UNIVERSITY OF THESSALY
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

EFFECT OF FIBRE ORIENTATION AND LAY UP ON THE MECHANICAL PROPERTIES OF CARBON FIBRE REINFORCED POLYMER

by

VASILIKI KARAMINTZIOU
Mechanical Engineer, University of Thessaly, 2024

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at the University of Thessaly

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Abstract

The thesis "Effect of Fibre Orientation on the Mechanical Properties of Carbon Fibre Reinforced Polymer" explores how the orientation of carbon fibers affects the mechanical performance of carbon fiber-reinforced polymers (CFRPs). The study focuses on tensile tests of unidirectional and bidirectional fabrics with orientations of 0°, 0°|90°, and -45°|45°. Experimental methods were used to determine Young's modulus and stress-strain behavior, while Finite Element Analysis (FEA) simulations provided a numerical perspective.

The results showed that the unidirectional 0° orientation exhibited the highest tensile strength and Young's modulus (285.2 GPa), while the -45°|45° orientation had the lowest modulus (23.9 GPa). The 0°|90° configuration fell in between, with a modulus of 122.3 GPa. FEA simulations closely matched experimental data for 0°|90° but showed discrepancies for -45°|45°, as the simulations are linear and do not take into account the transition to the plastic region.

The research concludes that fiber orientation plays a key role in determining the mechanical properties of CFRPs, with unidirectional fibers being optimal for high tensile strength. The study highlights the need for improved simulation models to better predict the behavior of multidirectional composites and suggests future research on dynamic loading conditions and advanced modeling techniques.

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ΒΑΣΙΛΙΚΗ ΚΑΡΑΜΙΝΤΖΙΟΥ

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Αναπληρωτής Καθηγητής Μηχανικής Συμπεριφοράς Μεταλλικών Υλικών

Περίληψη

Η διπλωματική εργασία «Επίδραση του προσανατολισμού των ινών στις μηχανικές ιδιότητες πολυμερών ενισχυμένων με ίνες άνθρακα» διερευνά πώς ο προσανατολισμός των ινών άνθρακα επηρεάζει τη μηχανική απόδοση των πολυμερών ενισχυμένων με ίνες άνθρακα (CFRP). Η μελέτη επικεντρώνεται σε δοκιμές εφελκυσμού μονόπλευρων και αμφίδρομων υφασμάτων με προσανατολισμούς 0°, 0°|90° και -45°|45°. Χρησιμοποιήθηκαν πειραματικές μέθοδοι για τον προσδιορισμό του μέτρου ελαστικότητας Young και της συμπεριφοράς τάσεων-παραμορφώσεων, ενώ οι προσομοιώσεις ανάλυσης πεπερασμένων στοιχείων (FEA) παρείχαν μια αριθμητική προοπτική.

Τα αποτελέσματα έδειξαν ότι ο μονοκατευθυντικός προσανατολισμός 0° παρουσίασε την υψηλότερη αντοχή σε εφελκυσμό και το μέτρο ελαστικότητας Young (285,2 GPa), ενώ ο προσανατολισμός -45°|45° είχε το χαμηλότερο μέτρο ελαστικότητας (23,9 GPa). Η διαμόρφωση 0°|90° βρισκόταν στο ενδιάμεσο, με μέτρο ελαστικότητας 122,3 GPa. Οι προσομοιώσεις FEA ταίριαζαν στενά με τα πειραματικά δεδομένα για 0°|90°, αλλά παρουσίασαν αποκλίσεις για -45°|45°, καθώς οι προσομοιώσεις είναι γραμμικές και δεν λαμβάνουν υπόψιν τους της μετάβαση στην πλαστική περιοχή.

Η έρευνα καταλήγει στο συμπέρασμα ότι ο προσανατολισμός των ινών παίζει βασικό ρόλο στον καθορισμό των μηχανικών ιδιοτήτων των CFRP, με τις μονόπλευρες ίνες να είναι βέλτιστες για υψηλή αντοχή σε εφελκυσμό. Η μελέτη υπογραμμίζει την ανάγκη για βελτιωμένα μοντέλα προσομοίωσης για την καλύτερη πρόβλεψη της συμπεριφοράς των πολυκατευθυντικών σύνθετων υλικών και προτείνει μελλοντική έρευνα σε δυναμικές συνθήκες φόρτισης και προηγμένες τεχνικές μοντελοποίησης.

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CHAPTER 1 : INTRODUCTION

1.1: Definition and Historical Review

As the term indicates Composite Materials are the materials that consist of two different materials with different mechanical, physical and chemical properties. Recent years the term Fibrous Composite Materials refers to materials that are reinforced with fibers of a stronger material, either continuous or discontinuous, and a weaker matrix which distributes the fibers and transmits the loads to them. But composites are not a new technology. They exist from the ancient times. In 3400 B.C the Mesopotamians in Iraq created the first composite when they glued wood strips one by one in different orientations in order to create a plywood. In 1200 A.C, the Mongols started to manufacture their arcs with wood and cow tendons glued together. After the Industrial Revolution, the first synthetic resins started to be widely known, as they started to get a solid form after polymerization. In the 1930, Owens Corning released to the market the first glass fiber and after 30 years the first carbon fiber was patented. Carbon fibers became commercially available in the 1960s. Specifically, in 1963, the British company Royal Aircraft Establishment (RAE), in collaboration with Bristol Aeroplane Company, began producing high-performance carbon fibers using a process developed by Dr. W. Watt. These early fibers were made from polyacrylonitrile (PAN), which is still one of the most common precursor materials used today. This wide range includes applications in several industries such as automotive, aerospace, marine and energy. For example, composites are used for structural materials in airframe components such as the wings, fuselage, empennage and landing gear and in automotive technology mainly in engine, brake system, battery, body parts and other components. Composites are also key in the automotive industry, particularly in race cars, where aerodynamic parts like spoilers are made from carbon fiber to improve speed and handling. Wind turbine blades benefit from composite materials for their strength and light weight, maximizing energy conversion efficiency. Lastly, drones rely on composites for lightweight, aerodynamic designs, enabling greater maneuverability and endurance.

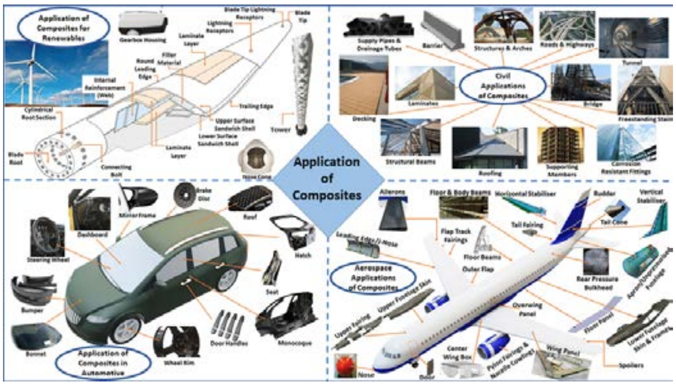


Figure 1.1 :Applications of Composite Materials

However, the main reason why composites are becoming widely known is their ability to combine maximum strength and minimum weight compared to classical materials. By creating layers of different orientations we can exploit the anisotropy of composites and achieve maximum possible strength in the direction of forces without having to add extra weight. Apart from strength and weight, composites have several characteristics that enable them to be the preferred choice in applications in recent years. Some of these characteristics are:

1. Fatigue resistance.
2. Anisotropy.
3. Corrosion resistance (Contact aluminum and carbon fibers excepts due to Galvanic Phenomenon).
4. Chemical resistance.
5. Fire resistance.
6. Ability to tailor reavired properties by design.

Nevertheless, in order to be able to use these characteristics and get the optimal structure of a component, we need to have knowledge of the properties of the composites we are going to use. Properties in composites depend on the properties of continent materials. The main reason that is different fibre materials and different types of matrices can be used to make a composite material with properties depending on the combination the corresponding properties of fibre and matrix. The most commonly used materials for fibers are Glass, Carbon, Aramid and Boron. The matrix materials usually include: Polymers (thermoplastic and thermoset resins), Metals (aluminum alloys, titanium alloys, oriented eutectics) and Mineral matrix (silicon carbide, carbon). Some of the advantages and disadvantages of Prepreg fabrics are listed below

Advantages

1. **Maximum strength.** Laminates that have been created with the Hand - Lay-up method usually end up with an excess of resin. Prepregs contain the appropriate amount of resin which is usually 35% , which is ideal for achieving maximum curing performance.
2. **Reduction of waste.** In cases where we apply the Hand – Lay-up method we use various items such as resin cups, brushes and rollers, whereas with Prepreg fabrics we don't need to make these wastes.
3. **Reduction of curing time.** After the heat curing cycle the part is ready. There is no need to wait 48 hours as during Hand – Lay-up method.
4. **Uniformity.** When the laminate is created by humans it is possible to exist either rich-to-resin areas and dry spots in the same part. With Prepregs, the elimination of the possibility is achieved.

Disadvantages

1. **High cost.** Although they are the optimal solution in many cases, their cost is quite high.
2. **Lifespan.** In order to be used, prepreg must be stored in a place with a sufficiently low temperature (for example in a freezer) or else they can be kept at room temperature for 6 months. In warmer environments their shelf life is going to be shortened.

1.2 Literature Review

Composite materials have become essential in advanced industries such as aerospace, automotive, and construction due to their exceptional mechanical properties, including high strength-to-weight ratio and resistance to corrosion. These materials are engineered by combining two or more distinct phases—each with unique physical, mechanical or chemical properties—to create a composite with enhanced performance beyond that of the individual components. The understanding of composite materials' mechanical properties is vital for optimizing their design and expanding their applications. This understanding is achieved through both experimental techniques and numerical simulations. Experimental methods provide valuable empirical data on the material's behavior under various conditions, while numerical simulations offer predictive insights into the performance of these materials in real-world scenarios. This bibliographic review aims to examine the main research on the mechanical properties of composite materials, focusing on both experimental approaches and numerical simulation techniques. By analyzing the contributions of notable researchers and their methodologies, this review will highlight the advances and limitations in the field and identify areas for future research.

Experimental Methods

Experimental techniques for assessing the mechanical properties of composite materials include tensile and compression testing, fatigue testing, and impact testing. For instance, Gibson (2016) has extensively reviewed the performance of fiber-reinforced polymers (FRP), discussing the effects of fiber orientation and matrix properties on overall material performance. Similarly, Kaw (2005) has contributed significantly to understanding the mechanical behavior of composite materials through experimental analysis, emphasizing the influence of fiber distribution and interface characteristics. Kaw (2006) explored the impact of fiber alignment on tensile properties, showing that composites with fibers aligned along the load axis exhibit superior tensile strength, while off-axis fibers lead to lower strength and anisotropic behavior. Additionally, Hossain et al. (2019) examined hybrid composites, indicating that the combination of different fiber types, such as carbon and glass, improves overall tensile performance, although stress concentrations at the interface can lead to premature failure. Daniel and Ishai (2006) highlighted that fiber misalignment and matrix cracks are common failure modes in compression, with buckling often dominating in laminated composites. Soutis and Curtis (2012) extended this by evaluating the compressive behavior of carbon fiber-reinforced polymers (CFRPs), finding that the compressive strength is significantly lower than the tensile strength due to the propensity for fiber buckling. Studies by Zhao et al. (2020) demonstrated that compression testing, when coupled with high-speed cameras, reveals real-time failure propagation, which aids in developing more damage-tolerant composite designs. Schürmann (2007) emphasized the complexity of fatigue in composites, noting that damage initiation and propagation often occur at the fiber-matrix interface. Zhou and Pochiraju (2014) examined thermoplastic composites under fatigue, highlighting that these materials show greater resistance to fatigue crack growth than thermosetting composites due to their ability to dissipate energy through viscoelastic deformation. Mallick (2007) noted that ultrasonic C-scan methods are especially effective for laminated composites, allowing for detailed mapping of subsurface defects. Wang et al. (2017) enhanced this technique by incorporating phased-array ultrasonics, which can scan complex geometries and provide more precise defect characterization.

Numerical Simulations

Numerical simulations play a crucial role in predicting the behavior of composite materials under various conditions. The Finite Element Analysis (FEA) method, as described by Zienkiewicz and Taylor (2000), allows for detailed modeling of composite structures, providing insights into stress and strain distributions. Additionally, Hashin and Rotem (1973) have developed models for predicting the mechanical response of composites based on fiber and matrix properties, contributing to the advancement of simulation techniques. By integrating both experimental data and numerical predictions, researchers like Hinton et al. (2004) have enhanced the understanding of composite materials' behavior. This combined approach helps bridge the gap between empirical observations and theoretical predictions, offering a comprehensive view of composite materials' mechanical performance. Kouznetsova et al. (2002) developed a multiscale approach where the microscale behavior (such as fiber breakage or matrix cracking) is modeled in detail, and its effects are upscaled to predict the overall performance of the composite. Fish and Yuan (2005) further extended this by introducing homogenization techniques, where the complex behavior at the microscale is averaged to develop simpler, yet accurate, material models for the macroscale. This approach significantly reduces computational costs without sacrificing accuracy. Camanho and Davila (2002) developed cohesive zone models (CZMs) that are widely used to simulate delamination in composite materials. These models introduce cohesive elements between plies, which represent the resin layers, and use traction-separation laws to simulate the progressive failure of these interfaces. Turon et al. (2007) extended CZMs by incorporating mixed-mode failure criteria, allowing them to simulate combined tensile and shear delamination, which is common in real-world applications.

1.2.1 Importance of Tensile Experiments in Composite Materials

Tensile tests are fundamental for evaluating the tensile strength, elasticity and behavior up to ultimate fracture of composites. Through these tests, we can understand how various factors, such as fiber ratio and matrix quality, affect the mechanical properties of the composite (Kaw, 2005). In addition, these tests allow the determination of the elastic modulus, yield strength and tensile strength limit, which are essential for the design and optimization of composites in practical applications (Cox et al., 2017). This information is critical for the application of composites in areas such as aerospace, automotive and shipbuilding, where materials with excellent mechanical properties are required.

1.2.2 Factors Affecting Tensile Properties

The tensile behavior of composites depends on several factors, such as the type and percentage of fibers, the quality of the matrix, the interface between the fibers and the matrix, and the orientation of the fibers. In figure 1.2 an orthotropic material is presented [54] and in Figure 1.3 there are different orientations and lay ups [53].

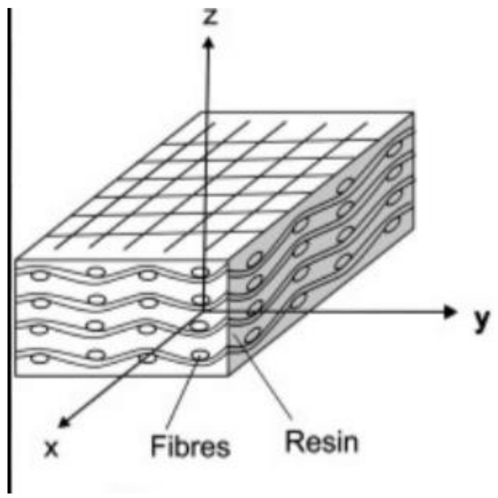


Figure 1.2 Orthotropic Material

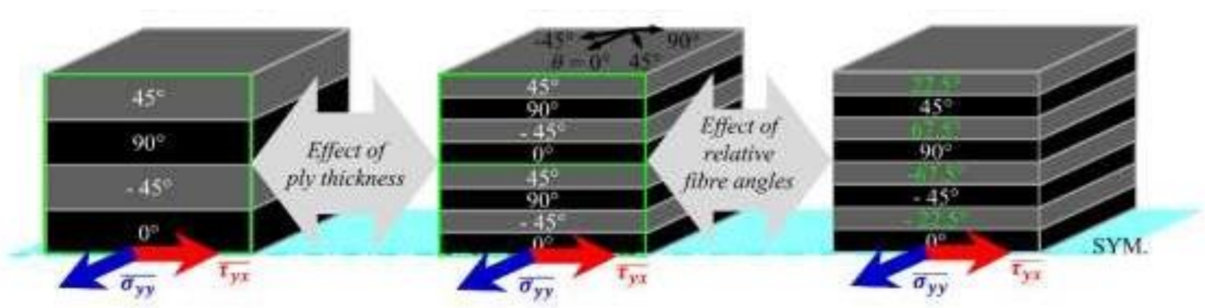


Figure 1.3 Different fiber orientations and lay ups

Type and percentage of fiber

The quality and quantity of fibers used in a composite material have a significant effect on its mechanical properties. Carbon and glass fibers are commonly used because of their high strength. Also, the volume ratio of the fibers relative to the matrix can have a significant effect on tensile properties. Sankar et al. (2018) found that increasing the percentage of carbon fibers increases the tensile strength and also the elastic modulus of the composite. the analytical equations between elasticity modulus and fiber percentage are as follows:

Load parallel to fibers : $E_c = E_f \times V_f + E_m \times V_m$

Load vertical to fibers : $\frac{1}{Ec} = \frac{Vf}{Ef} + \frac{Vm}{Em}$

Where,

E_c : Young's Modulus of Composite Material

E_f : Young's Modulus of Fibers

E_m : Young's Modulus of Matrix

V_f : Fractional fibre volume rate

V_m : Fractional percentage of matrix volume

Interface quality

The quality of the interface between the fibers and the matrix is critical to the performance of the composite. A strong interface improves load distribution and minimizes fiber delamination. Smith et al. (2019) reported that a strong interface leads to higher tensile strength and better overall mechanical behavior of the composite.

Fiber Orientation

Fiber orientation plays an important role in the behavior of the composite. Alignment of fibers with the direction of tensile loading can provide improved strength and reduced deformation. Jones et al. (2020) confirmed that fiber direction has a crucial effect on tensile strength, and the best properties are obtained when fibers are aligned with the direction of the applied load.

1.2.3 Experimental Methods

Various experimental methods have been used in the literature to study the tensile behavior of composites. Some of the most important ones are:

Uniaxial Loading Tensile Tests

The most commonly used method is uniaxial tensile testing, where a specimen of the composite is placed in a tensile machine and subjected to a gradual increase in tensile load until final fracture. Analysis of the results of these tests provides data on the tensile strength, elastic modulus, and overall behavior of the material (Cox et al., 2017). For example, Zhang et al. (2018) used uniaxial testing on carbon fiber-reinforced composites and found that increasing the percentage of fibers improves the tensile strength and elastic modulus of the material.

Tensile Tests under Multiaxial Loading

In many cases, the actual operation of composites involves complex load distributions. Multi-axial tensile tests represent these conditions, allowing the evaluation of tensile behavior under different loading directions. Wang et al. (2017) used multiaxial tests to examine the behavior of composites under complex loads. The results showed that multiaxial loading can induce different failure mechanisms compared to uniaxial tests, highlighting the importance of simulating such conditions for real-world materials.

Dynamic Tensile Testing

Dynamic tensile tests evaluate the response of composite materials to varying or cyclic loads, which are particularly important for fatigue resistance analysis. Anderson et al. (2019) performed dynamic tests on carbon fiber reinforced composites and observed that these materials offer improved cyclic loading resistance compared to glass fiber reinforced composites. This analysis is critical to understanding the long-term durability of the materials under real-world operating conditions.

1.2.4 Tensile failure mechanisms

The tensile failure mechanisms of composites in tension are complex and depend on many factors, including the interface, fiber orientation and internal imperfections. The most common failure mechanism is the fracture of fibers when the load exceeds their strength. However, in some cases, failure may be caused by the fibers detaching from the matrix or by the propagation of cracks within the matrix. Microscopic analysis after tensile loading can reveal details about failure mechanisms, providing valuable information for improving the interface and overall performance of composites (Liang et al., 2019). In Figure 1.4 are presented the schematic illustration of failure modes of the composite specimens with different fiber orientation angles [12].

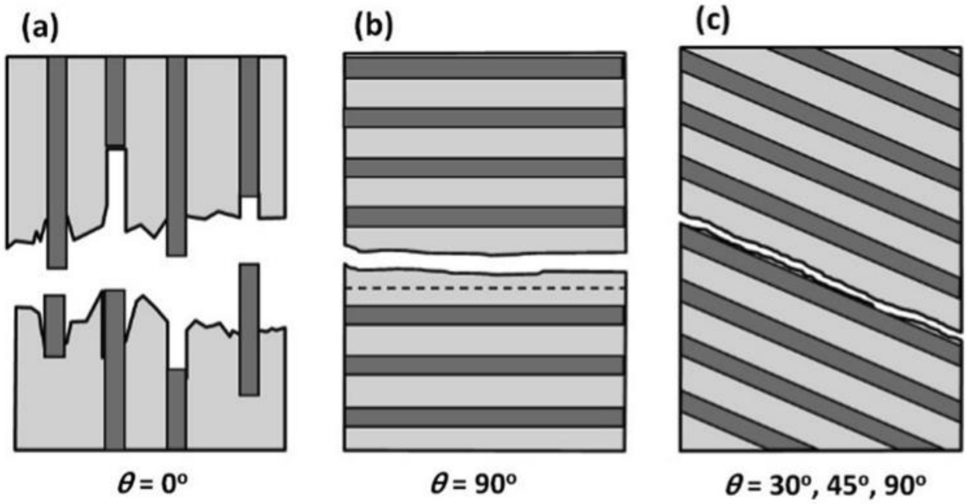


Figure 1.4 Schematic illustration of failure modes of the composite specimens with different fiber orientation angles (θ)

1.3: Diploma thesis Organization

This chapter sets out the objectives of the five chapters of this thesis, which will follow.

In the 1st chapter, reference is made to the scope of composites and the theoretical background required to understand the properties of composites both at the experimental and simulation level.

The 2nd chapter provides a detailed explanation of the study and design of specimens. The specimens, which are divided into three categories

1. Specimens with fiber orientation at 0°
2. Specimens with fiber orientation at 0|90°
3. Specimens with fiber orientation at -45|45°

are subjected to tensile loading resulting in stress-strain diagrams and thus in the determination of properties. This chapter includes a detailed description about the model , the machine and extensometers used as well as a commentary of the results.

In 3rd chapter a linear simulation of the experiments , in the same orientations, is performed in the primary stage and the results are commented,

In 4th chapter, the results obtained after the experiments and simulations are reported and commented.

The determination of mechanical properties is the main topic of this thesis. Through experiments and simulations we will try to determine the properties of the composites in different orientations, thus observing how the directionality and weave (Unidirectional and Bidirectional) of the fibres will affect the Elastic Modulus. Initially, tensile experiments will be performed on prepreg carbon fibers in the following directions: 0°, 0°|90° and -45°|45°. During the experiments, extensometers will be used to obtain the strain of the structure and hence, to calculate the maximum stress and Young's Modulus. Then, these structures will represent the models in simulation software in order to compare the experimental and computational results at the end of the research. Finally, the above results will be commented and some conclusions will be drawn about the variation of the elastic modulus at different orientations and lay ups.

CHAPTER 2: EXPERIMENTS

2.1 Materials and Specimens

In order to carry out the experimental procedure, fabrics from SGL company were used. "Prepreg" is the term for a reinforcing fabric which has been pre-impregnated with a resin system. This resin system (typically epoxy) already includes the proper curing agent. As a result, the prepreg is ready to lay into the mold without the addition of any more resin. In order for the laminate to cure, it is necessary to use a combination of pressure and heat.

In this thesis two types of fabrics were used, Unidirectional Epoxy Carbon Fiber Prepreg and an Epoxy Woven Carbon Fiber Fabric Prepreg (Twill weave). Unidirectional fabric predominantly features a high concentration of untwisted roving's in one direction (typically the warp direction), and a smaller amount of spun yarns in the other direction to secure the fabric and prevent it from spreading apart. The woven fabrics consist of fibers aligned in two perpendicular directions: one is known as the warp and the other as the fill (or weft) direction. The fibers are interlaced, with the fill yarns alternating over and under the warp yarns according to a specific pattern. Both of these fabrics have fiber volume fraction 60%. In Figure 2.1 are presented the different types of fabrics which were used.

Figure 2.1 The upper specimen is made of Unidirectional Fabric and the other two are made of Bidirectional Fabric

2.2 Manufacturing of Specimens

For the manufacturing of specimens, the experiments were initially layered and then the laminates were created. For the dimensions of the specimens, the suggested ones of the standard ASTM D3039 were followed. The used standard is and will be analyzed in subsection 2.3. At the beginning, the experiments were cut and created with a small offset. As the fabrics before curing are quite soft materials, scissors and cutters were used for their final shaping. Figure 2.2 shows the specimens after cutting and before the layering process. A release film was then added to a large steel plate so that the specimens could be easily detached from the plate. Then the specimens were layered and a layer of peel ply was added. Peel ply absorbs the excess resin and creates a uniform surface. It can also indicate if there is a uniform resin coverage on the part. Over peel ply, breather was placed which it keeps the Vacuum Bag from adhering on the part and ensures uniformed distribution of vacuum.

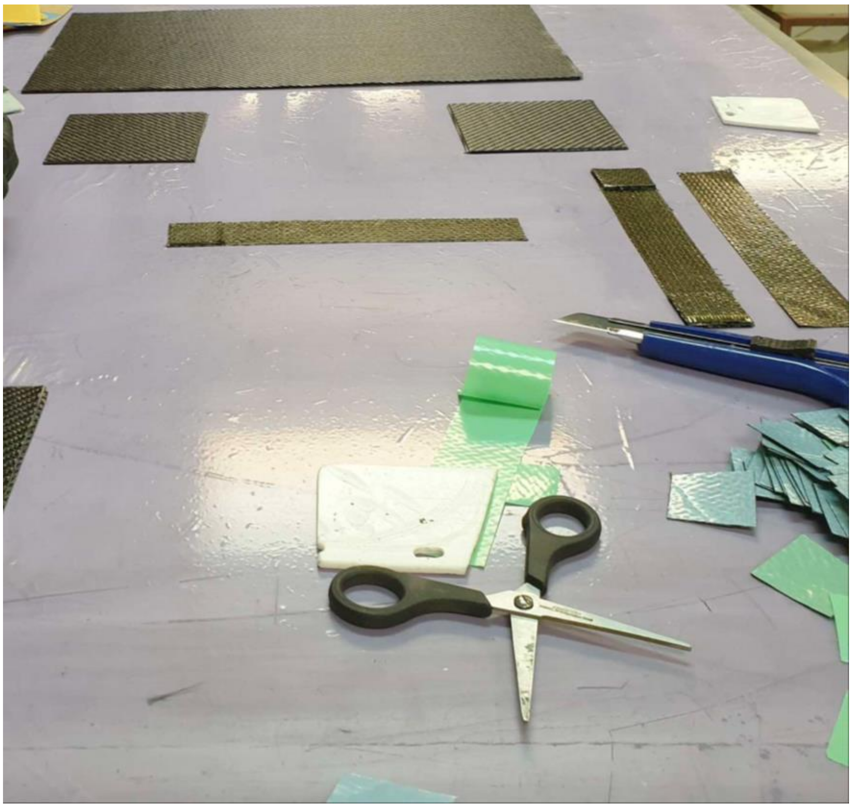


Figure 2.2 Specimens after cutting and before lay up

Then, they were cured in the suggested cycle as shown in Figure 2.3. For 40 minutes at 60 degrees Celsius and for 1 and a half hour at 110 degrees Celsius.

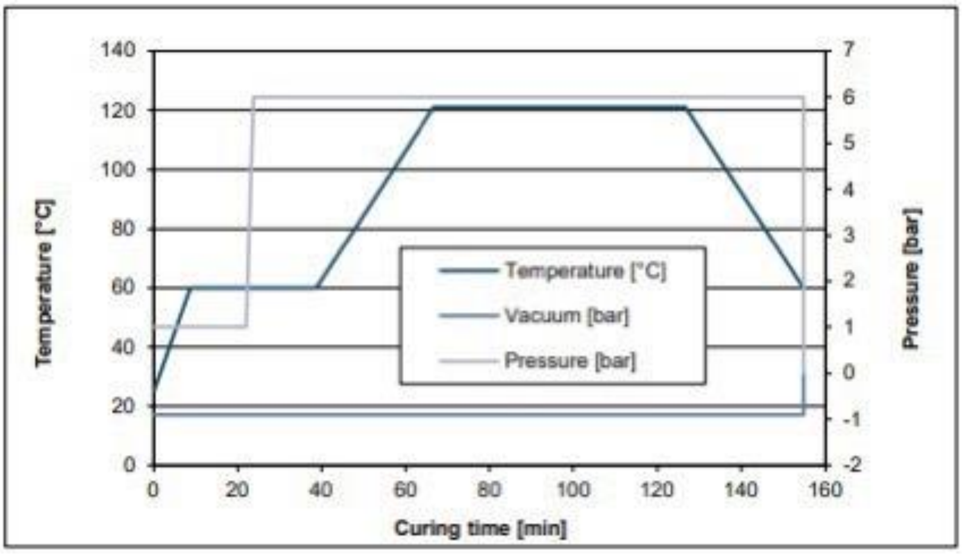


Figure 2.3 Curing Cycle suggested by SGL

The out of autoclave process was applied for curing the experiments. The Out of Autoclave (OOA) process is a composite manufacturing technique used to produce high-performance parts for industries such as aerospace and automotive. Unlike traditional methods that rely on high-pressure, high-temperature autoclaves, the OOA process cures composite materials using vacuum bagging and oven curing, making it a more cost-effective and scalable solution. Once the layup is complete, the part is sealed inside a vacuum bag. A vacuum is applied to remove air and compress the composite layers tightly against the mold, minimizing voids that can weaken the part. Instead of being placed in an autoclave, the part is cured in an oven, where the resin solidifies and bonds the composite structure under controlled temperatures, without the need for high pressures. In Figure 2.4 the specimens are in the bag under pressure before get into the curing oven. The experiments were performed in the laboratory of the Hellenic Aerospace Industry.

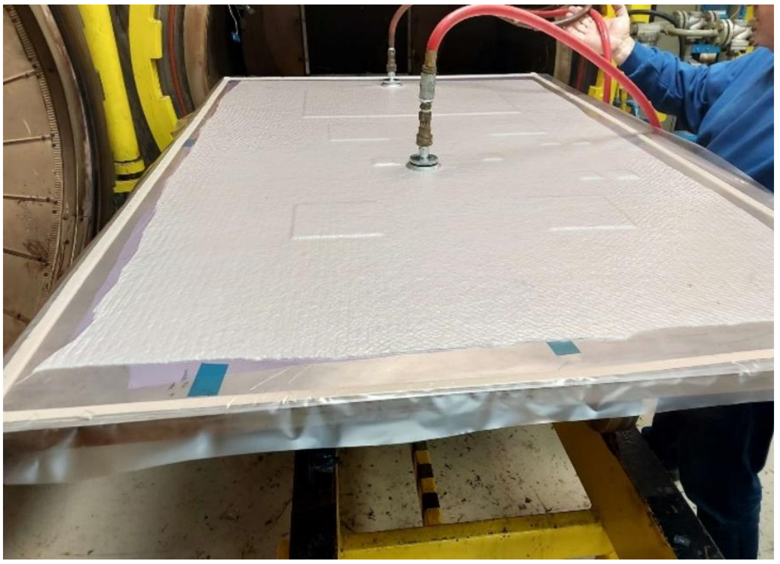


Figure 2.4 Specimens in the vacuum bag before curing

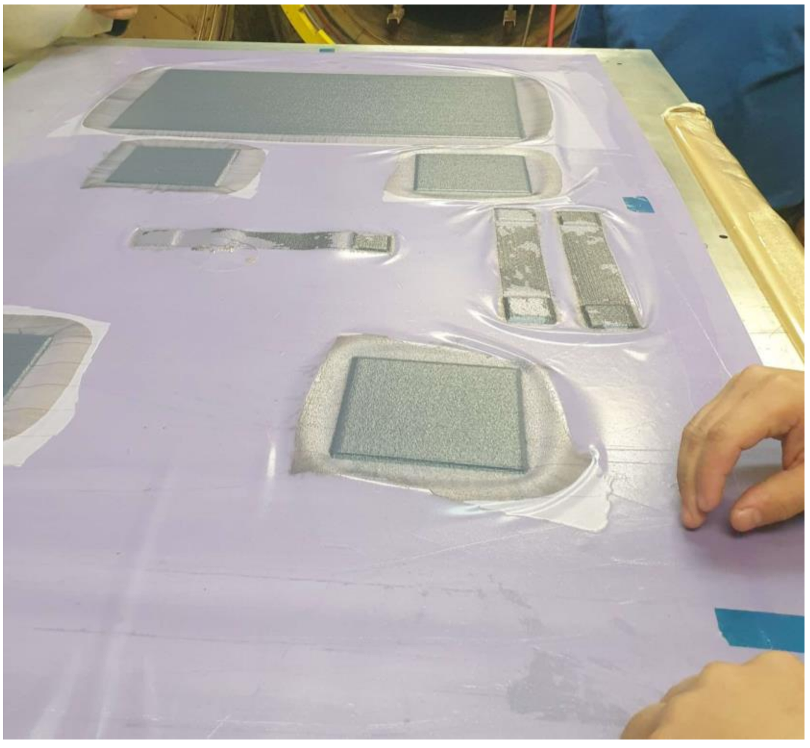


Figure 2.5 Specimens after curing in the Vacuum Bag

Finally, in order to give the specimens their final geometry, a cutting wheel was used as the materials have now acquired hardness and the use of scissors or cutters was impossible.

2.3 Standard Test Method

The standard test method followed is ASTM D3039 - Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. The standard describes the method for determination the in – plane tensile properties of polymer matrix composites. The materials can be either continuous or discontinuous – fiber reinforced as well as balanced and symmetric. A summary of the test is that a thin , flat strip having a constant rectangular shape is mounted to the tensile machine's grips and monotonically loaded in tension while the load is recorded. The ultimate strength is determined by the maximum load before failure. From the ultimate tensile strength , tensile modulus, Poisson's ratio, ultimate tensile strain and transition strain. In order to obtain accurate measurements of the strains, extensometers were used. Regarding the specimens, in order to take measurements, 3 specimens with a specific geometry were manufactured. The requirements of the standard are presented in Table 2.1. These requirements provide a sufficient number of fibers which represent the whole material satisfactorily.

Table 2.1 Tensile Specimen Geometry Requirements

Parameter	Requirement
Coupon Requirements	
Shape	Constant rectangular cross – section
Minimum length	Gripping + 2 times width + gage length
Specimen Width	As needed
Specimen Width Tolerance	±1% of width
Specimen Thickness	As needed
Specimen Thickness Tolerance	±4% of thickness
Specimen Flatness	Flat with light finger pressure
Tab Requirements (if used)	
Tab material	As needed
Fiber orientation (composite tabs)	As needed

Tab Thickness	As needed
Tab Thickness variation between tabs	±1% tab thickness
Tab Bevel angle	5° to 90°, inclusive
Tab step at bevel to specimen	Feathered without damaging specimen

For the dimensions of the experiments in this thesis, the recommendations of the standard were used. The dimensions can be found in Table 2.2.

Table 2.2 Tensile Specimen Geometry Recommendations

Fiber Orientation	Width (mm)	Overall length (mm)	Thickness (mm)	Tab length (mm)	Tab thickness (mm)	Tab bevel angle (°)
0°, UD	15	250	1.0	56	1.5	7 or 90
90°, UD	25	175	2.0	25	1.5	90
Balanced & Symmetric	25	250	2.5	Emery cloth	-	-
Random -Discontinuous	25	250	2.5	Emery cloth	-	-

2.3.1 Tabs

As concerns the geometry of the end tabs, in each case it depends on the orientation and the material of the specimen. In the tests conducted for the present thesis , emery cloth (150 grid) was used in the bidirectional specimens and incorporated steel tabs in the unidirectional specimens. As long as the tabs are bonded with the specimens, any high – elongation adhesive system that meets the environment requirements may be used. The used adhesive is TURBO

EPOXY 5’ White Blister 24ml. This adhesive is suitable for all metals, aluminum, wood, hard synthetic materials, porcelain, stone, clay, terracotta, concrete, marble, ceramics, gemstones, glass, plexiglass, most plastics, etc. Ideal for joining materials that are different from each other.

2.3.2 Procedure

Before conducting the experiments, several parameters must be determined along with general instructions to ensure accurate and consistent results. The parameters include the type and geometry of the coupons, the tensile properties and the desired data format, as well as the relevant environmental parameters. It is important to report any deviations from the test method during the experimentation process. Prior to tension testing, the area A=w × h should be determined at three locations within the gauge section of the specimen. The standard constant head displacement for the test is set at 2 mm/min. Additionally, the strain rate should be selected to ensure that failure occurs within a timeframe of 1 to 10 minutes. When preparing for the test, the specimen must be placed into the grips, ensuring that the long axis of the specimen aligns with the test direction. The load should then be applied to the specimen until failure occurs. It is essential to continuously record the load versus displacement or to do so at frequent regular intervals. In cases where the specimen fails, it is crucial to document the maximum load, strain, and displacement before rupture. The failure mode of the specimen should also be recorded, as illustrated in Figure 2.6. If failure occurs within one specimen width of the tab or grip, it inecessary to consider factors such as tab material, tab alignment, tab angle, tab adhesive, grip type, grip pressure, and grip alignment to accurately assess the situation.

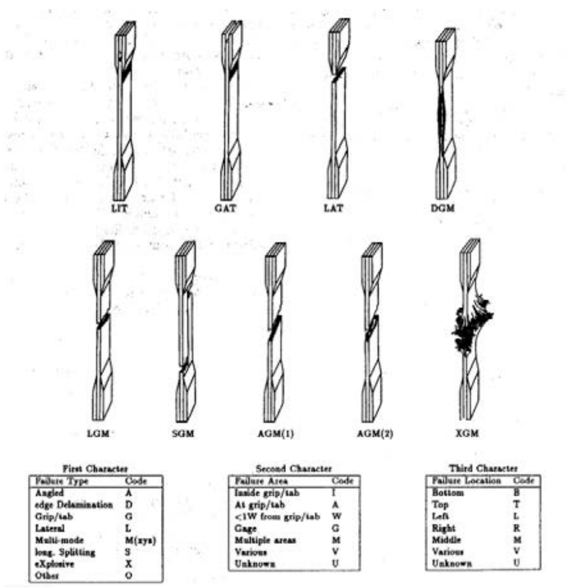


Figure 2.6 Failure modes according to ASTM D3039

2.4 Tensile Machine & Extensometers

The tensile machine that used to carry out the experiments is the Instron 8801, which is presented in Figure 2.7. Instron 8801 s a compact servohydraulic fatigue testing system that meets the challenging demands of various static and dynamic testing requirements.

Figure 2.7 Instron Testing Machine

Regarding the extensometer Instron Dynamic Axial Clip – on, was used. The 2620 Series dynamic strain gauge extensometers are precise and lightweight devices used for direct measurement and closed-loop control of strain in various static and high-frequency cyclic materials testing applications. Figure 2.8 shows the Instron Dynamic Axial Clip – on extensometer series 2620 on one of the experiments

Figure 2.8 Set up of the experiment

2.5 Experiments

Initially a parametric analysis was conducted. This parametric analysis consists of two specimens at 0° and 0°|90° which have only one ply of fabric. These experiments were carried out in order to evaluate the material behavior of the ply. Regarding the geometry of the specimens , the proposed dimensions of the standard were used (except for the thickness since only one layer of fabric was used). Tables 2.3 and 2.4 show the dimensions of the specimens. Figures 2.9 and 2.10 show the diagrams of Load – Extension and Stress – Strain of Unidirectional Fabric. Figures 2.11 and 2.12 show the diagrams of Load – Extension and Stress – Strain of Bidirectional Fabric. Then some experiments were conducted consisting of several plies of fabric in order to achieve the density of the model. For each orientation, 3 specimens were manufactured and measurements were taken in 4 different areas of each specimen before the experiments. In Figure 2.13 are typical constructions of the specimens. The Tables 2.6, 2.7 and 2.8 lists the dimensions of each specimen. To calculate the normal uniaxial stress, the following relation was used:

$$\sigma = \frac{F}{A} \quad (1)$$

where:

F : Load

A : Average area of specimen $A = w \times t$ (2) measured at 4 different points of specimens

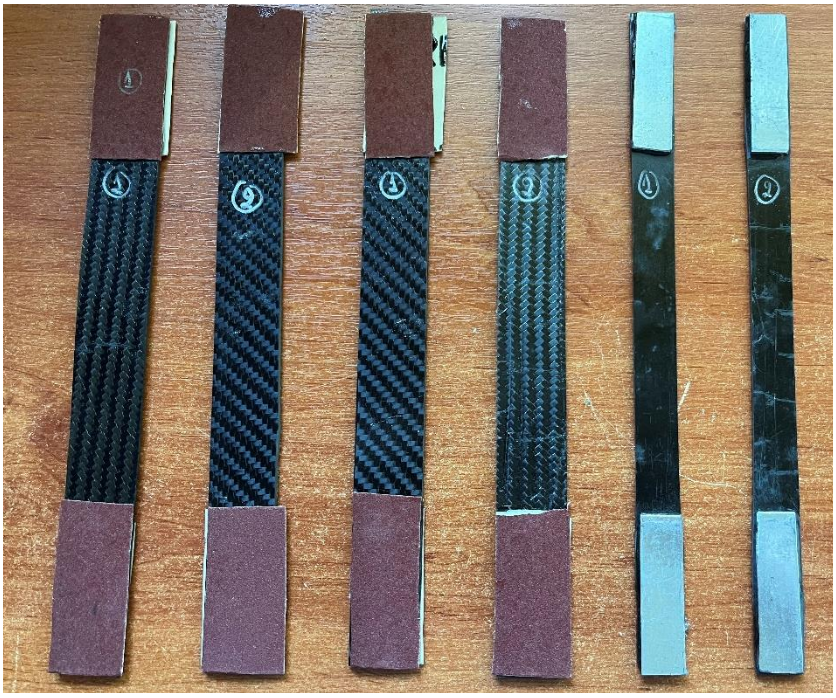


Figure 2.13 Specimens

2.6 Load – Extension & Stress – Strain Diagrams

2.6.1 Load – Extension & Stress – Strain Diagrams of Parametric Unidirectional Specimens

Table 2.3 Dimensions of initial experiments of Unidirectional Fabric

UNIDIRECTIONAL					
(mm)	WIDTH 1	WIDTH 2	WIDTH 3	WIDTH 4	THICKNESS
SPECIMEN 1	15.02	15.07	15.06	15.08	0.15

SPECIMEN 2	15.05	15.05	15.03	15.03	0.15

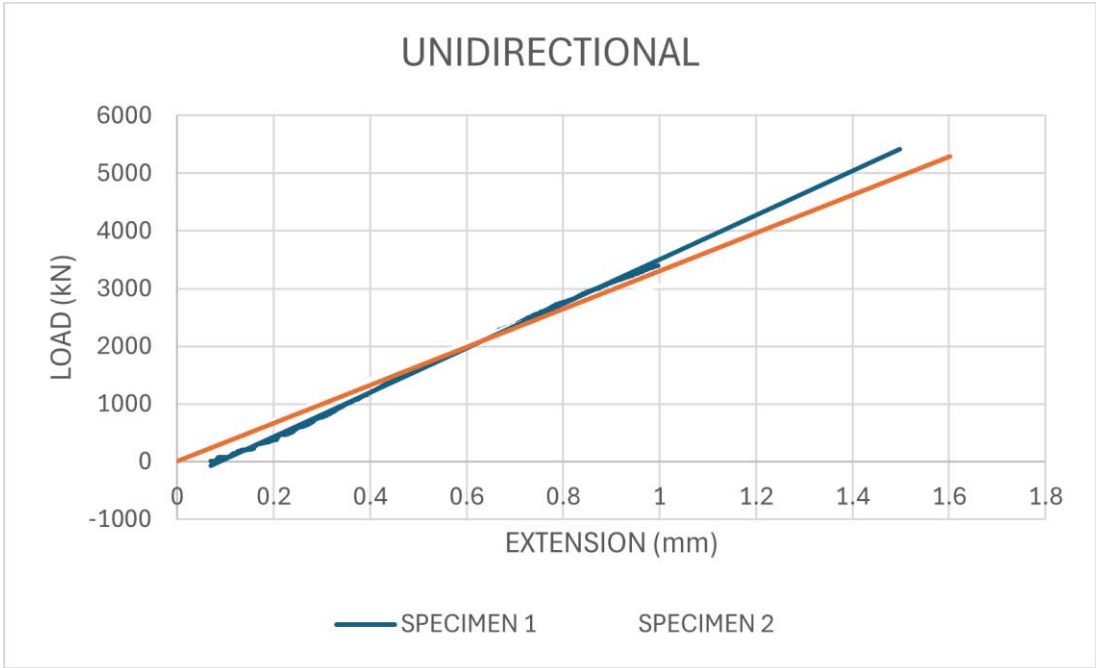


Figure 2.9 Load -Extension Diagram of Unidirectional Fabric

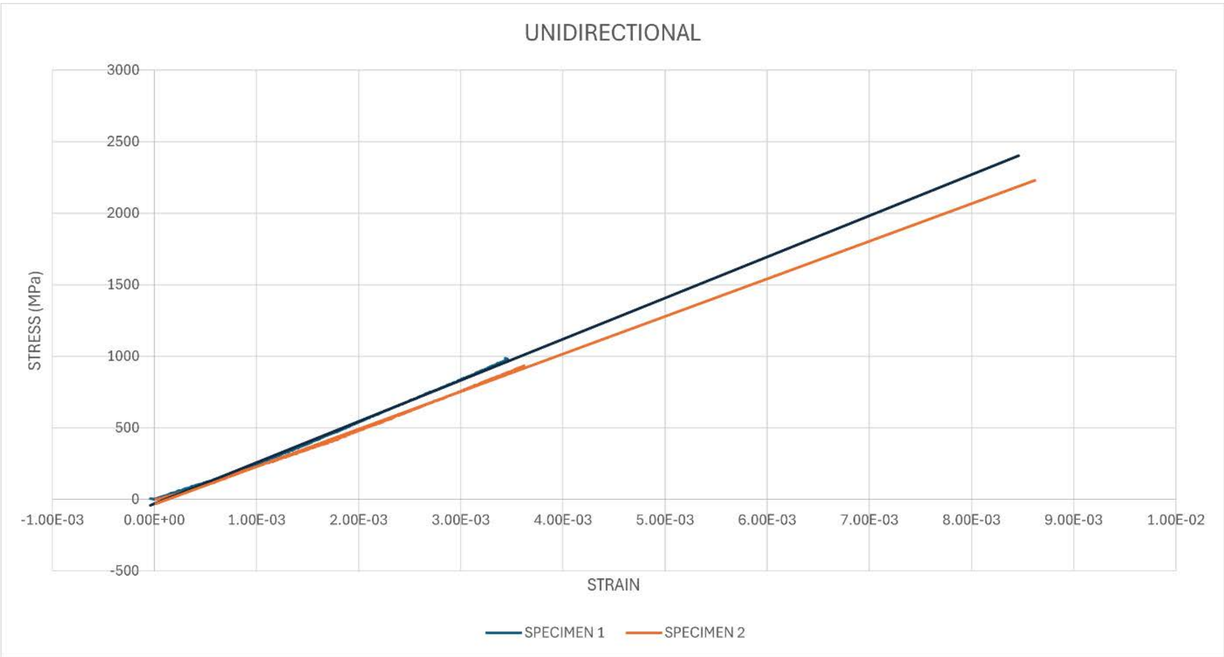


Figure 2.10 Stress – Strain Diagram of Unidirectional Fabric

2.6.2 Load – Extension & Stress – Strain Diagrams of Parametric Bidirectional (0°|90°) Specimens

Table 2.4 Dimensions of initial experiments of Bidirectional Fabric

BIDIRECTIONAL (0°|90°)					
(mm)	WIDTH 1	WIDTH 2	WIDTH 3	WIDTH 4	THICKNESS
SPECIMEN 1	25.02	25.04	25.02	25.02	0.25
SPECIMEN 2	25.04	25.05	25.05	25.06	0.25

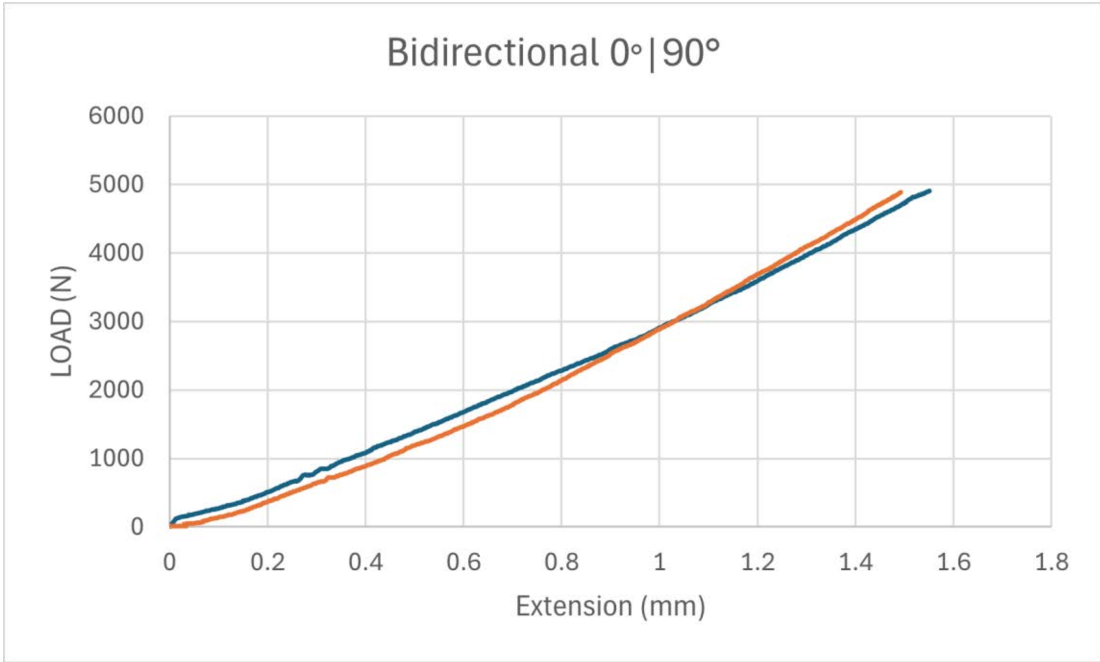


Figure 2.11 Load -Extension Diagram of Bidirectional Fabric at 0°|90°

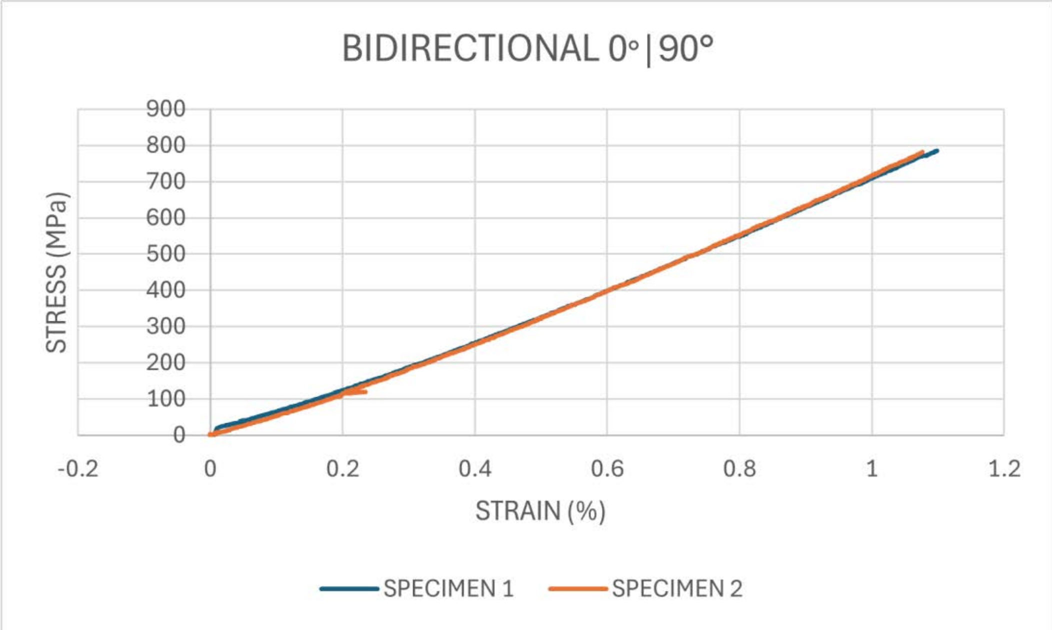


Figure 2.12 Stress - Strain Diagram of Bidirectional Fabric at 0°|90°

Through the experiments some results were obtained in terms of the elastic modulus of a single layer. The results are presented at Table 2.5. The calculation has been done according to Hooke's Law

$$E= \frac{\sigma max}{\varepsilon max}$$

Where,

σmax: Maximum Stress at MPa

εmax: Maximum Strain

Table 2.5 Maximum Stress , Maximum Strain and Young's Modulus of parametric experiments

	0°	0°|90°
σmax (MPa)	2400	942
εmax	0.008	0.011
E (GPa)	300	85.63

2.6.3 Load – Extension & Stress – Strain Diagrams of Unidirectional Specimens

Table 2.6 Dimensions of Unidirectional specimens at four different points

UNIDIRECTIONAL					
	WIDTH 1 (mm)	WIDTH 2 (mm)	WIDTH 3 (mm)	WIDTH 4 (mm)	THICKNESS (mm)
SPECIMEN 1	15.09	15.02	15.03	15.1	1
SPECIMEN 2	15.01	15.08	15.08	15.01	1
SPECIMEN 3	15.01	15.05	15.05	15.04	1

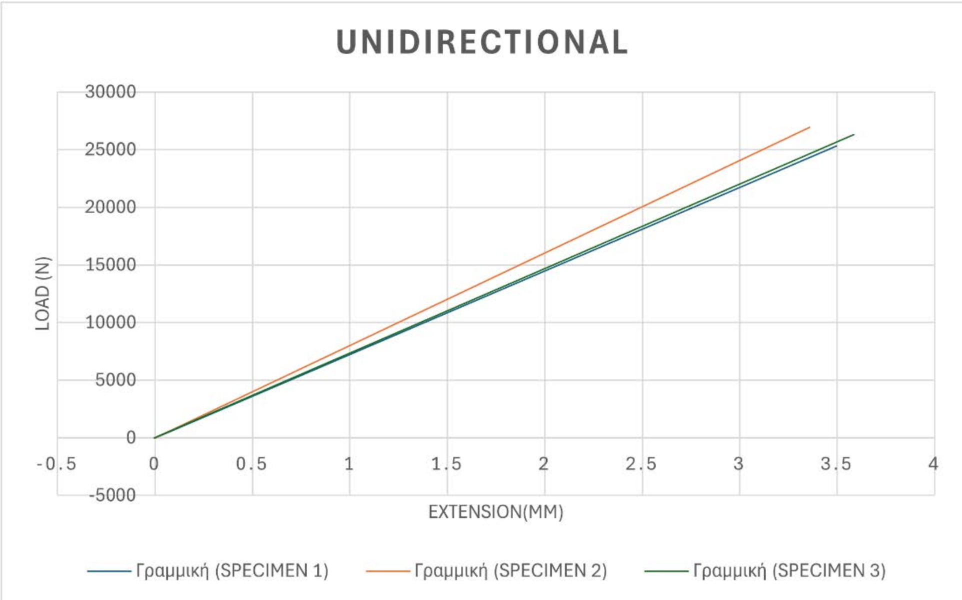


Figure 2.14 Load -Extension Diagram of Unidirectional Fabric

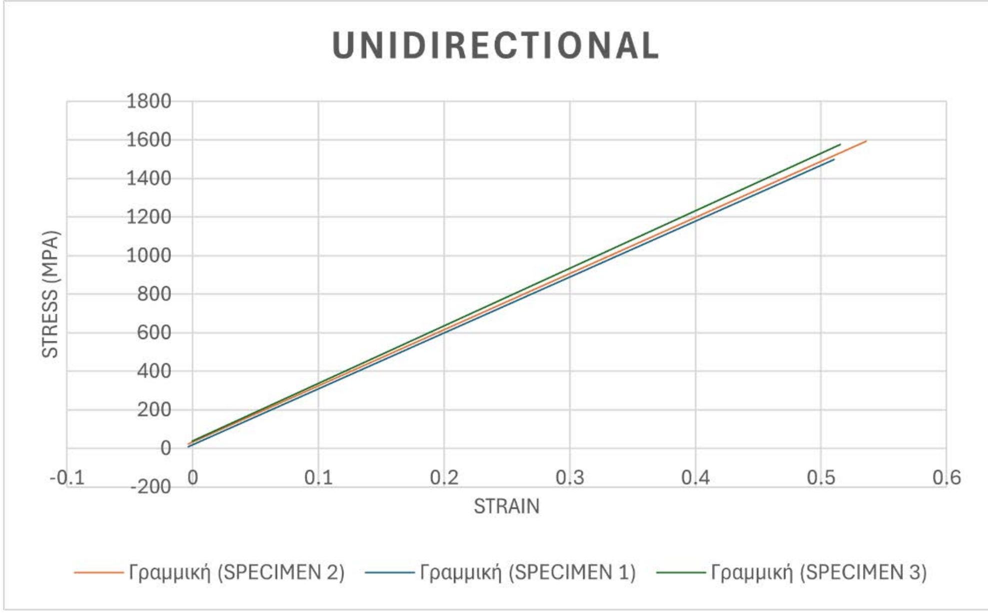


Figure 2.15 Stress - Strain Diagram of Unidirectional Fabric

2.6.4 Load – Extension & Stress – Strain Diagrams of Bidirectional (0°|90°) Specimens

Table 2.7 Dimensions of Bidirectional (0°|90°) specimens

BIDIRECTIONAL (0°|90°)					
	WIDTH 1 (mm)	WIDTH 2 (mm)	WIDTH 3 (mm)	WIDTH 4 (mm)	THICKNESS (mm)
SPECIMEN 1	25.09	25.03	25.03	25.00	2.5
SPECIMEN 2	25.03	25.00	24.90	24.90	2.5
SPECIMEN 3	25.07	25.08	25.05	25.05	2.5

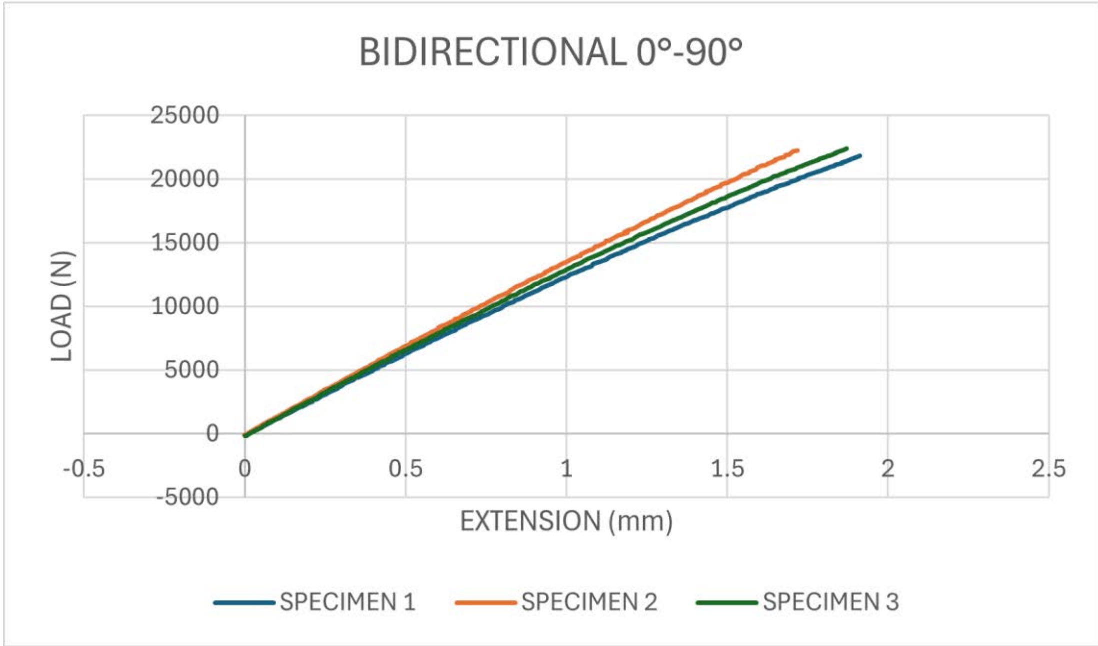


Figure 2.16 Load -Extension Diagram of Bidirectional Fabric (0°|90°)

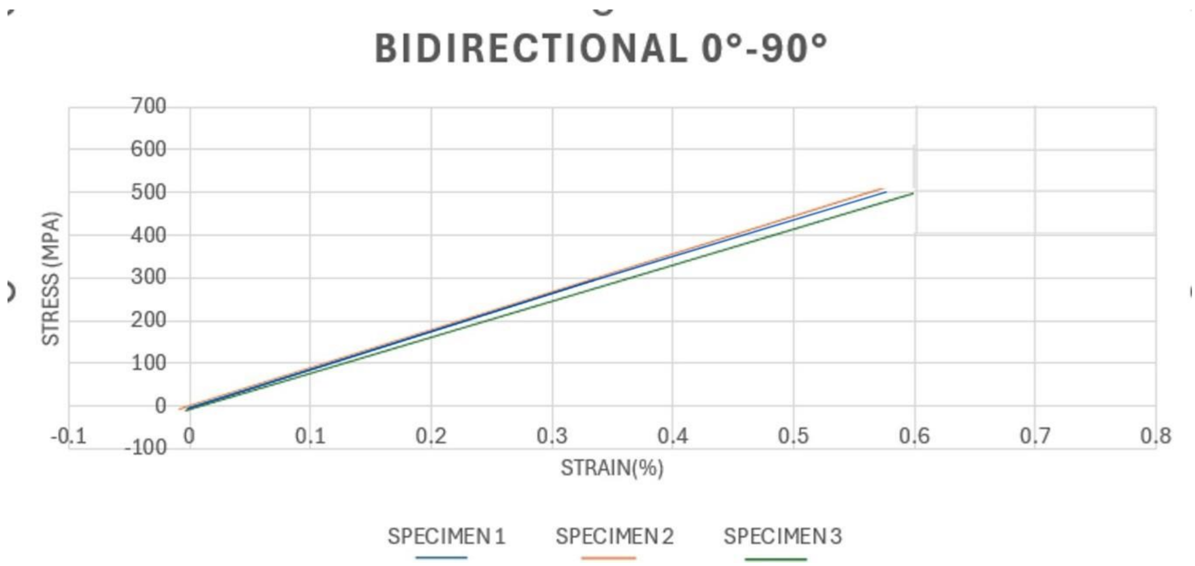


Figure 2.17 Stress - Strain Diagram of Bidirectional Fabric (0°|90°)

2.6.5 Load – Extension & Stress – Strain Diagrams of Bidirectional (-45°|45°) Specimens

Table 2.8 Dimensions of Bidirectional (-45°|45°) specimens

BIDIRECTIONAL (-45°|45°)					
	WIDTH 1 (mm)	WIDTH 2 (mm)	WIDTH 3 (mm)	WIDTH 4 (mm)	THICKNESS (mm)
SPECIMEN 1	25.1	25.09	25.07	25.04	2.5
SPECIMEN 2	25.08	25.06	25.05	25.03	2.5
SPECIMEN 3	25.02	25.02	25.04	25.02	2.5

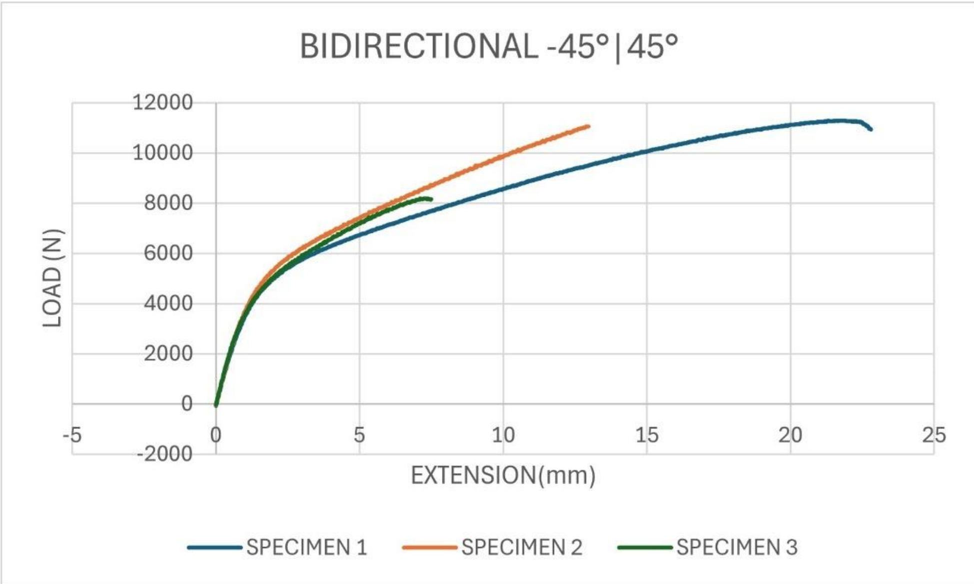


Figure 2.18 Load -Extension Diagram of Bidirectional Fabric (-45°|45°)

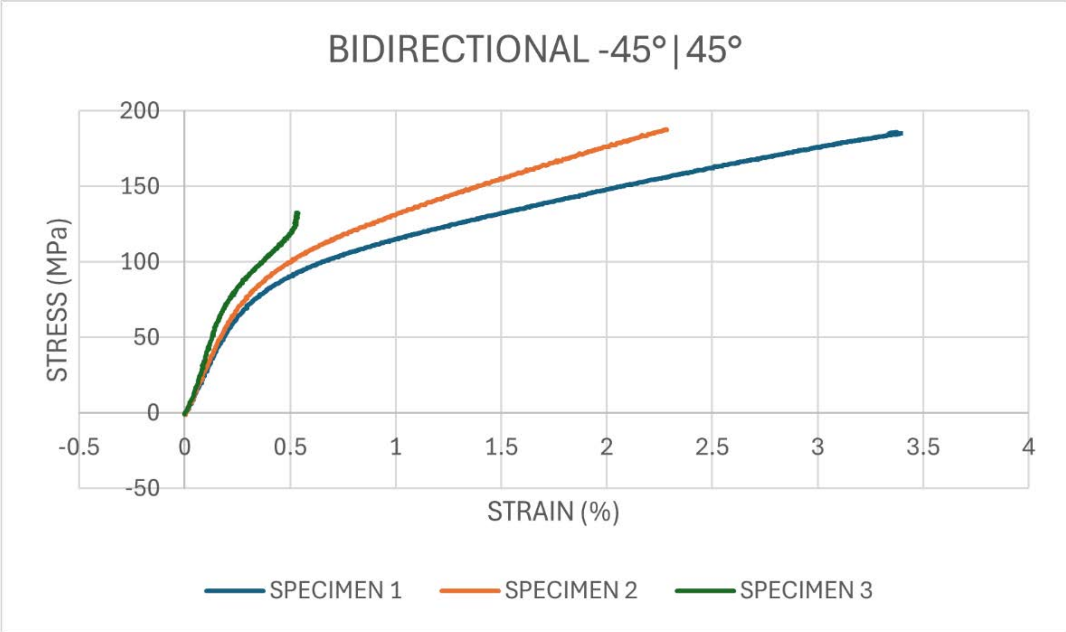


Figure 2.19 Stress - Strain Diagram of Bidirectional Fabric (-45°|45°)

2.7 Calculation of Young's Modulus

The calculation of the modulus of elasticity will be done by Hooke's law (according to ASTM D3039).

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (3)$$

where,

$\Delta\sigma$: difference in applied tensile stress between the two strain points , MPa

$\Delta\varepsilon$: difference between the two strain points (nominally 0.002)

E: tensile modulus of elasticity, GPa

Regarding the starting point and the end point to be used , we choose two points proposed by the standard. The starting point will be 1000 με (1με = 10^-6 ε, ε:strain) and the end point will be 3000 με. In case a bending check is required, the point 2000 με can be used.

2.7.1 Young's Modulus of Unidirectional Fabric

According to the experimental data of chapter 2.6.3 the maximum stress, the maximum strain, the stress difference between two points having 0.002 strain difference and the modulus of elasticity of Unidirectional Fabric are presented in table 2.9

Table 2.9 Calculation of Young's Modulus of Unidirectional Fabric

	Specimen 1	Specimen 2	Specimen 3
σmax (MPa)	1608.41	1701.41	1483.76
εmax	0.0050	0.0053	0.0051
$\Delta\sigma$ (MPa)	592.7	563.3	555.5
$\Delta\varepsilon$	0.002	0.002	0.002
E (GPa)	296.3	281.6	277.7

To conclude, the average Young's Modulus in 0° orientation is 285.2 GPa.

2.7.2 Young's Modulus of Bidirectional (0°|90°) Fabric

According to the experimental data of chapter 2.6.4 the maximum stress, the maximum strain, the stress difference between two points having 0.002 strain difference and the modulus of elasticity of Bidirectional (0°|90°) Fabric are presented in table 2.10

Table 2.10 Calculation of Young's Modulus of Bidirectional (0°|90°) Fabric

	Specimen 1	Specimen 2	Specimen 3
σmax (MPa)	500	490	450
εmax	0.0059	0.0058	0.006
$\Delta\sigma$ (MPa)	180	173.3	174.5
$\Delta\varepsilon$	0.002	0.002	0.002
E (GPa)	90	86.6	87.25

To conclude, the average Young's Modulus in 0°|90° orientation is 87.95 GPa.

2.7.3 Young's Modulus of Bidirectional (-45°|45°) Fabric

According to the experimental data of chapter 2.6.5 the maximum stress, the maximum strain, the stress difference between two points having 0.002 strain difference and the modulus of elasticity of Bidirectional (-45°|45°) Fabric are presented in table 2.11

Table 2.11 Calculation of Young's Modulus of Bidirectional (-45°|45°) Fabric

	Specimen 1	Specimen 2	Specimen 3
σmax (MPa)	185.41	187.78	141.9
εmax	0.03	0.028	0.0048
$\Delta\sigma$ (MPa)	43.8	47.4	52.4
$\Delta\varepsilon$	0.002	0.002	0.002
E (GPa)	21.9	23.7	26.2

To conclude, the average Young's Modulus in -45°|45° orientation is 23.9 GPa.

2.8 Analysis of results

2.8.1 Study of failure modes

After conducting the experiments, the specimens were examined to observe the failure in the fiber-matrix interaction zone. As expected, the mode of failure in each case depends on the orientation of the fibers. The analysis showed that the failure of the composite was due to fracture and separation of the carbon fibers, as well as matrix fracture. The presence of small holes and traces of matrix resin adhered to the fibers indicated strong bonding at the fiber/matrix contact surface, which allowed effective stress transfer from the matrix to the fibers. This mode of failure is consistent with the tensile test results, where the maximum tensile stress and maximum strain were observed at 0° orientation. The failure mode is presented in Figure 2.20.

Figure 2.20 Failure mode at 0° orientation

The specimens in the other two cases showed a different behavior, as shown in Figure 2.21. At 0°|90° and -45°|45° orientations , the composite becomes easier to deform and so the elongation becomes larger.

Figure 2.21 Failure mode at 0°| 90° and -45°|45° orientations

2.8.2 Effect of fiber orientation on Young's modulus

The results that emerged are presented in Table 2.14.

Table 2.12 Effect of fiber orientation

	0°	0°|90°	-45°|45°
E (GPa)	285.2	87.95	23.9

As shown in Table 2.12 , orientation 0° is the optimum direction for the uniaxial tensile strength of the fabric. It is observed that the elastic modulus at Unidirectional fabric is marginally twice the elastic modulus of Bidirectional fabric at 0°|90°. This result is perfectly reasonable, since in Unidirectional the fibers are exclusively in the 0° direction while in Bidirectional the fibers are equal in the 0° and 90° directions. At -45°|45° the elastic modulus is significantly lower than the other two cases , equally an expected result as direction 0° is not reinforced with fibers at all.

2.9.2 Effect of Lay up on Young's Modulus

The results that emerged are presented in Table 2.15

Table 2.13 Effect of Lay up on Young's Modulus

	0°	0°|90°
E (GPa) – 1 ply	300	85.63
E (GPa) – Multiple plies	285.2	87.95

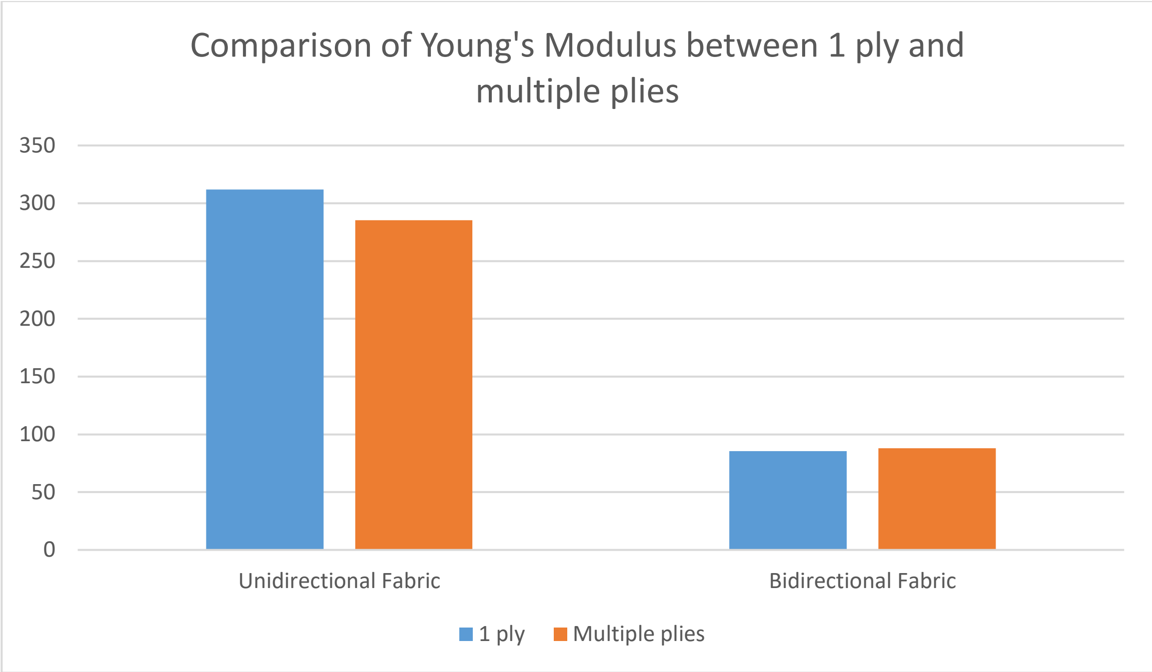


Figure 2.22 Comparison of Young's Modulus between 1 ply and multiple plies

As expected, increasing the thickness of the specimen does not affect the modulus of elasticity of the composite as it depends only on the materials of which it is composed (fibres and matrix). The quantity that is affected is the stiffness of the composite and with the increase in thickness it also increases. The small difference in Bidirectional Fabric is most likely due to misalignment of the specimen on the tensile machine or due to the creation of out of plane strains.

CHAPTER 3: ANALYTICAL SOLUTION AND NUMERICAL SIMULATION

In this chapter the analytical solution and a first approach to the experiments through simulations in elastic region is developed and some conclusions about the simplicity of the simulations are drawn.

3.1 Analytical Solution

To calculate the modulus of elasticity of a composite material containing fibres either only parallel or perpendicular or some parallel and some perpendicular to the load , the rule of mixtures can be used. The rule of mixtures is commonly used to calculate the properties of composites when the properties of the matrix and the fibres are known.

The elastic modulus of carbon fibers ranges from **500 GPa to 800 GPa**, depending on the type (high modulus carbon fibers). In contrast, the elastic modulus of pure epoxy resin typically ranges between **2.5 GPa and 4 GPa**.

Elastic Modulus of Unidirectional Fabric at 0°

For unidirectional carbon fiber, where the fibers are aligned parallel to the applied load, the elastic modulus can be calculated using the rule of mixtures:

$$E=Vf \times Ef+Vm \times Em$$

Where:

- $Vf=0.6$ is the fiber volume fraction,
- $Ef=500GPa$ is the elastic modulus of the carbon fibers,
- $Vm=0.4$ is the matrix (resin) volume fraction,
- $Em=2.5GPa$ is the elastic modulus of the epoxy resin.

Thus, the elastic modulus of the unidirectional fabric at 0° is:

$$E=0.6 \times 500+0.4 \times 2.5=301GPa$$

Elastic Modulus of Bidirectional Fabric at 0°|90°

In the case of bidirectional fabric, the fibers are oriented in two directions (0° and 90°), with half the fibers aligned with the load and the other half perpendicular to it. Therefore, it is necessary to calculate the elastic modulus for both directions and then find the average value.

Calculation of Parallel Elastic Modulus

For the fibers aligned parallel to the load, the rule of mixtures is again applied:

$$E = Vf \times Ef + Vm \times Em$$

$$E = 0.3 \times 500 + 0.7 \times 2.5 = 152.8\text{GPa}$$

Calculation of Perpendicular Elastic Modulus

For the fibers perpendicular to the load, the elastic modulus is calculated using the inverse rule of mixtures:

$$\frac{1}{E} = \frac{Vf}{Ef} + \frac{Vm}{Em}$$

$$\frac{1}{E} = \frac{0.3}{500} + \frac{0.7}{2.5} =$$

$$E = 3.57 \text{ GPa}$$

The average elastic modulus of the bidirectional fabric is then:

$$E = \frac{152.8 + 3.57}{2} = 78.18\ GPa$$

3.2 General Description of Finite Element Analysis

The finite element method is a numerical method used to simulate the behavior of materials under various loads using commercially available software, with various assumptions. With the use of FEA, the time required for the final design of a part, is significantly reduced and there is also an overview of the stress distribution. This method gives approximate results which reflect reality to a satisfactory degree. In the beginning, the finite element method found application in structural analyses. Then it was extended to other problems such as thermal, electrical and fluid problems.

A general description of the method is the following:

In engineering problems there are some variables that are unknown and are called field variables. In structural problems these variables are usually displacements, in fluid problems they are velocities, and in electrical problems electric and magnetic potentials. In a continuum, there are infinitely many unknowns to consider. The finite element method addresses this by limiting the number of unknowns. It does so by dividing the solution domain into smaller sections called elements. Some examples of elements are presented in Figure 3.1. Within each element, the unknown field variables are represented using assumed approximating functions, also known as interpolating functions or shape functions. The approximating functions are defined using the field variables at specific points known as nodes or nodal points. Thus, in finite element analysis, the unknowns are the field variables at these nodal points. Once the values at the nodes are determined, the field variables at any point within an element can be calculated using interpolation functions. After selecting the elements and determining the nodal unknowns, the next step in finite element analysis is to assemble the properties of each element. For instance, in solid mechanics, it is essential to determine the force-displacement relationship, or the stiffness characteristics, of each individual element. Mathematically, this relationship is expressed as:

$$[k]e\{\delta\}e = \{F\}e \quad (1)$$

where,

[k]e : Element stiffness matrix

{δ}e : Nodal displacement vector of the element

{F}e : Nodal force vector

The components of the stiffness matrix, k_{ij}, represent the force in the coordinate direction 'i' resulting from a unit displacement in the coordinate direction 'j'. The element properties are then used to assemble the global properties of the structure to form the system equations:

$$[K]\{\delta\}=\{F\} \quad (2)$$

Afterward, boundary conditions are applied. Solving these simultaneous equations yields the nodal unknowns. With the nodal values obtained, further calculations can be made to determine the required quantities, such as stresses, strains, and moments, in solid mechanics problems.

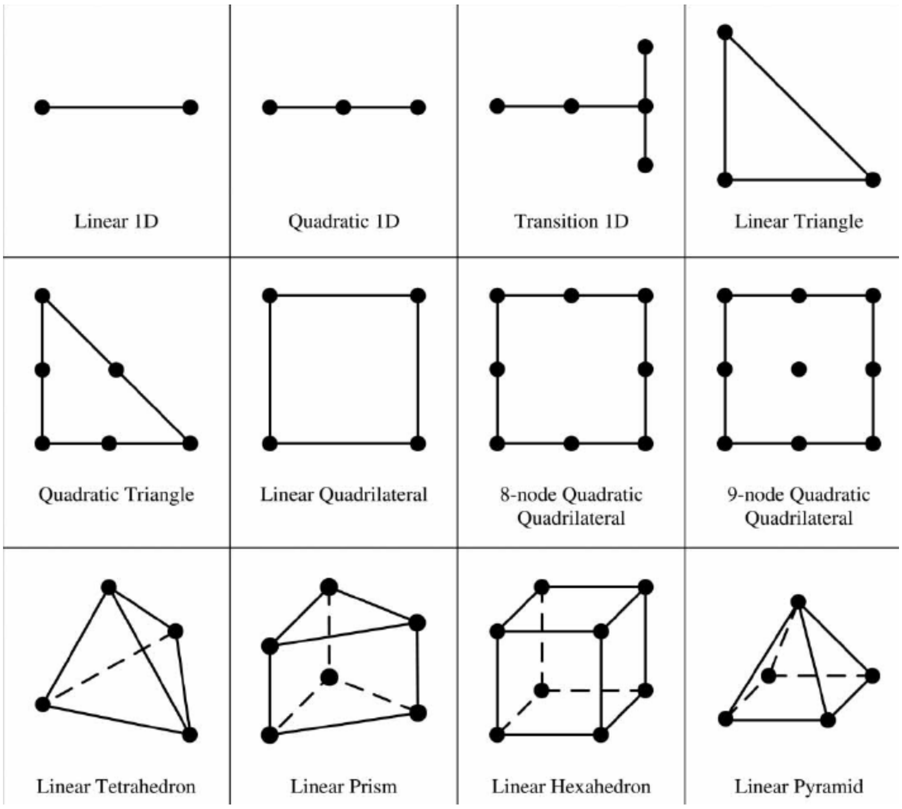


Figure 3.5 Examples of elements

3.3 Model Description

The models based on the finite element method were developed in FE Code Optistruct/ Altair. Regarding the geometry of the models, the dimensions suggested by ASTM D3039 have been used and have been analyzed in tables in the previous chapter. As for the orientations tested in simulation initially were 0°|90° and -45°|45° in order to confirm that the experiments and simulations converge. At this point it is necessary to underline the importance of the use of software simulations as they provide the possibility for accurate results in a very short period of time, reducing the cost of manufacturing several specimens for experiments and avoiding manufacturing errors that can lead to incorrect calculations.

3.4 Simulation Process

The steps involved in setting up the simulation are as follows:

1. Design of component
2. Meshing

3. Properties and Materials
4. Boundary Conditions and Loads
5. Run model and Results

3.4.1 Design of component

As mentioned above, the models will have the geometry indicated in the standard. We will design two 2D surfaces. The geometry of the models is shown in Figure 3.3.

Figure 3.6 Geometry of models

3.4.2 Meshing

In order to obtain accurate stress distribution result, the structured meshing technique was used to mesh the model with “Linear four noded general purpose shell element with reduced integration”. Four – node element means, every element consists of 4 nodes while reduced integration means the order of integration is lower than that of full integration. Then the length of the elements will be 12.5 mm, as shown in Figure 3.4.

Note: Both of models have the same element size.

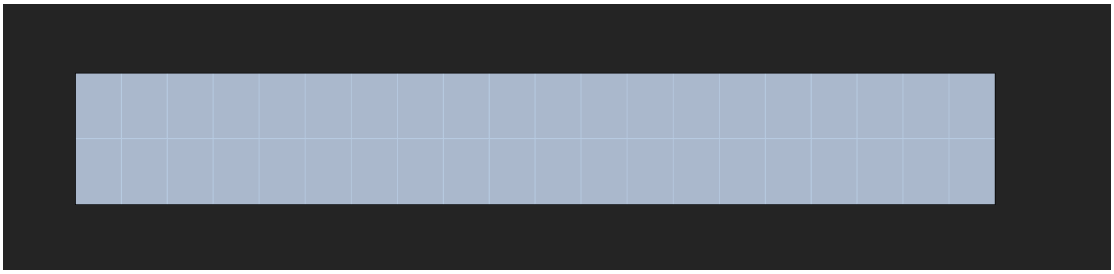


Figure 3.7 Meshing of models

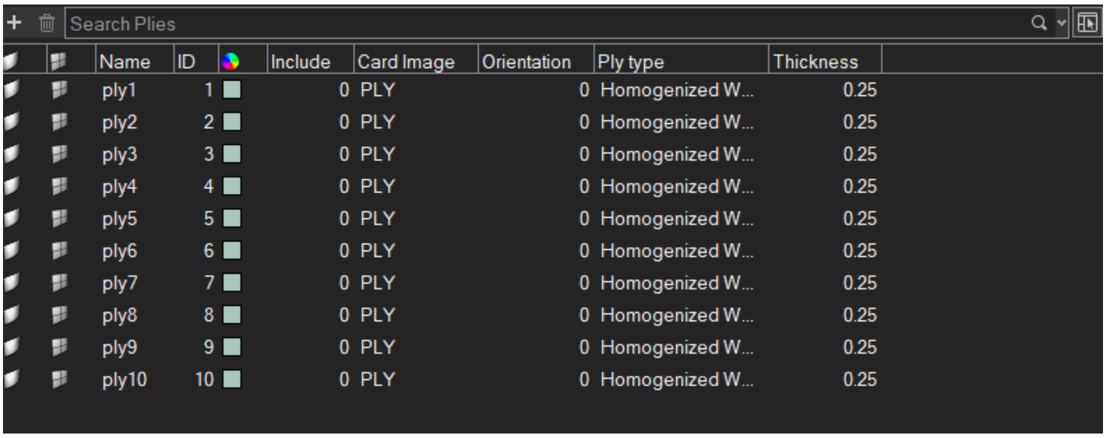
3.4.3 Properties and Materials

The process followed in order to create the laminates is as follows:

First a ply was created that had specific properties:

- Thickness: 0.25mm (for bidirectional fabric) .
- Orientation: In each case the orientation of the fibers we are considering. In Figure 3.5 there is an example from the creation of the laminate at 0°|90° .
- Ply Type: "Homogenized Woven" for Bidirectional fabric.

Afterwards, the plies were multiplied according to the thickness required by each experiment. The 0°|90° and -45°|45° models of 10 plies.



Name	ID	Include	Card Image	Orientation	Ply type	Thickness
ply1	1	0	PLY	0	Homogenized W...	0.25
ply2	2	0	PLY	0	Homogenized W...	0.25
ply3	3	0	PLY	0	Homogenized W...	0.25
ply4	4	0	PLY	0	Homogenized W...	0.25
ply5	5	0	PLY	0	Homogenized W...	0.25
ply6	6	0	PLY	0	Homogenized W...	0.25
ply7	7	0	PLY	0	Homogenized W...	0.25
ply8	8	0	PLY	0	Homogenized W...	0.25
ply9	9	0	PLY	0	Homogenized W...	0.25
ply10	10	0	PLY	0	Homogenized W...	0.25

Figure 3.8 Example of plies at 0°|90°

Then a property was created. Creating properties for components in HyperMesh/OptiStruct is a critical step in FEA modeling. It ensures that the material behavior, physical attributes, and analysis settings are accurately defined. This leads to realistic simulation results, guiding engineers in design validation, optimization, and decision-making processes. Without proper property definitions, the analysis results could be inaccurate or misleading, resulting in poor design choices and potential failure in real-world applications.

PCOMPP card was used in these simulations, which defines the properties of a composite laminate material used in ply-based composite definition.

Last but not least, the materials were created. MAT9OR card was used in these simulations , which defines the material properties for linear, temperature-independent, and orthotropic materials for solid elements in terms of engineering constants. The properties of the materials used have been taken from the datasheets provided by the company.

In the Figures 3.6 the properties of the materials are presented. (Young's Modulus in MPa and Density in kg/mm^3)

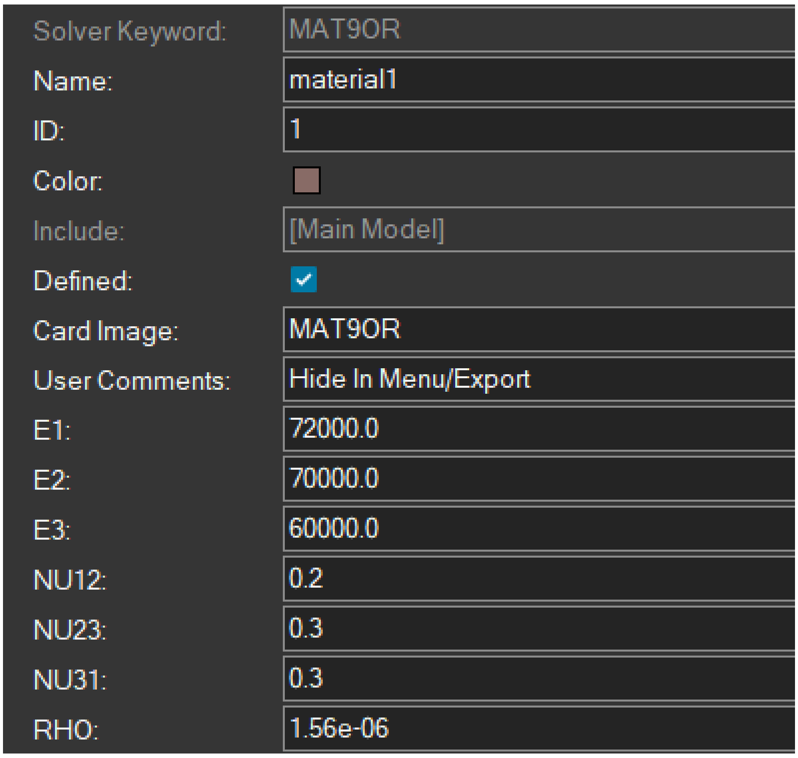


Figure 3.9 Properties of Bidirectional Fabric

3.4.4 Boundary Conditions and Loads

In this thesis a linear approach was followed to simulate the specific experiments. Regarding the boundary conditions, one side of the specimen (corresponding to one tab) was fixed without any degree of freedom and the other side of the specimen (corresponding to the other tab) was fixed with one degree of freedom in the axis where movement is allowed (in these simulations it is the x-axis).

In terms of loads, 10 different loads were applied. An RBE2 node was created to implement the load. RBE2 node defines a rigid body whose independent degrees of freedom are specified at a single independent node and whose dependent degrees of freedom are specified at an arbitrary number of dependent nodes. It was used to apply a force to the primary node and distribute it to the secondary nodes in such a way that no additional stiffness is introduced into the system. Figure 3.6 shows the structure of the boundary conditions and loads.

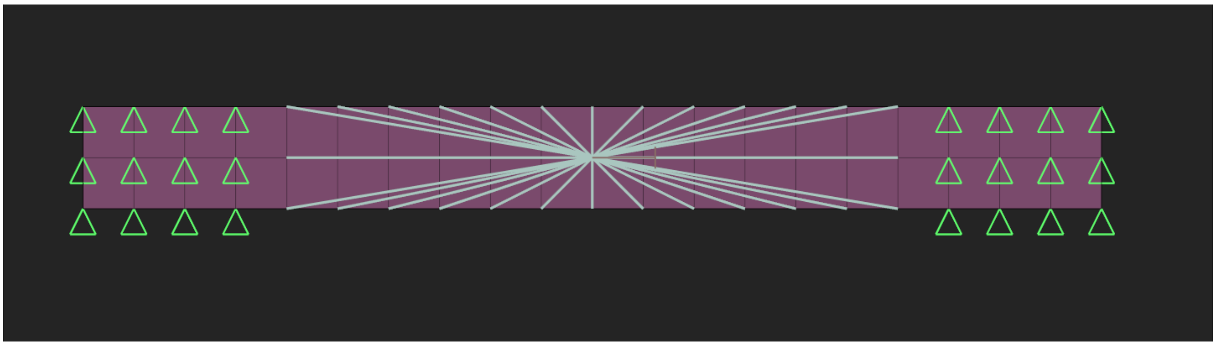


Figure 3.6 Boundary Conditions and Loads

3.4.5 Run model and Results

As mentioned before , the solver OptiStruct was used for the linear solution of the simulations. Tables 3.1 and 3.2 present the results concerning the composite stresses and strains.

Table 3.1 Results of 0°|90° model

FORCE (N)	COMPOSITE STRESSES (MPa)	STRAINS (%)
2000	32.46	0.0286
4000	64.92	0.0572
6000	97.38	0.0858
8000	129.80	0.1144
10000	162.25	0.143
12000	194.81	0.1716
14000	227.26	0.2002
16000	261.47	0.2305
18000	294.03	0.259
20000	324.61	0.289
22000	357.07	0.314

Table 3.2 Results of -45°|45° model

FORCE (N)	COMPOSITE STRESSES (MPa)	STRAINS
1000	6	0.02
2000	11.66	0.04
3000	23.33	0.07
4000	34.99	0.09
5000	46.66	0.12
6000	58.32	0.145
7000	69.99	0.169
8000	81.65	0.193
9000	93.31	0.217
10000	104.97	0.241

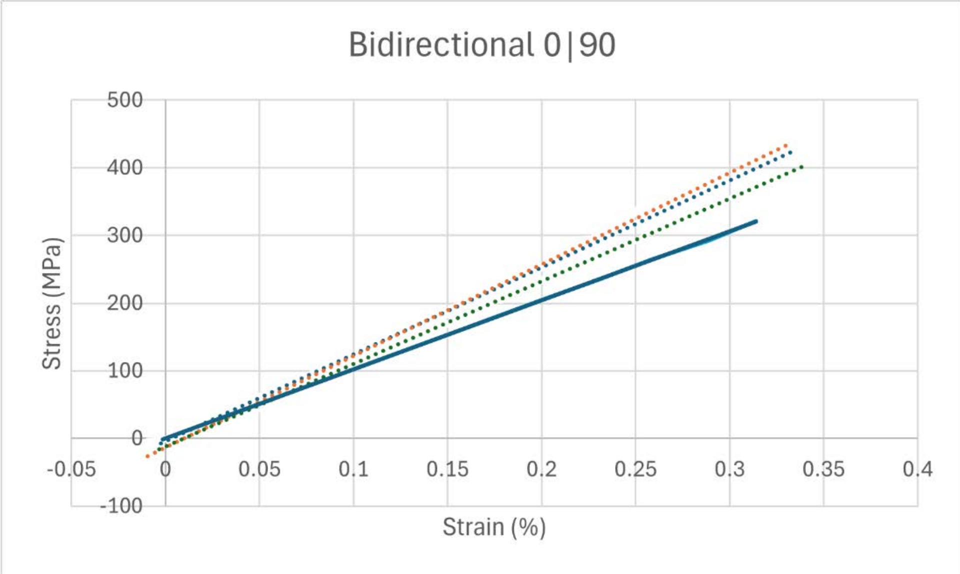


Figure 3.7 Experiments vs Simulation of 0°|90°

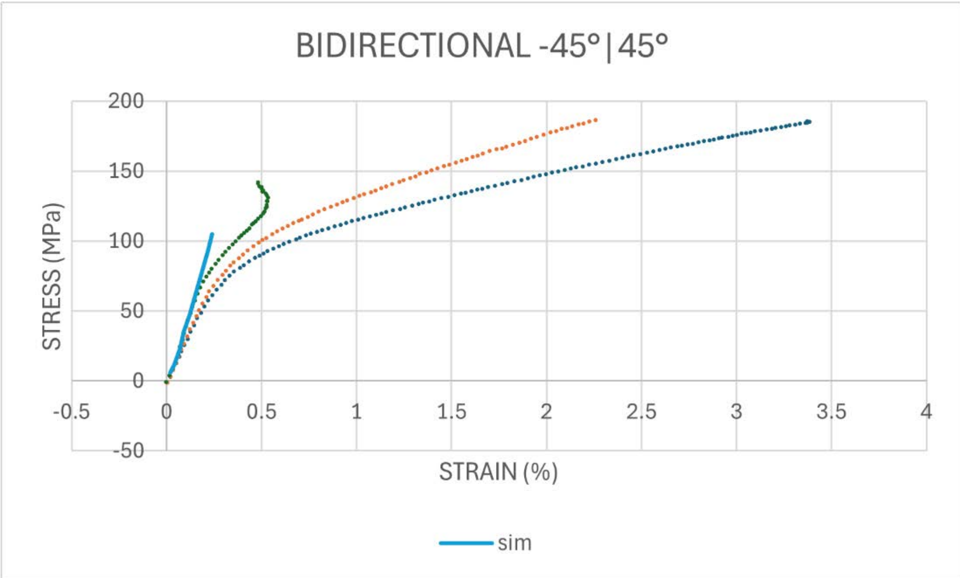


Figure 3.8 Experiments vs Simulation of -45°|45°

According to the simulations, the results are presented at Table 3.

	0°|90°	-45°|45°
σmax (MPa)	357.07	104.97
εmax	0.314	0.241
E (GPa)	113.6	46.65

3.5 Comparison between analytical solution, numerical simulation and experiments

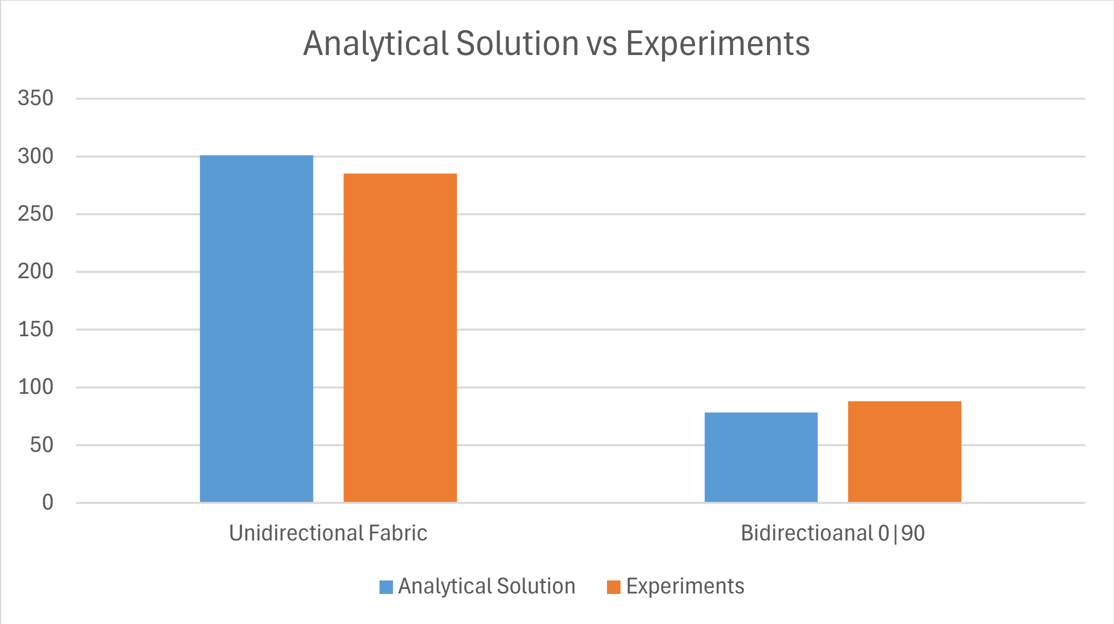


Figure 3.9 Analytical Solution vs Experiments

As can be seen from the graph, the analytical solution converges well with the experiments. However, he differences between analytical solutions and experimental results for composite materials often arise from various factors. Analytical models, such as the rule of mixtures, simplify assumptions, like uniform fiber-matrix distribution and perfect bonding, which are not always realistic. In practice, microstructural defects, such as voids, weak interfaces, or impurities, degrade the material's performance. Additionally, analytical models usually assume linear elastic behavior, whereas real materials may exhibit nonlinear behavior or localized failures. SFurthermore, the properties of fibers and matrices can vary in practice due to manufacturing inconsistencies or environmental influences. Experimental conditions, such as non-uniform loading, stress concentrations, or errors during measurement, also contribute to deviations. Lastly, time-dependent phenomena like creep, fatigue, or stress relaxation can further widen the gap between theory and experiment. Thus, while analytical solutions offer valuable approximations, experimental results reflect the complex, real-world behavior of composite materials.

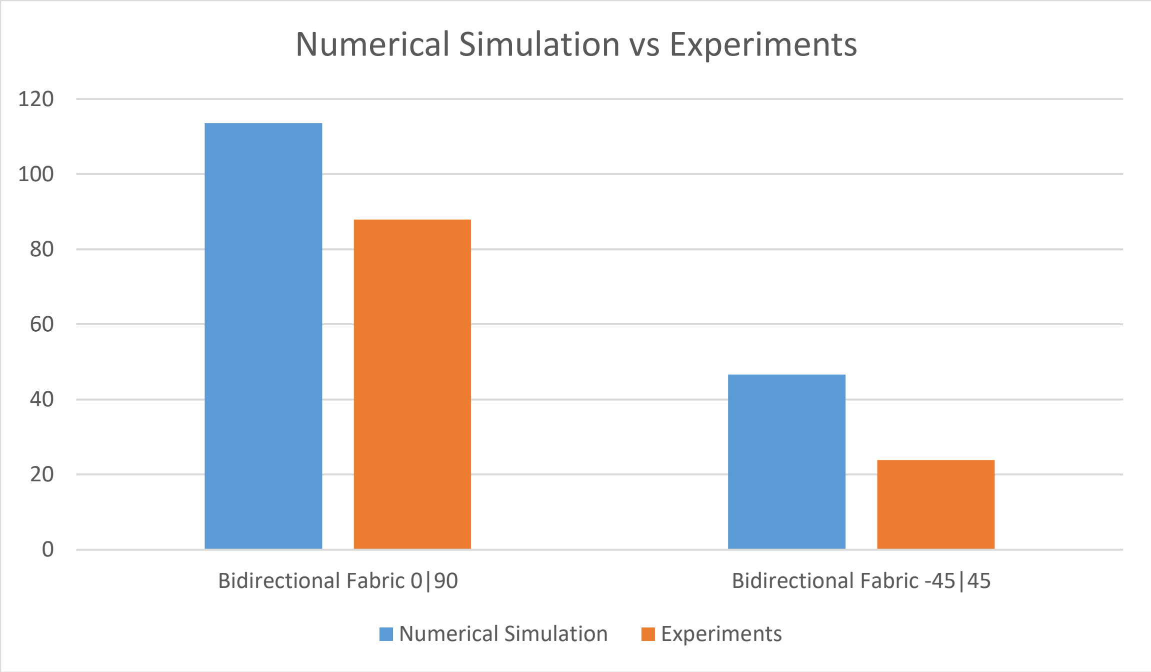


Figure 3.10 Numerical Simulation vs Experiments

The difference between simulations and experiments often arises due to simplifications and assumptions made in the simulation models. In simulations, ideal conditions are typically assumed, such as perfect bonding between fibers and matrix, uniform material properties, and flawless geometry. However, in real experiments, there are often imperfections, such as defects, voids, non-uniform fiber distributions, or imperfect bonding, which affect the material's performance. Additionally, environmental factors, manufacturing variations, and measurement inaccuracies can also contribute to discrepancies. Simulations may not fully capture complex behaviors, such as damage progression, plasticity, or non-linearities, leading to differences from experimental results.

CHAPTER 4: CONCLUSIONS – SUGGESTIONS FOR FURTHER STUDY

This thesis demonstrated that fiber orientation plays a critical role in the mechanical properties of Carbon Fibre Reinforced Polymers (CFRPs). The tensile tests showed that unidirectional fibers aligned at 0° have the highest tensile strength and Young's modulus, reaching 285.2 GPa, making them the most effective configuration for bearing uniaxial loads. Bidirectional fibers in the 0°|90° orientation exhibited moderate strength (122.3 GPa), while fibers at -45°|45° displayed significantly lower mechanical performance, with a Young's modulus of 23.9 GPa. Finite Element Analysis (FEA) simulations confirmed experimental results for the 0°|90° orientation, showing close agreement. However, a significant discrepancy was observed in the simulations for the -45°|45° orientation. This suggests that current simulation models may not fully account for phenomena such as fiber debonding from the matrix and crack propagation in composite materials. These issues contribute to the nonlinear behavior observed during testing, especially in the lower-performing orientations.

Suggestions for Future Study:

1. **Enhanced Simulation Models**: The study revealed the need for more accurate simulations, particularly for complex fiber orientations such as -45°|45°. Future work should focus on developing advanced numerical models that better capture the nonlinear behavior of composite materials. This includes incorporating more detailed representations of matrix cracking, fiber debonding, and other failure mechanisms at the microstructural level. Incorporating multiscale modeling or micromechanics approaches could improve simulation accuracy.
2. **Dynamic and Fatigue Testing**: While this study focused on static tensile properties, future research should extend to dynamic loading conditions, such as fatigue or impact testing. These tests are critical for understanding how CFRPs behave under real-world operating conditions, where materials are subjected to cyclic or shock loads. Exploring how fiber orientation influences fatigue resistance and long-term durability could provide valuable insights for industries like aerospace and automotive, where reliability is essential.
3. **Inclusion of More Fiber Types and Matrix Materials**: This study examined carbon fibers and epoxy matrices, but future research could explore the effects of different fiber types (e.g., glass, aramid) and matrix materials (e.g., thermoplastics). This would allow

for the optimization of composite materials for specific applications, especially where cost or specific material properties, such as thermal resistance or flexibility, are key considerations.

4. **Experimental Techniques for Failure Mechanisms**: More detailed experimental analysis of failure mechanisms, such as scanning electron microscopy (SEM) of fracture surfaces, could offer deeper insights into how different orientations influence the failure modes. Understanding the microscopic behavior at the fiber-matrix interface could help improve material design and the selection of adhesive systems for better bonding.
5. **Hybrid Composite Configurations**: Another area for future study is the investigation of hybrid composite configurations. By combining fibers with different orientations or even different fiber types within the same composite, it may be possible to achieve an optimal balance between strength, stiffness, and flexibility. This approach could expand the range of applications for CFRPs, especially in structures that require multidirectional load-bearing capacity.
6. **Thermal and Environmental Effects**: Investigating the influence of environmental factors, such as temperature changes, humidity, or chemical exposure, on the mechanical properties of composites would be valuable. Since CFRPs are often used in harsh environments, understanding how different fiber orientations respond to these conditions is critical for ensuring long-term performance and reliability.

The findings of this thesis offer valuable insights into how fiber orientation affects the mechanical performance of CFRPs, with clear implications for optimizing material design for specific engineering applications. While significant progress has been made in understanding the tensile properties of CFRPs, there remains much potential for advancing both experimental techniques and simulation models. By addressing the gaps identified in this study, future research could significantly enhance the use of CFRPs in high-performance, weight-sensitive applications across various industries.

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