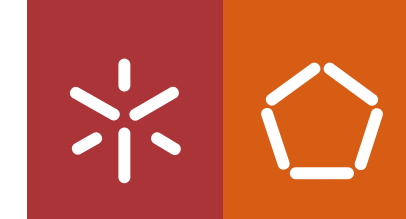


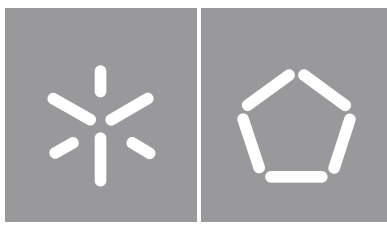


Berta Maria Durães Vaz da Silva

**Characterisation plan of fibrous
reinforcements for simulation of composite
materials production processes**

Universidade do Minho
Escola de Engenharia





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materials production processes**

Dissertação de Mestrado

Mestrado Integrado em Engenharia de Polímeros

Trabalho efetuado sob a orientação de:

Professor Doutor João Pedro Gil Nunes

Doutora Joana Mafalda Moura Malheiro

DIREITOS DE AUTOR E CONDIÇÕES DE UTILIZAÇÃO DO TRABALHO POR TERCEIROS

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A todos vocês, o meu mais sincero agradecimento!

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

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Resumo

Plano de caracterização de reforços fibrosos para simulação de processos de produção de materiais compósitos

O projeto desenvolvido foca-se na caracterização de reforços fibrosos e foi desenvolvido no Pólo de Inovação de Engenharia de Polímeros, no âmbito da conclusão do Mestrado Integrado em Engenharia de Polímeros realizado na Universidade do Minho.

A presente dissertação, baseia-se na adaptação de equipamentos ou metodologias de teste para o estudo do comportamento de reforços de fibra de vidro e carbono com diferentes estruturas durante o seu processamento, quer por infusão de resina assistida a vácuo quer por termofomação.

A primeira etapa deste projeto baseou-se na seleção das propriedades a ser estudadas que, neste caso, foram a deformação ao corte e a compressão. Seguindo-se de uma pesquisa preliminar, da elaboração dos casos de estudo e de um primeiro esboço dos planos de ensaio. A segunda etapa focou-se no estudo das propriedades em questão, as ferramentas necessárias, normas e procedimentos existentes. Daqui surgiram os primeiros desenhos dos acessórios para adaptação dos equipamentos disponíveis no PIEP aos testes pretendidos. Foram efetuadas simulações estruturais e foram fabricadas as versões finais dos acessórios.

A terceira etapa, e fase crucial do projeto, consiste na preparação e realização dos testes práticos. Destes foram analisados os resultados obtidos experimentalmente e comparados com os resultados teóricos calculados. Por fim, foram retiradas conclusões relativas ao trabalho elaborado e às variações dos resultados.

palavras-chave: compósitos de tecido entrelaçado, reforços fibrosos, drapeabilidade, deformação em viés, compactação

Abstract

Characterisation plan of fibrous reinforcements for simulation of composite materials production processes

The developed project is focused on the characterisation of fibrous reinforcements and was developed in PIEP, the Centre for Innovation in Polymers Engineering, in the scope of the Integrated Masters in Polymer Engineering accomplished at the Universidade do Minho.

The present dissertation is based on the adaptation of test equipment or test methodology to study the behaviour of different carbon and glass fabric reinforcements with different structures during their processing by vacuum-assisted resin infusion and thermoforming.

The first stage of this project was based on the selection of the properties to be studied which, in this case, were the bias deformation and the compression. This was followed by preliminary research, the elaboration of the case studies and the first draft of the test plans. The second stage focused on studying the properties in question, the necessary tools, standards and existing procedures. From here arose the first drawings of the different fixtures to adapt the equipment available at PIEP to the intended tests, structural simulations were performed, and the final versions of the fittings were manufactured.

The third and crucial stage of the project consisted of preparing and carrying out the practical tests. Afterwards, the results obtained experimentally were analysed and compared with the theoretical results calculated. Finally, conclusions were drawn regarding the work prepared and the variations in the results.

keywords: woven fabric composites, fibrous reinforcements, drapability, bias extension, compression

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List of Abbreviations

BET	bias-extension test.
CAD	Computer-Aided Design.
CRM	continuous random mat.
CT	computed tomography.
DEP-UM	Department of Polymer Engineering at Universidade do Minho.
FAST	Fabric Assurance by Simple Testing.
FE	Finite Element.
FR-PMC	Fibre-reinforced polymer matrix composites.
FRP	fibre-reinforced polymer.
HM	high modulus.
HS	high strength.
IAPMEI	Support Institute for Small and Medium Enterprises and Innovation.
IM	intermediate modulus.
NDT	non-destructive testing.
PAN	polyacrylonitrile.
PFT	frame test method.
PIEP	Centre for Innovation in Polymers Engineering.
PMC	polymer matrix composite.
PTFE	Polytetrafluoroethylene.
RTM	resin transfer moulding.
UHM	ultra-high modulus.

VARI	Vacuum Assisted Resin Infusion.
VARIM	Vacuum Assisted Resin Infusion Moulding.
VARTM	Vacuum Assisted Resin Transfer Moulding.
VBRTM	Vacuum Bag Resin Transfer Moulding.
VOC	volatile organic compounds.

Chapter 1: Introduction

1.1 Motivation

Nowadays, the most promising method to minimise defects and increase the efficiency of composite material parts design and manufacture process is through simulation tools. A useful simulation tool must accurately predict the behaviour of reinforcement materials when it conforms to the geometry of the mould. However, the accuracy of a simulation depends, to a large extent, on the material properties considered, and it is necessary to characterise the material properly.

In the production processes of composite materials, for example, thermoforming and Vacuum Assisted Resin Infusion (VARI), the final quality of the product is influenced by the resin behaviour and how the two-dimensional reinforcement material adapts to the three-dimensional geometry of the mould – drape. The ease with which the reinforcement adjusts to the mould depends on several properties, such as compressibility, bias distortion, bending, among others. However, the characterisation methods are often not adequate to the simulation software needs and the use of conventional equipment. Thus, to characterise the reinforcement materials, to feed the production process simulation software, PAM-Composites™, existing in PIEP, it is necessary to adapt and develop test methods and equipment accessories.

1.2 Introduction to PIEP

The Centre for Innovation in Polymers Engineering (PIEP) 1.1 is a private non-profit association with a significant technological and scientific matrix and a business management model that provides an excellent response to delivering products and services.

Located in the Azurém Campus of Universidade do Minho, PIEP is the result of an industry initiative in close collaboration with the Department of Polymer Engineering at Universidade do Minho (DEP-UM) and the Support Institute for Small and Medium Enterprises and Innovation (IAPMEI).

PIEP intends to respond promptly to the R&D+i needs of companies in the plastics and related sectors, developing new materials and supporting the creation of innovative products, processing technologies and productive tools based on promoting sustainable development principles. PIEP also makes a significant contribution in terms of training, supporting the development of human resources with practical skills in

industrial innovation processes in the field of polymer engineering.

One of PIEP's many objectives is to convert ideas into products, promoting the development of products either internally or by participating in consortia with national and international companies. Thus, the Centre's activities have been oriented to the most diverse sectors where polymer engineering is applied, namely automotive, aeronautics, space and defence, naval, railways, energy, construction, electronics, health, packaging and even footwear.



Figure 1.1: PIEP - Centre for Innovation in Polymers Engineering. [1]

1.3 Objectives

The dissertation aims to elaborate a test plan to characterise glass and carbon fibrous reinforcements, considering the properties that govern the conformation of this kind of material into a three-dimensional geometry. For the development of an adequate test plan, the following objectives are proposed:

- I. Study of the properties associated with drape (conformation into 3D geometry) of fibrous reinforcements in composite materials;
- II. Definition of the properties to be evaluated (case-study) and determination of the existing characterisation methods;
- III. Elaboration of the test plan for characterisation of reinforcement materials through the adaptation of equipment, the adaptation of existing standards and/or procedures, and definition of test conditions;
- IV. Test plan validation, through the implementation of the solutions developed in III in the characterisation of reinforcement materials.

The results obtained from the developed test plan should adequately feed the simulation software PAM-Composites™, in order to accurately predict the production process of composite material parts.

1.4 Dissertation structure

This work is organised into five chapters:

Chapter 1 – Introduction, presents the motivation that gave origin to the present study, its objectives, and a succinct company introduction.

Chapter 2 – Literature review and Chapter 3 – State of the art, serve as background chapters. The second chapter provides a theoretical contextualisation of the materials and production processes studied and the conformation of continuous fibre reinforcements in three-dimensional shapes. The third chapter presents an overview of the state-of-the-art on the subject of deformation phenomena and properties of interest to the study.

Chapter 4 - Experimental work, provides a description of the samples, equipment and experimental procedures used for each study.

Chapter 5 - Results and discussion, presents the results obtained from the performed tests and respective discussions.

Chapter 6 - Conclusion, contemplates the overall conclusions of this project and provides future work proposals to continue this investigation.

Finally, this dissertation ends with the presentation of extra information in the Appendix section.

Chapter 2: Literature Review

2.1 Fibre-reinforced polymer matrix composites

Fibre-reinforced polymer matrix composites (FR-PMC) are used in many applications, ranging from aerospace to automotive, industrial and consumer products. The high stiffness-to-weight ratio, low electromagnetic reflectance, and the ability to embed sensors and actuators have made FR-PMC an attractive alternative material. In many other cases, fibre-reinforced polymer composite materials are being developed and used to replace metal components. [2]

A polymer matrix composite (PMC) is a multiphase system of two or more constituent materials with significantly different properties (Figure 2.1) [3, 4]. They are composed of a polymer matrix, which is the continuous phase surrounding the dispersed fibres (reinforcing material); hence, they are often called a fibre-reinforced polymer (FRP) [4, 5]. The matrix spreads the load applied to the composite between each of the individual fibres and protects them from damage caused by abrasion and impact, making the fibres the main load-bearing component [6, 7].

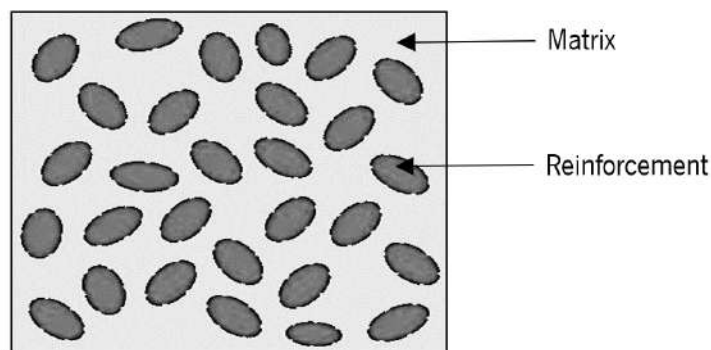


Figure 2.1: Schematic representation of a composite's structure. Adapted from [8].

When the fibre and matrix are joined to form a composite, they remain separate and distinct within the finished structure, retaining their identities and, when combined acquiring unique characteristics that the raw materials individually do not possess [3, 4, 9]. Properties such as high strength and stiffness, ease of moulding complex shapes, high environmental resistance, and low density make the FR-PMCs ideal for many applications. Overall, the final composite properties are determined by both fibres and polymer properties, fibre ratio to polymer, and fibre geometry and orientation (examples illustrated in Figure 2.2) [7].

In a PMC, the matrix can be either a thermoplastic or a thermosetting polymer. The two alternatives differ in manufacturing, processing, and final product properties [9]. As reinforcement, glass fibres, carbon and/or aramid fibres are among the most common. They can be either continuous or discontinuous in length and arranged in many orientations (unidirectional, bidirectional, multidirectional, or completely random) [5].

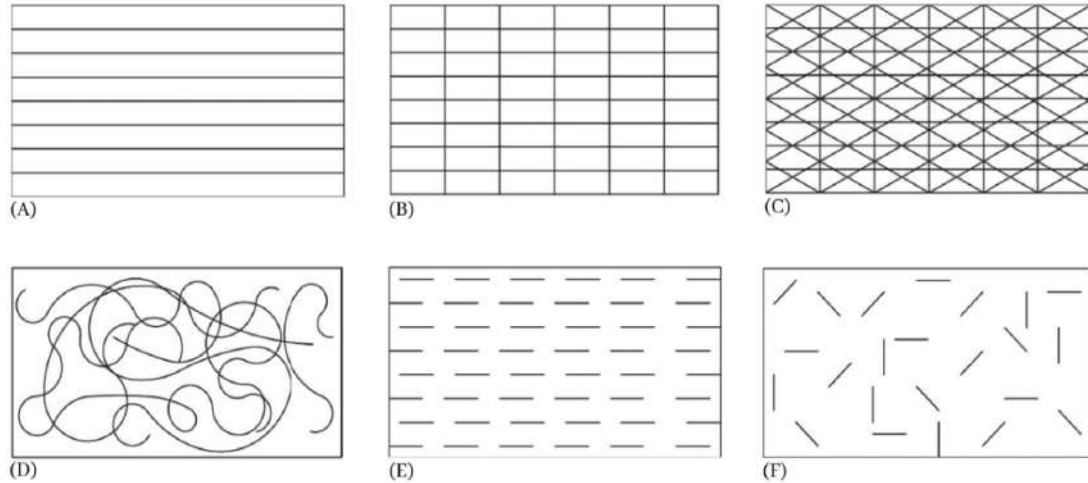


Figure 2.2: Schematic representation of fiber orientation in PMCs: (A) unidirectional, continuous; (B) bidirectional, continuous; (C) multidirectional, continuous; (D) random, continuous; (E) unidirectional, discontinuous; (F) random, discontinuous. Adapted from [5]

A lamina is a typical sheet of composite material, and it represents a fundamental building block. In many applications, FR-PMCs are used in laminated form. A laminate is a collection of laminae stacked to achieve the desired stiffness and thickness according to the design and structural requirements. The stacking sequence is the order in which the laminae with different fibre orientations are stacked, and it is designed to obtain the desired laminate properties. A fibre-reinforced lamina can be stacked so that the fibres in each lamina are oriented related to the axial or y-direction (Figure 2.3). Any fibre direction angle can be used, but this results in a very complex fibre architecture and layup, so 0° , 90° , $+45^\circ$ and -45° are the most common. The layers are usually bonded together with the same matrix material as in the lamina. [5, 10, 11]

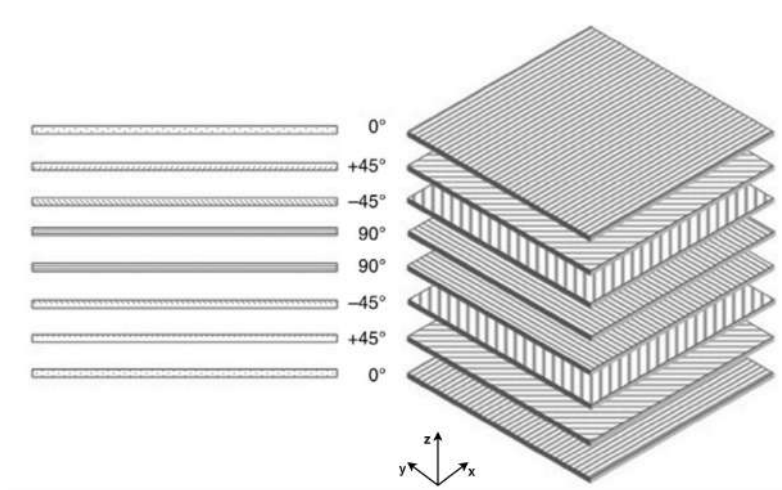


Figure 2.3: Diagram of a symmetrical and balanced laminate. Layup: $[0/+45/-45/90/90/-45/+45/0]$. Adapted from [11]

When constructing a laminate, the layup can be both symmetrical and balanced. Meaning that the lamina fibre direction pattern is mirrored about the midplane of the laminate, preventing it from warping and bending. A balanced laminate comprises an equal number of $+\theta$ and $-\theta$ plies, reducing shear coupling. [11]

2.1.1 Thermoplastic and thermoset matrices

There are two alternates in PMCs' matrix selection associated with their different structures: thermoplastic and thermoset, each presenting many matrix choices. The main difference between the two is that thermoplastic materials can be repeatedly softened by heat, and thermosetting resins cannot be changed after the curing chemical reaction has been completed. [9, 10]

Thermoplastics can be seen as ensembles of randomly packed and entangled linear chains. Their mobility depends on the molecular build-up in molecular weight, the nature of the repeating units, among other factors, whilst thermosets are covalently bonded networks with all polymer segments present being attached to one giant macromolecule under ideal conditions [10]. Figure 2.4 presents a scheme of the physical structure of thermoplastic and thermosetting polymers.

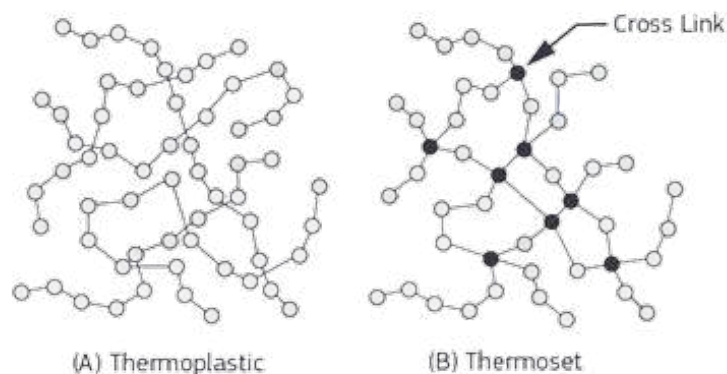


Figure 2.4: Schematic representation of thermoplastic (A) and thermoset (B) polymers' structure. Adapted from [12]

Thermoplastic polymers can be moulded, melted, and remoulded without altering their physical properties or severe damage, allowing reprocessing and recycling. They readily flow under stress at elevated temperatures, allowing them to be fabricated into the required component, become solid and retaining their shape when cooled to room temperature [13–15]. Thermoplastic matrices offer the potential to reduce the cycle time for fabricating structural composites and expand the options for rapidly forming parts after lamination [16].

Raw thermoplastic resins are solid at room temperature, but a physical change occurs when heat and pressure are applied; however, it is not a chemical reaction and does not result in permanent, non-reversible change. It is difficult to impregnate the thermoplastic resin within the reinforcing fibre structure because of its solid natural state. First, heat and pressure are applied to both fibres and matrix up to the resin melting point; afterwards, the composite needs to be cooled while still under pressure. Thermoplastic matrix composites are more rigid, less brittle, and less dense than thermosets, with excellent impact resistance and damage tolerance. [13, 17]

The advantages of thermoplastics and the reasons they are often considered in high-performance applications, despite the difficulty of processing, are their high strain to failure, increased fracture toughness, better impact tolerance, short processing cycle time, shelf life, recyclability, and reparability. However, the most significant advantage of thermoplastics may lie in their potential for rapid, low-cost, mass production of reinforced composites. [5, 18]

Traditional FR-PMC uses a thermosetting resin as the matrix that holds the structural fibre firmly in place. In a thermoset resin, the uncured resin molecules are crosslinked through a catalytic chemical reaction, most often exothermic. The molecules create solid bonds with one another, changing the resin state from liquid to solid. These composites are strong and have excellent fatigue strength. They are extremely brittle and have low fracture toughness values. A thermosetting resin, once catalysed, cannot

be reversed or reshaped, meaning that its shape cannot be altered once the composite is formed. When reheated, they can degrade and might burn. Thus, it is challenging to recycle and, depending on the process, only the reinforcing fibre used can be reclaimed. [13–16]

A majority of continuous FRP matrix composites contain a thermoset as the matrix. The principal reason for this is their very low viscosity when the fibres are incorporated into them. Other reasons for selecting thermosets as matrix are their higher thermal stability, higher creep resistance, and better chemical resistance than thermoplastic polymers. [5]

2.1.2 Continuous fibre reinforcements

In composite materials, the reinforcement phase can be found in many forms, such as particles, fibres, or sheets. The predominant form of reinforcement material in PMCs is fibrous, existing a wide range of fibres available that can vary by length, arrangement, and material type.[11, 15]

Fibres can be considered short, long, or continuous. Continuous fibres are geometrically characterised as having a very high length-to-diameter ratio. Their length runs the entire length of the manufactured part, and they are generally more robust and stiffer than bulk material [11]. Continuous fibre composites usually have a preferred orientation and can be combined into more complex structures. Examples of continuous reinforcements include helical winding (roving and tow), braids and fabrics. [19, 20]

Roving is the simplest and most common form of fibre structure. It can be chopped, woven or otherwise processed to create secondary fibre forms for composite manufacturing, such as mats, woven fabrics, braids, knitted fabrics and hybrid fabrics. Rovings are supplied by weight, with a specified filament diameter. Similarly, the tow is the basic form of carbon fibre. Both of them are continuous filament strings helically winded. [21, 22]

Mats are non-woven fabrics made from randomly distributed fibres and aggregated with an emulsion or powder binder that provides stability and must be soluble in impregnation. Continuous mats are designated by continuous random mat (CRM); they provide better conformability and better properties of the composite because their fibres are randomly oriented, mats are isotropic — they possess equal strength in all directions. [7, 22]

In polymeric composite terms, a fabric is defined as a manufactured assembly of long fibres to produce a flat sheet of one or more layers of fibres. These layers are held together with the mechanical interlocking of the fibres themselves or using a secondary material to bind them together and hold them in place, giving the assembly sufficient integrity to be handled. [7]

Fabric types are categorised by fibre orientation and the various construction methods used to hold

the fibres together. The main fibre orientation categories are: unidirectional, woven and multiaxial.

- i. Unidirectional fabrics – A unidirectional (UD) fabric is one in which most fibres run in one direction only. Authentic UD fabrics offer the ability to place fibre in the component exactly where it is required and in the optimum quantity. [7, 22]
- ii. Woven fabrics – Woven fabrics are produced by the interlacing of warp (0°) and weft (90°) fibres in a regular pattern or weave style. The mechanical interlocking of the fibres maintains the fabric integrity. Drape (the ability of a fabric to conform to a complex surface), surface smoothness and stability of a fabric are controlled primarily by the weave style [7, 11]. Following are some of the more commonly found weave styles (Figure 2.5):
 - a. Plain – Each warp passes alternately under and over each weft fibre. The fabric is symmetrical, with good stability and reasonable porosity. However, it is the most difficult of the weaves to drape, and the high level of fibre crimp imparts relatively low mechanical properties compared with other weave styles. [7, 22]
 - b. Twill – One or more warp fibres alternately weave over and under two or more weft fibres in a regular repeated manner. Superior wettability and drape are seen in the twill weave over the plain weave with only a slight stability reduction. With reduced crimp, the fabric also has a smoother surface and slightly higher mechanical properties. [7, 22]
 - c. Satin – Satin weaves are fundamentally twill weaves modified to produce fewer intersections of warp and weft, allowing fibres to be woven in the closest proximity. Satin weaves are very flat, have good wettability and a high degree of drape. The low crimp gives good mechanical properties. However, its low stability and asymmetry need to be considered when assembling multiple layers of these fabrics to ensure that stresses are not built into the component. [7, 22]
 - d. Basket – Basket weave is fundamentally the same as plain weave except that two or more warp fibres alternately interlace with two or more weft fibres. It is flatter and, through less crimp, stronger than plain weave but less stable. [7]

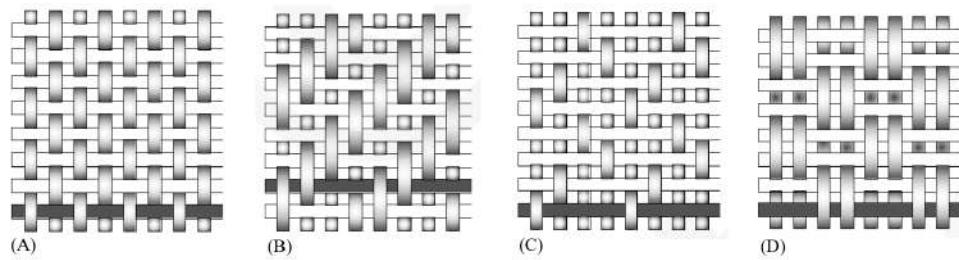


Figure 2.5: Woven fabrics examples: (A) plain; (B) twill; (C) satin; (D) basket. Adapted from [7].

- e. Hybrid fabrics – The term hybrid refers to a fabric with more than one type of structural fibre in its construction. It is possible in a woven hybrid to have one fibre running in the weft direction and the second fibre running in the warp, but it is more common to find alternating threads of each fibre in each warp/weft direction. In a multi-layer laminate, if low weight or thinness are required, a hybrid fabric allows the two fibres to be presented in just one layer of fabric. The most usual hybrid combinations are carbon/aramid, aramid/glass and carbon/glass. [7, 22]
- iii. Multiaxial fabrics – These fabrics consist of one or more layers of long fibres held in place by a secondary non-structural stitching thread. The main fibres can be any of the structural fibres available in any combination. The stitching thread is usually polyester due to its combination of appropriate properties to bind the fabric together and cost. The stitching process allows various fibre orientations to be combined into one fabric beyond the simple 0/90° of woven fabrics. Stitched multiaxial fabrics provide better mechanical properties because the fibres are always straight and non-crimped and that more orientations of fibre are available from the increased number of layers of fabric. Also, improved component build speed because fabrics can be thicker and with multiple orientations so that fewer layers need to be included in the laminate sequence. [7, 21]

The most common types of fibre material used in PMCs are carbon, glass and aramid. To a lesser degree, basalt fibres, natural fibres and self-reinforcing fibres can also be found as reinforcements [5, 11]. The reinforcement is selected accordingly to the mechanical properties required for the composite, being fibres the main load-carrying member in an FR-PCM [5]. The general characteristics of glass and carbon fibres are briefly discussed below.

- i. Glass fibres – Glass fibres are the most common type of reinforcement used in PMCs; they generally have good specific strength and stiffness properties and are inexpensive. Glass fibre is made by melting the constituent materials together (silica, kaolin, limestone, colemanite) and drawing the

melt into a fibre. They have a diameter of 5–25 μm and are coated with a "size" to improve the adhesion with the matrix material. Due to their low cost, glass fibres are typically used to reinforce large structures such as wind turbines blades and boat hulls. [7, 11, 22]

The predominant constituent of glass fibre is silica (silicon dioxide, SiO_2), or sand; however, there are different types of glass fibre, each with slightly different compositions and properties:

- a. E-glass (electrical) – Is the most commonly used fibre in PMCs. It has good tensile and compressive strength and stiffness, good electrical properties and relatively low cost, but impact resistance relatively poor. [7, 11]
 - b. C-glass (chemical) – They have the best resistance to chemical attack and are often used on the surface as an outer layer of pipes and tanks rather than as a reinforcement. [7, 11]
 - c. R, S or T-glass (stiffness) – This type of glass fibre has improved mechanical and thermal properties, having higher tensile strength and modulus than E-glass, with better wet strength retention. These fibres are developed for aerospace and defence industries; this and low production volumes mean a relatively high price. The terminologies (R, S, T) are manufacturers trade names; they vary according to where they are produced. [7, 11]
- ii. Carbon fibres: When considering the widely used reinforcements, carbon fibre is the most expensive but has the best specific stiffness properties. Carbon fibres are produced by the controlled oxidation, carbonisation and graphitisation of carbon-rich organic precursors already in fibre form. The most common precursor used to manufacture carbon fibres is polyacrylonitrile (PAN) because it gives the best carbon fibre properties, but fibres can also be made from pitch or cellulose. Once formed, the carbon fibres have a surface treatment applied to improve matrix bonding and chemical sizing, protecting them during handling. [7, 11]

Carbon fibre is available in different grades, categorised by the modulus range in which their properties fall. These ranges are referred as high strength (HS), intermediate modulus (IM), high modulus (HM), and ultra-high modulus (UHM). Although carbon fibres have the highest specific stiffness, very high strength in tension and compression, and high resistance to corrosion, creep, and fatigue, their impact strength is lower than either glass or aramid [7, 11, 22]. Due to their high cost, carbon fibres are typically used in aerospace and high-end automotive applications [11].

2.2 Composite materials production processes

2.2.1 Vacuum-assisted resin infusion

In the literature, vacuum infusion is known under different acronyms: Vacuum Assisted Resin Transfer Moulding (VARTM), Vacuum Assisted Resin Infusion Moulding (VARIM), Vacuum Bag Resin Transfer Moulding (VBRTM), Vacuum Assisted Resin Infusion (VARI) process and so on. All involve the same technology and describe methods based on the impregnation of a dry reinforcement by a liquid resin driven under vacuum. [23]

The vacuum-assisted resin infusion is a closed-mould process capable of manufacturing high-performance and large scale FR-PMCs parts with low tooling cost. The process combines the benefits of high quality, repeatability and clean handling of the resin transfer moulding (RTM) process with the advantage of flexibility and scalability of open-mould hand layup processing. VARI processes are widely used in the marine, energy, infrastructure building, aerospace and defence industries. [23]

In a VARI process, the vacuum pressure is used to provide the compressive pressure against the reinforcement assembly that is sealed and sandwiched between the bagging film and the mould tool, as shown in Figure 2.6. At least two ports are included in the bag, one for the resin supply (at atmospheric pressure) and one for a vacuum pump. The pressure difference between the vacuum and the atmospheric pressure, nearly 1 atm (assuming there are no leaks in the assembly), is used to compress the fabric, secure it against the mould and draw the resin through it, resulting in a high fibre content composite. The curing generally takes place at room temperature, and once it is entirely into the solid state, the composite part is demoulded. [11, 23, 24]

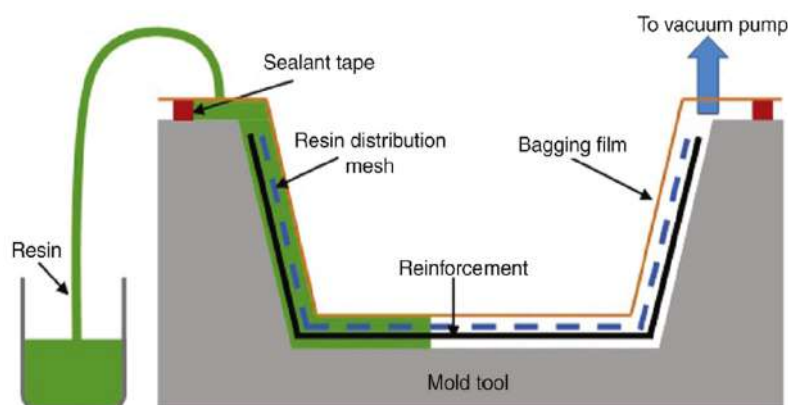


Figure 2.6: Vacuum-assisted resin infusion diagram. [11]

For a large or complex composite part (with inserts, hybrid fabric systems, co-cured parts), the process

can be intricate, and it can be challenging to produce consistent parts with no dry areas; consequently, multiple injection lines and vents could be used to improve the resin infusion. The flow distribution medium layer could also be placed in different patterns to create versatile resin infusion paths that can promote the resin infusion quality of a large or complex composite part. [11, 23]

VARI presents advantages such as flexible mould tooling design and selection of mould materials; the mould can be easily modified for manufacturing different part geometries; the ability to manufacture large and complex composite parts with good quality; the low volatile organic compounds (VOC) emission and, finally, visible dry spots can be easily removed by inserting a vacuum needle and drawing the air out. [23, 25]

2.2.2 Thermoforming

The use of the thermoforming process for smaller scale, higher volume applications is a highly efficient manufacturing method for polymer-based products. Thermoforming of polymeric sheets is widely used in the industry for many applications; it enables the rapid transformation of semifinished raw material into the required design form by combining heat and pressure. Relative short forming times are possible by the fast processing potential of thermoplastics. [26, 27]

Due to the geometries of thermoformed products being usually simple, one of the main applications is packaging production since the lowest thicknesses of walls can be easily achieved [27]. Thermoforming of PMCs is used for car structures manufacturing because it is a fast process, and the continuous reinforcements give good material properties [28].

The first stage of thermoforming involves heating the pre-consolidated laminate to a temperature above the melting point of the thermoplastic matrix system, which brings a substantial decrease in the stiffness of the sheet [27, 29]. By applying pressure or vacuum, the softened sheet is deformed into a male mould (positive forming) or a female mould (negative forming) (Figure 2.7) [27, 30]. During the contact with the mould, heat is lost, the temperature of polymer decreases and the material regains stiffness as it cools [27, 30]. When compared with injection moulding, thermoforming can be used for relatively small production series and, it is a more financially viable alternative for larger parts with lower volume. In addition to significantly reduce prototype and production tooling costs, thermoforming provides a much faster product development time because of the simplicity of the process and low equipment costs. [27, 31]

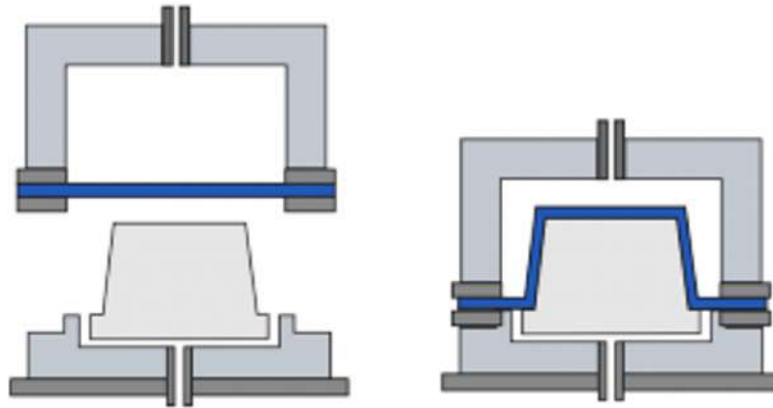


Figure 2.7: Thermoforming diagram. [32]

The main advantages of this process are the relatively low cost of thermoforming machines and the very low cost for the moulds, and it is easy to form large-area thin section parts. There are some disadvantages such as limited product shapes, difficulties in obtaining the required thickness distribution, and limitations in service temperature, which may induce strain recovery or shrinkage. [30]

2.3 Drapability

According to British Standards, fabric drape is defined as the ability of fabric (a circular specimen of the fabric of known size) to deform when suspended under its weight under specified conditions. Fabric drapability is dependent on variables such as fabric properties, object shape over which it is draped and environmental conditions. In composite materials, drapability refers to the ability of a fabric to conform to the surface of a mould. [33, 34]

Researchers have worked on interpreting drape by quantitative methods. The significance and importance of quantitatively analysing, understanding and measuring drape are increasingly becoming realised by researchers and workers in the industry. It is important to find a reliable, efficient, and accurate method to measure this attribute and properly reflect real fabric drape characteristics. Understanding drape using measured parameters can help evaluate and ensure the intended appearance of the final product and improve computer simulation. [33]

Generally, there are two approaches employed to evaluate drape, either (1) objectively by measuring either physical and mechanical properties related to drape, namely shear, bending and weight or drape values on a drapemeter; or (2) subjectively to relate it with the end-use product. [33]

The textile draping process remains one of the most critical steps in the production of FR-PMCs. In the draping process, the two-dimensional, flat textile is adapted to a 3D geometry, which induces shear

deformations and, thus, changes in local yarn orientation. Since the reinforcement yarns bear the load in fibre-reinforced composites, these changes in yarn orientation can profoundly influence the mechanical properties of the finished part. [32, 35]

Furthermore, high shear angles reduce the infusion permeability of the preform, thus further increasing the need for adequate control and monitoring of the draping process [32]. Owing to the anisotropy and discontinuity of the fabrics and the considerable difference in load-bearing capacity for tensile and compressive loads, the measurement of shear properties is more complex than for many other materials [36, 37].

As there are many composite materials, possible fabric woven architectures, and changes in tooling conditions, the development of high-quality forming processes is necessary but can be difficult. A way to understand the draping process can be through numerical simulations of the composite forming process, giving an initial validation of the feasibility of the process, determination of suitable parameters and prediction of potential defects and problematic regions. This method helps avoid a time-consuming and costly "trial and error" development. [38, 39]

Chapter 3: State of the Art

3.1 Shear properties

Characterisation of the shear resistance is needed to accurately predict the fabric draping during forming of a 3D-shaped composite part. Throughout the manufacture of composites parts to create complex geometries, in-plane tension is generally used to mitigate process-induced defects such as wrinkling and, to some degree, to control the final fibre orientation distribution across the component after forming [40–42]. Tension is controlled through boundary conditions applied to the perimeter of the material using a blank-holder or using springs [42, 43]. The shear compliance of dry woven engineering fabrics is related to the in-plane tensions acting along the two sets of tows within the fabric [44, 45]. This can be intuitively understood due to the increased normal forces acting between overlapping tows (weave crossovers), increasing internal sliding friction during the fabric deformation. [46–48] Thus, for these materials, blank-holder conditions applied during the forming process are expected to change the material's shear compliance and the fabric's forming response, such as its propensity to wrinkle [45, 49].

The development of design tools to improve efficiency in manufacturing is an ongoing process, and the rapid increase in affordable computational power is making this approach ever more relevant. Various techniques for modelling textile composites' forming process have been proposed, including kinematic [50] and Finite Element (FE) simulations [40, 41, 47, 48]. The former has the advantage of being fast and easy to use while the latter is more computationally expensive and requires greater user-expertise but is generally considered the more accurate method of the two due to its ability to include realistic boundary conditions and material behaviour [43, 51].

The fibre volume fraction in the final composite part obtained by thermoplastic thermoforming can be high. The forming process must be performed at a temperature close to or higher than the resin's melt temperature to render the textile reinforcement deformation possible. The manufacturing of double-curved parts requires in-plane shear deformations (change of direction of the warp and weft yarns) of the composite prepreg to conform to the shape. [52, 53]

Depending on the geometry of the final composite parts, on the reinforcement type (weaving, properties of fibres) and manufacturing parameters (tool loads, blank holder, temperature), double-curved shape manufacturing may lead to defects (wrinkling, porosities, fibre fracture). Simulation software for compos-

ites forming has been developed to predict the conditions for the process feasibility and optimise the main forming parameters [53]. These software packages need the mechanical behaviour of the composite ply during forming. As finite shell elements generally model this ply, the mechanical behaviour of the prepreg ply during forming is given by the biaxial tensile properties [54–57], the in-plane shear properties [49, 58–69] and the bending properties [70–72]. In-plane shear is the predominant deformation mode, and the in-plane shear properties are very important for forming simulation. In the case of thermoplastic prepreg forming, the in-plane shear behaviour must be measured at high temperatures because the forming is performed above the melt temperature of the matrix. Many works have been done concerning the in-plane shear properties of textile reinforcements at room temperature. [61–63, 65–69]

Intraply shear (trellis) deformation of the laminate's individual plies has been recognised as the dominant deformation mode for shaping regions of a part where a three-dimensional deformation of the fabrics is required, such as at corners or over spherical regions. Experimental methods used to characterise the trellis shear deformation allow for the determination of four critical material parameters known as the pre- and post- locking shear modulus, the shear angle and the intraply shear viscosity of the fabric, all measured above the melt temperature of the polymer matrix and during cooling. [60, 73]

For a given reinforcement, there is a limit to shear angle. Over this value, wrinkling appears [40, 49, 74, 75]. This limit, known as “locking angle”, depends on textile reinforcement properties, although there is no direct relation between shear angle and wrinkling. Wrinkling is a global phenomenon depending on all strains and stiffnesses and on boundary conditions. [40] Because in-plane shear is the main deformation mode of textile reinforcement during forming, it is the most studied property of textile composite reinforcement. It is essential data for draping simulations. [76–80]

Studies on experimental fabric in-plane shear behaviour began in the sixty's with the works of Lindberg [81] and Grosberg [82, 83]. The physical phenomena during in-plane shear, such as contact and friction between the yarns, are related to shearing properties. Spivak introduced in 1968 the “test of bias-extension” as a relatively simple test that can be compared to “rather sophisticated instrumental or experimental methods” that have been previously used to analyse in-plane shear properties [84]. Nevertheless, the geometry and the resulting kinematics of the test are not yet specified. Skelton determines the limit shear angle from the fabric and yarns geometry [85]. McGuinness and O. Bradaigh experimentally analyse the shearing of fabric reinforced thermoplastic sheets using a picture frame test [86]. This picture frame test is one of the two main experiments used to measure textile reinforcement properties. The bias-extension test is the second one. The description of the bias-extension test with its specificities, the specimen's geometry, and the different shear zone were made by Wang et al. in 1998 [87].

The picture-frame (trellis-frame) and bias-extension tests are the two experimental tests mainly used for in-plane shear characterisation of composite reinforcements and prepregs [69]. Some other tests have been proposed in which a rectangular fabric specimen is clamped on two opposite edges that prescribe an in-plane shear deformation to the specimen [81, 83, 88]. In these tests, the specimen is generally subjected to shear and tensions. To avoid tensions, a rigid bar can be added to the two free edges. In this case, the test is close to the picture frame. A shear test using torsion has been recently proposed to analyse UD prepregs (limited to minor shear strains). However, their mechanical behaviour is specific because of the lack of cohesion in the direction normal to the fibres [89].

A substantial advantage of the uniaxial bias-extension test is that the yarns of the sheared zones are free at their edge (at least one), and consequently, there is no tension in the yarns (or only minimal tensions due to the warp-weft interactions). In the picture frame, all the yarns are clamped in the frame, and any misalignment of the specimen leads to an increase of the measured load. Several comparison studies have been performed [60, 64, 67, 90].

Some researchers have tried to characterise the wrinkle and fibre paths from ideal trajectories in the composite materials by applying non-destructive testing (NDT) methods [91–105]. These methods are such as the eddy current at 2D and 3D [92, 94–96], X-ray computed tomography (CT) [93], ultrasonic techniques [97, 98], and image processing method [99–105]. In this regard, one of the most accessible and economical methods is the image processing method. [99]

For example, the shear–tension coupling and wrinkling of the woven engineering fabrics were investigated by Harrison et al. [45] and Nosrat-Nezami et al. [100]. Further, Alsayednoor et al. [101] addressed the impact of two testing error sources, namely, the pre-tension and wrinkle, on the accuracy of the uniaxial bias extension test results. They used three-manual, 2D and 3D digital image correlation methods to measure the shear angle and compare it to the calculated one. In one other study, a new setup was devised by Harrison et al. to improve the uniaxial bias extension test accuracy by applying an anti-wrinkle apparatus [102]. They also used the image processing technique to characterise the new setup results. Based on this setup, the out of plane wrinkles was found to be decreased during the tests. This could be regarded as a reason for such errors. Then, the obtained results were compared with their analytical counterparts [102]. Rashidi and Milani proposed a new method for decreasing the out of plane effects in wrinkling and de-wrinkling characterisation of the woven fabrics. It was so-called the multi-step biaxial bias extension test. The method enables forming and flattening wrinkles of different sizes and providing insight into de-wrinkling mechanisms. They showed a positive effect on decreasing the wrinkling behaviour of the woven engineering fabrics during the test [103]. Moezzi et al. [104, 105] also focused on charac-

terising woven engineering fabrics wrinkling behaviour with local non-uniformity by employing the image processing method. It was shown that local non-uniformity could be regarded as one of the most critical parameters in wrinkle onset and intensity. [91]

Measuring the in-plane shear in a textile material is difficult because the in-plane shear stiffness is slight compared to tensile stiffness. Consequently, any spurious tension during a test strongly perturbs the in-plane shear analysis. Therefore, one main advantage of the bias-extension test lies in the absence of spurious tensions in the yarns of the sheared zones. Another advantage is its relative simplicity and moderate size, and this factor is essential when the test is performed at a high temperature in an oven. [106]

An international benchmark has been launched to compare the experiments and results obtained by different laboratories on different composite reinforcements using both picture frame and bias-extension tests [69]. This benchmark has proved valuable because the materials and the tests are very different regarding continuous materials such as polymers or metals. Furthermore, it has been shown that the determination of the shear angle from the crosshead displacement is correct until $30\text{--}35^\circ$. Beyond this value, the direct measurement of the shear angle by optical methods is necessary. Finally, the benchmark has shown that standardisation methods are helpful to obtain shear properties that can be used in numerical simulations. [69, 106]

3.1.1 Bias extension test

The conventional bias-extension test (BET) is a relatively simple experiment involving a uniaxial extension of relatively wide textile samples aiming to determine the in-plane combined shearing and the tensile response of textile composite materials to testing displacement and velocity. [60, 87, 106–108]

The BET requires clamping a rectangular piece of woven material cut at the bias direction such that the warp and weft directions of the tows are orientated initially at 45° to the direction of the applied tensile force and subjected to a load elongation test. [64, 109]

Schematics in Figure 3.1 show respectively an undeformed and a deformed bias-extension specimen. The ratio between the initial length and width of the specimen is defined as aspect ratio: $\lambda = L_0/w_0$. For the three distinct shearing zones to exist, A , B and C in Fig. 3.1, the length, L_0 must be at least twice the width, w_0 . [60, 64]

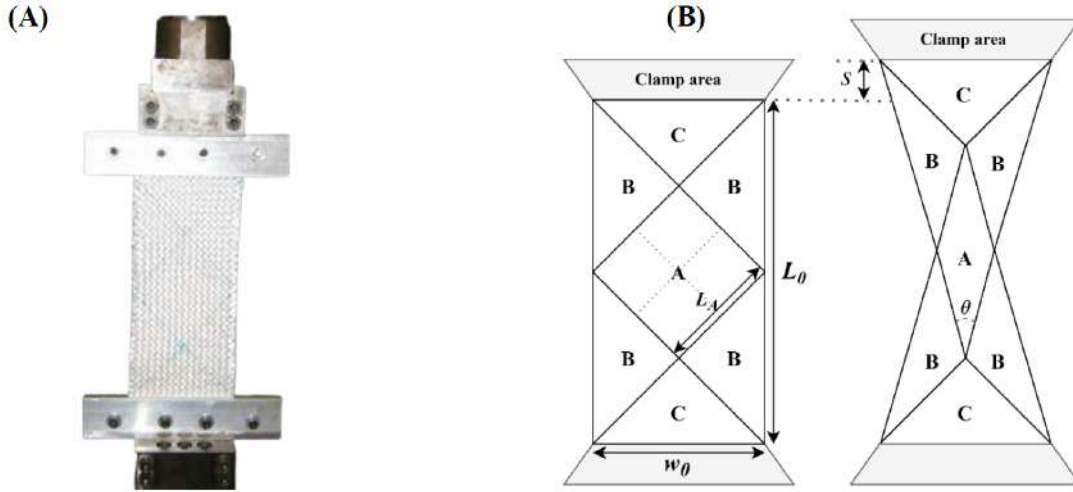


Figure 3.1: Bias extension test: (A) experimental setup [45] and (B) schematic representation of the test specimen showing the undeformed (left) and deformed (right) shapes of the specimen in the bias extension test where $\lambda = 2$.

With the clamping plates at each extremity of the specimen, both warp and weft yarns have a clamped end, so zone *C* remains undeformed throughout testing and does not contribute to the shear force. In central zone *A*, the warp and weft yarns have free ends, the non-sliding at crossovers, and the stretching of the specimen lead to a pure shear deformation depending on *s* (3.1). In zone *B*, the stretching of the specimen leads to a shear strain of a value half of that of zone *A*. [64, 106, 107]

Two relations are necessary to analyse the results of an in-plane shear test: a kinematic relation that relates the in-plane shear angle to the extension of the specimen and a relation between the shear stress in the fabric and the measured force on the tensile machine [106]. To establish these relations, the following assumptions are made:

- yarns are inextensible (more precisely, their elongation is null in the bias-extension test);
- there is no slippage between warp and weft yarns at the cross over points;
- bending stiffness of yarn is neglected.

These assumptions correspond to those of the “kinematical models” or “fishnet algorithm” used for fabric draping simulations based on geometry [110–112]. The two relations of the bias-extension tests (kinematic relation and shear load versus force on the tensile machine) have been established gradually [60, 67, 69]. The first one is the relation between the shear angle θ in the central zone *A* and the length of the stretched specimens [53, 106]. Based on the deformation mode presented, the shear angle in zone *A* can be calculated by [64]:

$$\theta = \frac{\pi}{2} - 2 \arccos \frac{w_0 + s}{\sqrt{2}w_0} \quad (3.1)$$

Where s is the tensile displacement, the shear angle in zone B is $\theta/2$. Increasing λ to higher values results in a larger area of region A . To detect the critical shear angle at slippage, the result variation of Equation 3.1 is monitored compared with the measured one during the test, and the divergence between these two is regarded as the onset of inter-yarn slippage. For bias extension tests with $\lambda = 2$, the side length of region A (L_A) is used to normalise force, displacement and displacement rates. [64, 107]

The shear angle θ can also be measured directly by an optical measure using a DIC (Digital Image Correlation) [68, 69, 113]. This optical method is well suited for measuring textile materials for which sensors in contact with the fabric are difficult to use. A DIC analysis obtains the displacement field within the yarn at different stages of the shear test. [106]

An energy argument is utilised to normalise the test data for different sizes of specimens in bias extension. Assuming that after matrix melting, the textile composite deforms as a “constrained Newtonian fluid”, the energy argument leads to the following relationship [114]:

$$\frac{\lambda - 1}{R(2\lambda - 3 + 2X)} \times \frac{F}{L_0} = \text{constant} \quad (3.2)$$

where F is the external force and

$$X = \frac{1}{4} \times \frac{\cos^2 \theta [1 + 3 \sin^2 \frac{\theta}{2}]}{\cos^2 (\frac{\theta}{2}) [1 + 3 \sin^2 \theta]} \quad (3.3)$$

and

$$R = \frac{s}{(\lambda - 1) \times L_0} \quad (3.4)$$

The error introduced by the non-Newtonian response becomes more significant as R diverges from 1. However, the above analysis holds only when the sample follows the idealised kinematics shown in Figure 3.1. It is a reasonable approximation for small shear angles but fails at the large shear stage because of the onset of inter-yarn slippage. [107]

The bias extension test is simple to perform, and it is not so significantly affected by the boundary conditions as long as the material sample is tightly clamped; thus, it provides more repeatable and reliable results. The main advantage of the test is a useful measurement of the critical shear angle before inter-yarn slippage happens. [64, 107]

However, it suffers from some limitations: the shear angle and angular shear rate in the material must be measured by time-consuming visual analysis; the deformation field within the material is not homogenous, preventing simple rheological analysis of the results and, the test induces a combination of

both pure shear and intra-ply slip. [64, 109]

3.1.2 Biaxial bias extension test

The biaxial bias extension test is a novel testing technique developed to investigate the shear–tension coupling and fabric wrinkling, combining the advantages of the picture frame and bias extension methods. [45, 109]

Biaxial bias extension testing is shown to be an accurate method of characterising wrinkling onset and fabric shear compliance versus in-plane tension for woven biaxial engineering fabrics. Such characterisation is challenging to conduct using regular picture frame or uniaxial bias extension tests. The technique requires a simple experimental setup, and analysis can be performed using image analysis software. [45]

The biaxial shear test is a modification of the bias extension test by incorporating a transverse load (Figure 3.2). Despite the difference in the longitudinal and transverse clamps lengths shown in Figure 3.2-A, the specimens are attached along the same fraction of the perimeter length on either side of the specimen, as indicates the yellow lines drawn along the clamp lengths. The fabric must be cut along the remainder of the specimen perimeter and therefore unconstrained along these edges. The effective specimen clamping areas are shown in Figure 3.2-B.

Weights are used to apply a constant transverse force to the fabric. By performing several tests with different transverse loads, it is possible to characterise the shear resistance of the fabric as a function of fibre tension. The contribution to the measured force due to the transverse load is easily subtracted from the recorded signal, leaving just the material response. [43, 45, 109]

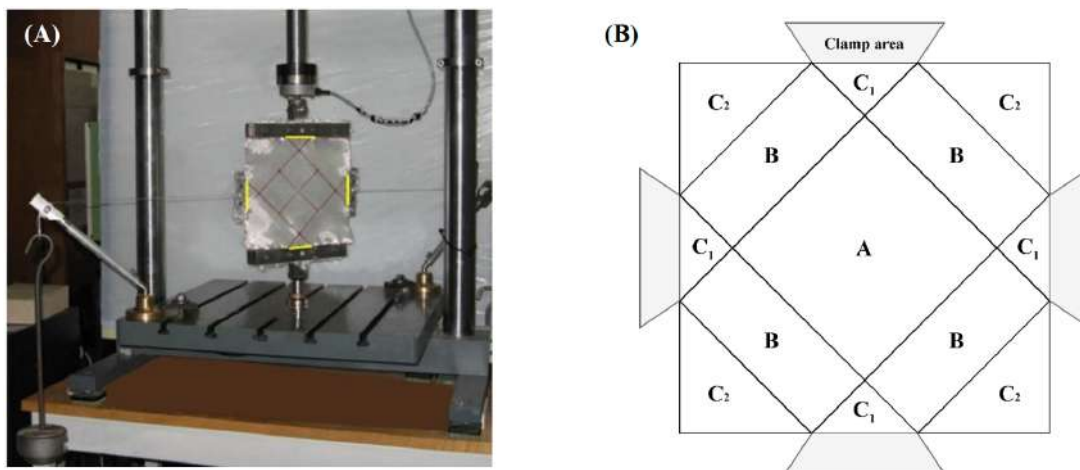


Figure 3.2: Biaxial bias extension test: (A) experimental setup [45] and (B) schematic representation of the test specimen.

Considering the square biaxial specimen of Figure 3.2-B, an idealised biaxial bias extension test sample

in which the material is divided into three regions. The specimen is clamped only along the edges of zone C_1 and is cut along the remainder of the length of the top and bottom clamps. If the tows within the sample are considered inextensible, and no intra-ply slip occurs within the sample (ideal kinematics), then one can show that the shear angle in zone A is always twice that in zone B, while zones C_1 and C_2 remain undeformed; the latter undergoes a rigid body translation and rotation during the test. The deformation in zone A can be considered equivalent to the deformation produced by the pure shear of a picture frame test and is defined by the shear angle, θ . [43]

The relative area of zones A and B is

$$A_A = \frac{A_B}{n} \quad (3.5)$$

where in general

$$n = \frac{4L_C}{L_T - L_C} \quad (3.6)$$

Where L_C is the length along which the specimen is clamped, and L_T is the side length of the square specimen. Since ideal kinematics are assumed, the shear angle in zone B is always half that of A:

$$\theta_B = \frac{\theta}{2} \quad (3.7)$$

A previous attempt to use a biaxial test setup to measure shear–tension coupling has been reported [61]; Sharma et al. pulled the fabric in two perpendicular directions at various rates, both directions oriented along with the bias direction of the sample [115]. Sample kinematics were found to compare well with ideal, pin-jointed net kinematics, though in contrast to results reported in [44, 67, 90, 116–118], only a minor shear tension-coupling was measured. Large scatter in the data and variable transverse loading during the tests make comparison with other investigations difficult. Galliot and Luchsinger [119, 120] proposed a new biaxial experimental and theoretical method of determining the shear compliance of coated fabrics. Shear–tension coupling of woven dry engineering fabrics has not yet been investigated using this technique. Thus, while there is strong evidence to suggest a shear–tension coupling exists, at least in plain weave engineering fabrics, to date, there has been no definitive quantitative experimental characterisation, and some results have suggested it may be small enough to neglect. [61]

The biaxial bias extension test can also be used to characterise wrinkling as a function on in-plane tension. Correctly predicting wrinkling during the forming of engineering fabrics is a problematic issue. For traditional materials such as metals, out-of-plane stiffness can be predicted from the material's mechanical properties, using a continuum approach. It is not the case for woven engineering fabrics whose fibrous

microstructure and out-of-plane bending stiffness are orders of magnitude lower than those of metals. [45]

Experimental characterisation of wrinkling of woven dry engineering fabrics using the picture frame and uniaxial bias extension tests have been performed previously to correlate wrinkling onset to the fabric structure, using simplified analytical models [49, 121]. However, it is clear that the occurrence of wrinkling is not just a function of the fabric structure but also of the stress field applied to the fabric during forming. Like shear stiffness, the out-of-plane bending stiffness is likely to be a function of the in-plane tensile stress. The current biaxial technique allows investigation of wrinkling behaviour under arbitrary in-plane tension conditions, and while it cannot provide a direct characterisation of this bending stiffness [87, 122], the modulus could be inferred using an inverse modelling approach.

This test is the first step towards a reliable method for parameter identification of shear–tension coupled constitutive models [48] and can be used inversely to fit out-of-plane bending stiffness model parameters [40, 122]. The biaxial bias extension test technique effectively measures both the fabric's shear–tension coupling and the onset of wrinkling, at least for plain-weave engineering fabrics. However, a method of normalising the test results for any given sample geometry must be developed if the unique underlying material response of the fabric is to be accurately characterised. [45]

3.1.3 Slip-bias extension test

A recent study [123] was conducted with the purpose to understand better the underlying mechanisms behind forming of fabrics under various clamping boundary conditions, and particularly their interaction with the shear response of the material; and, to develop a modified 2D characterisation test method along with its modelling, to arrive at faster equivalent forming simulations, without the need to explicitly include the pressure- and angle-dependent frictional contact through complex FE user-subroutines. This shear-slip formulation may be viewed as a first step to demonstrate how trivial modifications to standard fabric characterisation methods, such as conventional bias extension tests, could be exploited to achieve more cost-effective and accurate forming simulations. [123, 124]

A modified version of the BET is proposed in which experiments with variable unsymmetrical clamping pressures on the two opposite grippers can be carried out, schematically shown in Figure 3.3. This assists in assessing the effect of various boundary condition states closer to the actual forming on the shear response of the fabric and its formability. The sample is fully clamped on the upper end while being partially clamped at the bottom (so that the material can slip under this clamp). [123]

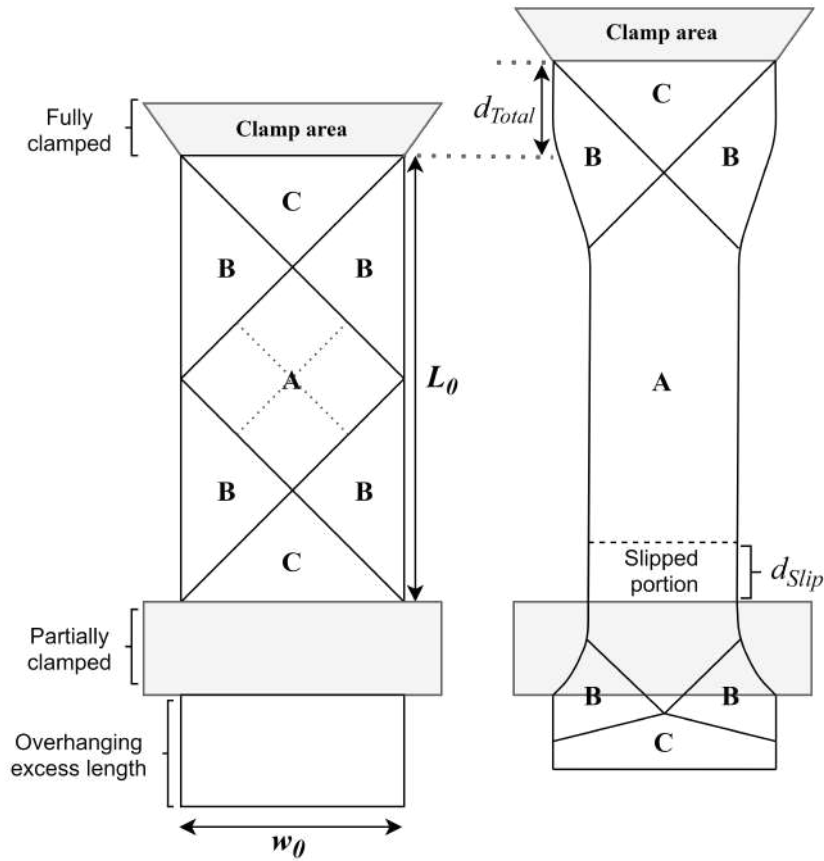


Figure 3.3: Slip-bias extension test: (A) schematic representation of the test specimen and (B) non-symmetric deformation zones in the specimen after imposing displacement. Adapted from [124]

In the slip-BE test, the shear deformation proceeds to a certain point, up to the maximum static frictional limit under the lower grip, followed by slippage of the overhanging excess length of the fabric nearby the clamp. [123]

As the shear deformation proceeds over the course of the test, the three shear zones at both ends begin to form almost symmetrically up to a point where grip-ply slippage takes place (corresponding to a dynamic friction state), and evolution of the shear angle in the middle area (zone *A*) stops. Depending on the applied clamping pressure on the lower grip, the onset of the latter slippage and final shear angle in zone *A* will vary. After the slippage onset, the overhanging excess length underneath the lower grip begins to slip upwards as the fabric strip goes under shear deformation underneath the grips. This forces the shear angles in zones *B* and *C* at the bottom to increase, expanding the pure shear area (zone *A*) to the bottom region, then reducing sample width near the grip. At the end of the test, due to slippage of the specimen near the lower grip, only the upper regions showed the undeformed triangle (zone *C*) followed by half sheared areas (zone *B*). [123, 124]

For a global displacement value from 0 mm to 25 mm, the shear angles follow the expected trend reported in previous studies with a gradual increase. It should be noted that the plateauing of shear angles

for the fully clamped case is due to the initiation of intra yarn slippage within the sample. For all the slip-BET, after the onset of grip-ply slippage, around 25 mm of global displacement, the average shear angle in zone *A* is plateauing to an almost constant value. From this point onwards, the shear deformation in the bottom gauge area does not follow the conventional BET with half sheared (zone *B*) and undeformed (zone *C*) regions. Instead, the bottom shear zones near the grip regions correspond to different shear resistance mechanisms, equal to the shear angle of zone *A*. The latter pure slippage mode represents the effective dynamic frictional behaviour of the fabric at a certain shear angle concerning the grip/blank holder. [123, 124]

The modified bias extension test characterises the fabrics shear behaviour under sliding clamp conditions instead of fully clamped, closer to the actual forming conditions. The key benefit of this simplified method is removing the need for a separate subroutine to account for the blank holder-ply frictional behaviour, which is a function of the fabric shear angle and normal force from the clamp. The simplified simulation resulted in a slightly improved prediction of the formed shape of the fabric, better predicting the yarn orientation, location, and value of the maximum shear angle, and a lower computational time than the conventional simulation using a constant friction coefficient. [123, 124]

Furthermore, a more comprehensive characterisation of slippage at a broader spectrum of clamping pressures, combined with a robust curve-fitting approach, could be used to address variations of local clamping forces that may exist in forming complex geometries. The described approach may also be extended to model the behaviour of pre-impregnated fabrics, e.g., incorporating other material characteristics such as the viscous behaviour of the resin. Simplified process simulations can be used in practice to provide faster insights to the process designers as to if and where defects such as high in-plane shear angles, in-plane and out-of-plane wrinkles, and excessive yarn tensile stresses may be developed in the final part. [123, 124]

3.1.4 Picture frame test

A picture frame, or trellis frame, is a fixture used to perform a shear test for woven fabrics [125–127]. Using the picture frame test method (PFT), uniform shearing of the majority of the fabric specimen is obtained. Displacement and load data are recorded to aid in the characterisation of pure shear behaviour. [69]

In this test, the sample is clamped into a rig such as that shown in Figure 3.4, with the fibre directions parallel to the arms of the rig. The rig is pinned at the four corners and thus imposes pin-jointed shear behaviour onto the sample. This eliminates any potential problems with fibre slippage, but any misalign-

ment between the fibre and the arms of the rig has a very significant effect on the measured stiffness due to the enormous difference in fibre direction and shear moduli. [59, 69]

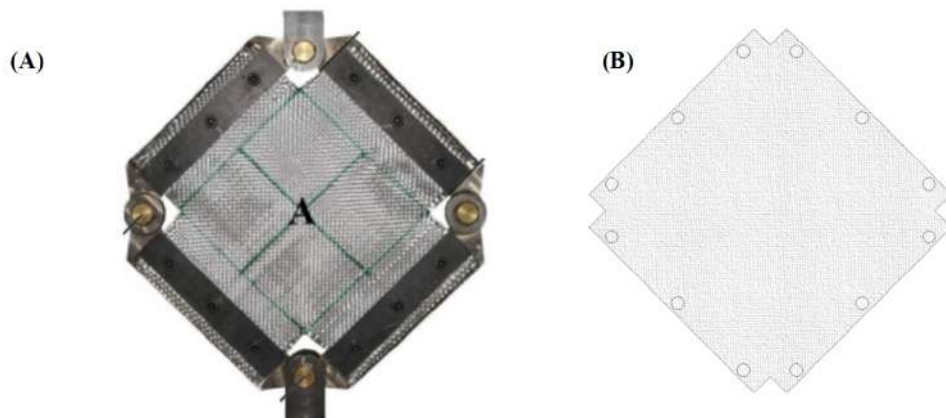


Figure 3.4: Picture frame test: (A) experimental setup [45] and (B) schematic representation of the conventional specimen.

A tensile force is applied across diagonally opposing corners of the picture frame rig, causing the picture frame to move from an initially square configuration into a rhomboid. Consequently, the sample clamped within the frame experiences pure shear. Different methods of holding the material have been discussed by McGuiness and O'Bradaigh [86]; the sample can be either pinned or clamped in the picture frame. [64]

As mentioned before, an international group of academic and industry researchers has gathered to design and conduct benchmarking tests of interest to the composite sheet forming community [69]. The researchers gathered at the University of Massachusetts Lowell for the Workshop on Composite Sheet Forming; the main objectives of the workshop were to understand state of the art better and to identify the existing challenges in both materials characterisation and numerical methods required for the robust simulations of forming processes. One direct outcome of the workshop, and the effort to standardise material characterisation methods, was a web-based forum exclusively for research on the forming of textile composites [128]. Other workshop outcomes are in publications [59, 62–64, 66, 67, 107, 129–171], highlighting recommended practices for experimental techniques and modelling methods. [69]

Differences among the groups were related to specimen preparation. For example, all of the unclamped fringe yarns were removed to eliminate the potential force contribution from the shearing of the yarns in the edge (arm) parts of the sample. Another group reported that they removed some of the yarns adjacent to the centre area of the sample to prevent the material from wrinkling during testing. Previous research [161] reported that care must be taken not to alter the tightness of the weave or local orientation of the remaining yarns when removing some yarns before testing the fabric. This statement was further

supported in this study, and it was noted that theoretically, in an obliquely oriented or misaligned specimen in the frame, one group of yarns would be under tension while the other would be under compression. Because a yarn cannot be compressed in the longitudinal direction, a misalignment would indicate that the yarn buckles out of the original plane and the onset of wrinkling in the fabric occur at lower shear angles than when the specimen is correctly aligned in the frame. [69]

Some tests were terminated at the onset of wrinkling, as the shear deformation is no longer uniform once wrinkling occurs. It was also noted that by “mechanically conditioning” the specimen, i.e., by shearing the fabric in the frame several times before starting the test, the variability in tension due to local deviations in orientation could be eliminated. This occurrence indicates the importance of the precise handling of both the sample and the test fixture. [69]

The fabric conforms to its final geometry mostly by yarn rotation, shearing between weft and warp yarns, denoted as the shear angle θ . θ is commonly assigned as zero (0) at the initial stage when weft and warp yarns are perpendicular to each other. This shear angle was used as a common parameter for comparison in the benchmark activity. [69]

Through trigonometric relations, the angle of the frame, α , is calculated

$$\cos \alpha = \frac{\sqrt{2}L_{frame} + d}{2 \times L_{frame}} \quad (3.8)$$

where L_{frame} is the frame length. The shear angle, θ , is calculated from the geometry of the picture frame

$$\theta = 90^\circ - 2\alpha \quad (3.9)$$

This value, θ , is also called the global shear angle. Note that this value is taken to be an average shear value over the entire specimen. The actual shear angle at any point on the fabric may vary.

Several authors [86, 172–174] observed that improper alignment of the fibres with the frame invalidates the recorded load-displacement curve of the picture-frame test because, in such cases, tensile loads are much higher than the effective shearing load are induced in the fibres. By using the modified specimen (Figure 3.5), the tensile loads in the fibres are almost inexistent, especially if care is taken to properly align the fibres with the frame because in this case, tensile loads in the fibres apply over a considerably reduced portion of the shearing surface of the specimen corresponding to the clamped fibres. [60]

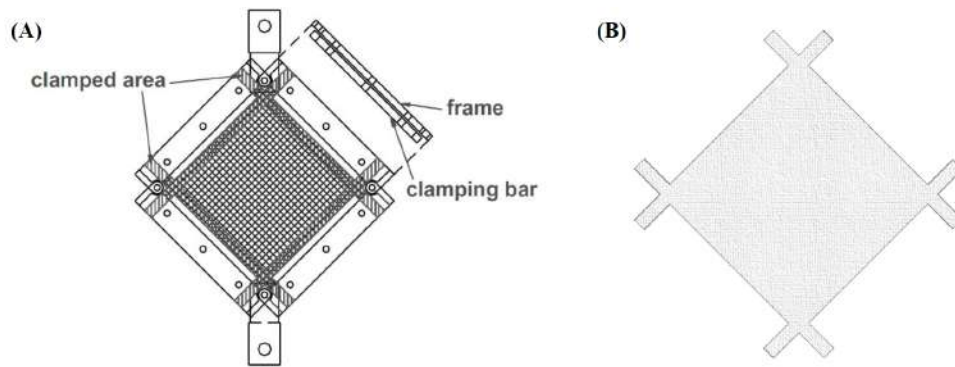


Figure 3.5: Modified picture frame: (A) test setup [60] and (B) schematic representation of the modified specimen.

A modified picture-frame method was proposed to eliminate these parasitic fibre tension forces. Tests were made using a modified version of the original picture-frame test. Instead of clamping the specimen over the whole length of the clamping bars, only small portions of this length, close to the pivoting points of the frame, were clamped, as shown in Figure 3.5-A. [60]

The load-displacement traces of the bias extension tests were compared to those obtained with this modified picture-frame method, and both tests gave similar shearing loads, representative of a pure intraply shear mode of deformation in each type of test. [60]

Further developments have since involved fitting a picture frame rig with load cells along the sidebars allowing the measurement and control of yarn tension during the test [67, 90, 118]. The latter technique addresses the issue of changing tension during the picture frame test due to two contributions; fabric misalignment and changing crimp. Improved accuracy can be expected in results obtained using the modified picture frame test compared with the pre-tensioned picture frame test as the instrumented picture frame rig allows the fibre tensions to be monitored and changed during the experiments. Results published in [67, 90, 118] show a dramatic decrease in the measured shear force to levels more comparable with uniaxial bias extension test data when in-plane tension is relaxed to zero during shear testing. [45]

The conventional picture frame test procedure is simple to perform, and results are reasonably repeatable. Since the material deformation is essentially homogeneous throughout the deforming sample (edge effects being ignored), the kinematics of the material deformation are readily calculated, facilitating rheological analysis of the results [86]. A major benefit is that the shear angle and current angular shear rate can be related directly to the crosshead displacement and displacement rate. However, one of the main concerns with the test is the boundary condition imposed on the sample. Loose pinning of the sample edges in the side clamps may fail to induce the required kinematics, whereas tight clamping of the sample edges can cause spurious results if the sample is slightly misaligned. Another concern with the

boundary conditions of the picture frame test is related to the influence of the metal rig on the temperature profile across the sample. During high-temperature testing required for thermoplastic composites, the rig has been shown to cool the material immediately adjacent to the deforming sample, which may influence results. [64]

An advantage of the picture frame test is that the entire sample undergoes pure shear, making possible rheological analysis of the material deformation [86, 172, 175]. This point, along with the ease and speed of the test and relative ease of the experimental data processing, has made it a popular experiment for characterising woven composite materials. [64]

Analysis of picture frame and bias extension results suggests that the deformation mechanisms involved in picture frame testing are closer to those that occur during component forming than those produced during bias extension testing. However, bias extension testing can provide a quick and reliable method of determining a materials' locking angle and check for adverse effects introduced by the more severe boundary conditions of the picture frame test. [64]

3.1.5 Novel picture frame test

A novel picture frame tester concept was introduced to extend the existing experimental basis for further developments of material models and broadening experimental methods of shear characterisation. Reproducible preparation and handling routines were defined, which kept fibre misalignments low and increased reproducibility significantly [100]. This new method allows both tensioned and untensioned characterisations.

The setup consists of four aluminium bars connected by four rotatory joints with Polytetrafluoroethylene (PTFE) bearings (Figure 3.6). A tensioning device was added to both axes, utilising pneumatic cylinders, which retain initiated tensions paths independent and only as a function of the applied pressure. The needles on the inner bars are employed for both tensioned and untensioned experiments. [100]

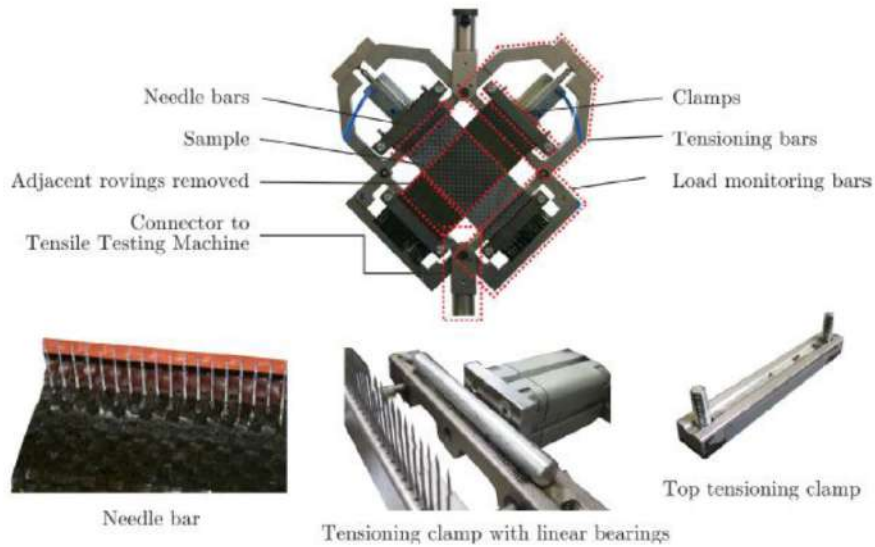


Figure 3.6: Design of the novel picture frame tester with mebrane tension initiation by pneumatic cylindres and load monitoring. [100]

For the untensioned experiments, prior works by Orawattanasrikul [176] have shown that the implementation of needles allows the fabric to rotate locally at the boundaries without the initiation of membrane tensions and reduces local bending; therefore, the rear clamps are not necessary. For the tensioned experiments, the needles are used to transfer the applied tensions from the movable tensioning clamps to the in-fibre direction of the fabric during shearing. The influence of friction between the needles and the rovings is neglected. The initiated membrane tensions are considered to be independent of the shearing angle. On the opposite side, load cells are included for initial calibration of the tensioning state on both axes and to monitor the stress state during testing. [100]

The size of picture frame testers and samples used in the conventional method are generally larger than the samples used in this study. While a larger sample size helps to homogenise the load response, it is a disadvantage for characterising the shear tension coupling of woven fabrics as each intersection point leads to stress deflexions to the crossing roving direction. Hence, smaller sample size is used to keep tension inhomogeneity low. [100]

To reduce preparation misalignments and to increase reproducibility, guidelines were defined for each handling step (Figure 3.7). The initial samples are cut off on an industrial cutting table with ultrasonic cutters to prevent fibre slippage and local fibres pull-out. To ease the cutting without fibre movement or pre-shearing of the fabric, a thin foil is applied on both sides of the fabric and set under vacuum continuously during cutting. The cut specimens are then placed on a positioning tool with the ascribed contour of the cross specimen to reduce misalignments and allow manual removal of rovings. A guidance tool is used to pierce the fabric with the picture frame tester's needles in a defined matter. After the

specimen is mounted on the picture frame tester, the cross-tool is removed, and the clamps are fastened with controlled torque. Mounted the tensile testing machine setup, the pneumatic drives are connected, the guidance tool is removed, and testing starts. [100]

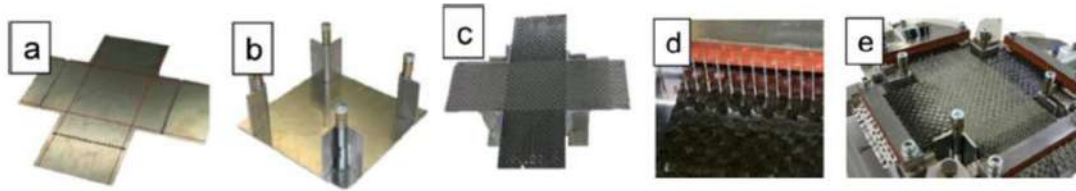


Figure 3.7: Handling and preparation tools: (a) positioning tool, (b) guidance tool, (c) fabric placed on positioning and guidance tool, (d) pierced fabric and, (e) picture frame tester fixed by guidance tool in unsheared configuration. [100]

Three limitations on the experimental setup can be derived. Due to the woven fabric's architecture and tensile deflections, the stress state on the fabric can be assumed to be inhomogeneous. The fibres rise at the needles during shearing, so an inhomogeneous state result inside the rovings because of the curvature at high shear forces. Moreover, friction occurs between the needles and the rovings resulting in superimposed shear responses. [100]

3.1.6 KES-FB1: Shear test

In 1972, Sueo Kawabata, alongside the Textile Machinery Society of Japan, introduced the Kawabata Evaluation System for Fabrics (KES-F, later to become the KES-FB system) [177]. The main purpose of this system is to objectively measure the appropriate fabric properties and then correlate these measurements with the subjective assessment of handle [70]. The KES system consists of four specialised instruments (FB1: tensile and shearing, FB2: bending, FB3: compression, and FB4: surface friction and variation) [178].

This system went through further developments to have a computerised and automated version with software to collect and analyse the output data. Even so, due to its high price, sensitivity in use, complexity and high maintenance costs, KES-FB is more suited to research applications [33].

The KES-FB is used for composite preforms [179–181], allowing a complete insight into the fabric behaviour at low loads. One can argue that low loads involved in the tension and shear KES-FB measurements are not that relevant to the behaviour of composite reinforcements. However, the knowledge of the initial behaviour is essential for validation of models of the phenomena, as the factors involved are present also at higher loads (e.g. frictional resistance in shear) but may be blurred by other factors (e.g. lateral compression of the yarns in shear) [159].

The Kawabata shear test (KES-FB1) is done by an entirely automated, computer-controlled device. A shear strain rate of 8.34×10^{-3} /sec is applied to the specimen under a constant extension load (10 gf/cm) up to a maximum shear angle of 8° in its long direction. The system produces stress (forces)-strain plots resulting from the applied force in one direction, and then it is released to apply it in the opposite direction [33, 178, 182, 183]. The plots show the hysteresis behaviour of a sample tested resulting from the energy loss during deformation. However, the main limitation is that Kawabata shear tester is designed to conduct up to 8° of shear angle, whereas the textile preforms can deform up to $50\text{--}60^\circ$ [33, 109].

The shear test is carried out using the same tester as the tensile test (Figure 3.8). The result of the test is a specific shear force–shear angle diagram. Based on the diagram, the so-called Kawabata parameters (which describe the deformability of the fabric) can be calculated: the hysteresis of shear force at a shear angle of 0.5° , the hysteresis of shear force at a shear angle of 5° and the shear rigidity, G [70, 177, 182, 184]. A higher shear rigidity, indicates a greater shearing resistance and a higher drape coefficient. It has been proved that the shear hysteresis at 5° explained over 70% of the variation in drape values of woven fabrics [183, 185].

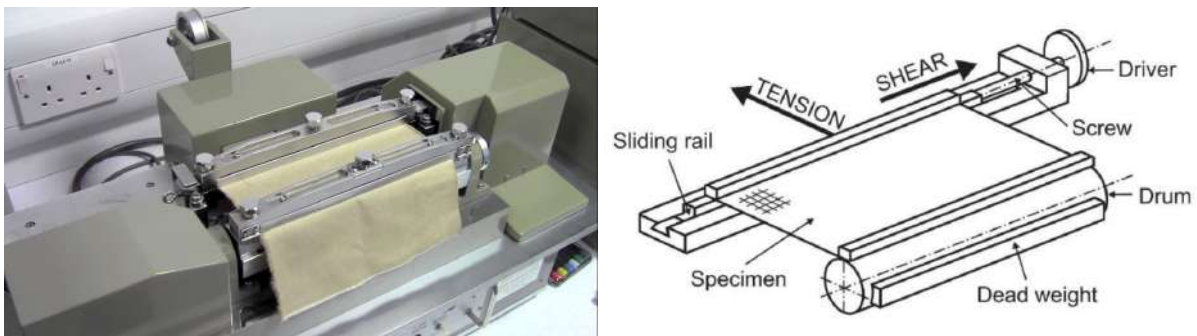


Figure 3.8: Kes-FB1: shear test apparatus (left) [186] and working principle (right) [182].

As shown in Figure 3.8, two parallel sides of the specimen are clamped at a distance of 50 mm, one attached with drum for tensile force application and the other attached with slide for shear force application. The constant normal pre-tension is generated by a weight attached to the rotating drum. The shear force is measured by a transducer connected to the attached sliding rail, and the shear strain is measured from the resulting displacement of the slide with a shear strain detector [70, 184, 187, 188].

3.1.7 Novel KES-FB1

A novel apparatus of the KES-FB1 test was developed. This apparatus makes it possible to carry out modified Kawabata-type shear tests, hence investigate the shear properties of sheet-like flexible materials and yarn pull-out tests on woven fabrics. The schematic drawing of the device can be seen in Figure 3.9.

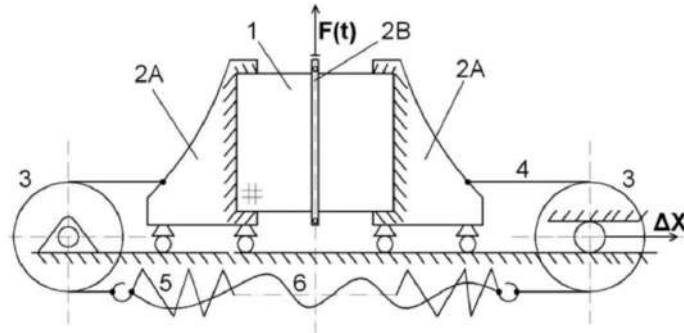


Figure 3.9: Novel KES-FB1: schematic representation of the apparatus. 1: specimen, 2A: side clamps, 2B: middle clamp, 3: rollers with appropriate bearing, 4: thin rope, 5: pretensioning steel spring, 6: strain limiting yarn. [182]

The setup of the measurement is symmetrical. There are two parallel clamps at the vertical edges of the rectangular specimen and a third parallel one in the middle. The two parallel edges of the test specimen (1) are clamped (2A), and the shear deformation in the specimen is generated by the vertical motion of the middle clamp (2B). The long, helical, linear characteristic spring (6) is a simple but precise construction suitable for inducing the required pre-tension. During the test, the two side clamps can move sideways on a horizontal rail due to the vertical force generated by the load device and the horizontal forces of the pre-tension spring mechanism. [182]

The device can be mounted to the tensile tester with four bolts. Before the test, for the insertion of the specimen, the whole apparatus can be turned to a horizontal position around the motherboard after removing two positioning pins. As soon as the specimen is well-positioned and well-fixed, the apparatus can be tilted back to the working position and fixed by the pins. Then the locking levers are to be loosened; thus, the side clamps can slide freely on the rail again. The pre-tension can be applied by the adjustment gears until reaching the proper strain of the spring. The middle clamping unit is then fixed, and hence the specimen is ready for the test. The apparatus mounted on a tensile test machine can be seen in Figure 3.10. [182]

The obtained results from this study conclude that the designed apparatus is suitable for conducting the modified Kawabata-type shear tests and can do cyclic tests. [182]



Figure 3.10: Novel KES-FB1: experimental setup. [182]

3.1.8 FAST-3: Extension meter

The Fabric Assurance by Simple Testing (FAST) system was developed in the 1980s by the CSIRO Division of Wool Technology, Australia, primarily for quality control and assurance of fabrics. [189, 190] It measures properties closely related to the ease of apparel manufacturing, handling characteristics, and surface finishing durability. [183, 187]

The FAST system consists of three instruments (FAST-1: compression meter, FAST-2: bending meter and FAST-3: extension meter) and a test method (FAST-4: dimensional stability test). Unlike the KES system, FAST measures only the resistance of the fabric to deformation and not its recovery from deformation. [33, 183, 187, 188] The FAST instruments are similar in operation to conventional measuring instruments, except that measurement is carried out using sensors, and the test results are displayed digitally. The FAST system measures the mechanical, dimensional and pressing performance-related propensities of fabrics. [183]

Compared with KES-FB, FAST is simpler, quicker to use, and yields more easily reproducible results, making it more suitable for use in the industrial area. The system's emphasis has been that it should be user friendly and robust, enabling fast and accurate measurements to be taken. Test results can be obtained within one hour. [33, 191]

The extension meter (FAST-3) is capable of measuring the fabric extensibility in warp, weft and bias directions over a range of loads, with direct reading of extension as a percentage of the initial gauge length. The fabric extension is displayed as a percentage with a 0.1% resolution. [187] A schematic diagram of the FAST-3 system is shown in Figure 3.11.

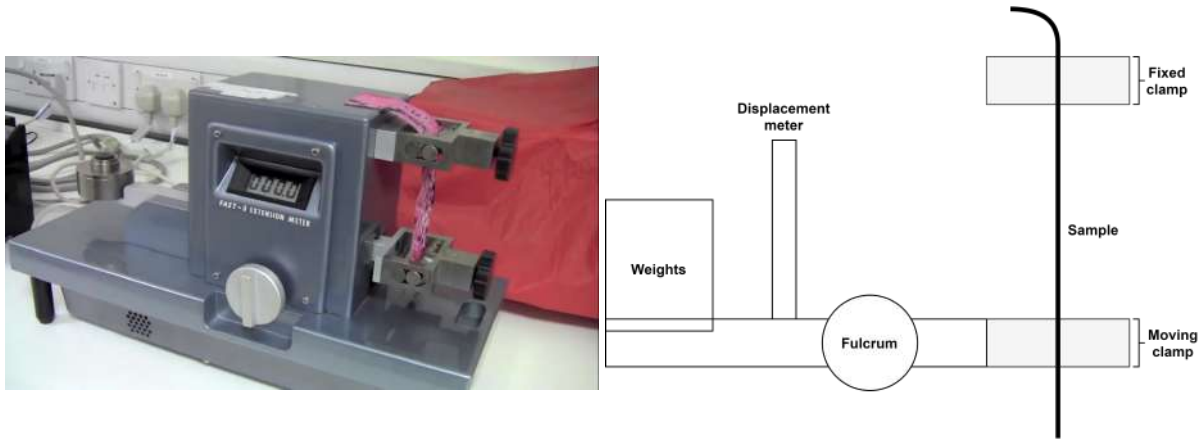


Figure 3.11: FAST-3: the extension meter instrument (left) [192] and working principle (right).

It measures the extensibility of a fabric sample at three loads: 5 (E5), 20 (E20) and 100 (E100) gf/cm (4.9, 19.6 and 98.1 N/m) in the warp and weft direction. The loads are chosen to simulate the level of deformation the fabric is likely to undergo during manufacture [33, 183, 193]. The difference between fabric extensibilities between E5 and E20 is used to calculate fabric formability, which is a measure of the ability of a fabric to absorb compression on its plane without buckling [178, 187, 188].

FAST-3 is also used to measure the bias extensibility of the fabric (45° to the warp direction) under a low load (E5). Bias extensibility is not used directly but is used to calculate shear rigidity, G [194]. Shear rigidity measures the ease with which a fabric can be deformed into a three-dimensional shape [193]. Low shear rigidity (below 30 N/m) indicates that the fabric is easily distorted in laying up and may give problems in handling. Conversely, a high value (above 80 N/m) indicates that the fabric is difficult to form into smooth, three-dimensional shapes, causing problems in moulding [178, 183, 187].

Shear rigidity, G [195] is calculated as:

$$G(N/m) = \frac{123}{EB5} \quad (3.10)$$

where $EB5$ is the extension in the bias direction at 5 gf/cm.

3.2 Compression properties

Testing of textiles refers to numerous procedures for assessing myriad fibre, yarn and fabric characteristics such as fibre strength and fineness, yarn linear density and twist and fabric weight, thickness, strength, abrasion, resistance, wrinkle resistance and stiffness. It is the application of engineering knowledge and science to measuring the properties and characteristics of and the conditions affecting textile

materials. [34]

Compression is defined as a decrease in intrinsic thickness with an increase in pressure. Intrinsic thickness is the thickness of the space occupied by a fabric subjected to barely perceptible pressure. The compression of fabrics is an inevitable phenomenon during fabric handling and processing. [196, 197]

Regardless of the fabric type or application, one of the most critical deformation modes, in many cases the dominant mode, is transverse compression, where the fabric is compacted through its thickness. An understanding of fabric transverse compression is required to understand reinforcement formability. This understanding assists with structural design issues, the design of new reinforcement materials themselves, and the optimisation of manufacturing processes. [197, 198]

It should be noted that fibrous materials are subjected to compression in various industrial and technical applications [199], and knowledge of their mechanical response is of interest to more than just the composites community [200]. In particular, the textile materials community extensively studied the transverse compression of fabrics. These investigations complement well the many investigations into fibrous materials carried out by the composites community [198].

The compression test for fabric is used to determine the fabric thickness at selected loads and reflects the "fullness" of a fabric. When measuring the compression properties of the fabric, it must be appreciated that all fabrics contain air, fibres, and yarns. When a fabric is compressed, three distinct stages in the deformation have been identified [201]:

1. Individual fibres protruding from the surface become bent and/or compressed. The resistance to compression in this region comes from the fibre bending stiffness.
2. The yarns come into close contact and are flattened and straightened, at which point, the inter-yarn and inter-fibre friction and the yarns' bending stiffness provide the resistance to compression until the fibres are all in contact with one another.
3. The yarns are compacted, and the individual fibres are squashed against each other. The resistance is controlled mainly by the fibres' transverse properties (or lateral compression).

The compression stages involve elastic deformation, frictional forces and the elastic recovery of the fibres from bending and lateral compression. So the compression property contains information about the handle of the fabric. The greater the radius of curvature of the transition between the first and third stages, the softer the fabric in compression. [34, 202]

The effectiveness of compression behaviour of woven fabrics depends upon the degree of pressure provided. This, in turn, is determined by several factors, including the physical and elastomeric properties

of the fabric, the type and shape of the yarns used, and most importantly, the compressive stress produced in the fabric during the application process. [196, 197]

When a specimen of material is loaded with an axial push so that it shortens, it is said to be in compression. It is the opposite of tension, in which a specimen is subjected to an axial pull so that it extends. On compression, the specimen shortens. The material tends to spread in the lateral direction, increasing the cross-sectional area. Compression properties are generally characterised by two parameters: compressive strength and compressive modulus. Compressive strength is the value of uniaxial compressive stress reached when the material fails. Compressive strength is the capacity of a material to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed. [196]

The ratio of the compressive or tensile force applied to a substance per unit surface area to the change in volume of the substance per unit volume is called the compression modulus. It is also known as bulk modulus, modulus of compression or modulus of volume elasticity. The ratio of mechanical stress to strain in an elastic material when that material is being compressed is called the modulus of elasticity. Modulus of compression is the compressive force per unit area per change in volume per unit volume. [196]

The ability of the fibre mass to recover from compression – its resilience – can be expressed in different ways; for example, the amount of energy recovered on the removal of the load is expressed as a percentage, or the ratio of the energy expended by the testing machine in compressing the material between the same limits of pressure, the ability to absorb work, area of the hysteresis loop. [196]

The transverse compression response of reinforcements is most easily determined by placing a preform between two fairly thick flat metallic plates installed in a standard universal testing machine. The plates must be kept as parallel as possible. For example, using a spherical alignment unit, it should be possible to keep plate misalignment to less than 0.01° [203]. Machine compliance needs to be carefully accounted for [204]. A displacement sensor is used to monitor actual thickness during the experiments [198].

From conservation of mass, the thickness h of a sample can be related to the volume fraction V_f through

$$V_f = \frac{A_m N}{\rho_s h} \quad (3.11)$$

Where A_m is the areal mass of the fabric, N is the number of layers and ρ_s is the density of the fibres. [198]

Several standard tests can be carried out. In the stress relaxation test, the material is compacted (usually at constant velocity) to a given volume fraction, and then that volume fraction is held constant,

allowing the stress to relax (reduction in stress at fixed volume fraction). [198]

In the creep test, the material is compacted using a (usually linearly ramped) force until a final force is achieved. This force is maintained, allowing the material to creep (continuing compaction at constant stress). [198]

The cyclic test involves repeated compaction and unloading to some fixed volume fraction or fixed level of applied force. Experiments should be repeated several times: even with a perfect experimental set-up and procedure, results inevitably vary due to material variability; this variability should be determined and quantified. [198]

The compaction curve for a fibrous material is the compaction stress versus volume fraction curve for a single (usually the first) compaction. The initial phase of the compaction curve is more or less linear. This is followed by a second phase, where the gradient increases rapidly. Finally, there is a third phase where the stress increases linearly with a steep gradient. [198]

During the first low-stress phase, fibres within yarns become closer together, and fibres and yarns undergo a small amount of bending. Low-resistance nesting of layers also occurs [205]. During the second phase, the number of fibre–fibre contacts increases and significant resistance is provided by fibre/yarn bending. All the while, friction between fibres must be overcome as fibres slide over one another. With woven fabrics, yarns flatten significantly. Finally, in the final phase, the fibres are in close contact, and further bending is difficult, so the resistance to load is dominated by individual fibre compression. [198, 206]

Reinforcement architecture affects the compaction curve. Generally, the more room for fibre movement, the more compressible the material [207]. For example, unidirectional fabrics are usually more compressible than plain weave fabrics because the yarn contacts in the latter provide resistance to fibre movement [208]. Random mats, with their initially low free–volume fraction, are highly compressible; however, when the volume fraction is increased significantly, they become less compressible due to a large number of fibre–fibre contact points and the resistance to fibre movement provided by a compacted entangled mass of fellow fibres [198].

One should distinguish between the compressibility, that is, the change in volume fraction with change in stress, and the actual applied stress; even though a random mat is generally more compressible than a woven fabric (Fig. 3.12), the compaction stress of the former will, in general, be much larger than that of the latter at any given volume fraction [198].

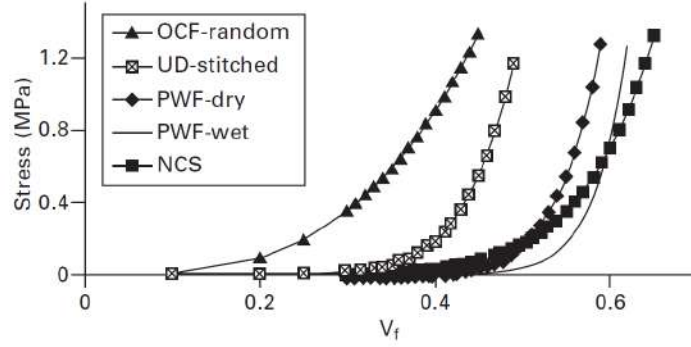


Figure 3.12: Compaction stress vs volume fraction compaction curves for a random mat, a stitched unidirectional fabric, dry and wet plain woven fabric, and a non-crimp bidirectional. [198]

The number of layers or plies of fabric in a lay-up affects the compaction curve. Usually, the more layers there are, the lower the compaction stress, with this increase in compressibility becoming less significant with each newly added layer [205]. Although the stress is lower, the compressibility is also lower. The explanation for this is that an increase in the number of layers increases the opportunity for nesting between layers and fibre movement in general [198, 209].

The compressional properties of fibre assemblies as a relationship between pressure and thickness of the assemblies have been studied by many researchers. However, the oldest investigation was carried out by Peirce [198], who experimentally demonstrated typical compressional curves of two fabrics, one hard, and the other soft, in compression. Based on this work, Hoffman and Beste [196] described Peirce's equation as follows:

$$T_w = T_0 \exp(-cP) \quad (3.12)$$

Where T_w is thickness of fabric under pressure P , T_0 is thickness of fabric under no pressure and c is a constant to be determined.

The pioneering work of Van Wyk [210] and subsequently its review by Carnaby [211] focused on the mechanics of the compression of fibre assemblies. They discussed a relationship describing the compression behaviour of the fibrous mass as [196, 198]:

$$P = \lambda \left[\frac{1}{v^3} - \frac{1}{v_0^3} \right] \quad (3.13)$$

Where v is the volume of the fibre mass, and v_0 is the value of v when P is equal to zero. [196]

Most of the study by De Jong et al. [212] and Van Wyk [210] concentrates on the compression of fibre assemblies. Their extension to the study of woven wool fabrics with measured values from KES-FB3 and other compression testers does not consider changes in the structural configuration of fabrics and

cross-section shape. [196]

Many other researchers have followed Wan Wyk's methodology, which involves specifying a probability density function giving the probable orientation of fibres spatially, so estimating the number of fibre-to-fibre contact points in an assembly, determining how the number of contacts increases with compaction, and hence relating stress, via the beam theory, to fibre volume fraction. For example, the increasing fibre alignment with compaction, allowances for different material symmetries and other refinements have been made. [198, 213–216]

The methodology cannot be easily used to analyse reinforcements with more organised architectures, for example, woven and knitted fabrics, and has not been used widely in recent times; however, it is still used in applications related to composites reinforcement deformation. [198, 217]

The early probability-orientation elastic models are often not of sufficient accuracy for many fabrics, and the mesoscale models are rather complex for modelling and predicting the simple compaction curve. For these reasons, many compaction-curve relations have been established without recourse to physical considerations and are valuable and easy-to-implement empirical relations. The most commonly used relation is the general power law [198, 204, 218–220]:

$$\sigma_f = mV_f^n \quad (3.14)$$

Where σ_f is the compaction stress, V_f is the fibre volume fraction and m and n are material parameters. This relation has been used to model a wide variety of materials, from random mats to textiles. The power index n typically takes a value in the range 3–19 [220], depending on the particular architecture of the material, though for most fabrics, it lies in the range 5–10. In general, the larger is m , the smaller is n [221]. The main advantages of Equation 3.14 are that it fits data from a wide range of materials and can easily be inverted to express volume fraction in terms of compaction stress. One physically unappealing drawback is that the function does not pass through the data point $(\sigma_f, V_f) = (0, V_{f0})$, where V_{f0} is the free volume fraction. [198]

Further, there is the possibility that V_f can become larger than 1 [222]. A more problematic feature is that the relation is often not of sufficient accuracy when used over a wide range of volume fractions. In fact, the compressibility β is seen to be:

$$\beta = \frac{1}{V_f} \frac{dV_f}{d\sigma} = \frac{1}{n\sigma} \quad (3.15)$$

Which is a rather constrained model for the observed changeable compressibility of fabrics during

compaction over a wide range of volume fractions. [198]

3.2.1 KES-FB3: Compression test

The Kawabata compression test (KES-FB3) describes the fabric behaviour at the load up to 5 kPa. It provides value for the thickness of the uncompressed fabric, which is difficult to measure otherwise. For the complete characterisation of the compaction of the fabric, KES-FB measurements should be combined with measurements on a Universal Testing Machine for the higher load range. [159, 177, 223]

The specimen used for the compression test is $2.5 \times 2.0 \text{ cm}^2$, and the effective pressure region is a circular area of 2 cm^2 . The specimen is compressed between two plates using a compression head, in the direction of its thickness to a maximum pressure of 50 gf/cm^2 (Figure 3.13). [177, 178, 183, 187]

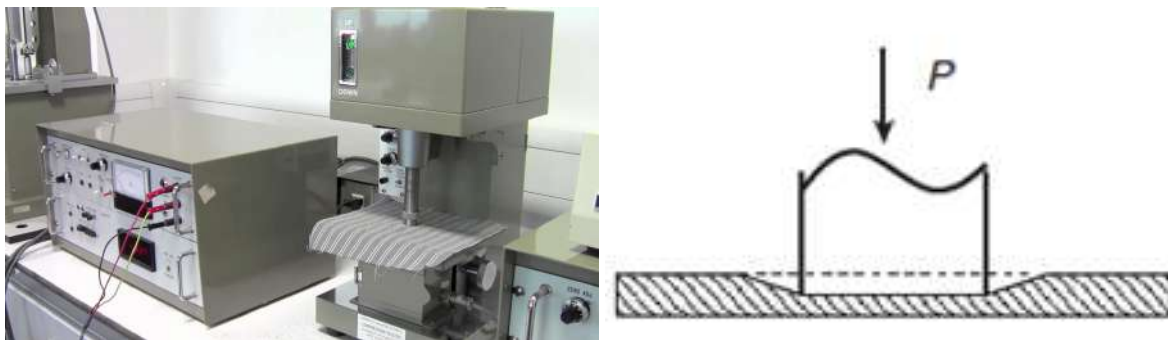


Figure 3.13: KES-FB3: compression test apparatus (left) [186] and working principle (right) [178].

A sample tested is placed on a plate, and the plunger moves downwards with a constant rate of $1 \text{ mm}/50 \text{ sec}$ until it reaches the pre-set upper limit of the compression force (50 gf/cm^2); it then moves upwards to recover the compression, and the load-deformation (pressure-thickness) curve is plotted. [33, 177, 183]

Figure 3.14 is the shape of the obtained pressure–thickness curve. From it, the following parameters are measured: linearity of compression curve, compressional energy, and compressional resilience. A higher compressional resilience value indicates a better recovery from compression. [178, 183]

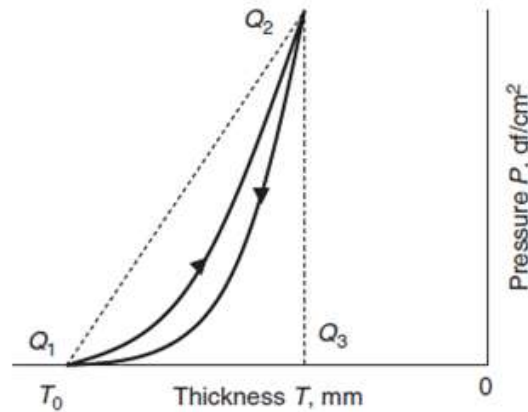


Figure 3.14: KES-FB3: compression curve. [178]

3.2.2 FAST-1: Compression meter

The degree of fabric compression and amount of fabric stabilisation affect the thickness of the fabric surface layer and consequently the appearance and handle of a fabric. The FAST-1 compression meter (Figure 3.15) has been developed to measure fabric thickness and, in addition, the variability and the durability of the thickness of the fabric surface layer. [190]

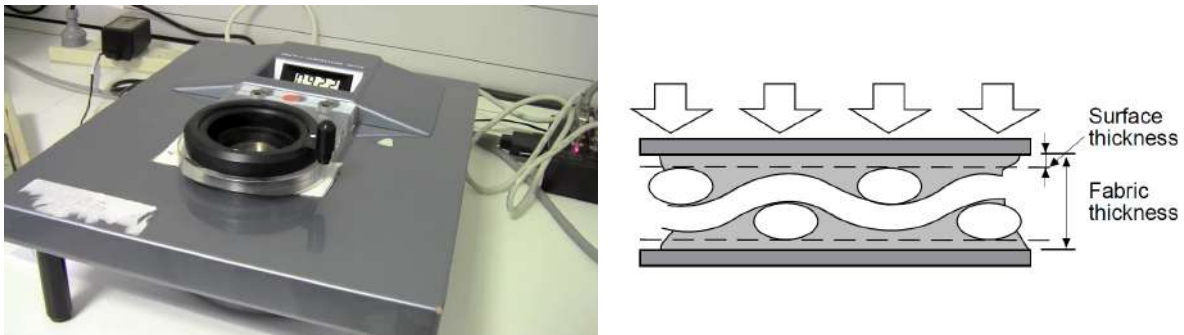


Figure 3.15: FAST-1: compression meter (left) [192] and working principle (right) [190].

The FAST-1 compression meter can measure fabric thickness to micrometre resolution at two predetermined loads, namely 2 gf/cm² (0.196 kPa) and 100 gf/cm² (9.81 kPa) on a 10 cm² area, and thereby enables the accurate measurement of surface layer thickness. [187, 190]

The surface layer thickness is a measure of the amount of compressible fibre or pile on the surface of the fabric and can be used to ascertain the extent and consistency of fabric surface processes [178, 183, 190]. This is based on the consideration that a fabric consists of an incompressible core and a compressible surface [177, 178]. The surface layer is defined as the difference in fabric thickness at the two predetermined loads [33, 190].

The measurements are usually made on the (conditioned) fabric and then repeated after the fabric

has been relaxed in steam on an open Hoffman press for 30 seconds to determine the surface layer's durability [177, 193]. The following parameters are determined by the FAST-1 compression meter [187, 190]:

- fabric thickness (T), is measured at a pressure of 2 gf/cm²;
- surface layer thickness (ST), is the difference in thickness of a fabric measured at pressures of 2 and 100 gf/cm²;
- released surface layer thickness (STR), is the measure of the ST after the fabric is exposed to steam or water.

The surface thickness could be a measure of fabric compressibility. The higher the surface thickness is, the more highly compressible the fabric. This determines the stability of a fabric in the manufacturing processes. [33]

3.2.3 ISO 5084 – Determination of thickness of textiles and textile products

This International Standard specifies a method for determining the thickness of textiles and textile products when under a specified pressure. It does not apply to textile floor coverings, non-wovens, geotextiles, and coated fabrics for which specific International Standards exist. [224]

For the purposes of this International Standard, the following definition for the thickness of a textile applies: perpendicular distance exerting a pressure of 1 kPa or less on the textile. [224]

The thickness of a specimen is measured as the distance between the reference plate on which the specimen rests and a parallel circular presser-foot that exerts a specified pressure on the textile area under test. [224]

A test specimen is placed between two reference plates which exert a known pressure on the specimen. The perpendicular distance between the reference plates is measured and recorded after a specified time. [224]

Apparatus

The confirmation system for the thickness tester shall comply with ISO 10012-1 [225] and shall incorporate (or be equipped with) the following elements: [224]

- i. Interchangeable presser-feet, of area appropriate to the type of fabric to be tested. The recommended presser-foot area for the test is $(2\,000 \pm 20) \text{ mm}^2$, corresponding to a circular presser-foot of diameter $(50,5 \pm 0,20) \text{ mm}$. If other test areas have to be used, the interested parties shall agree on this and shall be stated in the test report.
- ii. Reference plate, with a plane upper surface of diameter at least 50 mm greater than that of the presser-foot (i).
- iii. Means for moving the presser-foot (in a direction normal to the upper surface of the reference plate), so that its bearing surface is maintained horizontal and parallel to the upper surface of the reference plate (ii) and so that pressures of $(1 \pm 0,01) \text{ kPa}$ and $(0,1 \pm 0,001) \text{ kPa}$ can be applied to a test specimen supported on the plate.
- iv. Thickness gauge, capable of registering the distance between the bearing surface of the presser-foot (i) and the reference plates (ii) to an accuracy of 0,001 mm.
- v. Stopwatch.

Atmosphere for conditioning and testing

The textile samples shall be conditioned, and the test conducted in the standard atmosphere for conditioning and testing of textiles specified in ISO 139 [226]. [224]

Sampling, selection and conditioning of specimens

Take samples in one of the following ways, as appropriate: [224]

- a. Following the directions given in the relevant material specification.
- b. If such directions are not included in the material specification, following the procedure agreed upon by the parties interested in the test results.

Select test areas for samples in accordance with the recommended position of test areas or test specimens. For fabrics sensitive to deformation, e.g., certain knitted fabrics, cut test specimens according to the same recommended areas. If wide-width fabrics cannot be handled without distortion, cut test specimens. [224]

Condition the samples or test specimens in the relaxed state until equilibrium is reached with the standard atmosphere for testing. It is recommended to condition the samples at least for 16 hours in the relaxed state. [224]

Procedure

1. Clean the presser-foot and the reference plate. Check that the presser-foot shaft moves freely. Load the presser-foot to exert the appropriate specified pressure on the reference plate and set the thickness gauge to read zero. An applied pressure of $(1 \pm 0,01)$ kPa is recommended.
2. Raise the presser-foot and position the sample or test specimen, without tension and distortion, on the reference plate so that no part of the area to be measured is closer than 150 mm to the selvage. Ensure that the area chosen for the test is free from creases.
3. Lower the presser-foot gently onto the specimen and note the gauge reading after (30 ± 5) s.
4. Determine, in accordance with the procedure in 2. and 3., the thickness of at least five different areas on the sample or at least five test specimens. [224]

Expression of results

Calculate the arithmetic mean of the measurements determined in accordance with the procedure to an accuracy of 0,01 mm. Calculate the coefficient of variation to the nearest 0,1% and the 95% confidence limits to the nearest 0,01 mm. [224]

Test report

The test report shall include at least the following information: [224]

- a. Statement that the test was conducted in accordance with this International Standard and date of the test;
- b. Description of the fabric; width of narrow fabrics, if relevant;
- c. Area of the presser-foot used;
- d. Applied pressure;
- e. Number of tests;
- f. Thickness of the textile or textile product, presented as the arithmetic mean, expressed in millimetres and, if required, the coefficient of variation expressed as a percentage and the 95% confidence limits, expressed in millimetres;
- g. Any deviation, by agreement or otherwise, from the procedure specified, and the reason for this.

Test area position and alternatives for presser-foot area and applied pressure

If the test area of the presser-foot recommended in (i) is not used, use one of the following: [224]

- For narrow fabrics, e.g. usable width less than 50 mm, test area $(100 \pm 1) \text{ mm}^2$ corresponding to a circular presser-foot of diameter $(11,28 \pm 0,05) \text{ mm}$;
- For other fabrics, test area $(10\,000 \pm 100) \text{ mm}^2$ corresponding to a circular presser-foot of diameter $(112,84 \pm 0,5) \text{ mm}$.

If the pressure recommended before is not used, use $(0,1 \pm 0,001) \text{ kPa}$, e.g. for raised, pile or loop fabrics and certain knitted fabrics. [224]

3.2.4 DIN 53885 - Determination of textile and textile products compressibility

Following the adoption of ISO 5084 [224] as a national standard to supersede DIN 53855-1 [227], the German Materials Testing Standards Committee prepared a standard covering textile and textile product compressibility, which are not dealt with in ISO 5084. [228]

This standard specifies a method of determining the compressibility of textiles and textile products when a specified pressure is applied. It does not apply to floor coverings and geotextiles. [228]

Concepts

The initial thickness of a textile product is the distance between a reference plate and a presser-foot applying an initial test pressure, p_x , of 0,2 kPa to the textile, denoted by a_x . [228]

The final thickness of a textile product is the distance between a reference plate and a presser-foot applying a pressure equal to ten times the initial test pressure, p_{10x} , to the product, denoted by a_{10x} . [228]

Absolute compressibility is the difference between the initial and final thicknesses, $(a_x - a_{10x})$, denoted by Z_{Ax} . [228]

Relative compressibility is the ratio of the absolute compressibility, Z_{Ax} to the initial thickness, a_x , denoted by Z_{Rx} . [228]

Principle

The specimen is placed between a reference plate and a parallel circular presser-foot. A specified initial test pressure is applied through the presser-foot to the area to be tested, and the thickness, a_x , of the specimen is found by measuring the distance between the reference plate and the presser-foot. The pressure is then increased to a value ten times greater, and the thickness is measured again. [228]

Apparatus

The equipment used shall be that specified in ISO 5084 for textiles and textile products other than non-wovens, and that specified in ISO 9073-2 [229] for non-wovens. It shall be capable of applying test pressures ranging from 0,2 kPa to 2 kPa. [228]

Atmosphere for conditioning and testing

The specimens shall be conditioned and tested in the standard atmosphere specified in DIN 20139 [230]. [228]

Sampling, selecting test areas and conditioning of specimens

Sampling, selecting test areas, and conditioning of specimens shall be carried out for textiles and textile products other than non-wovens as specified in ISO 5084 and for non-wovens as specified in ISO 9073-2. [228]

Procedure

Test at least five different areas of the laboratory sample or at least five specimens, adopting the following procedure. [228]

1. Determine the initial thickness at a pressure of 0,2 kPa by the procedure specified in ISO 5084 for textiles and textile products other than non-wovens or that specified in ISO 9073-2 for non-wovens.
2. Raise the presser-foot and, during a recovery time of one minute in the unloaded state, add additional weights to exert a pressure of ten times the initial pressure.
3. Determine the final thickness at a pressure of 2 kPa by the procedure specified in ISO 5084 for textile and textile products other than non-wovens, or that specified in ISO 9073-2 for non-wovens.

Expression of results

Calculate the arithmetic means of the values determined as specified in the procedure for the initial thickness, a_x , and the associated final thickness, a_{10x} , to an accuracy of 0,01 mm, then calculate the coefficient of variation to an accuracy of 0,1% and the 95% confidence interval to an accuracy of 0,01 mm. [228]

Calculate the absolute compressibility, Z_{Ax} , in mm, as the difference between the thicknesses found: [228]

$$Z_{Ax} = a_x - a_{10x} \quad (3.16)$$

Calculate the relative compressibility, Z_{Rx} , as a percentage, using the following equation: [228]

$$Z_{Rx} = \frac{a_x - a_{10x}}{a_x} \times 100 = \frac{Z_{Ax}}{a_x} \times 100 \quad (3.17)$$

Chapter 4: Experimental work

4.1 Shear properties

4.1.1 Bias extension test

Design and simulation

Custom-made grippers were developed since the testing machine available at PIEP didn't supply adequate grippers to test the considered properties. For the Computer-Aided Design (CAD) modelling, the software Solidworks was used to design and test the accessories prior to manufacturing.

Considering the designs and dimensions presented on studies such as [69, 231] and the aesthetic of manufacturers' accessories [232, 233], the first drafts for the BET grippers were created (Figure 4.1) for a testing area of $200 \times 70 \text{ mm}^2$ ($\lambda = 2$).

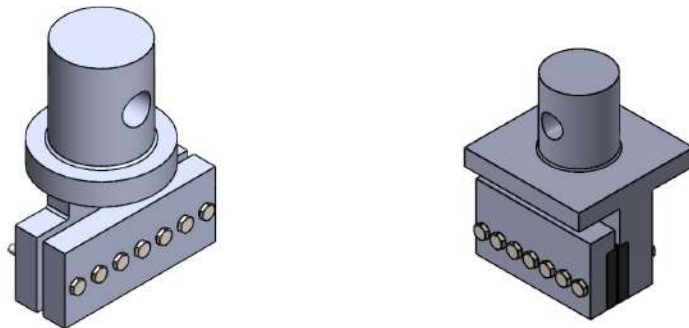


Figure 4.1: Bias extension test: first versions of the grippers created using Solidworks software.

They evolved to a more straightforward version of two pairs of steel plates (Figure 4.2) inspired by the grips used at NU's bias-extension tests in [69] and the study [170]. Ending up being the ones manufactured and employed. The technical drawings for each part can be found in Appendix A.1.1.

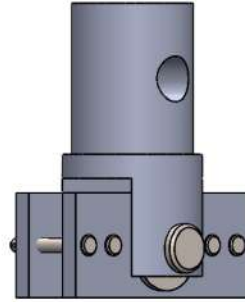


Figure 4.2: Bias extension test: final version of the grippers.

Static simulations were carried out to predict the behaviour of the grippers when subjected to the force of the machine and thus avoid future failures when performing the bias extension test. To be able to run the simulations on Solidworks, it was taken into account the maximum load of the testing machine, the direction of the force, and were defined the fixed points for each part.

The selected material to use in the numerical studies performed in this thesis was a common aluminium alloy (1060-H12) whose properties are presented in Table 4.1:

Table 4.1: Solidworks aluminium alloy 1060-H12 properties.

Property	Value	Units
Elastic modulus	6.9e+10	N/m ² (Pa)
Poisson's ratio	0.33	N/A
Shear modulus	2.6e+10	N/m ²
Mass density	2705	kg/m ³
Tensile strength	85 000 000	N/m ²
Yield strength	75 000 000	N/m ²

Since the maximum load of the Shimadzu universal testing machine is 50 kN, the simulations were executed both for 50 kN and 100 kN. Simulation results for 100 kN can be found in Appendix A.2.1. In figure 4.3, the pink arrows represent the direction of the force, and, in this case, the fixed point is the middle hole where the grippers are secured to the machine head.

As it can be seen in the Figures below, the maximum stress expected for a load of 50 kN is 840 MPa (Figure 4.3), which is equivalent to a 0.009 strain (Figure 4.4) resulting in a displacement of 0.37 mm (Figure 4.5).

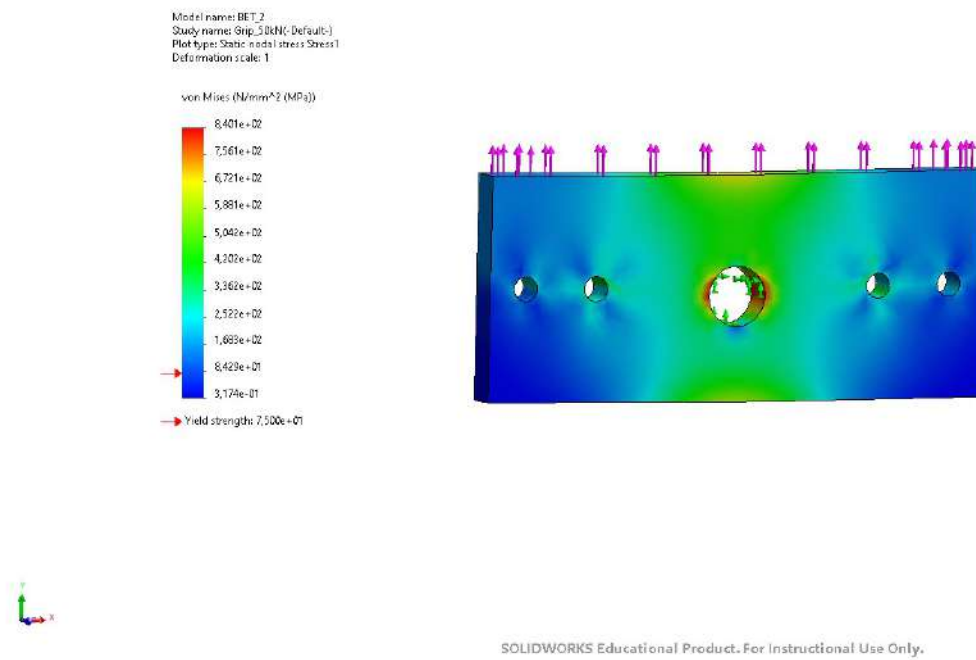


Figure 4.3: Bias extension test: gripper stress for 50 kN.

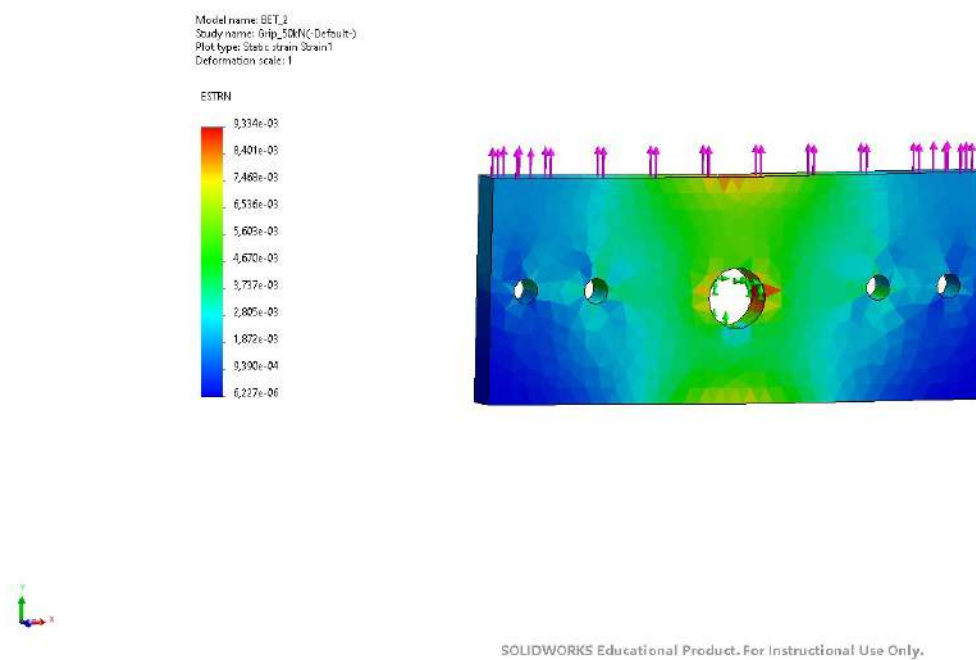


Figure 4.4: Bias extension test: gripper strain for 50 kN.

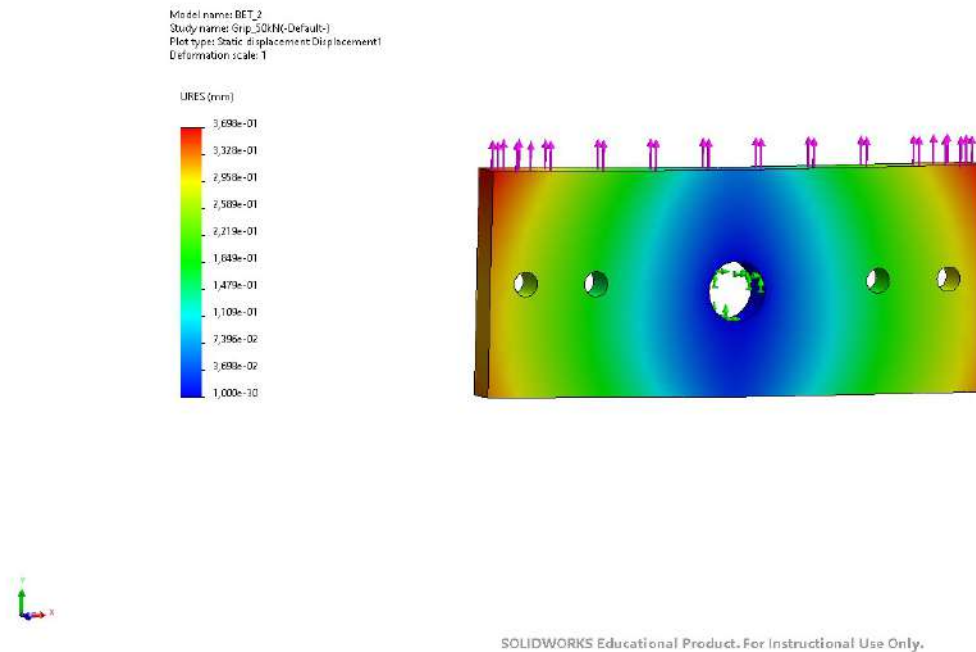


Figure 4.5: Bias extension test: gripper displacement for 50 kN.

Past the yield strength of the 1060-H12 alloy (75MPa), the deformation on the gripper is permanent and won't return to its original dimensions. The trouble here is that the part breaks in the red zone around the screw hole because the material's tensile strength is only 85 MPa. (Figure 4.3)

These values are not a concern for this study with fibrous reinforcements and other studies that may be done in the future, p.e. using thermoplastic or thermoset pre-impregnated or other semi-processed materials. Even if it is to take the sample materials to break, the testing machine won't reach force enough to deform the gripper's material.

Experimental procedure

For this experiment, two carbon and five different glass fibre reinforcement structures were chosen, the details of which are presented in Table 4.2.

The samples were cut from the fabric roll in a length to width ratio of 2 (120 x 60 mm²). Although considering the gripped area of the sample, the cutting area was expanded to 190 x 60 mm² so that it provides sufficient interaction between the fabric and the grips. The cuts were executed considering that in the testing position of the sample, the warp and weft directions of the tows were oriented at 45° to the applied force (Figure 4.6).

Table 4.2: Properties of the materials used in bias extension testing.

Reference	Fibre	Structure	0° (g/m ²)	+45° (g/m ²)	90° (g/m ²)	-45° (g/m ²)	CSM (g/m ²)	Stitching (g/m ²)	Total areal weight (g/m ²)
CF PW	Carbon	Balanced plain weave							195
CF T	Carbon	Balanced will							195
GF PW	Glass	Balanced plain weave							200
GF B45	Glass	Biaxial	-	200	-	200	+150/+225	8	408/558/633
GF B90	Glass	Biaxial	210	-	188	-	-	13	411
GF U200	Glass	Unidirectional	200	-	60	-	-	13	273
GF U400	Glass	Unidirectional	400	-	50	-	-	11	461

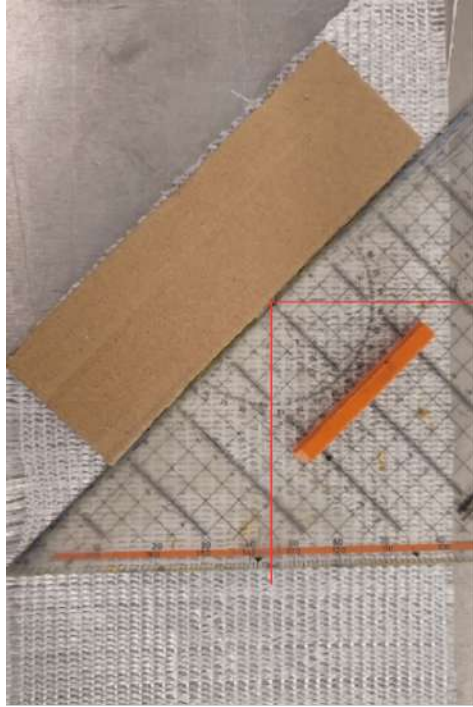


Figure 4.6: Bias extension test: sample cutting at 45°.

A particular recommendation for specimen preparation ensures that the sample has an aspect ratio of two and facilitates image analysis, significantly improving the repeatability of testing results. This procedure presented in [231] was followed, tracing lines along individual tows on the specimens prior to testing (Figure 4.7).

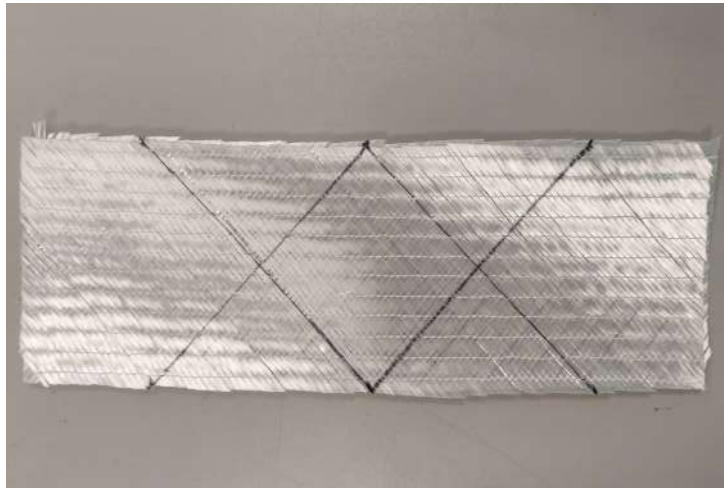


Figure 4.7: Bias extension test: lines traced prior to testing.

A Shimadzu Universal Testing Machine with a 50 kN load-cell was used to perform the bias extension at a 10 mm/min speed [100] (Figure 4.8).

The uniaxial bias extension test was carried out by fixing firmly the samples between the two clamps, equipped with a thin rubber inside to avoid the risk of slippage, and fitted by tying the screws. Tests were recorded using a digital camera attached to the machine, and sample kinematics were measured manually using the open-source image analysis software Image J [234].



Figure 4.8: Bias extension test: experimental setup.

The experiments were conducted until rupture or the maximum force was attained (in the cases that only occurred fibre slippage), and every test was run five times for each type of reinforcement material.

From the videos, images were extracted in an interval of 20 sec starting at $t=0$ (Appendix A.3), and

image analysis (Figure 4.9) was performed to correlate the crosshead displacement and the shear angle at the centre zone A of the sample.

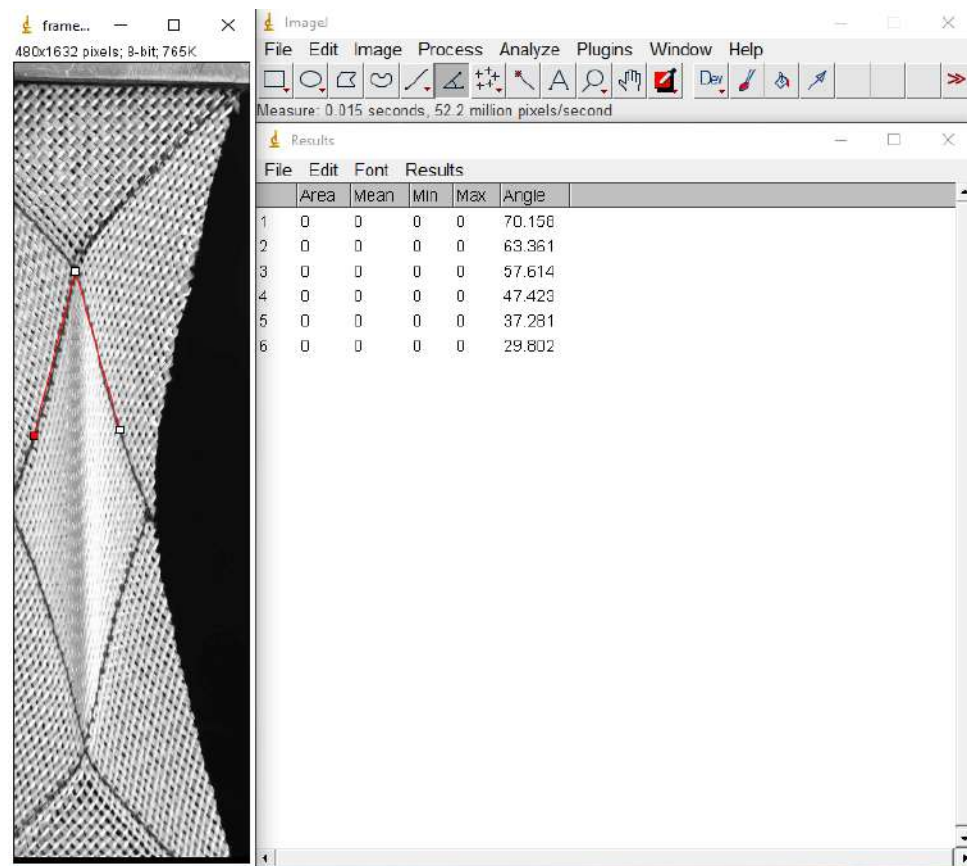


Figure 4.9: Bias extension test: analysis was performed using the ImageJ software.

4.1.2 Picture frame test

Design and simulation

Similar to the bias extension grippers, a frame had to be developed for the picture frame test. Resorting to the Solidworks software and considering the frames from studies such as X and Y, the frames represented in Figure 4.10 were developed. The version taken to manufacturing and used for the experimental procedure was the one on the right because it is more straightforward and facilitates the testing, since all grippers are equal. (Appendix A.1.2).

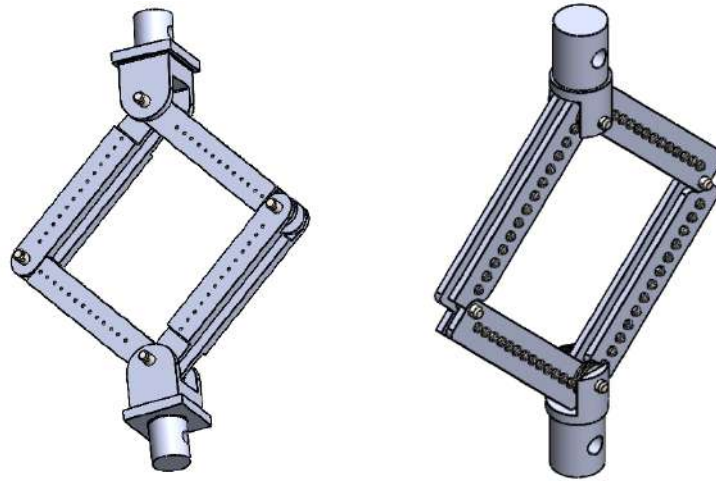


Figure 4.10: Picture frame test: versions of the grippers created using Solidworks software. Final version of the frame (right).

To run the simulations, the same points as for the BET grippers were considered: the maximum load of the testing machine, the direction of the force, and the fixed points for each part. The material was the 1060-H12 aluminium alloy (Table 4.1).

The simulations for the picture frame rig were also executed for both 50 kN and 100 kN. Simulation results for 100 kN can be found in Appendix A.2.2. The pink arrows represent the direction of the force. The fixed point is the middle hole where a screw secures the two plates, and the frame is at 90 degrees since it is the position that requires more effort to attain movement.

As it can be seen from the Figures below, the maximum stress expected for a load of 50 kN is 4651 MPa (Figure 4.11), which is equivalent to a 0.04 strain (Figure 4.12) resulting in a displacement of 9 mm (Figure 4.13).

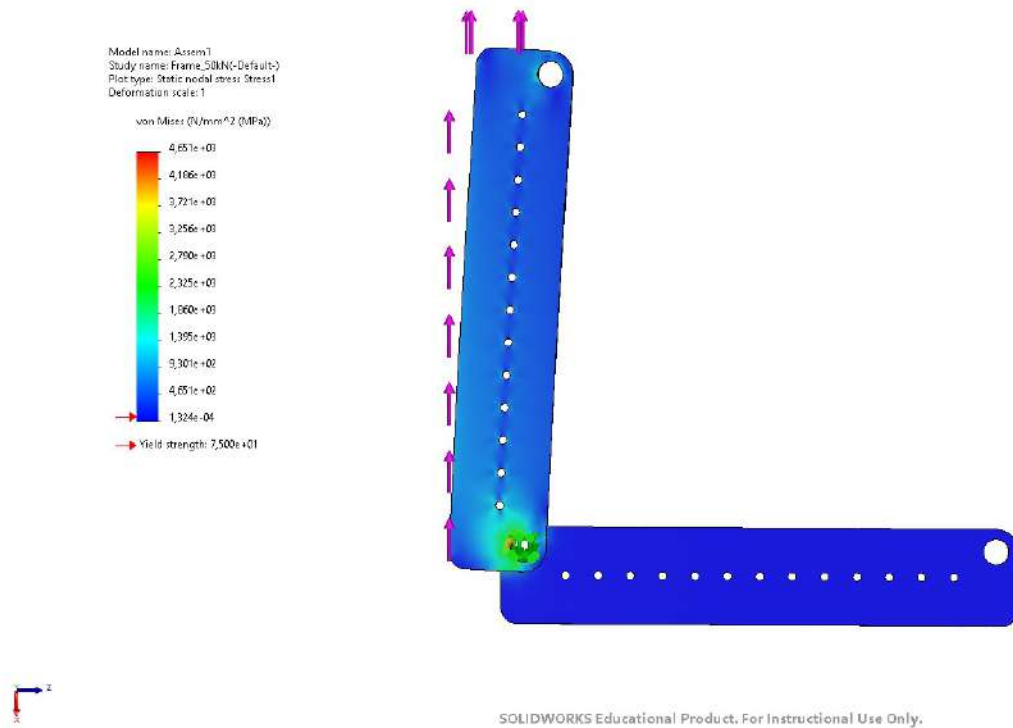


Figure 4.11: Picture frame test: frame rig stress for 50 kN.

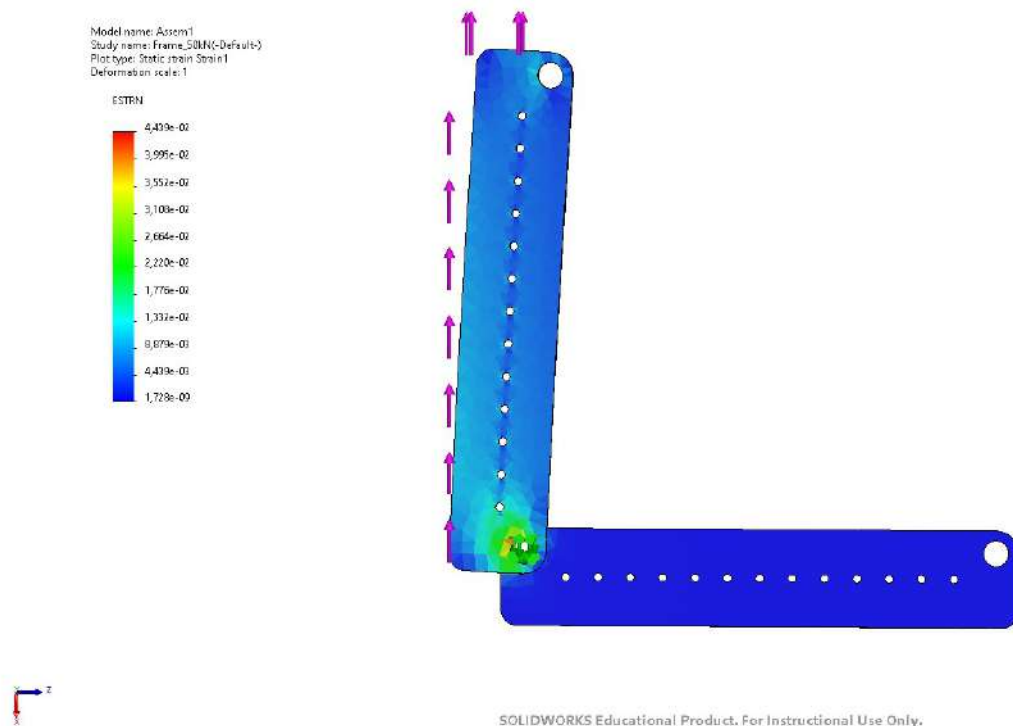


Figure 4.12: Picture frame test: frame rig strain for 50 kN.

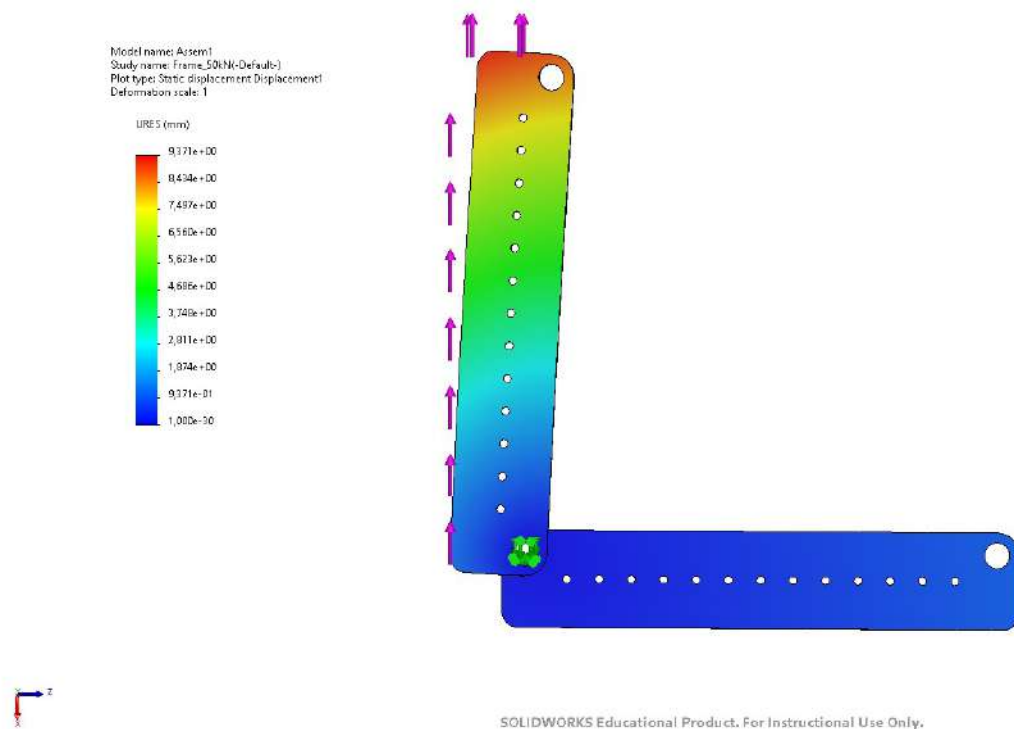


Figure 4.13: Picture frame test: frame rig displacement for 50 kN.

Permanent deformation and breakage happen around the screw hole due to stress values much greater than the yield and tensile strength of the 1060-H12. (Figure 4.11) However, overall the plates handle the stress very well, and little deformation can be seen (Figure 4.12). In this case, the displacement is not problematic because of the frame's axial movement when testing.

Even though the results from the finite element simulations for 50 kN, the accessories were manufactured with the same thickness as the one used in the simulations. This decision was based on the fact that the force applied while testing fibrous reinforcements is minimal compared with the machine's total strength; the frame won't be subjected to such heavy loads.

Experimental procedure

For this experiment, only the glass fibre reinforcement structures were used. The properties of the materials can be found in Table 4.3.

The samples were initially cut into $210 \times 210 \text{ mm}^2$ squares. Since the side length of the frame rig used is 150 mm, squares were cut at each end to obtain a gripped area with length of 130 mm and the shape presented in Figure 4.14 was achieved. The samples were cut with electric scissors to prevent fibre slippage and local fibre pull-out.

Table 4.3: Properties of the materials used in picture frame testing.

Reference	Fibre	Structure	0° (g/m ²)	+45° (g/m ²)	90° (g/m ²)	-45° (g/m ²)	CSM (g/m ²)	Stitching (g/m ²)	Total areal weight (g/m ²)
GF PW	Glass	Balanced plain weave							200
GF B45	Glass	Biaxial	-	200	-	200	+150/+225	8	408/558/633
GF B90	Glass	Biaxial	210	-	188	-	-	13	411
GF U200	Glass	Unidirectional	200	-	60	-	-	13	273
GF U400	Glass	Unidirectional	400	-	50	-	-	11	461

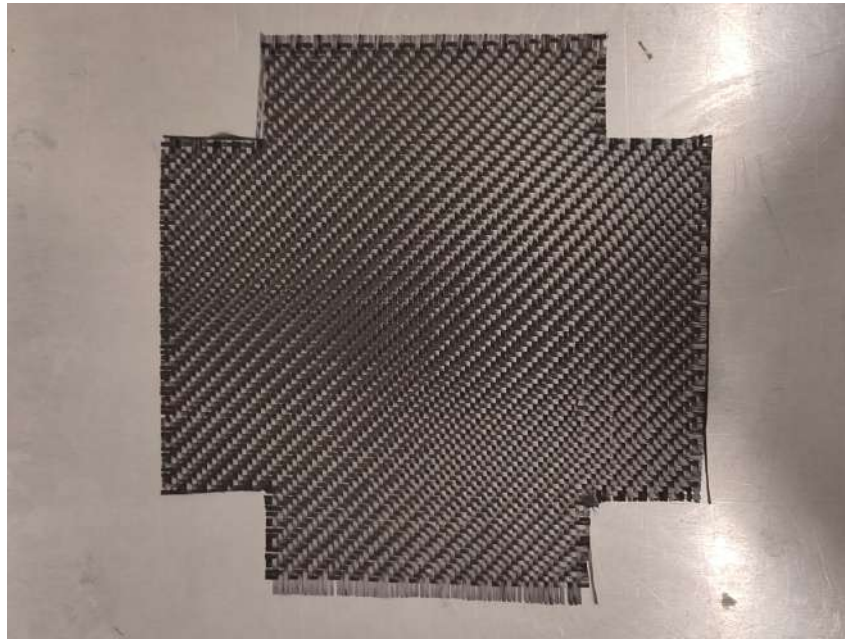


Figure 4.14: Picture frame test: preform of the samples.

The same Shimadzu Universal Testing Machine with a 50 kN load-cell was used to perform the picture frame test at a 10 mm/min speed.

The picture frame test was carried out by fixing firmly the samples between the frame rig and fitted by tying the screws. The frame was then mounted vertically on the testing machine. Tests were recorded using a digital camera attached to the machine, and sample kinematics were measured manually using the open-source image analysis software Image J. The experimental setup can be seen in Figure 4.15.

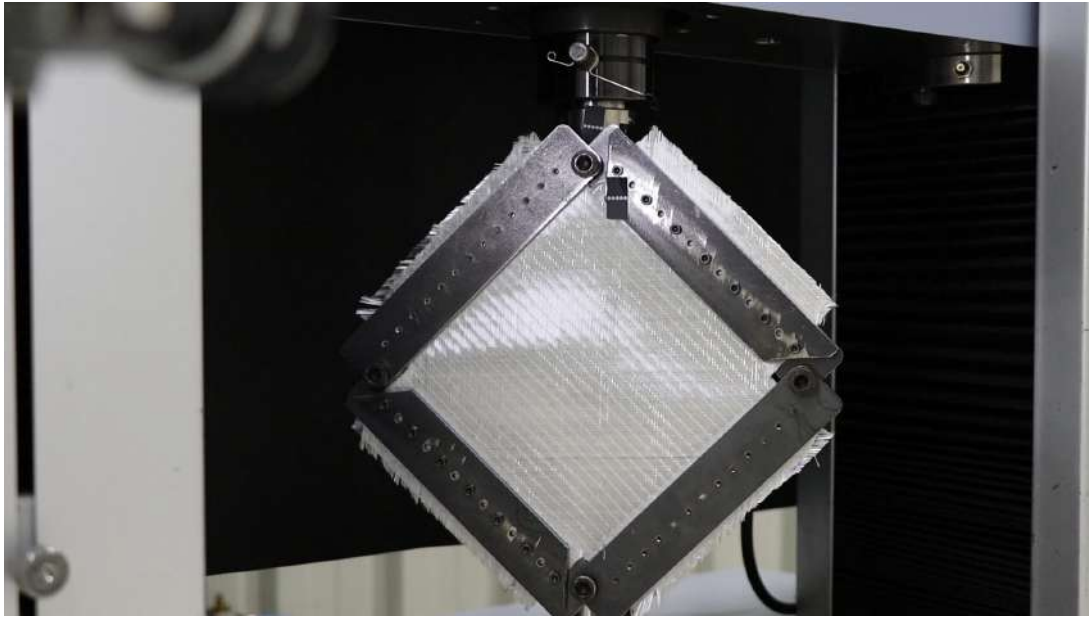


Figure 4.15: Picture frame test: experimental setup.

The experiments were conducted until rupture or until the maximum force was attained (in the cases that only occurred fibre slippage), and every test was run three times for each type of reinforcement material.

From the videos, images were extracted in an interval of 30 seconds starting at $t=0$ (Appendix A.3), and manual image analysis was performed using the same method as in the bias extension test.

4.2 Compression properties

Design and simulation

Following the same procedure as for the shear accessories, a set of plates was designed and tested for the compression test in accordance with the International Standard ISO 5084. Technical drawings are in Appendix A.1.3 and all simulation results can be found in Appendix A.2.3.

However, it did not go forward to manufacturing since PIEP had compression plates available, so it was possible to adapt and perform the tests without needing new plates.

Experimental procedure

For this experiment, a plain weave carbon fibre and five different glass fibre reinforcement structures were chosen, the details of which are presented in Table 4.4.

The samples were cut in $120 \times 120 \text{ mm}^2$ squares with the help of electric scissors (Figure 4.16).

Table 4.4: Properties of the materials used in compression testing.

Reference	Fibre	Structure	0° (g/m ²)	+45° (g/m ²)	90° (g/m ²)	-45° (g/m ²)	CSM (g/m ²)	Stitching (g/m ²)	Total areal weight (g/m ²)
CF PW	Carbon	Balanced plain weave							195
GF PW	Glass	Balanced plain weave							200
GF B45	Glass	Biaxial	-	200	-	200	+150/+225	8	408/558/633
GF B90	Glass	Biaxial	210	-	188	-	-	13	411
GF U200	Glass	Unidirectional	200	-	60	-	-	13	273
GF U400	Glass	Unidirectional	400	-	50	-	-	11	461

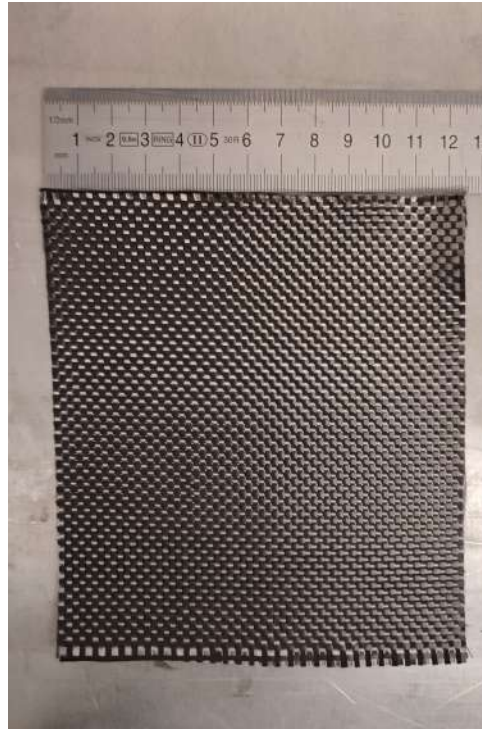


Figure 4.16: Compression test: cut carbon fibre sample.

Since the layers of a composite part generally have different orientations, to see the orientation's influence on the reinforcement's compressive behaviour, different cases were considered, going up to a stack of eight layers oriented at different angles (90°, 45° or 0°). Because of this, some tests were conducted using multiple samples of the same reinforcement in order to obtain the desired laminate structure.

For each reinforcement, the number of samples was cut according to the laminate layers to be tested, for example, in total were cut 27 samples of GF U200 (Table 4.5).

Table 4.5: Compression test: number of layers for each laminate tested for GF U200.

Test	Material	Number Layers	Laminate (°)
1	GF Unidirectional (200g/m2)	1	0
2		2	0/90
3		3	0/90/0
4		4	0/90/90/0
5		2	0/45
6		3	0/45/0
7		4	0/45/45/0
8		4	0/45/0/45
9		4	45/0/0/45

A Shimadzu Universal Testing Machine with a 50 kN load-cell was used to measure the fabric thickness. Both bottom and top plates have a diameter of 100 mm. The tests were performed at a 1 mm/min speed with a maximum load of 785,39 N, equivalent to 1 bar, which is related to the compression used in the VARI process, where the reinforcement is compressed to 1 bar of absolute pressure. Every test combination of parameters was run once using each type of reinforcement material.

Following the International Standard ISO 5084, the thickness gauge was set to read zero, and a pressure of approximately 7,5 N (corresponding to the recommended 1 kPa) was applied to calculate the initial thickness. The presser-foot was raised, and the sample was positioned in place without tension or distortion. The presser-foot was then lowered slowly onto the sample, and the initial thickness read in the gauge was noted (Figure 4.17).



Figure 4.17: Compression test: experimental setup.

The tests performed were single-cycle experiments which consist of compaction performed until the maximum load is achieved and then a rest period while compacted at that same load. Figure 4.18 is a schematic representation of the cycle.

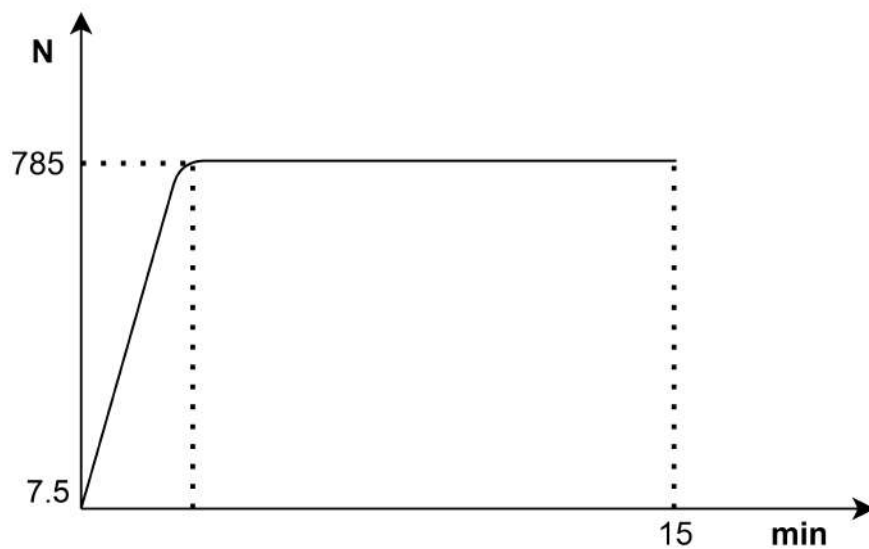


Figure 4.18: Compression test: schematic of the single cycle compaction.

Chapter 5: Results and discussion

5.1 Shear properties

5.1.1 Bias extension test

This section presents the graphs of the average shear angle values variation between the different materials tested and the comparison of the theoretical shear angle and the mean of the actual measured angle for each reinforcement type. The graphs representing all the individual angle values measured are in Appendix A.4.

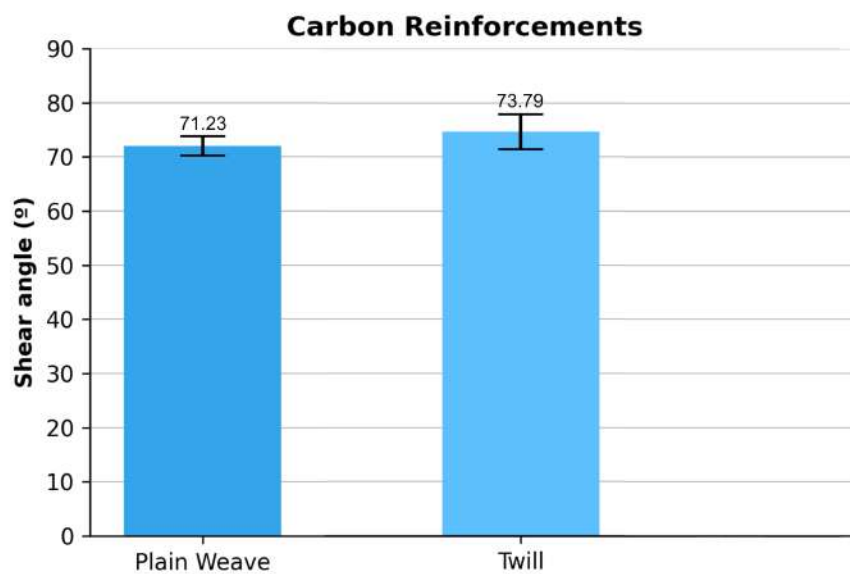


Figure 5.1: Bias extension test: Average shear angle variation of the different carbon samples, in degrees.

In Figure 5.1 it can be seen that the plain carbon presents a maximum shear angle value of 71.23°, which is lower than the twill of 73.79°.

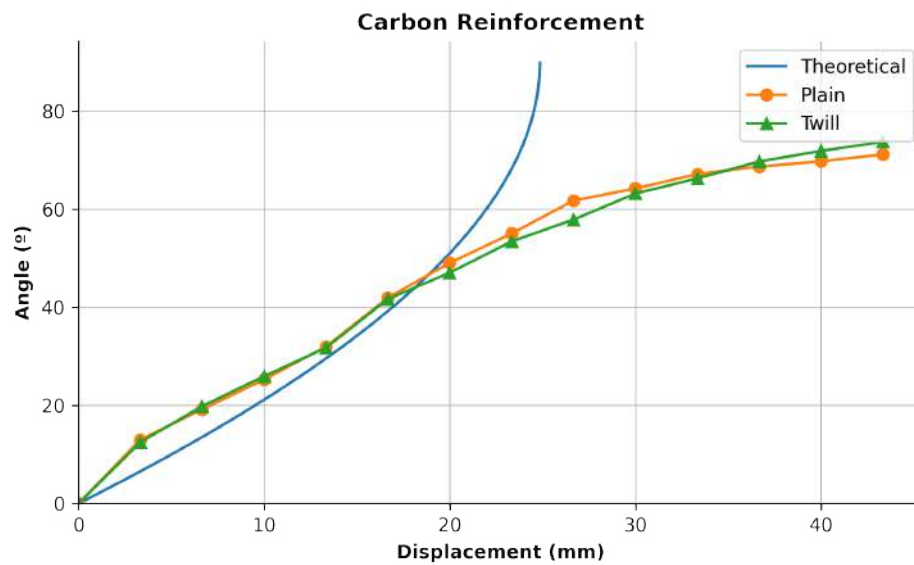


Figure 5.2: Bias extension test: Plot of the theoretical and average measured shear angle vs. displacement of the carbon samples.

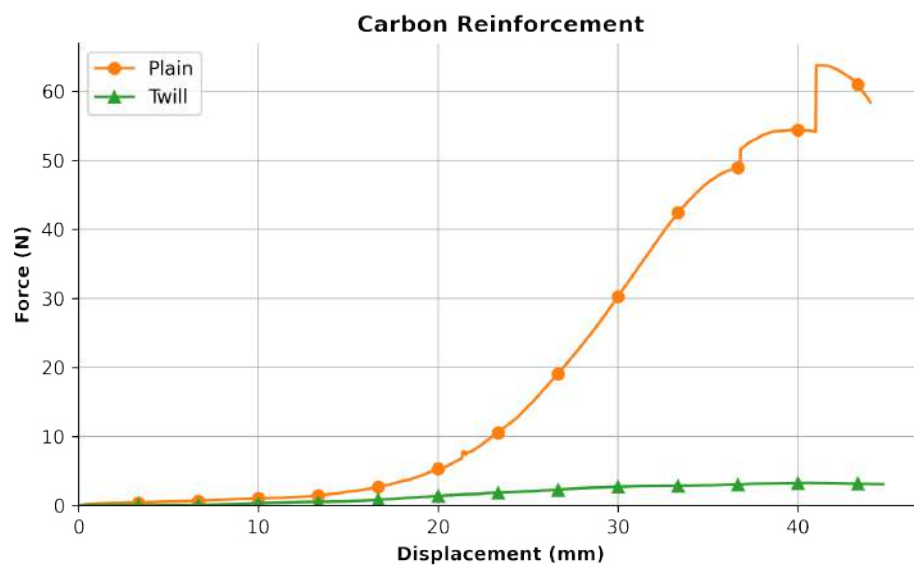


Figure 5.3: Bias extension test: Plot of the average force vs. displacement of the carbon samples.

In Figure 5.2 the solid lines with symbols represent the result from the measurements of angles based on the image analysis, while the solid blue line is the theoretical shear angle calculated by Equation 3.1. Both carbon structures present a similar behaviour and the theoretical shear angle calculated can accurately reflect the true shear angle in the fabric until it reaches a value of 43° . The difference between theoretical and true angles was below 8° until the 43° shear angle and became larger after that.

The twill weave show less shear resistance than the plain weave, which can be attributed to the lower

number of fibre interlaces than in the plain weave, the critical shear angle is similar, but lower shear force is needed, as can be seen in Figure 5.3.

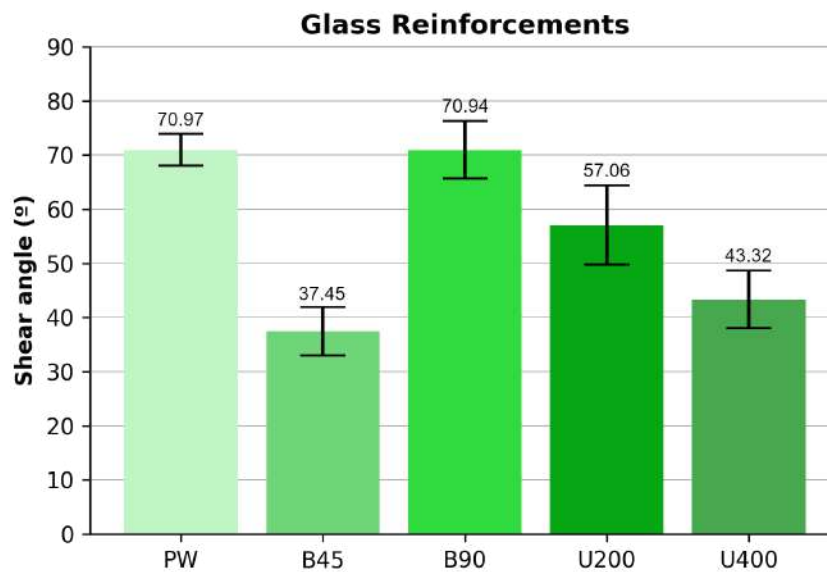


Figure 5.4: Bias extension test: Average shear angle variation of the different glass samples, in degrees.

Figure 5.4 shows that the B45 glass fabric presents the lowest shear angle value of only 37.45° while PW and B90 present the highest values, 70.97° and 70.94° , respectively.

Among the different types of reinforcement, the one with the greatest disparity of results between samples was the U200, with a standard deviation of 7.28° ; while the PW had the more consistent results with only a standard deviation of 2.89° .

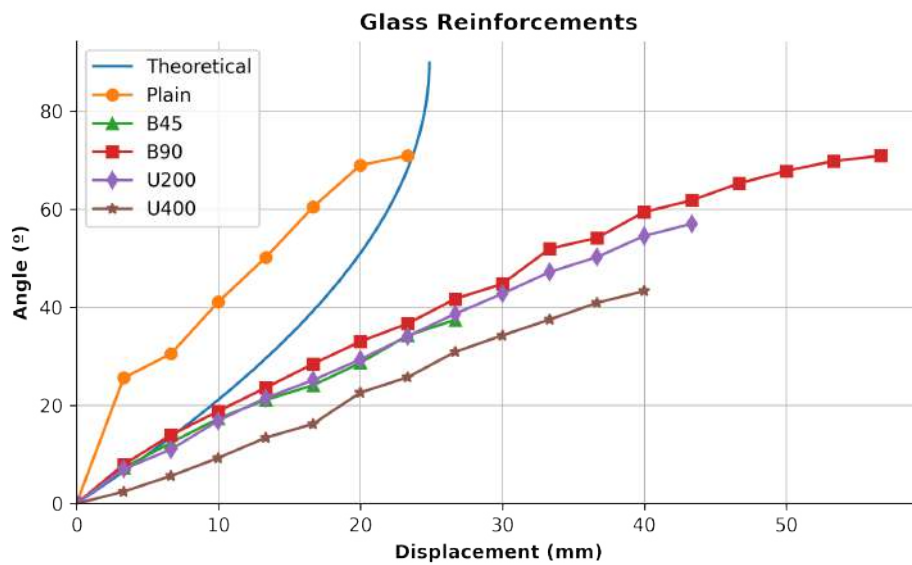


Figure 5.5: Bias extension test: Plot of the theoretical and average measured shear angle vs. displacement of the glass samples.

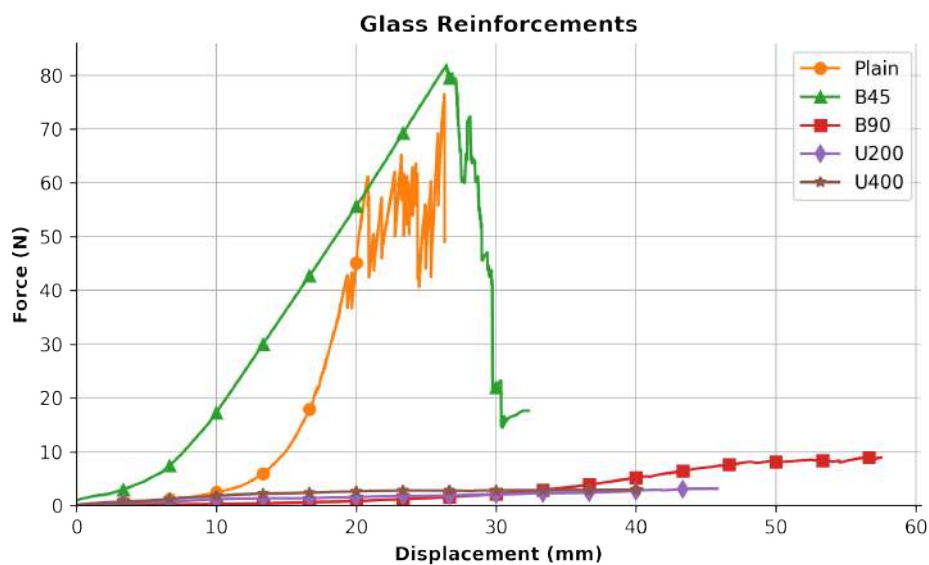


Figure 5.6: Bias extension test: Plot of the average force vs. displacement of the glass samples.

In Figure 5.5 it can be seen that the theoretical shear angle reflects very accurately the shear angle measured for most of the reinforcements until approximately 20°. Afterwards, the difference between theoretical and measured can be as much as 65°.

From analysing Figures 5.5 and 5.6 it can be concluded that when it comes to the biaxial structures, they present almost opposite behaviours. B45 presents a low shear angle and reached high force values (81.94 N) in little displacement (32.32 mm) occurring rupture, while B90 presents the highest shear angle

and reached only 8.95 N in a displacement of 57.51 mm occurring only fibre slippage.

Although B45 and B90 are both biaxial reinforcements with similar areal weight, they are very different in architecture, mainly in the stitching pattern (Figure 5.7). While in B45, a kind of lock-stitch is used in its structure, in B90, a kind of zigzag stitching is used, which is more flexible and allows wider distortions. These differences can explain the registered behaviour.

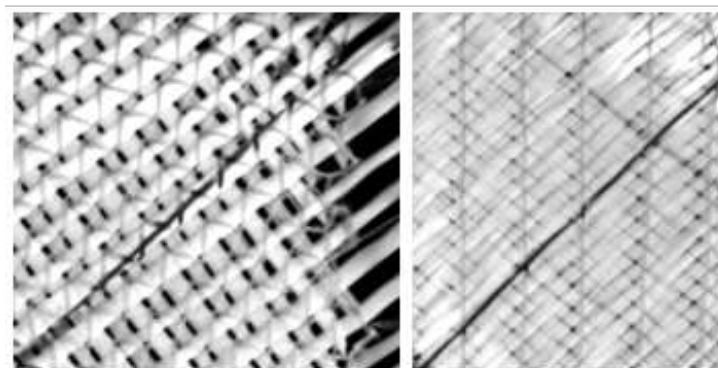


Figure 5.7: Stitch: B90 (left) vs B45 (right).

The unidirectional structures present similar shear angles (U200: 57.06° and U400: 43.32°) and almost the same displacements and force (U200: 45.79 mm, 3.17N; U400: 40.44 mm and 3.09 N). The difference between their behaviour is that U200 reaches higher shear angles in an early stage of the test, while U400 starts reaching higher angle values only around 2.6 N.

When comparing the two reinforcements with the highest shear angles, it can be noted that for the plain weave, PW, it was needed minimal displacement to reach maximum force, while for the B90, as mentioned before, it was necessary little force to end the test, but it took a significant displacement.

The large displacement observed for B90 occurs due to the flexible stitching, which allows more significant slip between the filaments within the fabric, sometimes at the expense of the reinforcement structure integrity (Figure 5.8). While the structure of the plain weave limits the slippage between filaments, more force is necessary to reach the same shear angle.

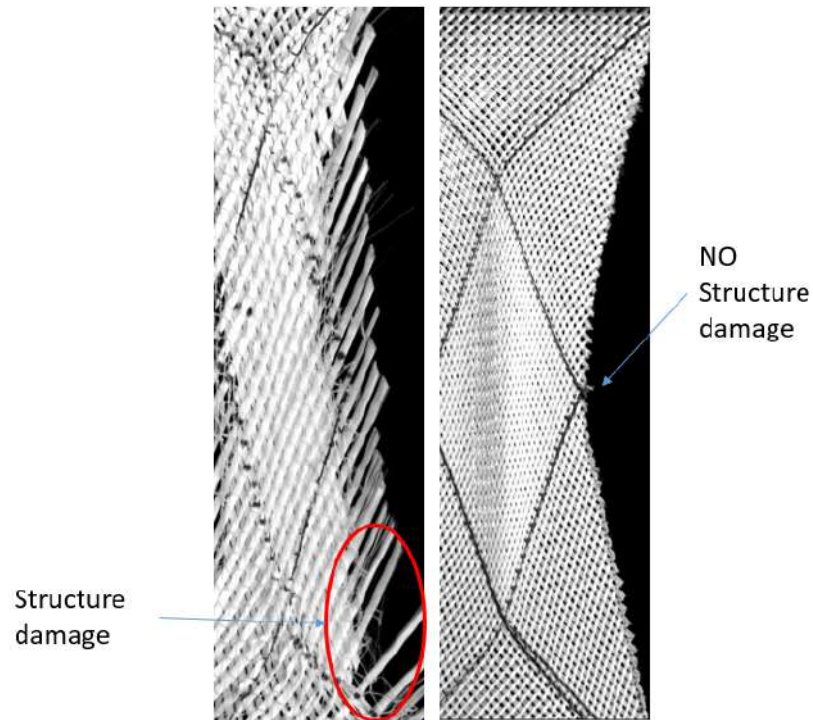


Figure 5.8: Distortion: B90 vs plain.

Another comparison that can be done is between the plain weaves, carbon and glass (Figure 5.9). They present almost the same shear angle (C: 71.23° and G: 70.97°) and similar behaviour regarding shear angle variation through force, as can be seen in Figure 5.10 and Figure 5.11.

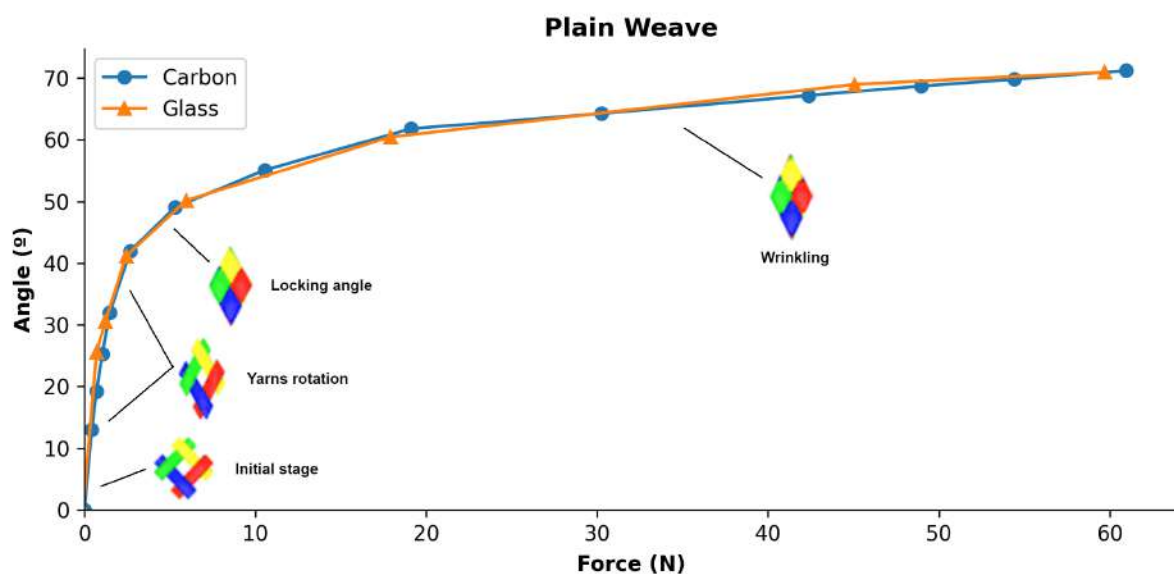


Figure 5.9: Bias extension test: Plot of the average measured shear angle vs force for the plain weaves.

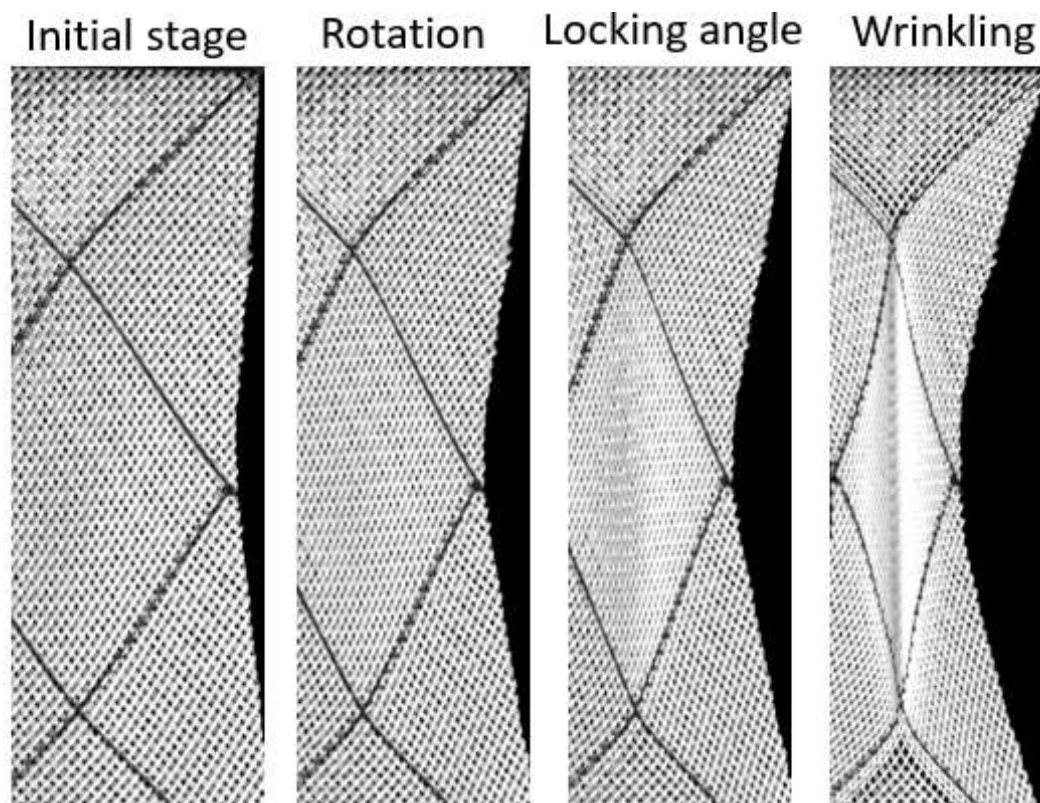


Figure 5.10: Bias extension test: glass fibre plain weave.

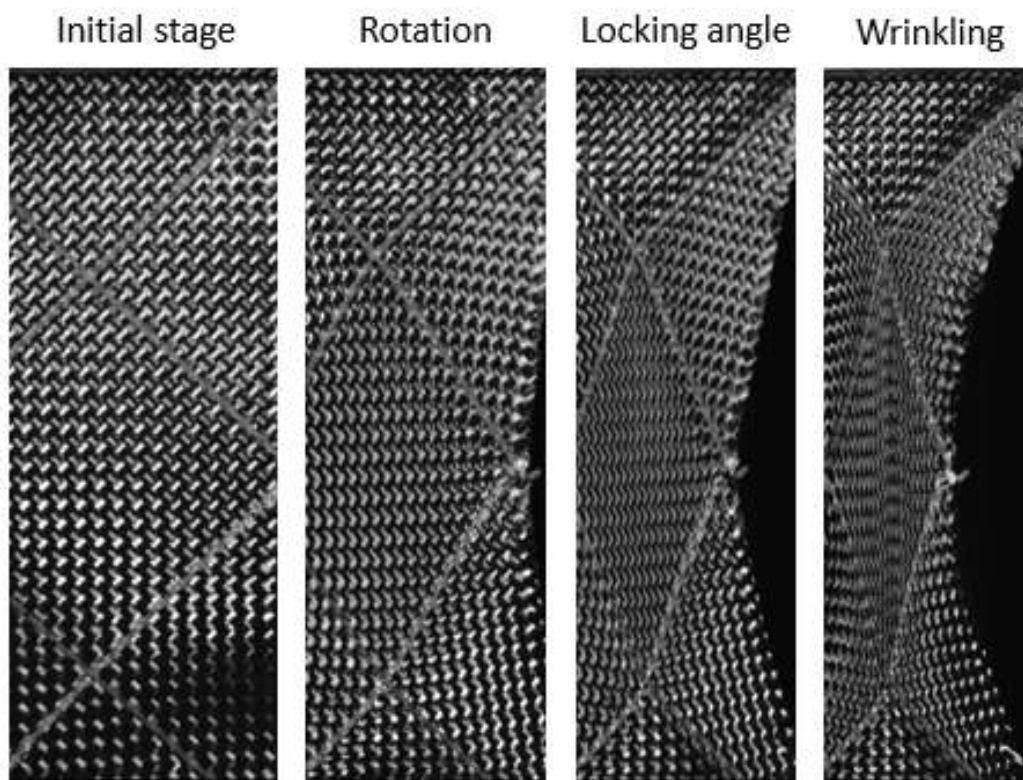


Figure 5.11: Bias extension test: carbon fibre plain weave.

In this case, the structure of the fibrous reinforcements plays a significant role (Figure 5.12). Although both reinforcements are plain weaves with similar areal weight (Table 4.2), the yarn density within the fabric structure is considerably different. The glass fibre plain weave has, on average, 1.5 more yarns (but thinner) in the same distance as the carbon fibre plain weave. This means that it has more fibre interlace points, resulting in more friction and more limited movement of the yarns. Consequently, for the same shear angle, the glass fibre plain weave presents more shear resistance than the carbon fibre plain weave, presenting less displacement for similar force values (see also Figures 5.3 and 5.6). In addition, other unaccounted factors, such as finishing treatments, can also contribute to the described behaviour.

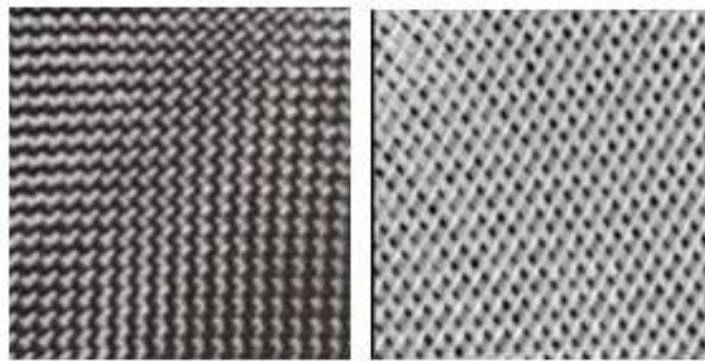


Figure 5.12: Structure of the plain weave: CF (left) vs GF (right).

5.1.2 Picture frame test

Comparing the results obtained from the picture frame test and the bias extension, PFT sampling shows more accuracy of results than the BET. The graphs representing all the individual angle values measured are in Appendix A.4.

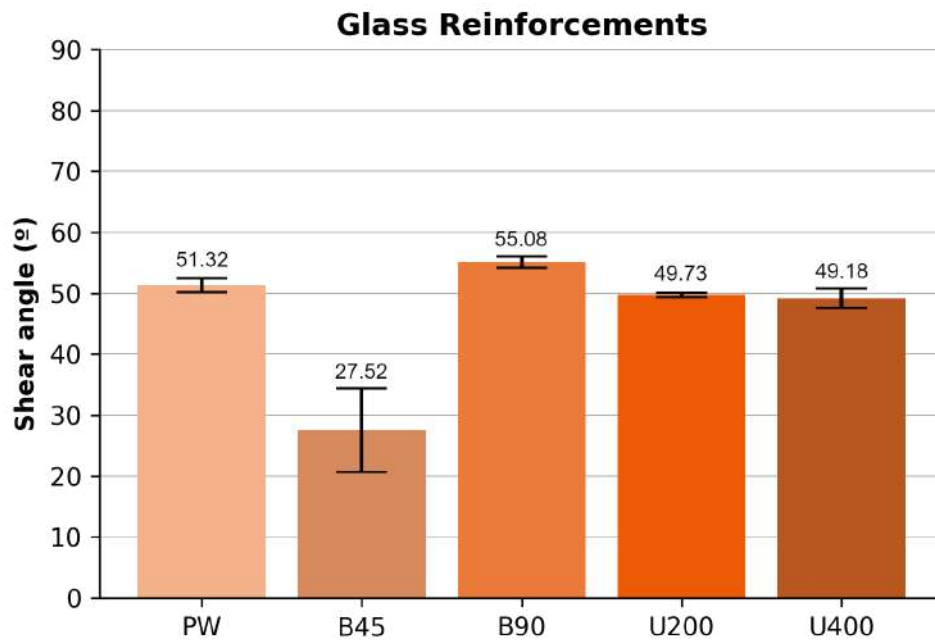


Figure 5.13: Picture frame test: Average shear angle variation of the different glass samples, in degrees.

It can be seen in Figure 5.13 that among the different types of reinforcement, the one with the greatest disparity of results between samples was B45, with a standard deviation of 6.84° . In contrast, U200 had the more consistent results with only a standard deviation of 0.33° , followed by B90 with 0.98° , U400 with 1.59° and PW with 1.11° .

The glass fibre reinforcements B90 and PW present the highest shear angles measured with 55.08° and 51.32° , respectively. Both U200 and U400 have almost the same shear angle, 49.73° and 49.18° , respectively. The lowest shear angle is from B5 with only 27.52° .

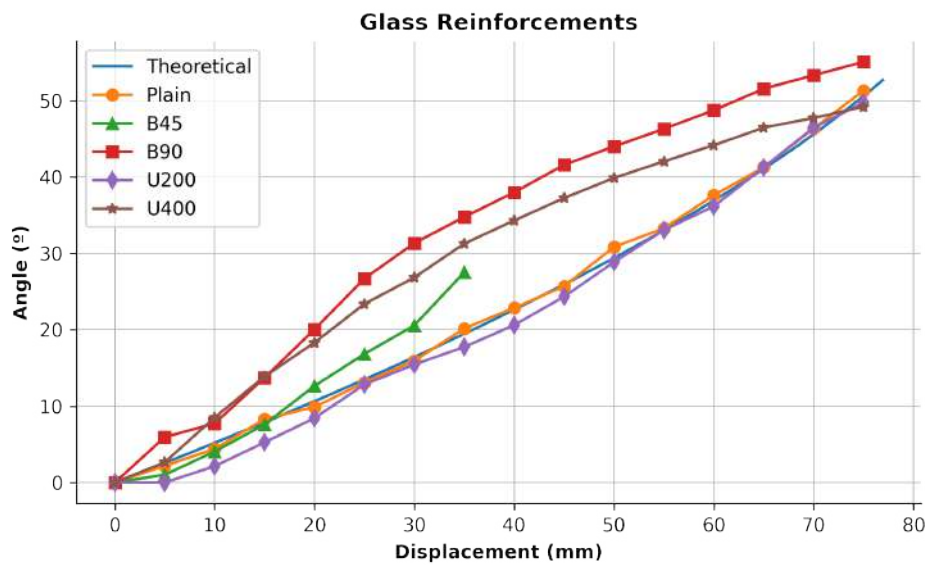


Figure 5.14: Picture frame test: Plot of the theoretical and average measured shear angle vs. displacement of the glass samples.

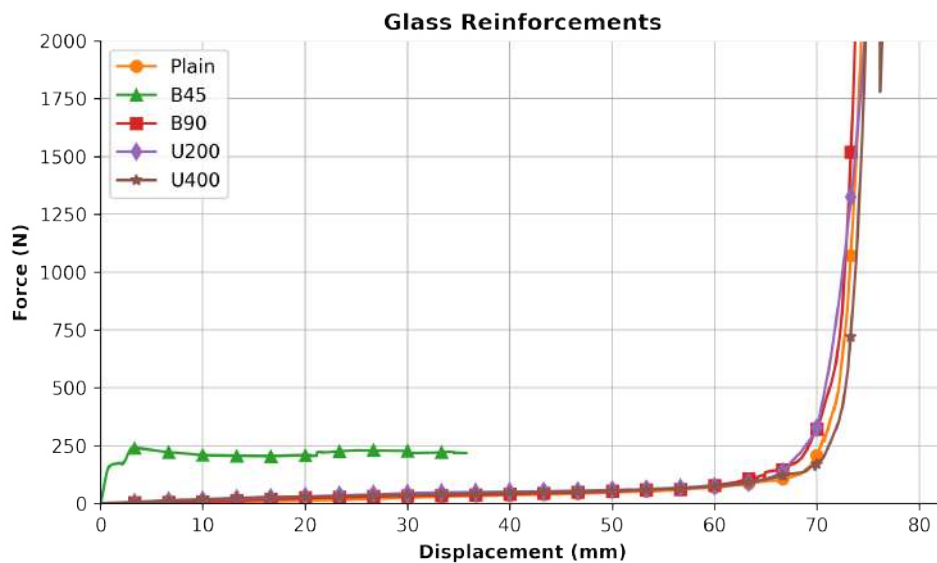


Figure 5.15: Picture frame test: Plot of the average force vs. displacement of the glass samples.

The Figure 5.14 shows that the theoretical shear angle reflects almost precisely the true shear angle of PW and U200. On the other hand, B90 and U400 show a behaviour utterly different to that of the theoretical but at higher shear angles, greater than 40° , the experimentally measured shear angle begins to converge towards the theoretical.

With the exception of B45, all other glass reinforcements have presented a pattern of behaviour regarding the force-displacement rate. Around approximately 70 mm of displacement, all forces, that up

until then were extremely low, significantly increased, reaching the maximum force in less than 10 mm of displacement. This rise in force during deformation might be associated not only with the lock-up of the material.

Data in Figures 5.14 and 5.15 indicates that although both unidirectional structures differ essentially in areal weight (thicker yarns in the case of U400 than in U200, but with a similar count of yarns per length and stitching pattern - Figure 5.16), their behaviour throughout testing is very distinct, U400 attains higher shear angles from the beginning, reaching a difference of almost 20° at 40 mm of displacement.

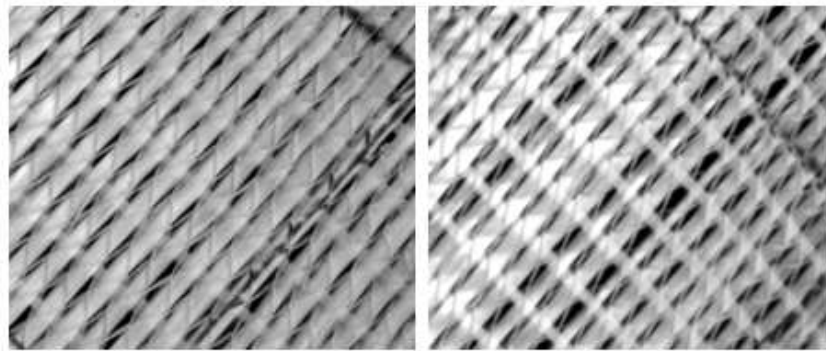


Figure 5.16: Structure of the unidirectional glass fibres: U400 (left) vs U200 (right).

As biaxial structures, B45 and B90 do not have the same structure, therefore do not present similar responses to shear. B45 has lower shear angle than B90, and the displacement is also considerably higher for B90 than for B45.

The most important difference between B90 and B45 is the orientation of the fibre relative to the direction of the load: in the production direction of the reinforcement, in B90, fibres are oriented at 0° and 90° , while in B45, fibres are oriented at $+45^\circ$ and -45° . During the PF test, the load is applied to the sample at 45° (Figure 5.17). This means that for B90, the load is applied at 45° relative to the fibre length, while for B45, the load is applied along the fibre length.

This behaviour is, then, explained by the fact that, during the picture frame test, the shear distortion is applied along the length of the fibres in B45. Due to the fibres' lack of extensibility, by increasing the applied load, the reinforcement structure starts to buckle and eventually starts to break. Resulting in minimal distortion. On the contrary, in bias extension tests, the stitching pattern was the main difference between reinforcement structures. In those tests, the load was applied, in both B90 and B45, at 45° relative to the fibre length direction (Figure 5.18).

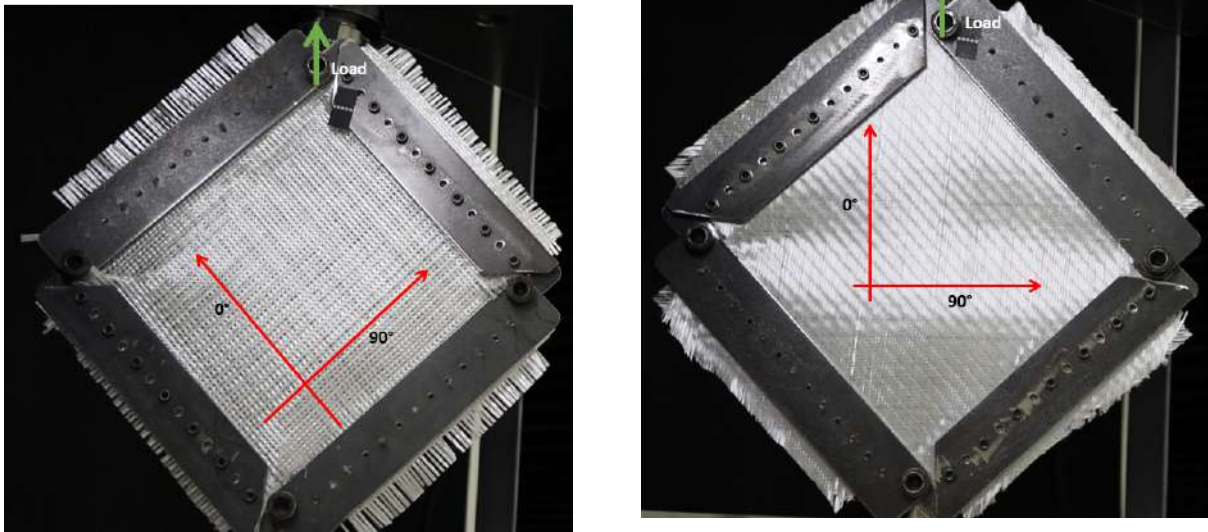


Figure 5.17: Picture frame test: sample orientation versus load. B90 (left) vs B45 (right)

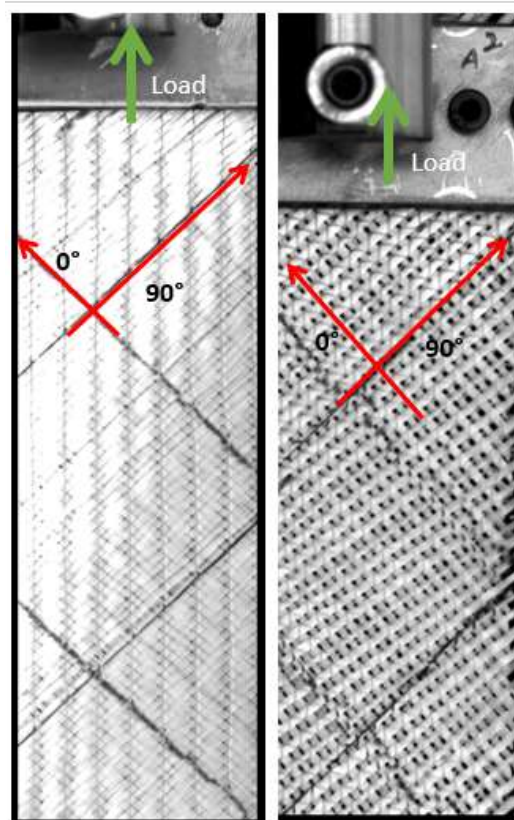


Figure 5.18: Bias extension test: sample orientation versus load. B45 (left) vs B90 (right)

When comparing the bias extension and picture frame tests, the more noticeable difference is between B45 results. In PFT, the fibre hardly distorts, and with the increasing force, it immediately starts to buckle, forming a wrinkle in the centre. This happens because the B45 in the roll is already oriented at $\pm 45^\circ$; as

the PFT test does distort at 45° , in this particular case, it is exerting force along the length of the fibre. As the fibres are inextensible, they start to wrinkle and break as the force increases. In the case of the BET, the same does not apply. For B45, the samples were cut in the direction of the fibre roll (at 45°) and not with the 45° rotation as for the other samples. If the fibres were rotated as in the other cases, the machine would exert load along the length of the fibres. And as in the PFT, it would have reduced/null distortion as seen in Figure 5.19.

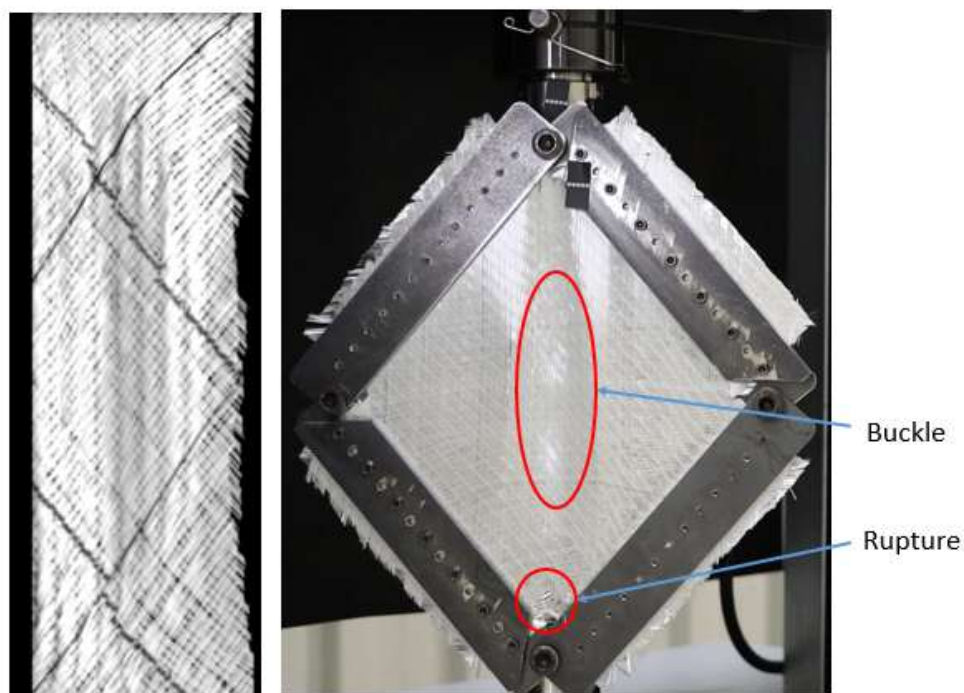


Figure 5.19: B45: with distortion (BET) vs without distortion (PFT).

5.2 Compression properties

For the compression results, the thickness at 7.5 N was measured and considered the initial thickness and appears in the cycle as a pre-load (Figure 4.18). Then, the load was increased up to 785.39 N and the final thickness was the value measured at the end of the 15 minutes of rest at that same force. The value was then subtracted from the initial one to obtain the thickness of the samples after compaction (absolute compressibility). The following tables show the thickness variation and the percentage of compaction (relative compressibility, according to DIN53885 3.17) of each laminate for the different fibrous reinforcements.

Table 5.1: Compression test: thickness variation of the glass U200 samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0	0.57	0.29	0.28	48.64
2	0/90	1.01	0.51	0.50	49.43
3	0/90/0	1.44	0.79	0.65	44.79
4	0/90/90/0	1.92	0.98	0.94	48.96
5	0/45	0.99	0.54	0.45	45.67
6	0/45/0	1.53	0.78	0.75	48.92
7	0/45/45/0	2.18	1.01	1.17	53.32
8	0/45/0/45	1.96	1.02	0.94	47.81

From Table 5.1 it can be seen the influence that the orientation has on the compressibility of the unidirectional reinforcement U200. For example, samples 2 and 5 have the same number of layers, but sample 5 is oriented at 45°. S2 presented a thickness after compression of 0.5 mm and S5 of 0.45 mm. This means that S2 holds up better to compression.

The opposite happens with S3 and S6, which differ from each other in the orientation of the middle layer, and have one more layer than S2 and S5. The same behaviour is observed for S4 and S7.

The results also show that the prediction of the compression of a complex laminate is not straightforward, and care should be taken with extrapolations because the accommodation of a specific layer depends on the adjacent layers. For example, laminates S4 and both S7 and S8 can be seen as the combination of S2 and S5, i.e., S4 and S7 are formed by overlapping S2 and S5, respectively, with rotation along the layer plane, and S8 is formed by just overlapping S5.

Table 5.1 shows that S4 has a bigger variation of thickness than S2 (S2 = 0.5 mm and S4 = 0.94 mm) but when comparing the percentage of compaction considering the initial thickness (Equation 3.17), S2 shows a slight higher value (S2 = 49.43% and S4 = 48.96%). S7 is the more compressible combination with a relative compressibility of 53.32%.

In general, it shows that for U200, less compaction is obtained with 90° fibre orientation and higher compression is obtained by overlapping layers with the same orientation.

Table 5.2: Compression test: thickness variation of the glass U400 samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0	0.69	0.38	0.31	45.20
2	0/90	1.30	0.75	0.55	42.31
3	0/90/0	1.94	1.13	0.81	41.60
4	0/90/90/0	2.50	1.49	1.01	40.16

Table 5.3: Compression test: thickness variation of the glass U200 samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0/0	1.01	0.57	0.44	43.95
2	0/0/90/90	1.75	0.97	0.78	44.23
3	0/0/90/90/0/0	3.00	1.50	1.50	49.78
4	0/0/90/90/90/90/0/0	3.87	1.97	1.90	49.10

Tables 5.2 and 5.3 help to understand the compaction with the highest and lowest grammage considering the same orientation. The laminates from U200 (200 g/m^2) have two layers for each layer of U400 (400 g/m^2). From the results, it can be concluded that double layers of U200 present higher compaction capability for S2, S3 and S4. But when it comes to having only one layer of U400 against two layers of U200 (S1), U400 shows a percentage of compaction of 45.20% while U200 only presents 43.95%.

This set of results indicates that care should be taken when replacing layers of reinforcement (for example, one layer of U400 for 2 layers of U200) because, due to their different behaviour to compaction, it results in different thickness and fibre volume fraction in the final composite part.

Table 5.4: Compression test: thickness variation of the B45 samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0	0.54	0.30	0.24	44.09
2	(0/90)/(90/0)	0.98	0.58	0.40	40.93

Table 5.5: Compression test: thickness variation of the B90 samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0	0.74	0.42	0.32	43.71
2	(0/90)/(90/0)	1.49	0.80	0.69	46.14

Regarding the biaxial fabrics, interpreting the data from Tables 5.4 and 5.5 it shows that B90 with a thickness variation of 0.32 mm at 0° orientation and 0.69 mm at $(0^\circ/90^\circ)/(0^\circ/90^\circ)$ has higher resistance to compressibility than B45, which presents 0.24 mm at 0° and 0.4mm at $(0^\circ/90^\circ)/(0^\circ/90^\circ)$.

Although they are both biaxial, balanced reinforcements (with similar weight in different directions) and similar total weight, their structure is very different (Figure 5.7). The multifilament of the B45 covers much more surface area than the B90. While the B90 allows accommodating the multifilaments of adjacent layers in the spaces between multifilaments, the B45 no longer has that space, resulting in less compaction as can be seen from S1 thickness variation results.

Table 5.6: Compression test: thickness variation of the glass plain weave samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0	0.21	0.15	0.06	30.13
2	0/0	0.46	0.35	0.11	23.22
3	0/0/0	0.74	0.52	0.22	28.51
4	0/0/0/0	0.95	0.67	0.28	29.92
5	45/0	0.44	0.33	0.11	24.43
6	45/0/45	0.76	0.55	0.21	28.47
7	45/0/0/45	0.98	0.70	0.28	27.65
8	45/0/45/0/45	1.21	0.88	0.33	27.05
9	45/0/45/45/0/45	1.46	1.10	0.36	24.76
10	45/0/45/0/45/0/45	1.76	1.24	0.52	29.26
11	45/0/45/0/0/45/0/45	1.99	1.44	0.55	27.86

Table 5.7: Compression test: thickness variation of the carbon plain weave samples at 785.39 N.

Sample	Laminate	Initial thickness [mm]	Final thickness [mm]	Absolute compressibility [mm]	Relative compressibility [%]
1	0	0.28	0.17	0.11	36.45
2	0/0	0.31	0.09	0.22	71.12
3	0/0/0	0.47	0.19	0.28	59.83
4	0/0/0/0	0.83	0.44	0.39	46.53
5	45/0	0.33	0.12	0.21	61.51
6	45/0/45	0.70	0.38	0.32	44.65
7	45/0/0/45	1.05	0.62	0.43	41.00
8	45/0/45/0/45	1.35	0.92	0.43	31.82
9	45/0/45/45/0/45	1.70	1.07	0.63	36.58
10	45/0/45/0/45/0/45	2.05	1.31	0.74	35.85
11	45/0/45/0/0/45/0/45	2.31	1.53	0.78	33.79

Directly comparing the results of the Tables 5.6 and 5.7, carbon presents for all laminate structures

higher relative compressibility.

In Table 5.6 it is possible to see that S4 with 4 layers oriented to 0° has 0.28 mm of thickness while, p.e., S7 with alternated layers at 0° and 45° also has 0.28 mm. Similar occurs in Table 5.7 for the same laminate samples. As they are balanced fabrics, in which the yarns are braided one by one, these results show that varying the orientation of the layers does not affect the compaction.

Chapter 6: Conclusion

6.1 Conclusions

Computer simulation of the large mechanical deformation during forming of engineering fabrics, such as the ones in this study, is an important topic due to the role of engineering fabrics in manufacturing advanced composite parts. This investigation demonstrates an attempt to characterise their mechanical forming properties using a combination of three test methods, bias extension and picture frame, which were used to characterise the shear behaviour of the fabrics and a compaction test used to characterise the compressive behaviour of the fabrics.

Firstly, the design and manufacture of equipment accessories were necessary to be able to put into practice the test methods researched. The grippers and picture frames turned out to be a more straightforward version of accessories found in other studies and even from the suppliers of the equipment themselves.

When comparing the results from bias extension and picture frame tests, the most considerable discrepancy in results were the glass plain weave and the biaxial 45°. As explained before, this was due to the different structures of the reinforcements and the orientation of the fibres to the applied load. The unidirectional fabrics presented similar behaviour in both tests. There are a few limitations to the bias extension test, such as the existing restraints provided by the grips; thus, the shear distribution is not uniform throughout the specimen. Also, more visible in the force-displacement plot, sudden drops in the load are associated with failure of the fabric near the grips: the sample starts to slide and slip. Some solutions to improve the bias extension test could be having larger samples while maintaining $\lambda = 2$ or securing the ends where the sample was cut with tape, preventing some of the slippage.

The optical methods showed that determining the shear angle mathematically from the crosshead displacement was a reasonable method to a certain extent for both tests performed. In this case, the collected data using optical measurements and the open source software ImageJ proved to be a great facilitator of the analysis work.

Results for the compaction load show that in biaxial and unidirectional glass fabrics, care should be taken when placing layers of reinforcement because, due to their different behaviour to compaction, it results in different thickness and fibre volume fractions in the final composite part. Regarding carbon and

glass balanced fabrics, the variation of the orientation of the layers doesn't show much impact on the compaction results. However, the results comparing the plain weaves were the opposite of the expected ones: carbon presented a higher compaction percentage than glass when it should be the contrary. Even though the areal weight is very similar, carbon has a lower density (approximately 1780kg/m^3) than glass (2600kg/m^3). This means that for the same area, are needed more carbon threads than glass threads to get the same weight. As a result, the carbon threads are thicker and have less space between them, in comparison the glass threads are thinner and have more space between them in the fabric. The less coverage (less filling) of the glass fabric allows for greater compaction because the fibres of one layer will settle into the spaces between fibres of the adjacent layers. In opposition, the carbon fabric has greater coverage (fuller), so it will have less compaction.

Nevertheless, the characterisation methods available were not suitable for the needs of the simulation software and with this work it was possible to adapt the conventional equipment at PIEP in order to characterise the reinforcement materials. The tests and results obtained can be used to simulate and predict fabric performance of composite materials processing in the simulation software for production processes PAM-Composites™.

6.2 Future work

The research work developed in this dissertation aims to contribute to a better understanding of the behaviour of fibrous reinforcements and, at the same time to optimise the simulation of the fabric performance in processing. Therefore, to continue the research developed in this document, the following activities are suggested:

- Investigate the material response under different conditions during bias extension and picture frame: implement testing with an environmental chamber for higher temperature; test to different speeds.
- Perform multiple cycle compaction tests to study the permanent deformation of the materials and when performing the single cycle, do the machine compliance measurements to obtain the thickness calculated by the subtraction of the calibration load-displacement curves.
- Create a database for the materials and properties tested in order to support the use of the simulation software.

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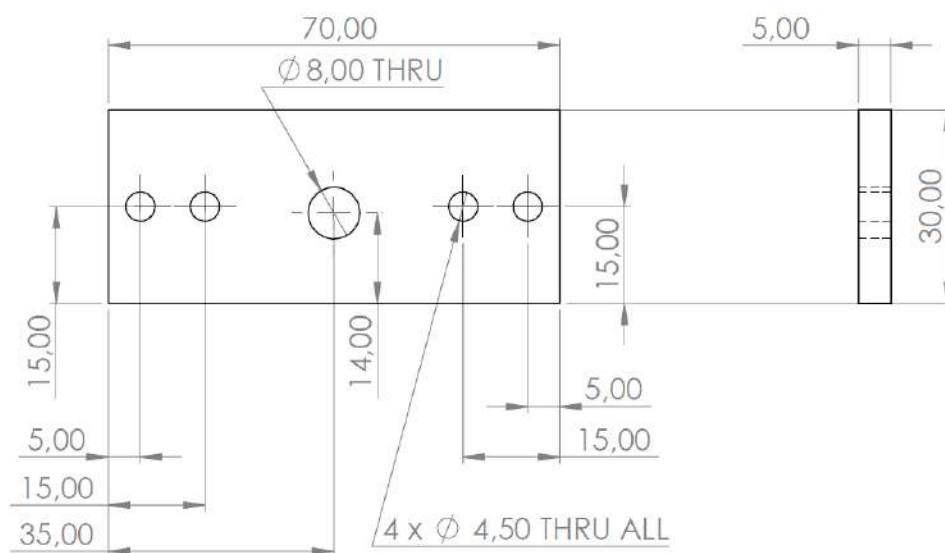
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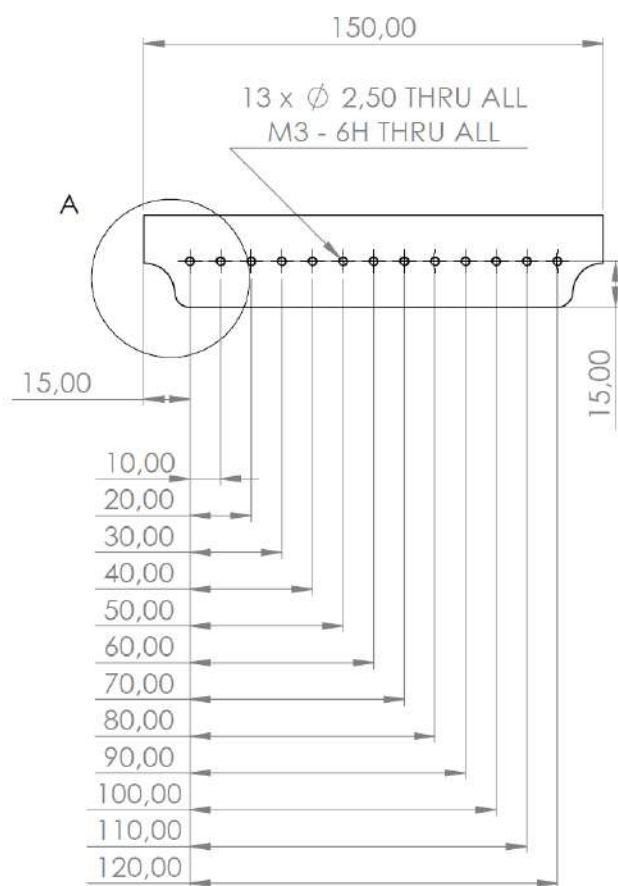
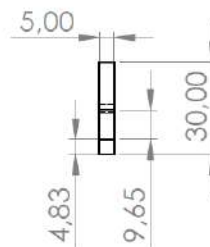
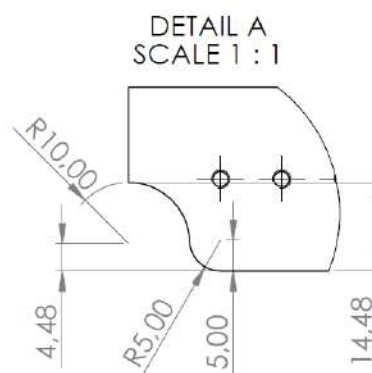
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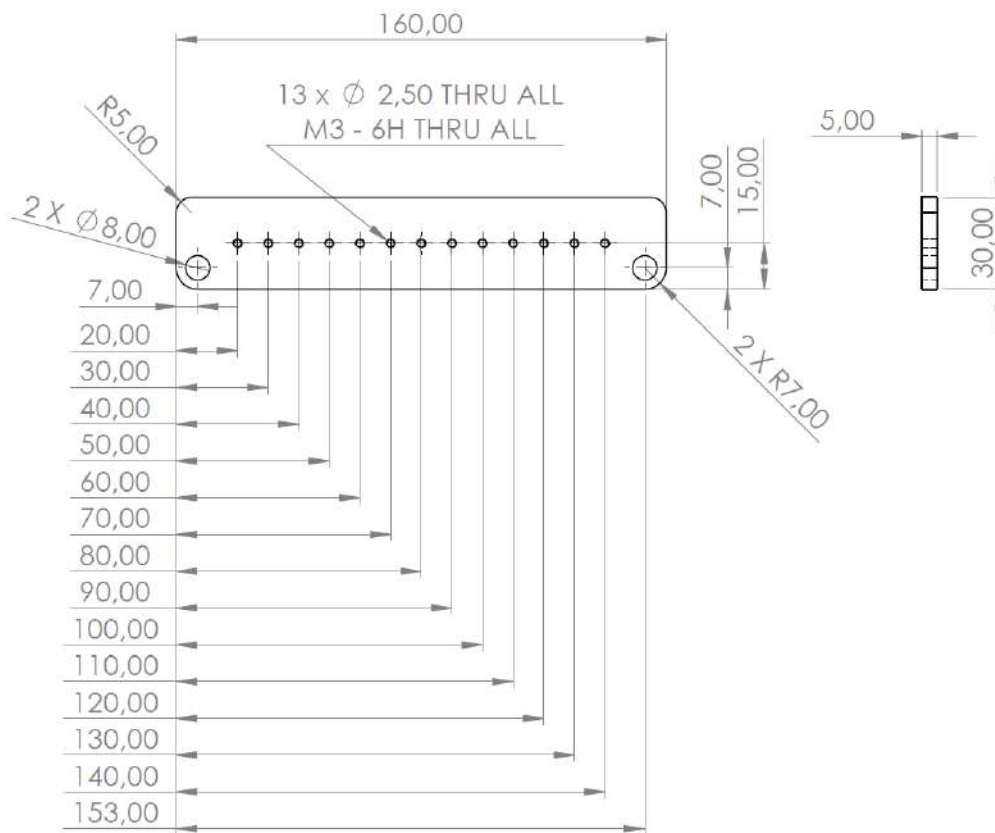
Appendix A: Appendix



DESENHO: BET_2	OBSERVAÇÕES:			
MATERIAL:	DESENHADO:	DATA:	ESCALA: 1:1	A4
QUANTIDADE: 4	APROVADO:	DATA:	REVISÃO:	FOLHA: 1

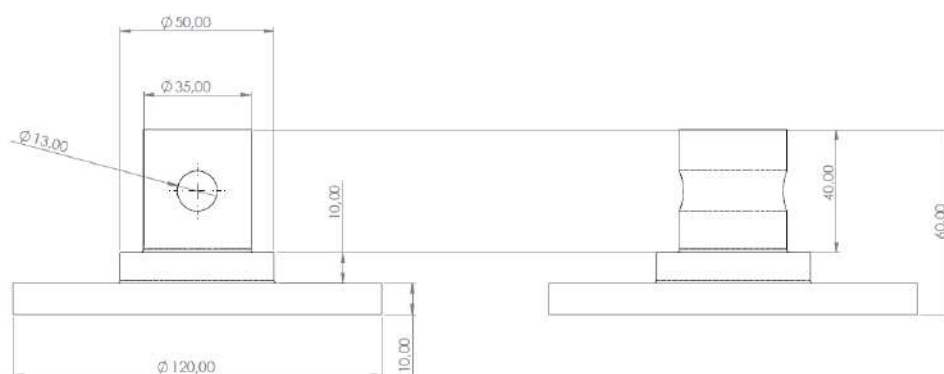


DESENHO: PFT_1-1	OBSERVAÇÕES:			
MATERIAL:	DESENHADO:	DATA:	ESCALA: 1:2	A4
QUANTIDADE: 4	APROVADO:	DATA:	REVISÃO:	FOLHA: 7



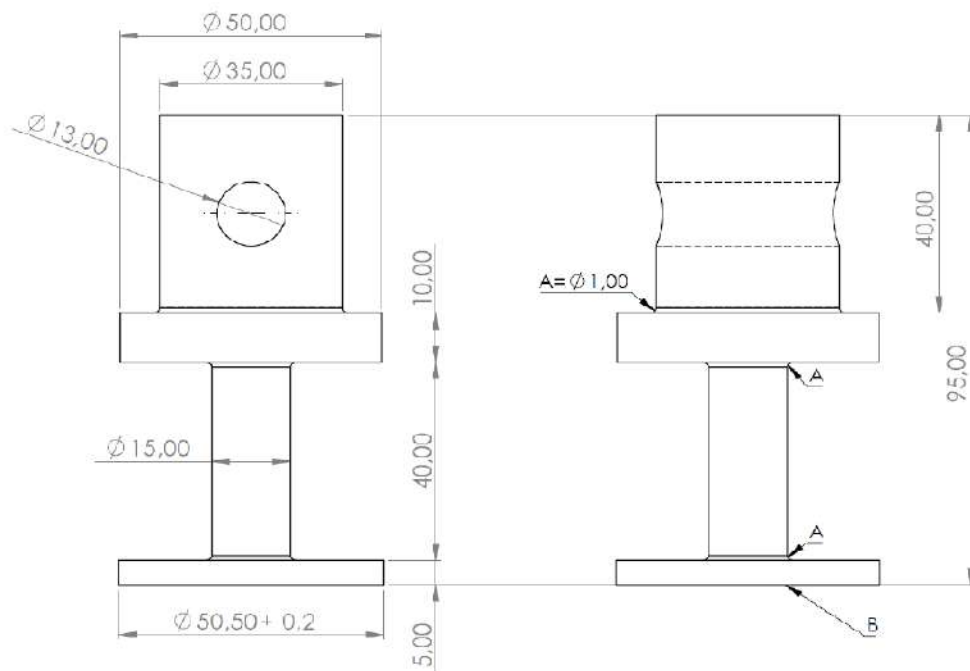
DESENHO: PFT_1-2	OBSERVAÇÕES:			
MATERIAL:	DESENHADO:	DATA:	ESCALA: 1:2	A4
QUANTIDADE: 4	APROVADO:	DATA:	REVISÃO:	FOLHA: 1

A.1.3 Compression test



NOTA:
Peça com arestas externas quebradas com Ch 1x45°.

DESENHO: <i>Compression_LowerGrip</i>	OBSERVAÇÕES:			
MATERIAL:	DESENHADO:	DATA:	ESCALA: 1:1	A3
QUANTIDADE: 1	APROVADO:	DATA:	REVISÃO:	FOLHA: 1



NOTA:

Peça com arestas externas quebradas com Ch 1x45°, exceto B.

DESENHO: <i>Compression_UpperGrip_ISO.5084</i>	OBSERVAÇÕES:			
MATERIAL:	DESENHADO:	DATA:	ESCALA: 1:1	A4
QUANTIDADE: 1	APROVADO:	DATA:	REVISÃO:	FOLHA: 1

A.2 Solidworks simulations

A.2.1 Bias extension test

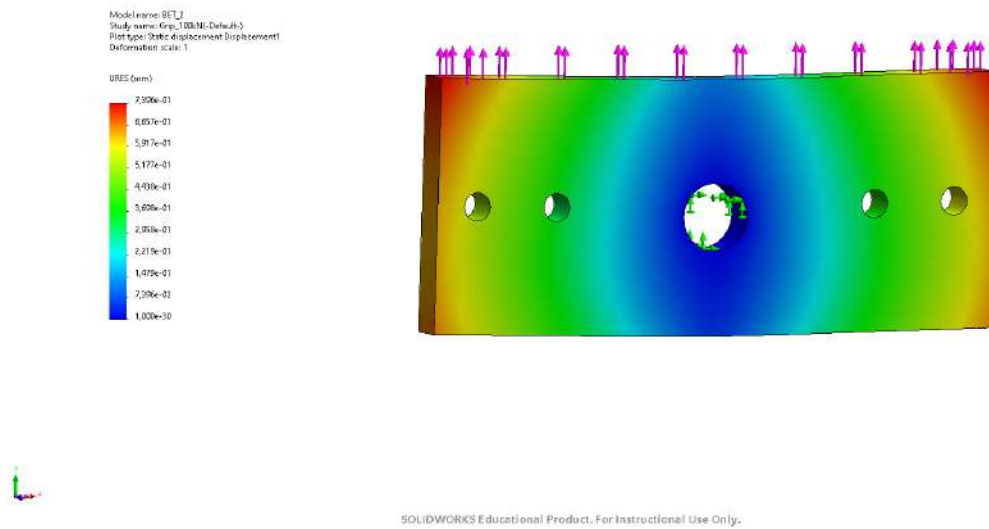


Figure A.1: Bias extension test: gripper displacement for 100kN.

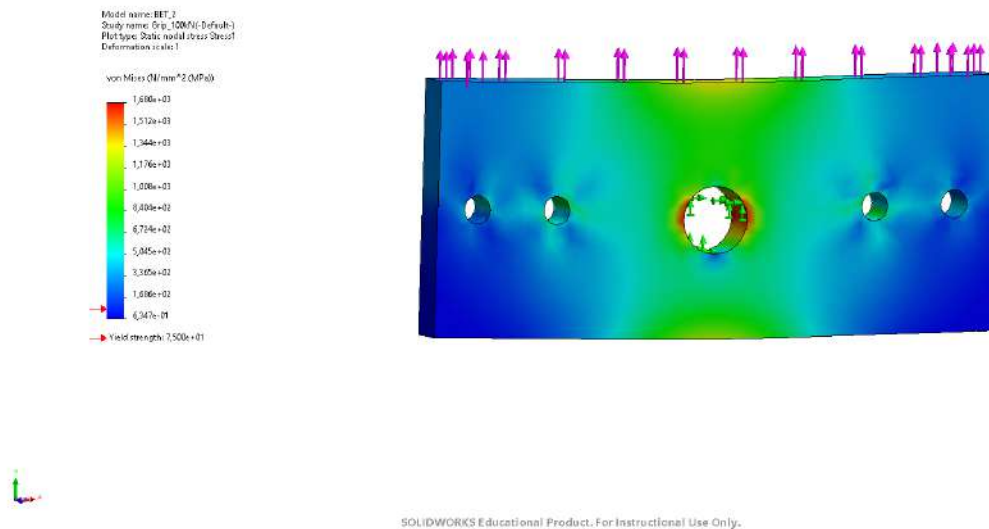


Figure A.2: Bias extension test: gripper stress for 100kN.

A.2.2 Picture frame test

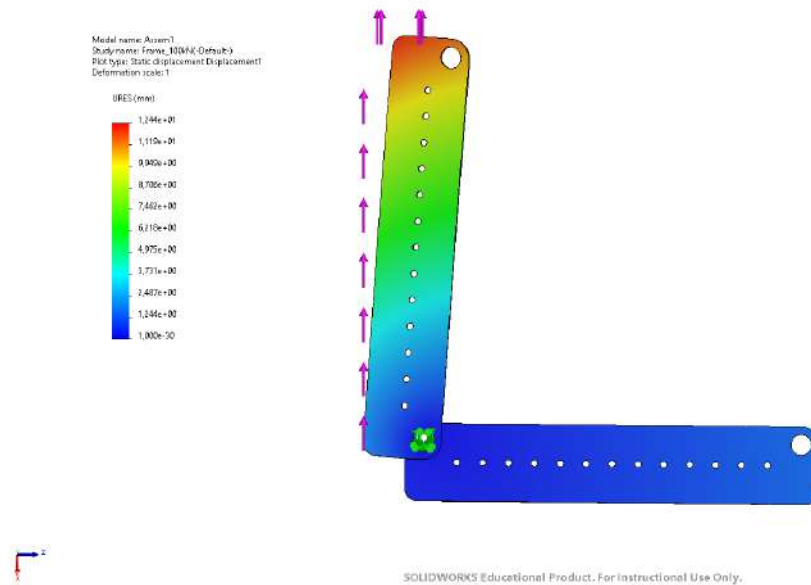


Figure A.3: Picture frame test: frame rig displacement for 100kN at 90°.

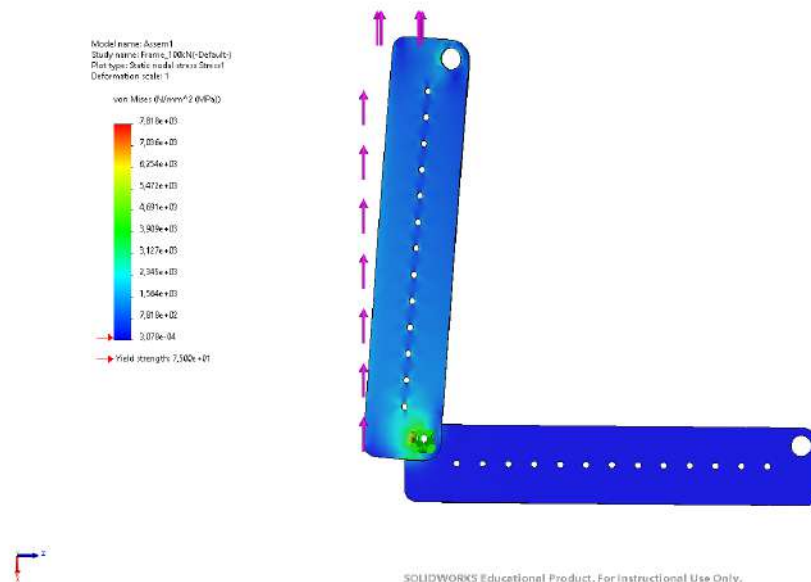


Figure A.4: Picture frame test: frame rig stress for 100kN at 90°.

A.2.3 Compression test

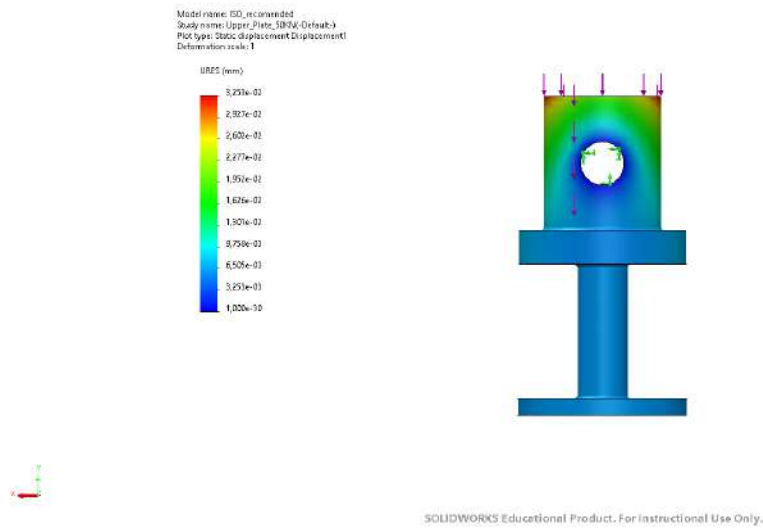


Figure A.5: Compression test: upper plate displacement for 50kN.

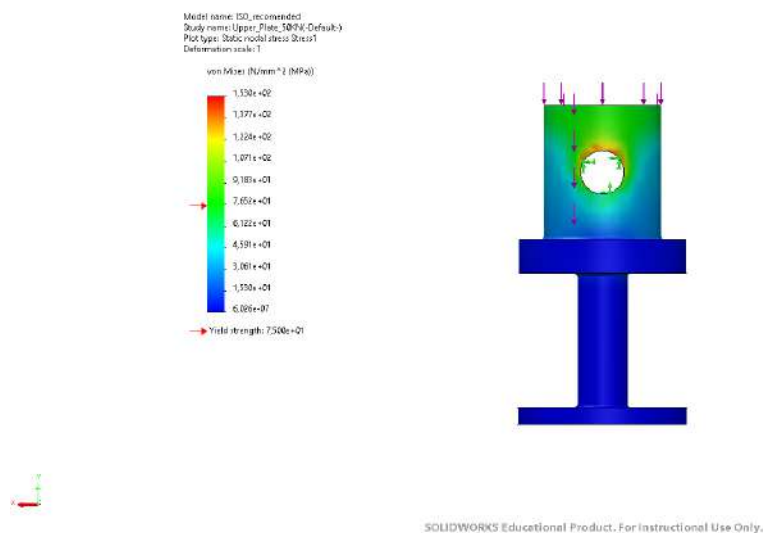


Figure A.6: Compression test: upper plate stress for 50kN.

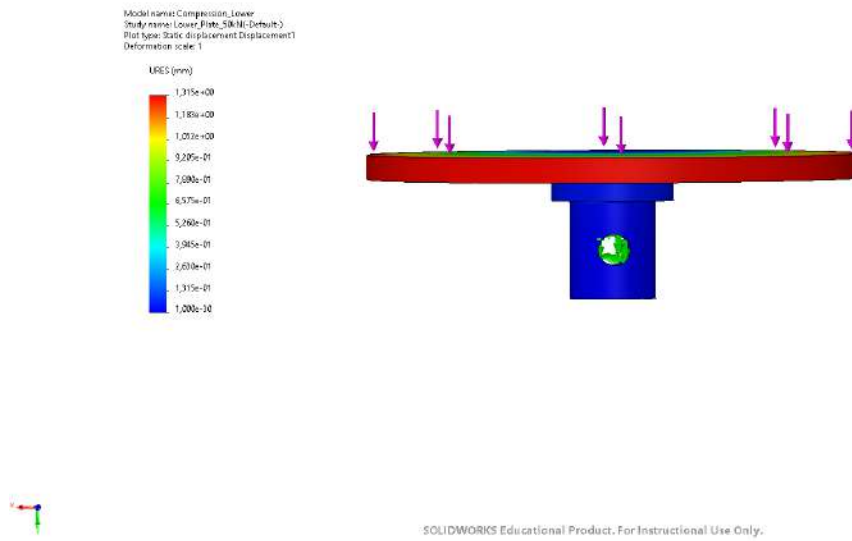


Figure A.7: Compression test: lower plate displacement for 50kN.

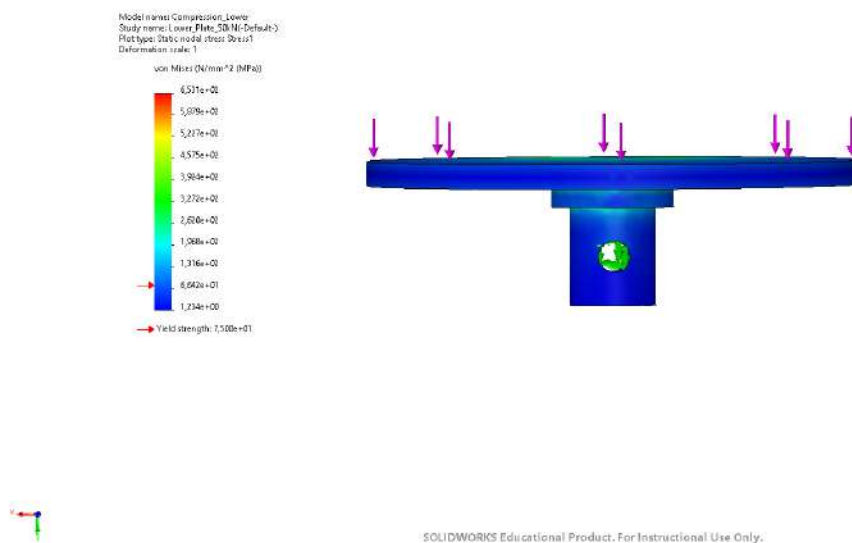


Figure A.8: Compression test: lower plate stress for 50kN.

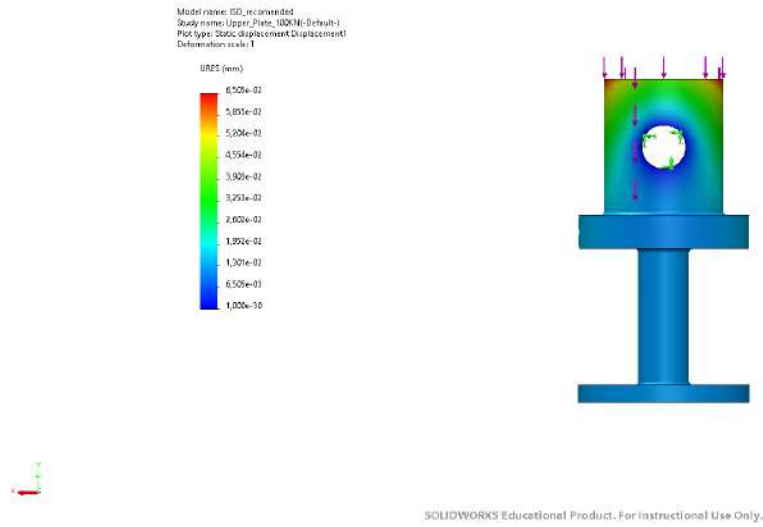


Figure A.9: Compression test: upper plate displacement for 100kN.

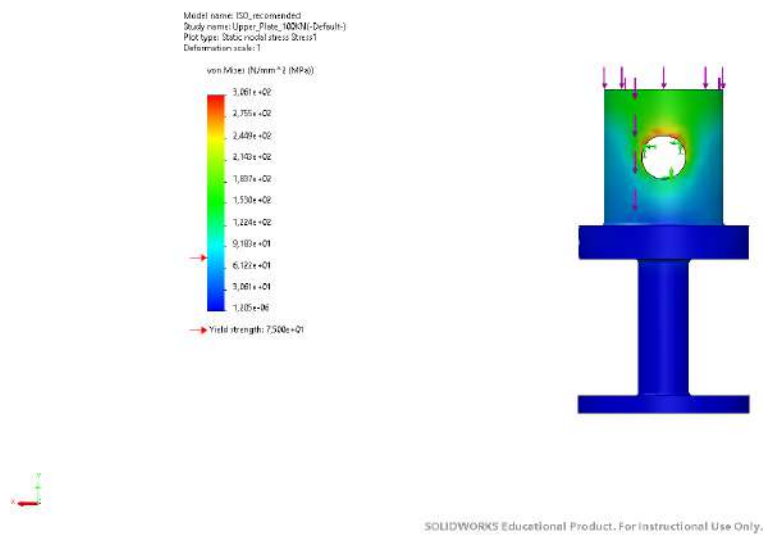


Figure A.10: Compression test: upper plate stress for 100kN.

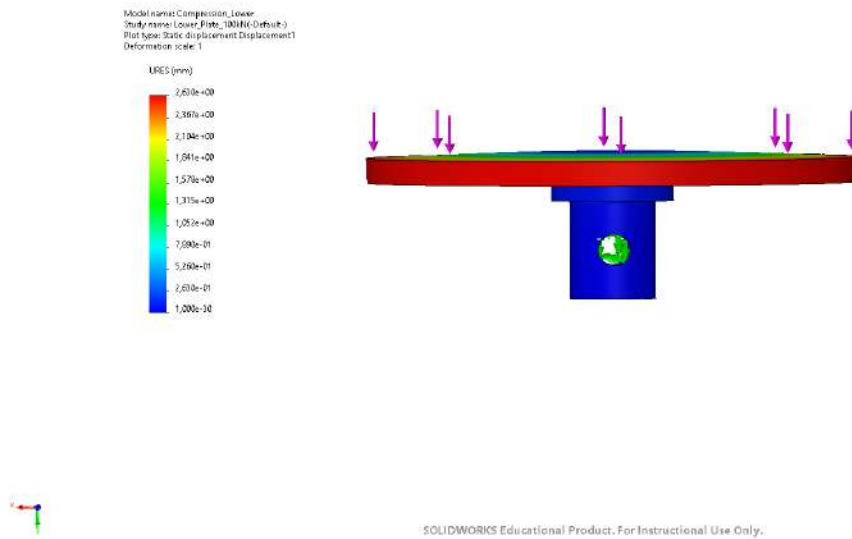


Figure A.11: Compression test: lower plate displacement for 100kN.

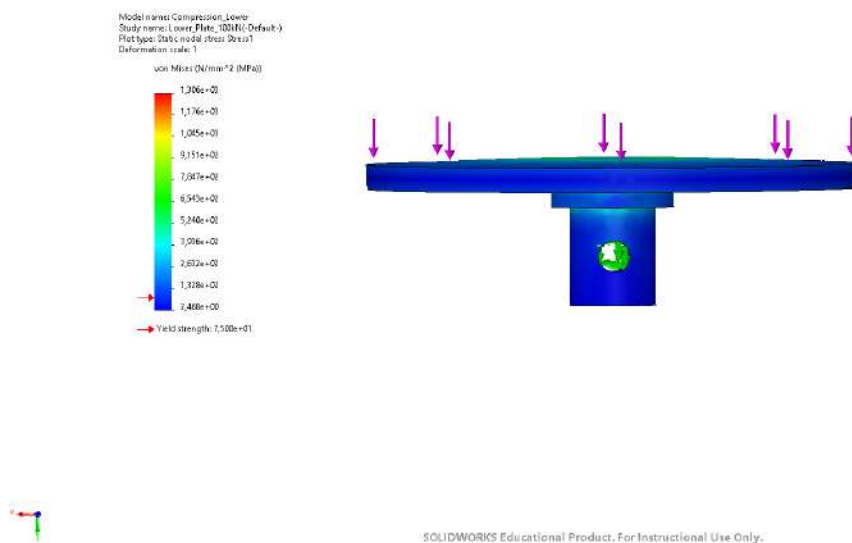


Figure A.12: Compression test: lower plate stress for 100kN.

A.3 Frame extraction script

```
1| import cv2
2| from os import listdir
3| from os.path import isfile, join
4|
5|
6| def convert_all(dest_folder, video_name):
7|     vidcap = cv2.VideoCapture(video_name)
8|     success, image = vidcap.read()
9|     count = 0
10|
11|     while success:
12|         cv2.imwrite(f"{dest_folder}/frame{count}.png", image)
13|         success, image = vidcap.read()
14|         print("Read a new frame: ", success)
15|         count += 1
16|
17|
18| def extractImages(pathIn, pathOut, ms_interval):
19|     count = 0
20|     vidcap = cv2.VideoCapture(pathIn)
21|     success, image = vidcap.read()
22|     success = True
23|     while success:
24|         vidcap.set(cv2.CAP_PROP_POS_MSEC, (count * ms_interval))
25|         success, image = vidcap.read()
26|         cv2.imwrite(pathOut + f"\\frame{count}.jpg", image)
27|         count = count + 1
28|
29|
30| def main():
31|     files_extension = ".avi"
32|     time_interval = 30
33|
34|     dest_folder = r"C:\Users\bmdvs\Code\results-thesis\src\data\shear\pft\
35|         Teste_video_ASTMD5035_20220621_PFT-gf_1_1C2"
36|     video_folder = r"C:\Users\bmdvs\Documents\thesis\pft\pft\videos"
37|     dest_dir = video_folder
38|
39|     onlyfiles = [f for f in listdir(video_folder) if isfile(join(
40|         video_folder, f))]
41|
42|     for _file in onlyfiles:
43|         if _file.endswith(files_extension):
44|             try:
45|                 dest_folder = os.path.join(dest_dir, _file.replace(
46|                     files_extension, ""))
47|                 video_name = os.path.join(video_folder, _file)
48|
49|                 if not os.path.exists(dest_folder):
50|                     os.makedirs(dest_folder)
51|
52|                 extractImages(video_name, dest_folder, time_interval *
53|                     1000)
54|             except:
55|                 pass
56|
57| if __name__ == "__main__":
58|     main()
```

A.4 Graphs

