer equipment. This was mainly due to the full field measurements capacity that provided additional information (such as 3D strain and displacement fields with various possible strain extractions) and capture of large deformation. The new apparatus design provided in addition compressive bias direction characterisation (largely non linear) that was not possible on previous smaller specimen (standard apparatus) because the gauge length relative to the specimen width was too small to allow proper shearing of the specimen.

The novel apparatus prove to be extremely reliable (infallible) on cross ply laminates [+45] testing as on [0/90] laminates the test was less precise in term of finding the ultimate strength (Chapter 3.2.2.2). This is understood to be due to the requirement that the specimen is mainly end-loaded, so that the specimen end is required to be flat to load the composites uniformly. Technically this is difficult to achieve during specimen preparation. As the strain to failure is large (+7%) on [+45] any slight improper loading will disappear as the specimen, readjust itself under the load. In the case of the [0/90] the failure strain is small (+0.8%) any specimen readjustments under load is nearly impossible. The specimen preparation influenced then the ultimate strength and failure strain in such test.

Another reason for the large scatter on [0/90] specimens is possible slight misalignment of the 0 degrees layer during manufacture which was difficult to achieve perfectly. A few degrees of misalignment in the layup during specimen preparation or inexact specimen shape following the 0/90 pattern can be the cause of 0 degrees tow misalignment. This would reduce the specimen mechanical properties significantly under compression loading.

To conclude, this new long gauge length apparatus provided a clear strain field that allowed for characterisation of the material in compression with repeatable results, in terms of modulus and strength on the [+45] laminate. Characterisation of modulus proves to be successful (achievable accurately) on the [0/90] specimens with negligible specimen misalignment. Also, some variance was observed on the strength of the specimen. The compressive apparatus has the advantage that it has the possibility to work under static as well as dynamic conditions. This is because, rather than loading the specimens through grips, the load is applied directly at the sample end. This setup permits the use of the drop weight apparatus for impact testing and dynamic loading.

The advantages are:

- Possibility to check for misalignment in 3 dimensions.
- Full strain field on the specimen until compressive failure.
- Possibility to use the visual strain recordings as extensometer to check for misalignment.
- Full stress strain curves recordings.
- Full stress strain curve in compression shear in accordance with tension shear data.
- Possibility to use an optical load cell.
- Possibility to use the rig in dynamic.

The disadvantages of this rig are:

- The rig requires perfect specimen preparation (geometry and fibres orientations)
- Tabbings is required.

## **7.4 High rate testing and material response**

The experimental set ups with different load cell set-ups, loading signals and material layups provided good results and overall coherence throughout the range of strain rates loading.

### **7.4.1 Dynamic in-plane loading**

The SHPB was particularly successful (provided good results) in tension and compression, combined with the DICM method. The compressive drop tower apparatus (Figure 43, Chapter 3.3.2.2) provided strong results (reliable and accurate) for the  $[\pm 45]$  layup. For the  $[0/90]$  lay up the load signal was less accurate and it was understood to be caused by the steel used to improve the load introduction. The drop tower tensile test (Figure 42, Chapter 3.3.2.1) was of interest but would require to be designed with additional strength. The sampling of the load and the strain was particularly difficult in this case; even so the load path to the load cell was straight forward.

The strain rate effects were shown to be of similar order for the tufted and untufted materials apart from the axial compressive load case which showed a stronger rate effect for the tufted laminate.

In general (Table 29) the Young's Modulus in the axial direction for both tufted and untufted composites, remained constant as the shear modulus slightly increased in the bias direction with increasing strain rate. As the strain rate increased, the  $[\pm 45]$  layup response behaved almost linearly; an increase in strength was observed with a reduced strain. In the axial direction ( $[0/90]$ ) load cases, strain and strength increased

with strain rate. These two different trends are found in the literature<sup>26; 88-93; 94-95</sup>. Some authors found increasing failure strains<sup>96-98</sup> while other authors found that the amount of strain would decrease during the dynamic event or would remain comparable<sup>94; 98</sup>. This PhD research shows that the material responses (for example failure strain) to strain rate are non linear and depended on the laminate layup sequence. In particular, a great sensitivity to a small increase in loading speed was observed for biaxial and axial layups. In static compression, it was observed in previous research that an increase in the bias direction failure strains occurred. This effect was not observed to occur at higher loading speeds. Effectively, the response in compression and tension in the bias direction was of the same order in term of stress and strain from intermediate to high strain rates. Therefore, the difference in damage between tension and compression in this layup does not necessarily need to be taken in account for dynamic modelling but is preferred for quasi-static models. Strain rate effects were slightly stronger in compression than in tension for the axial layups. This may be due to reduced Micro-buckling effects (potentially as if Micro-buckling was time dependant) leading to higher material axial compressive strength at high speed. The other possible reasons for such results would be the existence of a scale effect (specimens were not the same size at low and high speed), but this phenomenon would probably have appeared in axial tension (for which specimens had also different dimensions) unless an unforeseen buckling effect came into consideration in compression.

The DICM worked well even at low resolution and high strain rates. But tuning of the camera and appropriate speckle pattern becomes critical for possible post processing. The displacement readings were satisfactory in all cases and conditions as the strain readings would be noisier on large speckle patterns with low pixel

resolution. From displacement fields the generation of velocity, acceleration and strain rate fields are also possible but with reduced accuracy and long processing time. The image frame rate (number of images per seconds) can be so high presently that it might start to capture extremely fast mechanism occurring in the range of 5 Micro-second. Stress waves propagating at  $\pm 6000\text{m/s}$  could start to be detected; However further post-processing is required before holding solid conclusions. The tool could potentially lead to reveal shock waves in composite materials.

|                                                 | With increasing strain rates (up to $400\text{s}^{-1}$ ) | NCF composites                                                                                      | NCF Tufted composites                                                                                                                                                                             |
|-------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Tensile dynamic response</b><br><u>Axial</u> | Modulus<br>Strength<br>Strain                            | Close to quasi-static (63 GPa)<br>Increasing (up to 25%)<br>Increasing (up to 25%)                  | Close to quasi-static (56 GPa)<br>Increasing (up to 25%)<br>Increasing (up to 25%)                                                                                                                |
| <u>Bias direction</u>                           | Modulus<br>Strenght<br>Strain                            | Nearly linear now<br>Increasing (up to 50%)<br>Decreasing (up to 60%)                               | Nearly linear now<br>Increasing (up to 50%)<br>Decreasing (up to 60%)                                                                                                                             |
| <b>Compression in dynamic</b><br><u>Axial</u>   | Modulus<br>Strength<br>Strain                            | Close to quasi-static<br>Increasing (up 45%)<br>Increasing (up to 45%)                              | Close to quasi-static<br>Increasing (up 45%)<br>Increasing (up 45%)                                                                                                                               |
| <u>Bias direction</u>                           | Modulus<br>Strenght<br>Strain                            | Nearly linear now<br>Increasing (up to 50%)<br>Decreasing (up to 60%)                               | Nearly linear now Same<br>Increasing (up to 50%)<br>Decreasing (up to 60%)                                                                                                                        |
| <b>Dynamic delamination</b>                     | Mode I<br><br>Mode II                                    | No rate effects<br>Stick-slip response at high speed<br><br>Unsteady crack speed<br>No rate effects | Rate effects during crack initiation<br>Reduced crack speed<br>Stick-slip response<br><br>Slight rate effect measured. Crack speed reduced significantly<br>Rate effects during crack propagation |
| <b>Impact response</b>                          | Elastic response<br>Plastic response                     | Close to quasi-static<br>Hold the load longer than in quasi-static                                  | Close to quasi-static<br>Hold the load longer than in quasi-static                                                                                                                                |

**Table 29: Conclusive tufted and untufted NCF properties in dynamic**

### **7.5 Dynamic delamination Mode I**

The testing method, analyses and the new materials required full attention and careful partition of the results to avoid any misunderstandings of the results and

responses. The chosen material was not the simplest for which to monitor dynamic delamination and a UD prepreg laminate would have been simpler. Also the [0/90] textile composite with a [0/0] crack interface was the best layup possible solution for the NCF case that had to be characterised for the ITOOL project. This material had half the stiffness of comparable UD composites but was not much different in other respects from the UD pre impregnated case. A more complex material was also investigated which was the same NCF composites but tufted through the thickness (except at the precrack location). The new set up and new analysis allowed the successful high speed delamination comparison of untufted and tufted NCF composites up to 3 m/s.

The manner in which the crack propagates in Mode I was different with and without the tufts reinforcement. The stick-slip response was stronger for the tufted interface with inconstant crack propagation and reduced delamination speed by 70%. The untufted interface revealed no bridging but light reflection disparity (in line patterns), probably due to interface roughness differences being caused by crack speed variation or, more precisely, by the stick slip response. The tufted interface showed a strong bridging effect and tuft failures with no tuft sliding effect, unlike the Z pinned pre impregnated laminates. At high speed, the rate analysis did show rate effects at the crack initiation location that was stronger for tufted interface. This rate effect disappeared during the crack propagation for both materials in the range of validity of the test (the tests is only valid until 3 m/s as demonstrated in part 5.3.2).

#### **7.5.1 On the new load cell set up**

The setup showed more force signal oscillations for the tufted than untufted material that increased with speed. The new load cell set up showed reproducible results for the tufted interface. The tufted interface required a significantly larger

amount of force to start the crack. The delamination speed was much reduced in that case which meant that the new load cell set up worked well with a large amount of force and low crack speed. On the contrary the untufted interface showed irreproducible load recording. It was not clear if this was due to the apparatus or to the material, initially. It was possible that pre-crack minute flaws could influence the crack initiation and force response at high loading speed. Depending on the pre-crack states, the crack initiation would vary which could influence the load results. The other possible explanation was that the load cell did not fully capture the load at such a low level of the force, due to possible friction in the specimen holder. Finally, the simulations have shown that at high speed, the force in the upper arm was limited with this set up due to early crack failure. It is difficult to assess precisely which of those 3 causes is responsible for the reduced load acquisition of the untufted response to loading rate, but a combination of those 3 effects is likely. Therefore, the load cell set up did not prove useful in this research and a new approach of assessing the loading rate had to be addressed: the optical analysis.

### **7.5.2 On the optical analysis**

The use of the specimen's static compliance combined with optical analysis and crack recording provided interesting results at high speed. An assumption is that the beam compliance at low velocity did not bear strain rate effects. In plane rate effects on this material have been investigated and were showed to be limited in term of stiffness (Chapter 4.2.4). Optical analysis of cracks and arm displacements combined with arm compliance proved to be a good approach, to detect rate effects by the computation of the dynamic  $G_{IC}$ . It provided accurate strain energy release rate calculations in dynamical cases that would not have been made possible by the use of load cell recordings. The optical analysis also suggests that the load cell discrepancy

found for the untufted material is probably due to friction than to an effect of crack initiation defects that would drive the crack differently at high speed as the force calculated were pretty stable and reproducible.

### **7.5.3 On the dynamic delamination simulations**

Cohesive elements with adequate parameter estimation provided modelling of the crack interface in dynamic tests. The P links also provided modelling of the tufts with the untufted interface acting as a resin layer that provided a good representation of the tufted material. Further simulations have shown that the load recording in both arms become significantly different above 3m/s if only one arm was loaded. This had the effect to load the crack in a combination of Mode I and II. Simulations showed this effect would also appear for UD laminates. The simulations also showed that loading both arms at high speed would provide appropriate loading of the crack and allow rate effect investigation for rates as high as 20 m/s. The model also showed that load concentrations were evidenced at the crack tip location and up to 20 mm away from the crack after which the interface was not loaded anymore.

### **7.5.4 How to achieve mode I loading without exciting other modes**

The slight rate effect noted in the unreinforced interface, while using the optical analysis, was due to improper specimen loading above the 3m/s loading rate or 8 m/s crack speed. The test pictures of the untufted interface suggested that both arms did not bend in the same amount above that loading rate which was confirmed by the simulation monitoring difference force intensity in the DCB arms. The rate effect found above 3m/s loading rate for the untufted composites was therefore due to a combined delamination mode occurrence and not to the material itself.

### **7.5.5 On the validity of the dynamic delamination tests in Mode I**

If only one arm is loaded, the simulations, the load cell recording and the optical analysis showed that above 3 m/s, the untufted interface could not transmit the stresses in the upper arm properly and that the results could not be used for analysis. Furthermore, for the tufted NCF, a thicker laminate and stronger fastened loading blocks must be used as the force to initiate the crack increased significantly with increased loading speed. This led to laminate damage and loading block disbonding above the 3m/s loading rate.

### **7.5.6 Comparison with the literature**

The literature discrepancy (Chapter 2.8.1,  $G_{IC}$  dependent on the rate of loading<sup>106-108; 110; 117</sup> or not<sup>111; 112</sup>) is understood to be due to load signal acquisition difficulties. Furthermore in some cases researchers only loaded one arm and this generated mixed loading from a certain loading rate (superior to 3 m/s). In this PhD research, similar findings were obtained even with the new load cell set up specially designed for improving load recording. For the tufted interface, the new load cell set up showed encouraging results. Blackman<sup>111; 151</sup> found by loading one arm that no mixed mode loading was detected unlike in the present research. But Hug<sup>112</sup> has acknowledged that mixed mode loading is a possibility and he designed an experimental set up which used both arms in loading. This present thesis shows that there is a mixed mode loading occurring above 3m/s loading rate while loading one arm only and recommends an experimental set up like the one of Hug<sup>112</sup>, but with a constant delamination speed. Effectively, Hug<sup>112</sup> managed such an experiment but had to use 15 high loading rate load cycles to delaminate a specimen which meant that the delamination was not continuous. Kusaka<sup>117</sup> managed to load both arms at high speed

in a SHPB using a wedge insert. Such experiment should provide pure Mode I at high rates but load acquisition and optical analysis might not be possible.

In the range of validity of the tests (below 3 m/s), no rate effects were noted for the untufted interface apart from a positive crack initiation rate effect that disappeared during propagation. These results are in accordance with the work in a similar speed range of Blackman<sup>111; 151</sup> and Hug<sup>112</sup> that detected no or little rate effect. Also Blackman<sup>111; 151</sup> found a negative crack initiation rate effect as the present study found a positive crack initiation rate effect (the present study found a positive crack initiation rate effect).

Tufts showed fibre failure mechanism and initial rate effects during crack initiation which disappeared during crack propagation which are, in accordance with the literature<sup>114; 115; 118</sup> (Chapter 2.1.4) that used through the thickness reinforcement. The tufted interface showed strong bridging effects and tufts failures with no tuft sliding effect as in Z-pinned laminate. The literature used load cell acquisitions that proved very difficult in some experiments. This PhD research proves the benefit of using optical analysis for rate investigation in such cases.

#### **7.5.7 Open questions about dynamic delamination Mode I**

Delamination occurs at high speed during an impact event and reproducing such crack speed and loading on a beam that bends and oscillates is not ideal, especially as the speeds are increased significantly. Some authors have tried using Hopkinson bars to move away from the DCB specimen and provided sensible results. It is possible that other researchers could think of specimen types that are more appropriate for high speed loading than DCB specimens, which would reduce force oscillation on the crack. Thinking of new specimens geometries that do not bend so much might be of interest at higher speeds with optical analysis (such as impact wedge insert used by

Kusaka<sup>117</sup>). The loading of both arms have been carried by Hug<sup>112</sup> but at relatively low speed with discontinuous loading cycles; the simulations in this research have showed it would still carry Mode I crack loading at higher speeds. This solution is potentially the best using continuous loading. Also, loading both arms of a DCB at the same time is a difficult engineering challenge at higher speeds as synchronization will require strong accuracy to avoid mixed mode loading.

### **7.6    *Dynamic delamination mode II***

Delamination Mode II is characterized by a stick-slip crack propagation that is more intensive during low speed loading. Image analysis during delamination suggest pure Mode II loading for both interfaces loaded at various speeds.

Tuft influence on delamination Mode II of carbon epoxy NCF proves to be beneficial in static loading. Effectively, without tuft reinforcement, the crack propagates rapidly and the specimen quickly loses its stiffness and ability to resist loading. It is characterized by a sharp drop in load after crack initiation. In this case, crack initiation values are much larger to crack propagation values. If the interface is reinforced by tufts, the specimen continues to withstand increasing loading during the crack propagation phase. But crack initiation occurs at comparable loading values to the standard interface.

For the standard interface case, the load dropped during crack propagation but for the tufted interface the load increased during crack propagation. This influenced directly the  $G_{IIC}$  readings for both interface. The standard interface strain release energy rate in Mode II would be of around 2000 J/m<sup>2</sup> and dropping to about 1500 J/m<sup>2</sup> during crack propagation. The tufted interface would initiate delamination also at 2000 J/m<sup>2</sup> but this value would double during crack propagation to over 4000 J/m<sup>2</sup>. In this latter case a positive rate effect was observed.

The standard interface proves to have catastrophic behaviour in dynamic Mode II and the crack propagated at various speeds without any correlation with the specimen loading speed. In contrast the reinforced interface crack speed was linked positively to the loading speed. Crack propagation velocity could reach extremely high values in the standard resin interface case but, if reinforced by tufts, it would be reduced by a factor of about 7 to values similar to Mode I crack speed.

The load acquisitions proved to lack accuracy during crack propagation as the signal oscillates greatly at high speed, so that even filtering could not be used successfully. This made impossible investigation of rate effect through  $G_{IIC}$  calculation with a classical approach through load analysis. Therefore, optical analysis through careful optical crack and displacement measurement combined with specimen geometry and flexural properties, proved of interest. It allowed the calculation of the specimen compliance and therefore of the load during delamination. The technique proved accurate in static tests, and if applied in dynamic tests, it permitted  $G_{IIC}$  calculation for various crack speeds. No rate effects were seen in the standard interface but a slight increase in  $G_{IIC}$  with increasing crack speed was noticed for the tufted interface.

Unlike Mode I, the crack propagation was not obvious in Mode II and capturing its propagation at high speed was challenging. The Photron 1024PCI proved to be limited with low resolution (256\*256) for frame rates ranging between 6000 to 10000 images per second that made accurate crack tracking difficult. The chance to use an alternative camera occurred and it was found that the Photron SA1 with 1024\*896 at 6250 frame per second allowed accurate crack propagation tracking.

Overall, the tufts were beneficial in the dynamic Mode II response as they increased energy absorption considerably, reduced crack speed largely and possessed a slight rate effect.

### **7.7 *High speed in plane modelling: calibration***

The model could represent damage at quasi-static speed well in tension and compression but could not reproduce the failure strain difference between tension and compression in the bias direction. This is not important for dynamic models as, at higher loading, this experimental trend seemed to disappear. In axial high speed tension, the model results were excellent. In axial high speed compression, the representation was less successful; this is understood to be due to the size of the specimen model and to the strain rate laws which can only use either tensile or compressive strain rate effects. Allowing a differentiation between the two would lead to an increase number of the number of material parameters. Results were mixed at high speed in the bias direction.

The failure strain reduction and stress increase occurring at high rates could only be partially modelled because the present law is defined for a material response that was not found to appear in this PhD research. The law is defined for  $R_0$  (initial yield stress) to decrease but here  $R_0$  was found to increase experimentally.

The composite materials response being complex one can speculate how many material parameters are required to model it accurately for all layups, load cases and speeds. It seems the existing compromise is accurate for in- plane loading but already uses more than 33 parameters in the standard Ladeveze model<sup>10</sup>. For more accuracy could be implemented such as differentiation between tension and compression strain rate effects and modification of the shear strain rate law.

### **7.8 Parameters calibration and validation study**

Out of plane modelling on one shell or a stack of shells proved to be particularly difficult. The material model had a large number of parameters. For the UD damage ply model<sup>10</sup> not less than 34 parameters were required. Another 10 can be added for delamination and another 10 for strain rate representation. So that one material can require up to 55 parameters and even more if tufting is added.

For these parameters that need to be calibrated, the following issues will have to be addressed during calibration.

- Calibration of parameters following standard procedure such as the one recommended in PAM-CRAH<sup>8</sup> manual and in Ladeveze article<sup>10</sup>.
- Parameters that cannot be calibrated for some specific reasons such as during the use of a NCF fabric for UD ply model which means that some parameters are not obtainable experimentally ( $E_2$  and  $\nu_{12}$ ).
- Parameters that cannot be usually calibrated but that are attempted to be calibrated such as the initiation and propagation stresses in delamination Mode I and II.
- Parameters that are wrongly calibrated. This is a possibility especially when the parameters calibration do not follow an existing procedure (initiation and propagation stresses in delamination mode II)
- Parameters calibrated correctly but the FE model boundary conditions load more some of the parameters due to the boundary conditions to be slightly different in the model and the experimental set up leading to different responses between the model and the experiments.

This list of possible difficulties was experienced by the author and anyone using such model will have to face such difficulties. Apparently some parameters need to be

calibrated for specific purposes to reproduce the experimental results. A correctly calibrated in-plane parameter can turn out to be wrong for some loading cases such as specific out-of-plane loading. The software make a best attempt to reproduce extremely complex mechanisms but sometimes struggles in loading cases that combine compression, tension and delamination Mode I and II. It is still possible to run such simulation by modifications of materials parameters away from their calibration target but such process reduces the value of the simulation. Impact simulation out-of-the plane requires 4 to 5 parameters to be arbitrarily changed: Mode I and II initiation and propagations stresses (4 parameters) and possibly tensile or compression failure strain. Ideally the shear strain rate law should also be modified but in the code itself. The calibrated Mode I and II initiation and propagations stresses (4 parameters) behave well in pure mode I loading though. For this reason and time constraints no dynamic simulations were ran in impact mode but only in dynamic tension, compression and shear.

## Chapter – 8 Conclusions

In conclusion, the contribution to knowledge from this PhD research is summarised as follow:

### **8.1 *Consideration of novelties under static loads***

#### **8.1.1 Material characterisation:**

The full in plane and out-of-plane static characterisation of untufted and tufted carbon NCF and RTM6 resin took place<sup>152</sup>. It permitted the measurements of the elastic characteristics and damaging properties as well as the observance of the failure mechanism for various load cases. This test matrix and the measurements methods were novel on such composite materials. DIC measurements were used during in-plane characterisation which provided added measurements accuracy at high level of deformation (tension, compression and shear). Compressive strength in the axial direction showed lower strength than in tension as in the bias direction compressive and tensile responses were almost evenly matched. In reality composites structure in their in service life are subjected to multiples loading that the punch disc test permitted to represent to some extent. It offered a validation study of out of plane loading on the composite structure.

Comparison of tufted and untufted composite responses and mechanical properties enabled for appreciation of the effect of tufting on in plane and delamination responses<sup>152</sup>. Tufting effect reduced in plane properties in the case of laminate with axial fibres but had little effects on ones with bias directions layup. Out of the plane tufting improved significantly the delamination resistance in mode I and II.

### **8.1.2 Testing:**

The developments of a novel compression apparatus for DICM capture<sup>152; 153</sup> permitted the monitoring of strains and strain fields in compression. Such test provided good results on cross ply laminates [+45] in term of strength, strain and stiffness measurements. It was less efficient to capture accurately the maximum strength of [0/90] specimens but stiffness measurements were accurate. Such novel test and methods allow for the measurements of displacements or strain fields in compression which are of interest for the development of Photo-mechanic research field and the better understanding of compressive damage and failure mechanisms.

### **8.1.3 Damage detection methods: entering the world of Photo-mechanic:**

A novel method to detect damage with the use of DICM was developed. Damage was recorded in tension, compression shear tension, and shear compression for untufted and tufted laminates<sup>152</sup>. Such data enabled the comparison of damage propagation in the tufted and untufted materials. Such results were really novel and such methodology belongs to the field of Photo-mechanic research. The methodology is simple to use and can provide maps of damage progression for specimens or even structures.

### **8.1.4 Modelling:**

Modelling of untufted and tufted NCF in the plane and out of the plane<sup>153</sup> was permitted by the experimental acquisition of the material properties which in many respect were novel. So that, if the model material laws were not new the materials parameters obtained were novel. The in the plane calibration of Ladeveze UD model for NCF composites<sup>152</sup> permitted to model coupon specimen accurately. The estimation of delamination parameters using the novel technique developed by Dr Skordos provided good results in pure mode I<sup>153</sup>.

Further modelling aspect of novelty were the representation of tufts via P-Link as shown by Professor Pickett<sup>153</sup>. Such method provided good results in delamination Mode I as in Mode II further work remained which consist of tufts strength measurements and further model calibration.

The model was validated through multi-loading by means of a punch on a disc.

In the case of the disc modelled as a single shell, models and experimental results agreements were obtained by only the means of using a larger impactor than in the experiments and increasing the model compressive failure strain. The results of this validation study showed that among the 30 material parameters 2 needed to be tuned manually (not calibrated values to be used) to obtain a model response in accordance with the experiments. This is understood to be due to the nature of the loading (out of plane) and contact between the punch and the disc that over stress and over damage locally a few elements of the disc during contact. In reality in the experiments the area of contact between the punch and the disc is larger due to the formation of a dent which spread more the load and reduced the speed of damage progression on the disc. It is understood that during out of plane loading, increasing compressive failure parameters would be unnecessary to take in account the formation of a dent.

The second model validation was a multilayered shell laminate disc with delamination representation punched in its centre. The model and experiment agreements were also obtained by means of increasing a few calibrated parameters: this time it was stress initiation and propagation in delamination mode I and II. Those parameters corresponded to stress intensity factor and are particularly difficult to obtain.

The method based on crack opening to calibrate those prove correct only in Pure Mode I. Thermographic stress analysis or DIC during delamination of DCB, ELS or compact test specimens could be away to measure those stress intensity factors.

## **8.2 *Consideration of novelties under dynamic loads***

### **8.2.1 Material characterisation**

The full characterisation of Untufted and Tufted carbon NCF composites (RTM6 resin) at low ( $\pm 1\text{s}^{-1}$ ), intermediate ( $\pm 20\text{s}^{-1}$ ) and high strain rates ( $\pm 400\text{s}^{-1}$ ) in tension, compression (not low characterisation in compression), shear and shear compression<sup>154</sup> took place. From these tests and measurements the novel data gathered (Table 14-21) for different load cases and lay ups showed the modification of the material response as the speed of loading was increased. Such data set is a fine tool to calibrate or generate material models constitutive laws for impact simulations. For both tufted and untufted NCF composites, strong strain rate effects were detected from a low loading speed which increased the in-plane strength and failure strain of [0/90] layups as no or little effects were recorded on the material stiffness. Such strain rate effects were thought to be slightly stronger in compression than in tension. In the bias-direction failure strain decreased as strength increased with increasing loading rate so that at high strain the material response became almost linear. The elastic stiffness remained through loading with only a very slight increase detected if any. Comparison of tufted and untufted materials at high speed allow for appreciation of the effect of tufting. During in-plane testing in quasi-static, tufting reduced the compressive and tensile strength. At intermediate and high strain rates, strength reduction of the tufted material compared to the untufted one was only observed in tension but not in compression<sup>154</sup>.

Dynamic delamination monitoring in Mode I was carried out up to 3 m/s and in Mode II up to 5 m/s for the untufted and tufted NCF RTM6 composites. Tufts reduced crack speed considerably while increasing  $G_{IC}$  and  $G_{IIC}$ . No rate effects were monitored apart at crack initiation for the tufted material and at crack propagation in mode II also for this material.

The Impact loading of tufted and untufted discs to assess rate effects during out-of-plane loading, showed slight negative rate effect with no major differences between tufted and untufted responses. Such result is understood to be due to the fact that no fibre failure occurred and that delamination energy was not high enough to provoke tuft ruptures. The negative loading rate effect could be due to simply a contact change and a reduced dent formation at higher loading speed. The mode of damage was found to be delamination mode II mainly. The running of higher impact energy tests would be of interests to foresee if such trends would also be true when fibres and tuft failure occurs.

### **8.2.2 Testing**

The usage of dynamic DICM via high speed camera on tensile hydraulic machine at 10000 images/s was carried out. For intermediate strain rate a tensile and compressive apparatus<sup>154</sup> were designed. The compressive apparatus was the same as the one used in static. The tensile apparatus used a novel load cell set up (a static load cell). Strains were monitored with high speed DICM (40000-80000 image/s). Stress strains curves were produced by sampling load and strains.

At high strain rates the usage of SHPB in tension, compression, shear and shear compression was carried out. The strains were monitored with ultra-high speed DICM (200000-500000 image/s)<sup>154</sup>. Stress-strain curves were produced by sampling loads acquired from the bar via a strain gauge and the strain acquired optically

directly on the specimens. Such method proved to be of particular interest, novelty and reliable. Overall the use of high speed DIC leads to Photo-mechanic in the form of the possible computation of added field such as velocity and acceleration fields which could potentially lead to force fields.

A novel dynamic mode I test was designed. At the design stage of this test, help from fellow researchers are acknowledged (Dr Lamb<sup>149</sup> and Mr May<sup>141</sup>). The static load cell, optical approach was well validated to compute  $G_{IC}$  and to assess rate effects. An assessment of crack speed was also possible. The test was found to be only valid up to 3 meters per second loading speed.

In dynamic Mode II a modified ELS test was proposed that used a drop weight as mean of load introduction on the specimen. An optical approach was used to assess rate effects and was moderately validated to compute  $G_{IIC}$  due to difficulty with the calibration factor. Also the assessments of crack speed were relatively accurate with such tests.

Impact disc loading at intermediate loading rate (2-5 m/s) took place. The running of tests with higher mass and velocity is of interest.

### **8.2.3 Modelling**

The model used strain rate laws in tension, compression and shear for the untufted and tufted carbon composites. If the material was not new the experimental data set was and therefore so was the dynamic model. The material strain rate laws work well in tension and compression, but less well in shear<sup>154</sup>. The materials strain rate laws used either tensile or compressive parameters so that if the structure was under compressive and tensile dynamic load some averaging would be required. Developing the law for this usage would not be complex but would add further material parameters to the already very long list.

The dynamic delamination mode I model was fully working with calibrated parameters and proved helpful to represent the DCB behaviour at high speed and the understanding of possible mixed mode crack loading occurrence. In mode II a model instability in high speed delamination was detected.

### **8.3    *Overall conclusion***

This research showed the complexity of the failure mechanism occurring in composite materials. Modelling them at high speed in the plane and in impact remains a difficult challenge. The sensitivity to damage of some load cases (compression, impact, delamination) and lay-up (bias direction) means that aging composite air frame would require frequent non destructive monitoring and that safety factors needs to remain at a high level.

## Chapter – 9 Further work

Some potential research paths are now proposed.

- Modification required on the current finite element model.

The present NCF damage model requires further refinement of some parameters on the delamination Mode I and II propagation and initiation stresses. The problem is that obtaining the stress intensity factor experimentally is difficult and the attempted method used in this research requires further investigations. Other means of obtaining the stress intensity factor could be Thermo-elastic stress analyses or DIC. The in plane damage model requires in addition the modification of the in-plane strain rate laws in shear. Strain rates laws should ideally differentiate between tensile and compressive strain rate effect and for this the model modified. In addition the possibility of model instability in high speed delamination Mode II exists, and further investigation is required to check this potential difficulty.

- Novel concepts that could be explored for generating impact models.

- For structures that can be loaded in and out-of-plane, the idea of an out-of-plane-calibration surimposed on a in-plane calibration is of much interest. This added impact calibration method could make some parameters (such as the ply failure strains) more robust under impact.

- Another—possibility which requires less testing time for structure specifically loaded in impact is to use a simple composite (elastic) model and to calibrate it specifically in out-of-plane impact. Materials laws could be developed for such responses (which could be cyclic impact loading with rising impact energy).

- As a data base now exists for tufted laminates the full advantage of the modelling of tufts as P links could become available but it would require in addition the values of experimental tufts tensile and shear strengths.

Further validation studies could be extended such as dynamic crashing of tubes or dynamic bending of hollow beams which could perhaps add confidence on the validity of the current model. A high speed delamination mode I test with both arms loaded combined with the optical analysis would also be of interest to assess loading rate effect on Mode I delamination at higher speed than 3m/s.

Optical DIC method can generate damage fields through calculation on the strain field. The method could be applied to more complex 3 D structures and could perhaps be adapted to impact damage detections. With the dynamic DICM and high speed cameras, kinematic fields such as velocity and acceleration fields can be obtained. If the mass of the specimen and the acceleration fields are known, it might be possible to get the force field which could perhaps lead to the stress fields. This would allow bypassing the use of load cells in dynamic tests. Dynamic DICM is also approaching the time at which stress waves propagate, and shock waves could possibly be monitored which would be of interest to crashworthiness and defence industrial sector.

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## Appendix 1: Micro-mechanics for stiffness and strength (source Matthews<sup>1</sup>)

### Micro-mechanics for stiffness

Micromechanics for stiffness from the rules of mixtures:

$$E_{11} = \beta_1 * \beta_2 * E_f * V_f + E_m * (1 - V_f) \quad (\text{Rules of mixtures})$$

Source: Matthews<sup>6</sup>

Where:

- $V_f$ : is the fibers percentage in volume of the composites, depends

on the manufacturing process.

$V_f = 60\%$ : autoclave vacuum bagging.

55%: for vacuum bagging.

40%: for hand laminating.

Note:  $1 - V_f = V_m$  matrix percentage in the composites.

- $E_f$ : the young modulus of the fibres.
- $E_m$ : the young modulus of the resin.
- $\beta_1$ : Depends of the fabrics type:

$\beta_1 = 1$     unidirectional layer

$\beta_1 = 0.5$     woven fabric 0/90

$\beta_1 = 3/8$     random in plane

- $\beta_2$ : Lengths correction factor for short discontinuous fibres, (if continuous  $\beta_2 = 1$ )

- Longitudinal stiffness ( $E_{11}$ ) which is the elastic modulus in the longitudinal direction.

- Transverse stiffness  $E_{22}$

$E_{22}$  is the elastic modulus in the 2 direction

$$\frac{E_m}{E_{22}} = \frac{V_f}{\frac{E_f}{E_m}} + V_m \quad \text{or} \quad E_{22} = \frac{E_m}{\frac{V_f}{\frac{E_f}{E_m}} + V_m} \quad \text{source: Matthews}^6$$

For the transverse stiffness a corrected model can be used

- Shear Modulus  $G_{12}$  (in plane shear modulus in 1-2 axes)

$$\frac{1}{G_{12}} = \frac{V_f}{G_f} + \frac{V_m}{G_m} \quad \text{or} \quad G_{12} = \frac{1}{\frac{V_f}{G_f} + \frac{V_m}{G_m}} \quad \text{source: Matthews}^6$$

- Poisson's ratio  $\nu_{12}$  (major poisson's ration)

$$\nu_{12} = \nu_f * V_f + \nu_m * (1 - V_f) \quad \text{Source: Matthews}^6$$

Another equation that is useful to characterize a single ply is the way to calculate the ply thickness from the area / weight, the volume fibers fraction and the density

$$t = \frac{\text{weight} / \text{area}}{V_f * \rho_f}$$

### Micro-mechanics for strength

If micromechanics for stiffness are relatively accurate it is much more difficult to obtain proper complete model for strength because of the diversity of the failure mode. Though for unidirectional layer some model exist. In this review not every model will be studied only the one of those that is relevant for the study will be considered.

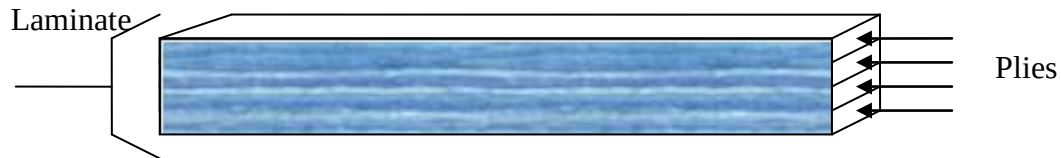
The followings models will be only applicable for unidirectional fibers with a high fibers fraction volume.

Longitudinal tensile strength:  $\sigma_{1t}^*$  dominated by the fibers strength.

$$\sigma_{1t}^* = \sigma_f^* * V_f$$

Longitudinal compressive strength:  $\sigma_{1C}^*$  dependant on resin properties, and bond strength and void content.

$$\sigma_{1C}^* = \frac{Gm}{(1-Vf)}$$



Also Matthews acknowledges that this formula over estimate the compressive strength compared to experimental tests. And so the value calculated will need to be lowered.

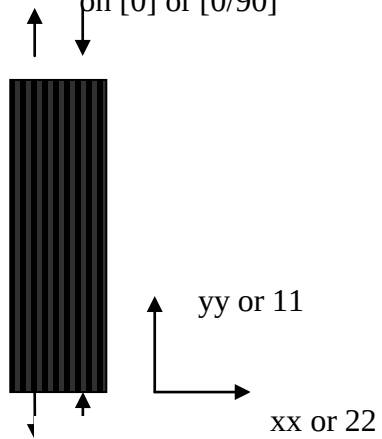
Transverse tensile strength  $\sigma_{2t}^*$ , has the particularity to be low compare to  $\sigma_{1t}^*$  and it is often less than the strength of the matrix polymer.

$$\sigma_{2t}^* = \sigma_m^* \left[ 1 - \left( \frac{Vf}{\pi} \right)^{1/2} \right]$$

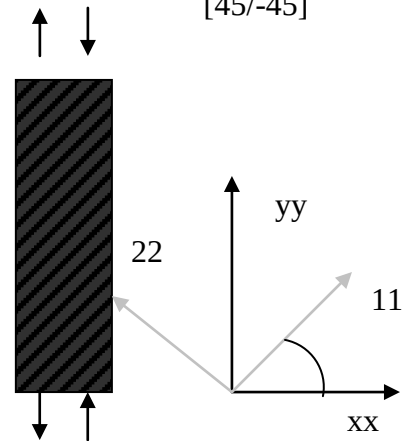
For transverse compressive strength and in plane shear failure, no proper model exists and so no approximation can be calculated which make the estimations of data sheet and approximations compulsory.

From the four tests mentioned above compression testing remains the most difficult to understand and use. In this research tensile response of composite laminates were characterized in the fibre direction and in the shear direction that characterise part of the elastic response of such material. On NCF type composite this can only be achieved on axial test on [0/90] specimen and tensile tests on [+45] degrees. Figure below shows the shear and axial testing methodology.

Tensile or compressive axial loading  
on [0] or [0/90]



Tensile or compressive shear loading  
[45/-45]



$$\sigma_{12} = \frac{\sigma_{yy}}{2}$$

$$\varepsilon_{12} = \frac{\varepsilon_{yy} - \varepsilon_{xx}}{2}$$

## Appendix 2: Classical guide laminate<sup>1</sup>

The final, or ultimate, failure load of an angle ply laminate is often coincident with, or only slightly higher than, the load to cause initial failure. This is not necessarily the case for other lay-ups and final failure can be at a considerably higher load than that to cause first ply failure.

It is clear that once a ply has sustained failure its stiffness in certain directions will have been reduced. However, unless the damaged ply has completely delaminated from the rest of the laminate it will still contribute to the overall stiffness of the plate. The magnitude of this contribution depends on the amount of damage, the fibre/matrix combination and the nature of the loading on the ply.

In general an iterative method is adopted, successively applying the approach described in section 9.3.1 until final failure has occurred. As a starting point the relative value of the forces and moments ( $N_x$ ,  $N_y$ ,  $N_{xy}$ ,  $M_x$ ,  $M_y$ ,  $M_{xy}$ ) acting on the laminate will be known from, say, a structural analysis of the component being designed. Alternatively a parametric study of a range of lay-ups could be carried out for an arbitrary set of load values. The steps taken are as follows.

1. Apply, in the previously-determined ratio, a small value of the loads to the laminate under consideration.
2. Using laminate analysis determine the plate strains and curvatures and hence the stresses and strains in each ply (in the principal directions).
3. Apply the chosen failure criterion to each ply.
4. If no failure has occurred increase the loads (maintaining their relative magnitudes) by the appropriate factor to give first ply failure.
5. Reduce the stiffnesses in the damaged plies and recalculate the **A**, **B** and **D** matrices.
6. Repeat steps 2 and 3 until no further failures occur.
7. Repeat steps 4, 5 and 6.
8. Repeat step 7 until failure (i.e. fibre fracture) of the last ply takes place. This defines the ultimate strength of the laminate.

Source: Matthews<sup>1</sup>

## Appendix 3: Impact energy <sup>43</sup>

- The strain energy is then,

$$U = \int_0^{\epsilon} \sigma d\epsilon$$

and the material obey Hookes law so that

$$U = E \epsilon^2 / 2 = \sigma^2 / 2 E$$

So, in a rectangular beam, for example, of width b, depth d and length l the strain energy stored will be.

$$U = \sigma^2 (b * d * l) / 2 E$$

- Greene <sup>[10]</sup> observed that the energy a composite panel can absorb for small deformations is:

$$energy = \frac{\sigma^2 ALr^2}{6Ec^2} \text{ with the } \sigma = \text{stress, } A = \text{cross sectional area, } r = \text{the depth or thickness}$$

of the panel, E=Young modulus, c the distance from the neutral axis to the outermost fiber of the beam.

## Appendix 4: Ladeveze model more information (Dr Skordos and PAM-CRASH™)

### Fiber Tensile Damage

The implemented law implies that the fiber damage is zero while  $\varepsilon_{11} < \varepsilon_1^{ft}$ , where  $\varepsilon_1^{ft}$  corresponds to the initial longitudinal fiber tensile damage threshold strain. Then the tensile fiber damage  $d^{ft}$  grows linearly between  $\varepsilon_1^{ft} \leq \varepsilon_{11} < \varepsilon_u^{ft}$  where  $\varepsilon_u^{ft}$  is the ultimate longitudinal fiber tensile damage strain. When this ultimate value is reached, the fiber tensile damage  $d^{ft}$  reaches the ultimate damage,  $d_u^{ft}$ . After this point, the tensile damage grows asymptotically towards  $d^{ft}=1.0$ , see Figure (ii).

The longitudinal damaged tensile Young's modulus calculation can be summarized as follows:

$$\begin{aligned} \text{sub-critical} & : E_1 = E_1^{0t} & \text{if } \varepsilon_{11} < \varepsilon_1^{ft} \\ \text{critical} & : E_1 = E_1^{0t}(1 - d^{ft}) ; d^{ft} = d_u^{ft} \frac{\varepsilon_{11} - \varepsilon_1^{ft}}{\varepsilon_u^{ft} - \varepsilon_1^{ft}} & \text{if } \varepsilon_1^{ft} \leq \varepsilon_{11} < \varepsilon_u^{ft} \\ \text{post-critical} & : E_1 = E_1^{0t}(1 - d^{ft}) ; d^{ft} = 1 - (1 - d_u^{ft}) \frac{\varepsilon_{11}}{\varepsilon_u^{ft}} & \text{if } \varepsilon_u^{ft} \leq \varepsilon_{11} < \infty. \end{aligned}$$

### Fiber Compressive Damage

Furthermore, the longitudinal compressive Young's modulus is calculated as follows.

$$\begin{aligned} \text{sub-critical:} & E_1^c = E_1^y & \text{if } |\varepsilon_{11}| < \varepsilon_1^{fc} \\ \text{critical:} & E_1^c = E_1^y(1 - d^{fc}) ; d^{fc} = d_u^{fc} \frac{|\varepsilon_{11}| - \varepsilon_1^{fc}}{\varepsilon_u^{fc} - \varepsilon_1^{fc}} & \text{if } \varepsilon_1^{fc} \leq |\varepsilon_{11}| \leq \varepsilon_u^{fc} \\ \text{post-critical:} & E_1^c = E_1^y(1 - d^{fc}) ; d^{fc} = 1 - (1 - d_u^{fc}) \frac{|\varepsilon_{11}|}{\varepsilon_u^{fc}} & \text{if } \varepsilon_u^{fc} \leq |\varepsilon_{11}| < \infty, \end{aligned}$$

## Strain rate calibration

$$\dot{\epsilon}_{11}^{ref} = \dot{\epsilon}|_{\text{quasi-static velocity}}$$

| X                                                                                                       | F <sub>1</sub>                                                                                  | F <sub>2</sub>                                                                                                |
|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| $\frac{\dot{\epsilon} _{\text{quasi-static velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$ | $\frac{E_{11}^0 _{\text{quasi-static velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$ | $\frac{\epsilon_{11}^R _{\text{quasi-static velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$ |
| $\frac{\dot{\epsilon} _{2\text{nd velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{E_{11}^0 _{2\text{nd velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{\epsilon_{11}^R _{2\text{nd velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$          |
| $\frac{\dot{\epsilon} _{3\text{rd velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{E_{11}^0 _{3\text{rd velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{\epsilon_{11}^R _{3\text{rd velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$          |
| $\frac{\dot{\epsilon} _{4\text{th velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{E_{11}^0 _{4\text{th velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{\epsilon_{11}^R _{4\text{th velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$          |
| $\frac{\dot{\epsilon} _{5\text{th velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{E_{11}^0 _{5\text{th velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{\epsilon_{11}^R _{5\text{th velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$          |
| ...                                                                                                     | ...                                                                                             | ...                                                                                                           |

After drawing the curves  $F_1 = f(X)$  and  $F_2 = f(X)$ , the fitting (linear, power or neperian logarithmic approximation) allows to find the parameters :  $D_{11}$ ,  $n_{11}$ ,  $D_{11}^u$  and  $n_{11}^u$ .

### Simple tension tests on $[\pm 45]_{2S}$

Using the procedure defined for the quasi-static case, the shear modulus, yield stress and strain rate are identified for each loading velocity:

$$\begin{cases} G_{12}^0|_{\text{quasi-static velocity}}, G_{12}^0|_{2\text{nd velocity}}, G_{12}^0|_{3\text{rd velocity}}, G_{12}^0|_{4\text{th velocity}}, G_{12}^0|_{5\text{th velocity}} \dots \\ R_0|_{\text{quasi-static velocity}}, R_0|_{2\text{nd velocity}}, R_0|_{3\text{rd velocity}}, R_0|_{4\text{th velocity}}, R_0|_{5\text{th velocity}} \dots \\ \dot{\epsilon}|_{\text{quasi-static velocity}}, \dot{\epsilon}|_{2\text{nd velocity}}, \dot{\epsilon}|_{3\text{rd velocity}}, \dot{\epsilon}|_{4\text{th velocity}}, \dot{\epsilon}|_{5\text{th velocity}} \dots \end{cases}$$

| $X_1$                                                                                                   | $F_1$                                                                                           | $X_2$                                                                                                   | $F_2$                                                                                 |
|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| $\frac{\dot{\epsilon} _{\text{quasi-static velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$ | $\frac{G_{12}^0 _{\text{quasi-static velocity}}}{G_{12}^0 _{\text{quasi-static velocity}}} - 1$ | $\frac{\dot{\epsilon} _{\text{quasi-static velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$ | $\frac{R_0 _{\text{quasi-static velocity}}}{R_0 _{\text{quasi-static velocity}}} - 1$ |
| $\frac{\dot{\epsilon} _{\text{2nd velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{G_{12}^0 _{\text{2nd velocity}}}{G_{12}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{\dot{\epsilon} _{\text{2nd velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{R_0 _{\text{2nd velocity}}}{R_0 _{\text{quasi-static velocity}}} - 1$          |
| ...                                                                                                     | ...                                                                                             | ...                                                                                                     | ...                                                                                   |

After drawing the curves  $F_1 = f(X_1)$  and  $F_2 = f(X_2)$ , the fitting (linear, power or neperian logarithmic approximation) allows to find the parameters:  $D_{12}$ ,  $n_{12}$ ,  $D_{R0}$  and  $n_{R0}$ .

**Note:**

- The evolution of shear modulus and yield stress may be different in function of time; that is the reason why two reference strain rates are defined.

#### Simple tension tests on [45]s

Using the procedure defined for the quasi-static case, the transverse and shear moduli and the strain rate are identified for each loading velocity:

$$\begin{cases} G_{12}^0|_{\text{quasi-static velocity}}, G_{12}^0|_{\text{2nd velocity}}, G_{12}^0|_{\text{3rd velocity}}, G_{12}^0|_{\text{4th velocity}}, G_{12}^0|_{\text{5th velocity}} \dots \\ E_{22}^0|_{\text{quasi-static velocity}}, E_{22}^0|_{\text{2nd velocity}}, E_{22}^0|_{\text{3rd velocity}}, E_{22}^0|_{\text{4th velocity}}, E_{22}^0|_{\text{5th velocity}} \dots \\ R_0|_{\text{quasi-static velocity}}, R_0|_{\text{2nd velocity}}, R_0|_{\text{3rd velocity}}, R_0|_{\text{4th velocity}}, R_0|_{\text{5th velocity}} \dots \\ \dot{\epsilon}|_{\text{quasi-static velocity}}, \dot{\epsilon}|_{\text{2nd velocity}}, \dot{\epsilon}|_{\text{3rd velocity}}, \dot{\epsilon}|_{\text{4th velocity}}, \dot{\epsilon}|_{\text{5th velocity}} \dots \end{cases}$$

For these tests, the reference strain rate is issued from the analysis of transverse modulus evolutions (increase in the modulus higher than 10%):

$$\dot{\epsilon}_{22}^{\text{ref}} = \dot{\epsilon}|_{\text{quasi-static velocity}}$$

| $X_1$                                                                                                   | $F_1$                                                                                           | $F_2$                                                                                           | $F_3$                                                                                 |
|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| $\frac{\dot{\epsilon} _{\text{quasi-static velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$ | $\frac{E_{22}^0 _{\text{quasi-static velocity}}}{E_{22}^0 _{\text{quasi-static velocity}}} - 1$ | $\frac{G_{12}^0 _{\text{quasi-static velocity}}}{G_{12}^0 _{\text{quasi-static velocity}}} - 1$ | $\frac{R_0 _{\text{quasi-static velocity}}}{R_0 _{\text{quasi-static velocity}}} - 1$ |
| $\frac{\dot{\epsilon} _{2\text{nd velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{E_{22}^0 _{2\text{nd velocity}}}{E_{22}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{G_{12}^0 _{2\text{nd velocity}}}{G_{12}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{R_0 _{2\text{nd velocity}}}{R_0 _{\text{quasi-static velocity}}} - 1$          |
| ...                                                                                                     | ...                                                                                             | ...                                                                                             | ...                                                                                   |

After drawing the curve  $F_1 = f(X_1)$ , the fitting (linear, power or neperian logarithmic approximation) allows to find the parameters :  $D_{22}$  and  $n_{22}$ .

Note: the curves  $F_2 = f(X_1)$  and  $F_3 = f(X_1)$  can be mixed with the results obtained for the laminate.  $[\pm 45]_{2S}$  in order to check the concordance of the results and moreover to improve the quality of fittings.

#### *Simple compression tests on $[0]_8$*

Using the procedure defined for the quasi-static case, the longitudinal Young's modulus, the rupture strain and strain rate are identified for each loading velocity:

$$\begin{cases} E_{11}^0|_{\text{quasi-static velocity}}, E_{11}^0|_{2\text{nd velocity}}, E_{11}^0|_{3\text{rd velocity}}, E_{11}^0|_{4\text{th velocity}}, E_{11}^0|_{5\text{th velocity}} \dots \\ \epsilon_{11}^R|_{\text{quasi-static velocity}}, \epsilon_{11}^R|_{2\text{nd velocity}}, \epsilon_{11}^R|_{3\text{rd velocity}}, \epsilon_{11}^R|_{4\text{th velocity}}, \epsilon_{11}^R|_{5\text{th velocity}} \dots \\ \dot{\epsilon}|_{\text{quasi-static velocity}}, \dot{\epsilon}|_{2\text{nd velocity}}, \dot{\epsilon}|_{3\text{rd velocity}}, \dot{\epsilon}|_{4\text{th velocity}}, \dot{\epsilon}|_{5\text{th velocity}} \dots \end{cases}$$

As for the case in tension, all the parameters can be standardized:

| $X$                                                                                                     | $F_1$                                                                                           | $F_2$                                                                                                         |
|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| $\frac{\dot{\epsilon} _{\text{quasi-static velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$ | $\frac{E_{11}^0 _{\text{quasi-static velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$ | $\frac{\epsilon_{11}^R _{\text{quasi-static velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$ |
| $\frac{\dot{\epsilon} _{2\text{nd velocity}}}{\dot{\epsilon} _{\text{quasi-static velocity}}}$          | $\frac{E_{11}^0 _{2\text{nd velocity}}}{E_{11}^0 _{\text{quasi-static velocity}}} - 1$          | $\frac{\epsilon_{11}^R _{2\text{nd velocity}}}{\epsilon_{11}^R _{\text{quasi-static velocity}}} - 1$          |
| ...                                                                                                     | ...                                                                                             | ...                                                                                                           |

The curves  $F_1 = f(X)$  and  $F_2 = f(X)$  can be mixed with the results obtained for the laminate in tension  $[0]_8$  in order to check the concordance of the results and moreover to improve the quality of fittings.

## Appendix 5: Delamination interface model (Source PAM-CRASH<sup>TM 8</sup>)

Damage starts in each direction when an elastic energy limit is exceeded. This limit is:

$$\begin{aligned} G_o^n &= \frac{t_n^{\max 2}}{2E_o} \\ G_o^s &= \frac{t_s^{\max 2}}{2G_o} \end{aligned} \quad (23)$$

Failure propagates gradually from that point until an ultimate energy limit ( $G_u^n$  and  $G_u^s$  for the mode I and II cases respectively) is reached. This limit corresponds to the ultimate strains of the interface

$$\begin{aligned} \varepsilon_u^n &= \frac{2G_u^n}{t_n^{\max}} \\ \varepsilon_u^s &= \frac{2G_u^s}{t_s^{\max}} \end{aligned} \quad (24)$$

over which the interface is deactivated. For mixed mode loading the initiation and completion of damage are calculated using a linear law:

$$\frac{G^n}{G_u^n} + \frac{G^s}{G_u^s} = 1 \quad (25)$$

