

Integrated thermal-structural simulation of unidirectional composite laminates

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Preface

This dissertation has been formatted according to the North-West University's approved guidelines for dissertations. This dissertation consists of seven chapters. Some of the figures used in chapters 1 and 2 of this dissertation were personally sketched (unless referenced otherwise) with the use of Microsoft Word and PowerPoint.

Abstract

Composites make for excellent structures for their high strength-to-weight and stiffness-to-weight ratios. However, the lack of dimensional accuracy in composite parts often gives rise to high manufacturing costs and high scrap rates in the aircraft industry. The cost and scrap rate of composite parts are the result of curing-process-induced deformation. There is a great interest in increasing the ability to understand and predict cure-induced distortions associated with cure-induced residual stresses by obtaining accurate material properties. This dissertation focused on thermal- and curing-induced stress analysis of unidirectional composite laminates by establishing material properties to ultimately provide an efficient and accurate representation of an integrated simulation model. An accurate and acceptable simulation model may prevent most of the current trial-and-error parts manufactured in the aircraft industry.

Material properties were established through coupon testing routed from flat plates manufactured in accordance with the relative American Society for Testing and Materials (ASTM) standards and requirements. The material used for this dissertation was carbon AS4 HexPly® 8552 epoxy resin prepreg. Coupon testing included the following data: Stress-strain data as a function of temperature and degree of cure (elastic modulus, shear modulus, and Poisson's ratio), coefficient of thermal expansion as a function of temperature, and degree of cure. The material properties were used as input results to develop an accurate thermal curing simulation model using Marc and MSC one software.

The simulation model was compared with actual manufactured parts to indicate the amount of displacement, caused by residual stresses. The simulation and actual parts included a balanced $[0/90]_4$ and unbalanced $[0/90]_4$ layup and were manufactured using the traditional bag layup method and cured in an autoclave. The manufactured plate results were compared with the simulation using a ROMER absolute arm.

This dissertation produced successful material properties, but the curing simulation model lacked the dimensional accuracy to predict material behaviour under thermal curing. A deviation of 2,98 % and 1,80% in the maximum displacement was obtained for the balanced and unbalanced layup with a minimum value of 96,42% and 91,7%. This dissertation provides a platform for future studies investigating carbon fibre composite as a solution for dimensional accuracy in the aviation industry.

Keywords: Composite, carbon fibre, warpage, residual stress, simulation model, aircraft industry

Declaration

The following statement from the co-authors/promotors confirms their individual involvement in this study and gives their permission that the relevant research may form part of this dissertation.

Mr Marinus Harm Wichers Responsible for compiling background and literature review, motivation, design and planning of the research project, interpretation of results and inscription of all sections forming this dissertation.

Mr CP Kloppers Dissertation supervisor. Responsible for intellectual input and the dissertation's technical input, design, and planning.

I Marinus Harm Wichers hereby declare that I approved the abovementioned dissertation and that my role in this study (as stated above) is representative of my contribution to the dissertation and supervised master's study.

Mr CP Kloppers

Supervisor

Mr Marinus Wichers

Student

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Chapter Layout

The layout of the dissertation is as follows:

Chapter 1: Research proposal

Chapter 2: Literature review

Chapter 3: Material characteristics

Chapter 4: Curing simulation

Chapter 5: Plate manufacturing

Chapter 6: Results comparison

Chapter 7: Conclusion and recommendation

References are provided at the end of the dissertation according to Vancouver referencing style.

Abbreviations

CFRP	Carbon fibre reinforced polymer
ASTM	American Society for Testing and Materials
CTE	Coefficient of thermal expansion (α_x)
UD	Unidirectional lamina
CLPT	Classical laminate plate theory
FEM	Finite element method
DSC	Differential Scanning Calorimetry
TMA	Thermomechanical Analysis
DMA	Dynamic Mechanical Analysis
3D	Three-dimensional
°	Degree angle
°C	Degree Celsius
°F	Degree Fahrenheit

1/K	Kelvin ⁻¹
°C/min	Degree Celsius per minute
CMC	Ceramic matrix composites
MMC	Metal matrix composites
IMC	Intermetallic matrix composites
CCC	Carbon-carbon composites
PMC	Polymer matrix composites
<i>et al.</i>	“and others”
%	Percentage
%CV	Percentage confidence interval
mm	Millimetre
cm	Centimetre
Hg	Mercury
Hr	Hour
KPa	Kilopascal
MPa	Megapascal
GPa	Gigapascal
E_x	Young’s modulus
G_x	Shear modulus
ν_x	Poisson’s ratio
F_x	Shear strength
β_x	Cure shrinkage
Ø	Degree of cure

CHAPTER 1

Research Proposal

This chapter offers introductory information on the research problem statement, namely the requirement of carbon-reinforced fibre thermoset composite material in the aircraft industry, followed by the problem statement, research aims and objectives.

1.1 Introduction and background

Dimensional accuracy is an essential manufacturing requirement of parts in the aircraft and aerospace industries. These advanced structures require property characteristics such as light weight, high strength, high tensile modulus, good fatigue resistance, and corrosion resistance (1, 2). Composites can be defined as a combination of two different phases, namely the reinforcing phase (I) and the matrix phase (II). The reinforcing phase (I) is referred to as a load-carrying component and the matrix phase (II) as the matrix which transfers the applied loads to the reinforcement. According to Siddiqui *et al.* (5), most of the reinforcing phase (I) composite materials consist of stiff and strong fibres, such as carbon, glass, or aramid. These stiff and strong fibres are fixed in a softer matrix (II) material, such as a thermosetting or thermoplastic polymer.

Strength, conductivity, ductility or desired characteristics of different materials are typically combined to form a composite with custom structural properties. The advantageous strength-to-weight ratio in composites has led to its increased popularity in aircraft construction, where multiple components are integrated into one structure for specific applications.

Notwithstanding its benefits, one of the problems with using composite materials is the occurrence of thermal and cure-induced stresses. Thermal and curing stresses are caused due to the mismatch between the different composite constituents' and coefficient of thermal expansion (CTE) induce distortions in manufactured parts.

Carbon fibre-reinforced polymers (CFRP) have gained extensive use as structural components in the aerospace industry (6, 7). Manufacturing is key in composite engineering and includes a traditional vacuum bag layup and an autoclave curing cycle (8). Curing parts in an autoclave is used when requiring good dimensional stability, and reliability as process-induced deformations must be minimal, the use of this process attracted the attention of industries and researchers.

1.2 Problem statement and motivation

The lack of dimensional accuracy in composite parts causes increased costs related to manufacturing and high scrap rates in the aircraft industry. Moreover, curing-process-induced deformation is a significant problem that limits the use of carbon fibre/epoxy composites. The lack of understanding the material characteristics to predict the cure-induced distortions in composite parts associated with cure-induced residual stresses requires further investigation.

1.3 Research aim and objectives

The primary **research aims** of this dissertation are:

- i. To use carbon AS4 HexPly® 8552 epoxy resin prepreg material to determine the material's properties at various stages in the curing process through coupons routed from plates manufactured from the material and tested per the relative American Society for Testing and Materials (ASTM) standards.
- ii. To Develop a thermal curing simulation model using the material properties obtained through coupon testing as input results to predict the behaviour of the material.

The **objectives** of this dissertation are:

- i. Manufacture flat plates from the carbon AS4 HexPly® 8552 epoxy resin prepreg material using the traditional bag layup method for various stages in the curing process.
- ii. Route test coupons from the flat plates manufactured and test the material in accordance with the required ASTM standards to obtain the material properties required as input results for the thermal curing simulation model.
- iii. Comparing the results obtained of the material properties from the coupon tests with properties of the same material test data from literature as a verification.
- iv. Use the material properties obtained as input results for the thermal curing model to simulate a plate manufactured with a balanced and unbalanced layup.
- v. Manufacture plates in a balanced and unbalanced layup as used in the industry using the material's curing process in an autoclave.
- vi. Compare the material displacement results of the manufactured plates with the results obtained from the thermal curing simulation to determine the validity of the thermal curing simulation model.

CHAPTER 2

Literature Review

This chapter provides background and relative literature, including results from previous studies, on all aspects of this dissertation.

2.1 Introduction

Integrated analysis is highly significant in scientific research and the industrial application of carbon fibre-reinforced polymer composites (3). The focus of the ensuing literature is thermal- and curing-induced stress analysis of unidirectional composite laminates in order to establish material properties and, ultimately, an efficient and accurate representation of a simulation model. Relative topics regarding the title, problem statement, aims and objectives from Chapter 1 are researched and discussed to obtain better knowledge of the different aspects that were addressed in this dissertation.

2.2 Composite materials

A composite material has two independent, chemically distinct phases (Figure 1). In the material's first phase, the matrix is usually low in stiffness and weak, and the second phase is the reinforcement that produces greater stiffness and strength (12-14). The matrix and reinforcement are chosen for their desirable complementary mechanical properties, whilst their deficiencies are neutralised (13, 14). Combining materials generally produces improved properties when compared to the constituent materials individually. The application of fibrous reinforcement dates back to the biblical era in Egypt, where primitive straw-reinforced clay bricks were used to build structures (15). Composites became increasingly popular since, and by 1942, reinforced plastics were already being used in aircrafts (16). The first high-strength carbon fibres were introduced in the early 1960s, followed by applications of advanced composites to aircraft components in 1968 (16). While composite materials have several advantages, they are not without their disadvantages (17). The advantages and limitations are described in detail in Appendix A.

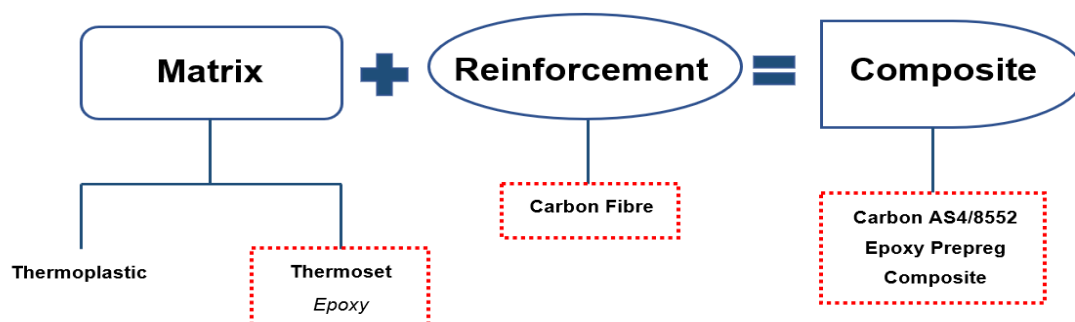


Figure 1: Phases of composite material

From figure 1 the red square boxes indicate the materials used in this dissertation. Notably, an additional interphase matrix can also exist between the reinforcement and matrix due to chemical interactions and other processing effects (12, 18). There are many types of matrices and reinforcement (19). These matrices include ceramic-matrix composites (CMCs), metal-matrix composites (MMCs), intermetallic-matrix composites (IMCs), carbon-carbon composites (CCCs), and polymer-matrix composites (PMCs). Polymer-matrix composites (PMCs) (20) are then subdivided into two groups: thermoset or thermoplastic. Reinforcements include carbon fibre, glass fibre, aramid, and other natural fibres such as cellulose (21).

In this dissertation, the focus was on combining a thermoset epoxy matrix and a carbon fibre reinforcement to form a carbon AS4 HexPly® 8552 epoxy resin prepreg for fabrication purposes in the aviation industry (Figure 2). The following paragraphs describe the thermoset and thermoplastic processes and requirements.

Firstly, thermosets (the matrix) must be polymerised and cross-linked when cured and heated with a hardening agent (22-24). It is of note that thermosets resist melting when reheated but evidently do not decompose when reintroduced to high thermal temperatures. The foremost used thermosets are epoxies due to their more advanced thermal and overall mechanical properties when compared to other thermoset polyesters (e.g. polyimides and vinyl esters) (22-24). Thermoset epoxies exhibit a relatively wide range of stiffness and are therefore used in high-performance composites and aircraft structures (25).

Secondly, carbon fibres (the reinforcement) are used in advanced composites for their range of strength and stiffness (26). For instance, carbon AS4 is well-known for its high strength and stiffness-yielding properties (27). Carbon fibres are manufactured from organic fibres such as rayon, polyacrylonitrile, or petroleum pitch (28). The typical manufacturing process includes molten thermoplastic resins spun into thinner filament-like structures with the use of textile machinery apparatus (28). Thereafter, the fibres are drawn and undergo oxidation under tension at air temperature between 31 °C – 200 °C. The final product was carbonised by pyrolysis at ± 80 °C in a nitrogen atmosphere (12). Carbon fibres are mechanically and thermally anisotropic due to the nature of the manufacturing process (12); for instance, in the radial direction, the stiffness is much lower and the coefficient of thermal expansion much higher than in the axial direction (12, 26, 27).

Prepreg tapes are formed when parallel fibres are pre-impregnated with resin and partially cured. The prepreg should be refrigerated at a recommended temperature estimate of -18 °C until final use.

2.3 General properties of a composite material

The properties of a composite define its behaviour and are made up of the properties of the respective constituents, their geometries, and the distribution thereof (29). The fibre volume ratio, also known as the volume (or weight) fraction of reinforcement, and the distribution of reinforcement are two defining variables that affect the homogeneity (properties that are the same at every point) or uniformity of the material (12). The less uniform the distribution, the higher probability of a more heterogeneous (properties that vary from point to point) material. A highly heterogeneous material has a higher variable scatter in properties and thus a higher probability of failure in the weakest areas. The geometry and orientation of the reinforcement also affect the system's anisotropic properties.

The phases of the composite system play different roles depending on the type and application of the composite material (14, 30). The different types of composite materials follow:

- *Low- to medium-performance composite materials*: The reinforcement, generally as short fibres or particles, could provide relative stiffening but only restricted strengthening of the materials. The matrix is the main load-bearing constituent concerning the material's mechanical properties.
- *High-performance structural composites*: The normally continuous fibre reinforcement determines material stiffness and strength in the fibre direction. The matrix phase ensures protection for sensitive fibres, bonding, support, and local stress transfer from one fibre to another. The interphase, although small in dimensions, can play a crucial role in regulating the failure mechanisms, failure propagation, fracture toughness, and overall stress-strain behaviour that lead to failure in the material.

2.4 Classifications of composites

There are two primary groups of composite materials, namely particle-reinforced and fibre-reinforced composites (13-15, 29, 30) (Figure 2).

Particle-reinforced composites have particles of different shapes and sizes. They can either be oriented in one direction or randomly oriented (12, 30). Composites with particles orientated in one direction tend to be anisotropic or orthotropic (31), while those with a random particle orientation are quasi-isotropic. The matrices of particle-reinforced composites tend to have a random dispersion (31).

Fibre-reinforced composites are subdivided into single-layer and multi-layered composites (32). Single-layer composites are either short-fibred or continuous-fibred composites, especially within polymer-matrix composites (21). Continuous-fibre composites contain long, continuous fibres with a parallel (unidirectional continuous-fibre composite), right-angled (cross-ply or woven-fabric continuous-fibre composite), multidirectional orientation (multidirectional continuous-fibre composite) (33). In the latter case, the composite can be characterised as a quasi-isotropic material for a certain number of fibre directions and distribution of fibres. Continuous-fibre composites, such as carbon and glass fibres, offer the best mechanical properties (stiffness and strength) for high performance (21, 33). These composites are often used in special applications like aircraft components where advanced fibre properties are fully used (21).

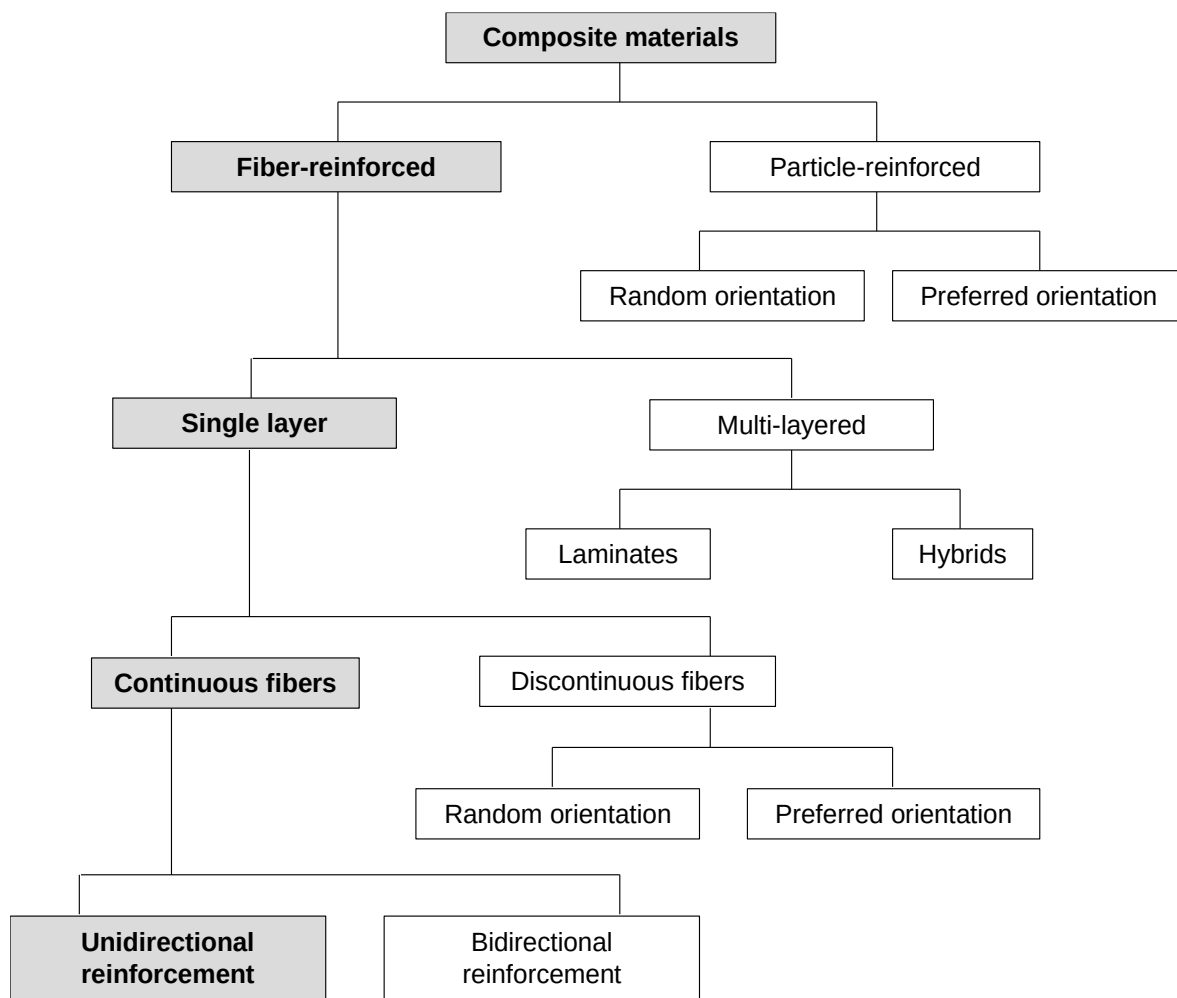


Figure 2: Classification of composites.

From figure 2 the grey highlighted route illustrates the focus of this particular dissertation. Therefore, the approach emphasised in this dissertation is based on unidirectional reinforcement.

2.5 Mechanics of composites

2.5.1 Geometric and configurable characteristics of composite materials

Composites consist of heterogeneous materials with various geometric and configurable characteristics (13). The material properties of composites (e.g. stiffness, strength, thermal expansion, thermal conductivity, and permeability) are all associated with the direction or orientation of the principal axes (12, 13, 15, 29). From a geometric perspective, isotropic materials are defined as materials with properties in the same direction but independent of the axis orientation. Isotropic materials have extensive numbers of symmetrical planes, while *anisotropic* materials vary in direction, depend on the axis orientation, and have no planes of symmetry. The stress-strain relations of anisotropic materials are difficult to analyse due to the additional influence of role parameters on the material's physical behaviour, such as the type of reinforcement, reinforcement volume fraction, interface strength, and properties of the constituents (21). *Orthotropic* materials are characterised by a minimum of three perpendicular planes of symmetry.

Unidirectional fibres are often referred to as unidirectional laminae (UD) (34, 35). The laminae are orthotropic in nature and thus have three planes of symmetry: (I) an axis in the direction of the fibres (longitudinal), (II) an axis normal to the fibres in the plane of the lamina (in-plane transverse), and (III) an axis normal to the plane of the lamina. On the other hand, laminates contain multi-layered unidirectional laminae at different axial orientations called layups. The configurations of materials include the concepts of laminae and laminates. Hybrid composites consist of different types of materials, where in this dissertation, for instance, unidirectional carbon-epoxy is different materials layered up in a specified stacking sequence. A lamina, or a ply, is a plane composed of unidirectional fibres or woven fabric in a matrix. This dissertation chose a layup that consists of eight layers of 8552/34%/UD194/AS4/1219MM carbon fibre unidirectional plies. There will be two samples, of which one layup sequence will be balanced and the other unbalanced, but both will be symmetrical.

2.5.2 Micro and macro mechanical analyses

The scale of analysis concerning mechanical behaviour can be subdivided into micro- and macro mechanical analyses (12, 14, 21, 30) (Figure 3). Microscopic and macroscopic evaluations are performed to inspect the inhomogeneity of composite materials (21). The analysis type depends on the composite material's characterisation and desired behavioural properties. At the constituent level, the scale of observation is in the order of the fibre diameter, particle size, or matrix interstices between reinforcement (12).

2.5.2.1 Micromechanics

Micromechanical analyses are performed at the composite's fibre and matrix level to detect local failures, which include fibre failures (tensile, buckling, splitting), matrix failures (tensile, compressive, shear), interactions between constituents, and debondings between fibres and matrices. Composite materials are treated as homogeneous materials during micromechanical analysis and the identified mechanical properties represent the entire laminate. A micromechanical approach can be used to determine and investigate a composite's respective material properties. These material properties include failure mechanisms and strength, fracture toughness, and fatigue life.

2.5.2.2 Macromechanics

Macromechanical analyses consider the average stresses and lamina strength values in the absence of local failure mechanisms (21). A laminate's overall behaviour is analysed as a function of the lamina properties and stacking sequence. This approach is convenient for analysing a composite's overall stress. Macromechanics considers the unidirectional lamina as a quasi-homogeneous anisotropic material with its own average stiffness and strength properties (12). The approach emphasised in this study was based on both micro- and macromechanics.

2.6 Unidirectional composite materials and their properties

Unidirectional laminae consist of parallel fibres orientated in one direction (Figure 5). Unidirectional laminae are the basic units of a composite structure and are produced when a unidirectional tape is impregnated with resin and placed onto the surface of a tool which provides the shape of a composite part; these are called prepregs (29). All subsequent tables (Tables 4, 5 and 6) are applicable to Figure 4 and illustrate the variables generally used to analyse unidirectional lamina. Fibre-composite materials can have many degrees of anisotropy in their various properties. The largest differences occur between properties in the longitudinal (fibre) and transverse (normal to the fibre) directions in unidirectional composites. Ratios of some properties along these two directions for some typical composite materials such as carbon/epoxy are listed in Table 6.

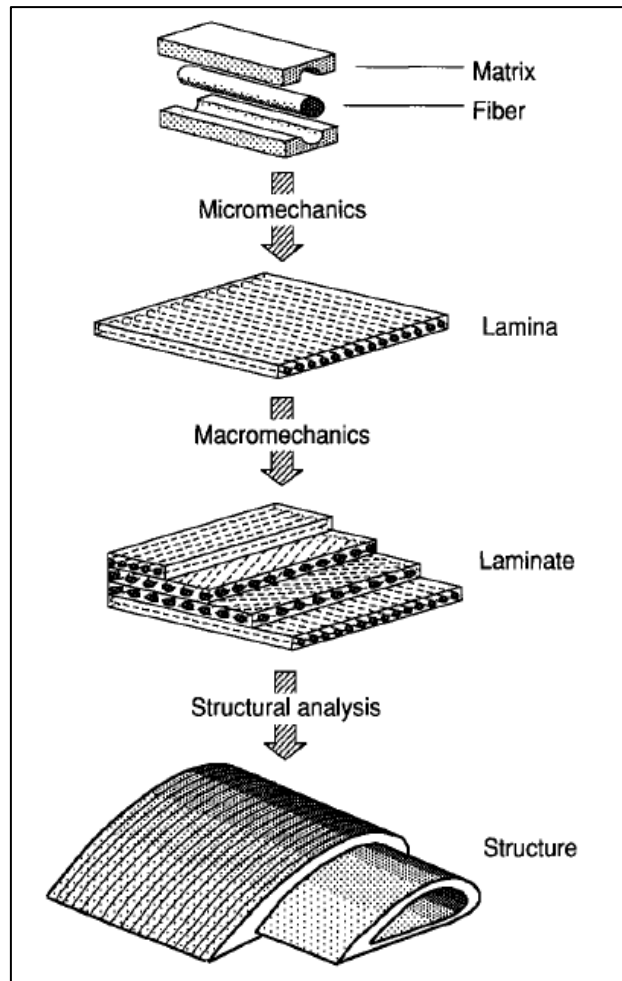


Figure 3: A schematic diagram.

Figure 3 illustrates the various levels of analyses and configuration of composite materials. Structural analysis uses methods such as finite element analysis coupled with lamination theory can be used predict the overall behaviour of the structure (11).

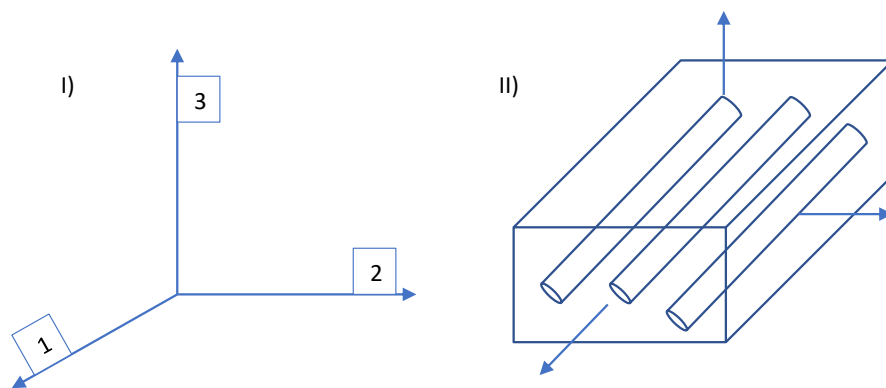


Figure 4: (I) A unidirectional fibre-reinforced laminate.

Figure 4 shows 1 = Longitudinal axis. 2 = Transverse axis. 3 = Loading axis. (II) Illustrates the parallel fibres in the unidirectional lamina, also related to this figure (I).

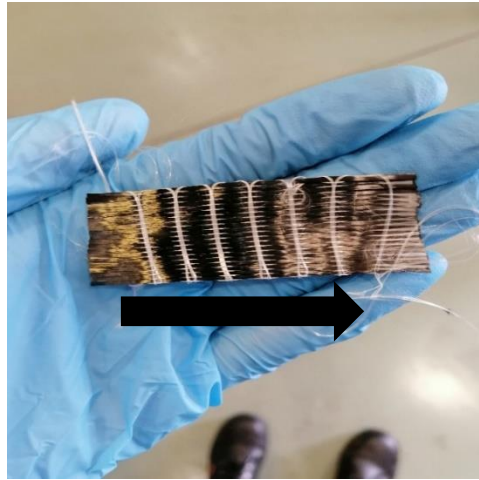


Figure 5: The dry carbon fibres in a unidirectional direction.

Figure 5 illustrates what typical dry fibres are, and how the direction is defined.

Table 1: The unidirectional properties used in analyses (12, 21, 34-36).

E_1, E_2, E_3	Young's moduli along the principal ply directions.
G_{12}, G_{23}, G_{13}	Shear moduli in 1-2, 2-3, and 1-3 planes, respectively (These are equal to G_{21} , G_{32} and G_{31} respectively).
$\nu_{12}, \nu_{23}, \nu_{13}$	Poisson's ratios (The first subscript denotes the loading direction, and the second subscript denotes the strain direction; these Poisson's ratios are different from ν_{21} , ν_{32} and ν_{31} , that is, subscripts are not interchangeable).
F_{12}, F_{23}, F_{13} (if applicable)	Shear strengths in 1-2, 2-3, and 1-3 planes respectively. (These are equal to F_{21} , F_{32} and F_{31} respectively).
$\alpha_1, \alpha_2, \alpha_3$	Coefficients of thermal expansion (CTE) along principal ply directions.
$\beta_1, \beta_2, \beta_3$	Coefficients of moisture expansion along principal ply directions (cure shrinkage).

Table 1 indicates the properties required as input results for the thermal curing simulation, and a brief explanation of each property.

2.7 Residual stresses and strains in composites

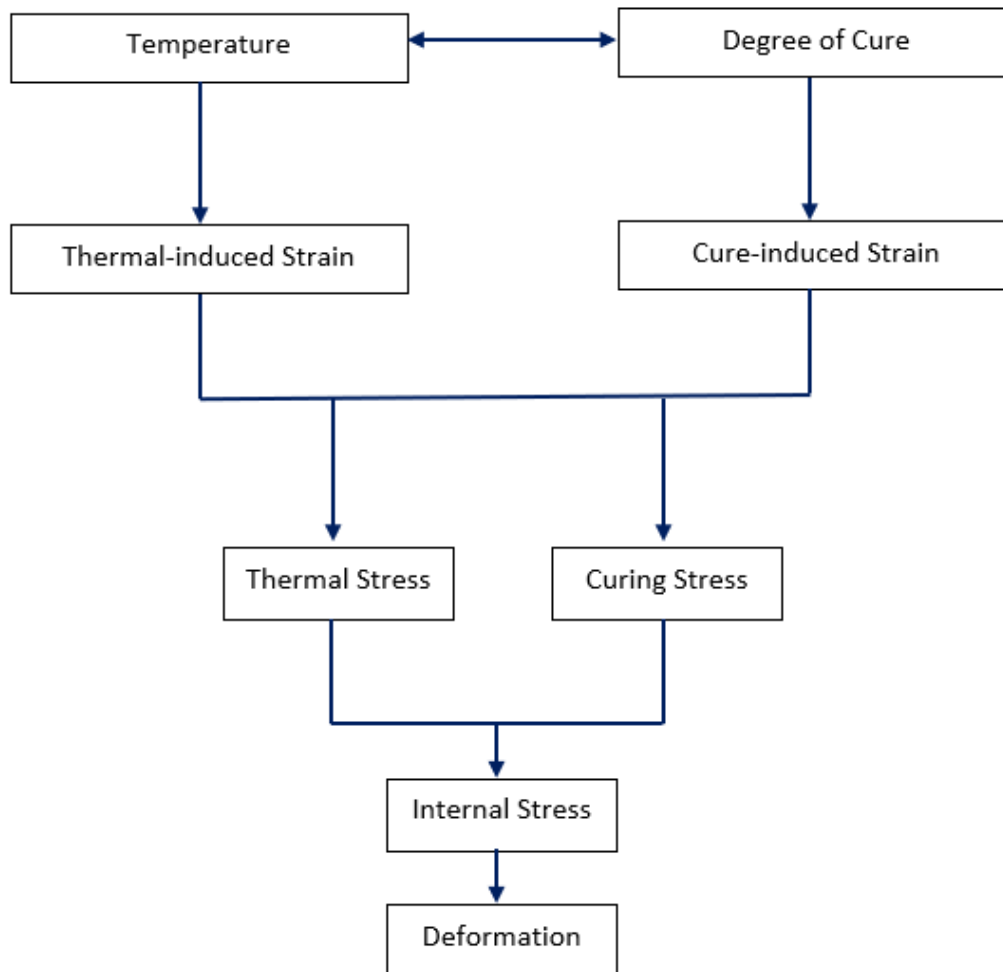


Figure 6: Thermal- and curing-induced stresses.

Adapted from Wang *et al.* (3). Figure 6 shows a schematic diagram that illustrates how thermal- and curing-induced stresses cause deformations of composite parts.

Thermal-induced residual stresses are internal stresses that occur within a part during the curing process (37) (Figure 6). Increased thermal stress is the result of mismatched coefficients of thermal expansion (CTE) between the fibre and the matrices (38). The difference in thermal expansion causes variable expansion or contraction in composite constituents even if there is a uniform temperature change (38). These mismatched coefficients of thermal expansion that occur during fabrication cause mechanisms of differential shrinkage in composites (39-41). Since residual stresses prevent the advantageous high-strength potential of composites, this shrinkage is important when performing stress analyses on composite structures.

Thermal stress distribution is a crucial factor when dealing with the performance of composite materials (21, 38, 42, 43). Residual stresses act on both a fibre-matrix interface and on a ply-to-ply scale within a laminate, which influences a composite's micro- and macromechanical behaviour (32, 44-47).

On a microscopic scale, when considering a fibre embedded within a matrix in the single cell model during temperature changes, cooling from the melting temperature of the matrix to room temperature can lead to the matrix shrinking onto the fibre (21, 48). This enhances the adhesion of the matrix on the fibre.

On a macroscopic scale, the coefficient of thermal expansion is entirely dependent on the ply orientation (21, 49). In this case, the composite is built up from different layers where thermal residual stresses occur due to different ply orientations within the composite. The thermal stresses acting depend on the materials used and the layup of composite, which is very important for the composite's integrity.

2.8 Stress and strain

Stiffness and strength characteristics of unidirectional composites are associated with the stress-strain relation system (25). Any potential deformities or failure mechanisms of composite parts can be traced back and predicted by the state of stress and strain (13, 15). Therefore, stress and strain are fundamental variables for composite materials' mechanical and thermal behaviour (21, 38, 49). Stress can be defined as a measurement of any internal forces that can exist within the composite body (52). There is no direct measurement for stress; it is subdivided into three levels of average stress. These three levels of average stress include (52):

- Micromechanical (local stress): Focuses on the calculation with regard to phases of fibres, matrices, the interface and voids between fibres and matrices.
- Ply stress: Investigates the calculation of assumed homogeneity within each ply or ply group. The fibres and matrices are observed as one component and are no longer recognised as two distinct phases.
- Laminate stress: Determines the average ply stress across a laminate's thickness. The individual plies are seen as one.

The strain of a material can be defined as the spatial variation of displacement (53). Strain and stress are local properties and, more often than not, differ from one point to another. On the contrary, homogeneous stress or strain is only done in cases where testing of certain material properties is needed.

2.9 Micromechanical residual stresses

To recapitulate, fibre and matrix stresses vary from point to point within each constituent phase. The average of these fibre and matrix stresses is referred to as the ply stress (30). The ply or group ply stress exists in irrespective planes. In this dissertation, the plane stress is demonstrated in a three-dimensional stress space where the three orthogonal axes correspond with three stress components (30). This method of illustration was adapted from Hahn *et al.* (30), who demonstrated the three stress components in three directions at 0° , 90° and 45° angles (illustrated by the axis x , y and z) respectively (Figure 8). Strain vectors can also be portrayed in strain space. Because of the coupling between the normal strain components, known as the Poisson effect, the response to a uniaxial stress creates a biaxial strain state. For example, for conventional as well as unidirectional materials, an extension is coupled with a lateral contraction if the applied uniaxial stress is tensile. The unit strain vectors are shown as the result of uniaxial longitudinal and transverse tensile stresses, respectively. If the applied stress is compressive, the direction of all the stress and strain unit vectors will be reversed.

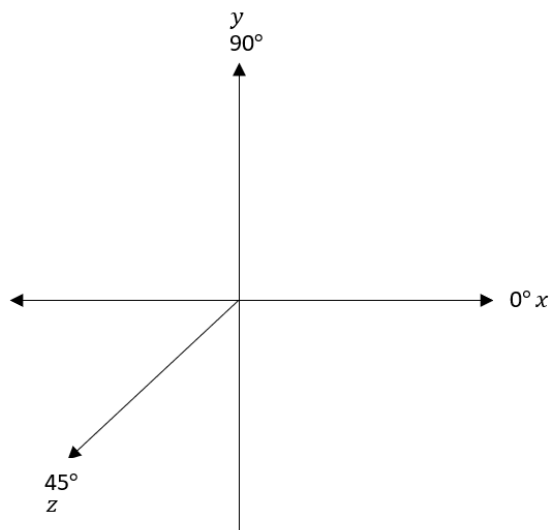


Figure 7: A 3-dimensional stress-space.

Figure 7 shows a 3-dimensional stress-space where the three orthogonal axes correspond to three stress components in the 0° , 95° and 45° angles (corresponds to the axis x , y and z).

Two orthogonal planes of symmetry exist for unidirectional composites: one plane is parallel to the fibres (also referred to as longitudinal), and the other is transverse to the fibres. Symmetry exists when the structure of the material on one side of the plane is the mirror image of the structure on the other side. There are two orthotropic planes of symmetry of unidirectional composites. Axes x - y coincide with the longitudinal and transverse directions. This material

symmetry is called orthotropic and on-axis. With assumed linearity, superpositioning can be used, which is a powerful tool. For example, the net result of combining two states of stress is precisely the sum of the two states. The on-axis stress-strain relation can be derived by superpositioning the results of the following simple tests.

Furthermore, the stiffness of unidirectional composites relative to the material symmetry axes (axes parallel and transverse to the fibres) is dictated by elastic constants. These constants are the coefficients of the various forms of the stress-strain relations in fibrous composites and include the following: elastic constants, transverse stresses, and thermal properties.

2.10 Method of composite manufacture

Composite manufacturing is an interactive process and is highly dependable on the pre-selected material, especially the matrix, as well as the chosen design of the structure itself (48, 54). The properties obtained from the manufactured result (final product) are associated directly with the utilised method of fabrication (5, 44, 55-58). It is of utmost importance that the end-product has met all the requirements at the end of the manufacturing process. These general requirements include the absence of flaws such as voids, cracks, and fibre waviness (5, 57, 58). They further require uniform and presumed properties, successfully cured with stiffening, high strength, and fatigue endurance capabilities. However, the temperature should be fixed within the pre-set values and the thermal distribution should be uniform.

2.10.1 Traditional bag layup (I) and autoclave moulding (II)

In this literature study, the process of autoclave moulding was researched, which included the traditional vacuum bag layup assembly (54). The autoclave method is globally used for most high-performance structures that are typically used in transportation industries such as aviation, aerospace and marine (8). Unfortunately, this moulding process is known to be labour intensive and costly (12) but does, however, deliver superior dimensional-tolerant products. The autoclave moulding process utilises prepregs that are sized and shaped beforehand (5). These prepreg sheets are then stacked into layers to ultimately form the desired layup. A bleeder/breather system consisting of dry glass fibre fabric or mat is used to absorb excess resin and allow the escape of volatiles during curing (12). The prepreg layup assembly then undergoes the traditional bag layup (I), which entails the layup being sealed with a vacuum bag onto a tool plate (Figure 8).

Hereafter, the composite part is cooled down gradually and controlled to avoid further residual stress and microcracking.

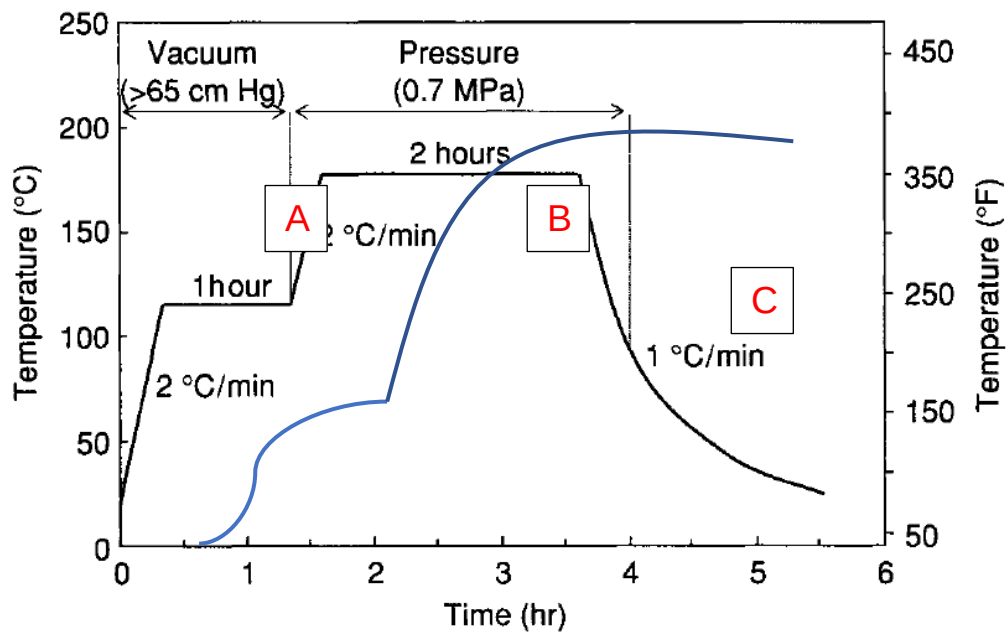


Figure 10: The curing cycle for a typical carbon/epoxy system (12).

From figure 10 the different phases is defined and illustrated as: Phase A = Viscous phase, Phase B = Rubbery phase and Phase C = Glassy phase.

This dissertation, however, had the following curing cycle:

Table 2: Curing cycle for this dissertation.

a.	Applied full vacuum.
b.	Applied 7-bar gauge autoclave pressure.
c.	Vented vacuum when autoclave reached approximately 1 bar gauge.
d.	Heated at 2°C/min to 110°C ± 5°C.
e.	Held at 110°C ± 5°C for 60 minutes ± 5 minutes.
f.	Heated at 2°C/min to 180°C ± 5°C.
g.	Held at 180°C ± 5°C for 120 minutes ± 5 minutes.
h.	Cooled at 2°C per minute.
i.	Vented autoclave pressure when the component reached 60°C or below.

2.11 Extent of cure and cure shrinkage.

Cure-induced residual stresses arise from thermal expansion mismatch between constituent phases, chemical shrinkage of the resin, temperature and degree of cure gradient through the thickness (44, 47, 59, 60). The section that follows focuses on the extent of cure and cure shrinkage, which include spring-in and warpage.

The curing of composite materials is one of the parameters most affecting their mechanical behaviour (61). The degree of curing describes the conversion rate achieved during curing. The degree of curing, ϕ , is the amount of heat converted divided by the reaction enthalpy and can be described with the following principal formula (16):

$$\phi = \frac{H}{\Delta HR}$$

During polymerisation, thermosetting resin undergoes a significant increase in density and a corresponding reduction in volume, commonly referred to as cure shrinkage (54). One effect of resin cure shrinkage is both in-plane and through-thickness reductions in part dimensions (54).

Shrinkage tension will be more transverse to the fibre direction than within the fibre direction itself (39, 40). Therefore, cure shrinkage on residual stress will show similar results to that of a reduction in part temperature and thus can be analysed in a similar manner. Cure shrinkage tension to the end result residual stress differs from situation to situation (54).

Using the chemical shrinkage of resin and fibre fraction, the volume chemical shrinkage of composite can be found according to (39):

$$(\text{Shrinkage}_{\text{composite}}) = (\text{Shrinkage}_{\text{resin}}) - (\text{Fiber volume } \%) \times H,$$

where H is a hindrance factor that is experimentally determined. Its value depends on the type of reinforcement and resin.

Composite materials have an anisotropic nature that causes temperature-induced distortions during the curing cycle. In order to avoid drastic shape changes of composite parts due to curing-induced distortions, the geometry of tooling are modified on a trial-and-error basis (62, 63). This process is costly and requires extrapolated past experiences (4). Distortions are assumed to be minimal when layups are in balance and symmetrical. Therefore, numerous studies focused on variables that can alter the success of minimal distortional outcomes following the experimental and finite element method (FEM) (36, 55, 64-70). These studies considered one or more of the succeeding variables such as part thickness, material type, layups and tool material. This study continues to focus on a novel *integrated* simulation model that includes both micro- and

macromechanics to attempt a more efficient solution with minimal failure, distortions, and deformations. In addition, the mould material with a similar CTE value as a composite product produces less post-cure deformation (10).

On that note, composite materials that tend to deform after manufacturing are referred to as spring-in and warpage (Figure 12).

Firstly, spring-in is the result of curing-induced distortions and is subdivided into two categories (56, 71, 72). These categories are:

1. Thermoelastic: The occurrence of shape change because of mismatched CTEs in the in-plane and through-thickness orientations. The process is reversible with elevated temperatures.
2. Nonthermoelastic: The occasional result of curing and consequent cure shrinkage. The process is non-reversible.

Spring-in depends on many parameters like cure temperature, applied pressure, part geometry, part material, part thickness, layup sequence, mould surface, and mould thermal expansion (73, 10). Moreover, Darrow and Smith (74) concluded that for thin parts (< 2 mm), spring-in was dominated by fibre volume fraction gradient and mould stretching effects, whereas for thick (> 2 mm) parts, spring-in was dominated by thickness cure shrinkage (10).

Warpage of a flat panel is another a common distortion of shape change in composites during manufacturing caused by mismatched thermomechanical properties of the fibre and resin, as well as volumetric shrinkage of the resin during the cross-linking process. This leads to induced residual stress (32, 41). When residual stress increases, a higher stress concentration (75) and cracked matrices (45, 58, 76-79) occur before mechanical loading. This is believed to be one of the main reasons for short service life.

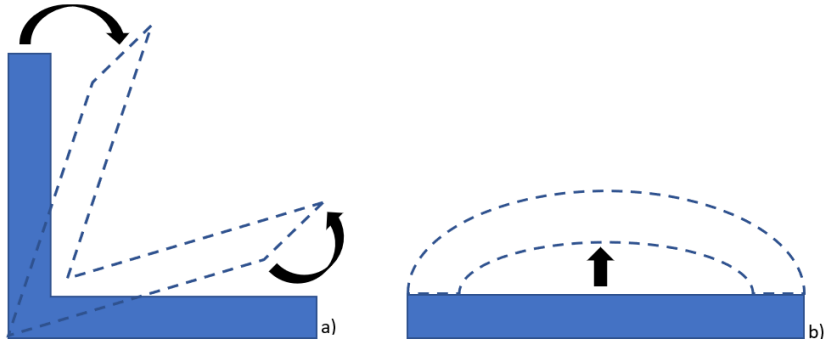


Figure 11: a) spring-in and b) warpage prediction for carbon/epoxy Fiorina et al. (80).

2.12 Results according to the relevant literature

Table 3: Material properties.

Properties	Phase B – Rubbery	Phase C – Glassy
E_{11}	132200 MPa	135000 MPa
E_{22}	165 MPa	9500 MPa
G_{12}	44.3 MPa	4900 MPa
G_{23}	41.6 MPa	3270 MPa
ν_{12}	0.346	0.3
ν_{23}	0.982	0.45
α_{11}	0	0
α_{22}	0	$32.6 \mu\epsilon/^{\circ}\text{C}$
β_{11}	0	0
β_{22}	-0.48%	0

Table 3 illustrates the rubbery and glassy state properties of AS4/8552 unidirectional composite adapted from Ersoy et al. (83).

Table 4: Material properties.

Properties	Phase B – Rubbery	Phase C - Glassy
E_{11}	66200 MPa	72600 MPa
E_{22}	4280 MPa	11382 MPa
G_{12}	43.0 MPa	4085 MPa
G_{23}	44.3 MPa	4900 MPa
ν_{12}	0.83	0.438
ν_{23}	-0.0007	0.039
α_{11}	0	$2.7 \mu\epsilon/^\circ\text{C}$
α_{22}	0	$45.2 \mu\epsilon/^\circ\text{C}$
β_{11}	0	0
β_{22}	-0.98%	0

Table 4 illustrates the equivalent homogeneous rubbery state properties of AS4/8552 cross-ply composite adapted from Ding *et al.* (4).

Given the convenience of gaining required material properties from previous work (72, 81-83), the section below uses previous studies as verifying sources that are elucidated further in subsequent chapters of this dissertation.

Table 5: Results according to the relevant literature: five comparative studies.

➤ Ding <i>et al.</i> (4)	Material properties (AS4/8552)
➤ Falco <i>et al.</i> (35)	Material properties (AS4/8552)
➤ Shah <i>et al.</i> (10)	Spring-in
➤ Chen <i>et al.</i> (84)	Warping
➤ Wang <i>et al.</i> (3)	Integrated solution

Ding and colleagues (4) proposed a modified analytical solution model from Wisnom *et al.*'s (72) original work. Wisnom *et al.* originally developed an analytical solution for spring-in curved thermoset matrix composites by including low shear stiffnesses of materials in the rubbery phase prior to curing. The researchers understood the roles of thermal stress and chemical shrinkage during the interchange between gelation and vitrification with regard to cross-ply carbon-epoxy C-sections (72). Ding *et al.* (4) replaced the notion of plane stress with generalised plain strain for both unidirectional and cross-ply C-sections composite parts between the phases of gelation and vitrification. The authors used the material properties of Hexcel (11) AS4/8552 unidirectional prepregs for the verification process. They also assumed that the mechanical material properties were constant within each material phase during curing. The predicted and measured rubbery and glassy state properties of unidirectional AS4/8552 composites by Ersoy *et al.* (83) used by Ding *et al.* are given in the following tables. Regarding cross-ply laminates, the classic laminate plate theory by Ding *et al.* (4) was used to estimate their equivalent homogeneous properties based on lamina properties. The results are also given in the following tables.

In addition, the analytical solution model Ding *et al.* (4) proposed also incorporated the influence of thickness on the spring-in of composite parts, given in the table below.

Table 6: Unidirectional spring-in results.

Thickness (mm)	Spring-in angle (°)	
	Cross-ply (90/0) _{ns}	Unidirectional
1	1.30, 1.26	1.03, 1.02
2	1.19, 1.16	0.95
3	1.09	0.78
4	0.93	0.66

Falco *et al.* (35) used finite element method (FEM) analysis on unidirectional composite laminates to capture crack paths in unidirectional fibre-reinforced plies. Falco and colleagues (35) used this approach of virtual testing to demonstrate that the laboratory tests are robust and reliable in composite materials screening, design, and certification. The researchers focused on the kinematic representation of fibre-reinforced polymers in unidirectional composite coupons as they deemed it necessary to predict the final failure of the manufacturable material accurately. The original plane-stress formulation was extended to consider three-dimensional stress states. They

used standard and non-standard test methods to measure ply elastic properties, thermal expansion coefficients, as well as ply and interface strength values and critical energy release rates in three material directions (longitudinal, transverse, and shear). Material properties used as inputs for the ply and interface model were specific for Hex Ply AS4/8552 unidirectional prepreg carbon fibre-reinforced polymer-matrices with nominal density $\rho = 1.58 \cdot 10^{-6}$ kg/mm³ and nominal ply thickness $t_p = 0.184$ mm. These properties can be measured using test standards defined by the American Society for Test Standards (ASTMD3039, ASTMD3410 and ASTMD3518 (34, 35, 50, 86).

Table 7: Material properties.

Properties	Mean (CV %)
E_{1t} (GPa)	137.1 (1.4)
E_{1c} (GPa)	114.3 (0.9)
E_{2t} (GPa)	8.8 (0.3)
E_{2c} (GPa)	10.1 (0.8)
G_{12} (GPa)	4.9 (0.8)
V_{12}	0.314
V_{23}	0.487
α_1 ($^{\circ}\text{C}^{-1}$)	$0.21e^{-06}$
α_2 ($^{\circ}\text{C}^{-1}$)	$3.30e^{-05}$

Table 7 shows the elastic properties and thermal expansion coefficients of AS4/8552 CFRP prepregs measured by Fokker *et al.* (51). Adapted from Falco *et al.* (35). Symbols t = test ply after the onset of damage and c = control ply for validation.

Shah *et al.* (10) investigated the influence of mould materials, curing cycle, layup sequence, and laminate thickness on spring-back deformation during autoclave curing. The researchers fabricated numerous parabolic reflectors with the unidirectional prepreg system. An experimental approach was adopted for determining process parameters that gave minimum spring-back deformations. They found that the mould material and laminate thickness significantly affected spring-back deformations of parabolic reflectors. Despite their positive findings, the researchers also speculated that the layup sequence and curing cycle did not have significance because of

the influence of mould part interaction and area moment of inertia on spring-in occurrence, respectively. Shah *et al.* (10) used prepreg material HCU200/A45, carbon/epoxy unidirectional tape manufactured by Hindoostan Technical Fabrics Company for the manufacturing of parabolic reflectors. Two different curing cycles – single hold and double hold – have been applied to an autoclave machine for CFRP prepreg curing.

Wang *et al.* (3) focused on an integrative model to predict cure-induced stress of carbon fibre-reinforced epoxy matrix laminates that included thermodynamics, curing kinetics, and microstructural stress-strain. To develop a cure-microstructure-property-deformation correlation, they studied a simulation solution for the curing process-induced internal stress and deformation of composite parts. The researchers made use of carbon fibre-epoxy composite (EPON 862/W/IM7) material. The chosen laminate plate had dimensions of 300 mm x 300 mm x 3.6 mm and a stacking sequence of $[0_8/45_8]$ or $[0_8/90_8]$.

Wang *et al.*'s (3) results are demonstrated in Figure 12. They found that the Von Mises stress in the laminates with a stacking sequence of $[0_8/90_8]$ is higher than that in the laminates with a stacking sequence of $[0_8/45_8]$ (46, 90). The cured composite laminate had saddle-like deformations caused by the differences in deformities between the differing fibre directions and the anisotropic material modulus.

It is of note that this study worked with material moduli related to microstructural parameters (based on the crosslinking theory), while the computational formula of material modulus in other published articles is an empirical expression which is the function of temperature and degree of cure instead of the microstructural parameter.

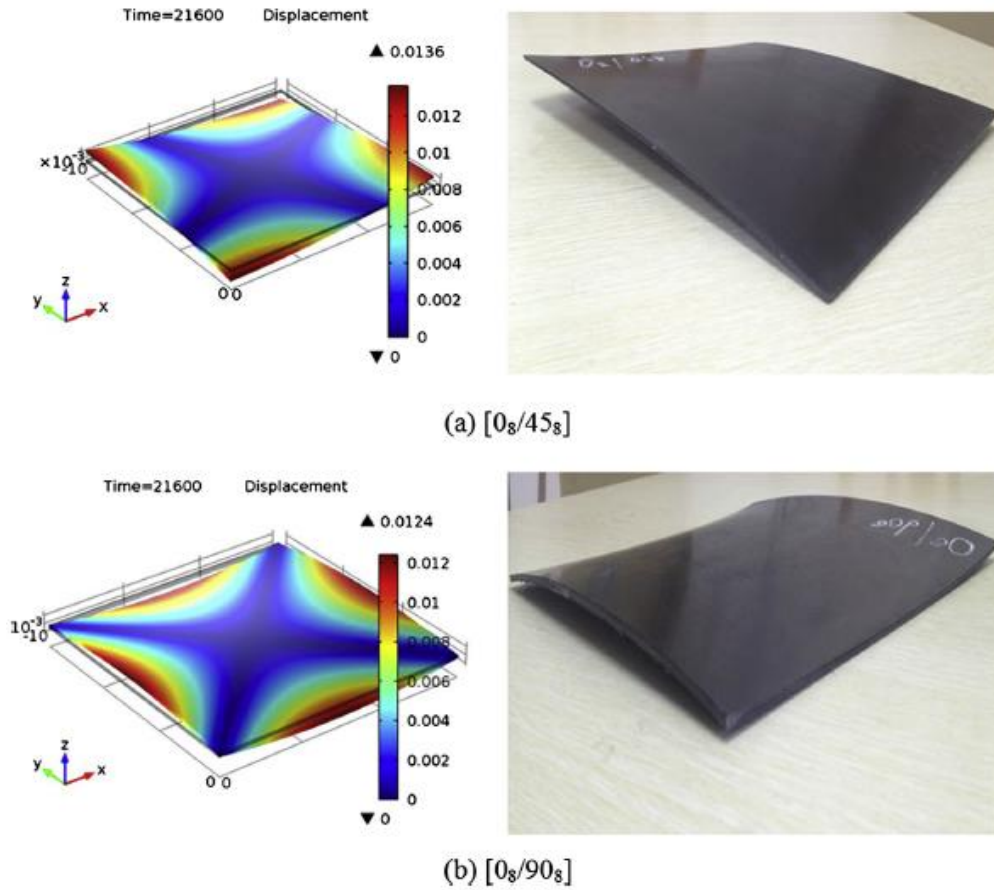


Figure 12: The warpage results by Wang et al. (3).

2.13 Summary

Trial-and-error experiments to predict process-induced internal stress and deformation are time-consuming and costly. Finite element simulation has been conducted over the past 20 years to investigate the internal stress and curing deformation of carbon fibre/epoxy composite parts. Although various studies on the numerical simulation of process-induced internal stress have been conducted, these studies focused mostly on the effect of processing conditions on the internal stress of composite parts (45). The mechanical properties of carbon fibre/epoxy composite materials depend on the processing conditions as well as the composite's microstructure. In this regard, both theoretical research and industrial applications are needed to establish a relationship between the curing process, microstructure, property, and deformation for carbon fibre/epoxy composite parts, and this research is becoming an urgent yet challenging task. The integrated cure-microstructure-property-deformation correlation analysis received limited attention from the viewpoint of curing theory and process simulation (3).

CHAPTER 3

Material Characteristics

Chapter 3 illustrates the results obtained from the material tests done to satisfy the aim and objectives of this study discussed in Chapter 1. Also, it describes the manner in which the tests were performed to receive all the necessary data required for the simulation model. All ASTM standards used are attached in Appendix B.

3.1 Introduction

The material tests were performed according to ASTM standards. Each sample was cut out with a computer numerical control (CNC) router from a flat plate manufactured in the fibre direction. The flat plate thickness was constructed with the use of ASTM requirements. The plates were manufactured using the autoclave and traditional bag layup processes. All tests were done at three different degrees of cure (Figure 13). Three respective points were chosen to test the properties of the material throughout the curing cycle. These points are represented by the numbers 2, 3 and 5. Point 2 illustrates the gelation point of the material, point 3 the start of curing, and point 5 the fully cured result.

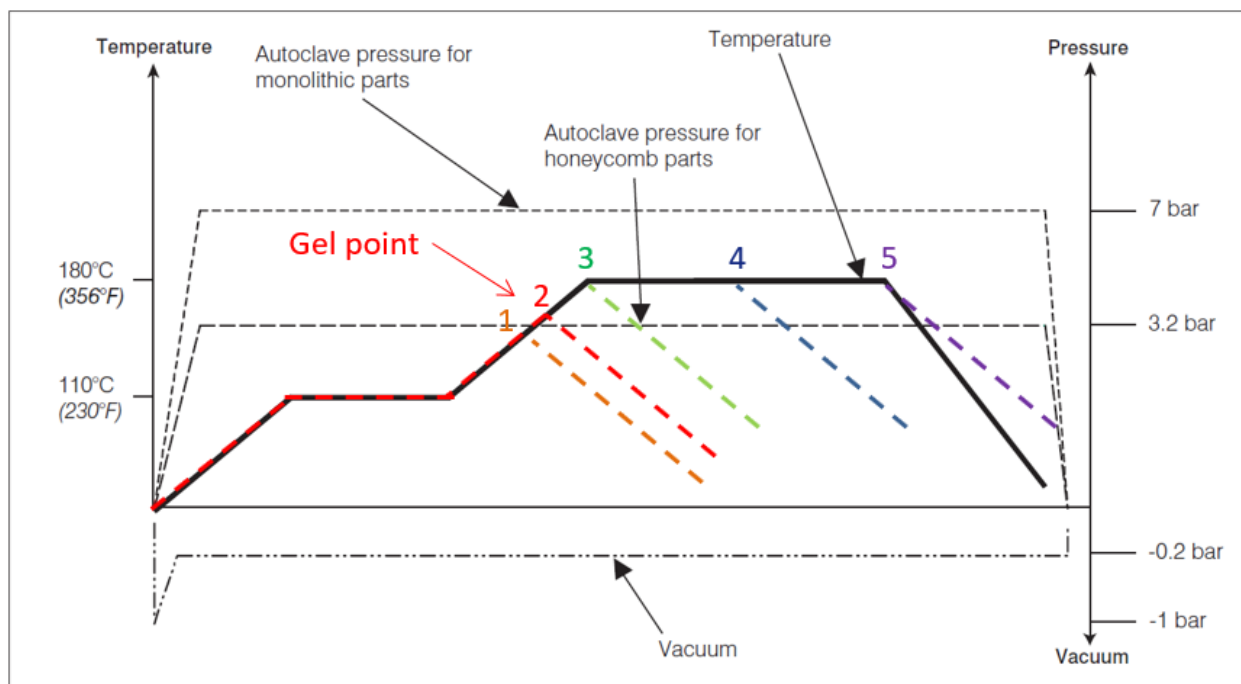


Figure 13: Cure cycle and degree of cure (DOC) points.

Tests performed to obtain the specific material properties for the simulation model were the following:

- Tensile tests.
- Shear tests.

- Poisson's ratio.
- Coefficient of thermal expansion.
- Cure kinetics.

See Appendix B for test plans.

3.2 Material tests

With regard to material tests, different properties have been calculated, of which only the properties related to the simulation are shown.

3.2.1 Tensile test

The ASTM D3039 / D3039M-17 were used for tensile tests. This test method is used to determine the in-plane tensile properties of a polymer-matrix composite material that is reinforced by high-modulus fibres. A thin flat strip of UD material with a constant rectangular cross-sectional is mounted in the grips of a tensile testing machine (Figure 14). This is done to test the tensile properties. The flat strip of UD material, or sample, is loaded in tension while the force is recorded. See Appendix B for test plans for the specimen dimensions and geometry.

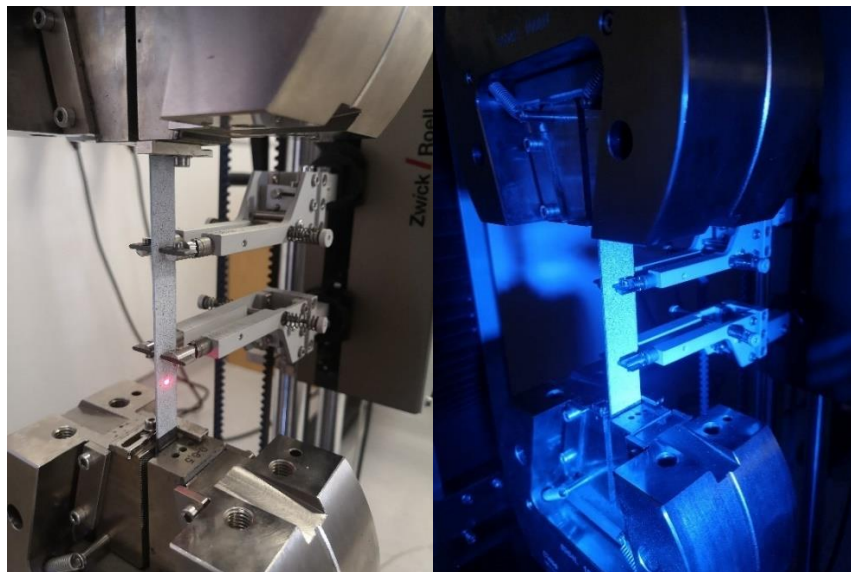


Figure 14: Tensile testing machine with a UD sample.

Thereafter, stress/strain graphs are obtained as a result in order to calculate the tensile modulus. The following figures illustrate these graphs at 0° and 90° angles, respectively.

3.2.1.1 0°-axis orientation

3.2.1.1.1 Degree of cure (DOC) 2

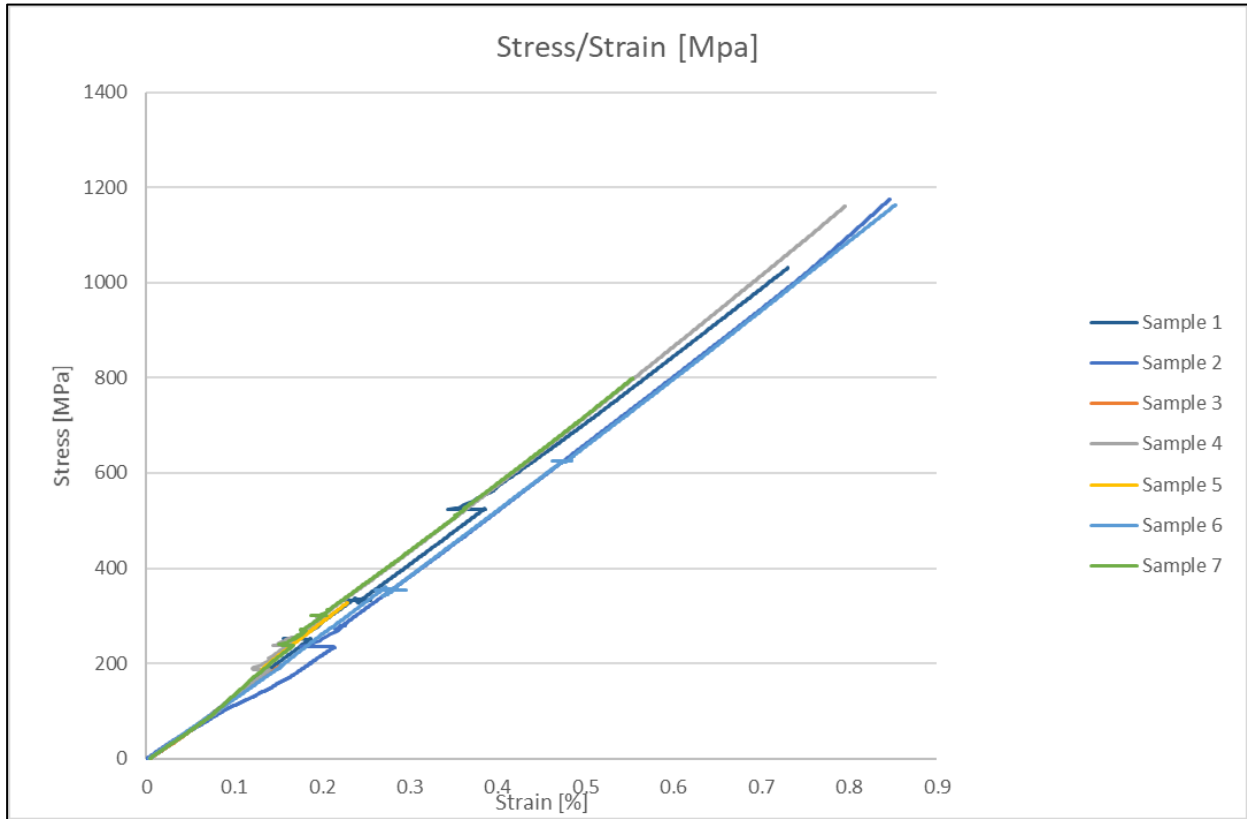


Figure 15: Degree of cure 2 stress/strain graph at a 0°-axis orientation.

Table 8: Calculated tensile moduli for DOC 2 at 0°.

Sample	Young's modulus (MPa)
1	121867
2	125431
3	121830
4	134017
6	132514
7	126949

Average	127101
---------	--------

Figure 15 and table 8, illustrates the results from testing the coupons at DOC2 as seen although the material is not fully cured the material still has stiffness. Early signs of fibre breakage and delamination is also observed.

3.2.1.1.2 Degree of cure (DOC) 3

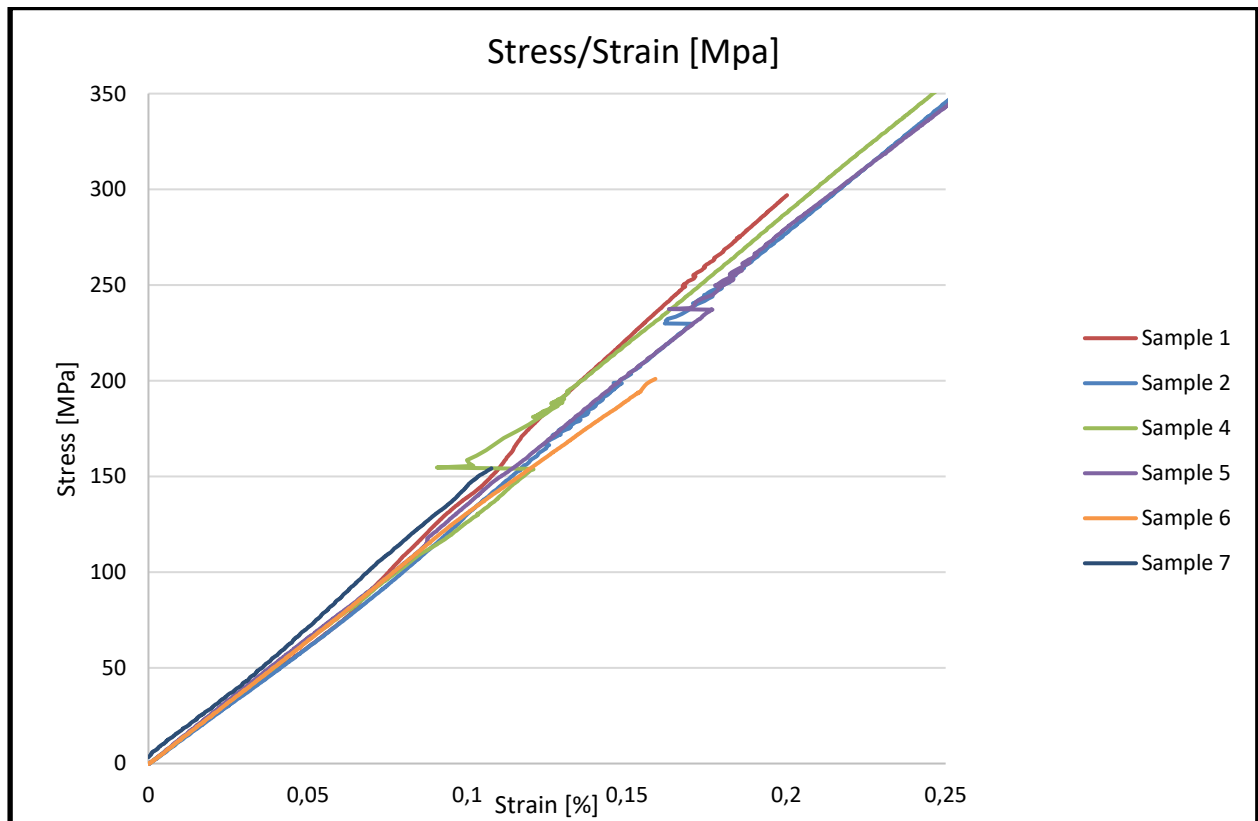


Figure 16: Degree of cure (DOC) 3 stress/strain graph at a 0°-axis orientation.

Table 9: Calculated tensile moduli for DOC 3 at 0°.

Sample	Young's modulus (MPa)
1	124510
2	122391
4	126842
5	133129
6	129332

7	127112
Average	127219

Figure 16 and table 9 shows similar results obtained from DOC2. This is shown when comparing the average modulus. Figure 16 also shows early signs of fibre breakage this is the result of the resin not being able to have enough time to flow evenly and creates voids.

3.2.1.1.3 Degree of cure (DOC) 5

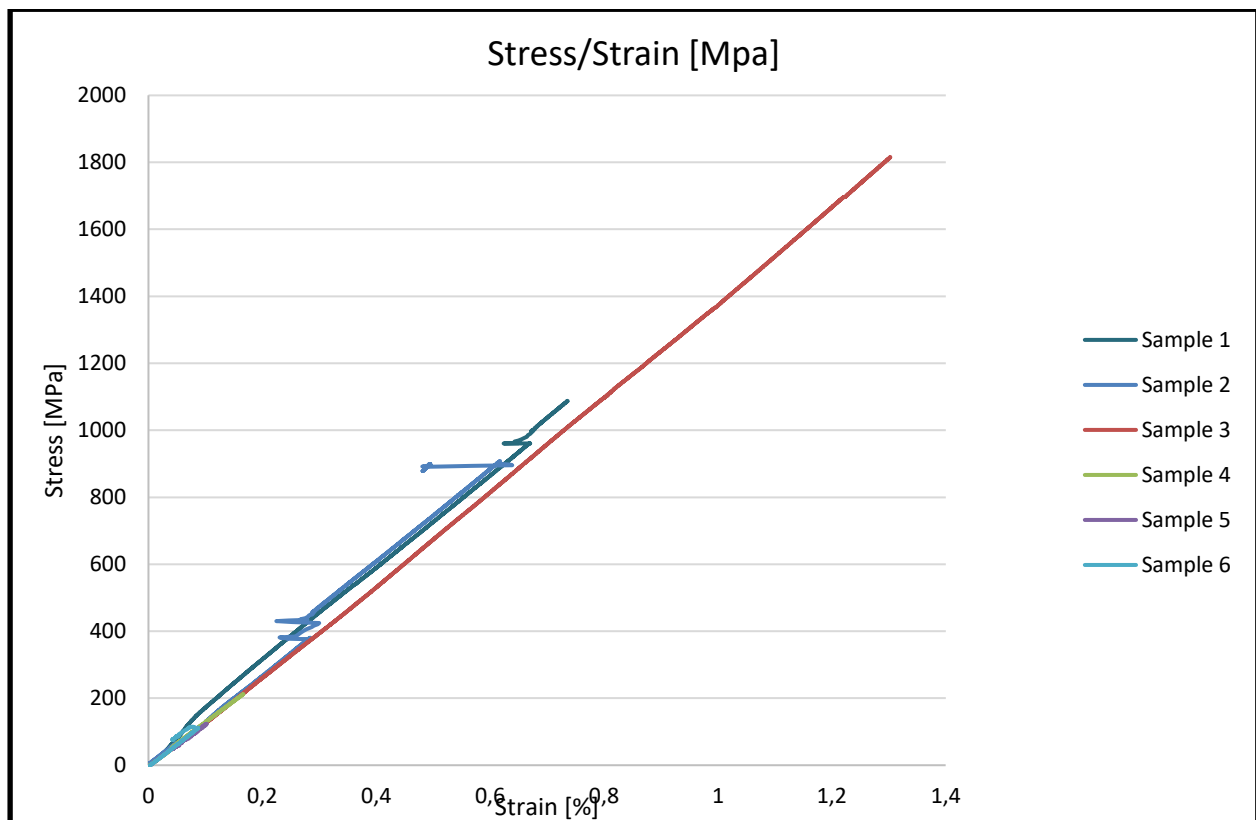


Figure 17: Degree of cure (DOC) 5 stress/strain graph at a 0°-axis orientation.

Table 10: Calculated tensile moduli for DOC 5 at 0°.

Sample	Young's modulus (MPa)
1	145175
2	135335
3	130296
4	126138

5	133877
6	125519
Average	132723

Figure 17 shows a fully cured coupon sample tested. As seen, there is an increase in the stiffness of the samples compared to DOC2 and DOC3 samples tested. Less fibre breakage is observed due to the resin being fully cured and less voids obtained in the sample.

3.2.1.2 90°-axis orientation

3.2.1.2.1 Degree of cure (DOC) 2

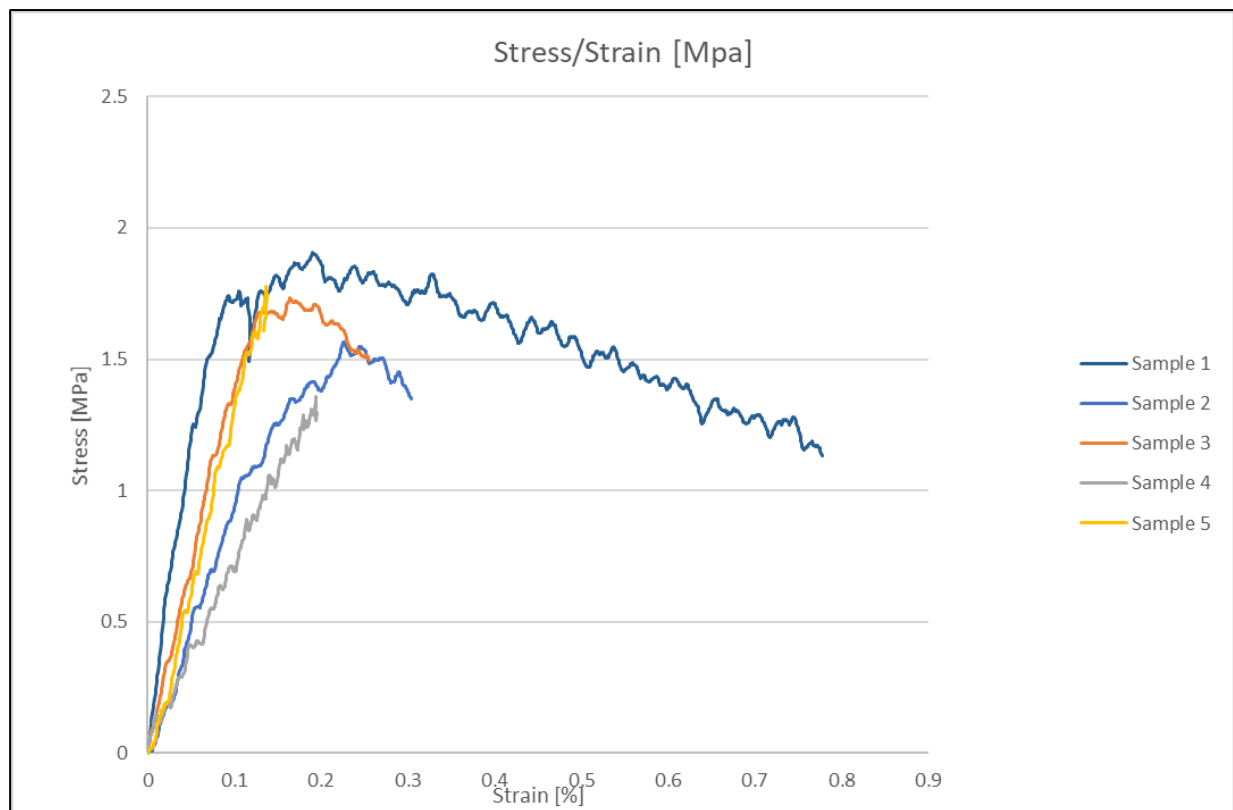


Figure 18: Degree of cure (DOC) 2 stress/strain graph at a 90°-axis orientation.

Table 11: Calculated tensile moduli for DOC 2 at 90°.

Sample	Young's modulus (MPa)
1	2542
2	987
3	1417

5	1326
Average	1568

Figure 18 and table 11 illustrates a sample tested in the 90°, as seen there is a decrease in the stiffness of the sample compared to the 0°. This is a result of delamination in the fibres appose to having strength in the fibre direction.

3.2.1.2.2 Degree of cure (DOC) 3

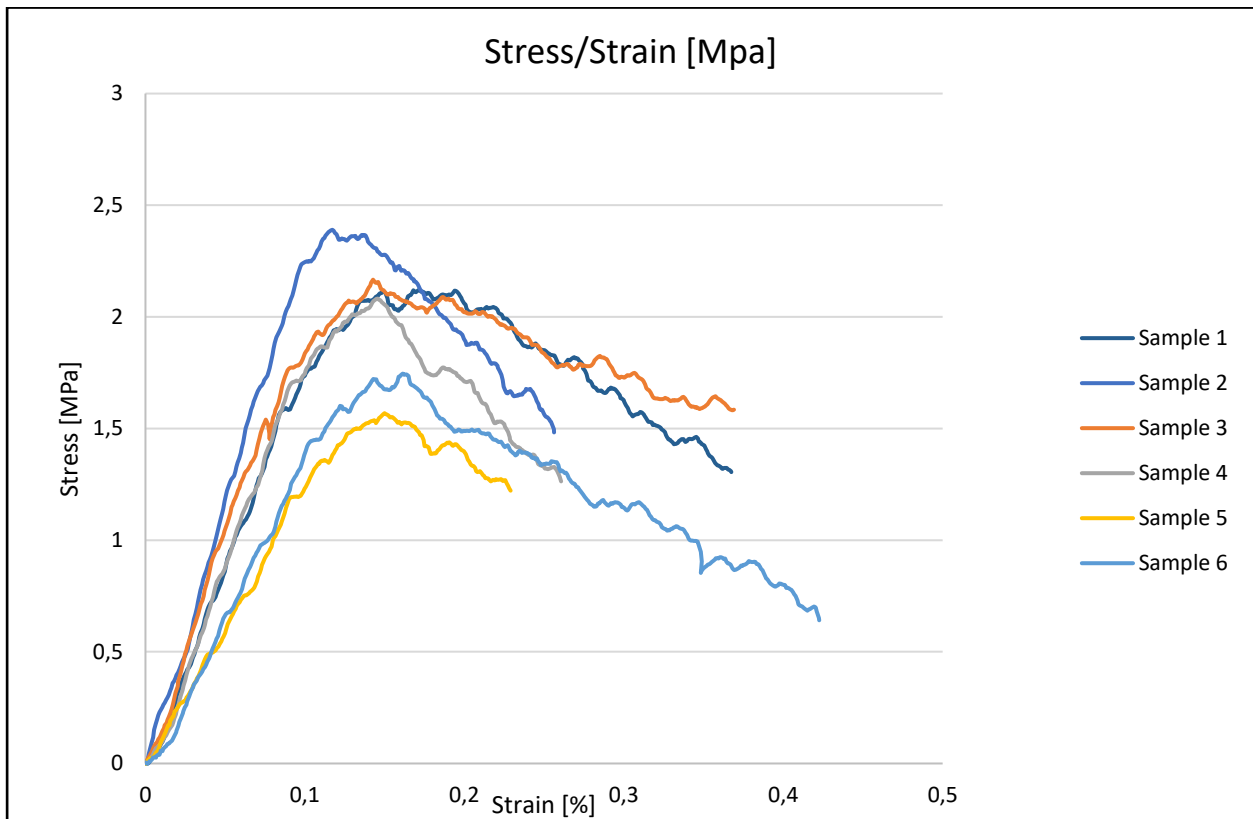


Figure 19: Degree of cure (DOC) 3 stress/strain graph at a 90° axis orientation.

Table 12: Calculated tensile moduli for DOC 3 at 90°.

Sample	Young's modulus (MPa)
1	1828
2	2248
3	2224
4	1918
5	1222

6	1431
Average	1812

Figure 19 and table 12 shows a similar result to DOC2 but with a slight increase in stiffness. This illustrates the resin in the material being slightly more cured than in DOC2.

3.2.1.2.3 Degree of cure (DOC) 5

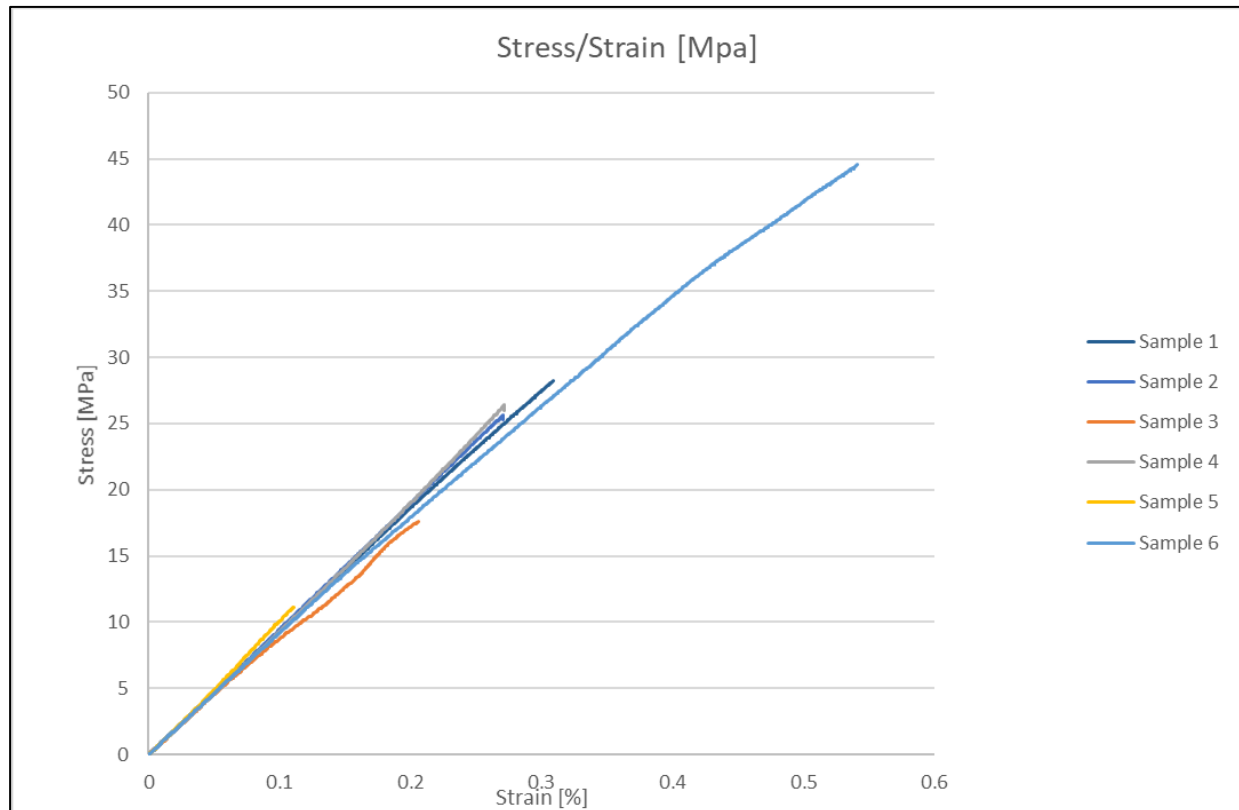


Figure 20: Degree of cure (DOC) 5 stress/strain graph at a 90° axis orientation.

Table 13: Calculated tensile moduli for DOC 5 at 90°.

Sample	Young's modulus (MPa)
1	9199
2	9500
3	8463
4	9693
5	10190
6	8613

Average	9276
---------	------

The results compared to DOC 3 samples show a significant change in the 90° tensile properties, with an increase in stiffness with the degree of cure, whereas for the 0°, the increase in stiffness is less significant.

The result of this shows the effect the degree of cure has on the tensile stiffness in the 0° and 90° direction of the material. This can be considered expected behaviour when increasing the degree of cure of the thermoset prepreg material.

The Young's modulus (E) was determined using the Excel spreadsheet, as shown in Appendix B. The calculations are based on ASTM E 111 – 17. This was done to determine all the Young's moduli in this study.

3.2.2 Shear tests

The ASTM D3518 / D3518M-94 and ASTM D3039 / D3039M-17 were used for shear tensile tests. This test method is used to determine the in-plane shear response properties of a polymer-matrix composite material that is reinforced by high-modulus fibres. A thin flat strip of UD material with a constant rectangular cross-sectional and layup in a $\pm 45^\circ$ direction is mounted in the grips of the tensile testing machine to test the shear properties. The UD material, or sample, is loaded with tension while the tensile testing machine records the forces. Thereafter, stress/strain graphs are obtained as a result in order to calculate the shear moduli.

The following figures illustrate these aforementioned graphs at $\pm 45^\circ$ angles.

3.2.2.1 Degree of cure (DOC) 2

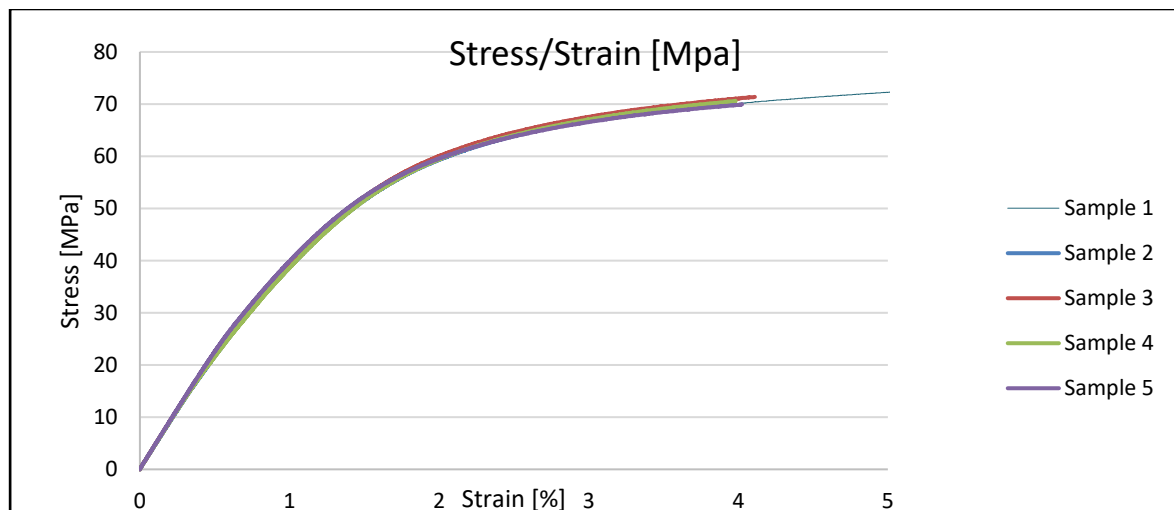


Figure 21: Degree of cure (DOC) 2 stress/strain graph at a $\pm 45^\circ$ axis orientation.

Table 14: Calculated shear moduli for DOC 2 at $\pm 45^\circ$.

Sample	Young's modulus (MPa)
1	4610
2	4569
3	4654
4	4607
5	4661
Average	4661

3.2.2.2 Degree of cure (DOC) 3

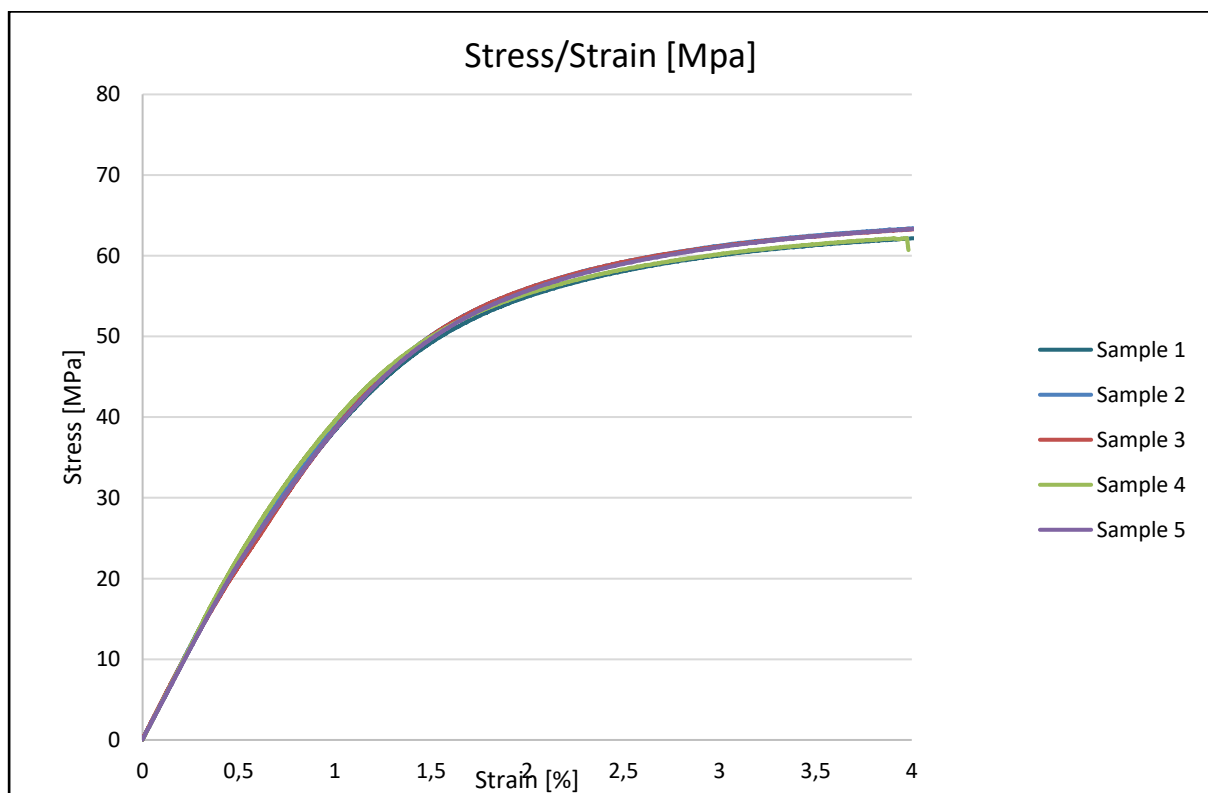


Figure 22: Degree of cure (DOC) 3 stress/strain graph at a $\pm 45^\circ$ axis orientation.

Table 15: Calculated shear moduli for DOC 3 at $\pm 45^\circ$.

Sample	Young's modulus (MPa)
--------	-----------------------

1	4643
2	4673
3	4828
4	4697
5	4605
Average	4689

3.2.2.3 Degree of cure (DOC) 5:

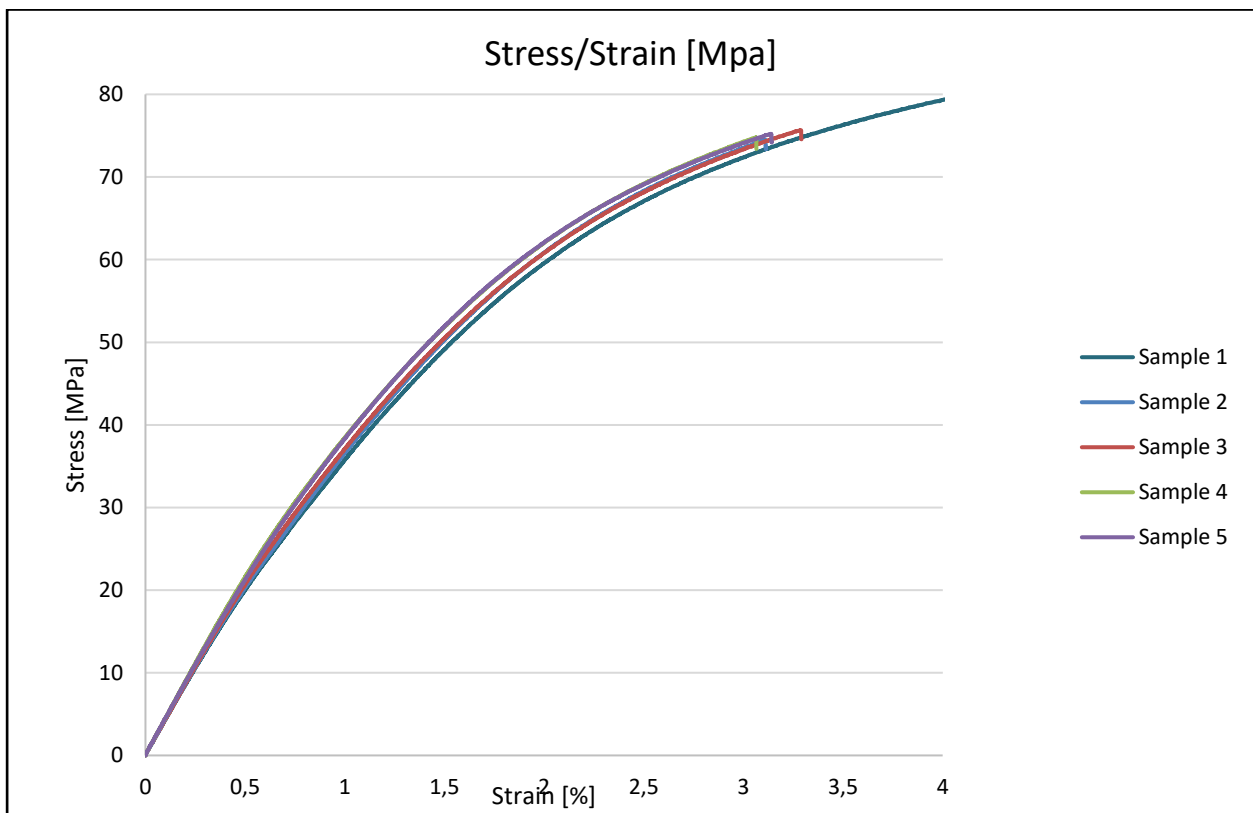


Figure 23: Degree of cure (DOC) 5 stress/strain graph at a $\pm 45^\circ$ axis orientation.

Table 16: Calculated shear moduli for DOC 5 at $\pm 45^\circ$.

Sample	Young's modulus (MPa)
1	4325
2	4275
3	4321

4	4473
5	4467
Average	4372

As seen from the results obtained in Section 3, there is no significant change in the shear modulus as a result of the degree of cure. The reason may be that this test determines the in-plane shear response, thus, testing the fibres and not the resin. It is noted that DOC 5 has a slightly higher stress than DOC 3 at 3% strain, resulting in a stronger sample due to resin cure.

3.2.3 Poisson's ratio

The ARAMIS GOM (GOM – Precise Industrial 3D Metrology, Braunschweig Germany) camera system was used to determine the Poisson's ratio for the samples tested in each applied direction.

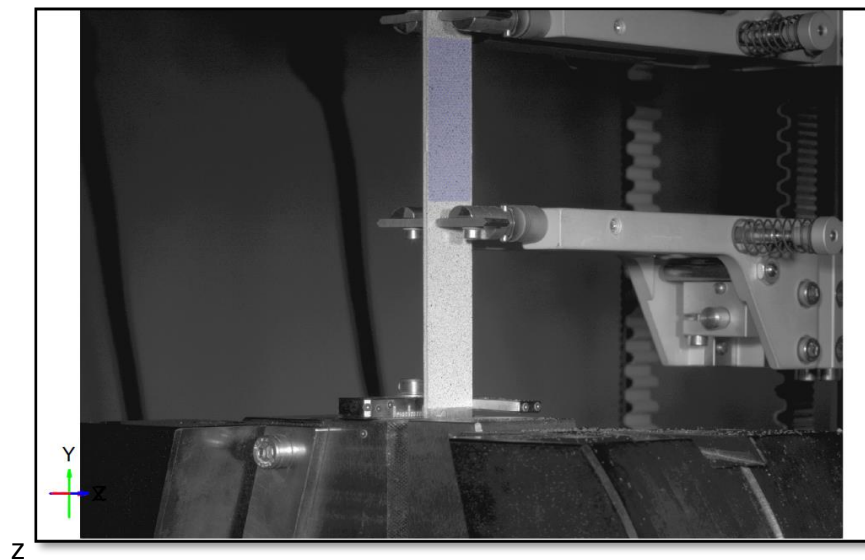


Figure 24: The ARAMIS GOM

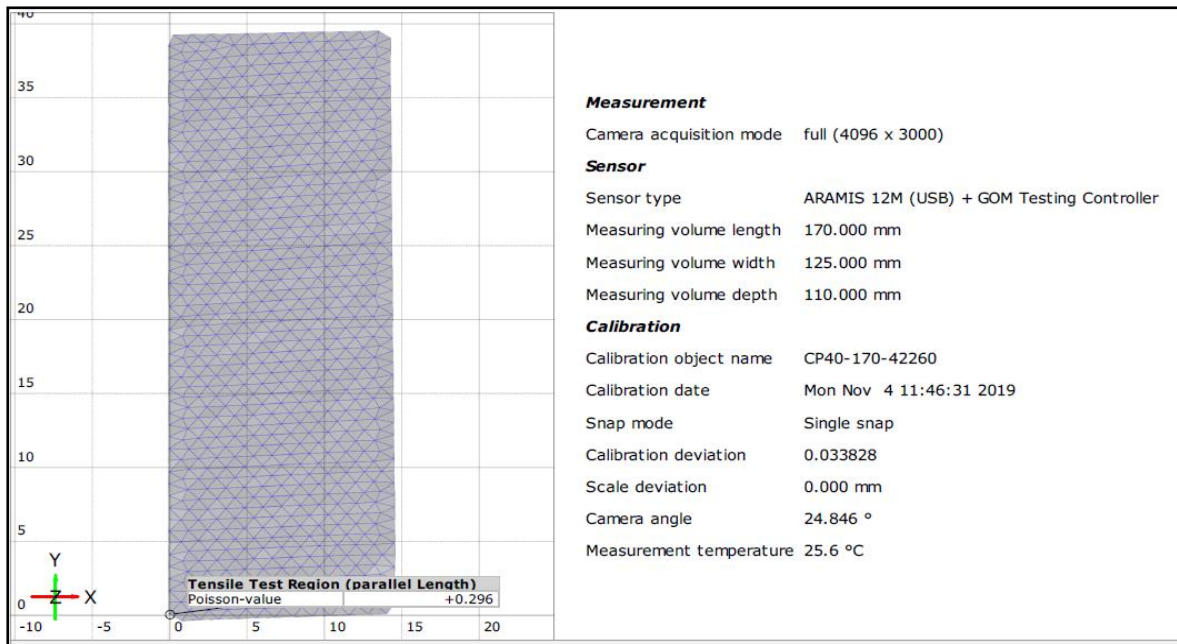


Figure 25: GOM Poisson's value.

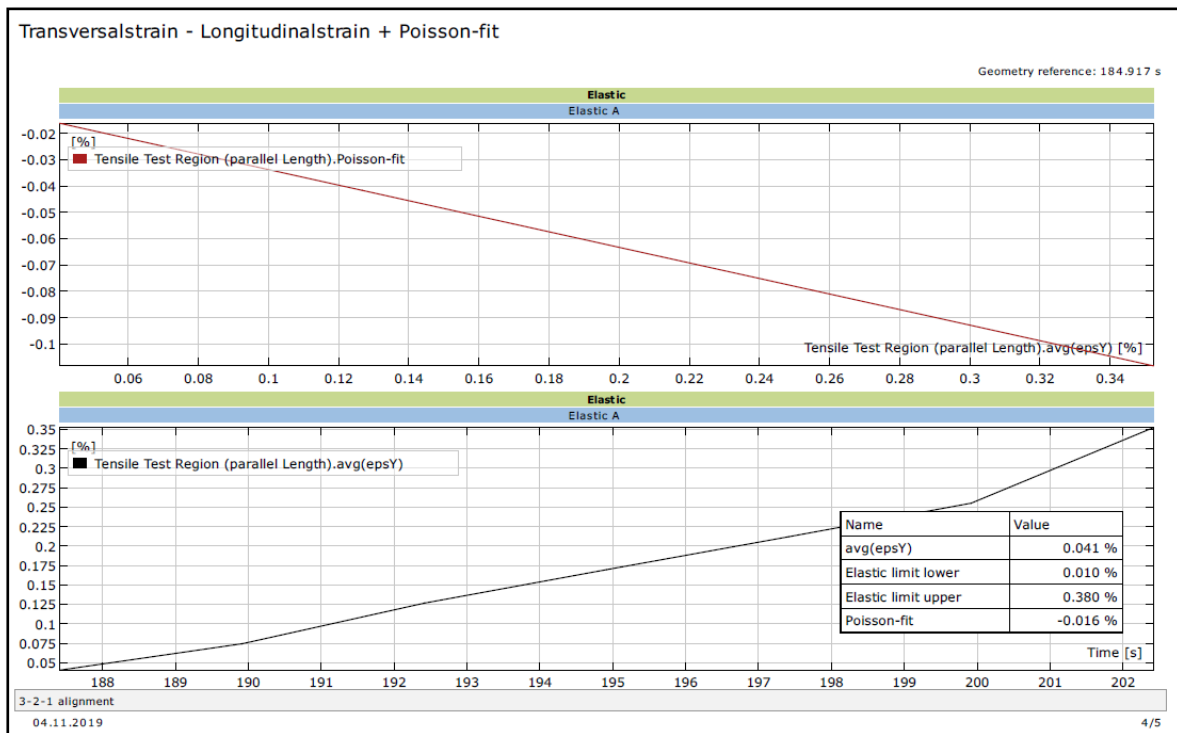


Figure 26: Poisson-fit and average strain.

Using the built-in function from the GOM, the sample was acquisitioned and a mesh constructed in the gauge length of the sample. As the sample was pulled in the tensile tester, the GOM calculated the average strain. This was then plotted onto the Poisson-fit curve calculated by the GOM. The results obtained from the test are shown in Table 17 below. See Appendix C for the Poisson reports.

3.2.3.1 Poisson results

3.2.3.1.1 0°:

Table 17: Poisson results.

Sample	DOC 2	DOC 3	DOC 5
1	0.304	0.279	
2	0.303	0.305	0.296
3	0.3	0.305	0.302
4	0.302	0.279	0.301
5	0.302	0.306	0.308
6	0.309	0.299	0.301
Average	0.303	0.296	0.302

3.2.4 Coefficient of thermal expansion (CTE)

The CTE of UD samples were tested at the Centre for Rubber Science & Technology, a department situated at Nelson Mandela University. The tests were done using a dynamic mechanical analysis (DMA) on two different degrees of cure samples and in two directions (0° and 90°). The tests were performed with three samples each, and the average results obtained for the materials are given below. The samples were tested using a TA-Instrument DMA Q800 and were subjected to a controlled load force of 0.5 N at a gauge length of 10 mm over a temperature range of 33–200 °C with a constant heat rate of 2°C/min. Figures 28-31 illustrate the descriptive data obtained.

Table 18: CTE results.

Material	CTE				
	(10e-06/°C)				
UD	RUN 1	RUN 2	RUN 3	AVERAGE	STD DEV
DOC 2/5 -0°	-33.0	-34.0	-30.1	-32.4	1.6694
DOC 2/5 -90°	68.8	68.9	97.4 *	78.4	13.496 *
DOC 5/5 -0°	-35.8	-34.6	-35.8	-35.4	0.5740
DOC 5/5 -90°	31.4	34.4	31.6	32.5	1.3747

The temperature ranges chosen for the CTE calculations in the graphs below are:

- DOC 2/5 = 33 - 180°C
- DOC 5/5 = 61 - 180°C

* IF run 3 of sample DOC 2/5-90° is excluded, an STD of 0.0569 is obtained.

For the averaged strain vs temperature data, along with the measured data, please refer to Appendix B (X00600000RA046 – 2).

The following graphs illustrate the curves of strain vs temperature for each material:

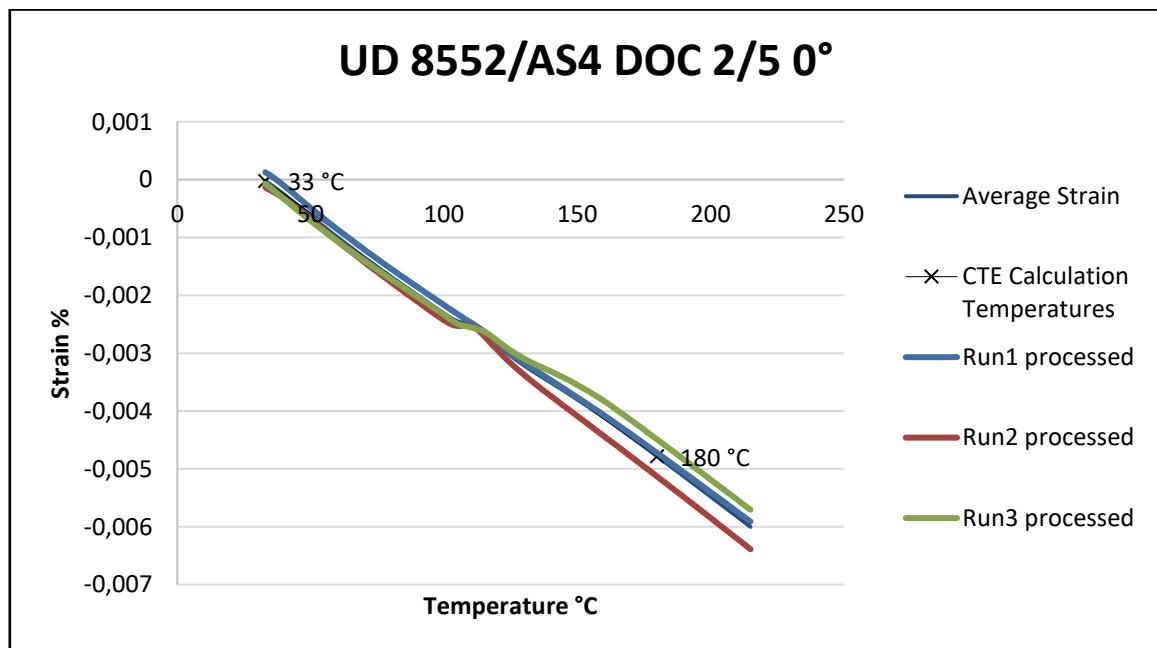


Figure 27: UD 8552/AS4 DOC 2/5 0°.

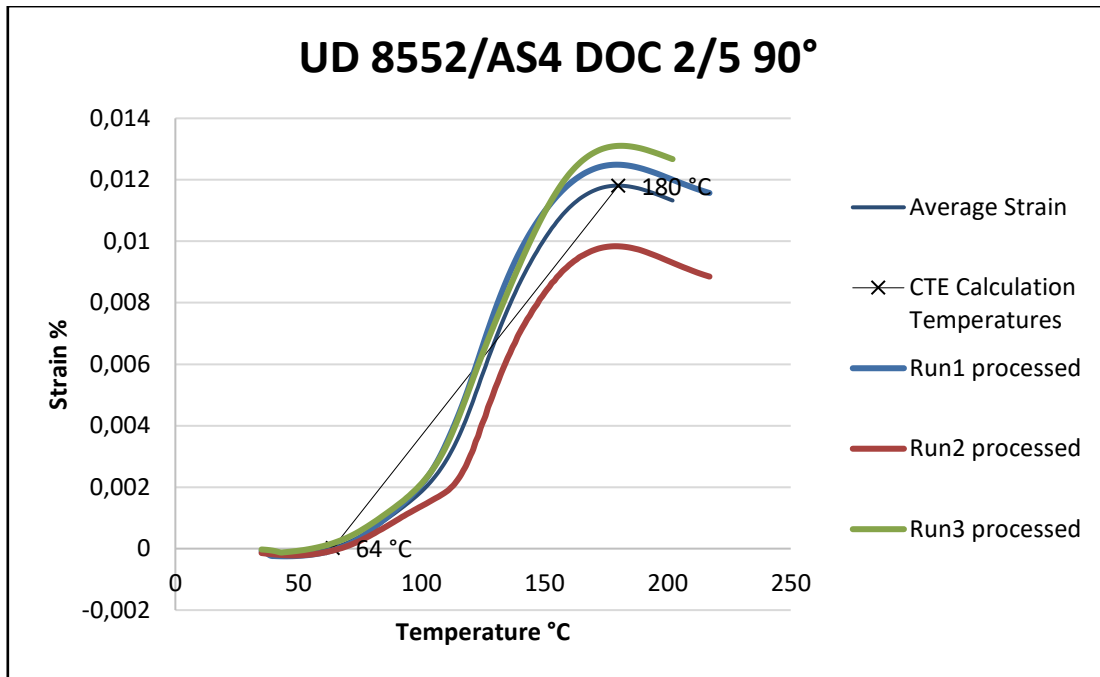


Figure 28: UD 8552/AS4 DOC 2/5 90°.

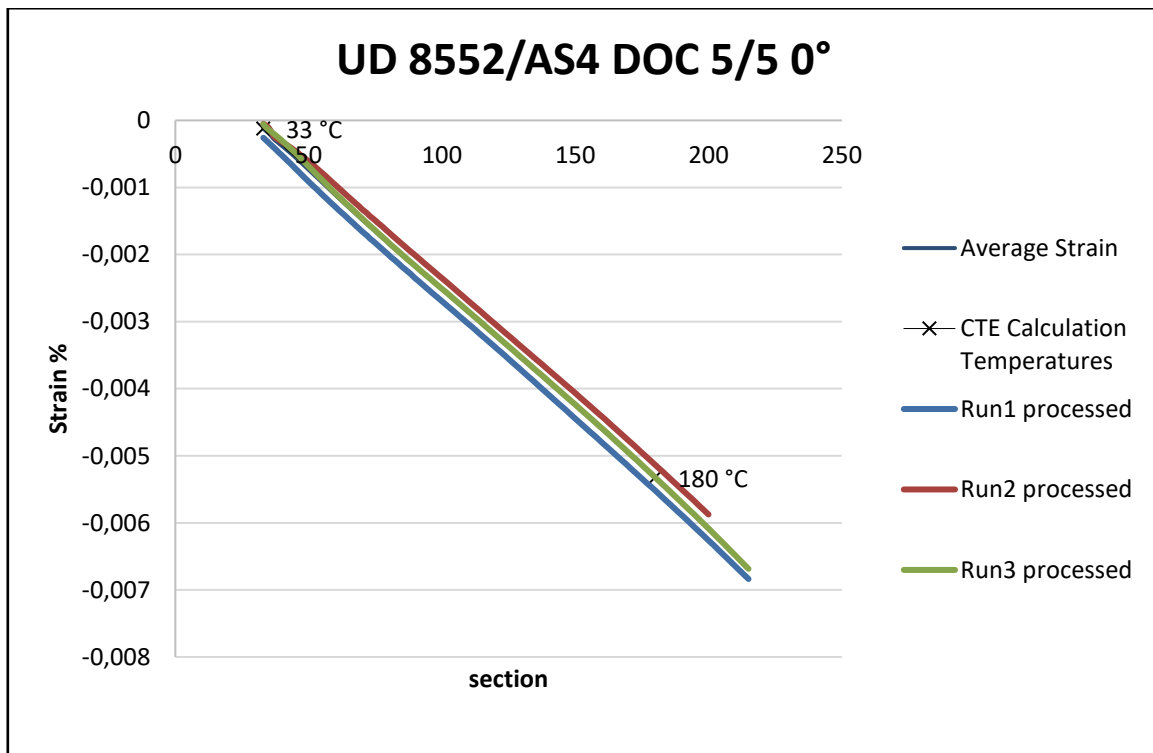


Figure 29: UD 8552/AS4 DOC 5/5 0°.

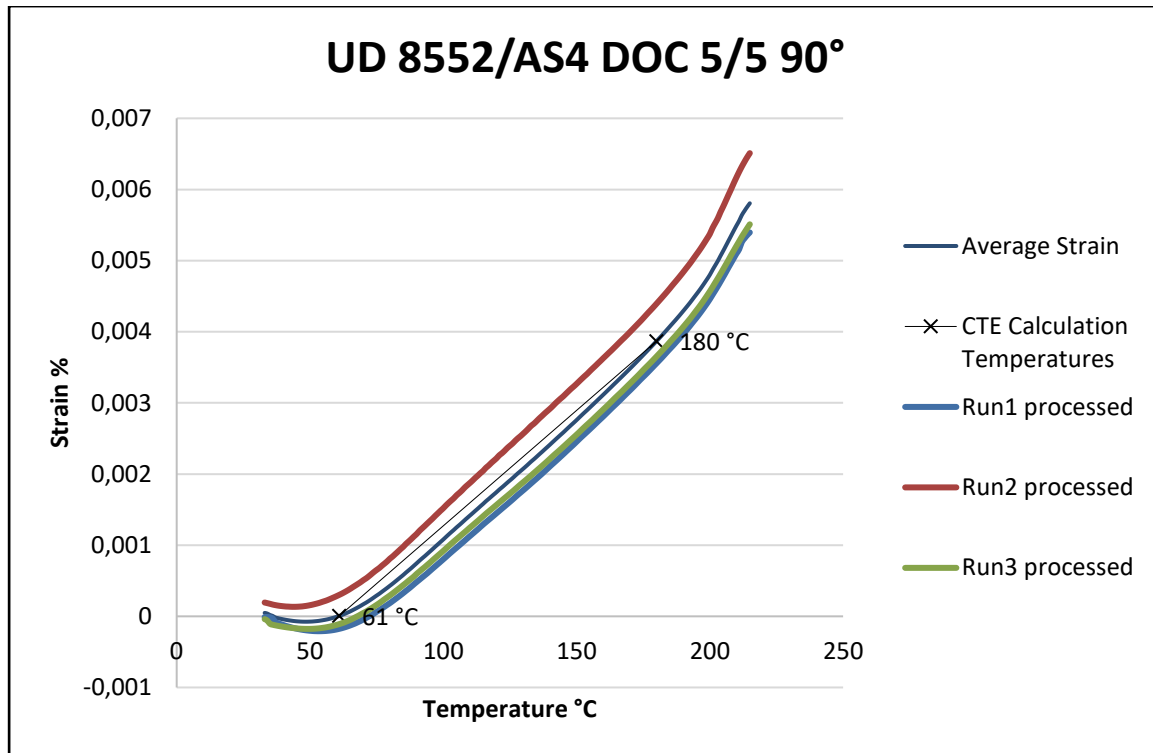


Figure 30: UD 8552/AS4 DOC 5/5 90°.

Figure 27 to 30 shows the CTE of the different samples that were calculated for the full temperature ramp of the cycle, as seen in the graphs above. A negative CTE was obtained for the samples in the 0° direction, as seen from the literature, where carbon does not have a positive CTE in the longitudinal direction during cure although it has a positive CTE in the transverse direction. This forms part of the reason why warpage is obtained during the curing of composite parts.

3.2.5 Cure kinetics

A differential calorimetry cure kinetics study was conducted on the Hexcel (11) 8552 epoxy resin prepreg material to determine the desired cure kinetics. Both dynamic and isothermal methods were used in the analyses.

Table 19: Mass of samples.

Sample	m1 (g)	m2 (g)	m3 (g)	m3-m2 (g)	% Resin
1	4.4234	50.0464	52.7822	2.7358	38.1516
2	4.373	49.4223	52.1375	2.7152	37.9099

3	4.3763	50.0424	52.763	2.7206	37.8333
Average					37.9650

The mass of the actual resin was determined for each measured sample, and calculations were adjusted accordingly.

Table 20: The results for the total heat required to cure the prepreg.

Energy required to cure	Sample weight mg	Resin weight mg	Sample ΔH J/g	Peak temperature °C	Resin ΔH J/g
CarbonPP Run1	24	9.1116	202.8332	229.97	534.264
CarbonPP Run2	22.6	8.5801	204.7825	230.41	539.399
CarbonPP Run3	23.4	8.8838	208.3137	230.57	548.7
CarbonPP Run4	22.4	8.5042	205.6877	230.55	541.783
CarbonPP Run5	23.5	8.9218	206.0998	230.54	542.868
Average			205.5434	230.41	541.40

The total heat of cure, $\Delta H_{resin\ total}$, for the resin was determined using a dynamic scanning method highlighted in testing method 1, as well as $\Delta H_{residual}$ for each of the cycles, calculated by determining the resin heat of cure from the ramp of 10°C/min from 110-310°C in methods 2-5:

$$\Delta H_{resin\ total} = \frac{\Delta H_{sample} \times m_{sample}}{m_{resin}}$$

$\Delta H_{resin\ total}$ was determined as 541.40 J/g, where $\Delta H_{residual}$ and is listed for each cycle in Table 22.

$$\Delta H_s = \Delta H_{resin\ total} - \Delta H_{residual}$$

Therefore,

$$\alpha = \frac{\Delta H_s}{\Delta H_{resin\ total}} \times 100$$

Table 21: The results for the % cure after each step in the cure cycle.

Cure cycle characteris ation	Sample weight mg	Resin weight mg	Sample ΔH J/g	Peak temperature °C	Resin ΔH J/g	Step ΔH J/g	%Cure

1st step - ramp to 110 °C							
CarbonPP	22.8	8.66	198.307	229.96	522.34	19.06	3.5%
CarbonPP	22.2	8.43	200.290	229.94	527.57	13.84	2.6%
CarbonPP	22.8	8.66	198.400	229.66	522.59	18.82	3.5%
Average							3.2%
2nd step - ramp to 110 °C, soak for 60 min @ 110 °C							
CarbonPP	23.6	8.96	193.046	227.91	508.48	32.92	6.1%
CarbonPP	21.9	8.31	192.396	227.90	506.77	34.63	6.4%
CarbonPP	22.5	8.54	191.465	228.31	504.32	37.08	6.8%
Average							6.4%
3rd step - ramp to 110 °C, soak @ 110 °C for 60 min, ramp to 180 °C							
CarbonPP	22.6	8.58	62.447	257.92	164.49	376.92	69.6%
CarbonPP	23.2	8.81	62.635	257.74	164.98	376.42	69.5%
CarbonPP	22.8	8.66	62.751	257.4	165.29	376.12	69.5%
Average							69.5%
4th step - full cure cycle, ramp to 110 °C, soak @ 110 °C for 60 min, ramp to 180 °C, soak @ 180 °C for 120 min							
CarbonPP	22.8	8.66	16.888	249.29	44.48	496.92	91.8%
CarbonPP	23	8.73	19.999	250.8	52.68	488.73	90.3%
CarbonPP	22.9	8.69	16.703	250.63	44.00	497.41	91.9%
CarbonPP	23.9	9.07	16.778	250.45	44.19	497.21	91.8%
CarbonPP	24.9	9.45	18.639	251.12	49.10	492.31	90.9%
Average							91.3%

Table 22: A summary of the DSC test results from Table 23 (% cure results).

Cure cycles	% α
1st Step	3.2
2nd Step	6.4
3rd Step	69.5
4th Step	91.3

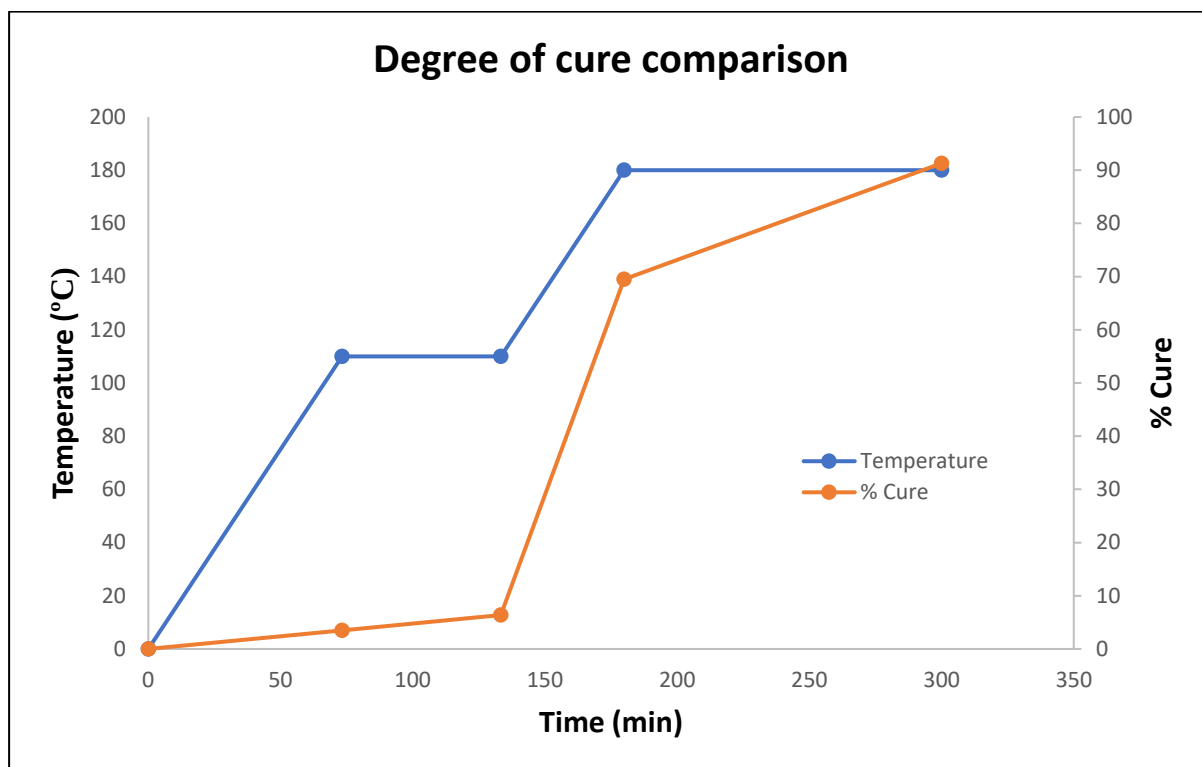


Figure 31: Degree of cure comparison.

The degree of cure was calculated with the use of the following formula indicated below to develop projected values represented in Figure 31. The % cure is shown.

$$\alpha = \alpha_o + \frac{1}{\Delta H_C} \sum_{i=1}^{n-1} (\dot{H}_{baseline} - \dot{H}_i) \times \Delta t$$

3.3 Summary of the results obtained

Table 23: Results summarised.

Properties	DOC 5 – fully cured
------------	---------------------

E_{11}	132723 (MPa)
E_{22}	9277 (MPa)
G_{12}	4372 (MPa)
G_{23}	3199 (MPa)
V_{12}	0.302
V_{32}	0.450
V_{31}	0.022
α_{11}	-35.4 (10e-06/°C)
α_{22}	32.5 (10e-06/°C)
β_{11}	91.3 %

Table 24: 0°, standard deviation and coefficient of variation.

0°	Standard deviation	Coefficient of variation
DOC 2	5199	4.1
DOC 3	3747	2.9
DOC 5	4425	3.3

Table 25: 90°, standard deviation and coefficient of variation.

90°	Standard deviation	Coefficient of variation
DOC 2	675	43
DOC 3	213	11.8

DOC 5	416	4.5
--------------	-----	-----

Table 26: $\pm 45^\circ$, standard deviation and coefficient of variation.

$\pm 45^\circ$	Standard deviation	Coefficient of variation
DOC 2	37.8	0.8
DOC 3	84.8	1.8
DOC 5	91.6	2.1

3.4 Material characteristics compared to literature

The table below illustrates the properties obtained through various tests performed from the same material with the properties seen in the current literature.

Table 27: Literature material properties.

	Ding <i>et al.</i>	Falco <i>et al.</i>	Cam-Rp-2010	Ameya <i>et al.</i>	Sylvain <i>et al.</i>	Graciani <i>et al.</i>	Average
E₁₁ (GPa)	135.0	137.1	131.6	135.0	130.0	131.5	133.4
E₂₂ (GPa)	9.5	8.8	9.2	9.5	9.4	9.2	9.3
G₁₂ (GPa)	4.9	4.9	4.8	4.9	4.0	4.8	4.7
G₂₃ (GPa)	3.3	-	-	3.3	4.7	3.3	3.6
v₁₂	0.300	0.314	0.302	0.300	0.175	0.302	0.3
v₂₃	0.450	0.487	-	0.450	0.300	0.400	0.4

Table 28: Material database vs the current literature.

Properties	Average	DOC 5 – fully cured	Percentage deviation [%]
E₁₁ (GPa)	133.4	132.7	0.52
E₂₂ (GPa)	9.3	9.3	0
G₁₂ (GPa)	4.7	4.4	6.38
G₂₃ (GPa)	3.6	3.2	11.11

V_{12}	0.3	0.302	0.66
V_{31}	0.4	0.450	11.11

Table 28 shows a correlation in the properties obtained compared to the articles that used the same material in their respective studies. A comparison was made of the average values regarding the different articles. The average was chosen given that in material testing, different machines may affect the value differently.

3.5 Conclusion

A significant change in the 90° tensile properties can be seen in the results compared in Section 3, with an increase in stiffness with degree of cure. The increase in stiffness for the 0° axis orientation is, however, not as significant. These results show the degree of cure's effect on the material's tensile stiffness in the 0° and 90° directions. This can be considered expected behaviour when increasing the degree of cure of the thermoset prepreg material.

The results obtained in Section 3 show no significant change in shear moduli. This may be due to the test used to determine the in-plane shear response and testing the fibres and not the resin. In addition, it should be considered that DOC 5 had a slightly higher stress than DOC 3 at 3% strain, which resulted in a stronger sample due to resin cure.

CHAPTER 4

Curing Simulation

This chapter focuses on the curing simulations calculated by Marc software for the flat plates with the properties obtained in Chapter 3. It further highlights the various simulation models for the different layups defined in Chapters 2 and 5.

4.1 Introduction

Marc is a FEM simulation software from MSC one used to accurately simulate material behaviour under static, dynamic, and multi-physics conditions. Marc's ability to model nonlinear material behaviour and transient environmental conditions is part of why this software is used to solve design problems in different industries. Marc is optimised to deliver comprehensive solutions and solve composite curing simulations using a thermal/structural transient analysis. The simulation is used to calculate the final distorted state of a composite part after curing.

The simulation took place in multiple phases:

4.2 Simulation phases

4.2.1 Phase 1: Pressurisation

The model was pressurised at 7 bar from the beginning of the simulation and held at this pressure until the cooling phase. This is needed due to the fact that pressure distribution can cause the resin to transfer non-uniformly and, in turn, cause non-uniform thickness of the final part.

4.2.2 Phase 2: Curing

A temperature vs time is applied to the model along with the pressurisation of the flat plate. The data from the temperature vs time is obtained directly from the data used to cure the flat plate in the autoclave chamber. This is then used to simulate the conditions in the autoclave accurately. The curing process causes increased residual stresses, which causes overall distortion and warpage.

4.2.3 Phase 3: Cooling

The pressurisation is lowered to vacuum conditions during the cooling phase.

4.2.4 Phase 4: Removal/gravity

Assuming that no failure has occurred, the flat plate is modelled with the use of gravity to determine the overall warpage. Material warpage is caused by the curing and cooling down processes.

4.3 Flat plate simulation

Multiple simulation models were used to verify whether the material properties obtained in Chapter 3 are acceptable. The models simulated were categorised as a) balanced and b) unbalanced layups. The assumption was to expect warpage on both these layups. Validation was executed by comparing the results obtained from Chapter 4 and Chapter 5 from the manufacturing section of balanced and unbalanced flat plates. Figure 32 illustrates the setup process used in the models and the results obtained. Table 29 shows the Finite Element Analyses (FEA) model units used:

Table 29: FEA model units.

Name	Unit
Force	KN
Length	m
Stress	Pa
Time	s
Temperature	K

4.4 Unbalanced layup simulation

4.4.1 Geometry and mesh

Figures 33 and 34 show the geometry and mesh used. Each of the components is included as a separate body for meshing reasons. As seen in Figure 32, a surface is created to be in contact with the plate. The surface is moved to be in contact with the flat plate at the start of the analysis. This is done to reduce the time required to solve the contact at the start of the analysis by avoiding floating bodies. Solid composite elements (HEX8) are used as it improves the contact conditions in the model.

A global coordinate system is applied to the plate because of its rectangular shape. Figure 33 shows the 0° being in the X-direction (red) and 90° in the Y-direction (green).

4.4.2 Model

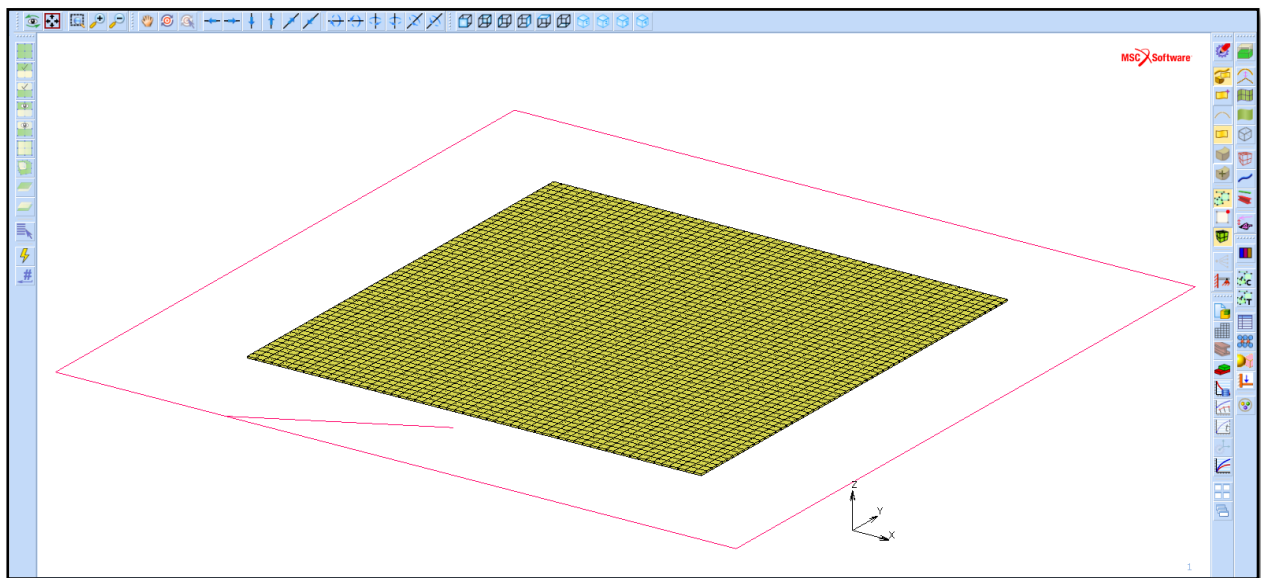


Figure 32: Flat plate model.

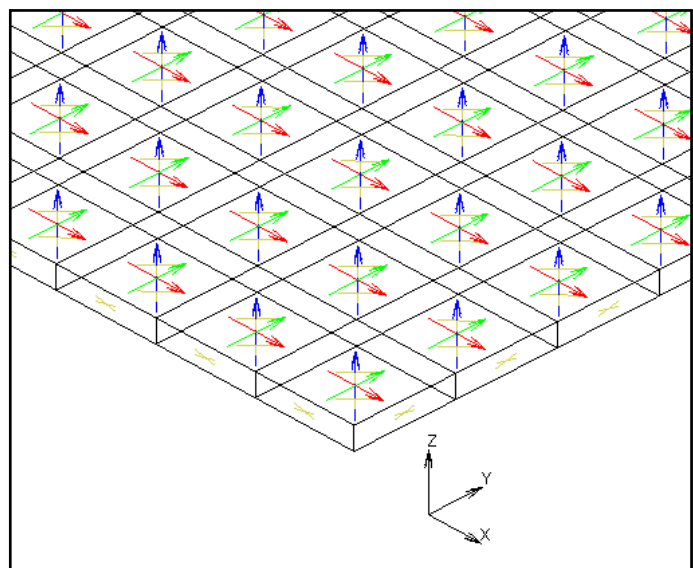
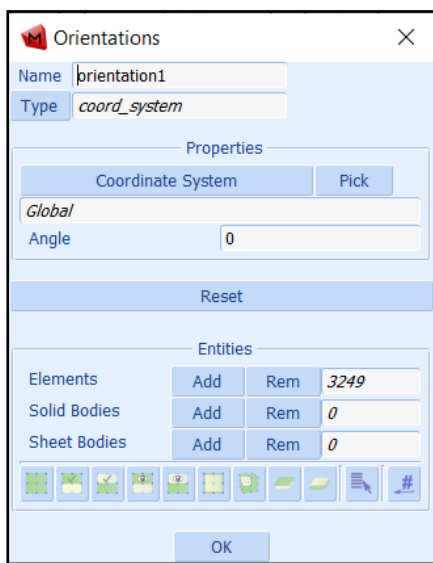


Figure 33: Orientations.

4.4.3 Material properties

The material properties applied in the model are shown in Figure 34 to Figure 36, with the table value inputs given in Appendix E.

With regard to the composite material and property, the laminate property consists of eight plies, solid composite elements are used and there is one layer of elements through the thickness. The elements are orientated so that Phase 4 is on the outside for all elements. This creates an asymmetric layup where each of the element layers has the same ply definition but in the reverse direction.

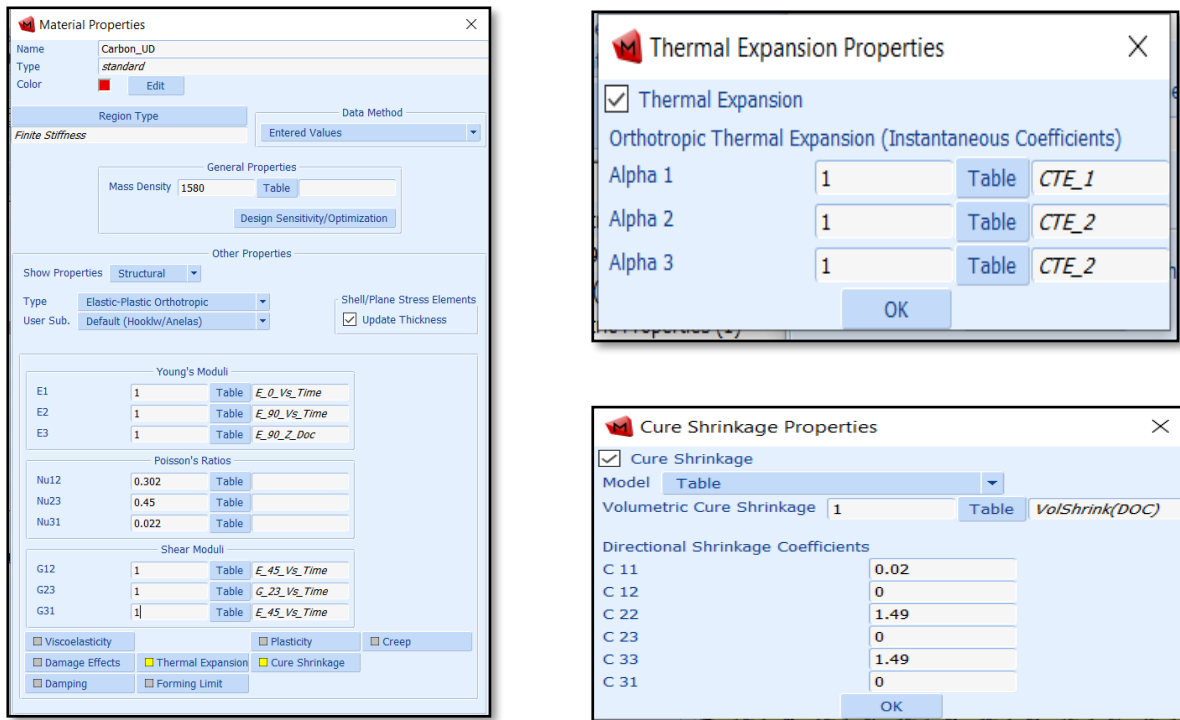


Figure 34: Structural material properties.

Material Properties

Name: Carbon_UD
Type: standard
Color: ■ Edit

Region Type: Finite Stiffness Data Method: Entered Values

General Properties

Mass Density: 1580 Table Design Sensitivity/Optimization

Other Properties

Show Properties: Thermal Type: Orthotropic

Conductivity

☐ User Sub. Ankond

K1: 1 Table UD_Conductivity_K11
K2: 1 Table UD_conductivity_K22
K3: 1 Table UD_conductivity_K22

Specific Heat: 1471 Table
Mass Density: General 1580 Table
Emissivity: 0 Table
Enthalpy Of Formation: 0 Table
Ref. Temperature: 0 Table

☐ Latent Heat ☐ Curing

Entities

Elements: Add Rem 0
Solid / Sheet / Wire Bodies: Add Rem 0

OK

Curing Properties

☒ Curing

Curing Rate Model: Johnston And Hubert (1995)

A1: 244800
E1: 66500
M: 0.76016
N: 1.7233
Diffusion Constant: 4.31
Critical Degree Of Cure: -1.648
Critical Degree Of Cure W/Temp: 0.005475
Resin Cure Reaction Heat: 566
Fiber Volume Fraction: 0.55
Resin Density: 1300

OK

Figure 35: Thermal material properties.

Material Properties

Name: Layup_Un_Symm
Type: composite
Color: ■ Edit

Region Type: Finite Stiffness Data Method: Entered Values

General Properties

Reference Plane: 0
Single Layer: Append Insert Copy Remove Material
Layer Range: Copy Remove

Layers: 8 Settings: Auto ID Absolute Thickness

Index	ID	Material	Thickness	Angle
1	1	Carbon_UD	0.19	0
2	2	Carbon_UD	0.19	0
3	3	Carbon_UD	0.19	90
4	4	Carbon_UD	0.19	0
5	5	Carbon_UD	0.19	0
6	6	Carbon_UD	0.19	90
7	7	Carbon_UD	0.19	0
8	8	Carbon_UD	0.19	0

Sum: 1.52

Other Properties

Show Properties: Thermal No Properties Required

Entities

Elements: Add Rem 3249
Solid / Sheet / Wire Bodies: Add Rem 0

OK

Geometric Properties

Name: carbon
Type: Structural 3-D Solid Composite/Gasket
Color: ■ Edit

Properties

Thickness Direction: Face 4 (1-2-3-4) To Face 5 (5-6-7-8)

Element Technology

☐ Constant Temperature
☐ Solid Composite Only
☐ Constant Dilatation

Entities

Elements: Add Rem 3249
Solid Bodies: Add Rem 0

Clear OK

Figure 36: Geometric and layup.

Figures 34 to 36 represent the properties determined and used in the simulation in Marc. Figure 34 shows all the structural values used, Figure 35 the thermal properties used, and the curing model used was a built-in Marc model. Figure 36 shows the geometric properties used and the unbalanced layout.

4.4.4 Contact

The contact bodies used in the analyses and the properties of the contact interactions are shown in Figure 37. The friction coefficient used in the touch contact is chosen as a low value to keep the plate in position during the analysis. The contact heat for touch contact transfer is 0 by default.

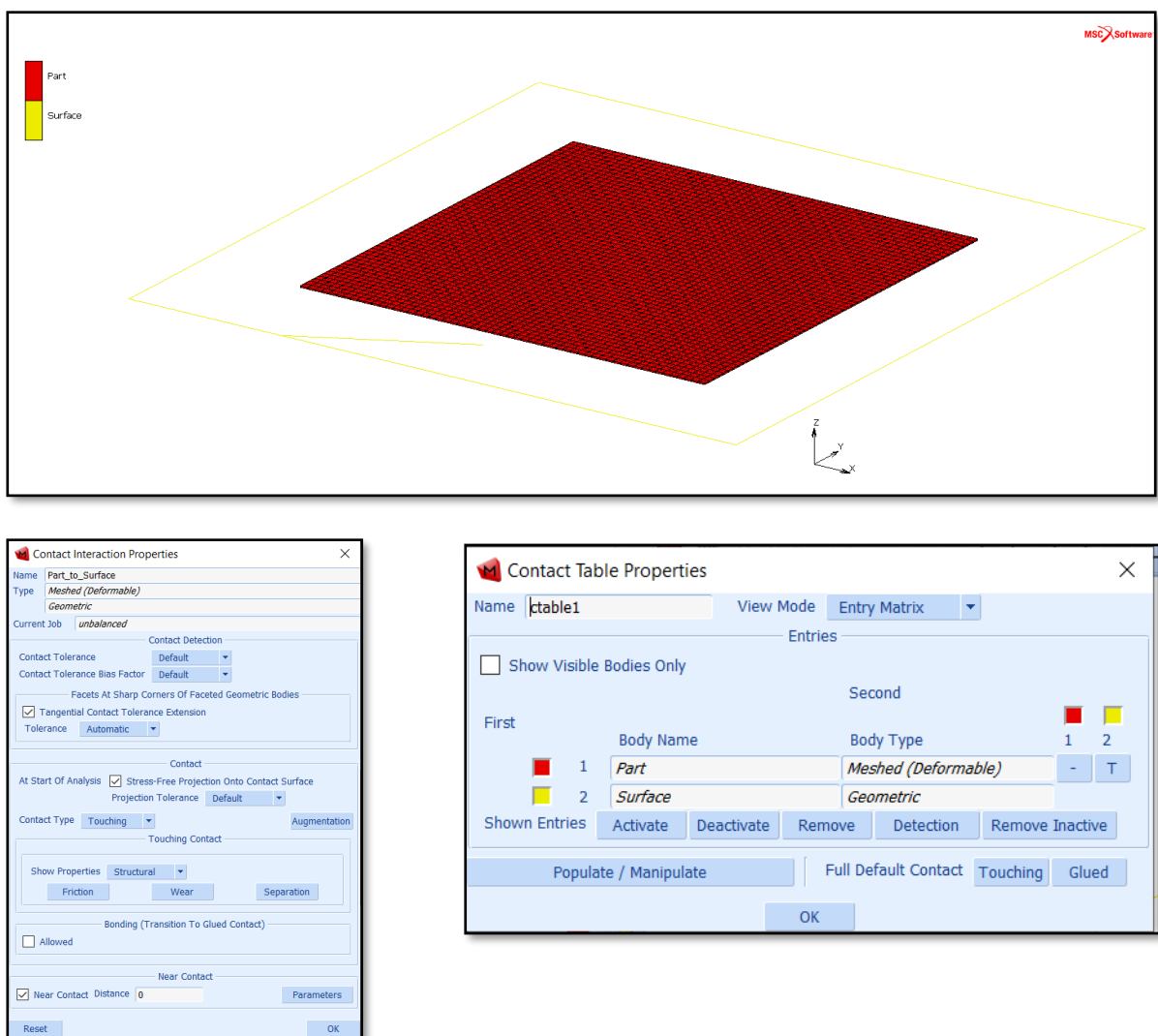


Figure 37: Contact properties.

4.4.5 Loads and boundary conditions

Figures 38 and 39 show the initial and boundary conditions used in the analysis. Two initial conditions were used in the model. The initial temperature of all nodes is required for thermal analysis. If no initial temperature is specified for a node, it is assumed to be 0. An initial degree of cure is also specified for all elements of the plate.

The pressure load of 7 bar is applied to the outside faces of the plate. Temperature is applied to the model through a face film (convection) and to the plate's outside faces by adding the autoclave's temperature profile.

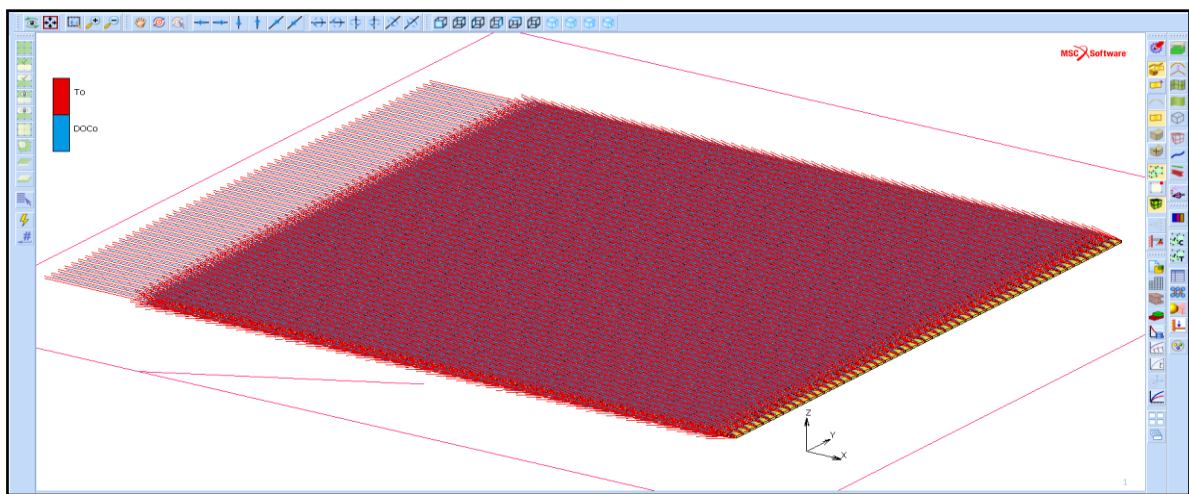


Figure 38: Initial conditions.

From Figure 38 an initial condition of 383,15 K for temperature and 0,4% for the degree of cure was used.

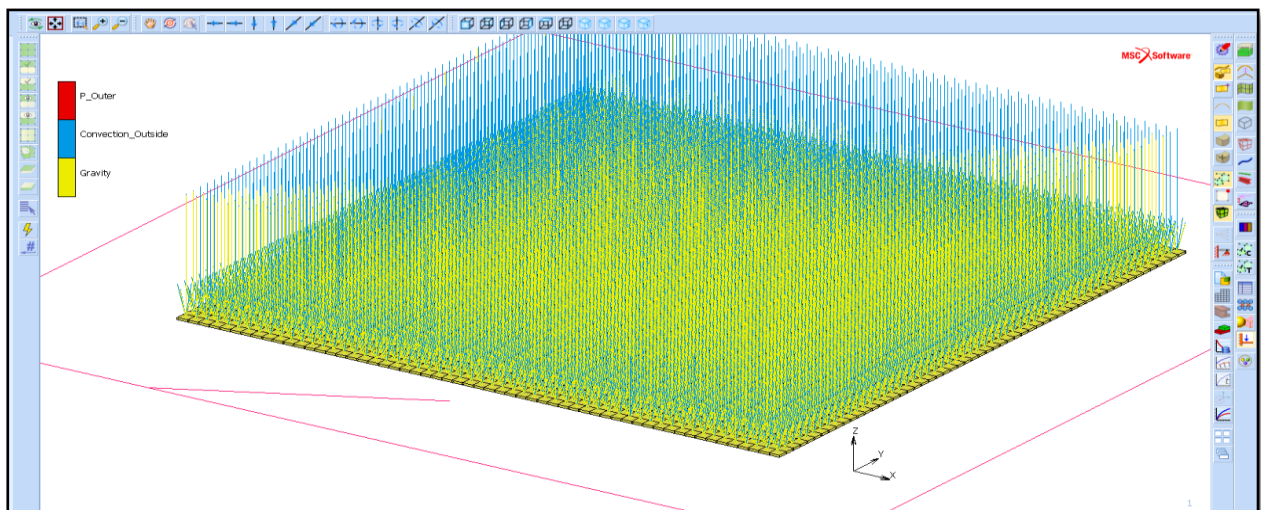


Figure 39: Boundary conditions.

Figure 39 illustrated all the boundary conditions used and how they were applied in the simulation onto the flat plate. As seen a gravity of -9.81 m/s^2 and pressure of 1 KPa were applied in the negative Z direction. The red border around the plate illustrated a representative of the Aluminium bed the plate is cured and sealed onto, inside the autoclave.

4.4.6 Analysis

A thermal/structural analysis was used for the curing cycle. Figure 40 shows the analysis settings that were used.

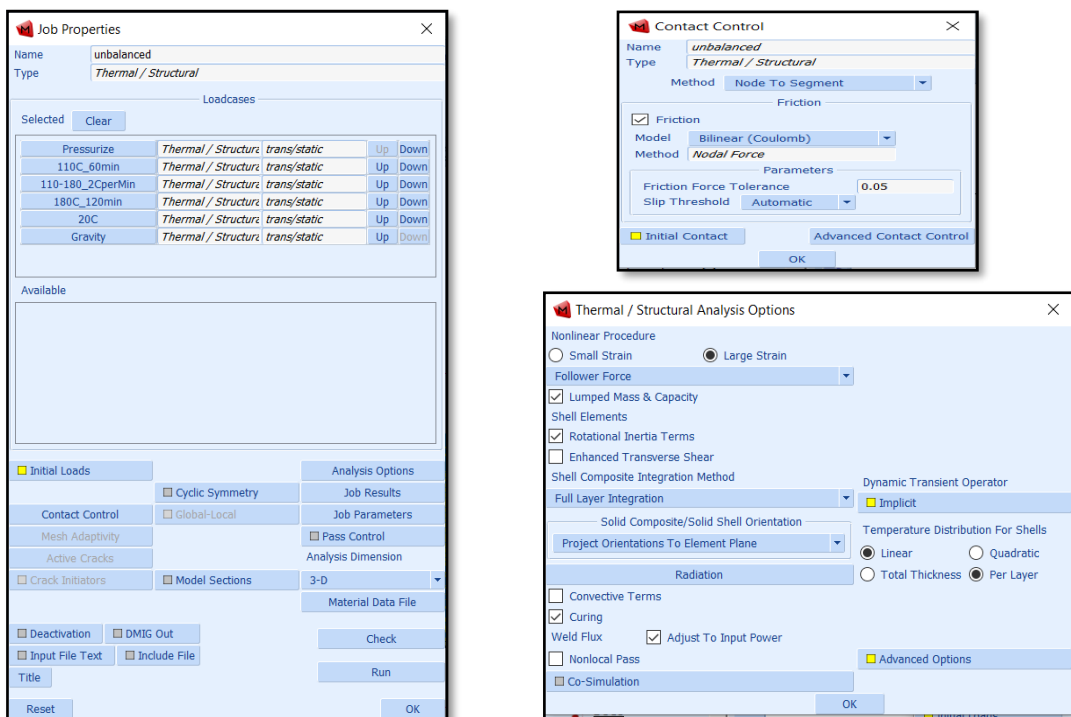


Figure 40: Analysis.

Figure 40 illustrated the analysis method used in the simulation. An initial load is applied to the plate. As seen in figure 40 the jobs applied to the plate is in correlation with the curing graphs used for the autoclave. Initial contact is also added so simulate the flat plate is sealed onto the aluminium bed with a small friction between the material and the aluminium plate.

4.5 Balanced layup

The balanced layup had similar model trees, models, and material properties, while only the layup was different.

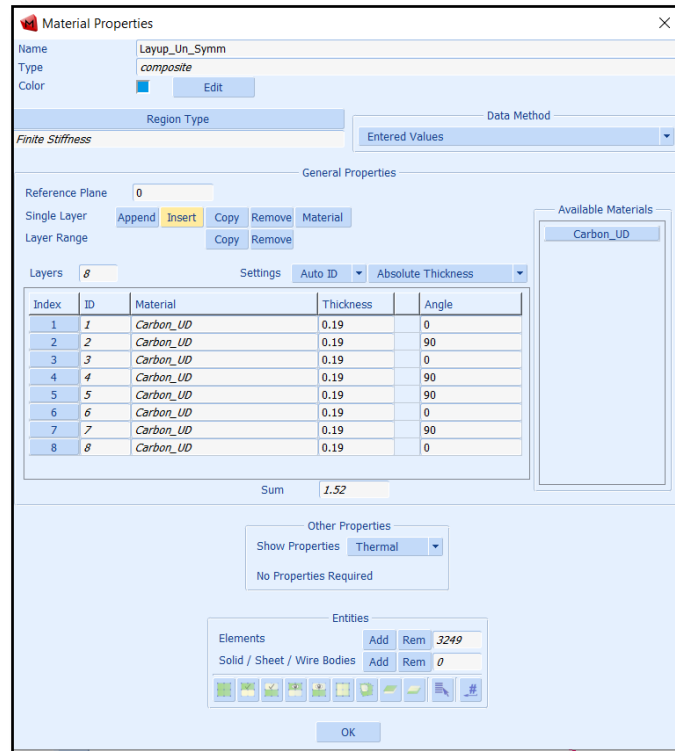


Figure 41: Balanced layup.

Figures 36 and 41 illustrate a cured ply thickness of 0.19 mm. This thickness is what is use internally for all the parts manufactured from UD material. A small friction of 0.05 N is assumed (Figure 40) to ensure the plate does not move from the surface during the simulation. The simulation does not include the first ramp up to 110°C, as no significant effect occurs during this time. Thus the simulation starts at 100°C and full 7 bar pressure.

CHAPTER 5

Plate Manufacturing

The following chapter focuses on the manufacturing process of the flat plates, the builds using the bag layup process, as well as the results obtained from two different layups. Moreover, the ensuing chapter also clarifies the scanned data that was obtained.

5.1 Introduction

The same layup and conditions of the simulation were manufactured in order to validate whether the properties used in the simulation model of the flat plate are acceptable. The plates were manufactured using the bag layup process. Two sets of plates were manufactured. The first set was manufactured using a balanced layup of $[0/90]_4$, and the second set was manufactured from an unbalanced layup of $[0/90]_4$. Both layups are still symmetric. The layup sequences are illustrated in Tables 30 and 31, respectively.

Table 30: Balanced layup.

Ply (P) number	Orientation (°)	Remarks
P1	0	Ply 400 mm x 400 mm
P2	90	Ply 400 mm x 400 mm
P3	0	Ply 400 mm x 400 mm
P4	90	Ply 400 mm x 400 mm
P5	90	Ply 400 mm x 400 mm
P6	0	Ply 400 mm x 400 mm
P7	90	Ply 400 mm x 400 mm
P8	0	Ply 400 mm x 400 mm

Table 31: Unbalanced layup.

Ply (P) number	Orientation (°)	Remarks
P1	0	Ply 400 mm x 400 mm
P2	0	Ply 400 mm x 400 mm
P3	90	Ply 400 mm x 400 mm
P4	0	Ply 400 mm x 400 mm
P5	0	Ply 400 mm x 400 mm
P6	90	Ply 400 mm x 400 mm
P7	0	Ply 400 mm x 400 mm

P8	0	Ply 400 mm x 400 mm
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After the plates had been cured, they were hand-trimmed to the dimensions shown in Tables 30 and 31. The thickness of each plate was measured using a micrometre. The plates were also scanned using a Romer (3D Scanner). The measured points were then compiled and compared to the simulation model to determine whether the same shape of warpage was obtained.

The cure cycle used to manufacture the plates is:

Plate curing cycle: ***Deg of cure 8552: Cycle 5***

- a. Apply full vacuum
- b. Apply 7-bar gauge autoclave pressure
- c. Vent vacuum when autoclave reaches approximately 1 bar gauge
- d. Heat at 2°C /min to 110°C ±5°C
- e. Hold at 110°C ±5 °C for 60 minutes ± 5 minutes
- f. Heat at 2°C/min to 180 °C ±5 °C
- g. Hold at 180°C ±5 °C for 120 minutes ±5 minutes
- h. Cool at 2°C per minute
- i. Vent autoclave pressure when the component reaches 60°C or below

5.2 Plate manufacturing

Figures 43 and 44 are schematic representations of how the plates are manufactured. Attached in Appendix D is a typical work instruction used to manufacture flat plates.

5.2.1 Balanced layup

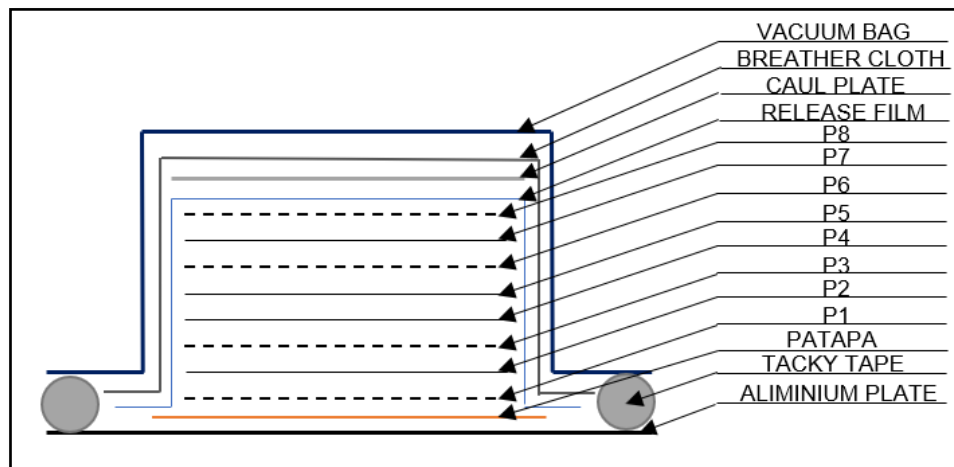


Figure 42: Schematic illustration of a balanced plate manufactured.

5.2.2 Unbalanced layup

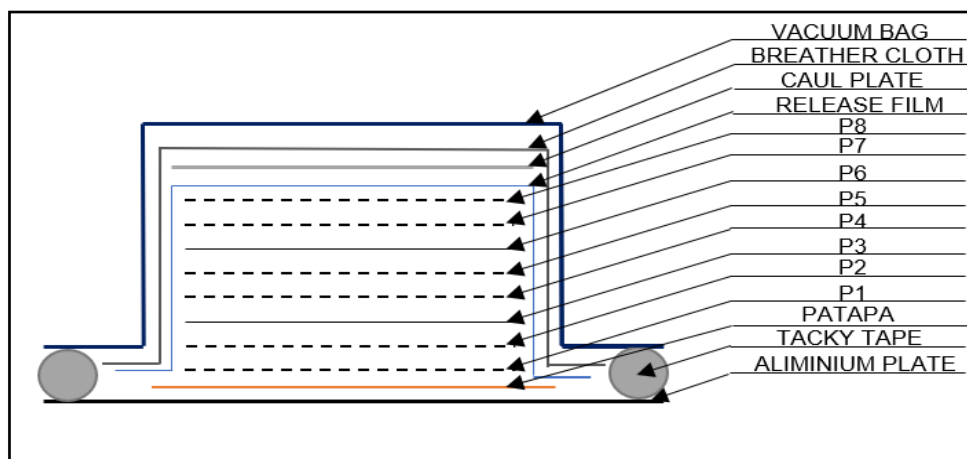


Figure 43: Schematic illustration of an unbalanced plate manufactured.

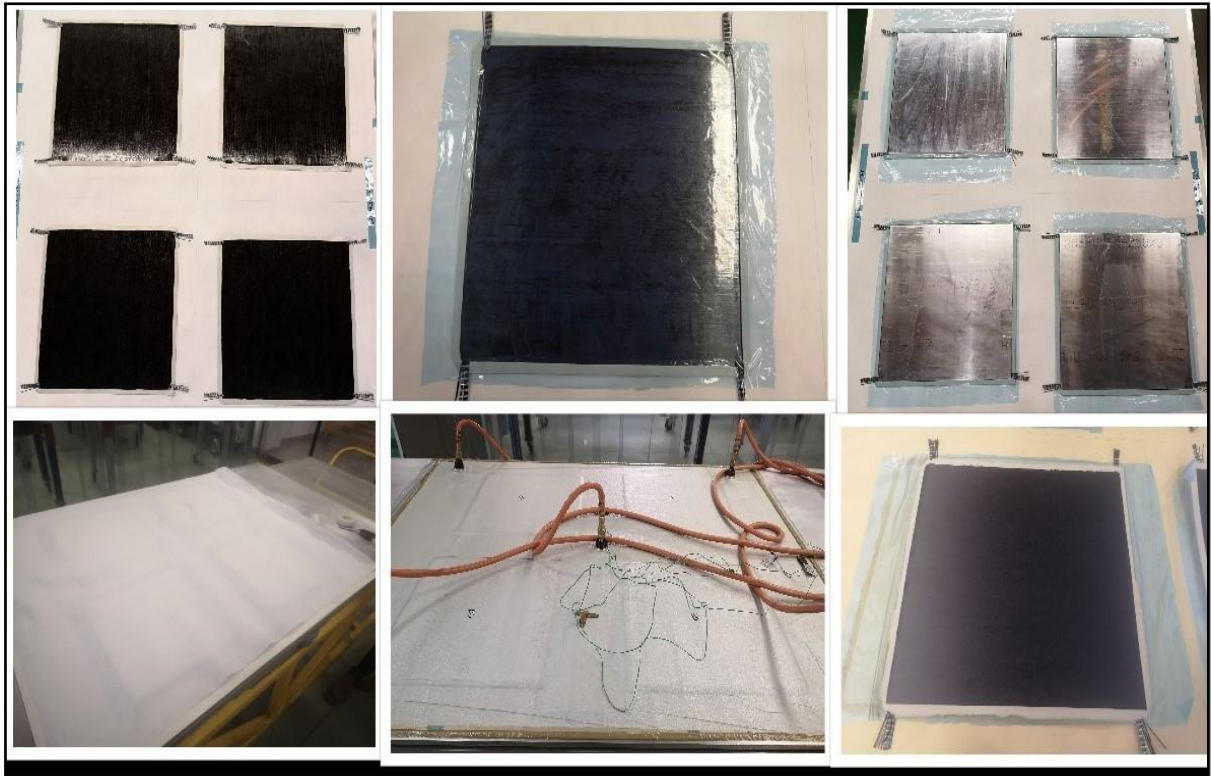


Figure 44: Plate manufacturing process.

Figure 44 illustrated how the plated were manufactured. The material is placed onto a non-adhesive paper and stacked in accordance with figure 42 and 43. Tape is placed around the edges of the material to prevent any resin from flowing out of the part. A perforated release film is used to protect the part from the breather cloth. The parts are then sealed with a vacuum bag and checked for any leaks. Thermocouples are placed onto each part and connected to the autoclave. If no leaks are detected the parts are placed into the autoclave and cured using the programmed curing cycle.

5.3 Manufacturing process

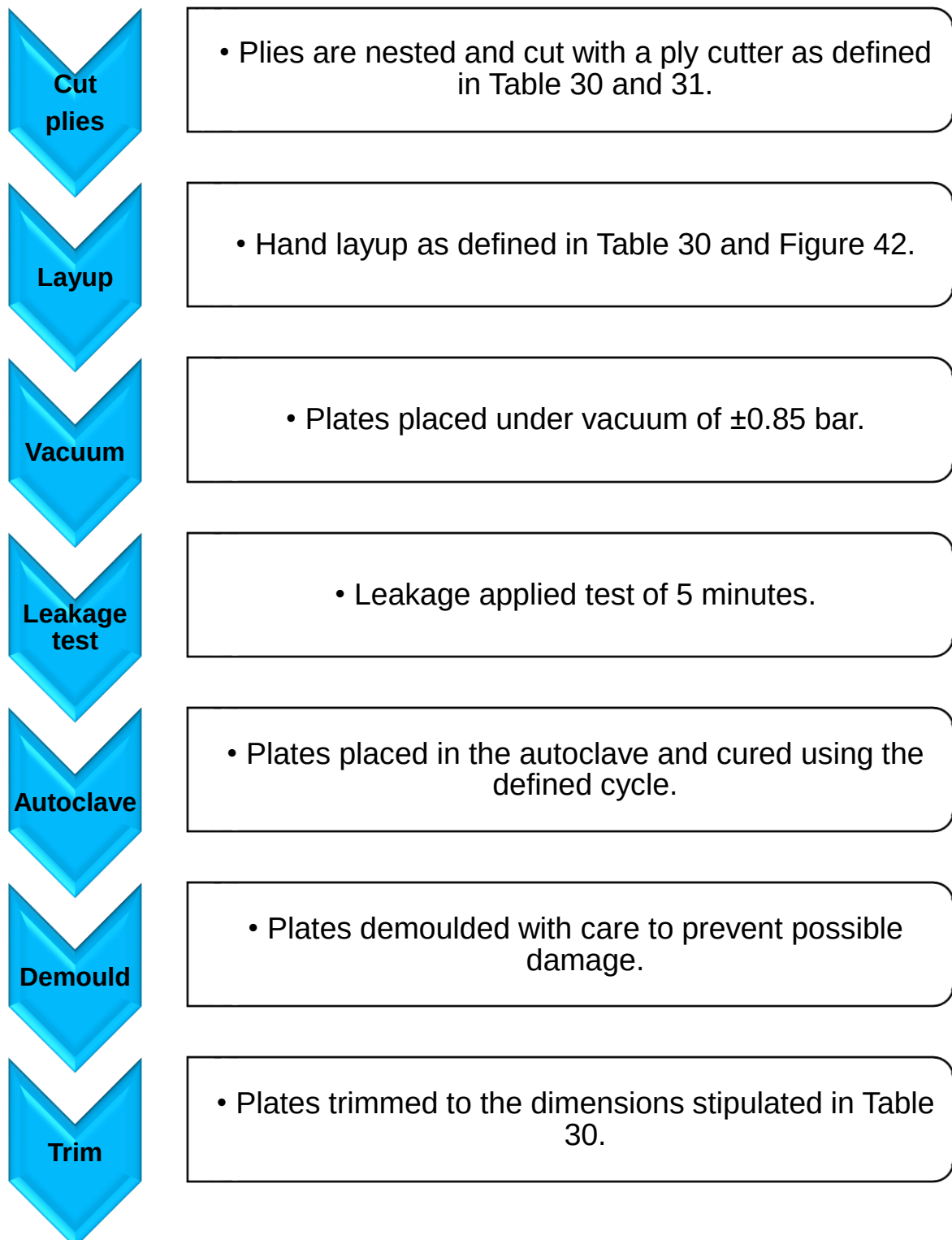


Figure 45: Manufacturing process.

5.4 Results

5.4.1 Autoclave

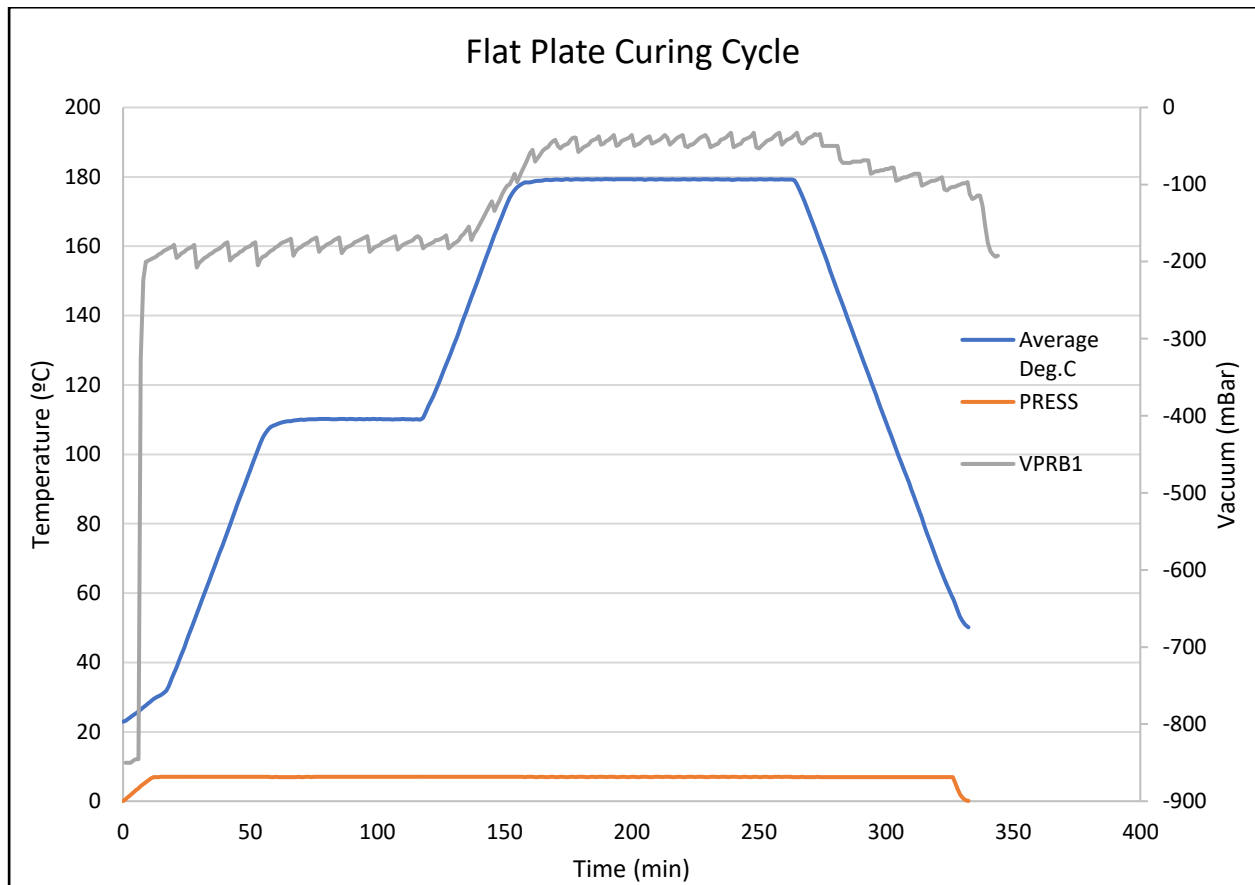


Figure 46: Autoclave cycle of manufactured plates.

Figure 46 illustrates the curing cycle of the flat plates. Figure 46 shows that there was a minor leak in the bag, as the vacuum decreased to about -50 mbar. This had no significant impact on the results as the plates did not experience any positive pressure. The leak functions to seal itself off again. The pressure of 7 bar was maintained for the entire cycle as seen in figure 46. The abbreviations in figure 46 show the average temperature in the autoclave (blue), the pressure in the autoclave (orange), and the vacuum experienced on the plate in grey. If the vacuum value is positive, it indicates that the bag obtained a leak and no consolidation could be obtained.

CHAPTER 6

Results Comparison

Chapter 6 compares the results obtained in Chapters 3, 4, and 5 to validate the composition of the manufactured plates displacement with the simulation model displacement.

6.1 Plate manufacturing results

To obtain the results of the manufactured plates a Romer 3D scanner was used. The Romer is a portable 3D coordinate measuring device, it is designed to enhance the movement of the human arm which offers several degrees of freedom. For the measurement of the plates the Romer was fitted with a laser with an accuracy of ± 0.079 mm.

Each plate had to be sprayed with white paint, as the Romer operates with reflecting light, because the material is black the laser penetrates the resin in the material and can cause the light to not reflect as effectively, this can cause the results to be inaccurate. The plates were held in position in a manufactured jig. Four of balanced plates were scanned and the results are obtained below. Only three of the unbalanced plate results were used as one plate failed in the manufacturing process.

6.1.1 Balanced manufactured plate results

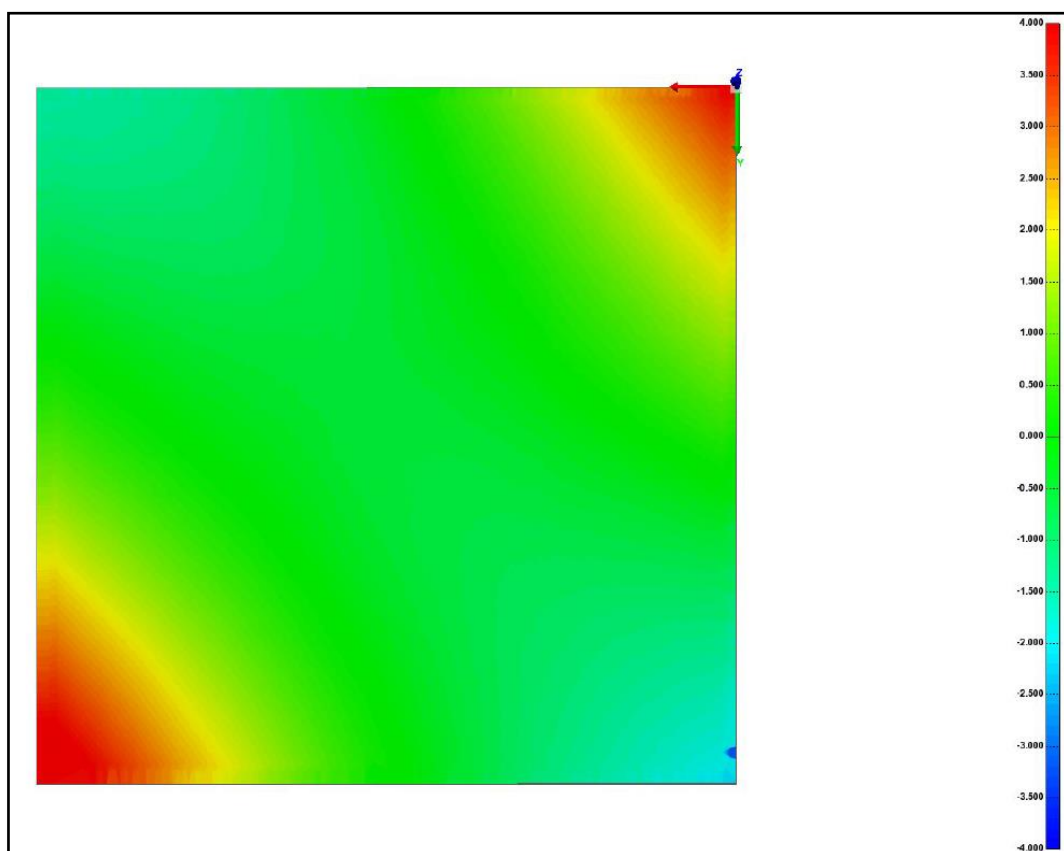


Figure 47: Balanced plate 1

Figure 47 shows that balanced plate 1 had a maximum displacement value of 4 mm and a minimum displacement value of -2 mm. Figure 47 shows that the opposite corners of the plate warped in the same direction, this is a good indication of the plate being balanced and symmetric but lack the stiffness of the 45° plies.

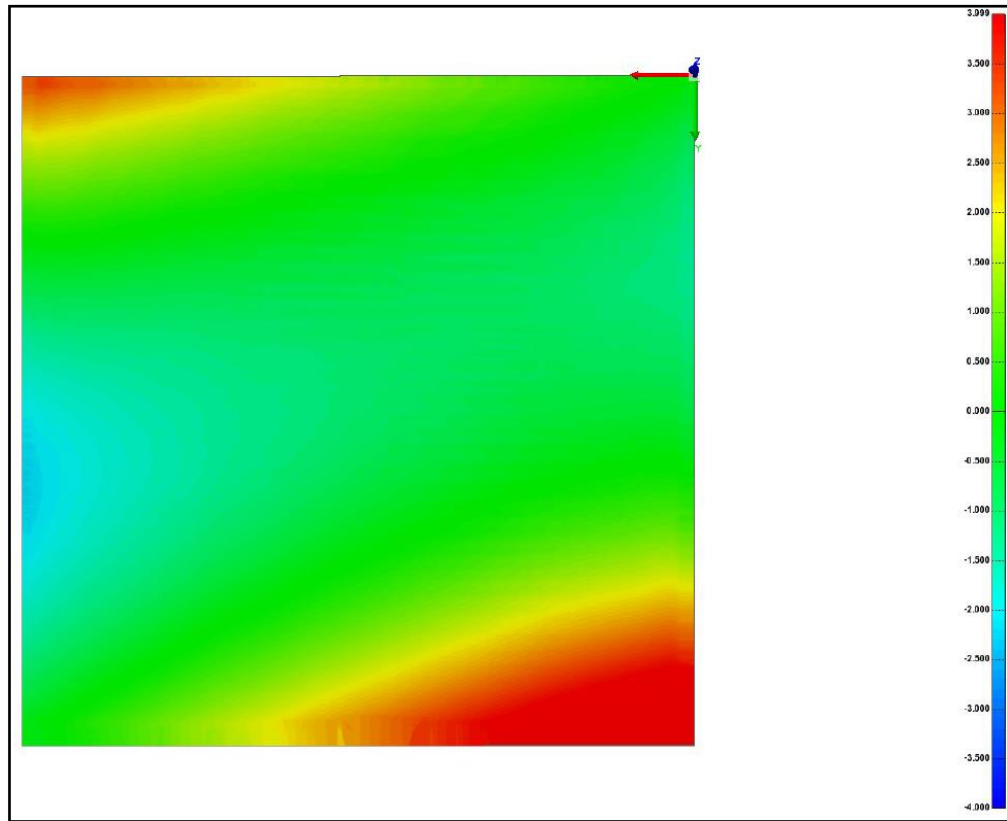


Figure 48: Balanced plate 2

Figure 48 indicates a maximum displacement value of 3,999 mm and a minimum displacement value of -2 mm. Figure 48 shows that the bottom right-hand corner of the plate warped more than its opposite corner and that the minimum warpage was more to the middle left-hand side of the plate. A possible explanation for this is that the plate was more constrained by the aluminium plate and vacuum bag towards the top right-hand corner of the plate.

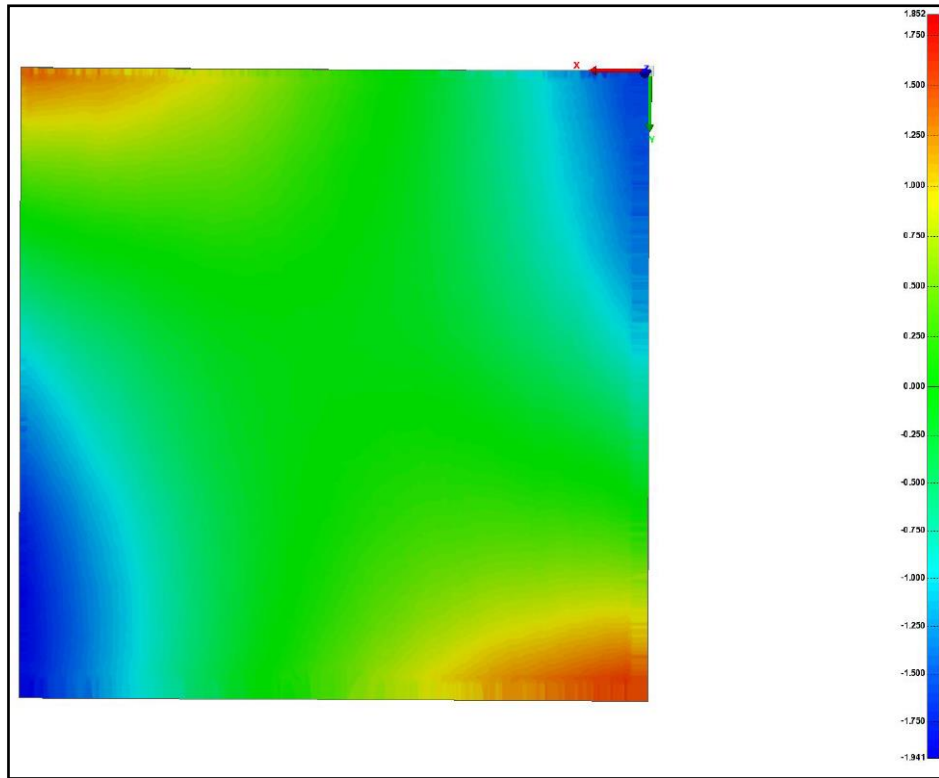


Figure 49: Balanced plate 3

Figure 49 indicates a maximum displacement value of 1,852 mm and a minimum displacement value of -1,941 mm. Figure 49 displays a similar warpage shape and direction as seen in plates 1 and 2. The result of the displacement values is less than in plates 1 and 2 which can possibly indicate that the plate held a better vacuum in the manufacturing process.

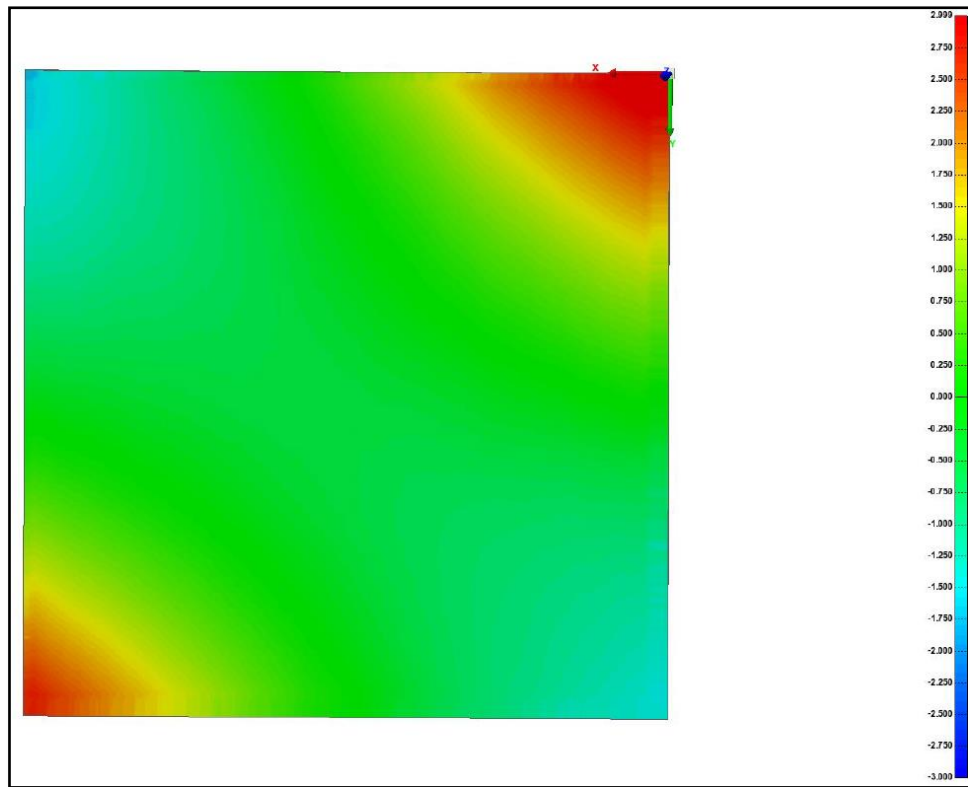


Figure 50: Balanced Plate 4

Figure 50 indicates the shape warpage behaviour compared to plates 1, 2, and 3 with a maximum displacement value of 2,999 mm and a minimum displacement value of -1,750 mm.

6.1.2 Unbalanced manufactured plate results

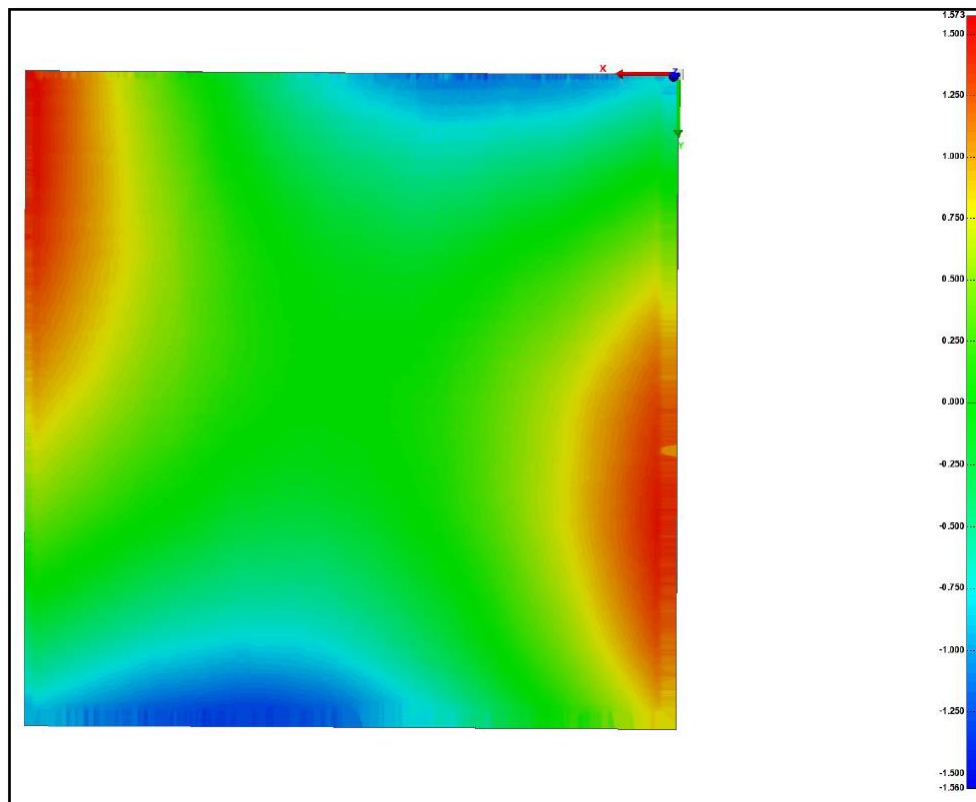


Figure 51: Unbalanced plate 1

Figure 51 shows the results of an unbalanced manufactured plate 1, with a maximum displacement value of 1,573 mm and a minimum displacement value of -1,560 mm. Figure 51 shows that the opposite corners warp in the same direction. This indicates that the layup is symmetric but adding plies in the $\pm 45^\circ$ direction should add stiffness to the plate to limit the amount of warpage obtained.

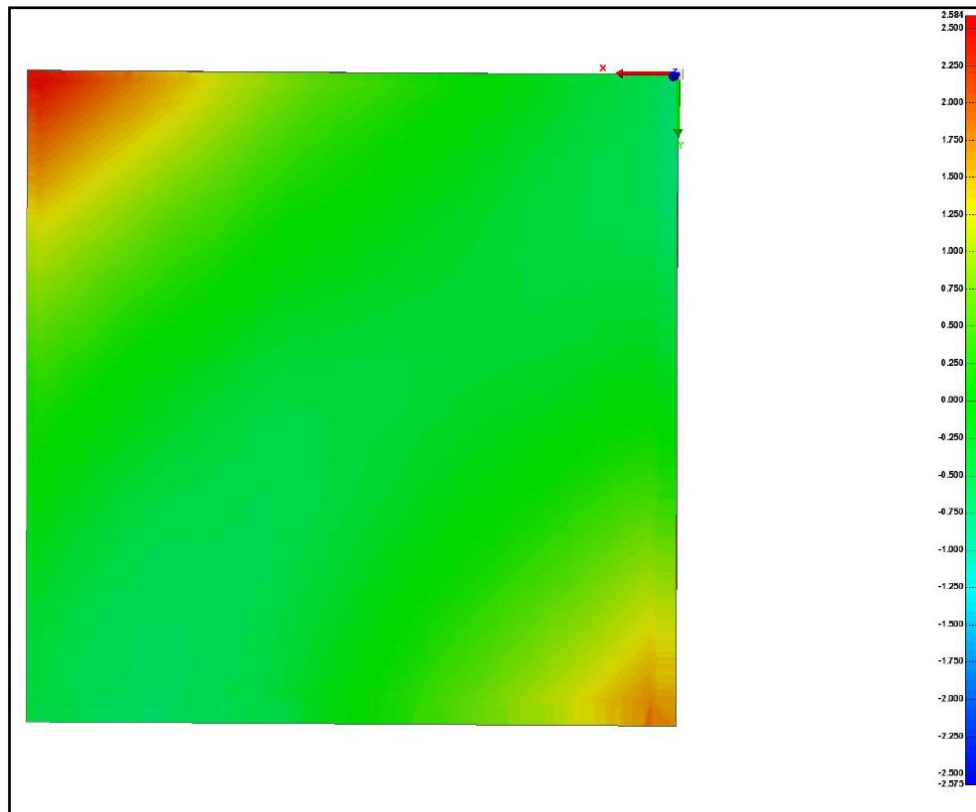


Figure 52: Unbalanced plate 2

Figure 52 shows that unbalanced plate 2 had a maximum displacement value of 2,584 mm and a minimum displacement value of -0,500 mm. the maximum displacement is seen to be at the top left corner of figure 52, where the other corners show less displacement. This could indicate that the plate held its vacuum for an even resin flow as it may have been constrained better in these corners.

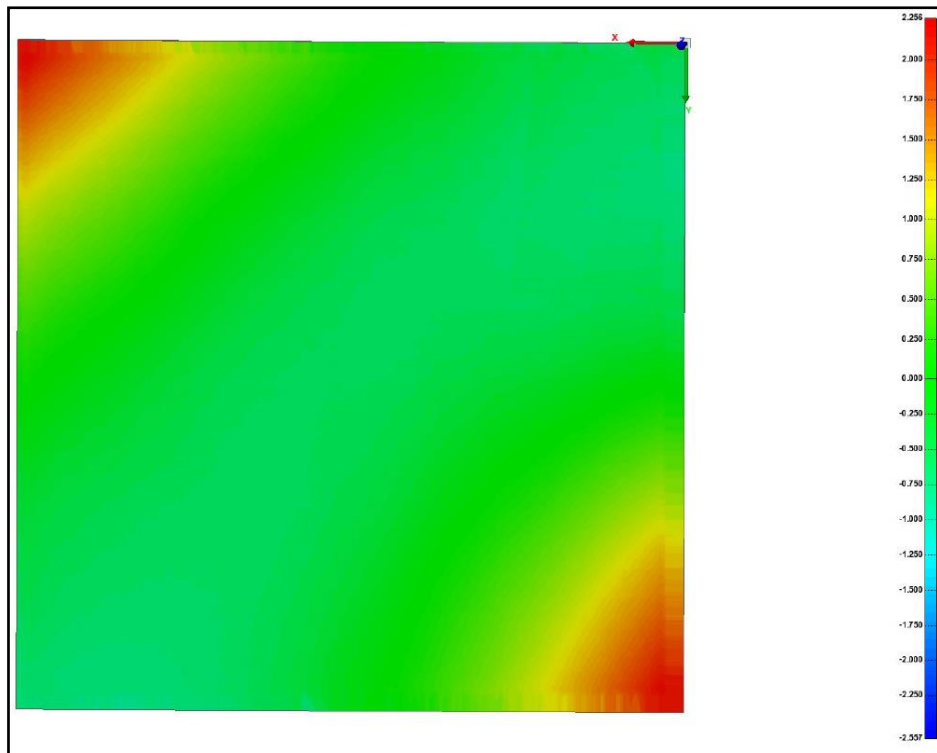


Figure 53: Unbalanced plate 3

Figure 53 shows a similar result to figure 52 with a maximum displacement value of 2,256 mm and a minimum displacement value of 0,750 mm. By comparing the similarities of figure 53 and 52 it indicates that although most of the fibres are in the 0° by adding two 90° plies to the layup the amount of warpage obtained in the corners is less and indicating that the warpage shape is different from the balanced layup.

6.2 Simulation plate results

6.2.1 Balanced simulation plate

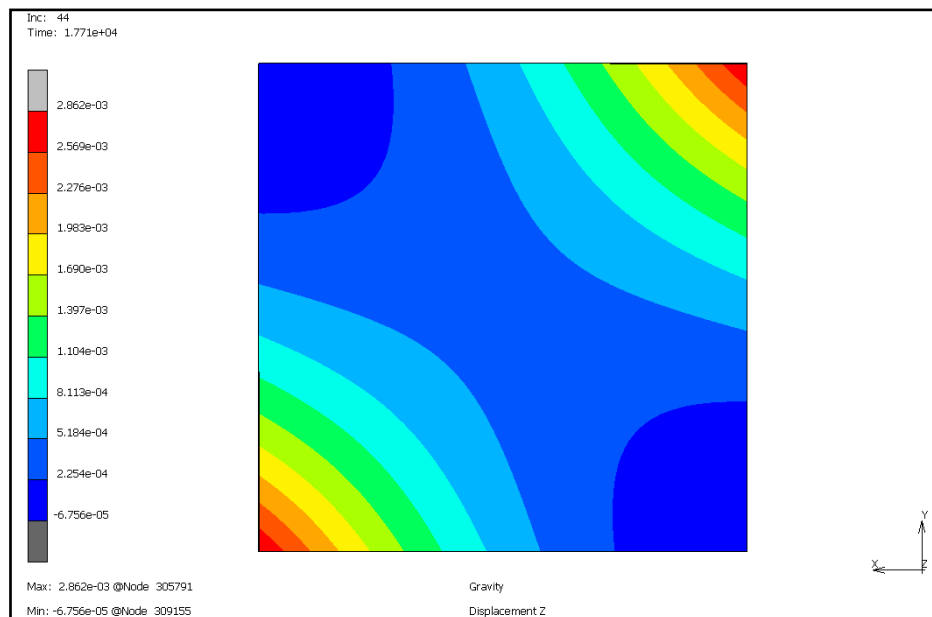


Figure 54: Balanced plate simulation

Figure 54 indicates the simulation results obtained from the balanced plate. The results show that the plate had a maximum displacement value of 2,862 mm and a minimum displacement value of 0,06756 mm. The balanced plate simulation results shows that the opposite corners warp in the same direction. The warpage shape indicates a similar result to the balanced warpage shape of the manufactured plates shown in figure 50.

6.2.2 Unbalanced simulation plate

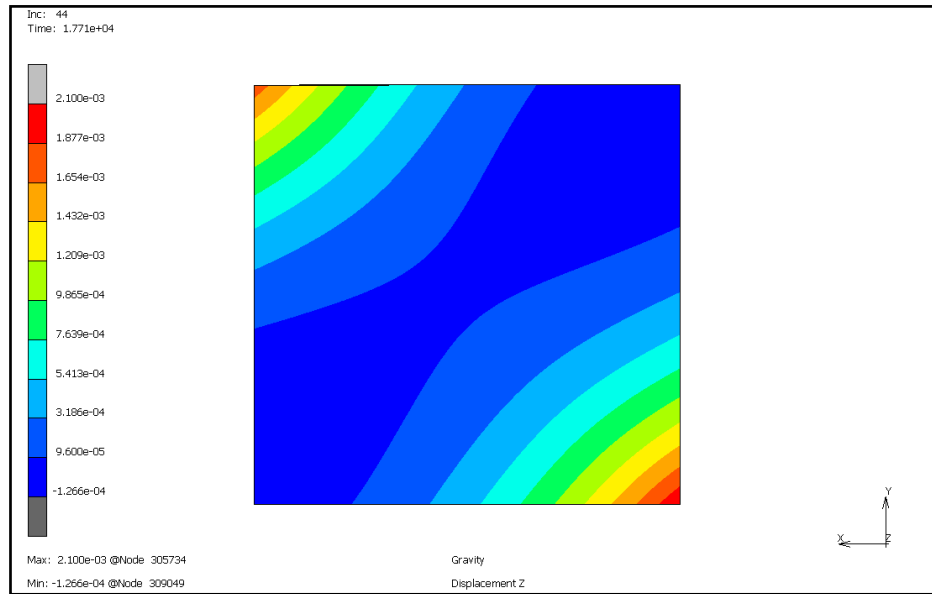


Figure 55: Unbalanced plate simulation

Figure 55 indicates the results obtained from the unbalanced plate simulation. The results show a maximum displacement value of 2,100 mm and a minimum displacement value of 0,1266 mm. The warpage shape shows similar result to the warpage shape obtained in the unbalanced manufactured plate from figure 53.

6.3 Simulation vs plate manufacturing

To validate the method and processes currently used in the manufacturing of the composite components, the simulation model displacement results are compared with the actual part manufactured displacement measured results. Both the balanced and unbalanced results were simulated and are shown in Figures 47 to 53. The critical result obtained in the simulation is the displacement, which indicates the maximum warpage obtained during the autoclave curing process. This is critical in preventing the trial-and-error method currently used in the manufacturing of composite components.

Figures 47 to 50 shows that even though the plates are balanced and symmetric, internal residual stresses still cause the plate to warp. The residual stresses are caused by the shrinkage in the plate and the CTE difference during the curing and cooldown of the plate. This is because the fibres are only at 0° and 90°. The scanning of the manufactured plates shows the same result is obtained. In order to obtain a more accurate warpage result, fibres in +45° and -45° need to be placed in the layup of the plates, this will add stiffness in the required direction and potentially

decrease the above warpage. The manufacture plate from figure 50 indicated the best correlation to the simulation value obtained in figure 54.

Table 32: Balanced displacement comparison

Displacement Comparison		
Layup	Simulation (mm)	Average Manufacturing (mm)
Maximum Balanced	2.862	2.950
Minimum balanced	-0,068	-1,897

From table 32 the average maximum displacement for the balanced manufactured plates is 2,950 mm with figure 47 being disregarded as an outlier. The average minimum displacement for the balanced manufactured plates is -2,138 mm. By comparing the average maximum displacement results of the manufactured plates to the maximum simulation displacement value from figure 54 of 2,862 mm the data indicates that there is an acceptable correlation in the maximum displacement. A Similar warpage pattern is obtained indicating that the simulation can potentially predict the material behaviour during the curing process.

In contradiction the data in table 32 indicates a poor correlation in comparing the minimum average displacement of the balance manufactured plates of -1,897 mm to the minimum displacement value of -0,068 mm of the simulation result. This could be the result of keeping one corner constrained in the simulation in order for the simulation to be able to solve. If this constraint is not used in the simulation the plate would just be “hanging in space” and no solution can be obtained. This constrained is only applied at the end of the simulation when the gravity boundary condition is applied.

Figures 51 to 53 shows the results obtained from the unbalanced and symmetric manufactured plates. As mentioned above the internal residual stresses still cause the plate to warp. The shrinkage in the plate and CTE difference during the curing and cooldown of the plate has an effect on the material behaviour and result. By adding fibres in the +45° and -45° direction will add stiffness to the plate.

Table 33: Unbalanced displacement comparison

Displacement Comparison		
Layup	Simulation (mm)	Average Manufacturing (mm)
Maximum Unbalanced	2.100	2.138
Minimum Unbalanced	-0.127	-1,539

From table 33 the average maximum displacement for the unbalanced manufactured plates is 2,138 mm. The average minimum displacement for the unbalanced manufactured plates is -1,539 mm. By comparing the average maximum displacement results of the manufactured plates to the maximum simulation displacement value from figure 55 of 2,100 mm the data indicates that there is an acceptable correlation in the maximum displacement. A Similar warpage pattern is also obtained and also indicates that the simulation can potentially predict the material behaviour during the curing process. Figure 53 the unbalanced manufactured plate 3 indicated the best correlation to the simulation result with a deviation of 0,156 mm for the maximum displacement.

Table 33 indicates a poor correlation in comparing the minimum average displacement of the balance manufactured plates of -1,539 mm to the minimum displacement value of -0,127 mm of the simulation result. Even though the unbalanced layup was expected to provide a higher warpage result, Table 33 shows that the warpage obtained is less than the balanced layup. The possible reason for this result is that although the layup was unbalanced, it was still symmetric. This is not bad result, as this showed the effect of one 90° ply in the curing of the plate. The same constraints were applied as for the balanced simulation thus can be the reason for the poor correlation in the minimum displacement results.

CHAPTER 7

Conclusion and Recommendations

This Chapter summarises the main findings of this study and reviews the problem statement, aims and objectives, set out in Chapter 1. Thereafter, recommendations are made for future studies.

7.1 Introduction

Materials in the aircraft and aerospace industries are expensive. Thus, understanding material behaviour during manufacturing that includes curing will essentially eliminate costs related to the fabrication of composite parts. Factors such as material waste, tooling costs, and labour time will benefit from an alternative solution model that replaces the well-known trial-and-error methods currently used by most aircraft industries.

This dissertation aimed to establish material characteristics through coupon testing and the use of properties as input results to provide a thermal curing simulation model that predicts the displacement behaviour for a composite plate. The model is validated by comparing the simulation model's displacement with the displacement of actual plates manufactured in an autoclave. Thermal- and curing-induced stresses of unidirectional composite laminates were analysed.

7.2 Conclusion

Using the AS4 HexPly 8552 epoxy resin material, flat plates were manufactured, and test coupons were routed from them. The coupons were used to determine material properties of the specific material. The properties obtained were compared to the same material properties from the literature. As seen from table 28 the properties obtained for this dissertation indicated an acceptable correlation with the literature, verifying the input results used for the curing simulation model were accurate. The deviation percentage for Young's modulus was 0,52 % and 0 % respectively in the different directions.

Balanced and unbalanced plates were manufactured using the materials specifications and curing process. The plates were scanned using Romer (3D scanner) to determine and evaluate the amount of warpage with regard to the plates profile and displacement. The material properties obtained were used as input results in the thermal curing simulation and the manufactured plates were simulated. The simulation results were compared with the results from the manufactured plates.

The result comparison indicated that a correlation was obtained in comparing the maximum displacement of the balanced and unbalanced manufactured plates with the simulated plates. From the results the balanced layup showed a maximum deviation of 0,088 mm in the positive z displacement but a -1,829 mm in the negative z displacement were obtained. This large deviation

in the negative z value indicated that a fault occurred in the simulation or the scanning of the plates and would require further investigation.

The results comparison for the unbalanced plate manufactured and simulation also indicated a correlation in the maximum displacement result with a deviation result of 0,038 mm in the positive z displacement. But as per the balanced layup the unbalanced minimum deviation result of -1,412 mm in the negative z direction were obtained.

Thus, the conclusion made from the results obtained, is that a curing simulation model can be used to predict the material behaviour of a composite part as some pattern in the curing-process-induced deformation is observed. But the curing simulation model developed for this dissertation is unsuccessful and would require more investigation on why a large deviation in the negative z direction is obtained. Also, further investigation is required regarding the measuring procedures of the manufactured plates.

The aims and objectives stated in Chapter 1 were addressed throughout this dissertation. Although the results obtained to satisfy objective VI and determine the validity of the curing simulation model were unsuccessful. It can be concluded that the rest of the aims and objectives were successfully achieved.

7.3 Recommendations for future studies

- In the testing of samples, it is recommended in the ASTM requirements that tabs from the same material should be used. This was challenging as some of the tabs broke, and it was difficult to route a 7° angle from the carbon fibre tabs. It is recommended that, for future testing of carbon fibre samples, the samples are tested without tabs or using fibreglass tabs with a powerful adhesive characteristic.
- For future manufacturing and obtaining more data, it is recommended that more thermocouples and a pressure sensor should be used. An automated layup machine can be used to avoid these human errors.
- More focus can be done to determine why the displacement in the negative z direction does not correlate.
- Investigate alternative means to measure the manufactured parts.

- Further testing can be done on manufacturing to determine the friction and slippage related to the curing process, and an aluminium bed with its comparable properties can be added to the current simulation.

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Appendices

APPENDIX A: ADVANTAGES AND DISADVANTAGES OF THE USE OF COMPOSITES.

	ADVANTAGES	DISADVANTAGES
Micromechanics	-High stiffness of fibres -High-strength fibres -Elastic and nonconductive qualities -Matrix stress transfer capability	-Reduced transverse tensile strength appreciably (local stress around fibres)
Macro mechanics and mechanical characterisation	-Lightweight -Chemical and corrosion resistant -Controlled and predicted material behaviour (from constituents' properties)	-Anisotropic and orthotropic analyses are much more complex and dependant on costly machinery and computational procedures
Structural design, analysis and optimisation	-Enables simultaneous material optimisation (e.g. minimum weight, maximum dynamic stability, cost-effectiveness)	-Labour intensive -Requires a reliable database of material properties, standardised structural analysis methods, modelling and simulation techniques, and models for materials processing
Manufacturing technology	-Structural parts, rather than generic material form, are fabricated with relatively simple tooling -A variety of fabrication methods suitable for various applications are available (e.g. autoclave moulding)	-Composite fabrication is still dependent on skilled hand labour with limited automation and standardisation -Possibly requires more stringent, extensive, and costly quality control procedures
Maintainability, serviceability and durability	-Long fatigue lives in hostile environments -Usually easily maintained and repaired	-Some composites (e.g. thermoset polymer) suffer from sensitivity to hygrothermal environments -Internal service-induced damage growth require sophisticated non-destructive techniques for its detection and monitoring. -Protective coatings against erosion, surface damage, and

		lightning strike are necessary from time to time
Cost-effectiveness	- Reduction in acquisition and/or life cycle costs (e.g. weight savings, lower tooling costs, reduced number of parts and joints, fewer assembly operations, and reduced maintenance)	-High cost of raw materials, fibres, prepreg (resin pre-impregnated fibres), and auxiliary materials used in fabrication and assembly of composite structures. - Composite manufacturing processes are expensive, because they are not yet fully developed, automated, and optimised

Table 1. The table below was adapted from Daniel *et al.* (12)

APPENDIX B: TEST PLANS

METHOD FOR DETERMINING THE TENSILE PROPERTIES OF A COMPOSITE LAMINATE

REFERENCES

[1] ASTM D3039 / D3039M-17, Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM International, West Conshohocken, PA, 2017, www.astm.org

INTRODUCTION

This document defines the test method, test specimens, testing procedure and method of analysis to determine the in-plane tensile properties of a polymer matrix composite material that is reinforced by high-modulus fibres. For the testing of the tensile properties, a thin flat strip of UD material having a constant rectangular cross-sectional is mounted in the grips of the tensile testing machine and will be monotonically loaded in tension while recording the force

PROPERTIES OBTAINED FROM THIS TEST METHOD:

- Ultimate tensile strength
- Ultimate tensile strain
- Tensile chord modulus of elasticity
- Poisson's ratio
- Transition strain

FACTORS THAT CAN INFLUENCE TEST RESULTS:

- Material
- Material preparation and lay-up
- Specimen stacking sequence
- Specimen preparation
- Specimen conditioning
- Environment of testing
- Specimen alignment and gripping
- Speed of testing
- Time at temperature
- Void content
- Volume percent reinforcement

TEST EQUIPMENT

All test equipment used for measurements shall be calibrated and have the supporting calibration certificates.

The following equipment will be required:

1.1. Micrometres and Calipers

- The accuracy of the instruments shall be suitable for reading to within 1% of the sample width, length and thickness.

1.2. Testing machine

- A tensile machine that complies with practice E4 as per ASTM 3039 or equivalent.
- A testing machine with a stationary and movable head.
- The drive mechanism must be able to move the moveable head at a controlled velocity with respect to the stationary head.
- The force sensing device of the machine must be capable of indicating the total force being applied to the specimen. It has to have no inertia lag at the specified testing rate, and indicate the force with an accuracy of $\pm 1\%$ of the indicated value.
- The machine heads shall each carry one grip for holding the specimen to ensure the direction of the force that is applied is coincident with the longitudinal axis of the specimen. Sufficient pressure must be applied to prevent slippage between the coupon and the grips. For the tabbed specimen, the grips should be long enough that they overhang the bevelled portion of the tab by 10 mm.
- Ensure system alignment is done, to prevent premature failure.
- Take zero strain point either before or after gripping.

1.3. Strain-Indicating device

- Strain transducer or extensometers will be used to record force-strain data.
- An extensometer which complies with Practise E38 as per ASTM 3039 or equivalent. It shall be capable of determining the relative change in the gauge length on the test specimen at any time during the test. It is desirable but not essential that this instrument should automatically record this change. The instrument shall be essentially free from inertia lag at the specified speed of testing and shall be capable of measuring the change of gauge length with an accuracy of 1% of the relevant value or better. This corresponds to $\pm 1\mu\text{m}$ for the measurement of the modulus, based on a gauge length of 50 mm. When an extensometer is attached to the test specimen, care shall be taken to ensure that any distortion of or damage to the test specimen is minimal. It is essential that there is no slippage between the extensometer and the test specimen.
- For Poisson's ratio measurements, the strain-indicative devices are required for both longitudinal and transverse directions

1.4. Environmental test chamber

- A chamber capable of enclosing the test fixture and specimen while they are mounted in the testing machine and capable of achieving the specified heating rates, test temperatures, and environments. Temperature measurements shall be accurate to $\pm 2^\circ\text{C}$.

TEST SPECIMEN DIMENSIONS

For the testing, six specimens shall be tested per condition unless valid results can be gained through the use of fewer specimens.

Parameter	Requirement
Coupon Requirements:	
Shape	Constant rectangular cross-section
Minimum length	Gripping + 2 times with+ gauge length
Specimen width	As needed
Specimen width tolerance	$\pm 1\%$ of width
Specimen thickness	As needed
Specimen thickness tolerance	$\pm 4\%$ of thickness
Specimen flatness	Flat with light finger pressure
Tab Requirements(if used):	
Tab material	As needed
Fibre orientation(Composite tabs)	As needed
Tab thickness	As needed
Tab thickness variation between tabs	$\pm 1\%$ tab thickness
Tab bevel angle	5 to 90°, inclusive
Tab step at bevel to specimen	Feathered without damaging specimen

Table 32: Tensile Specimen Geometry Requirements [1]

For the use of tabs it is recommended to use the same material and orientation as that being tested, with a similar number of plies than that of the test specimen at each side.

Select the specimen width and thickness accordingly to ensure failure is obtained in the gauge section and ensure the specimen contains a sufficient number of fibres in the cross-section to be statistically representative of the bulk material. Tabs are strongly recommended when testing UD materials to failure in the fibre direction.

Fibre Orientation	Width [mm]	Overall Length [mm]	Thickness [mm]	Plies	Tab Length [mm]	Tab Thickness [mm]	Tab Plies	Tab Bevel Angle, °
0° unidirectional	15	250	1.52	8	56	2.09	11	7

Table 33: Tensile Specimen Geometry

DRAWING NOTES:

1. INTERPRET DRAWING IN ACCORDANCE WITH ANSI Y14.5M-1982, SUBJECT TO THE FOLLOWING:
2. ALL DIMENSIONS IN MILLIMETRES WITH DECIMAL TOLERANCES AS FOLLOWS:
NO DECIMAL .X .XX
 ± 3 ± 1 ± .3
3. ALL ANGLES HAVE TOLERANCE OF ± .5°.
4. PLY ORIENTATION DIRECTION TOLERANCE RELATIVE TO $\overline{A}$ WITHIN ± .5°.
5. FINISH ON MACHINED EDGES NOT TO EXCEED 1.6√ (SYMBOLY IN ACCORDANCE WITH ASA B46.1, WITH ROUGHNESS HEIGHT IN MICROMETRES.)
6. VALUES TO BE PROVIDED FOR THE FOLLOWING, SUBJECT TO ANY RANGES SHOWN ON THE FIELD OF DRAWING: MATERIAL, LAY-UP, PLY ORIENTATION REFERENCE RELATIVE TO $\overline{A}$, OVERALL LENGTH, GAGE LENGTH, COUPON THICKNESS, TAB MATERIAL, TAB THICKNESS, TAB LENGTH, TAB BEVEL ANGLE, TAB ADHESIVE.
7. NO ADHESIVE BUILDUP ALLOWED IN THIS AREA.

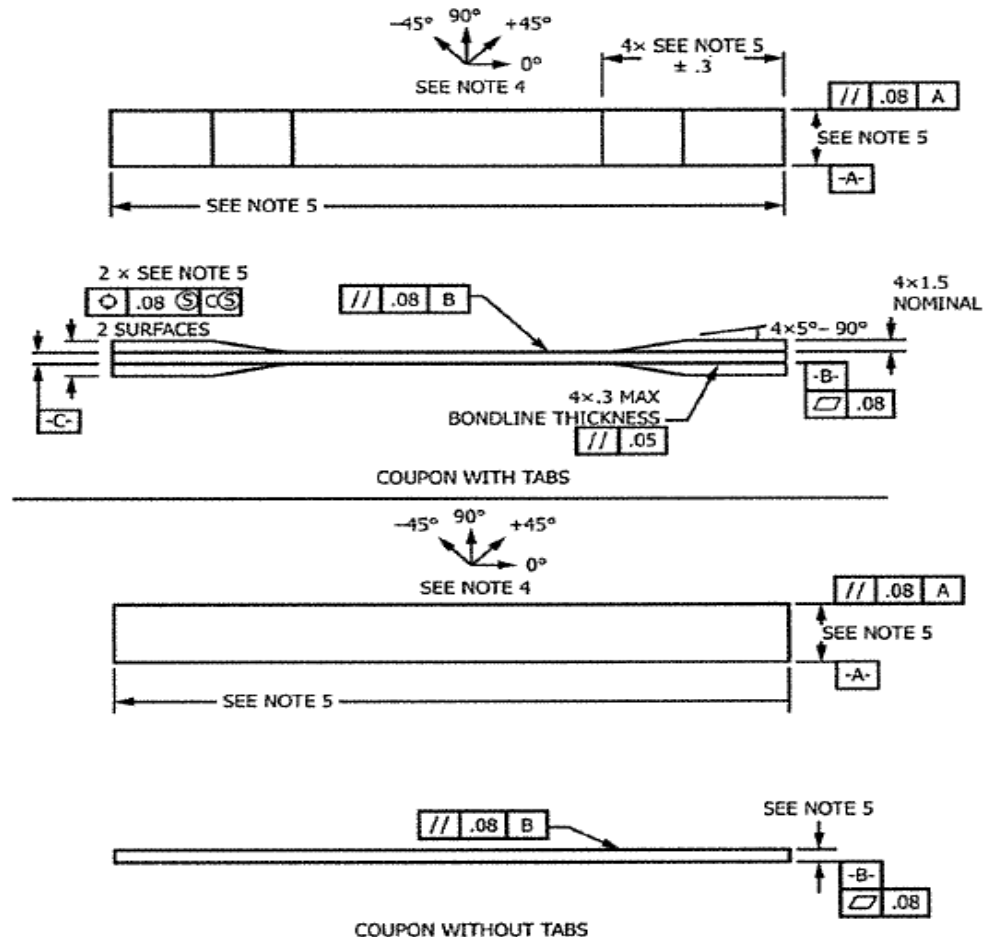


Figure 47: Tension Test Specimen Drawing [1]

PROCEDURE

1.5. Parameters to be specified before test

- Specimen sampling method, coupon type and geometry, and conditioning travellers.
- The tensile properties and data reporting format desired.
- Environmental conditioning test parameters.

1.6. General instructions

- Report deviations from the test method, whether intentional or inadvertent.
- Measure the specimen, the thickness and width shall be measured at three places in the gauge section and report the average of the thickness and width.

1.7. Speed of testing

- The speed of testing must ensure an almost constant strain rate in the gauge section.
- The strain rate should be selected to produce failure within 1 to 10 min.

1.8. Specimen insertion

- Place the specimen in the grips of the testing machine, taking care to align the long axis of the gripped specimen with the test direction.

1.9. Transducer installation

- Attach the strain-indication transducers to the specimen symmetrically about the mid-span, mid-width location.
- When determining the modulus of elasticity, it is recommended that at least one specimen per like sample be evaluated with back-to-back axial transducers to evaluate the percent bending.

1.10. Failure Mode

- Record the mode and location of failure of the specimen as seen in figure 2.

TEST REPORT

The test report will include the following information:

1. The revision level or date of issue of this test method.
2. The date(s) and location(s) of the test.
3. The name(s) of the test operator(s).
4. Any variations to this test method, anomalies noticed during testing, or equipment problems occurring during testing.
5. Identification of the material tested, including material specification, material type, material designation, manufacturer, manufacturer's lot or batch number, source (if not from manufacturer), date of certification, expiration of certification, filament diameter, tow or yarn filament count and twist, sizing, form or weave, fibre areal weight, matrix type, prepreg matrix content, and prepreg volatiles content.
6. Description of the fabrication steps used to prepare the laminate, including fabrication start date, fabrication end date, process specification, cure cycle, consolidation method, and a description of the equipment used.
7. Ply orientation-stacking sequence of the laminate.
8. If requested, report density, volume percent reinforcement, and void content test methods, specimen sampling method and geometries, test parameters, and test results.
9. Average ply thickness of the material.
10. Results of any non-destructive evaluation tests.

11. Method of preparing the test specimen, including specimen labelling scheme and method, specimen geometry, sampling method, coupon cutting method, identification of tab geometry, tab material, and tab adhesive used.
12. Calibration dates and methods for all measurement and test equipment.
13. Type of test machine, grips, jaws, grip pressure, alignment results, and data acquisition sampling rate and equipment type.
14. Results of system alignment evaluations, if any such were done.
15. Dimensions of each test specimen.
16. Relative humidity and temperature of the testing laboratory.
17. Environment of the test machine environmental chamber (if used) and soak time at environment.
18. Number of specimens tested.
19. Speed of testing.
20. Transducer placement on the specimen and transducer type for each transducer used.
21. If strain gauges were used, the type, resistance, size, gauge factor, temperature compensation method, transverse sensitivity, lead-wire resistance, and any correction factors used.
22. Stress-strain curves and tabulated data of stress versus strain for each specimen.
23. Percent bending results for each specimen so evaluated.
24. Individual strengths and average value, standard deviation, and coefficient of variation (in percent) for the population. Note if the failure force was less than the maximum force before failure.
25. Individual strains at failure and the average value, standard deviation, and coefficient of variation (in percent) for the population.
26. Strain range used for chord modulus and Poisson's ratio determination.
27. If another definition of modulus of elasticity is used in addition to chord modulus, describe the method used, the resulting correlation coefficient (if applicable), and the strain range used for the evaluation.
28. Individual values of modulus of elasticity, and the average value, standard deviation, and coefficient of variation (in percent) for the population.
29. If another definition of Poisson's ratio is used in addition to the chordwise definition, describe the method used, the resulting correlation coefficient (if applicable), and the strain range used for the evaluation.
30. Individual values of Poisson's ratio and the average value, standard deviation, and coefficient of variation (in percent) for the population.
31. If transition strain is determined, the method of linear fit (if used) and the strain ranges over which the linear fit or chord lines were determined.
32. Individual values of transition strain (if applicable), and the average value, standard deviation, and coefficient of variation (in percent) for the population.
33. Failure mode and location of failure for each specimen.

ANALYSIS OF TEST RESULTS

Tensile Stress/Tensile Strength:

$$F^{tu} = \frac{P^{max}}{A}$$

$$\sigma_i = \frac{P_i}{A}$$

Where:

F^{tu} = ultimate tensile strength, MPa

P^{max} = maximum force before failure, N

σ_i = tensile stress at i th data point, MPa

P_i = force at i th data point N

A = average cross-sectional area, mm²

Tensile Strain/ Ultimate Tensile Strain:

$$\varepsilon_i = \frac{\delta_i}{L_g}$$

where:

ε_i = tensile strain at i th data point, $\mu\varepsilon$

δ_i = extensometer displacement at i th data point, mm

L_g = extensometer gauge length, mm

Tensile Chord Modulus of Elasticity

$$E^{chord} = \frac{\Delta\sigma}{\Delta\varepsilon}$$

where:

E^{chord} = tensile chord modulus of elasticity, GPa

$\Delta\sigma$ = difference in applied tensile stress between the two strain points

$\Delta\varepsilon$ = difference between the two strain points

Poisson's Ratio by Chord Method

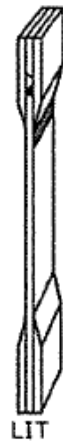
$$\nu = -\frac{\Delta\varepsilon_t}{\Delta\varepsilon_l}$$

Where:

ν = Poisson's ratio

$\Delta\varepsilon_t$ = difference in lateral strain between two longitudinal strain points

$\Delta\varepsilon_l$ = difference between the two longitudinal strain points



LIT



GAT



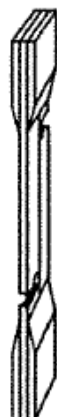
LAT



DGM



LGM



SGM



AGM(1)



AGM(2)



XGM

First Character

Failure Type	Code
Angled	A
edge Delamination	D
Grip/tab	G
Lateral	L
Multi-mode	M(xyz)
long. Splitting	S
eXplosive	X
Other	O

Second Character

Failure Area	Code
Inside grip/tab	I
At grip/tab	A
<1W from grip/tab	W
Gage	G
Multiple areas	M
Various	V
Unknown	U

Third Character

Failure Location	Code
Bottom	B
Top	T
Left	L
Right	R
Middle	M
Various	V
Unknown	U

Figure 48: Tensile Test Failure Codes

METHOD FOR DETERMINING THE IN-PLANE SHEAR PROPERTIES OF A COMPOSITE LAMINATE

INTRODUCTION

This Document defines the test procedure, test specimens, and the method of analysis to be used in order to establish the in-plane shear properties of a composite laminate.

REFERENCES

- [Ref 1] ASTM D3518 Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a $\pm 45^\circ$ Laminate – Issue 13
- [Ref 2] ASTM D3039 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials – Issue 17

CONFORMITY INSPECTIONS & TEST WITNESSING

All test samples are to be inspected for conformity by the test facility Quality Inspector. Records of this inspection shall be kept on file.

TEST EQUIPMENT

All test equipment used for measurements shall be calibrated and have the supporting calibration certificates.

The following equipment will be required:

1.1. Micrometres and Calipers

- The accuracy of the instruments shall be suitable for reading to within 1 % of the sample width, length and thickness.

1.2. Testing machine

- A tensile machine that comply with practice E4 or equivalent.
- A testing machine with a stationary and movable head.
- The drive mechanism must be able to move the moveable head at a controlled velocity with respect to the stationary head.
- The force sensing device of the machine must be capable of indicating the total force being applied to the specimen. It has to have no inertia lag at the specified testing rate and indicate the force with an accuracy of ± 1 % of the indicated value.
- The machine heads shall each carry one grip for holding the specimen to ensure the direction of the force that is applied is coincident with the longitudinal axis of the specimen. Sufficient pressure must be applied to prevent slippage between the coupon and the grips. For the tabbed specimen, the grips should be long enough that they overhang the bevelled portion of the tab by 10 mm.
- Ensure system alignment is done, to prevent premature failure with elastic property data.
- Take zero strain point either before or after gripping.

1.3. Strain-Indicating device

- Strain transducer or extensometers will be used to record force-strain data.
- An extensometer which complies with Practice E38 or equivalent. It shall be capable of determining the relative change in the gauge length on the test specimen at any time during the test. It is desirable but not essential that this instrument should automatically record this change. The instrument shall be essentially free from inertia lag at the specified speed of testing and shall be capable of measuring the change of gauge length with an accuracy of 1% of the relevant value or better. This corresponds to $\pm 1\mu\text{m}$ for the measurement of the modulus, based on a gauge length of 50mm. When an extensometer is attached to the test specimen, care shall be taken to ensure minimal distortion of or damage to the test specimen. There must be no slippage between the extensometer and the test specimen.
- For Poisson's Ratio measurements, the strain-indicative devices are required for both longitudinal and transverse directions.

1.4. Environmental test chamber

- A chamber capable of enclosing the test fixture and specimen is mounted in the testing machine, capable of achieving the specified heating rates, test temperatures, and environments. Temperature measurements are accurate to $\pm 2^\circ\text{C}$.
-

TEST SPECIMEN DIMENSIONS

Specimen dimensions are defined as follows:

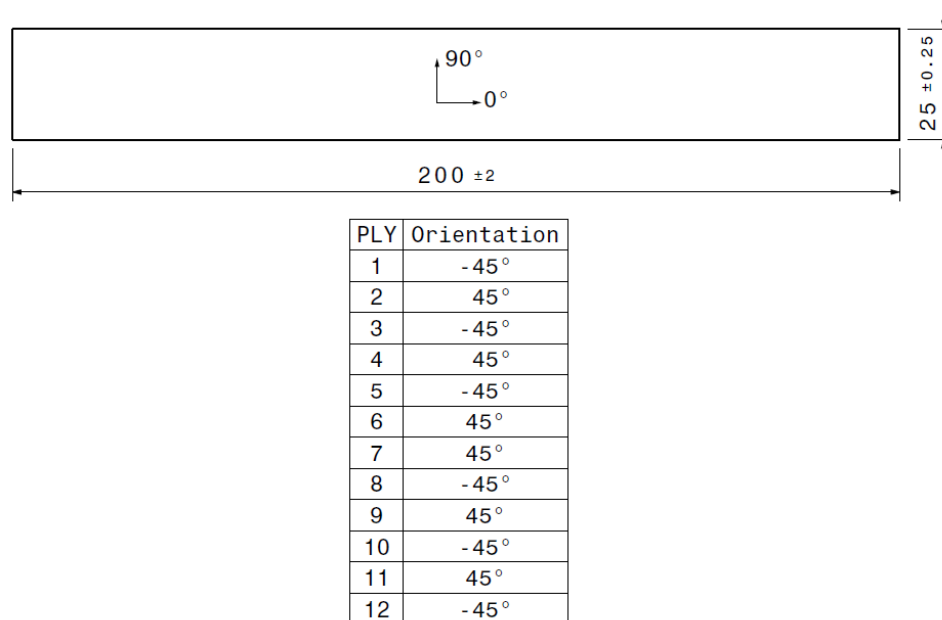


Figure 57: Test Specimen Definition

- Length 200 mm
- Width 25 mm
- Number of plies 12 plies
- Thickness tolerance of $\pm 4\%$ of thickness

Tabs are not required for this test specimen. The ply orientations are such that the laminate test specimen is both balanced and symmetrical. At least six specimens per test shall be used.

TEST PROCEDURE

- 1 Measure the width to the nearest 0.1mm and the thickness to the nearest 0.02mm at the centre of each specimen and two additional points, one at each side of the centre. Record the minimum and maximum values for width and thickness of each specimen. Calculate the arithmetic means for the width and thickness of each specimen which shall be used for calculation purposes.
- 2 Place the test specimen in the grips, taking care to align the longitudinal axis of the test specimen with the axis of the testing machine.
- 3 Measure the force, longitudinal and lateral strain during testing.
- 4 Set the testing speed to 2 mm/min or a strain rate of 0.01 min^{-1} .
- 5 Strain measurement
 - 5.1 If strain gauges are being used place two strain gauges at the centre of the test specimen, one along the 0° and the other along the 90° .
 - 5.2 If extensometers are being used, place the lateral extensometer at the centre of the test specimen and the longitudinal at equal distances from the midpoint.
- 6 Apply the tensile force to the test specimen while recording the data until failure. If ultimate failure does not occur within 5% engineering strain, truncate the data to the 5% engineering strain mark. This is to ensure that a fibre angle of $\pm 45^\circ$ is maintained. If the data is truncated, this should be noted in the report.
- 7 For data recording of force vs strain, a sampling rate of 2 to 3 data points per second and a target minimum of 100 data points per test should be used.
- 8 When testing at temperatures other than ambient temperatures, the temperature of the sample is recorded at minimum at the start and end of the test.

TEST REPORT

The test report shall include the following information;

- 1 The revision of the test method used.
- 2 Date and of test.
- 3 Any deviation from the test method.
- 4 All the data necessary for identification of the material tested, including type, source, manufacturer's code number and history, where these are known.
- 5 Dimensions of each test specimen.
- 6 Manufacturing method used to manufacture laminate. E.g. Flat place with vacuum bagging.
- 7 All test equipment used.
- 8 Calibration certificate or data for all test equipment.
- 9 Number of specimens tested.

- 10 Speed of testing.
- 11 Test temperature at start and end of each test.
- 12 The position of the strain measurement device on the specimen, as well as specifications of the strain measurement device.
- 13 Individual test results.
- 14 For all of the measured test results, the individual, average and standard deviation must be presented.

ANALYSIS OF TEST RESULTS

1.5. In-Plane Shear Stress

$$\tau_{12i} = \frac{P_i}{2A}$$

Where:

τ_{12i} = In – plane shear at point i (MPa)

P_i = load at point i (N)

A = Average cross – sectional area (mm^2)

1.6. Engineering Shear-Strain

$$\gamma_{12i} = \varepsilon_{xi} - \varepsilon_{yi}$$

Where:

γ_{12i} = Engineering shear strain at point i ($\mu\varepsilon$)

ε_{xi} = longitudinal normal strain at point i ($\mu\varepsilon$)

ε_{yi} = lateral normal strain at point i ($\mu\varepsilon$)

1.7. Shear Modulus of Elasticity

$$G_{12} = \frac{\Delta\tau_{12}}{\Delta\gamma_{12}}$$

Where:

G_{12} = Shear modulus of elasticity (GPa)

$\Delta\tau_{12}$ = Difference in engineering shear stress between two points (MPa)

$\Delta\gamma_{12} = \text{Difference in engineering shear strain between two points}$

METHOD FOR DETERMINING THE COEFFICIENT OF LINEAR THERMAL EXPANSION OF THERMOSET MATERIALS BY THERMOMECHANICAL ANALYSIS

INTRODUCTION

This document defines the test method, test specimens, testing procedure and method of analysis to determine the coefficient of linear thermal expansion (CTE) for thermoset materials as a function of temperature. For this test, samples of the thermoset material are tested by thermomechanical analysis (TMA).

In order to determine the coefficient of linear thermal expansion, a sample is heated at a controlled rate and measurements is taken of the elongation of the sample with an increase in temperature.

Properties obtained from this test method:

- Coefficient of linear thermal expansion.

Factors that can influence test results:

- Sample uniformity and dimensions
- Temperature
- Scan Rate

REFERENCES

[Ref 3] ASTM E831-05, Standard Test Method for Linear Thermal Expansion of Solid Materials by Thermomechanical Analysis

TEST EQUIPMENT

All test equipment used for measurements shall be calibrated and have the supporting calibration certificates.

The following equipment will be required:

Micrometre / Vernier

- The instrument shall be capable of measuring a range of up to 10 mm to determine specimen dimensions to within $\pm 25 \mu\text{m}$.

1.1. Thermomechanical Analyser (TMA)

- Test is performed on a TMA Q400 instrument.

TEST SPECIMEN DIMENSIONS

At least three specimens shall be tested.

Specimens shall be between 2 and 10 mm in length and shall not exceed 10mm in width with a thickness of more than 20 % of the length. The ends of the sample shall be flat and parallel within $\pm 25 \mu\text{m}$. It is recommended to use a sample of 6 x 6 x 6mm.

If other dimensions are used, this is to be noted in the report.

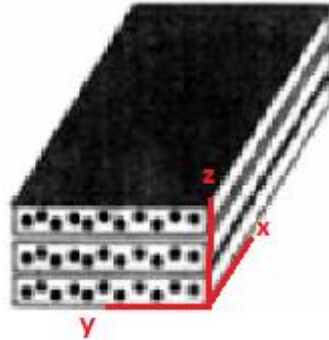


Figure 58: Unidirectional Material

From figure 1:

- X direction = 0°
- Y direction = 90°

The tests will be performed in all the directions, with the material being layed-up in the 0° direction

TEST PROCEDURE

- Measure the initial specimen dimensions. The specimen length (in the test direction of expansion) shall be measured to $\pm 25 \mu\text{m}$ at 20 to 25 $^\circ\text{C}$.
- Place the specimen in the specimen holder under the probe. Place the temperature specimen in position on, or near, as near the specimen as possible.
- Move the furnace to enclose the specimen holder.
- Apply an appropriate load force to the sensing probe to ensure that it is in contact with the specimen. A force of between 1 and 100 mN can be used depending on the compressibility of the specimen and the temperature range to be investigated. The incremental force above that is required to make contact with zero force is noted in the report.
- Select appropriate ordinate and abscissa range sensitivity settings on the graphical representation.
- Heat the specimen at a constant heating rate of 5 $^\circ\text{C}/\text{min}$ over the desired temperature range and record the changes in specimen length and temperature to all available decimal places. If other heating rates are used, this shall be noted in the report.
- Calculate the mean coefficient of linear thermal expansion rounded to the nearest 0.1 $\mu\text{m}/\text{m}^\circ\text{C}$ for the desired temperature range using Equation 1. Use the calibration coefficient as required.

TEST REPORT

The test report will include the following information:

34. The revision level or date of issue of this test method.
35. The date(s) and location(s) of the test.
36. The name(s) of the test operator(s).
37. Complete identification of test specimens
38. Any variations to this test method, anomalies noticed during testing, or equipment problems.
39. Specimen orientation with respect to the original part.
40. Method of test specimen preparation.
41. Dimensions of the test specimen.
42. Description of the thermomechanical analysis apparatus, including manufacturer and model number and calibration certificate.
43. Purge gas and medium if used.
44. The midpoint temperature (T) and the temperature range (ΔT) at which the coefficient of linear thermal expansion has been determined, using Equation 2.
45. The average value of the coefficient of linear thermal expansion in $\mu\text{m}/\text{m}^\circ\text{C}$ as determined from the three specimens.
46. Expansion curves obtained
47. Any other equipment used for testing as well as calibration certificates for all equipment used for testing.

ANALYSIS OF TEST RESULTS

Equation 1: Mean Coefficient of Linear Thermal Expansion

$$\alpha_m = \frac{\Delta L_{sp} \times k}{L \times \Delta T}$$

$$k = \frac{\alpha_{ref} \times L_{ref} \times \Delta T_{ref}}{\Delta L_{ref}}$$

Where:

α_m = Mean coefficient of linear thermal expansion ($\mu\text{m}/\text{m}^\circ\text{C}$)

ΔL_{sp} = Change of specimen length (μm)

L = Specimen Length at room temperature (m)

ΔT = Temperature difference over which the change in specimen length is measured ($^\circ\text{C}$)

k = Calibration coefficient

α_{ref} = Mean coefficient of linear thermal expansion for reference material ($\mu\text{m}/\text{m}^\circ\text{C}$)

ΔL_{ref} = Change of reference material length due to heating (μm)

L_{ref} = Reference material length at room temperature (m)

ΔT_{ref} = Temperature difference for change in reference length (°C), typically 100 °C

Equation 2: Midpoint Temperature of Temperature Range ΔT

$$T = \frac{\Delta T}{2} + T_R$$

T = Midpoint Temperature of Temperature Range ΔT (°C)

ΔT = Temperature difference over which the change in specimen length is measured (°C)

T_R = Temperature at Start of Range ΔT (°C)

METHOD FOR DETERMINING THE CURE RATE OF A COMPOSITE LAMINATE USING DIFFERENTIAL SCANNING CALORIMETER

INTRODUCTION

This document defines the test method, test specimens, testing procedure and method of analysis to determine the kinetics of a composite prepreg material. For this test, samples of the uncured pre-preg material of 7-10 mg of resin are tested using a differential scanning calorimeter (DSC).

For this test, a sample is heated at a controlled rate and measurements are taken of the difference in heat flow between a reference empty pan and test material due to energy changes in the material.

Properties obtained from this test method:

- Rate of the degree of cure as a function of temperature and degree of cure.

Factors that can influence test results:

- Material
- Sample preparation
- Scan rate
- Sample size

REFERENCES

[Ref 4] ASTM D3418-15, Standard Test Method for Transition Temperature of Fusion and Crystallisation of Polymers by Differential Scanning Calorimetry

[Ref 5] ASTM D3171-15, Standard Test Method for Constituent Content of Composite Materials

TEST EQUIPMENT

The following equipment will be required to perform Differential Scanning Calorimetric testing. Only equipment that complies with AQI 01.025.06-1 shall be used.

1. A Differential Scanning Calorimeter (DSC) such as Perkin Elmer DSC4000 with Intra Cooler.
2. Analytic Balance with 0.001mg accuracy.
3. 50µl Aluminium pans with a perforated lid.
4. Crimping press compatible with the pans being used.
5. 7mm round punch.
6. Nitrogen – 99.99% purity.

TEST SPECIMEN DIMENSIONS

Three (3) uncured specimens of 120x120mm shall be used for testing from each specimen:

- A 100x100mm specimen is used to determine the resin content
- A specimen with a mass such that the resin being tested results in 7-10 mg.

TEST PROCEDURE

1.1. Procedure for Resin Content

- For each batch of material tested, the resin content shall be determined and used to determine the mass of the actual resin tested.
 - Weigh each specimen to the nearest 0.0001g.
 - Place each specimen into a 100ml (minimum) beaker.
 - Add 20ml of a compatible acid to digest the resin. For 8552, epoxy sulfuric is recommended.
 - Place the beaker on a hot plate and heat until the mixture starts to fume.
 - After the solution is saturated, oxidise the reaction. For 8552, hydrogen peroxide is recommended.
 - Allow the beaker to cool. There should be no nondigested laminate present on the fibres.
 - Filter the contents into a pre-weighed sintered glass filter under a vacuum of 17 kPa or better. Wash the fibres three times with distilled water. Then with 20ml of acetone.
 - Place the specimen in an oven at 100 °C minimum until the specimen is dried (approximately 1 hour).
 - Place the fibres in a desiccator to avoid reabsorption of moisture.
 - Cool the filter to room temperature. Weigh the specimen to the nearest 0.0001g.
 - The resin weight can now be calculated using the initial and final specimen weight. From this, the resin content can be calculated.
- The acids used for digestion and oxidation should be specified in the relevant test plan. A list of acids with their compatibility can be found in [Ref 5].

1.2. Procedure for Cure Rate

- The specimens are to be tested for the same temperature-time curve that will be used to cure the material being tested. Figure shows an example of a curing cycle curve.
 - The first cycle (reference cycle) is done on an uncured sample starting from room temperature. The temperature is increased at a rate of 10°C/min until a maximum temperature is reached, which is higher than the temperature range of interest.
 - A similar uncured sample is used for each cycle thereafter, starting from room temperature. The temperature is then increased (or maintained) as required by the curing process of interest. After each cycle, the temperature is again increased at a rate of 10 °C/min up to the maximum temperature.
 - As an example of this, the material with a curing cycle, as shown in Figure , is tested:
 1. From 25 °C to 310 °C at a rate of 10 °C/min. (Reference cycle)
 2. From 25 °C to 110 °C at a rate of 1.5 °C/min, then to 310 °C at a rate of 10 °C/min.
 3. From 25 °C to 110 °C at a rate of 1.5 °C/min, then hold at 110 °C for 60 min, then to 180 °C at a rate of 1.5 °C/min, then to 310 °C at a rate of 10 °C/min.

4. From 25 °C to 110 °C at a rate of 1.5 °C/min, then hold at 110 °C for 60 min, then to 180 °C at a rate of 1.5 °C/min, then hold at 180 °C for 120 min, then to 310 °C at a rate of 10 °C/min.
- For all of these tests, one of the pans contains the sample being tested, with the reference pan being empty.

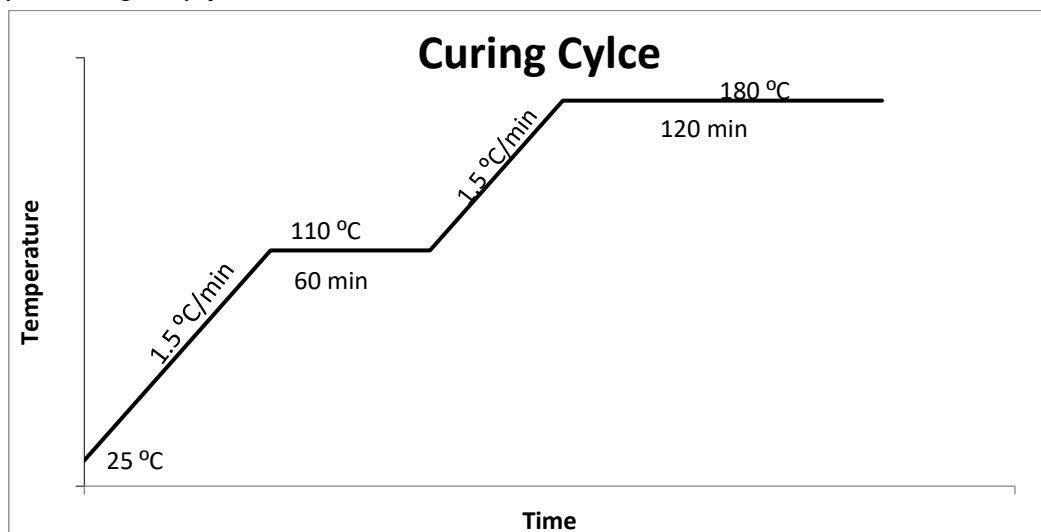


Figure 59: Example of a curing cycle

TEST REPORT

The test report will include the following information:

48. The revision level or date of issue of this test method.
49. The date(s) and location(s) of the test.
50. The name(s) of the test operator(s).
51. Complete identification of test specimens
52. Any variations to this test method, anomalies noticed during testing, or equipment problems.
53. ΔH and $\Delta H_{(100)}$ Reaction enthalpy curves as well as data corrected for 100% resin content.
54. Extent of cure and extent of cure rate for points of interest.
55. Specimen mass and resin content.
56. Equipment used for testing as well as calibration certificates for all equipment used for testing.

ANALYSIS OF TEST RESULTS

Equation 3: Resin content determination

$$\%W = \frac{(m_1 - m_2)}{m_1} \times 100$$

where:

$\%W$ = Resin content as percentage of initial mass (%)

m_1 = Initial mass of specimen (g)

m_2 = Final mass of specimen (g)

Equation 4: Extent of cure

$$\alpha(100) = \frac{\Delta H_{A(100)} - \Delta H_{B(100)}}{\Delta H_{B(100)}} \times 100$$

where:

α = Extent of Cure (%)

ΔH_A = Reaction Enthalpy of Reference Cycle (J/g)

ΔH_B = Reaction Enthalpy of Cycle of Interest (J/g)

(100) = Data corrected to 100 % resin content

Equation 5: Cure Rate

$$\alpha = \alpha_o + \frac{1}{\Delta H_c} \sum_{i=1}^{n-1} (\dot{H}_{baseline} - \dot{H}_i) \times \Delta t$$

where:

α = Degree of Cure (%)

α_o = Preceding Degree of Cure (%)

ΔH_c = Total heat of cure (J/g)

$\dot{H}_{baseline}$ = Baseline Heat (W/g)

$\dot{H}_i$ = Initial Heat of Cure (W/g)

Δt = Change in time (s)

METHOD FOR DETERMINING THE EXTENT OF CURE FOR A COMPOSITE LAMINATE USING DIFFERENTIAL SCANNING CALORIMETER

INTRODUCTION

This document defines the test method, test specimens, testing procedure and method of analysis to determine the extent of cure of a composite laminate as a function of temperature and degree of cure. For this test, samples of the pre-preg material and cured material of 21-24 mg are tested using a differential scanning calorimeter (DSC).

For this test, a sample is heated at a controlled rate and measurements are taken of the difference in heat flow between a reference empty pan and test material due to energy changes in the material.

Properties obtained from this test method:

- The extent of cure as a function of temperature and degree of cure.

Factors that can influence test results:

- Material
- Sample preparation
- Scan rate
- Sample size

REFERENCES

[Ref 6] ASTM D3418-15, Standard Test Method for Transition Temperature of Fusion and Crystallisation of Polymers by Differential Scanning Calorimetry

[Ref 7] ASTM D3171-15, Standard Test Method for Constituent Content of Composite Materials

TEST EQUIPMENT

The following equipment will be required to perform Differential Scanning Calorimetric testing. Only equipment that complies with AQI 01.025.06-1 shall be used.

1.1. Extent of cure

1. A Differential Scanning Calorimeter (DSC) such as Perkin Elmer DSC4000 with Intra Cooler.
2. Analytic Balance scale with 0.001mg accuracy.
3. Laboratory glassware.
4. Laboratory oven operated at 120 °C.

1.2. TEST SPECIMEN DIMENSIONS

Three (3) cured specimens of 120x120mm shall be used for testing of which from each specimen:

- A 10x40mm specimen is used to determine the resin content
- A specimen with a mass such that the resin being tested results in 21-24 mg.

TEST PROCEDURE

1.3. Procedure for Resin Content

- If Resin content is needed see procedure X0060000TJ008

1.4. Procedure for Extent of Cure (Cured)

- The specimens are to be tested for the same temperature-time curve that will be used to cure the material being tested.
 - The first cycle (reference cycle) is done on an uncured sample starting from room temperature. The temperature is increased at a rate of 10 °C/min until a maximum temperature that is higher than the temperature range of interest.
 - As an example of this, the material with a curing cycle will be tested:
 1. From 25 °C to 310 °C at a rate of 10 °C/min. (Reference cycle)
- For all of these tests, one of the pans contains the sample being tested, with the reference pan being empty.

TEST REPORT

The test report will include the following information:

57. The revision level or date of issue of this test method.s
58. The date(s) and location(s) of the test.
59. The name(s) of the test operator(s).
60. Complete identification of test specimens
61. Any variations to this test method, anomalies noticed during testing, or equipment problems.
62. ΔH and $\Delta H_{(100)}$ Reaction enthalpy curves as well as data corrected for 100% resin content.
63. Extent of cure and extent of cure rate for points of interest.
64. Specimen mass and resin content.
65. Equipment used for testing as well as calibration certificates for all equipment used for testing.

ANALYSIS OF TEST RESULTS

$$\alpha(100) = \frac{\Delta H_{A(100)} - \Delta H_{B(100)}}{\Delta H_{A(100)}} \times 100 [\%]$$

where:

α = Extent of Cure (%)

ΔH_A = Reaction Enthalpy of Reference Cycle (J/g)

ΔH_B = Reaction Enthalpy of Cycle of Interest (J/g)

(100) = Data corrected to 100 % resin content

Equation 6: Extent of Cure

EXAMPLE OF EXCEL CALCULATIONS TO DETERMINE YOUNG'S MODULUS

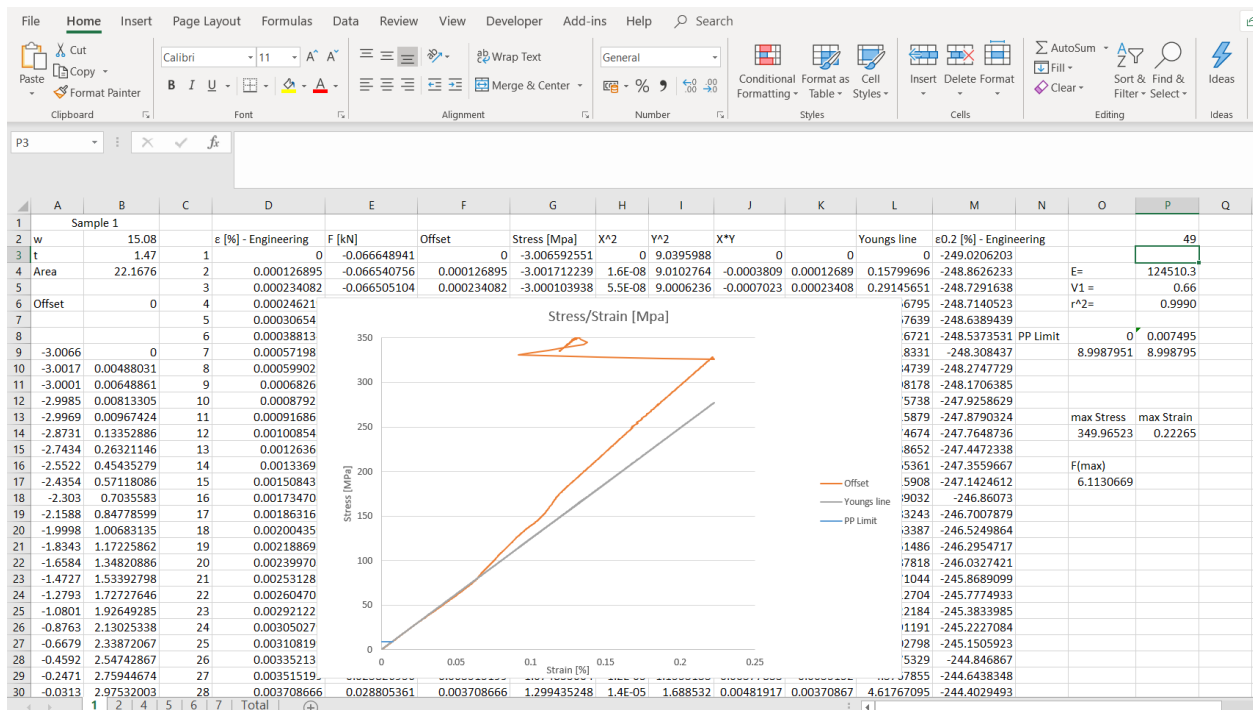
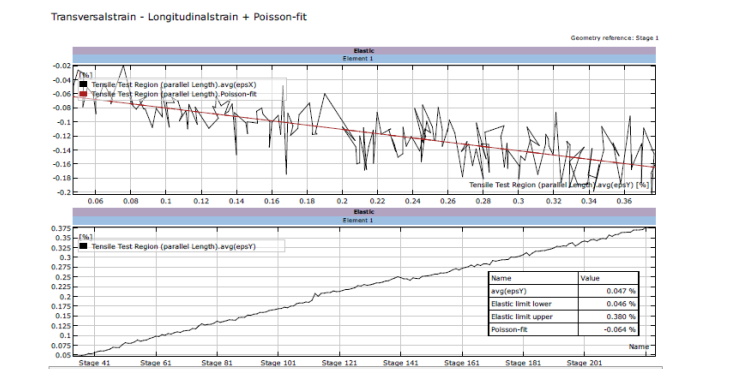
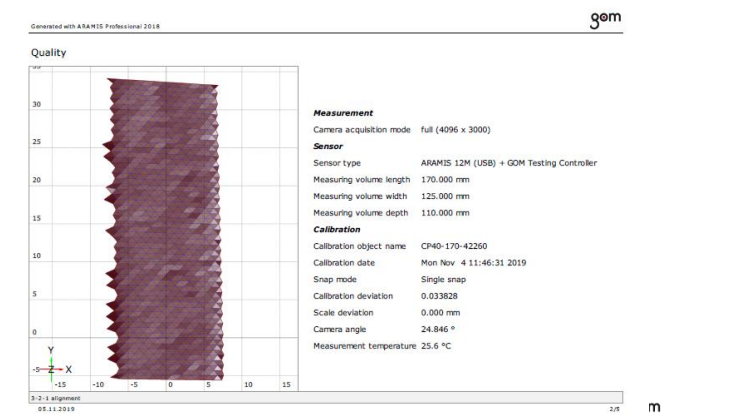


Figure 1: Example of excel calculations to determine Yong's Modulus

APPENDIX C: POISSON'S REPORTS



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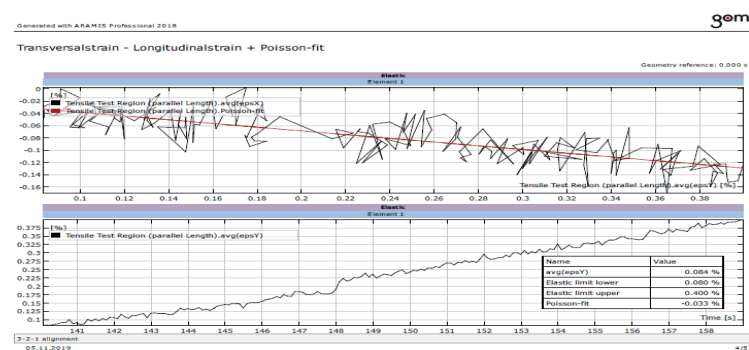
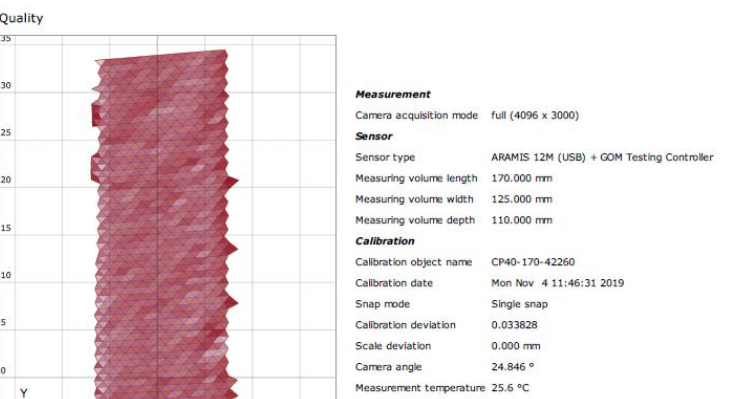
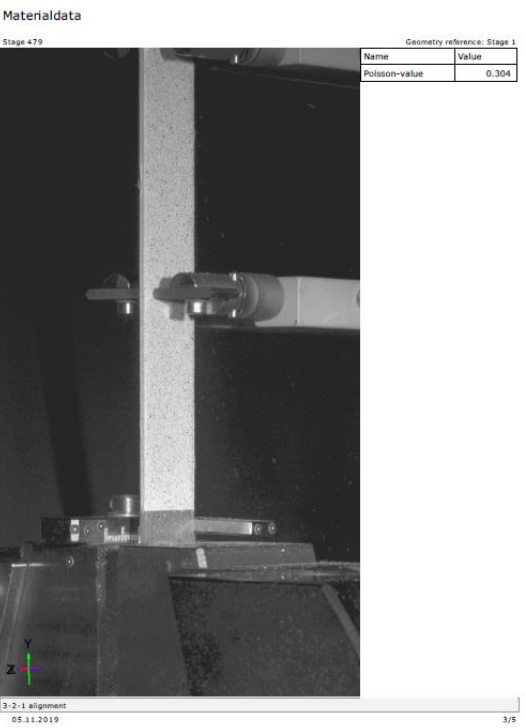
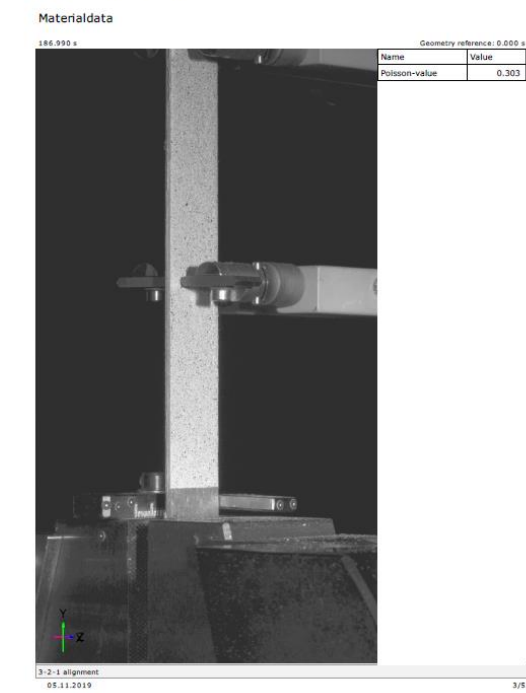


Figure 1: DOC 2 Poisson's Report Test 1 and Test 2

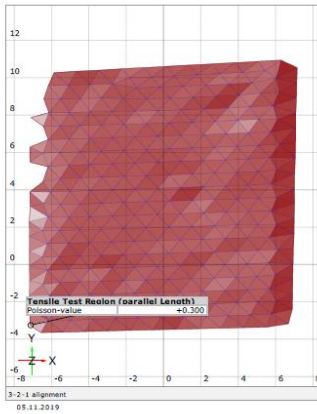
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Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller

Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

Snap mode Single snap

Calibration deviation 0.033828

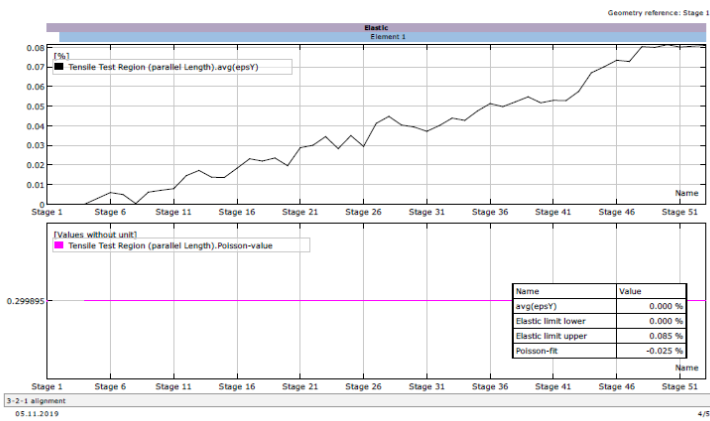
Scale deviation 0.000 mm

Camera angle 24.846 °

Measurement temperature 25.6 °C

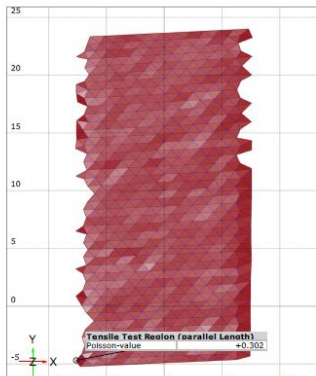
Generated with ARAMIS Professional 2018

Transversalstrain - Longitudinalstrain + Poisson-fit



Generated with ARAMIS Professional 2018

Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller

Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

Snap mode Single snap

Calibration deviation 0.033828

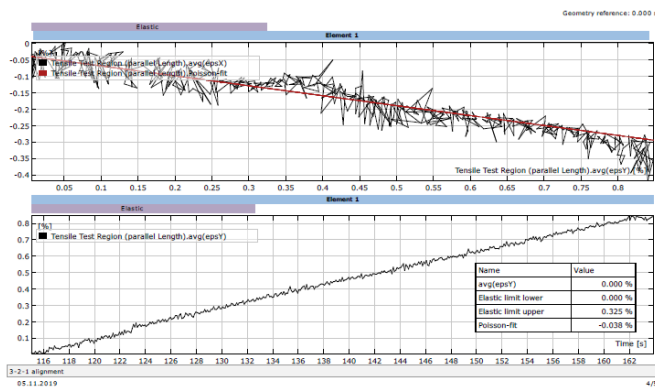
Scale deviation 0.000 mm

Camera angle 24.846 °

Measurement temperature 25.6 °C

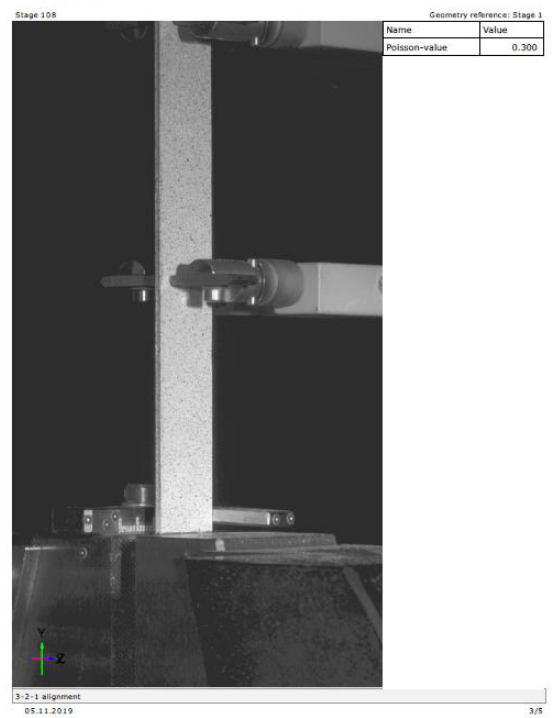
Generated with ARAMIS Professional 2018

Transversalstrain - Longitudinalstrain + Poisson-fit



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Materialdata



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Materialdata

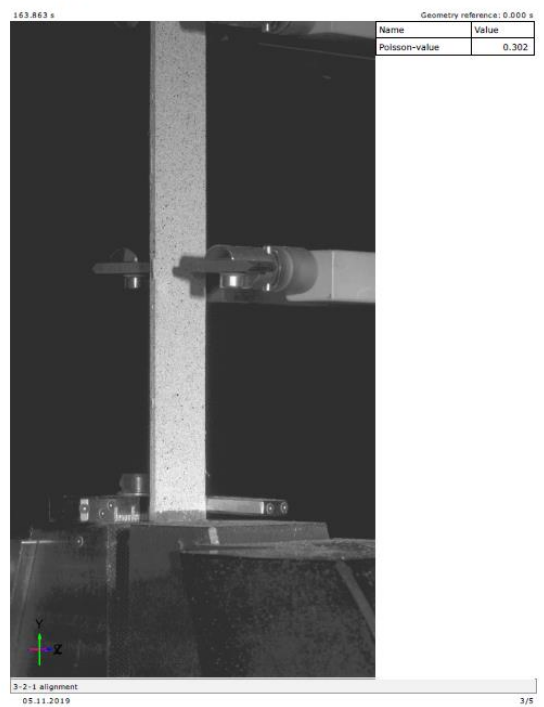
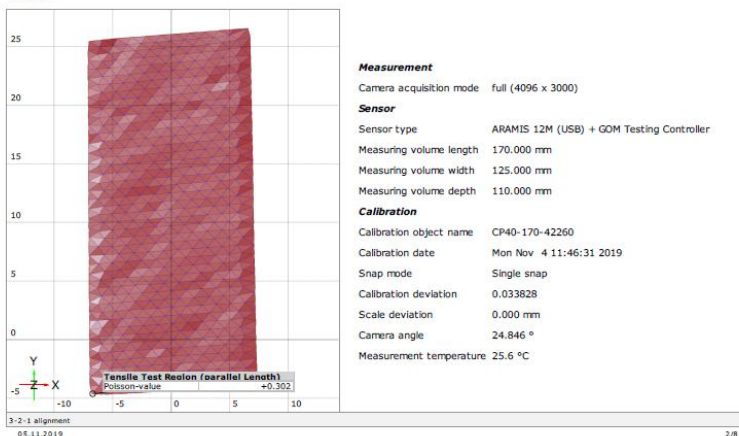
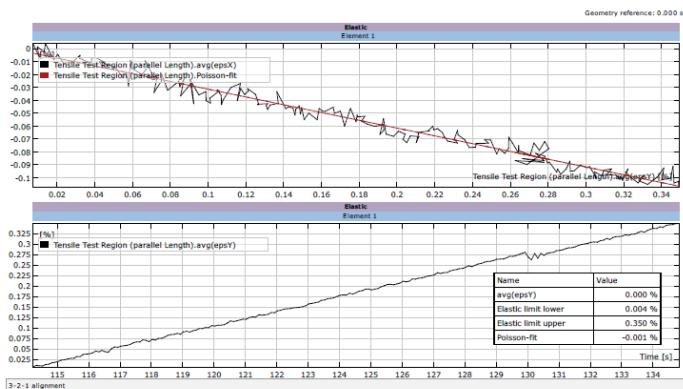


Figure 2: DOC 2 Poisson's Report Test 3 and Test 4

Quality



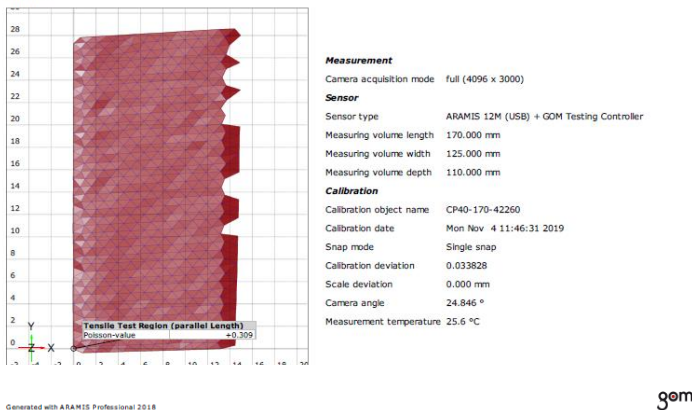
Transversalstrain - Longitudinalstrain + Poisson-fit



Generated with ARAMIS Professional 2018

gom

Quality



Transversalstrain - Longitudinalstrain + Poisson-fit

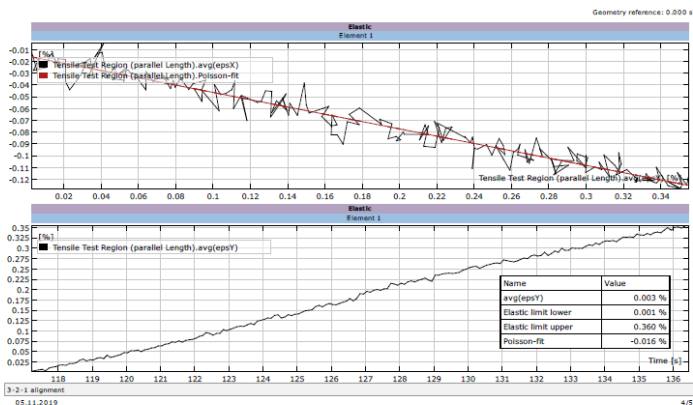
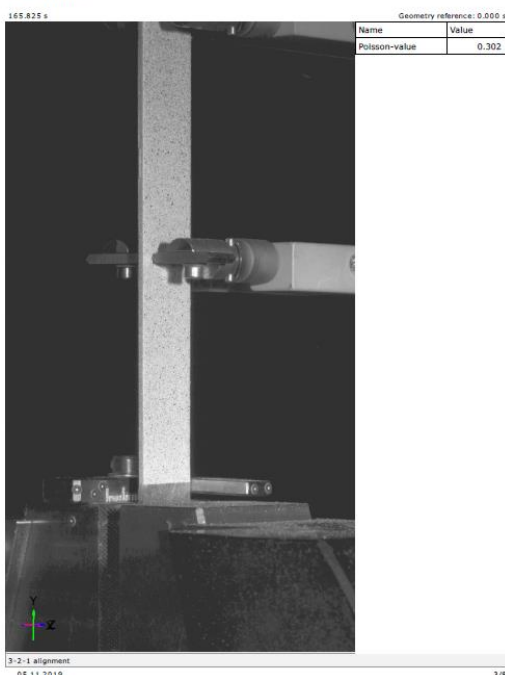


Figure 3: DOC 2 Poisson's Report Test 5 and Test 6

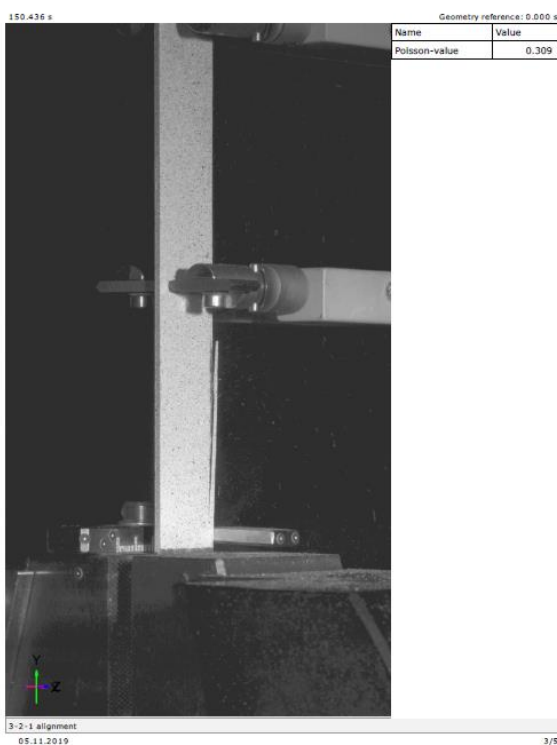
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Materialdata



Generated with ARAMIS Professional 2018

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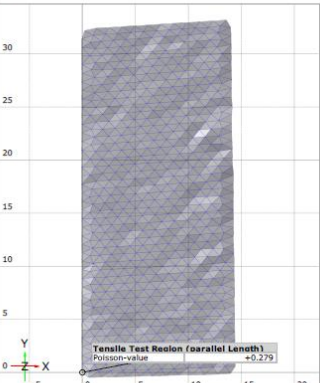


DOC 3:

Generated with ARAMIS Professional 2018

gom

Quality



Measurement

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Sensor

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Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

Snap mode Single snap

Calibration deviation 0.033828

Scale deviation 0.000 mm

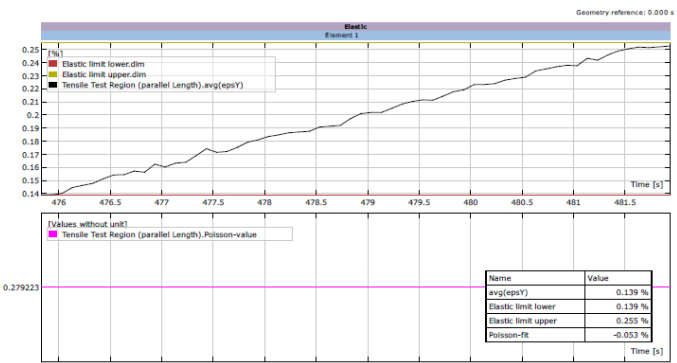
Camera angle 24.846 °

Measurement temperature 25.6 °C

Generated with ARAMIS Professional 2018

gom

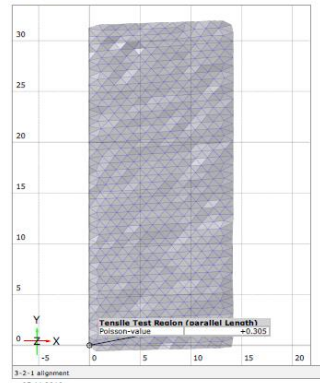
Transversalstrain - Longitudinalstrain + Poisson-fit



Generated with ARAMIS Professional 2018

gom

Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller

Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

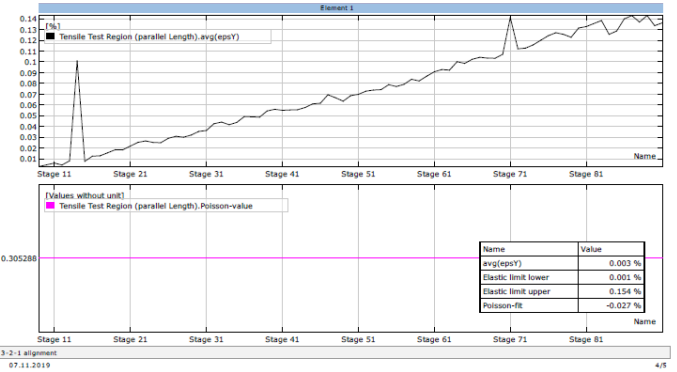
Snap mode Single snap

Calibration deviation 0.033828

Scale deviation 0.000 mm

Camera angle 24.846 °

Measurement temperature 25.6 °C

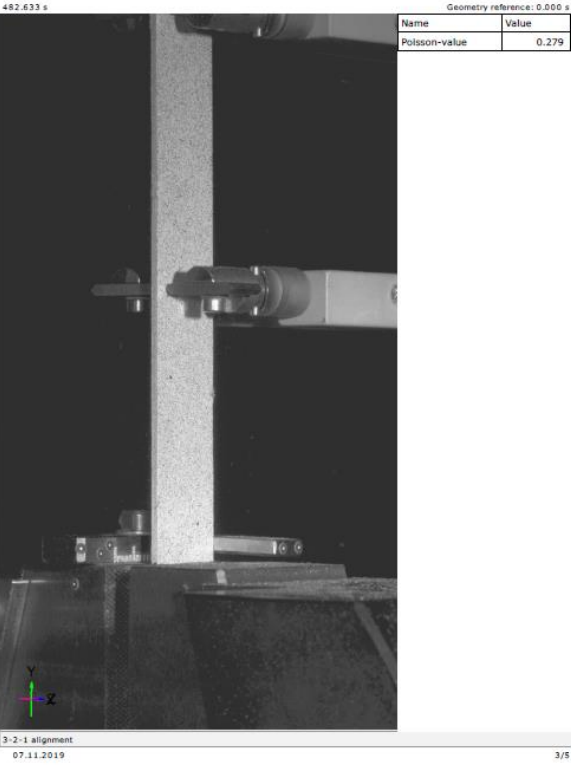


Generated with ARAMIS Professional 2018

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Materialdata



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Materialdata

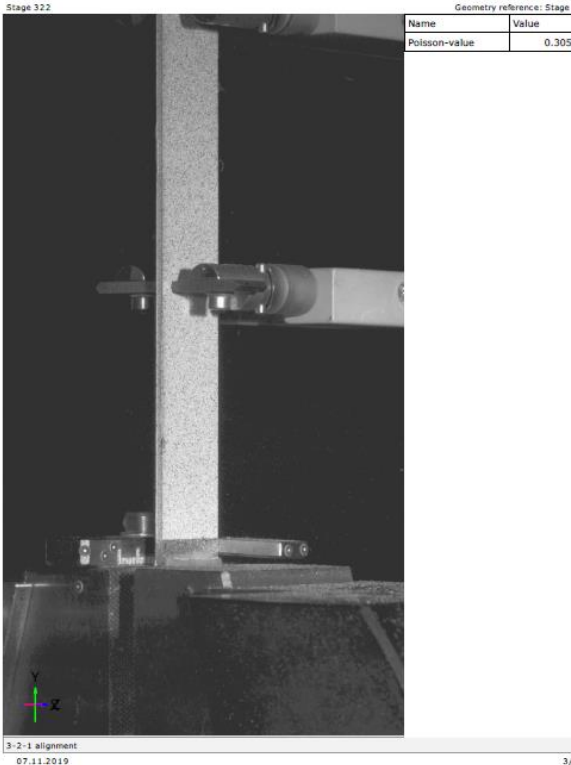
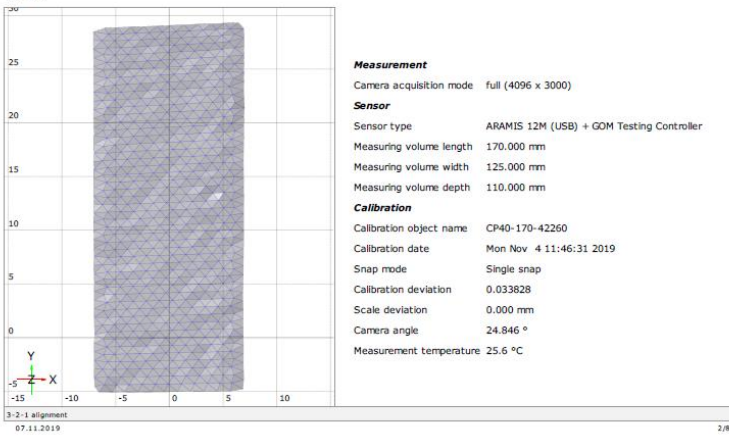


Figure 4: DOC 3 Poisson's Report Test 1 and Test 2

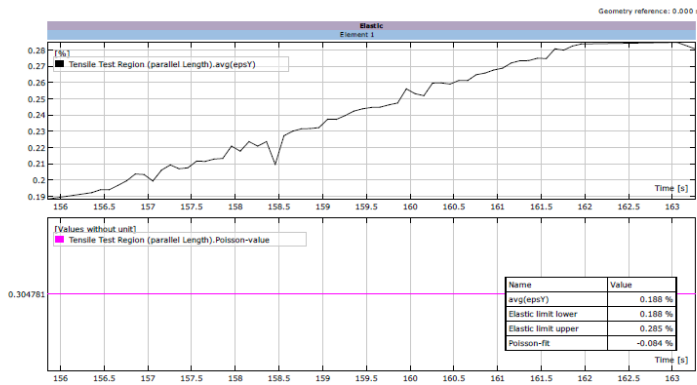
Quality



Generated with ARAMIS Professional 2018

gom

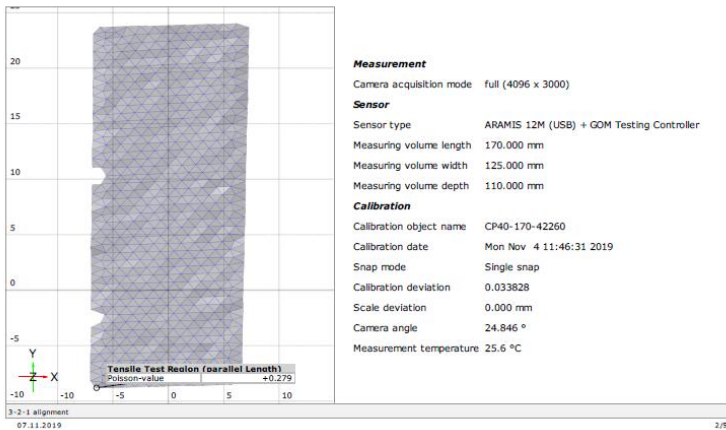
Transversalstrain - Longitudinalstrain + Poisson-fit



Generated with ARAMIS Professional 2018

gom

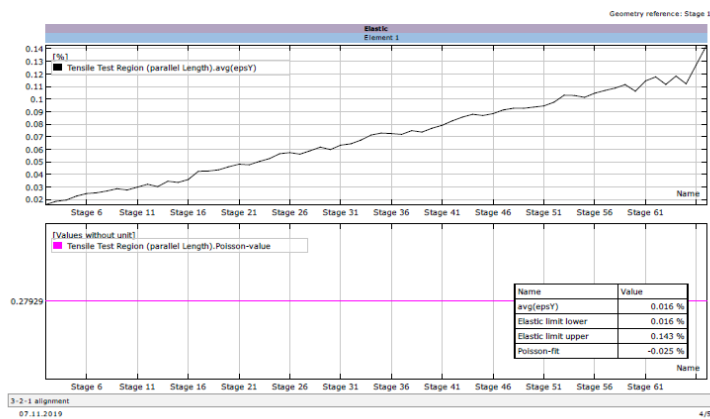
Quality



Generated with ARAMIS Professional 2018

gom

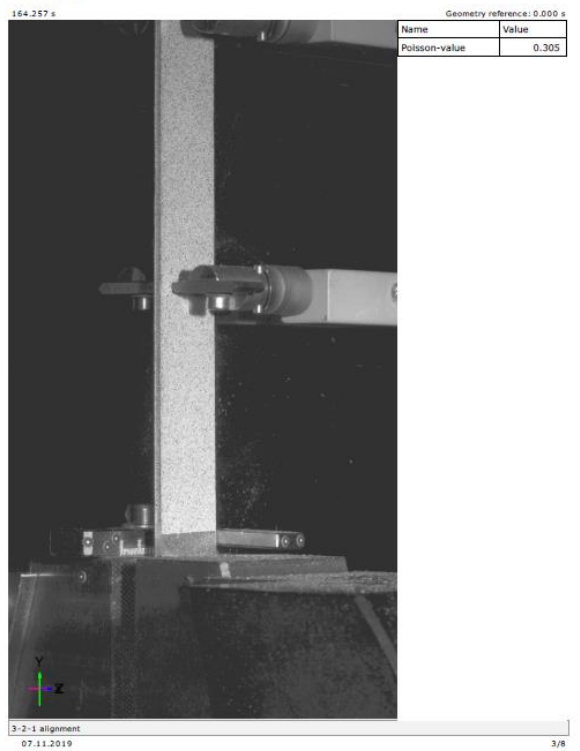
Transversalstrain - Longitudinalstrain + Poisson-fit

3-2-1 alignment
07.11.2019

4/8

Generated with ARAMIS Professional 2018

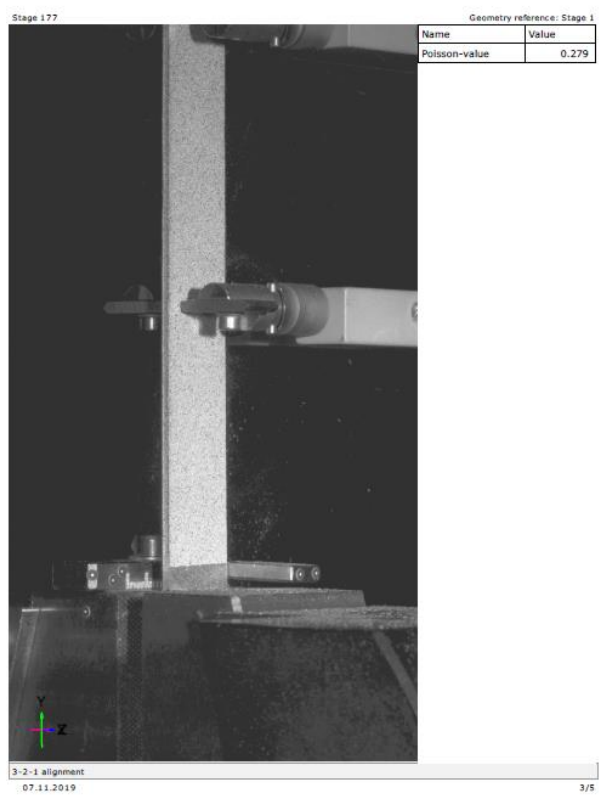
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3/8

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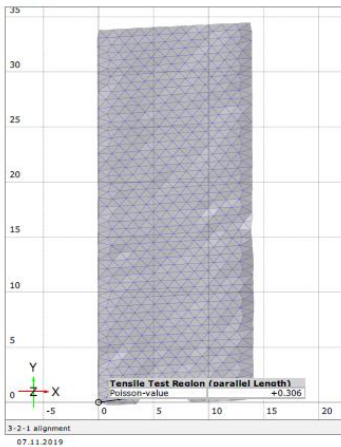
Materialdata



3/5

Figure 5: DOC 3 Poisson's Report Test 3 and Test 4

Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller

Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

Snap mode Single snap

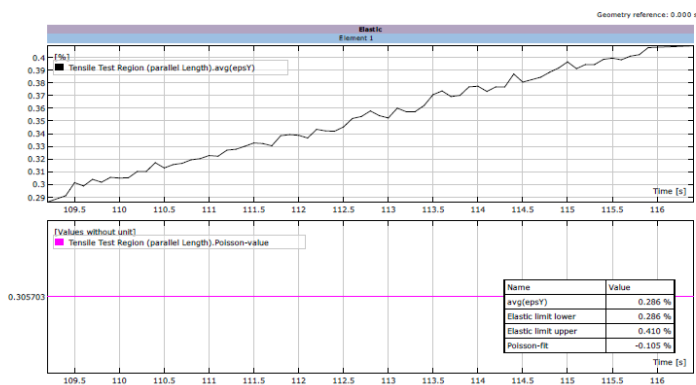
Calibration deviation 0.033828

Scale deviation 0.000 mm

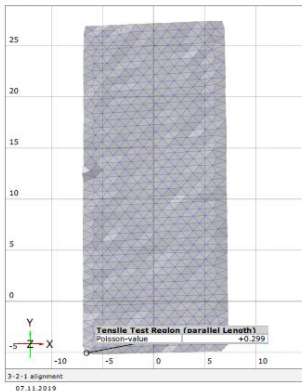
Camera angle 24.846 °

Measurement temperature 25.6 °C

Transversalstrain - Longitudinalstrain + Poisson-fit



Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller

Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

Snap mode Single snap

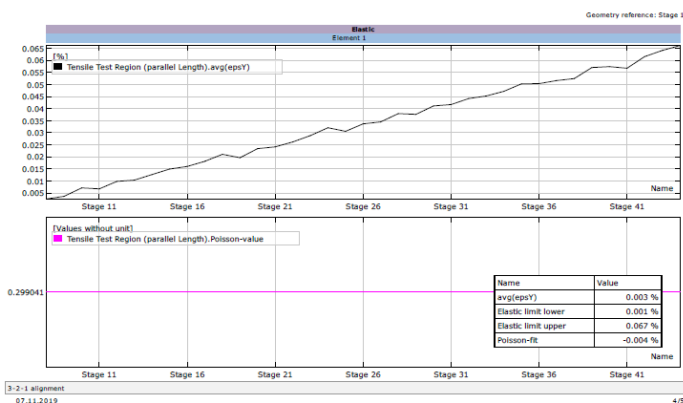
Calibration deviation 0.033828

Scale deviation 0.000 mm

Camera angle 24.846 °

Measurement temperature 25.6 °C

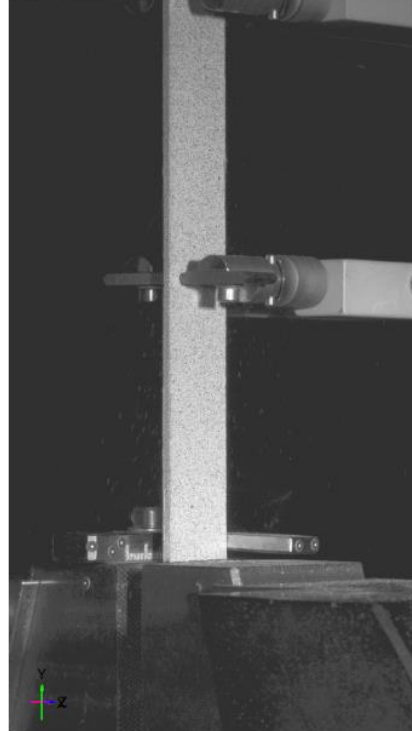
Transversalstrain - Longitudinalstrain + Poisson-fit



Materialdata

122.201 s

Geometry reference: 0.000 s



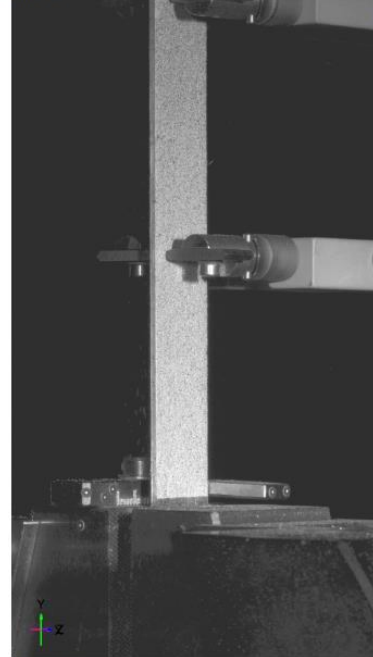
Name	Value
Poisson-value	0.306

3/5

Materialdata

Stage 138

Geometry reference: Stage 1



Name	Value
Poisson-value	0.299

3/5

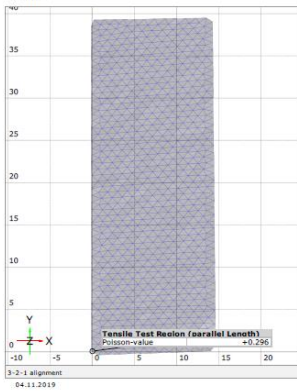
Figure 6: DOC 3 Poisson's Report Test 5 and Test 6

DOC 5:

Generated with ARAMIS Professional 2018

gom

Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller
Measuring volume length 170.000 mm
Measuring volume width 125.000 mm
Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260
Calibration date Mon Nov 4 11:46:31 2019
Snap mode Single snap
Calibration deviation 0.033828
Scale deviation 0.000 mm
Camera angle 24.846 °
Measurement temperature 25.6 °C

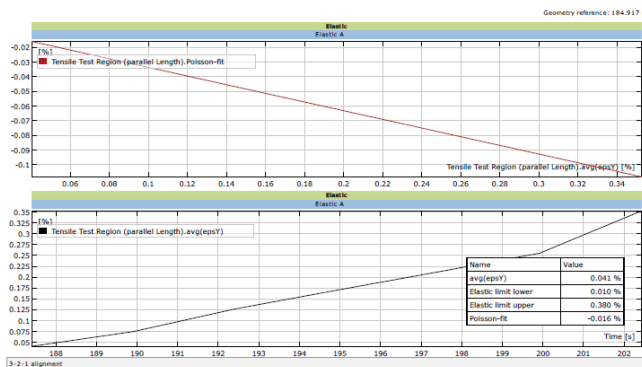
3-2-1 alignment
04.11.2019

2/5

Generated with ARAMIS Professional 2018

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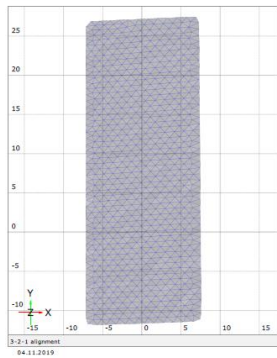
Transversalstrain - Longitudinalstrain + Poisson-fit



Generated with ARAMIS Professional 2018

gom

Quality



Measurement

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller
Measuring volume length 170.000 mm
Measuring volume width 125.000 mm
Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260
Calibration date Mon Nov 4 11:46:31 2019
Snap mode Single snap
Calibration deviation 0.033828
Scale deviation 0.000 mm
Camera angle 24.846 °
Measurement temperature 25.6 °C

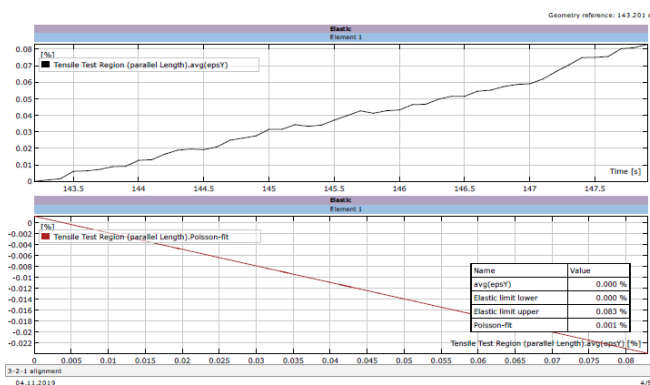
3-2-1 alignment
04.11.2019

2/5

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gom

Transversalstrain - Longitudinalstrain + Poisson-fit



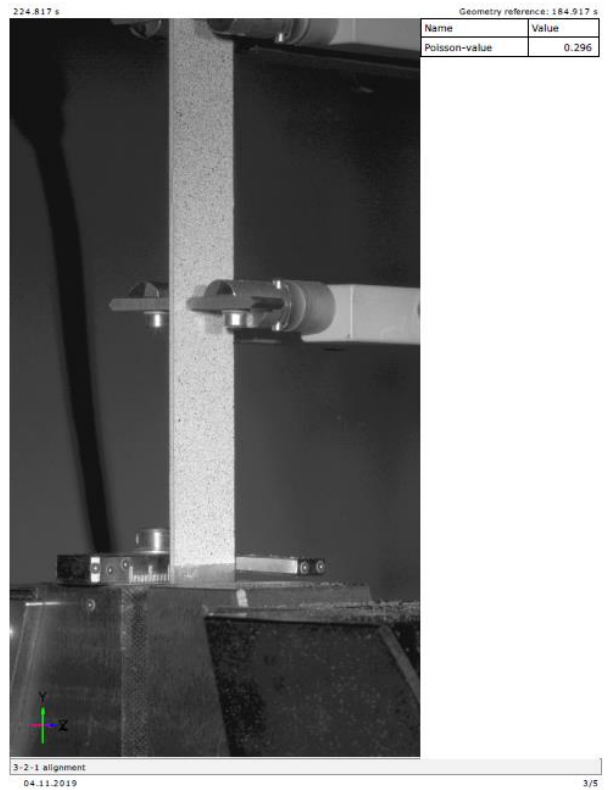
3-2-1 alignment
04.11.2019

4/5

Generated with ARAMIS Professional 2018

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Materialdata



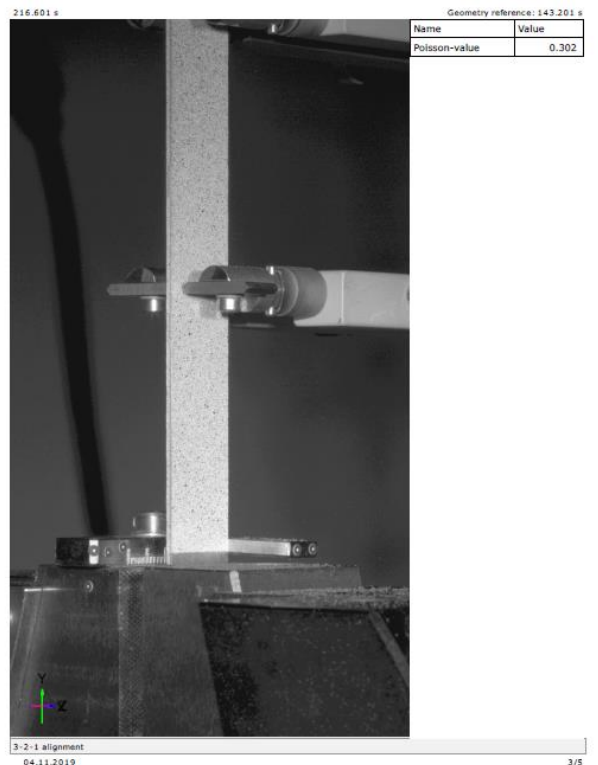
3-2-1 alignment
04.11.2019

3/5

Generated with ARAMIS Professional 2018

gom

Materialdata

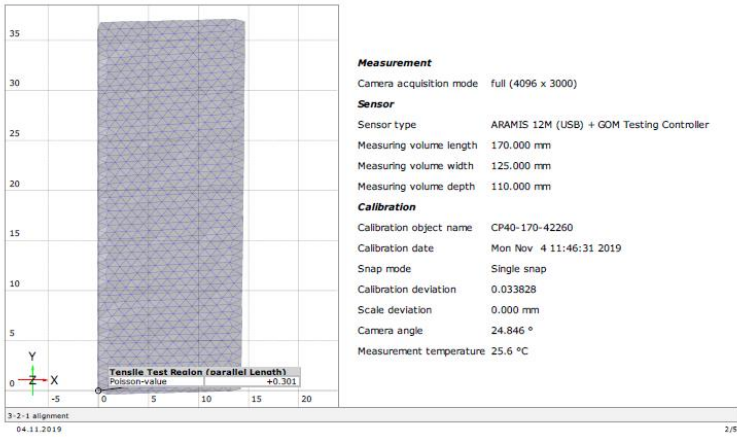


3-2-1 alignment
04.11.2019

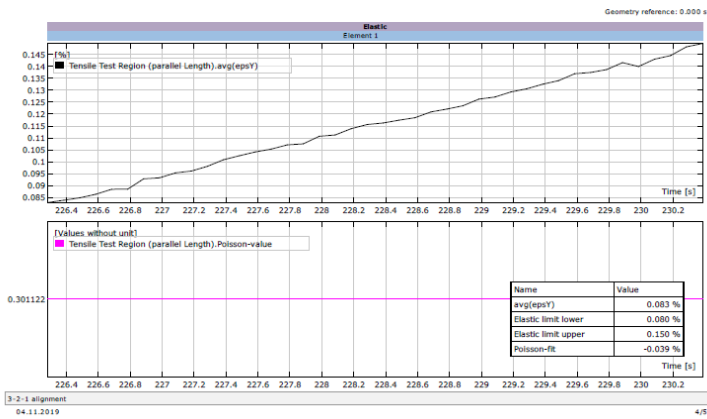
3/5

Figure 7: DOC 5 Poisson's Report Test 2 and Test 3

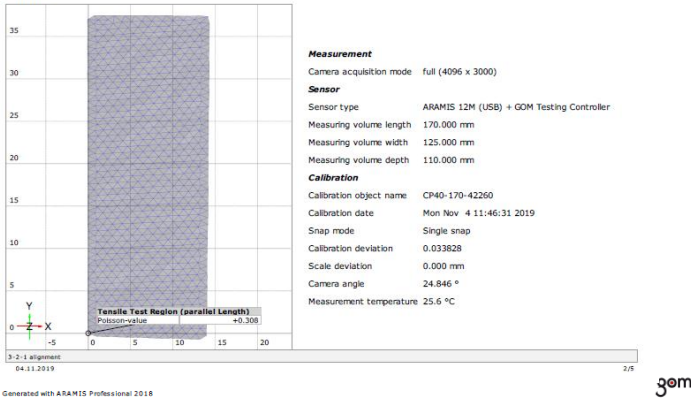
Quality



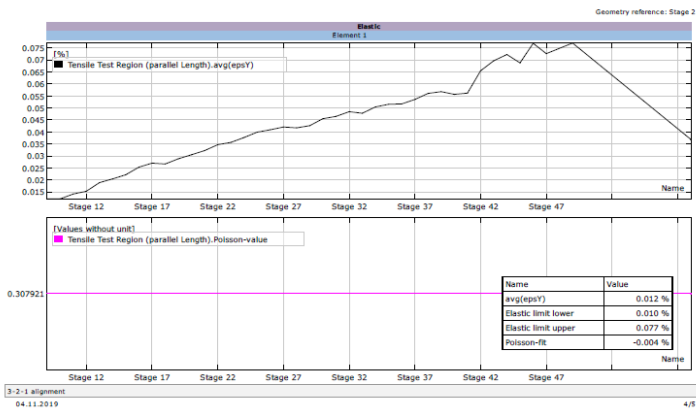
Transversalstrain - Longitudinalstrain + Poisson-fit



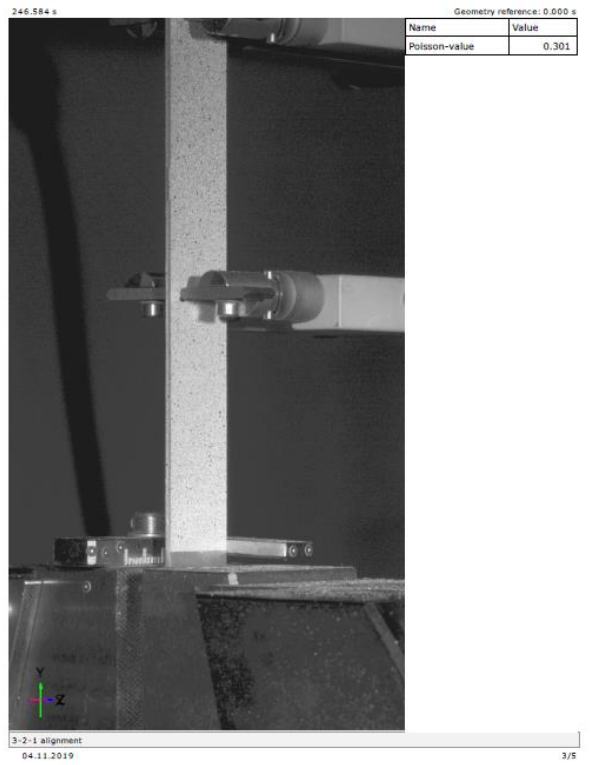
Quality



Transversalstrain - Longitudinalstrain + Poisson-fit



Materialdata



Materialdata

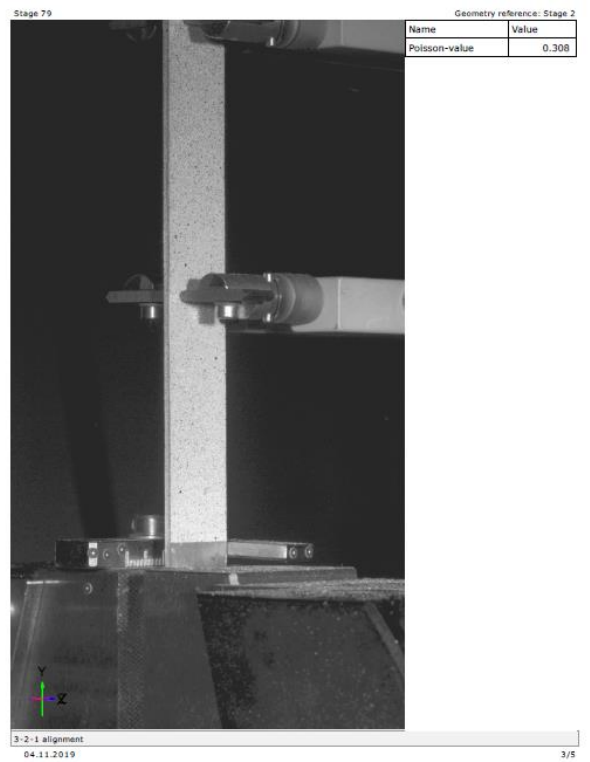
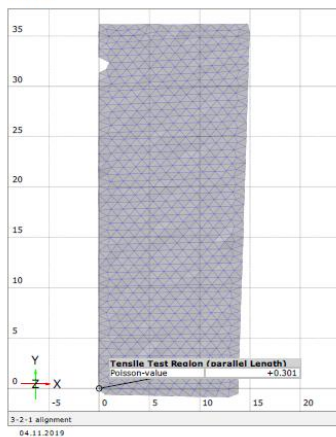


Figure 8: DOC 5 Poisson's Report Test 4 and Test 5

Quality

**Measurement**

Camera acquisition mode full (4096 x 3000)

Sensor

Sensor type ARAMIS 12M (USB) + GOM Testing Controller

Measuring volume length 170.000 mm

Measuring volume width 125.000 mm

Measuring volume depth 110.000 mm

Calibration

Calibration object name CP40-170-42260

Calibration date Mon Nov 4 11:46:31 2019

Snap mode Single snap

Calibration deviation 0.033828

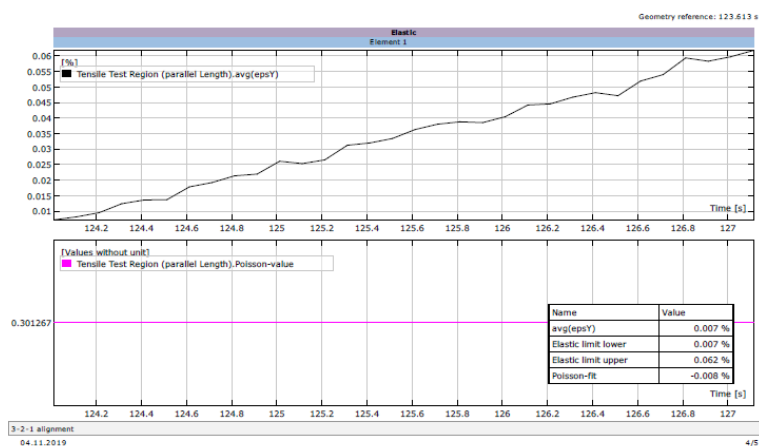
Scale deviation 0.000 mm

Camera angle 24.846 °

Measurement temperature 25.6 °C

2/5

Transversalstrain - Longitudinalstrain + Poisson-fit

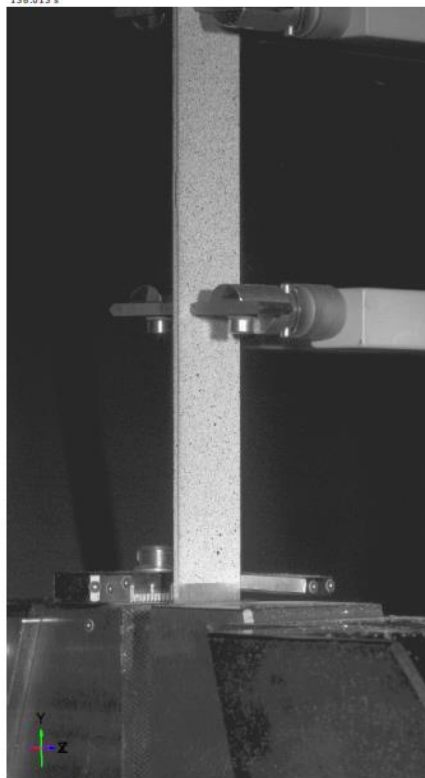


4/5

Materialdata

136.813 s

Geometry reference: 123.613 s



Name	Value
Poisson-value	0.301

3/5

Figure 9: DOC 5 Poisson's Report Test 6

APPENDIX D: FLAT PLATES MANUFACTURING DATA

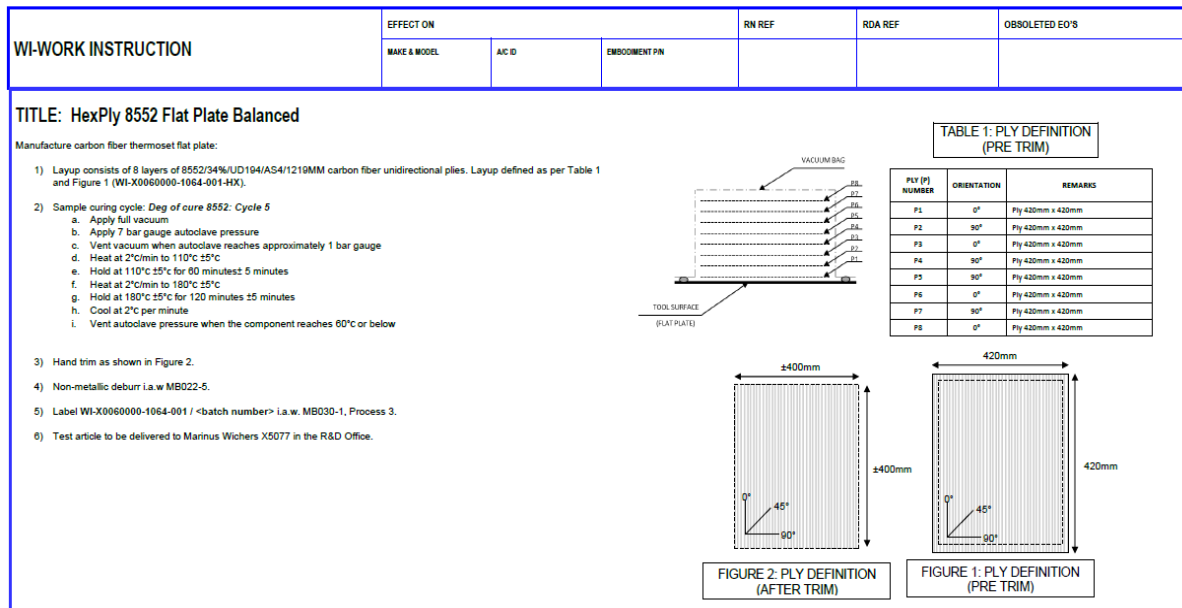


Figure 1: Work Instruction Balanced layup

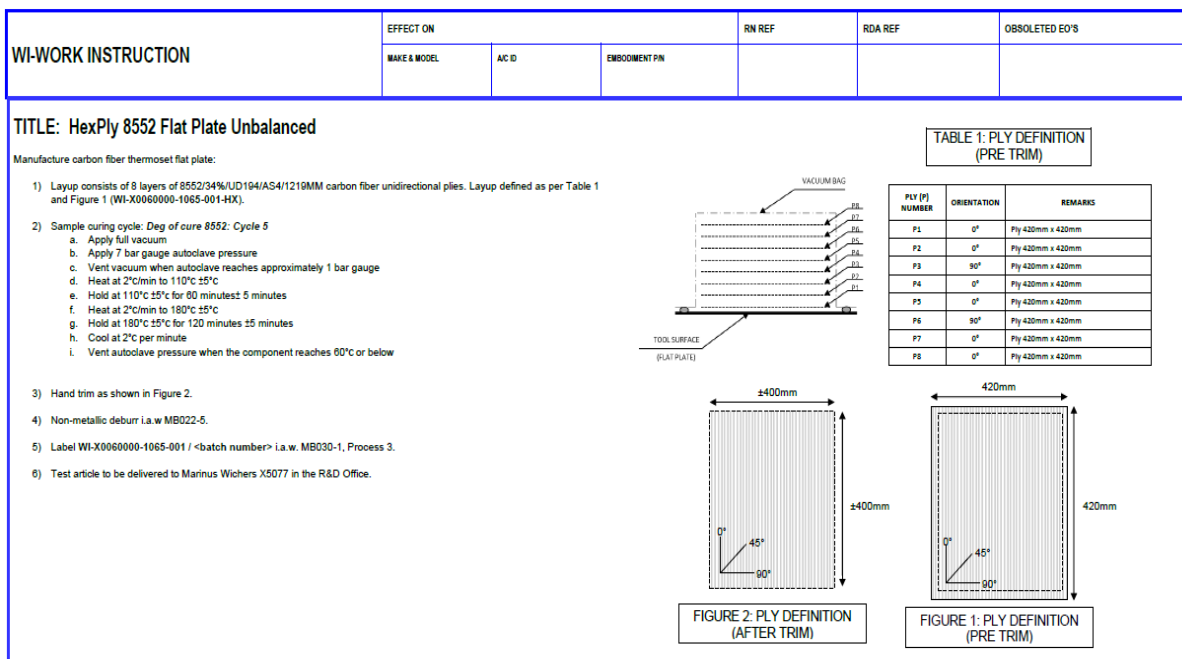


Figure 2: Work Instruction Unbalanced layup

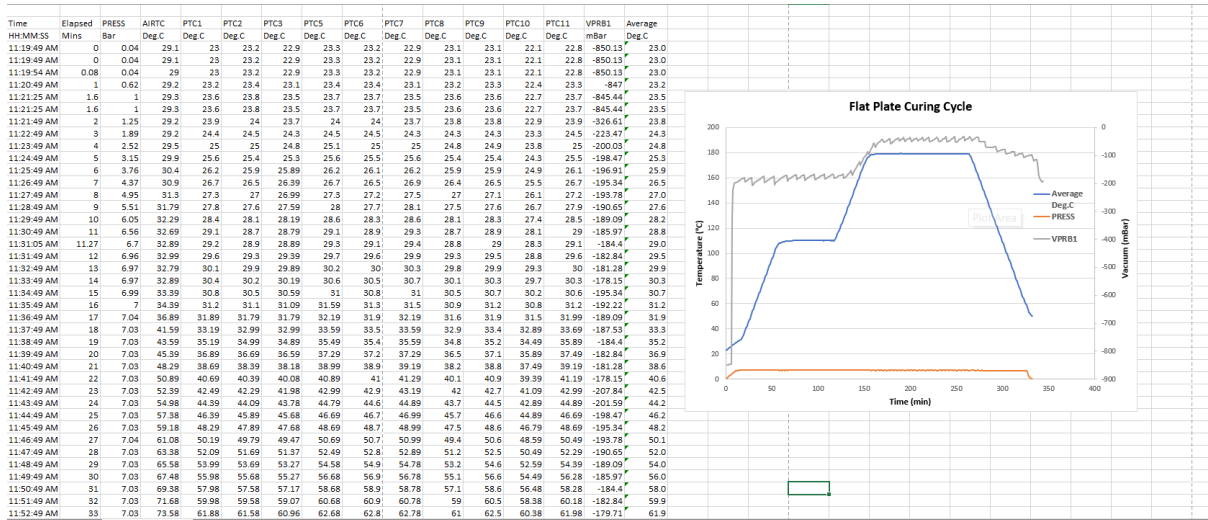


Figure 3: Flat Plates Autoclave Cure Cycle data

3D SCANNING DATA (ROMER):

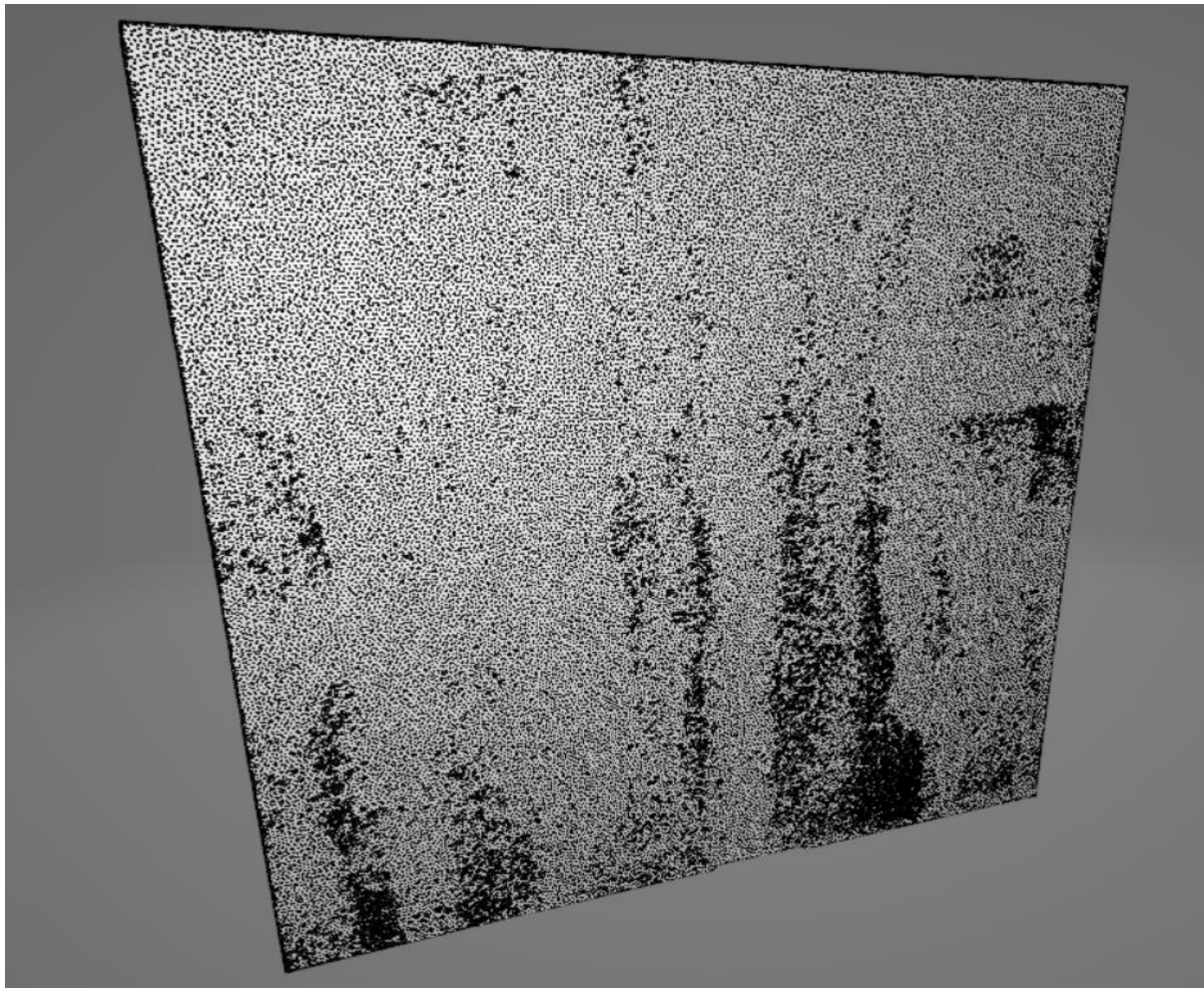


Figure 4: 3D Scanning Data points Balanced Plate

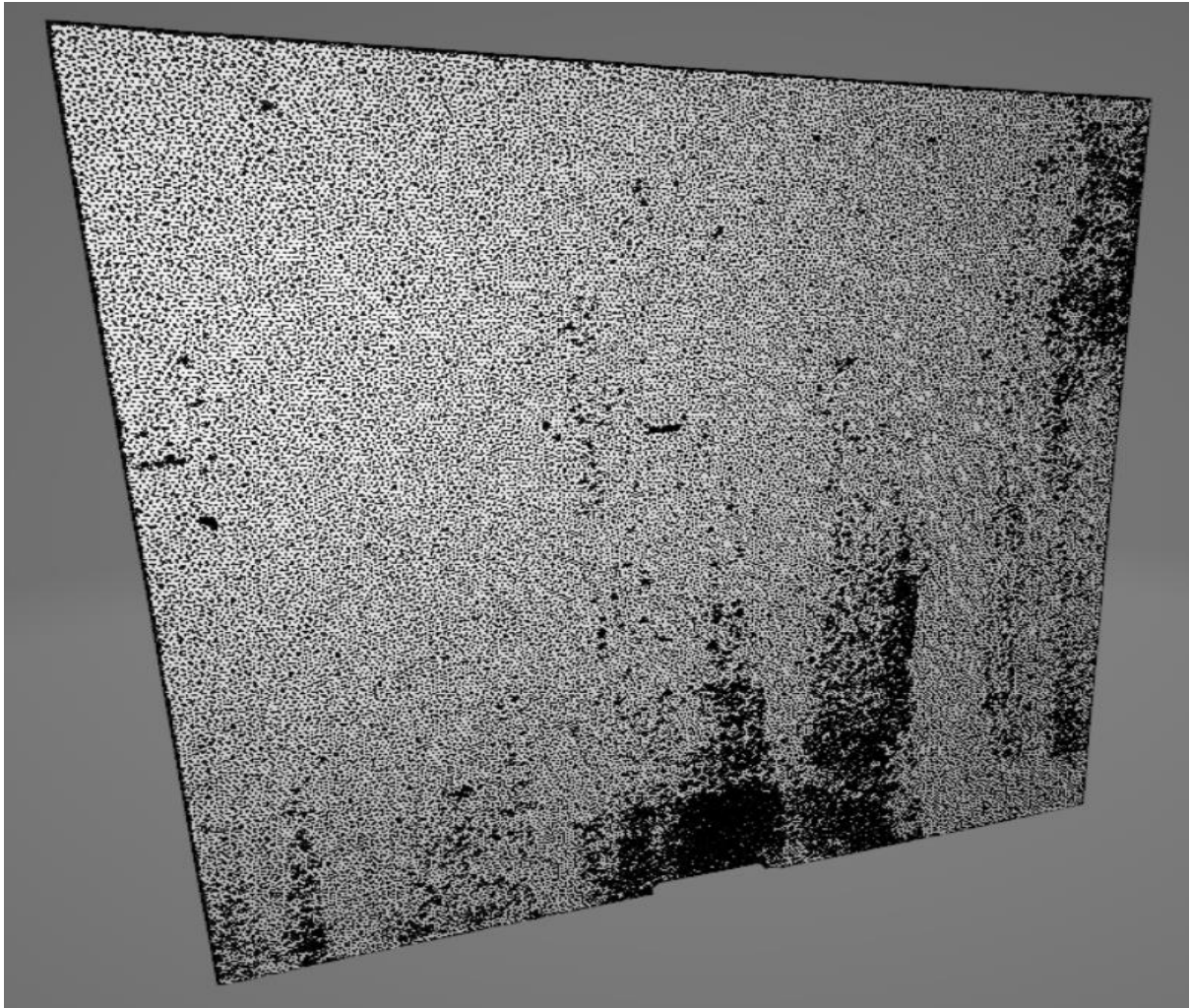


Figure 5: 3D Scanning Data points Unbalanced Plate

APPENDIX E: SIMULATION DATA

March Simulation tables data:

O15														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Pressure			volshrinkage			Cycle temp			CTE 1		CTE 2		
2	V1	F		V1	F		V1	F		V1	F	V1	F	
3	0	0		0.00E+00	0.00E+00		0	3.83E+02		3.83E+02	-1.00E-07	3.83E+02	3.27E-05	
4	0	1		1.00E-01	1.00E-02		3601	3.83E+02		4.53E+02	-7.00E-07	4.53E+02	4.00E-05	
5	15000	1		1	1		5701	4.53E+02						
6	17701	0					12901	4.53E+02						
7							17701	2.93E+02						
8	Conductivity K11			Conductivity K22										
9	V1	F		V1	F		E 0 Vs DOC			E45 Vs DOC				
10	2.98E+02	2		2.98E+02	5.00E-01		V1	F		V1	F			
11	4.53E+02	3		4.53E+02	7.00E-01		0	1.27E+11		0	4.30E+09			
12							3.20E-02	1.27E+11		3.20E-02	4.37E+09			
13							6.40E-02	1.27E+11		6.40E-02	4.37E+09			
14	Shrinkage			DOC Vs Time			6.95E-01	1.27E+11		6.95E-01	4.66E+09			
15	V1	F		V1	F		9.13E-01	1.33E+11		9.13E-01	4.66E+09			
16	0	0		0	4.00E-01		1	1.33E+11		1	4.66E+09			
17	1.00E-01	1.00E-02		3600	5.00E-01									
18	1	1		4000	6.00E-01		E 90 Vs DOC			G23 Vs DOC				
19				5700	7.00E-01		V1	F		V1	F			
20	Table 18			8000	8.00E-01		0	1.50E+09		0	5.50E+08			
21	V1	F		12900	9.60E-01		3.20E-02	1.57E+09		3.20E-02	5.60E+08			
22	0	7.00E+09		17700	9.60E-01		6.40E-02	1.57E+09		6.40E-02	5.60E+08			
23	6.95E-02	7.00E+09					6.95E-01	1.81E+09		6.95E-01	6.47E+08			
24	9.13E-01	9.28E+09					9.13E-01	9.28E+09		9.13E-01	3.31E+09			
25	1	9.28E+09					1	9.28E+09		1	3.31E+09			
26														
27														

Figure 1: Table Date used for March Simulation

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