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CHARACTERIZATION OF INNOVATIVE THERMOPLASTIC SANDWICH PANELS FOR ROAD AND RAIL CONTAINERS

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Abstract

This thesis explores the mechanical characterization of innovative thermoplastic sandwich panels used in road and rail containers. Conducted in collaboration with AGESIA at Ghent University (Belgium), the research addresses significant performance issues identified during true-scale testing, where failures of the sandwich panels raised concerns about their structural integrity and reliability.

A thorough literature review emphasizes the benefits of thermoplastic composites, including weight reduction, enhanced load capacity, and recyclability, all contributing to improved sustainability in transportation applications. The study includes mechanical testing of the sandwich panel components, specifically Glass Fiber Reinforced PA6 and PET foam core, under various loading conditions at both ambient and elevated temperatures. Key static tests—including tensile, compression, and flexural tests—were conducted to assess the mechanical properties of the materials.

The results indicate that the initial composite exhibited unsatisfactory mechanical properties due to manufacturing quality issues. Subsequent testing of a composite from an alternative supplier showed significantly improved performance, providing important insights into the influence of material selection on structural behavior.

This research investigate the in-service behaviour of thermoplastic sandwich panels for road and rail containers. Furthermore, it offers recommendations for optimizing the manufacturing process and material choices for sandwich panels, ultimately aiming to enhance their performance and reliability in the transportation sector.

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List of Symbols and Abbreviations

<i>GFR</i>	Glass-Fiber-Reinforced
<i>PA6</i>	Polyamide 6
<i>SEM</i>	Scanning Electron Microscope
<i>TPCs</i>	Thermoplastic Composites
<i>CFRTCs</i>	Continuous-Fiber-Reinforced Thermoplastic Composites
<i>SFRTCs</i>	Short-Fiber-Reinforced Thermoplastic Composites
<i>VBO</i>	Vacuum-Bag-Only
<i>ISC</i>	In-Situ Consolidation
<i>IPSS</i>	In-Plane Shear Strength
<i>ILSS</i>	Interlaminar Shear Strength
<i>E</i>	Young's Modulus [MPa]
v_f	Fibre volume fraction
v_m	Matrix volume fraction
ν	Poisson ratio [-]
G_{12}	Shear modulus [MPa]
α	Efficiency factor [-]
ε_i	Direct strain [-]
γ_{ij}	Shear strain [-]
σ_i	Direct stress [MPa]
τ_{ij}	Shear stress [MPa]
x, y, z	Cartesian coordinate system
U, V, W	Displacement components in x, y, and z-directions [mm]
$[A, B, D]$	Extension, coupling and bending stiffness matrices [N/mm], [N], [Nmm]

$C_E, C_G, C_\sigma, C_\tau$	Constants defining core material properties [-]
ρ	Density [kg/m^3]
I	Moment of inertia [kgm^2]
EI	Flexural rigidity (bending stiffness) [Nmm]
B	Width of beam [mm]
t	Component Thickness [mm]
D	Total sandwich thickness [mm]
d	Distance between the centers of the skins [mm]
L	Support span length [mm]
M	Bending moment [Nmm]
S	Shear stiffness [N/mm]
V	Shear load [N]
P	Load [N]
k_b, k_s	Deformation coefficients for beams and panels [-]
F	Peak strength [N]
Δ	Deflection [mm]
k	Shear correction factor [-]
T_g	Glass transition temperature [$^{\circ}\text{C}$]
RH	Relative humidity [%]
RTM	Resin Transfer Moulding
$VARTM$	Vacuum Assisted Resin Transfer Moulding
CIB	Covalent Intermediate Bonding
DIC	Digital Image Correlation
VRO	Variable Ray Origin
RBM	Rigid Body Motion
FOV	Field Of View
$ASTM$	American Society for Testing and Materials
$LVDTs$	Linear Variable Differential Transformers

Chapter 1

Introduction

1.1 Background and Motivation

Composite materials have emerged as a critical component in the advancement of modern engineering applications, particularly within the transportation sector. Their unique properties—such as high strength-to-weight ratios, stiffness-to-weight ratios and enhanced durability—make them ideal for use in road and rail containers. Among these composites, thermoplastic sandwich panels are increasingly favored for their potential to reduce weight, leading to lower fuel consumption and increased load capacity, all while maintaining structural integrity, which is essential for efficient transport solutions. Furthermore, the recyclability of thermoplastic composites offers significant sustainability advantages, contributing to a circular economy.

Despite their advantages, challenges remain in the practical application of these materials (1.1). A significant issue was encountered by AGESIA during true-scale testing of their containers (1.2), where the thermoplastic sandwich panels exhibited failures that compromised their structural performance. This problem not only raised concerns regarding the safety and reliability of the containers but also posed potential financial repercussions for the company.

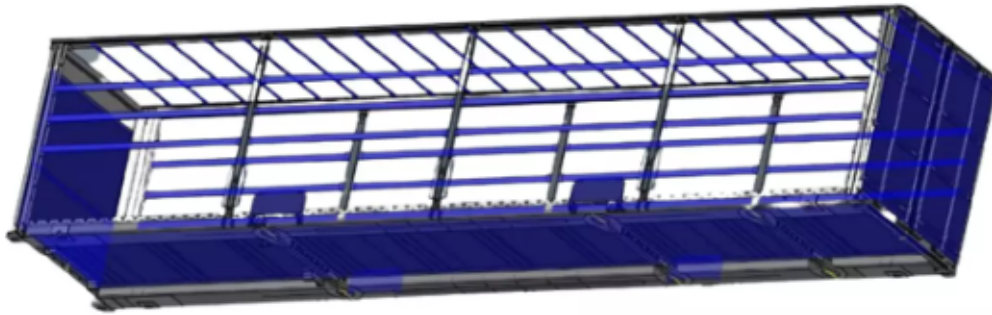


Figure 1.1: Design of a new swap floor for intermodal 45ft curtain side container, replacing the heavy metal floor construction. Courtesy of AGESIA.



Figure 1.2: True-scale testing of the container's floor. Courtesy of AGESIA.

1.2 Objectives of the Study

In response to these challenges, this study conducted at Ghent University (Belgium) aims to conduct a comprehensive characterization of the materials constituting the sandwich panels, specifically GFR PA6 and PET foam. The primary objectives are to investigate the mechanical properties of these materials and the in-service behaviour of the sandwich panels. This research will include static tests such as tensile, compression, and bending tests, performed at both ambient and elevated temperatures. Additionally, analytical models will be developed to predict the flexural behavior of the panels, providing further insight into their performance.

Initial results from the mechanical characterization indicated disappointing properties for the GFR PA6 composite, attributed to manufacturing quality issues. In order to address these challenges, a composite from an alternative supplier was tested, which resulted in significantly better outcomes. This research seeks to identify the root causes of the initial failures and to provide recommendations for enhancing the manufacturing quality of composite materials used in sandwich panels.

1.3 Structure of the Thesis

The work is structured as follows:

Chapter 2 provides an in-depth literature review concerning the thermoplastic composite materials used, the properties and characterization of sandwich structures and the analytical models for the flexural behavior of sandwich panels.

Chapter 3 describes in detail the panel's constituent materials and configuration, static testing procedures, and data acquisition.

Chapters 4 and 5 present the results obtained from static tests on the individual constituents and the panel as a whole, respectively. Chapter 5 also introduces a comparison between panels with composite skins from two different suppliers, which have the same constituents but different textile architectures.

Chapter 6 proposes the application of analytical models for predicting the panel's bending behavior and includes a comparison with the experimental results.

Conclusions are summarized in Chapter 7, which also provides suggestions for possible future work.

Chapter 2

Literature Review

2.1 Composite Materials Overview

Composite materials [1] consist of at least two components, typically a strong, stiff element embedded in a softer matrix, as seen in natural biological materials like wood and bone. These materials often exhibit anisotropy, meaning their properties vary depending on the direction of measurement. In composites, anisotropy is usually controlled to enhance performance, a key difference from conventional materials, which are often assumed to be isotropic. Artificial composites can be designed with tailored properties by aligning fibers to meet specific load requirements.

Composites come in various types, with the matrix being polymeric, metallic, or ceramic, and reinforcements often carbon or glass fibers. While polymer-based composites dominate industry, metallic and ceramic composites (MMCs and CMCs) are also significant, each improving specific properties such as high-temperature performance or toughness. The properties of composites depend on the characteristics of their constituents, such as stiffness, strength, toughness, and density. Thermal properties must also be considered to avoid internal stresses caused by mismatched thermal expansions. Overall, composites offer attractive combinations of properties, often unobtainable in single materials, with great potential for engineering applications (Fig.2.1)(they rank second only to steel in industrial importance, with a global market value exceeding \$100 billion [2]).

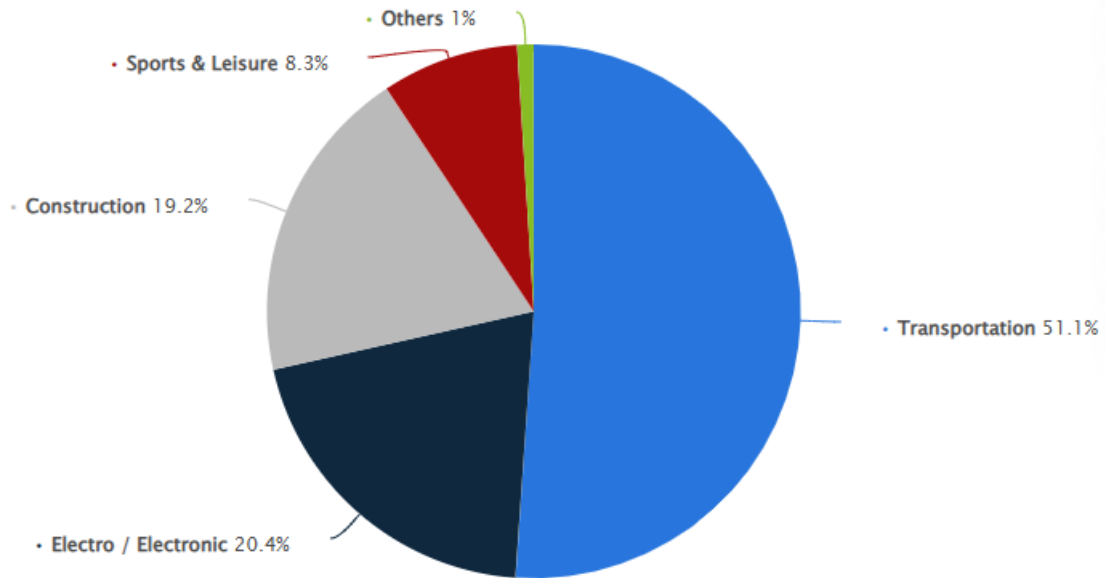


Figure 2.1: Use of composites in Europe by application industries: Estimates for year 2022. Courtesy of statista.com

Various types of reinforcements are used in composite materials, each tailored for specific matrix systems. Common reinforcements include high-stiffness, low-density fibers like carbon, glass, and aramid (e.g., Kevlar) for polymer matrix composites. Many fibers exhibit anisotropy, with axial properties (e.g., stiffness) being most significant. Tensile strength values for these fibers vary due to their sensitivity to flaws (which are common in brittle materials), with fine fibers generally having fewer large defects, resulting in higher fracture strengths. Glass fibers are used extensively in composites. Their atomic structure is amorphous, based on SiO_4 tetrahedra, and modified by oxides to reduce the glass transition temperature, making the material easier to deform. The most common type, E-glass, has a balance of properties ideal for composites. Glass fibers are produced by melting raw materials and drawing fine filaments, typically 8-15 μm in diameter. Although high tensile strength (3-4 GPa) is desirable, composite toughness, influenced by fiber-matrix bonding and energy-absorbing mechanisms, is crucial for engineering applications. To protect against damage and promote bonding, glass fibers are treated with a polymer coating (size) during manufacturing.

Fibers alone cannot bear loads or transmit them effectively in engineering applications due to their small size. To overcome this, fibers are embedded in a matrix material, forming a composite. The matrix binds the fibers, transfers loads between them, and protects them from environmental damage and handling. The matrix significantly influences key mechanical properties of the composite, such as transverse strength, shear properties, and compression. It also often determines the composite's maximum service temperature. Polymers, are the most commonly used matrix materials for fiber composites due to their low cost, ease of processing, good chemical resistance and low density. However, their application is limited by their low strength, low stiffness and low operating temperatures. Polymeric matrices can be thermosetting or thermoplastic. Unlike thermosetting resins, thermoplastics are not cross-linked.

In many applications, achieving a high fiber volume fraction (f) is desirable, typically by aligning long fibers in a specific direction. While theoretically, closely packed cylinders could occupy over 90% of the volume, practical constraints limit this to around 60-70% to prevent excessive fiber contact, which can create complications. For many uses, strong stiffness and strength are needed primarily in the plane of a sheet or plate, while properties in the through-thickness direction are less critical. Therefore, composite structures often consist of thin sheets, called laminae or plies, with fibers aligned in one direction. These laminae are stacked in a predetermined sequence to form a laminate (Fig.2.2), allowing for tailored properties based on expected loading conditions. Each lamina is treated as homogeneous for predicting the overall elastic properties of the laminate.

Continuous fibers can be arranged in various ways beyond stacking unidirectional plies, utilizing textile technologies such as weaving, braiding, and knitting. In a typical woven assembly, the warp and weft fibers intersect at a 90-degree angle, allowing for flexibility in draping and shaping, which is beneficial for non-planar structures. However, this arrangement leads to an inhomogeneous fiber distribution, and the maximum fiber volume fraction typically reaches only about 40-50%.

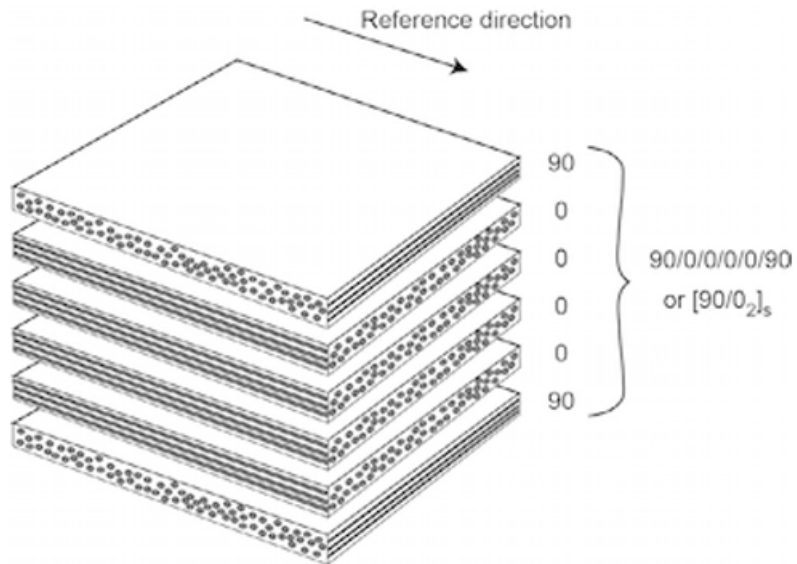


Figure 2.2: Schematic description of a fibre laminate (stack of plies). [1]

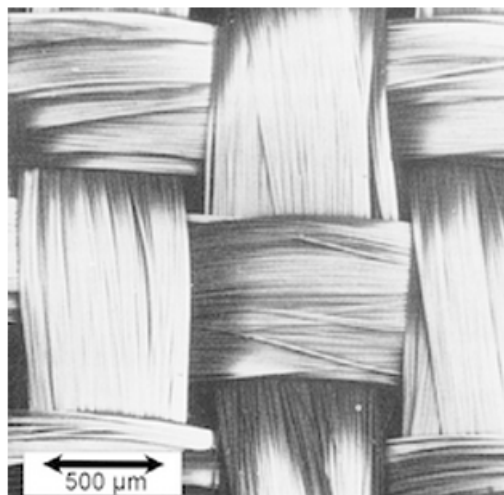


Figure 2.3: Micrography (SEM) of a Woven roving assembly, glass fibres. [1]

2.2 Thermoplastic Composite Materials for Structural Applications

Thermoplastic composites (TPCs) have several advantageous properties [3], especially in terms of recyclability and environmental sustainability. One of their primary benefits is the ability to be melted and reprocessed, making them fully recyclable, reducing waste and contributing to environmental regulations aimed at minimizing scrap. Furthermore, TPCs typically exhibit strong resistance to moisture absorption, which means their mechanical properties remain stable even in wet or hot condition and they also display high fracture toughness and impact resistance, making them suitable for structural applications where durability is crucial.

2.2.1 Recycling

About the recycling [4] of continuous-fiber-reinforced thermoplastic composites (CFRTCs), the main methods are mechanical, thermal, and chemical recycling:

- **Mechanical Recycling:** This method involves shredding or grinding composite scraps into smaller pieces, which can be reprocessed by techniques like compression or injection molding. However, mechanical recycling often reduces the length of reinforcing fibers, which weakens the material, turning CFRTCs into short fiber composites (SFRTCs). These materials retain some of their mechanical properties but lose the benefits of continuous fibers. Improving fiber preservation and optimizing process parameters can enhance the mechanical properties of recycled composites.
- **Thermal Recycling:** This method, which includes pyrolysis, removes the polymer matrix at high temperatures to recover the fibers. The main limitation is that only the fibers are retained, while the thermoplastic matrix is degraded and lost. High temperatures used during thermal processes can also damage the mechanical properties of the recovered fibers.
- **Chemical Recycling:** This process involves dissolving the polymer matrix using solvents, allowing the recovery of both fibers and matrix materials. Chemical recy-

cling is more environmentally friendly compared to thermal methods since it operates at lower temperatures, but it requires careful handling of solvents.

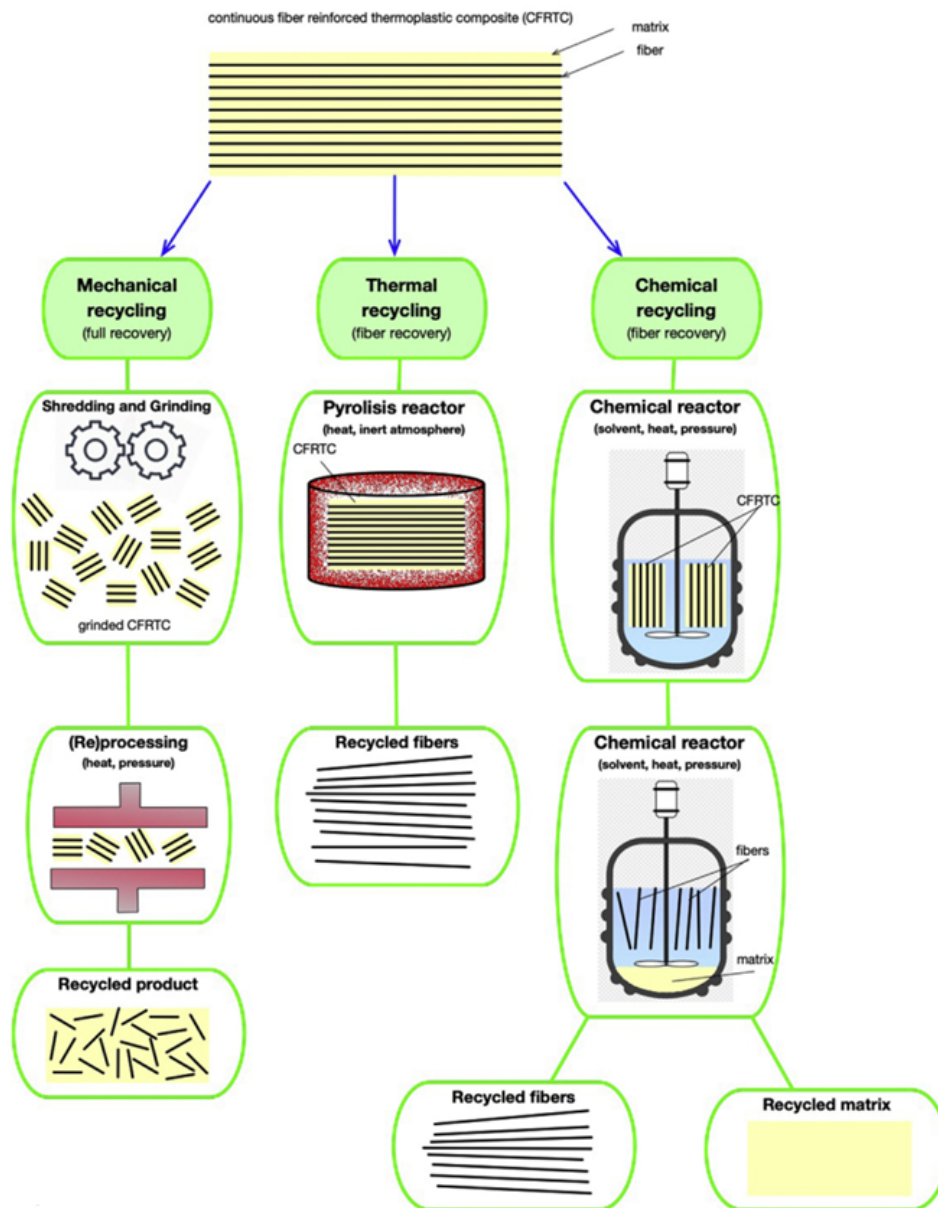


Figure 2.4: Recycling methods for CFRTCs

2.2.2 Processing

However, not only advantages characterize the use of thermoplastic composites. In fact, there are challenges in processing TPCs, particularly due to their high melt viscosity, which complicates fiber impregnation. This high viscosity can make it difficult to manufacture composites with continuous fibers, which are essential for achieving the necessary

strength and stiffness in structural applications. Additionally, thermoplastics often require higher processing temperatures compared to thermosetting polymers, which increases the complexity and cost of manufacturing processes. Despite these challenges, advancements in manufacturing techniques have made it possible to improve the processability of thermoplastic composites.

A recent research work conducted at Universidad Politecnica de Madrid [5] has investigated how processing parameters influence the quality and void content of continuous fiber-reinforced thermoplastic composites (CFRTCs), specifically focusing on their manufacturing process and the impact of voids on mechanical properties.

The study evaluates three manufacturing methods: vacuum-bag-only (VBO) in an oven, hot-press, and in-situ consolidation (ISC) using automated fiber placement. The quality of these processes is measured by their ability to minimize void content and maximize mechanical integrity. Hot-press manufacturing generally produced laminates with lower void content and better mechanical properties compared to VBO and ISC methods. The study finds that higher temperatures and pressures during the hot-press process improve consolidation, resulting in fewer voids. However, ISC, despite its advantages in process speed and automation, showed more challenges in achieving consistent quality. Laminates produced using ISC exhibited higher void content and inferior mechanical performance compared to the other method, particularly because of irregularities in fiber distribution and voids concentrated in the outer plies.

The presence of voids significantly affects the mechanical properties of thermoplastic composites. The study shows a correlation between increasing void content and a decline in key mechanical properties, such as in-plane shear strength (IPSS) and interlaminar shear strength (ILSS). A critical void content threshold was identified, beyond which the properties deteriorated rapidly. This threshold varies by manufacturing process, with VBO and hot-press laminates tolerating up to 1.2% and 2.7% void content, respectively, before experiencing significant mechanical degradation.

The study highlights the challenges in controlling void content during the manufacturing process. VBO laminates tend to have higher void content due to the lower consolidation pressure in the vacuum bag method, requiring more precise temperature control for proper air evacuation. Hot-press methods are better at reducing voids but require careful

management of temperature and pressure to avoid material degradation. ISC, while innovative, suffers from issues like insufficient compaction in the upper layers of the laminate, resulting in interlaminar voids and poorer mechanical performance.

In conclusion, achieving high-quality thermoplastic composites depends on optimizing processing parameters like temperature and pressure to minimize void content, as even small increases in voids can significantly impact the material's mechanical performance.

2.3 Overview of Sandwich Panel Structures

2.3.1 Historical Background



Figure 2.5: Mosquito Aircraft.

John Montagu [6] (1718-1792), the 4th Earl of Sandwich and British first lord of the Admiralty during the American Revolution, famously gave his name to the sandwich. The story goes that he either lacked the time or had a healthy appetite and needed a quick meal during two meetings, thus coining the term based on the concept of sandwiching a meal between obligations. The construction of a typical sandwich, which consists of two slices of bread with a filling usually of meat, inspired the term "sandwich construction" in the building and materials industry. This method involves using two thin, high-performance

material sheets as the bread, with a low-density material filling the space between them, similar to a culinary sandwich. The concept of utilizing two cooperating faces separated by a material for enhanced structural properties was first discussed by the Frenchman Duleau in 1820 and later by Fairbairn, it wasn't commercially applied until the 20th century. Significant use of sandwich panels began in World War I with materials like asbestos and fibreboard, and expanded in World War II with the mass production of sandwich laminates like those used in the Mosquito aircraft (Fig.2.5), which featured veneer faces and a balsa core.

2.3.2 Definition

A sandwich element [6] is composed of three main parts: two thin, stiff, and strong outer layers (faces) and a thick, light, and comparatively weaker core (Fig.2.6). These layers are adhesively bonded to facilitate load transfer between components. According to ASTM, a structural sandwich is defined as a type of laminated composite made from different materials bonded together to maximize the structural benefits of each component.

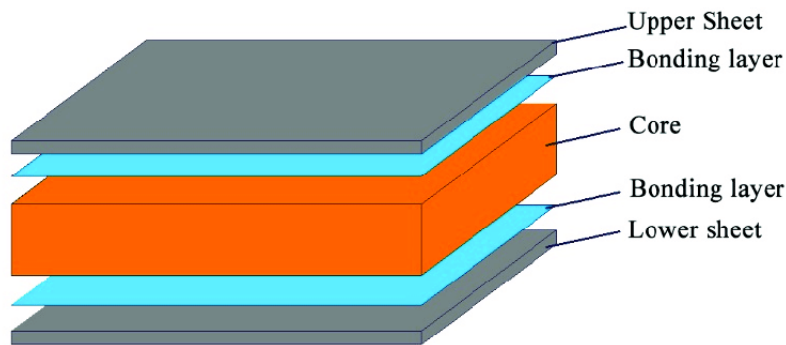


Figure 2.6: Schematic of a sandwich structure

The structural operation of a sandwich element is similar to that of an I-beam, where material is strategically placed at the flanges, far from the neutral axis, to efficiently counteract bending moments. The core of the sandwich acts like the web of the I-beam, providing continuous support to the faces and resisting shear forces while stabilizing the faces to prevent buckling or wrinkling. The adhesive's role is critical in this structure, needing to be strong enough to handle the shear and tensile stresses that develop between the core and the faces. Typically, the faces of the sandwich are composed of high-performance,

thin materials, whereas the core is thicker and lighter but possesses lower performance capabilities. The design process for a structural sandwich is comprehensive, integrating both geometrical design and material selection to meet specific application needs and design requirements.

A sandwich element offers the advantage of maximizing the use of each material component within a structure, leading to an impressive stiffness-to-weight and bending strength-to-weight ratios. The integration of composite materials has enhanced these benefits, as composites often exceed the strength of traditional metals like aluminum or steel, although they typically have lower moduli resulting in reduced stiffness. Sandwich composites resolve this by ensuring continuous support for the face sheet, maintaining flatness even under significant compressive stress. The use of cellular core materials eliminates the need for additional thermal insulation, keeping structural weight low due to their low thermal conductivity. Manufacturing sandwich elements in large sheets reduces the need for connections such as rivets and bolts, simplifying assembly and reducing costs. Fiber composite faces allow for even large structures to be produced almost seamlessly, enhancing load distribution and reducing stress concentrations.

However, there are notable disadvantages. There is a general lack of knowledge among engineers and designers about sandwich construction. The novelty of the concept in many applications underscores the need for ongoing research and development, particularly as current manufacturing methods are labor-intensive and not highly automated, complicating quality control.

2.3.3 Applications

Sandwich constructions are utilized across a wide range of industries, from building to aerospace, due to their advantageous properties like high stiffness, strength, and integrated thermal insulation. Examples include:

- **Transportation:** Vehicles often use sandwich constructions to reduce weight and enhance performance. For instance, sandwich structures in trucks and shipping containers enhance payload capacity and thermal insulation for transporting cold

goods.



Figure 2.7: Traditional heavy rail container, made of steel.

AGESIA has revolutionized the structural components of vehicles by replacing traditional heavy metal floor constructions (Fig.2.7) with a new sandwich structure that eliminates the need for the old heavy metal supporting framework. This innovative approach not only lightens the structure but also increases the loading capacity. Notably, AGESIA's re-engineered swap floors for a major entity in intermodal transport leverage structural thermoplastic composites, achieving significant weight savings and allowing for additional cargo capacity. This achievement, recognized at the SPE ACCE Conference with the 2023 People's Choice Award, underscores AGESIA's commitment to advancing automotive technology through collaboration with Johns Manville and Aerlyte, using Neomera PA-6 organosheets to enhance the functionality and sustainability of automotive constructions. Thus, key benefits for the transportation sector are:

1. Reduced Mass: Improves fuel efficiency and performance.
2. Efficiency in Package Space and Cost: Enhances packaging efficiency, lowering costs and space requirements.
3. Increased Cargo Volume: Expands utility with larger cargo capacity.

4. Enhanced Load-Carrying Capacity: Strengthens load-bearing without compromising safety.
 5. Serviceability: Simplifies maintenance for longer component lifespan.
 6. Exceptional Impact Resistance: Ensures durability against impacts and environmental challenges.
- Marine Applications: Both pleasure boats and larger ships adopt sandwich constructions. These designs provide benefits such as high energy absorption, low weight, and corrosion resistance, which are critical in marine environments.
 - Energy: Large wind-mill blades are mainly made of single skin composites but some parts have cores making up a sandwich structure.
 - Civil Engineering: In civil infrastructure, sandwich panels are favored for their light weight and thermal insulation properties.
 - Aerospace: Sandwich designs are prevalent in aerospace applications where weight reduction is crucial. Components in Helicopters such as fuselage, flooring, tail-boom and main rotors, or wings, flaps, stabilizers and doors in aircraft are constructed using sandwich techniques to achieve optimal performance and durability. In space exploration, sandwich constructions are employed in the design of antennas and solar panels, leveraging their lightweight and durable characteristics to function effectively in the harsh conditions of space.

2.3.4 Estimating Properties of Face Materials

The primary aim is to determine the approximate properties of a lamina, which is a thin orthotropic layer of composite material considered the smallest unit in constructing a composite laminate (Fig.2.8). These properties of the lamina are then used to calculate the characteristics of the laminate, which will serve as the face sheet of the sandwich. The use of the orthotropic approximation for the lamina is justified by several reasons. Often, a lamina comprises unidirectional, bidirectional, or randomly arranged layers of reinforcement, which can be effectively treated as orthotropic layers. Employing an orthotropic model simplifies computational processes compared to using a general anisotropic model.

For a detailed exploration of the theoretical framework and derivations behind specific formulas, please consult "The Handbook of Sandwich Construction" by D. Zenkert [6].

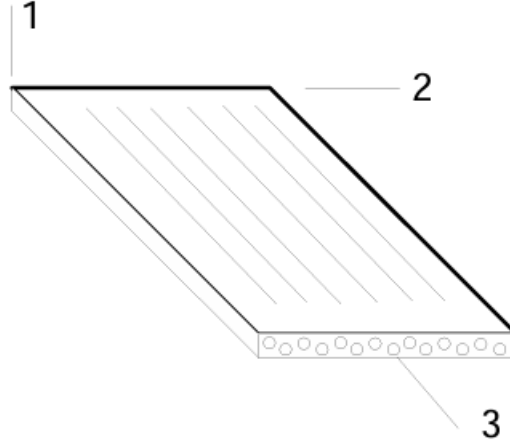


Figure 2.8: Example of a composite lamina.

The average modulus in the fibre direction of a uni-directional composite lamina E_1 is according to the rule-of-mixtures

$$E_1 = E_f v_f + E_m v_m \quad (2.1)$$

The apparent Young's modulus in the direction transverse to the fibres can be assessed as

$$\frac{1}{E_2} = \frac{v_f}{E_f} + \frac{v_m}{E_m} \quad (2.2)$$

The Poisson ratio is

$$\nu_{12} = \nu_f v_f + \nu_m v_m \quad (2.3)$$

The in-plane shear modulus G_{12} is found by assuming that the shear stress acting on the fibres and the matrix are equal

$$\frac{1}{G_{12}} = \frac{v_f}{G_f} + \frac{v_m}{G_m} \quad (2.4)$$

The tensile modulus of a unidirectional composite can be estimated using the rules-of-mixture. However, in practice, composite laminates often consist of various fabrics such as weaves, roving, mats, and sometimes in combination with unidirectional layers. To accommodate these varied materials, the rule-of-mixtures for the fiber direction can be

adapted by incorporating reinforcement efficiency factors

$$E_1 = \sum_i \alpha v_i E_i \quad (2.5)$$

In practical terms, calculating the efficiency factor for a laminate involves considering only the proportion of fibers that align with the direction being studied. For instance, in a bi-directional symmetric weave, half of the fibers lie in the 1-direction (Fig.2.8) and the other half in the 2-direction, leading to an efficiency factor of 0.5. This efficiency factor, denoted as α , represents the fraction of fibers oriented in the relevant direction.

With the previous properties calculated, the compliance matrix for the lamina can be determined using equation , which relates strain to stress (Hooke's law):

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{pmatrix} \frac{1}{E_1} & \frac{-\nu_{21}}{E_2} & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} \quad (2.6)$$

Inversing this matrix, the stiffness matrix for the lamina is obtained.

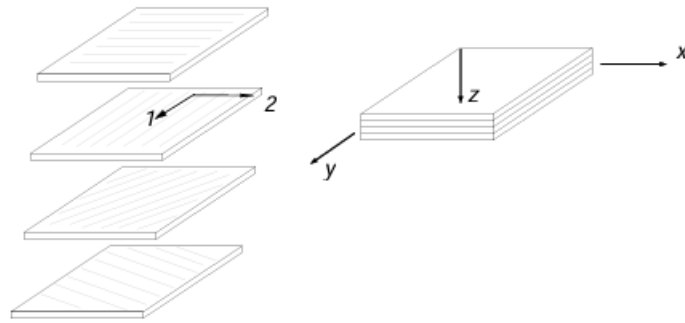


Figure 2.9: A stack of lamina (laminate)

In the production of composite laminates, multiple laminae are stacked on top of one another (Fig.2.9), each oriented differently relative to the global coordinate system. To accurately characterize the behavior of the entire laminate, it is essential to understand the behavior of each individual lamina within the global coordinate system (x, y, and z) rather than its local coordinate system (1, 2, and 3). The stiffness of each lamina in the x-y plane of the global coordinate system is determined using a transformation matrix. Once the stiffness properties of the lamina are established, they can be utilized to calculate the

stiffness of the laminate, assuming that the thickness and position of each lamina in the stack are known.

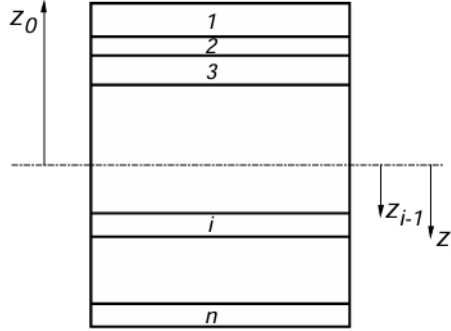


Figure 2.10: Geometry of a generic laminate with n layers.

$$\begin{pmatrix} N \\ M \end{pmatrix} = \sum_{i=1}^n \int_{z_{i-1}}^{z_i} \begin{bmatrix} Q_i & Q_i z \\ Q_i z & Q_i z^2 \end{bmatrix} \begin{pmatrix} \epsilon_0 \\ \kappa \end{pmatrix} dz = \begin{pmatrix} A & B \\ B & D \end{pmatrix} \begin{pmatrix} \epsilon_0 \\ \kappa \end{pmatrix} \quad (2.7)$$

$$[A, B, D] = \sum_{i=1}^n Q_i \left[(z_i - z_{i-1}), \frac{1}{2}(z_i^2 - z_{i-1}^2), \frac{1}{3}(z_i^3 - z_{i-1}^3) \right] \quad (2.8)$$

A is called the extensional stiffness matrix, **B** the extension-bending coupling matrix, and **D** the bending stiffness matrix. By calculating the components of the stiffness matrix, we can determine the required properties for the face sheet.

$$\nu_{21} = \frac{A_{12}}{A_{11}} \quad \text{and} \quad \nu_{12} = \frac{A_{12}}{A_{22}} \quad (2.9)$$

$$E_x = \frac{A_{11}(1 - \nu_{12}\nu_{21})}{t} \quad (2.10)$$

$$E_y = \frac{A_{22}(1 - \nu_{12}\nu_{21})}{t} \quad (2.11)$$

$$G_{xy} = \frac{A_{66}}{t} \quad (2.12)$$

While the rules of mixture provide a fairly accurate estimate of the tensile modulus of elasticity in the longitudinal direction (E_x), they tend to underestimate it in the transverse direction (E_y). Given that twill weave fabrics employ an equal amount of fibers in both

the longitudinal and transverse directions, it is reasonable to assume that the moduli in these directions are equivalent. Originally designed for unidirectional fabrics, the rules of mixture have been adapted to include an efficiency factor to account for the fiber distribution in other fabric types like weaves. Despite being straightforward and easy to apply, ongoing research is aimed at refining these models to offer more precise predictions of the properties of laminates made from woven fabrics. Classical Laminate Theory and other advanced analytical approaches seek to enhance predictions by considering the interactions between different laminae, moving beyond the simple empirical methods of the rules of mixture, which estimate composite properties based solely on constituent properties and their volume fractions.

Expanding upon traditional methods, micromechanical models offer a deeper analysis by considering the properties and interactions of individual fibers and matrix materials. A notable example of such a model is the Halpin-Tsai model [7], which is significant due to the variability in constituent properties and their interactions. Despite the continuous advancement in property prediction for laminates, it has been established that the precision achieved by these alternative methods does not surpass the value of experimental testing. While the rules of mixture provide a useful preliminary method for estimating modulus values, definitive values are ultimately acquired through empirical testing. This highlights the ongoing importance of experimental validation in the field of composite research.

2.3.5 Estimating Properties of Core Materials

Gibson and Ashby [8] have authored a comprehensive book on the behavior of cellular materials. The book's theoretical foundation emphasizes that the principal mode of deformation in these materials is derived from cell wall bending, as opposed to tension or compression. Foams come in a broad spectrum of densities, presenting the primary design challenge of choosing the correct density. Observations from material data for foams and honeycombs indicate that their mechanical properties tend to vary depending on the density of the material. Thus, in general, we can formulate this as

$$E_c = C_E \rho^k, \quad G_c = C_G \rho^l, \quad \sigma_c = C_\sigma \rho^m, \quad \text{and} \quad \tau_c = C_\tau \rho^m \quad (2.13)$$

The formulas developed by Gibson and Ashby are based on having detailed information about the unfoamed polymer's properties, which is not always readily available. Additionally, the analysis assumes access to other specific details, such as the ratio of open to closed cells, cell wall thickness, and cell geometry, which are sometimes difficult to obtain. When these properties are known, many mechanical properties can be accurately predicted using Gibson and Ashby's formulas. However, foam core manufacturers typically conduct extensive material testing and provide detailed data sheets that include most mechanical and physical properties, making this information accessible.

2.3.6 Modes of Failure

Given the multilayer and multimaterial nature of a sandwich structure, there are multiple and diverse potential causes of failure, which can affect the face sheets, the core, or the entire structure [17]. Structural functionality loss may result from either the failure of individual components or from overall or local instability. Depending on the geometry, material properties, and loading conditions, some failure modes will be more critical than others, limiting the structure's performance and load-bearing capacity. Among the most common and important failure modes are the following:

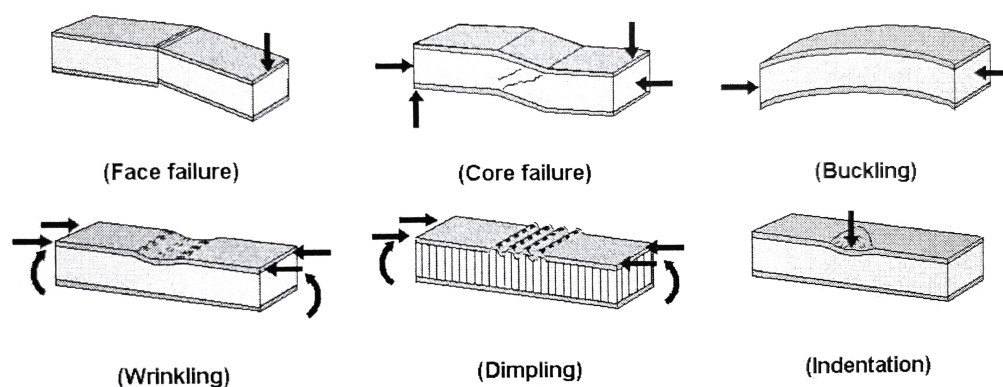


Figure 2.11: Main failure modes of a sandwich structure.

- face sheet failure (due to tension or compression);
- shear failure or instability of the core;
- global instability (buckling);

- local instability of the face sheets, wrinkling (for foam cores);
- local instability of the face sheets, dimpling (for honeycomb cores);
- indentation;
- delamination at the face-core interface.

For each of these failure modes, there are appropriate strength criteria available, with more or less complex formulations capable of predicting the critical stress conditions that trigger the specific failure mode. These critical values should then be compared with the stress conditions present in the structure due to the applied external loads. It is important to note that the different failure modes are influenced, to some extent, by the behavior of the structure itself. As previously mentioned, the face sheets primarily bear the bending component of the stress due to external loads, leading to tensile and compressive stresses in the face sheets, which are the main cause of their failure. Similarly, the core predominantly fails in shear. Compressive loads can also induce global instability phenomena, which, in addition to compromising the structure's functionality, can lead to the failure of the face sheets and the core due to reaching their respective tensile/compressive and shear limits. Excessive compressive loads can also cause local instability in the face sheets, a phenomenon sometimes observed on the compressed side of panels subjected to pure bending. Indentation, or local crushing of the core, can result from the application of high loads over too small an area of the panel. High stresses at the face-core interface, near free panel edges or around metallic inserts, can cause delamination that compromises the structure's functionality. This issue can usually be avoided at the face-core interface by selecting an appropriate adhesive and carefully controlling the manufacturing process.

2.4 Theory of Flexural Behavior of a Sandwich Structure

The composite nature of sandwich panels has been emphasized before. By integrating different materials, sandwich structures can achieve enhanced properties that surpass those of any single constituent material when used alone. In terms of a beam's flexural rigidity D , defined as IE , maximizing both the modulus of elasticity E of the material and the area moment of inertia I of the cross-section is key to achieving a stiffer beam. The modulus

of elasticity measures the material's resistance to bending, while the area moment of inertia accounts for the resistance provided by the geometry of the cross-section. The area moment of inertia, found using equation

$$I_y = \int z^2 dA \quad (2.14)$$

indicates that shifting more geometric weight away from the axis of rotation increases the I -value. By placing a lightweight, low-modulus core material between two high-modulus face skins, the area moment of inertia can be enhanced without adding much weight. Although the core material generally has a lower E-modulus and doesn't directly contribute to flexural stiffness, it indirectly plays a crucial role in the beam's flexural behavior by increasing the separation between the face skins (Fig.2.12).

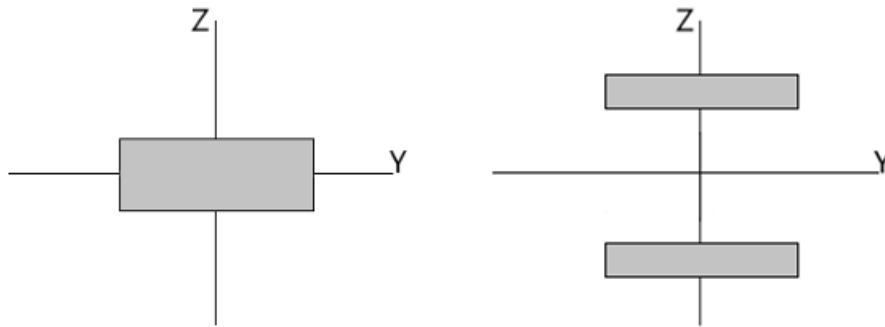


Figure 2.12: Same total cross sectional area for the skin material but different moment of inertia.

When the beam bends, it generates both longitudinal and transverse shear stresses within the material. When the core has high shear rigidity, the cross sections of the beam tend to remain nearly perpendicular to the neutral axis, which is the line passing through the centroids of the cross sections. Thus, by using two outer face skins with a high modulus of elasticity that can withstand substantial axial loads, and combining them with a core that has strong longitudinal and transverse shear rigidity, a material that is both lighter and stiffer is achieved. This potential is illustrated in Fig.2.13

In practice, analytical relationships are often used to predict the flexural behavior of a sandwich structure, typically focusing on the load-deflection response. These equations aim to estimate the beam's deflection when subjected to a transverse load at a specific

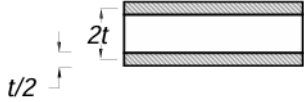
	Weight	Flexural rigidity	Bending strength
	1	1	1
	~ 1	12	6
	~ 1	48	12

Figure 2.13: Sandwich structure flexibility potential

point along its span.

2.4.1 Sandwich Stiffness

As Kuenzi [12] described, stiffness is crucial for the design of most structural elements. The stiffness D of a rectangular beam, characterized by thickness h , width b , and modulus of elasticity E , is calculated using the formula:

$$EI = E \frac{bh^3}{12} \quad (2.15)$$

For a sandwich structure with the same overall dimensions but incorporating a core of a different material with thickness c , the stiffness is derived as:

$$EI = \frac{E_f B (D^3 - t_c^3)}{12} + \frac{E_c B t_c^3}{12} \quad (2.16)$$

where E_f represents the modulus of elasticity of the face material, and E_c is the modulus of elasticity of the core material. This formula assumes that the face materials have uniform thickness. Formulas have been formulated for configurations involving face materials of various materials and thicknesses. Given that the core of the sandwich is extremely lightweight compared to the facings, it is likely to be a material with lower inherent stiffness. This reduced stiffness means that its contribution to the overall stiffness of the

sandwich can generally be ignored. Consequently, the last term of the earlier formula can be omitted, simplifying the expression for sandwich stiffness to:

$$EI = \frac{E_f B (D^3 - t_c^3)}{12} \quad (2.17)$$

This formula can also be expressed in an alternative form:

$$D = \frac{E_f B D^3}{12} \left(1 - \left(\frac{t_c}{D} \right)^3 \right) \quad (2.18)$$

So far, the discussion on design has primarily focused on determining the flexural stiffness, commonly termed EI , of the sandwich. This stiffness parameter is crucial for design, especially regarding deflection limitations. However, the deflection of a sandwich beam is not solely determined by flexural stiffness. It must also account for deflections due to shear deformations because the core material may have a lower shear modulus. To account for deflections of sandwich beams, the following expression needs to be integrated:

$$\frac{d^2 y}{dx^2} = \frac{M_x}{EI} + \frac{1}{S} \frac{dV_x}{dx} \quad (2.19)$$

where y is the deflection, x is the distance along the beam, M_x is the moment at point x , V_x is the shear load at point x , EI is the flexural stiffness, and S is the shear stiffness of the sandwich. For a sandwich with thin facings:

$$S = \frac{(D + t_c)B}{2} G_c \quad (2.20)$$

where G_c is the core shear modulus. Integration of (2.19) leads to the following general expression for the deflection of a sandwich beam or panel:

$$y = \frac{k_B P L^3}{EI} + \frac{k_s P L}{S} \quad (2.21)$$

where y is the deflection, P is the total load, L is the span, EI is the flexural stiffness given by an earlier formula, S is the shear stiffness, and k_B and k_s are constants dependent on the beam loading. The formula gives deflection in terms of the usual bending deflection (first term) and the shear deflection (second term). For a long span, the first term is usually

more significant, while for shorter spans, considering shear deflections becomes essential. Values for the constants k_B and k_s for several beam loadings are provided in Fig.2.14. In

Values of k_B and k_s for several sandwich beam loadings				
Loading	Beam Ends	Deflections at	k_B	k_s
Uniformly distributed	Both simply supported	Midspan	5/384	1/8
Uniformly distributed	Both clamped	do	1/384	1/8
Concentrated at midspan	Both simply supported	do	1/48	1/4
Concentrated at midspan	Both clamped	do	1/192	1/4
Concentrated at outer quarter points	Both simply supported	do	11/768	1/8
Concentrated at outer quarter points	Both simply supported	Load point	1/96	1/8
Uniformly distributed	Cantilever, 1 free, 1 clamped	Free end	1/8	1/2
Concentrated at free end	do	do	1/3	1

Figure 2.14: Values of k_B and k_s for several sandwich beam loadings.

this research, a four-point bending setup was utilized, which determined the constants k_B and k_s to be, approximately (because of the third-point loading configuration), $\frac{11}{768}$ and $\frac{1}{8}$, respectively.

The method for predicting deflection, which accounts for face skin bending and core shear deflection as described by [12], is also employed by Hexcel [13], a company specializing in advanced composite materials.

2.4.2 Sandwich Strength

If the core is weak ($E_c \ll E_f$) and the faces are thin ($t_f \ll t_c$), stresses along the thickness [6] of the panel can be plotted as illustrated in Fig.2.15

Still according to Kuenzi [12], the strength of a sandwich beam under bending and shear loads is determined by the ability of the facings to resist compression or tension and the core's ability to resist shear. The stresses in the facings from bending moments applied to the sandwich are expressed by the following formula:

$$F = \frac{2M}{t_f(D+t_c)B} \quad (2.22)$$

where F represents the mean compressive or tensile stress, M is the bending moment, t_f is the thickness of one facing, D is the total thickness of the sandwich, t_c is the core

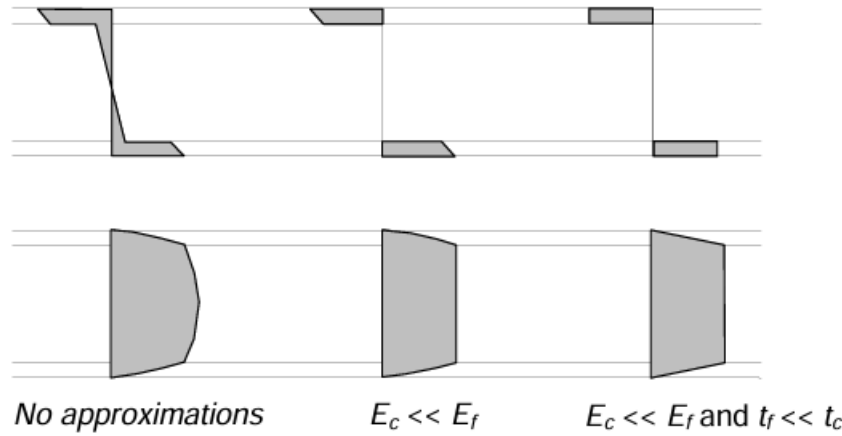


Figure 2.15: Direct and shear stresses for different level of approximations.

thickness, and B is the width of the sandwich.

The core shear stress is given by:

$$\tau_c = \frac{2V}{(D+t_c)B} \quad (2.23)$$

where τ_c denotes the core shear stress and V is the shear load on the sandwich.

Formulas (2.22) and (2.23) are approximations suitable for most sandwiches with thin facings and moderately rigid, thick cores.

These design criteria outlined for the stiffness and strength of sandwiches are applicable primarily to sandwiches with thin isotropic facings and isotropic cores, but they provide good approximations for orthotropic materials as well [12].

2.4.3 Alternative analytical evaluation of the Flexural Response: the Allen - Gibson approach

This alternative way to determine the flexural properties of the panel is described in [30]. The failure load for sandwich panels under static bending conditions was predicted by leveraging mechanical properties derived from tests on the sandwich constituents, and by applying the principles of classical beam theory. This theoretical approach presupposes that both the GFRP skins and the core materials exhibit linear behavior up until the point of failure. Fig.2.16 illustrates the configuration of the composite sandwich section, indicating the skin thickness t_s , core thickness t_c , and the distance d between the centers

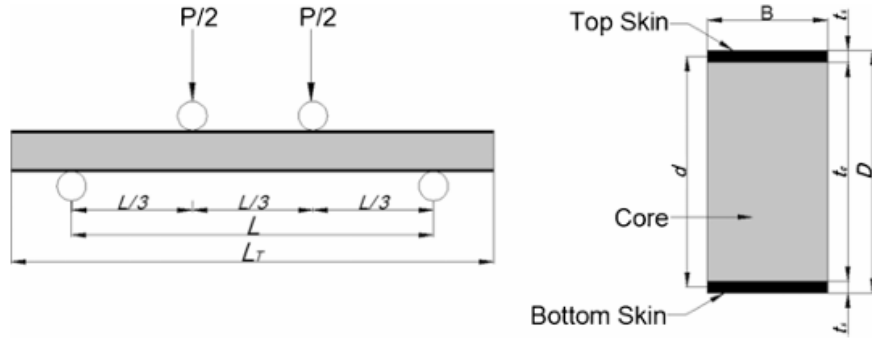


Figure 2.16: Schematic illustration of flexural test of composite sandwich panels

of the skins. According to researchers Allen [25] and Gibson [26], simple mechanics of materials formulas can be used to calculate the load for various failure modes, with the lowest predicted load determining the design limits of the composite sandwich panel. Typically, the prevalent modes of flexural failure observed in these panels include compressive or tensile failure of the skin, shear failure of the core, and compressive or tensile failure of the core.

- Compressive/tensile failure of the skin: Daniel and Abot [29] reported that failure of the skins in compressive or tensile modes occurs when the axial stress exceeds the material strength of the skins. However, it was noted that the skins possess a higher tensile strength compared to their compressive strength. Therefore, it is anticipated that compressive failure of the top skin is the likely failure mode for sandwich panels during testing, based on the classical theory which assumes a linear variation of axial strain across the panel's cross-section. According to Euler-Bernoulli beam theory, the peak strength, F_s , for this failure mode under four-point bending is predicted by:

$$F_s = \frac{12EI\sigma_s}{LE_sD} \quad (2.24)$$

where E_{los} is the flexural stiffness, σ_s and E_s are the maximum compressive strength and modulus of elasticity of the skins, and E_c is the modulus of the core. The flexural stiffness of the sandwich panels is computed as:

$$EI = \frac{Bt_s^3E_s}{6} + \frac{Bd^2t_sE_s}{2} + \frac{Bt_c^3E_c}{12} \quad (2.25)$$

where B , d , t_s , and t_c represent the width, total depth, skin, and core thicknesses of the sandwich panel respectively.

- Shear failure of the core: Shear failure in composite sandwich panels occurs when the shear strength of the core is exceeded. This typically happens at the neutral axis between the top and bottom surfaces of the panel, leading to a peak load F_c which can be calculated by:

$$F_c = \frac{2\tau_c EI}{\left(\frac{E_s t_s d}{2} + \frac{E_c t_c^2}{8}\right)} \quad (2.26)$$

where τ_c is the shear strength of the core material. The peak strength for shear failure is predicted using the shear modulus of the skin and the core, considering the much lower modulus of elasticity of the foam core compared to that of the skin. The transformed section of the sandwich panel is treated as an equivalent single skin, which is larger than the original due to the ratio of the shear moduli. Therefore, the expected peak shear strength F_{cs} for the composite sandwich panels is better estimated by:

$$F_{cs} = \frac{2\tau_c GI}{\left(\frac{G_s t_s d}{2} + \frac{G_c t_c^2}{8}\right)} \quad (2.27)$$

where G_s and G_c are the shear moduli of the skin and core, respectively, and GI is the transformed flexural stiffness with the moduli replaced by the corresponding shear moduli.

- Compressive/tensile failure of the core: The core material of the sandwich panel is susceptible to failure under excessive normal stresses, either in tension or compression. The critical load at which failure occurs, F_{ca} , is determined using the peak strength formulas for both tensile and compressive stresses:

$$F_{ca} = \frac{12EI\sigma_{ct}}{LE_c t_c} \quad (2.28)$$

for tensile failure, and

$$F_{ca} = \frac{12EI\sigma_{cc}}{LE_c t_c} \quad (2.29)$$

for compressive failure, where σ_{ct} and σ_{cc} represent the maximum tensile and compressive strength of the core, respectively.

- Load-deflection behaviour: The load-deflection behavior for composite sandwich panels incorporates both bending and shear deformations, drawing from the theories proposed by Timoshenko [27]. The approach highlights the significance of shear deformation in panels [28], particularly when the shear stiffness is relatively low compared to bending stiffness. The total deflection, Δ_{total} , is the sum of deflections due to bending (Δ_b) and shear (Δ_s), expressed as:

$$\Delta_{\text{total}} = \Delta_b + \Delta_s \quad (2.30)$$

For panels under four-point bending, bending moments and shear contributions are analyzed from the supports to the load points and from there to the mid-span. Integrating these contributions along the beam length, the bending deflection is given by:

$$\Delta_b = 2 \left[\int_0^a \frac{M(x)}{EI} \left(\frac{x}{2} \right) dx + \int_a^{L/2} \frac{M(x)}{EI} \left(\frac{L}{2} - x \right) dx \right] \quad (2.31)$$

where $M(x)$ is the bending moment at a distance x from the support, EI the flexural stiffness, and a the distance from the support to the nearest load point. Simplifying yields:

$$\Delta_b = \frac{23PL^3}{1296EI} \quad (2.32)$$

Shear deformation, accounted separately, uses a shear correction factor k to reflect shear flexibility, calculated as:

$$\Delta_s = \frac{k}{2G_cA} \left[P \left(\frac{L}{3} \right) \right] \quad (2.33)$$

Combining these, considering $a=L/3$ and assuming for the analysis a shear correction factor $K=1.0$, the total deflection at the mid-span under four-point bending is:

$$\Delta_{\text{total}} = \frac{23PL^3}{1296EI} + \frac{PL}{6GA} \quad (2.34)$$

2.5 Influence of Temperature

2.5.1 Polyamide 6 (PA6) Matrix

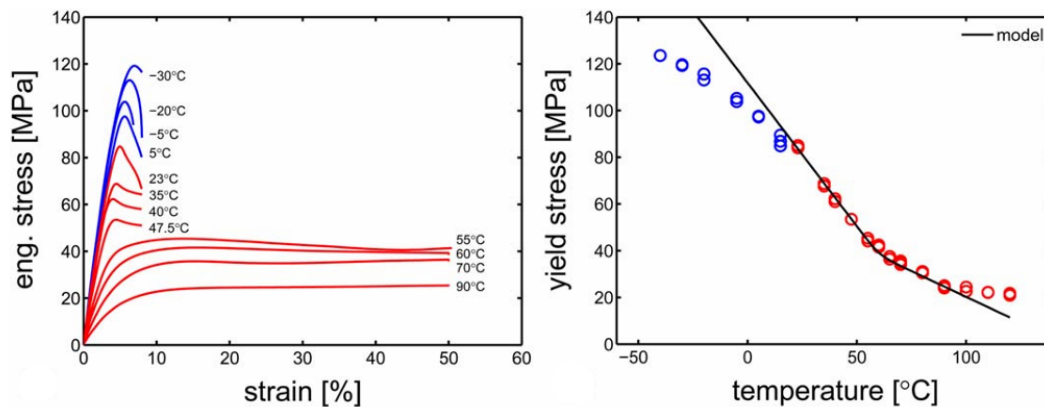


Figure 2.17: Example of temperature-dependence of stress-strain response of PA6 and Yield stress as a function of testing temperature (the line is the prediction based on the Ree-Eyring equation).

Polyamide 6 (PA6) is a widely used engineering polymer that has, in recent decades, been adopted for load-bearing applications such as mechanical components, under-hood automotive parts, and sports equipment. The transportation sector, like the applications just mentioned, often face challenging conditions, including high loads, elevated temperatures, and high humidity. As a result, ensuring the reliability of PA6 in these environments requires a thorough investigation of how humidity and temperature affect its mechanical properties. The glass transition temperature (T_g) of Polyamide 6 is highly dependent on the moisture content [9]. In its dry state, the T_g of PA6 is reported to be around +56°C, which aligns closely with the supplier's data indicating a T_g of +60°C. However, the T_g experiences a significant drop when the material absorbs moisture; at full saturation corresponding to a relative humidity RH 85%, the T_g drastically decreases to around -1°C. At standard atmospheric conditions (RH 50%), the T_g is approximately +23°C. Moreover, the T_g of PA6 is also sensitive to temperature variations. This variability in T_g underlines the polymer's sensitivity to environmental conditions. Based on a study carried out at Eindhoven University of Technology [9], the yield stress of PA6 decreases significantly as temperature increases (2.17). In tests ranging from -40°C to 120°C, the yield stress varies from approximately 125 MPa at low temperatures to about

20 MPa at higher temperatures. This is due to the different deformation mechanisms that dominate at varying temperatures, with the glassy amorphous phase contributing more at low temperatures. PA6's deformation is governed by two primary processes—an intra-lamellar mechanism (active below the melting point) involving crystallographic slip, and an inter-lamellar mechanism, which affects the amorphous regions. As temperature rises, the mobility in the amorphous regions increases, leading to a lower yield stress.

Referring then to the composite (Twill Wave 2x2 GFR PA6) [10], it shows a decrease in shear modulus and yield stress as the temperature increases. This effect is more pronounced at higher temperatures, where the composite exhibits increased ductility, indicating that the material becomes more flexible and less brittle. This change in ductility is indeed particularly noticeable at temperatures near or above the T_g of the polymer. In tests where the composite's behavior is primarily dominated by the fibers (Fiber-Dominated Properties), such as in certain directional tensile tests (0° and 90° fibre orientations), the impact of temperature on mechanical properties is less pronounced. The fibers can be considered practically insensitive to temperature, unlike the polymer matrix.

2.5.2 Polyethylene terephthalate (PET) foam

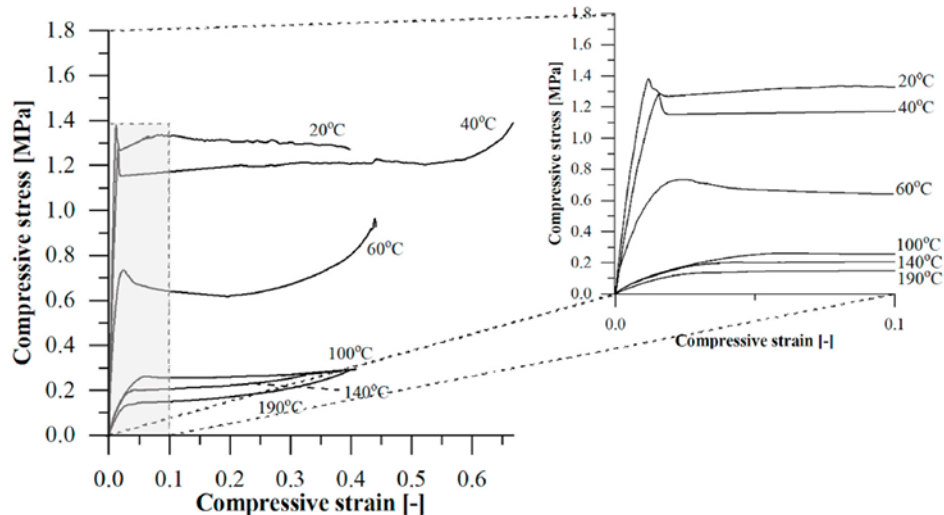


Figure 2.18: Compression stress vs strain curves at different temperatures.

A recent work [11] investigates the impact of temperature on the mechanical behavior of polyethylene terephthalate (PET) foam (with a measured density of 94 kg/m^3),

specifically focusing on its shear and compressive properties at elevated temperatures. It details how PET foam's mechanical integrity starts to degrade significantly as temperatures approach and exceed its glass transition temperature (T_g), which is around 65°C . Both compressive and shear strengths see marked reductions when the temperature nears or surpasses the T_g , emphasizing the potential compromise in structural capacity of PET foam in high-temperature environments.

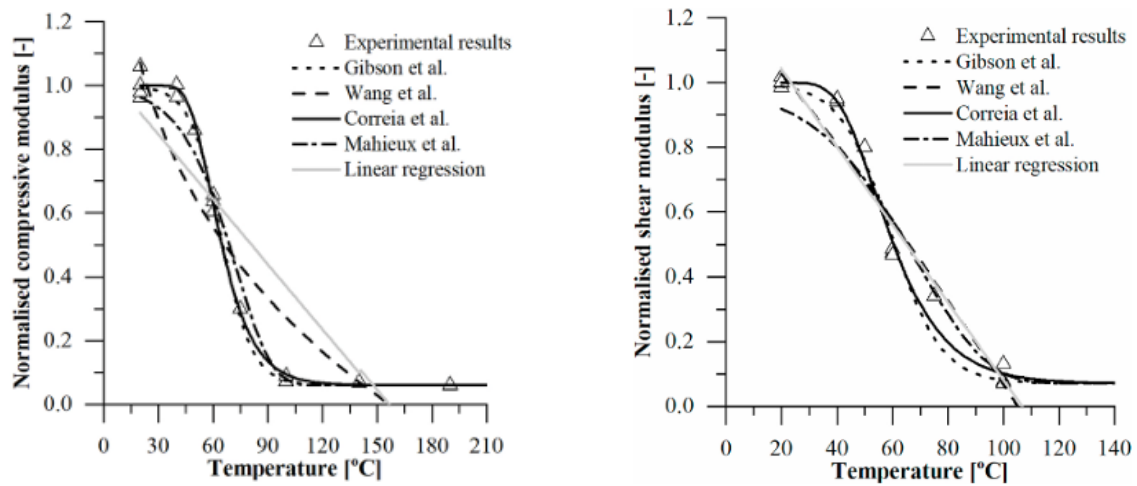


Figure 2.20: Variation of shear modulus with temperature.

Chapter 3

Materials and Methods

3.1 Description of the Thermoplastic Sandwich Panel

3.1.1 Skin Material: 2x2 Twill Glass Fiber Reinforced Polyamide 6

The 2x2 twill Glass fiber reinforced Polyamide 6 Organosheet used in this research as sandwich pannel's face material is a composite material consisting of continuous glass fibers embedded within a polyamide 6 (PA6) matrix. The fibers are arranged in a 2x2 twill weave pattern, which provides a balance between strength and flexibility.

2D woven fabrics are produced by interlacing yarns using a weaving loom. The yarns are classified into two main components: the warp, which runs along the length of the loom, and the weft, which runs perpendicular to it. The warp yarns are further divided into groups, with each group passing through a set of eyelets in a harness frame. These frames move up and down in a controlled sequence, allowing the weft yarns to be inserted according to a predetermined pattern, forming the fabric's structure. At the crossover points where the warp and weft yarns intersect, the yarns may bend (a phenomenon known as crimp) to pass over or under each other. A beat-up comb is then used to tightly pack the yarns into the fabric. The warp and weft yarns intersect at a 90° angle. The fabric's structure is defined by how the yarns interlace. In this case, in a twill weave, the warp and weft follow a 2/2 pattern (Fig.3.1), with two warp yarns alternating over and under two weft yarns at the crossover points. The glass fiber reinforcement significantly enhances the material's stiffness and strength, making it suitable for structural applications where

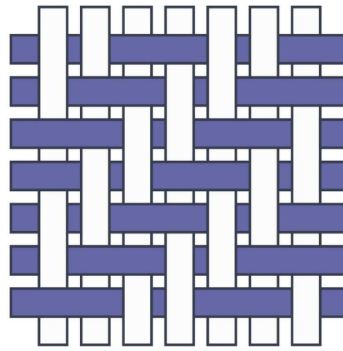


Figure 3.1: 2/2 Twill Wave

lightweight and durability are required. Polyamide 6 (PA6) serves as the matrix material, offering good thermal stability, chemical resistance, and excellent adhesion to the glass fibers. This combination of properties makes the 2x2 twill GFR PA6 Organosheet ideal for use in high-performance sandwich panels, particularly in transport and other industrial sectors where weight savings and high strength are critical.

For further information, particularly regarding the mechanical performance of the Organosheet, please refer to the datasheet [14].

3.1.2 Organosheet Manufacturing

The Johns Manville Neomera™ OS-6 Series 2/2 Twill Glass Fiber Fabric Reinforced Organosheet is created through a proprietary manufacturing process which involves the thorough impregnation of the woven fabric with PA-6 resin. This process ensures optimal resin distribution and strong bonding between the glass fibers and the thermoplastic matrix, enhancing the material's structural integrity and performance characteristics. Specific details on the manufacturing techniques, such as the exact methods of impregnation and curing, are part of Johns Manville's proprietary technologies. Organosheets are usually made by impregnating continuous fiber fabrics with a thermoplastic resin, which is then melted and pressed under heat and pressure to coat the fibers evenly, a process akin to the production of thermoplastic prepregs. The production can involve the use of automated lay-up machines and heated presses or rollers to ensure the thermoplastic matrix encapsulates the fibers thoroughly. Unlike RTM and VARTM that involve liquid resin systems and require a curing step, organosheet production typically uses solid thermoplastic resins that are melted during processing and do not require chemical curing, just cooling.

Given the characteristics of thermoplastic composites like the Neomera™ OS-6, the manufacture likely involves lamination and consolidation steps under heat and pressure. The

Description [unit]	Value
Fiber	E-glass, JM StarRov®886
Weaving style	2/2 twill
Fabric area weight [g/m^2]	1200
Yarn/Yarn count [$tex(g/1000m)$]	2400
Fiber content [vol]	46%
Thickness [mm]	2.0 ± 0.2
Sheet density [g/cm^3]	1.75

Table 3.1: JM Neomera Organosheet material card.

main properties of the composite are summarized in the table above.

3.1.3 Core Material: AIREX® T10.170 PET foam

The AIREX® T10.170 is a closed-cell, thermoplastic foam made from polyethylene terephthalate (PET) with a density of 170 kg/m^3 . This foam is designed for use as a lightweight core material in sandwich structures, offering a combination of strength, thermal stability, and durability. Due to its closed-cell structure, AIREX® T10.170 exhibits excellent moisture and chemical resistance, making it ideal for applications in marine, automotive, and industrial sectors where environmental exposure is a concern. The foam demonstrates good compressive strength, with values around 3.1 MPa, making it capable of withstanding high loads in sandwich panel applications. In the thickness direction, the elastic modulus reaches up to 180 MPa, providing the material with a high stiffness-to-weight ratio. This makes it suitable for structural uses where rigidity is important. AIREX® T10.170 foam is widely used as a core material in composite sandwich structures due to its lightweight properties, high mechanical strength, and ease of processing. Typical applications include marine structures, wind turbine blades, automotive body panels, and other areas where weight savings and structural integrity are crucial. It is also fully recyclable, aligning with growing industry trends for sustainable materials. For further information, particularly regarding the mechanical performance of the foam, please refer to the datasheet [15].

3.1.4 Panel Configuration and Geometry

The sandwich panel consists of two 3 mm thick face sheets and a 40 mm thick core (Fig.3.2).

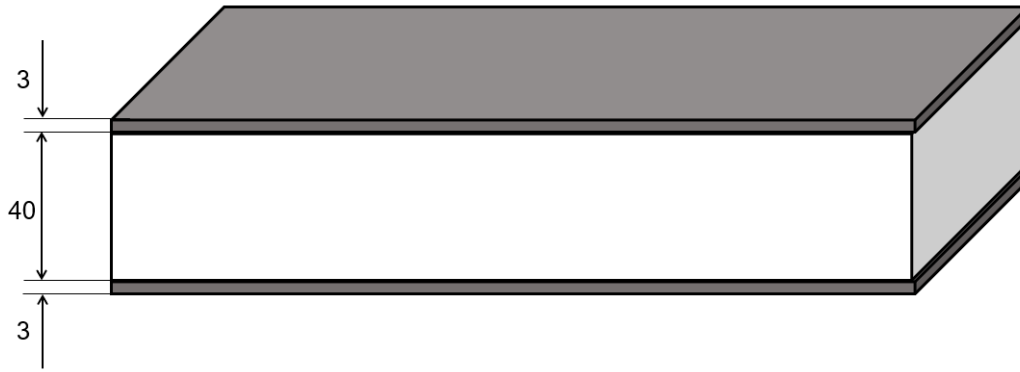


Figure 3.2: Thermoplastic sandwich configuration. Dimensions in [mm].

The constituents of the sandwich panel are bonded using a revolutionary technology for thermoplastic composites called Covalent Intermediate Bonding (CIB) [16].

The CIB process works by creating a covalent bond between polyethylene terephthalate (PET) foam and Polyamide 6 (PA6) skins under low pressure and low temperature. This method involves opening the molecular chains of both materials, enabling a chemical bond to form between them (Fig.3.3).

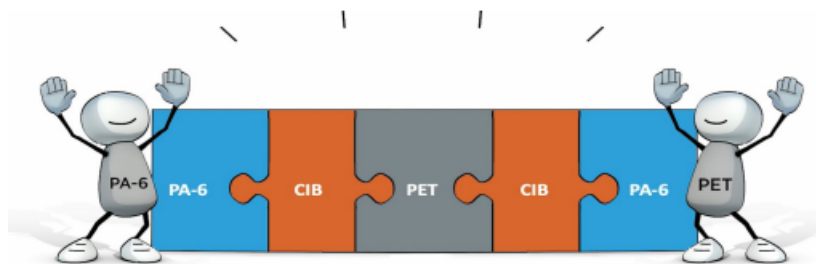


Figure 3.3: Covalent Intermediate Bonding (CIB).

CIB offers several advantages:

- It ensures a strong, reliable bond between the core and face sheets of the sandwich panel, eliminating issues like delamination, which can occur in traditional bonding methods;

- The bond created is not only mechanical but also chemical, resulting in enhanced durability and performance of the sandwich panel, especially under dynamic loads;
- CIB can be applied to bond thermoplastic composites to both other thermoplastics (TPC to TPC) and metals, expanding its application range in structural components, as seen in projects involving PA6 to steel bonding.

This technology is patent pending and represents a significant advancement in the production of lightweight, strong composite materials, especially for industries such as transportation and construction, where weight reduction and structural integrity are critical.

3.2 Mechanical Testing Procedures

3.2.1 Data acquisition: DIC technique

Digital Image Correlation (DIC) is an advanced optical method used to measure full-field displacement and strain in materials under load. It works by tracking the movement of a random speckle pattern applied to the surface of a specimen and recording images at different stages of deformation. DIC provides highly accurate, non-contact measurements that are valuable in understanding material behavior during testing. The VIC-3D system from Correlated Solutions is one of the leading systems for implementing 3D DIC. It captures and analyzes three-dimensional surface displacements and strains over the entire field of view using high-resolution cameras. The VIC-3D system has been applied in industries including aerospace, automotive, and civil engineering to measure material deformations, predict failures, and optimize designs.

Here is the procedure [18] to set-up the DIC measurement system used in this research:

1. Speckle Pattern Application:

Begin by applying white paint on specimen's surface, to create a uniform base and wait for the paint to dry. Then apply the speckle pattern: you can use spray cans, airbrush, or a stamp depending on the size of the area and the strain field you aim to capture. Ensure the speckles are well-distributed and bonded to the surface, with no reflection or detachment issues.



Figure 3.5: Spry can to apply the black speckle pattern

2. Camera System Setup:

- **Positioning Cameras:** Set up the stereo cameras (AVT) on a rail. The cameras should be positioned at an angle of approximately 15° between them. Ensure both cameras are securely mounted and positioned to cover the same field of view.
- **Focus and Lighting:** Adjust the focus and lighting for both cameras. Open the camera aperture and adjust the exposure time so that areas of the specimen are slightly overexposed. Then, close the aperture to increase the depth of field and ensure even lighting across both images.

It is recommended to use an additional light source, positioned so that its impact on the captured image is the same on both cameras.

3. Trigger Box and Connections:

- Connect the cameras to the Vic-Snap trigger box and the measurement system (e.g., tensile machine). Make sure to use the appropriate BNC connectors for voltage inputs.
- Ensure the trigger box is properly synchronized with the cameras and data acquisition system.

4. Calibration:

- Use calibration grids and capture multiple images while moving the target grid (along all its axes, so translation in three directions and rotation in three directions) in front of the cameras. Make sure to cover all areas of interest and check for proper focus and alignment of the grid with both cameras. After capturing the images, check them in the VIC-3D software to ensure they meet the calibration requirements.

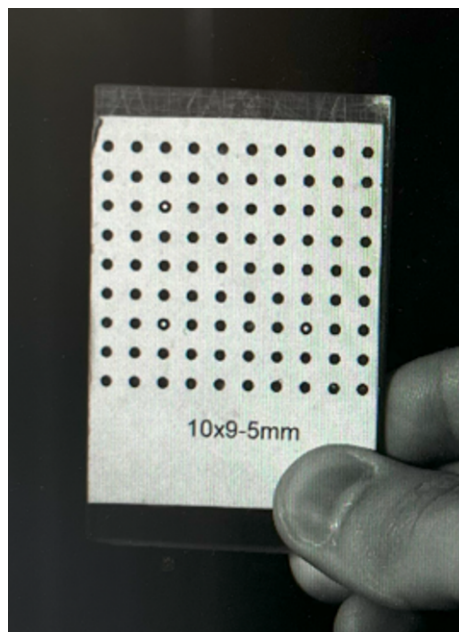


Figure 3.6: Example of calibration grid.

- After capturing the images, check them in the VIC-3D software to ensure they meet the calibration requirements.

5. Measurement:

Mount the specimen securely and ensure no disturbance to the camera setup. Use VIC-Snap to capture images and set the appropriate sampling frequency.

6. Post-Processing:

Once the images are captured, use VIC-3D to analyze the speckle pattern and calculate displacement and strain fields. Then visualize the results using the software's plotting tools. A more detailed description of the post-processing procedure will be

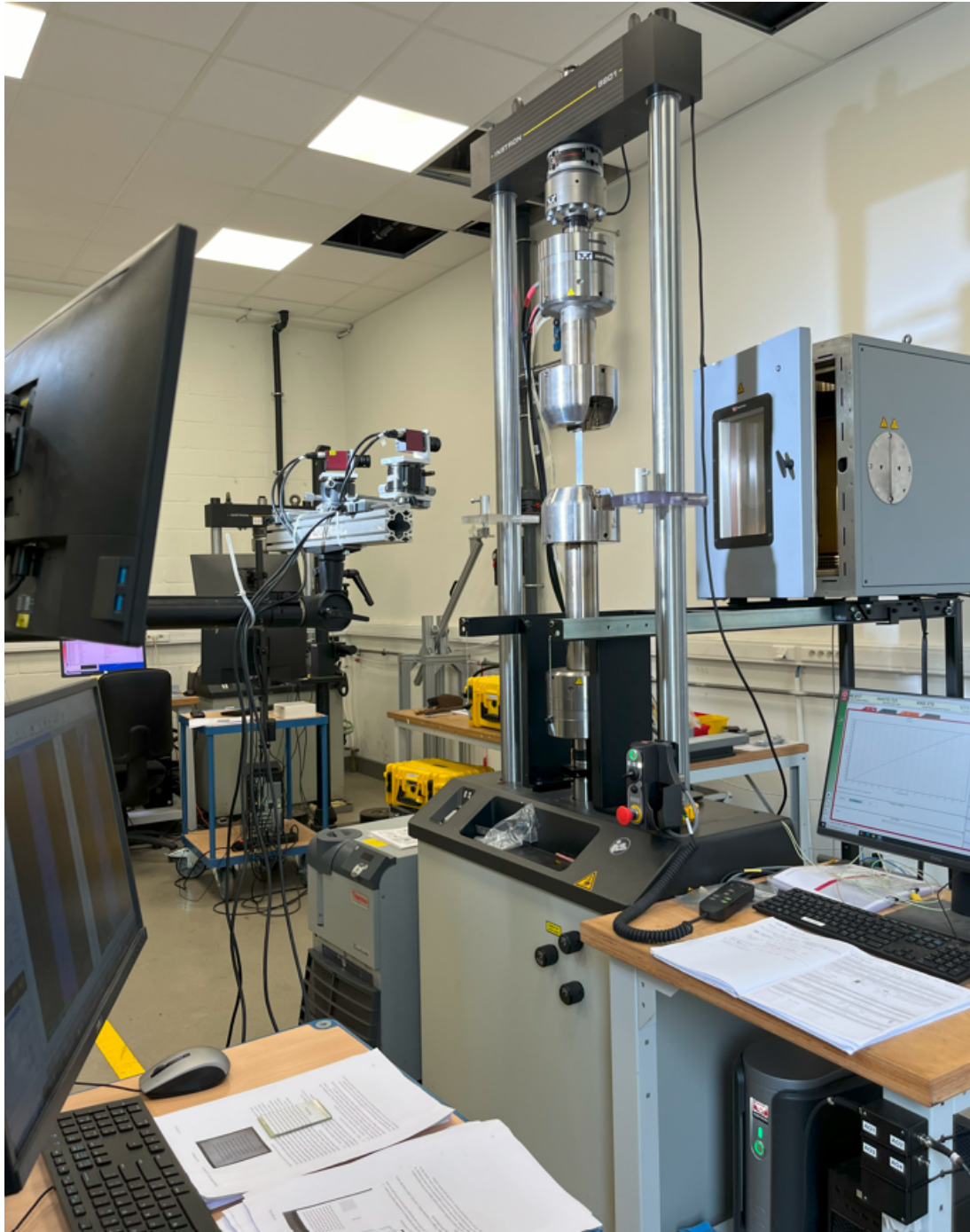


Figure 3.7: Measurement set-up.

provided later along with the presentation of the results from each different type of test.

The DIC technique was used as the measurement method in all tests conducted in this research. Measurement equipment includes:

- 8801 Hydraulic Instron (100kN load cell) or 5800 Electromechanical Instron (100kN load cell);
- DIC camera setup (AVT);
- DIC dongle and VicSnap trigger box;
- DIC acquisition PC;
- Cambo UST studio stand;
- Hedler Profilux LED 1000 (additional light).

3.2.2 DIC through the window of the temperature chamber

Using DIC in tests at a temperature of 50°C inside a temperature chamber is challenging because the presence of glass through which measurements are taken makes it more difficult to find the correct setup of the instrumentation, as well as the proper calibration of the system. For this reason, it is crucial to check some important aspects to ensure that the instrumentation is functioning correctly and that the presence of the glass does not compromise the accuracy of the measurements. Here is some useful tips:

1. Setup Preparation: ensure the camera sensors are as planar to the window as possible. If using a stereo DIC system, limit the stereo angle to a maximum of 20° and align the cameras symmetrically. Then verify that the window is clean and that the camera views are unobstructed when the window is in place. Moreover, it's crucial to ensure there is adequate space available to maneuver the chamber and its components, avoiding any impacts on the measurement setup. This prevents the need to reposition the cameras and subsequently recalibrate, which can be time-consuming.

2. Calibration at Room Temperature: perform the calibration with the temperature chamber's window in the same position as it will be during the tests. This ensures the refractive properties of the window are accounted for.
3. Image Capture: use the Variable Ray Origin (VRO) calibration model in Vic 3D, which allows for each pixel to have a different camera origin. This model is crucial for accurate calibration when refractive surfaces are present. Then capture a comprehensive set of calibration images. Move the calibration target throughout the entire volume of interest, ensuring sufficient tilts and rotations to cover all perspectives. Ensure images have good contrast, uniform lighting, and minimal glare or shadows.
4. Checking the Calibration: begin by taking images of a speckled specimen undergoing known Rigid Body Motion (RBM) at room temperature (Calibration Images). Ensure the chamber window is in the same position as it will be during the actual tests. Then run the Correlation Analysis and check Projection Errors: look for areas in the field of view (FOV) where projection errors are high, which might indicate inaccuracies in those regions of the FOV. Lastly, evaluate calibration accuracy:
 - 3D Shape: check if there are any distortions; a reasonable level of accuracy is expected despite unavoidable distortions;
 - Average Displacement: verify that the measured displacements match the known inputs;
 - Displacement and Strain Contours: assess these contours for any anomalies or inconsistencies that may suggest calibration errors.

Unsatisfactory calibration results can be fixed adjusting the light settings, the position of the target, or re-calibrating with different configurations. For the detailed procedure, please see Appendix A.

3.2.3 Testing Conditions: Room and Elevated Temperatures

All tests were carried out at both room temperature (RH 50%) and at 50°C to simulate the various environmental conditions to which the panel will be exposed during use. Testing

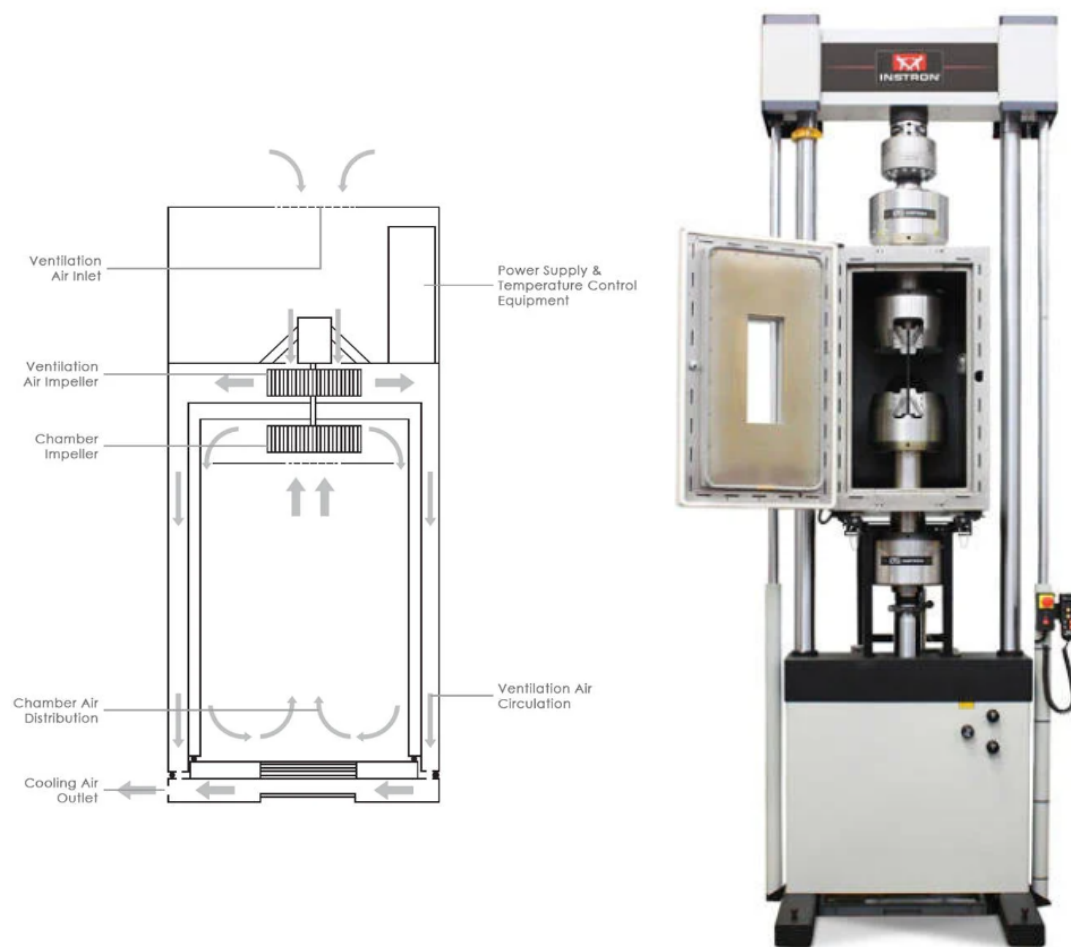


Figure 3.9: Enviromental chamber equipped on the testing machine.

at elevated temperatures is particularly critical given the use of thermoplastic materials, whose performance may vary with temperature changes. For this purpose, the environmental chambers equipped on the 8801 Hydraulic Instron testing machine (Fig.3.9) and on the 5800 Electromechanical Instron testing machine are used for tests at a $T=50^{\circ}\text{C}$. This chambers utilize a forced-convection system (Fig3.8) where hot or cold air is circulated around the specimen, grips, and pull rods, ensuring optimal heating and cooling rates, minimal thermal gradients, and stable thermal conditions. A dedicated Eurotherm 3208 temperature controller mounted to the chamber is used to select the required set-point temperature. Temperature is monitored and controlled by a Type N thermocouple inside the chamber.

3.2.4 Tensile Testing

The tensile properties of the composite face skins of the sandwich panel are determined following the ASTM D3039/D3039M standard [19], which outlines the methodology for testing polymer matrix composite materials reinforced with continuous high-modulus fibers.

In-plane shear tests are carried out following a similar procedure, according to ASTM D3518/D3518M, which describes the standard test method for in-plane shear response of polymer matrix composite materials by tensile test of a $\pm 45^\circ$ laminate.

The specimens are cut from the composite skins with a constant rectangular cross-

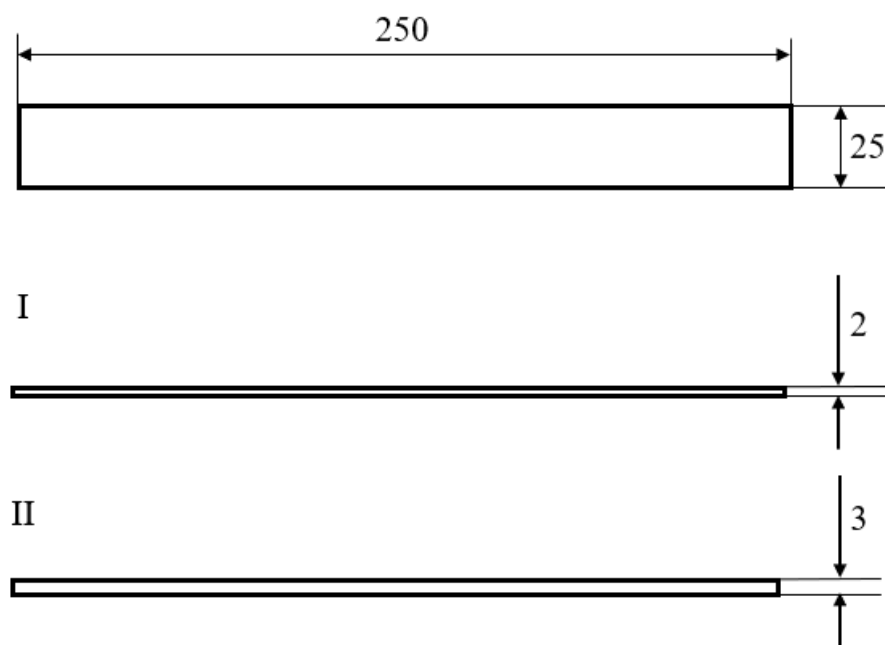


Figure 3.10: Tensile test's specimen geometry, dimensions in mm.

section. Each specimen is carefully machined with a circular saw, to avoid damage such as notches or delaminations, which could affect test results. The width and thickness of the specimens are measured at three points along the gage section, and the average value is used to calculate the cross-sectional area. Note that two different plates are tested, with thicknesses of 2 mm and 3 mm.

Glued cardboard tabs are provided on the specimen to facilitate gripping between machine grips and the sample.

A standard head displacement rate of 2 mm/min is used.



Figure 3.11: Broken specimen, with speckle pattern and tabs

3.2.5 Compression Testing

The ASTM C365 standard [20] details the procedure for determining the flatwise compressive properties of sandwich cores, specifically focusing on the core's compressive strength and modulus. The procedure can be adapted for various core materials, including foam, and is critical for ensuring that sandwich panels meet required specifications for mechanical strength and rigidity. According to this standard, the specimen geometry is shown in Fig.3.12, obtained from the PET panel using a circular saw.

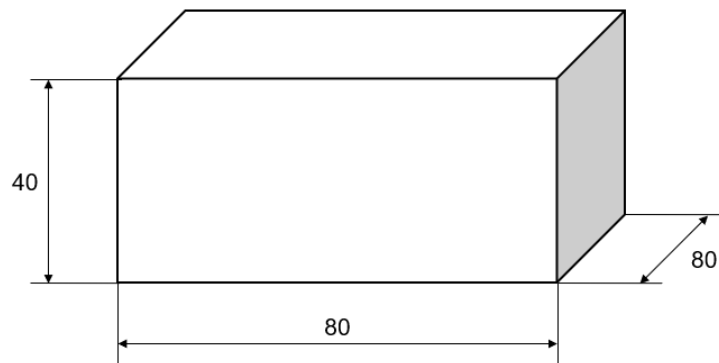


Figure 3.12: Compression test's specimen geometry, dimensions in mm

The setup mounted on the 5800 Electromechanical Instron (100kN loadcell) includes steel rods, clamping rings, and pins to achieve the perfect combination with minimal wobbling of the fixture. The load is applied using two spherical loading plates, so that they distribute the load as uniformly as possible across the entire loading surface of the specimen, at a constant head displacement rate of 0.5mm/min (according to the standard). For additional tests a head displacement of 5mm/min is also used.

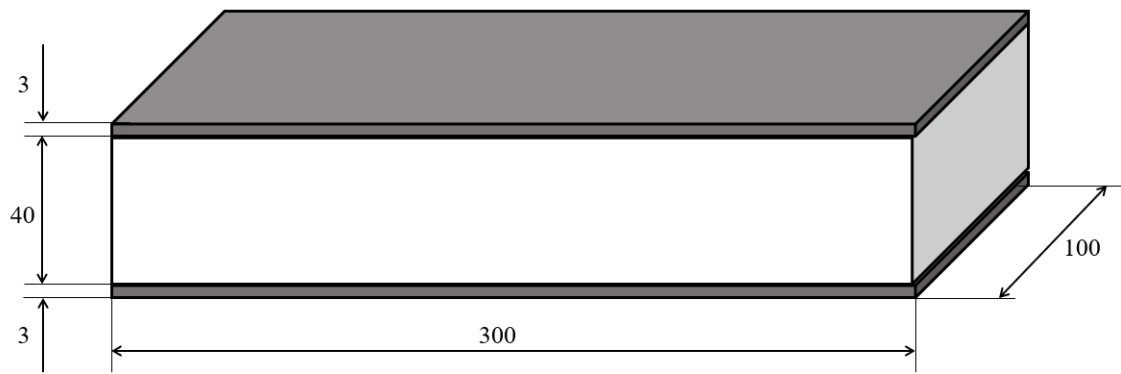


Figure 3.13: Bending test's specimen geometry, dimensions in mm.

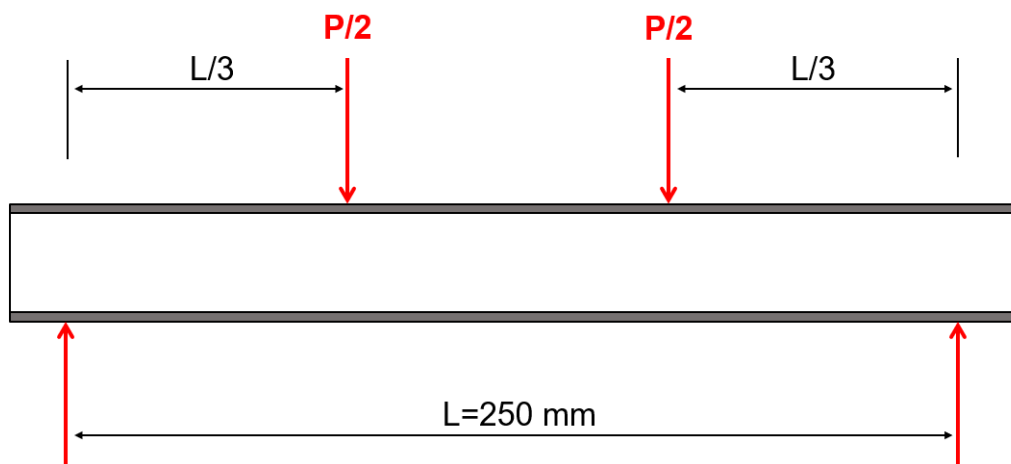


Figure 3.14: Third point loading configuration.

3.2.6 Flexural Testing of the Panel

The flexural test outlined by the ASTM C393 standard [21] determines the flexural properties of flat sandwich constructions.

The specimen, rectangular in cross-section, matches the thickness of the sandwich construction and is at least twice as wide as its total thickness. Additionally, the length of the specimen equals the span length plus extra length to ensure adequate support and load application during testing. Details of the specimen dimensions are illustrated in Fig.3.13.

Similar to the compression test setup, steel rods, clamping rings, and pins are utilized. Furthermore, the bending setup is assembled, comprising steel items, adjustable supports, and steel bars to transfer the load effectively. To conduct 4-point bending tests, a third point loading configuration is arranged (Fig.3.14), according to the standard.

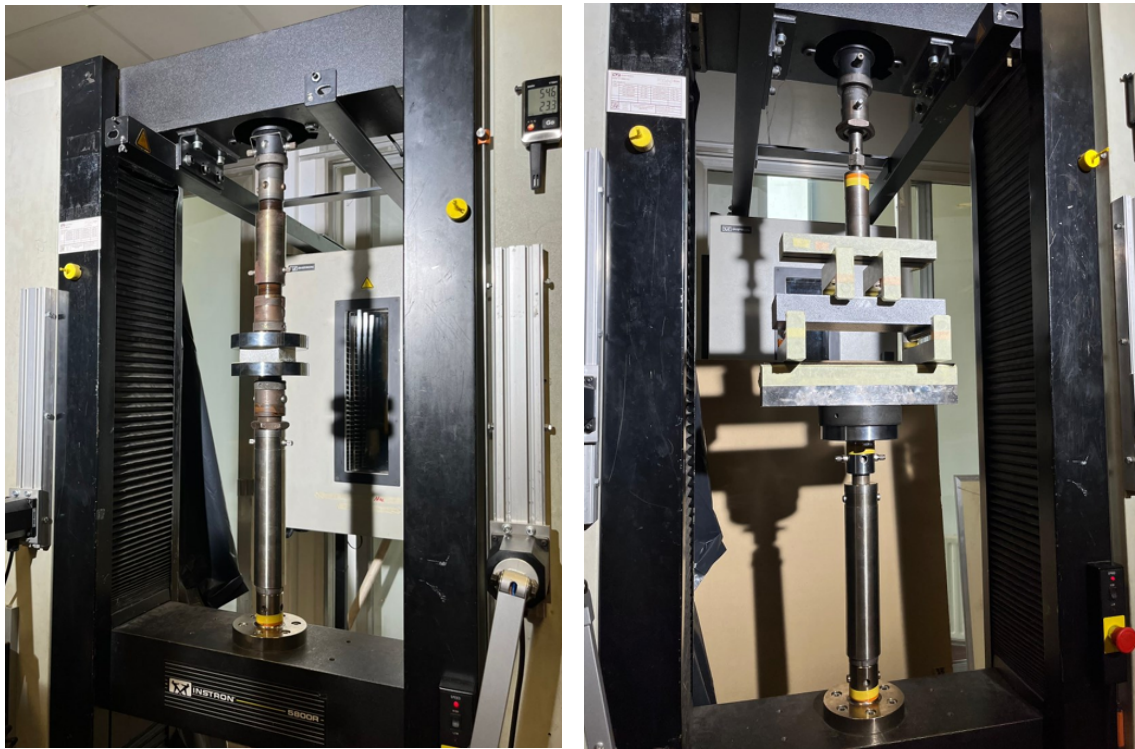


Figure 3.16: Bending test's setup.

Chapter 4

Mechanical Characterization of Constituent Materials

4.1 Microscopy

Given the background and motivations of this research, it is essential to first closely examine the materials in question, particularly the composite constituting the face skins. This initial assessment is crucial for understanding the material quality, which could influence subsequent tests. Not only can environmental conditions affect material performance, but poor manufacturing quality—a factor often negligently assumed to be adequate—can also have significant impacts.

For this reason optical microscopy images are taken. Initially, the sandwich panel was made up of 2 mm thick skins, which were later replaced by skins of the same material but with increased thickness (3mm). These thicker skins clearly offered better overall performance, which is why the mechanical characterization of the skins was conducted on both 2 mm and 3 mm thick samples. Both materials were then examined under a microscope. The images obtained are reported below (Fig.4.1).

The images immediately reveal the asymmetry of the layup, which will induce internal stresses in the material that will affect its response. However, what is most striking is a strong presence of voids in the polymeric matrix, especially in the 2mm thick plate. The voids vary in size and, in some areas, they are quite large. The 3mm thick plate definitely

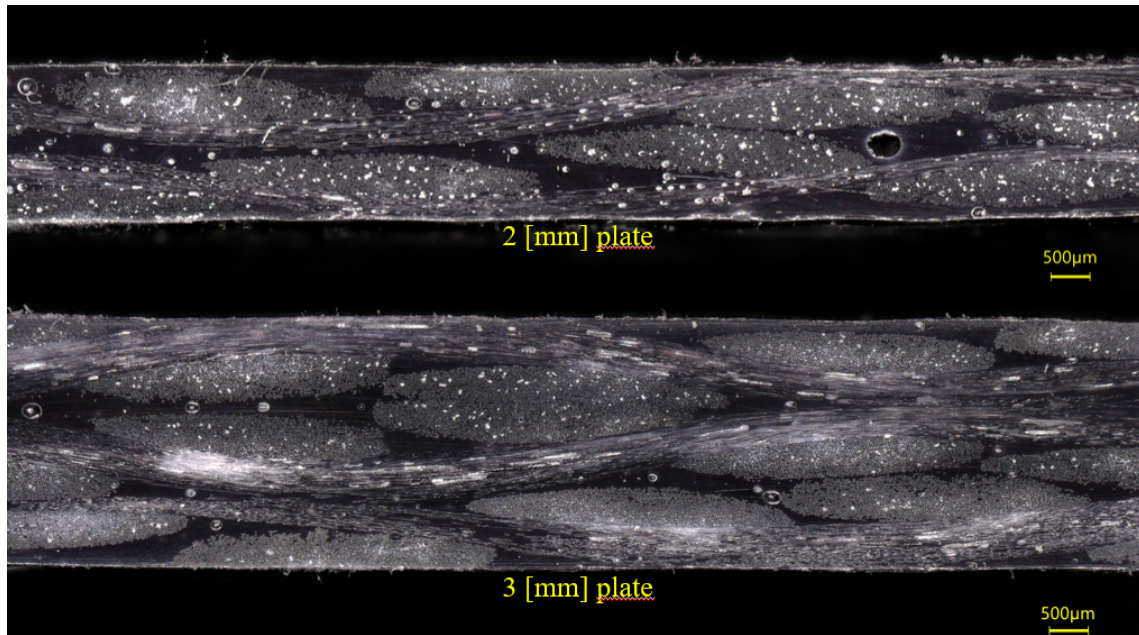


Figure 4.1: Microscopy of GFR PA6 plates.

has better quality, although it is also affected by this type of defect.

The presence of voids (holes) in the polymeric matrix of the composite can be attributed to several factors related to the manufacturing process [22]. Common causes include:

- **Inadequate Resin Distribution:** If the thermoplastic resin does not evenly saturate the fiber reinforcement during the manufacturing process, areas with insufficient resin coverage can lead to void formation. Unlike thermosets, thermoplastics do not involve a chemical curing reaction, but the pressure and heat applied during the consolidation phase must be sufficient to ensure complete and uniform impregnation (similar to a RTM process, see Fig4.2).
- **Air Entrapment:** Similar to thermoset composites, during the processing of thermoplastic organosheets, air can become trapped within the material, either between the fibers or within the resin itself. This is especially problematic if the processing parameters (temperature, pressure) do not adequately allow for the escape or proper compression of these air pockets.
- **Cooling and Solidification:** The rate at which the composite cools and solidifies can also impact void formation. Uneven cooling or too rapid solidification can prevent the resin from adequately filling gaps around the fibers, resulting in voids.

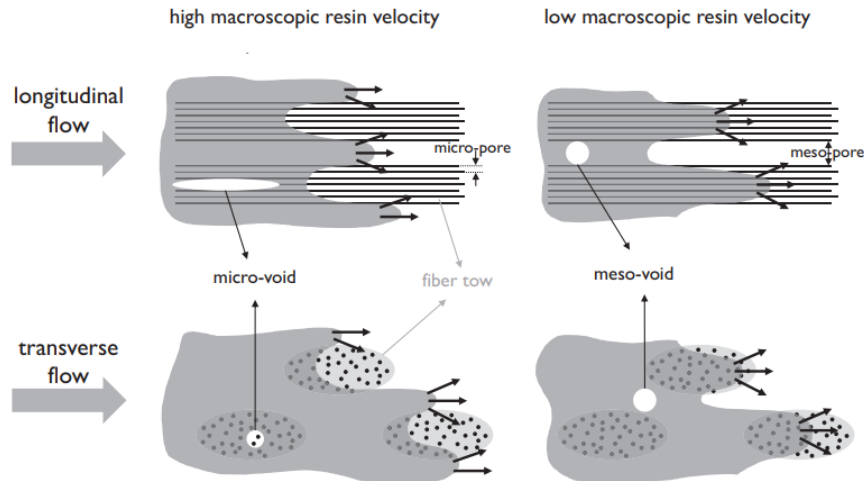


Figure 4.2: Void formation during longitudinal and transverse flow in liquid composite molding of a fibrous preform.

These factors are often interconnected, and improvements in the manufacturing process, such as employing techniques to ensure thorough impregnation and appropriate resin flow during the layup and consolidation stages can help mitigate void formation.

Concluding, overall production quality of the plates under analysis can be considered poor and will likely influence the material's performance in tests. However, it will be absolutely interesting to evaluate the extent of this poor quality on the results of the static tests.

4.2 Tensile Properties of Skin Material

4.2.1 Specimen and Test summary

Reference standard:

- ASTM D3039/D3039M

Specimen geometry:

- Rectangular, 250x25 [mm], $t_1=2$ [mm], $t_2=3$ [mm].

Specimen Preparation:

1. Cutting of specimens with a circular saw;

2. Application of white paint on the target surface, using airbrush;
3. Application of the speckle pattern, using a stamp;
4. Gluing of cardboard tabs.

Test setup:

- 8801 Hydraulic Instron, 100 kN load cell;
- Instron Environmental Chamber.

Measurement Setup (DIC):

- AVT cameras;
- VicSnap Triggerbox;
- Acquisition PC;
- Cambo UST studio stand (tripod);
- Hedler Profilux 1000 (additional light).

Speed of test:

- 2 [mm/min], according to ASTM D3039.

Number of valid tests:

- Room Temperature: two tests with the 2mm thick plate, one test with the 3mm thick plate.
- $T=50^{\circ}\text{C}$: two tests with the 2mm thick plate, three tests with the 3mm thick plate.

Note that "valid tests" refers to those tests in which both the breakage and the results acquisition are considered valid according to the standards and measurement procedures, respectively.

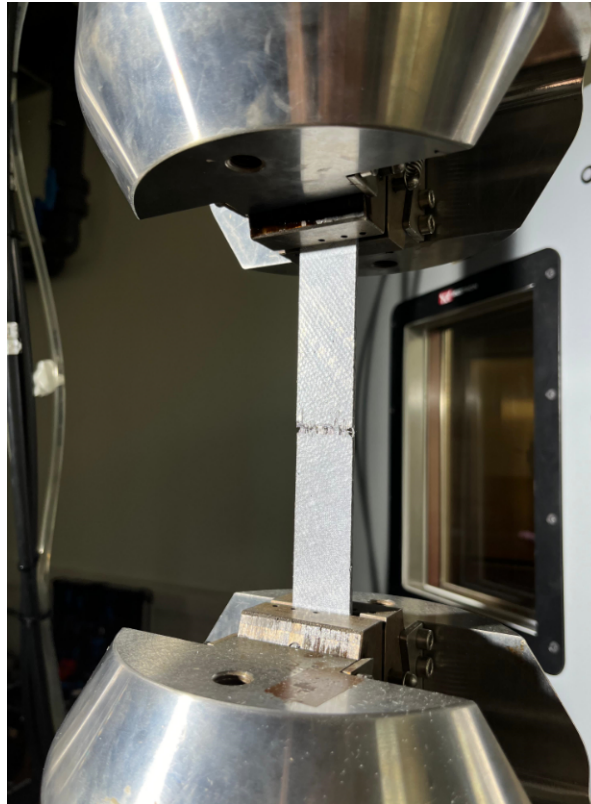
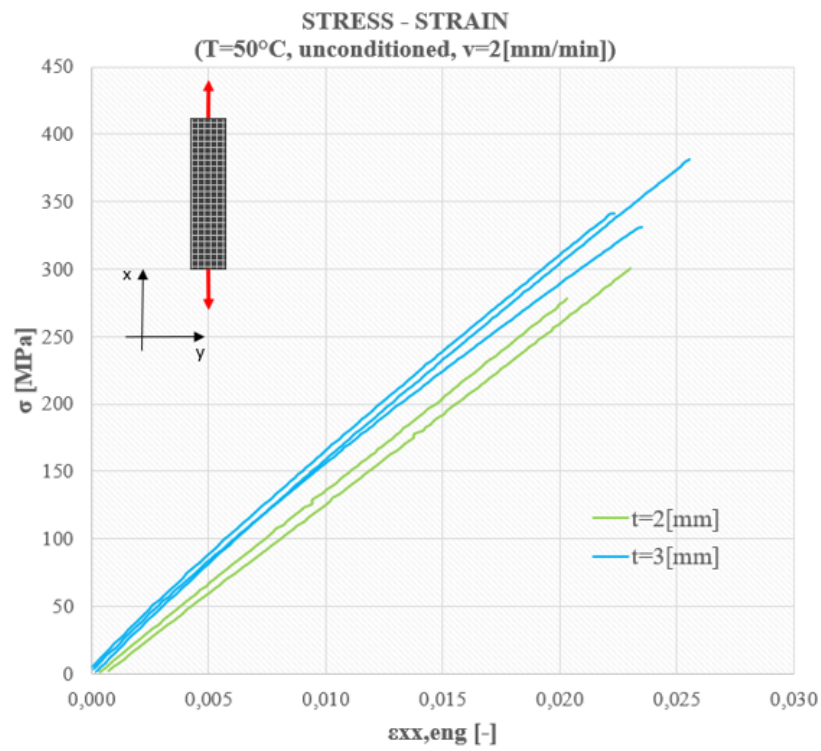
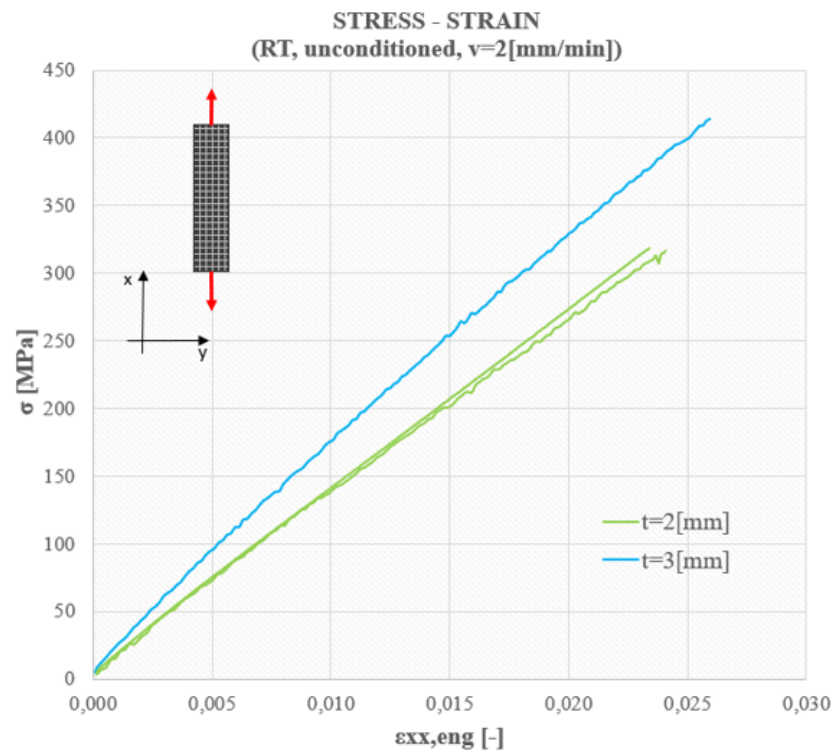


Figure 4.3: Example of valid breakage, according to ASTM D3039.

4.2.2 Results

The results, derived from rigorous testing following ASTM D3039/D3039M standards, provide insights into the composite's stress-strain behavior, ultimate tensile strength, and elasticity modulus. These results offer a comparative analysis and a comprehensive understanding of the composite's capabilities and limitations, both at room temperature and high temperature.



Multiple tests were conducted for each composite plate and under each environmental condition to ensure the repeatability of the obtained results.

The stress-strain curves of the material distinctly indicate its brittle behavior, particularly when tensioned along the fiber direction. This alignment results in a fiber-dominated response, which is evident from the almost perfectly linear trajectory observed in the curves. This characteristic demonstrates that the material maintains high stiffness and strength with minimal plastic deformation up to the point of failure. Such behavior is typical of fiber-reinforced composites, where the fibers provide significant load-bearing capacity, resulting in limited elongation before failure.

From the DIC images, one can observe the evolution of the deformation pattern, which

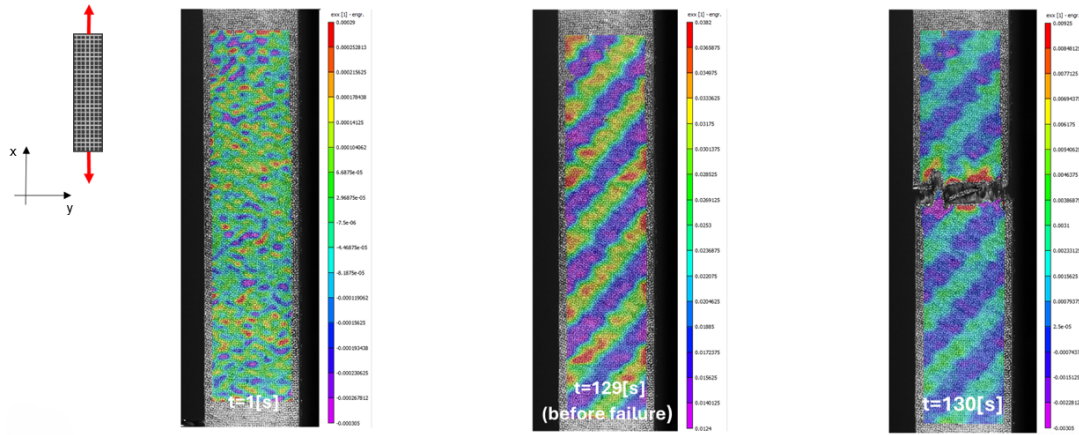
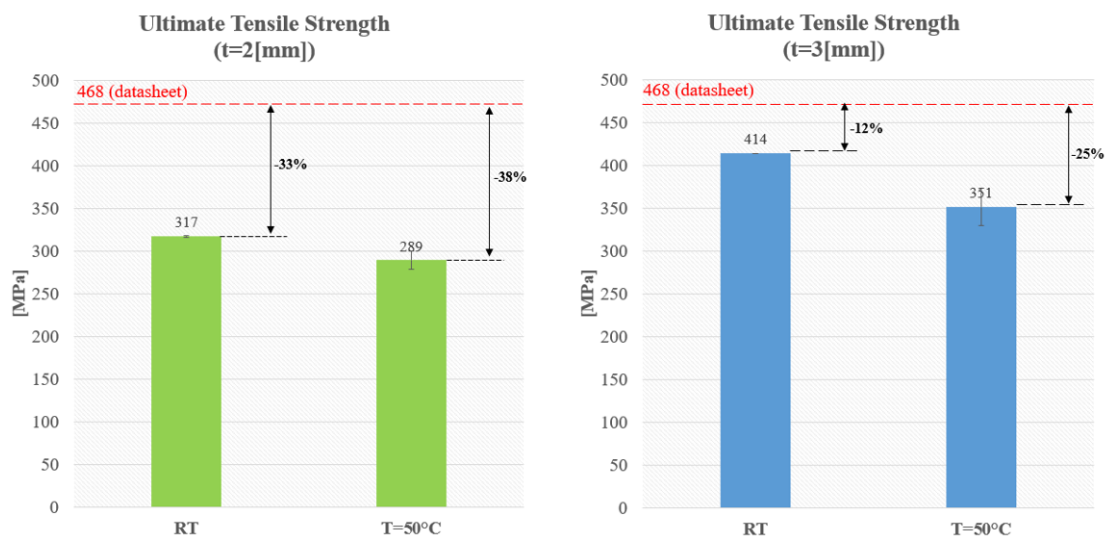


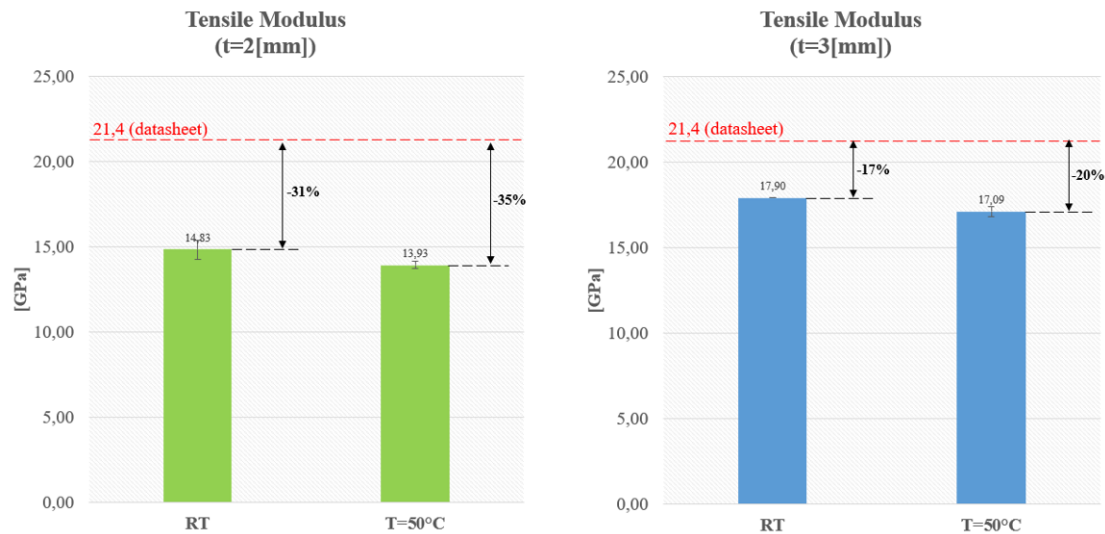
Figure 4.4: Strain ϵ_x diagonal pattern highlighted with DIC.

starts randomly and then stabilizes into a diagonal configuration characterized by 45-degree inclined bands relative to the load application direction. This directional pattern is well-defined, alternating between two precise levels of deformation. The behavior described is clearly illustrated in the contour shown in Fig.4.4 and can be easily explained looking at the woven geometry. In fact, in a 2/2 twill weave, the fibers alternate over and under each other in a diagonal pattern. This weave creates a mechanical interlocking of the fibers that results in the load being transferred diagonally when pulled along the fiber direction, causing the observed angled deformation. This effect highlights the anisotropic nature of the material, where the structural arrangement of the weave influences the deformation response under load. Interestingly, even after the specimen has failed and overall deformations have relaxed, the 45-degree pattern persists, indicating that a portion of the

deformation is irreversible. This suggests the elastoplastic behavior of the polymer matrix, which allows for some permanent deformation under load.

We now present a comparison between the values obtained in two series of tests conducted at different temperatures. These results are in turn compared with the values listed in the material datasheet provided by the manufacturer. These diagrams allow us to appreciate not only the effects of temperature on the material but also the discrepancy relative to the theoretical values of strength and modulus of the composite, which may be associated with issues of manufacturing quality. It should be noted that the comparison of values obtained in tests at $T=50^{\circ}\text{C}$ would not be directly comparable with the datasheet values, as these are referred to properties measured at room temperature. The comparison is therefore proposed simply to quantify the performance loss relative to the "base" material, which is theoretically almost defect-free and tested at room temperature.





From the results, it is observable that the effect of temperature, while present, is minimal. This is undoubtedly attributable to the fact that the contribution of the fibers is dominant over the material's response, as they are essentially inert to the temperature increase to which the specimen is subjected. Glass fibers indeed exhibit excellent thermal stability, which mitigates the overall thermal sensitivity of the composite.

However, the significant discrepancy observed at room temperature between the experimental results and the datasheet values raises concerns about potential variations in manufacturing quality or the presence of defects such as voids or misalignments in the fiber arrangement, particularly in the thinner 2mm plate, where a loss of both strength and elastic modulus of over 30% is observed. The lesser but still notable degradation in the thicker 3mm plate suggests a possibly more uniform material distribution or reduced impact of defects, underlining the complex interplay between material structure, manufacturing precision, and performance reliability.

4.2.3 Investigation

Further high-magnification images (Fig.4.5) are captured to better observe the defects present in the material and to confirm them as the primary causes of the material's property loss. It is noticeable that the voids measure up to more than one millimeter in diameter, creating significant discontinuities in the composite matrix. Furthermore, as observed in paragraph 4.1 (Microscopy), an asymmetrical or disordered lay-up can significantly

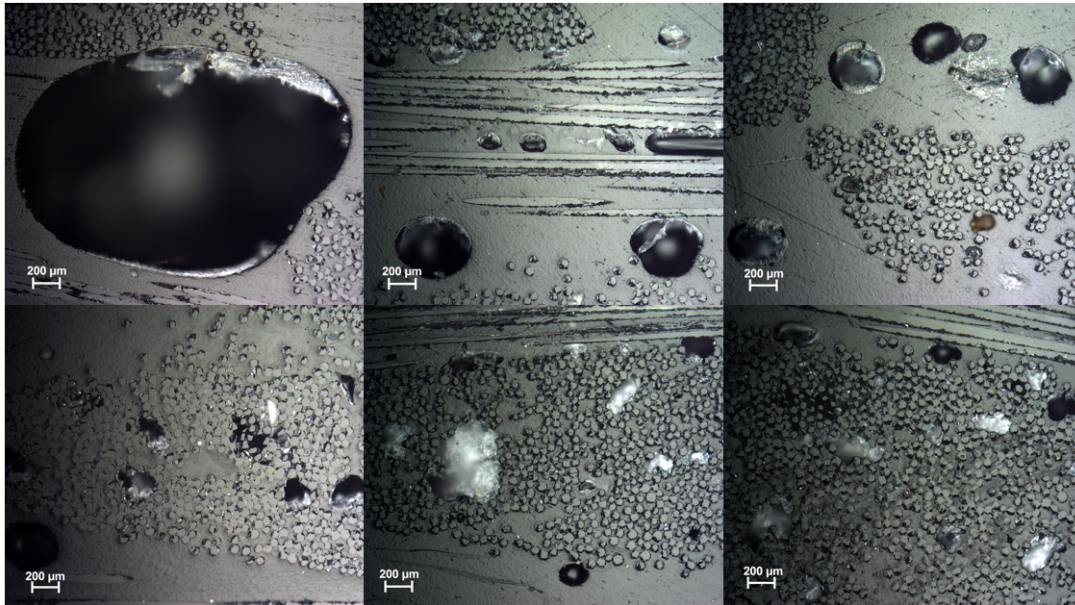


Figure 4.5: High-magnification images to better visualize voids' dimensions

impact the material's performance. When the fibers are not symmetrically aligned, it leads to uneven stress distribution, which can increase the likelihood of premature failure under operational loads. Additionally, irregularities in fiber orientation impair the anisotropic properties of composites, where strength and stiffness are designed to align with fiber directions. Such deviations not only weaken the material by altering expected load-bearing directions but also introduce defects like voids and wrinkles. These defects reduce the overall structural strength and serve as focal points for the initiation of damage as well. Consequently, the variance between experimental results and the specifications provided in datasheets can often be traced back to these lay-up inconsistencies, highlighting the necessity for meticulous control during the manufacturing process to preserve the composite's designed performance attributes.

Another area of investigation concerns the images obtained with DIC, specifically those related to displacement in the W direction (Fig.4.6). These images reveal a clear wavy pattern of displacement along the length of the specimen, making it necessary to identify the causes in order to explain this unexpected phenomenon. Initially, it was hypothesized that this behavior could be due to delaminations occurring in the material following the tensile tests. By closely examining the three-dimensional contours, it is possible to recognize a dual contribution to the displacement in the W direction, which arises not only from waviness but also from the bending of the panel, causing it to bow in

a specific direction. These displacements detected in the W direction reach values of over

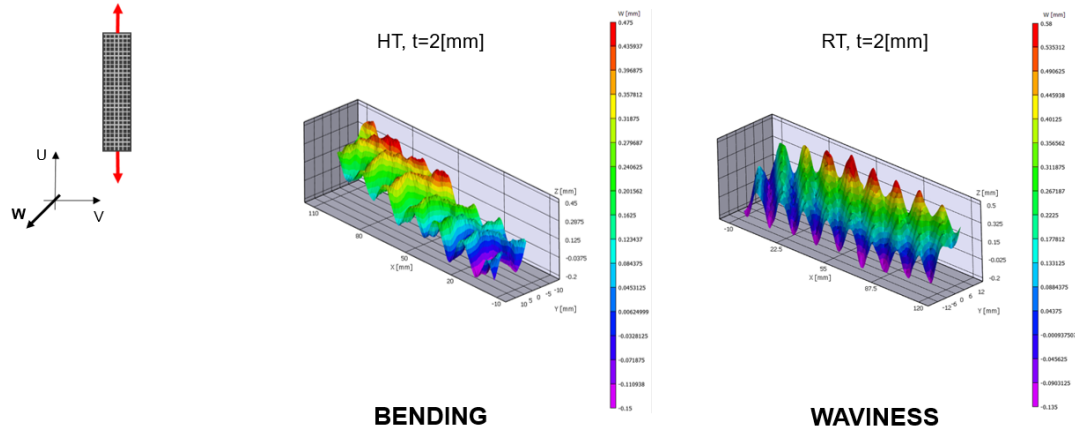


Figure 4.6: Two different contribution to the W displacement

0.5mm, which is 25% of the total thickness for the 2mm thick plate; Therefore it is not negligible at all. To uncover the causes of these two contributing factors, the following steps are taken:

1. Actual lay-up observation: to better explain the strange way the sample deforms. From microscopy image (Fig.4.7) it is clearly visible that the actual lay-up is asym-

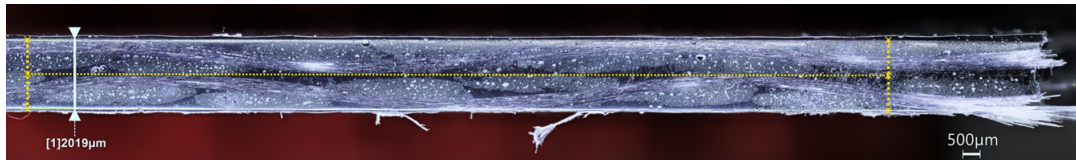


Figure 4.7: Microscopy image to visualize the actual lay-up of the panel.

metric.

2. Plate grinding: to see the effect of any residual stresses. In order to highlight the effects of this asymmetrical lay-up, which leads to residual stresses on the panel, half the thickness of a sample is grinded and a clear panel bending is directly visible, confirming the typical asymmetrical plate's behaviour.



Figure 4.8: Bending after grinding half the thickness of the sample.

3. Microscopy: on the specimen under tension, to see the actual deformation's shape. To tension the specimen, a manual tensile setup is used (Fig.4.9). It consists of

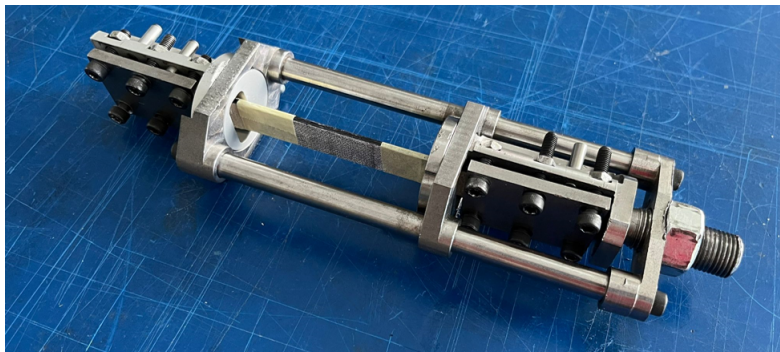


Figure 4.9: Manual miniature tensile setup

two grips (which are closed manually with bolts) and one of them is movable. The movement is achieved by screwing the nut onto the bolt that controls the position of the mobile part of the system. By rotating the bolt, the specimen is directly tensioned.

Firstly, contrary to what might have been assumed, there are no delaminations present in the material. Instead, it appears that the phenomenon of waviness is predominantly governed by the geometric configuration of the fiber fabric: it is evident that fibers aligned with the load direction tend to stretch naturally. This action causes them to exert a force on the fibers orthogonal to them in the W direction, influencing them to move more in one direction than the other. Consequently, these orthogonal fibers contribute to the wavy pattern observed in the DIC images, which this analysis seeks to explain. This behavior is facilitated by a matrix that can be considered highly elastic, as long as the material is under tension, and then relaxes

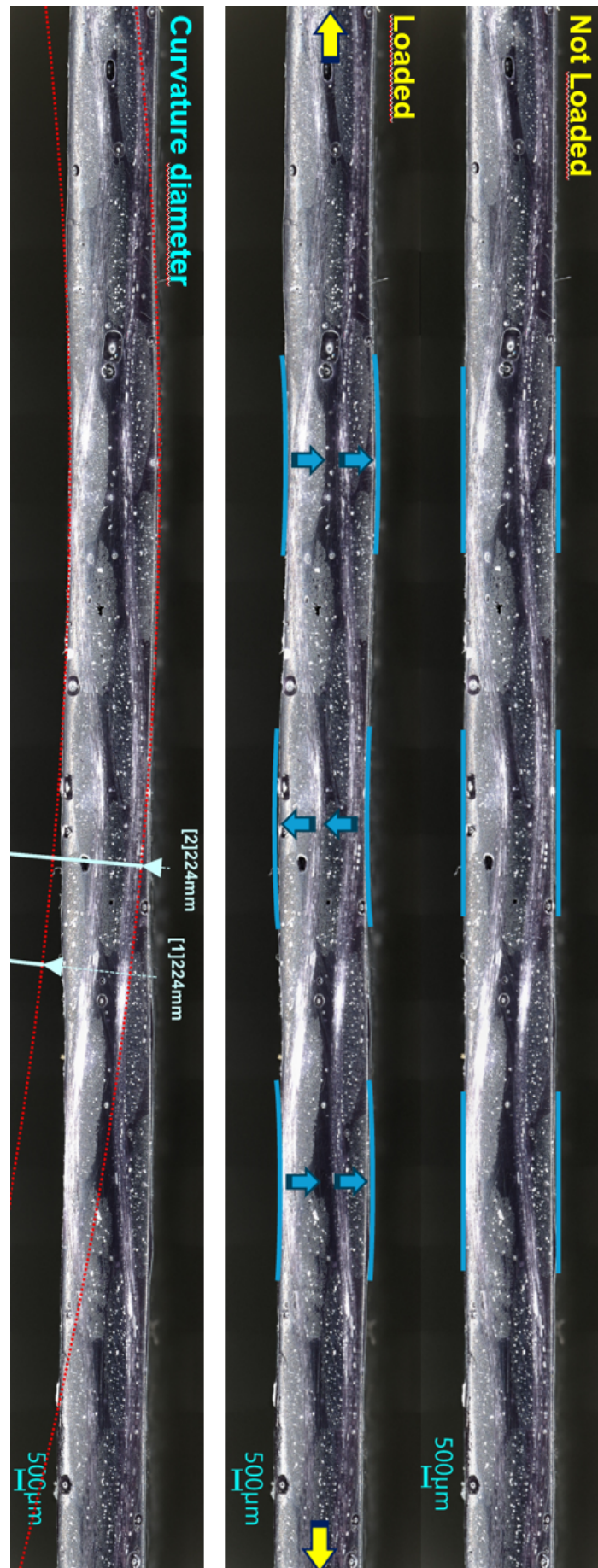


Figure 4.10: Actual waviness of the plate under tension.

once the load is removed.

4.3 In-Plane Shear Properties of Skin Material

Similarly to the tensile tests on the composite, in-plane shear tests are conducted on specimens with fibers oriented at $\pm 45^\circ$ relative to the load direction. This is done to assess the material's response when stressed in a configuration not dominated by the fibers, but by the matrix instead. This approach helps to evaluate the impact of stresses that are misaligned with the fiber orientation, as well as the effect of temperature on the polymer matrix and the interaction between the matrix and its reinforcement.

4.3.1 Specimen and Test summary

Reference standard:

- ASTM D3518/D3518M

Specimen geometry:

- Rectangular, 250x25 [mm], $t_1=2$ [mm], $t_2=3$ [mm], $\pm 45^\circ$ oriented.

Specimen Preparation:

1. Cutting of specimens with a circular saw;
2. Application of white paint on the target surface, using airbrush;
3. Application of the speckle pattern, using a stamp;
4. Gluing of cardboard tabs.

Test setup:

- 8801 Hydraulic Instron, 100 kN load cell;
- Instron Environmental Chamber.

Measurement Setup (DIC):

- AVT cameras;
- VicSnap Triggerbox;
- Acquisition PC;
- Cambo UST studio stand (tripod);
- Hedler Profilux 1000 (additional light).

Speed of test:

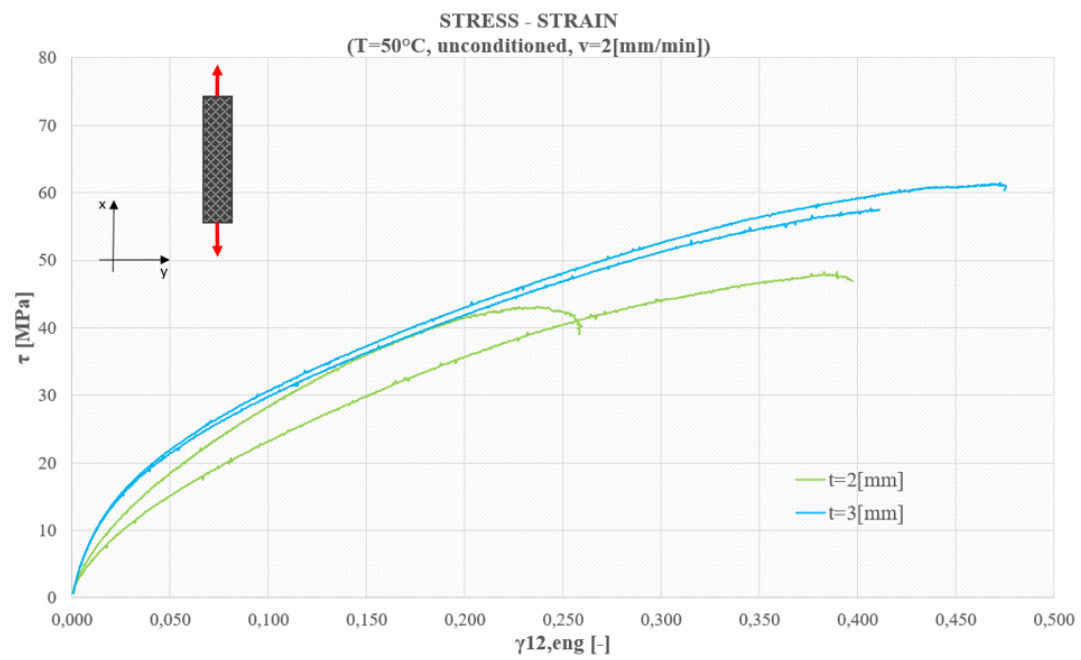
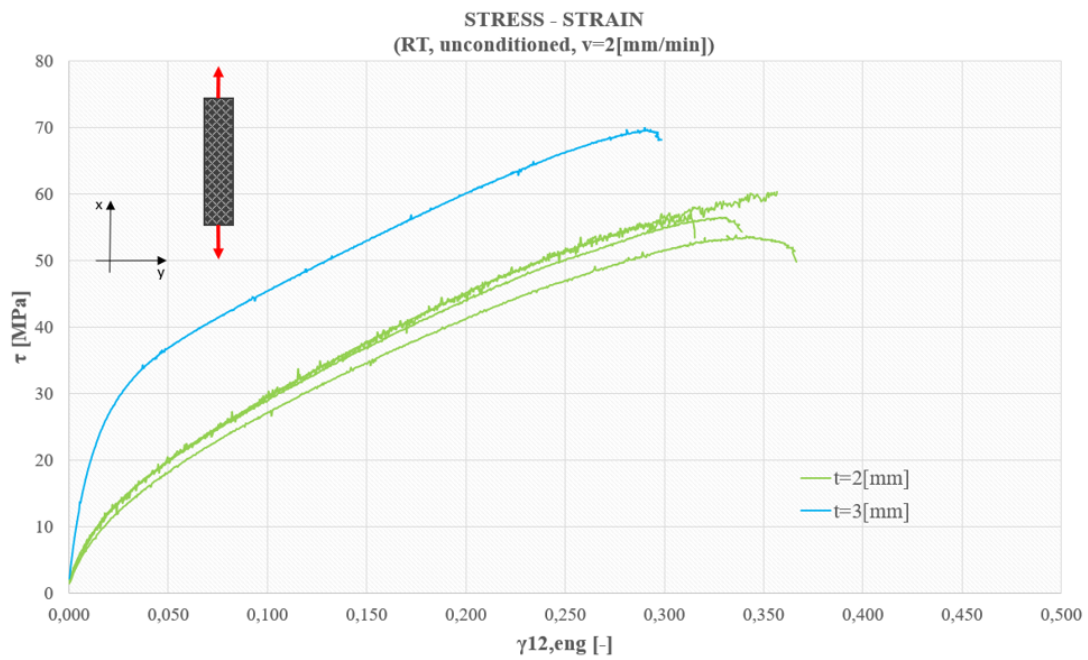
- 2 [mm/min], according to ASTM D3518.

Number of valid tests:

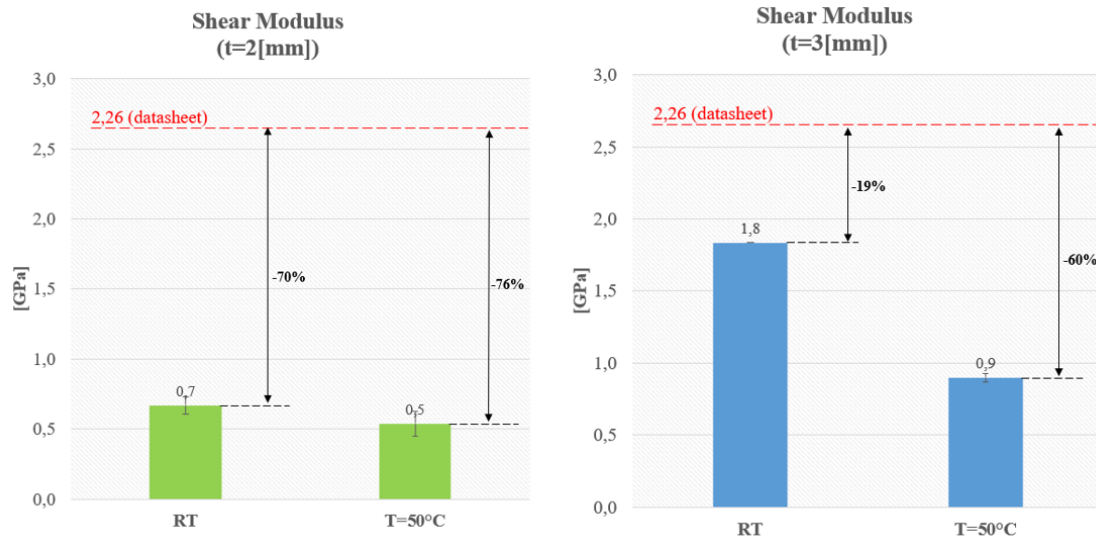
- Room Temperature: three tests with the 2mm thick plate, one test with the 3mm thick plate.
- $T=50^{\circ}\text{C}$: two tests with the 2mm thick plate, two tests with the 3mm thick plate.

4.3.2 Results

The outcomes of the in-plane shear tests, performed following the ASTM D3518/D3518M standard, provide crucial insights into the shear behavior of the composite. These tests are designed to assess the material's response to shear stresses applied within the plane of the laminate, focusing on its shear modulus of elasticity (which is the only information we have from the material's datasheet about the shear response of the composite and with which we can therefore make a comparison).



As done with the tensile tests, a comparison is proposed between the results obtained at the two different test temperatures and between the experimental results and the values reported in the material's datasheet.



Shear modulus is calculated as follows [23]:

$$\frac{G_{12}^{\text{chord}}}{G_{12}} = \frac{\Delta\tau_{12}}{\Delta\gamma_{12}} \quad (4.1)$$

where:

- G_{12}^{chord} = shear chord modulus of elasticity, GPa;
- $\Delta\tau_{12}$ = difference in applied engineering shear stress between the two shear strain points, MPa;
- $\Delta\gamma_{12}$ = difference between the two engineering shear strain points (nominally 0.004).

The results clearly demonstrate that temperature significantly impacts both tested panel thicknesses, particularly affecting the 3mm thick panel more distinctly. However, the most striking observation is the substantial reduction in the shear modulus of the composite, which falls well below the values specified in the datasheet (-70%). These tests, characterized by matrix-dominated behavior of the composite, underscore how the defects previously noted in the polymer matrix markedly affect the test results.

4.3.3 Investigation

In this case, the main objective is to verify the test results to accurately determine if the significant discrepancy between experimental outcomes and the datasheet values is real and assessed correctly.

For this reason, the accuracy of the results obtained through DIC is called into question. To address this, the measurements are repeated using virtual strain gauges at points on the strain contour where the deformation values were respectively the highest and lowest recorded. Finally, these results are compared with those previously derived. Examining

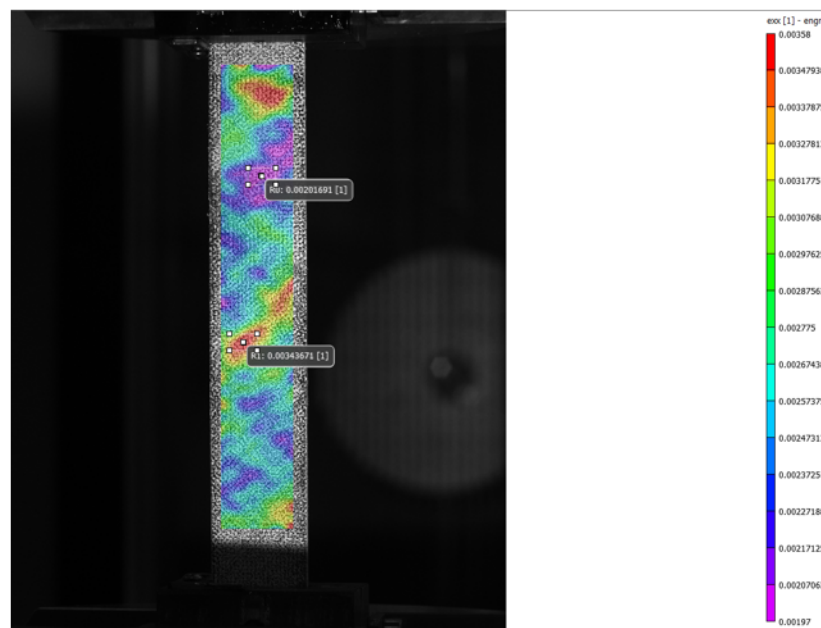


Figure 4.11: Virtual strain gauges position.

the results obtained from this dual measurement (Fig.4.12), it is observed that both strain gauges yield very similar results, which are still significantly different from the values stated in the material's datasheet. This confirms that the poor performance outcomes are not linked to the measurement method (DIC) and can therefore primarily be attributed, once again, to the low manufacturing quality.

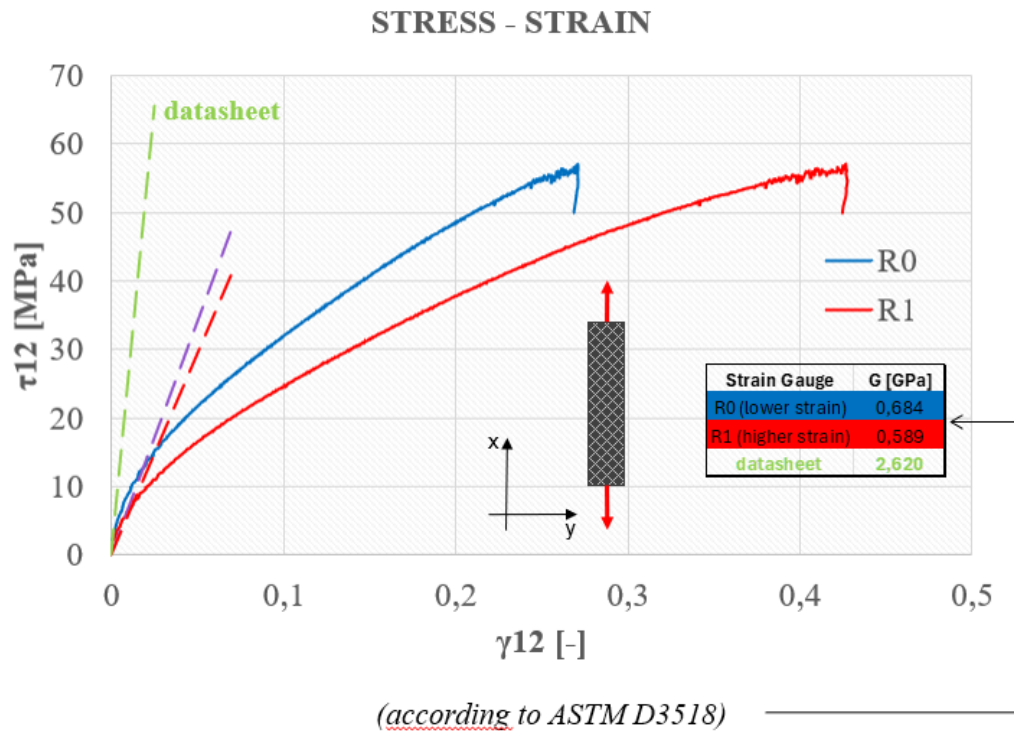


Figure 4.12: Virtual strain gauges position.

4.4 Compression Properties of Core Material

4.4.1 Specimen and Test summary

Reference standard:

- ASTM C365

Specimen geometry:

- Square, 80x80 [mm], t=40 [mm].

Specimen Preparation:

1. Cutting of specimens with a circular saw;
2. Surface polishing with sandpaper, to get a smooth finishing;
3. Application of white paint on the target surface, using spray can;
4. Application of the speckle pattern, using a stamp;

Test setup:

- 5800 Electromechanical Instron, 100 kN load cell;
- Instron Environmental Chamber.

Measurement Setup (DIC):

- AVT cameras;
- VicSnap Triggerbox;
- Acquisition PC;
- Cambo UST studio stand (tripod);
- Hedler Profilux 1000 (additional light).

Speed of test:

- 0,5 [mm/min], according to ASTM C365, 5 [mm/min] for additional tests.

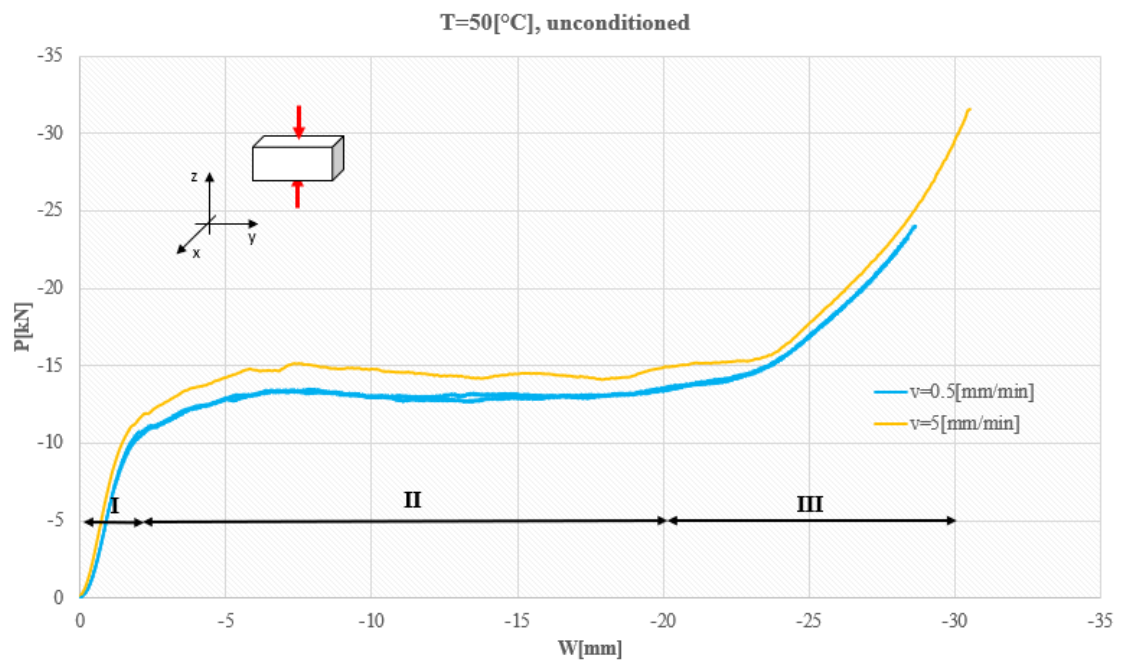
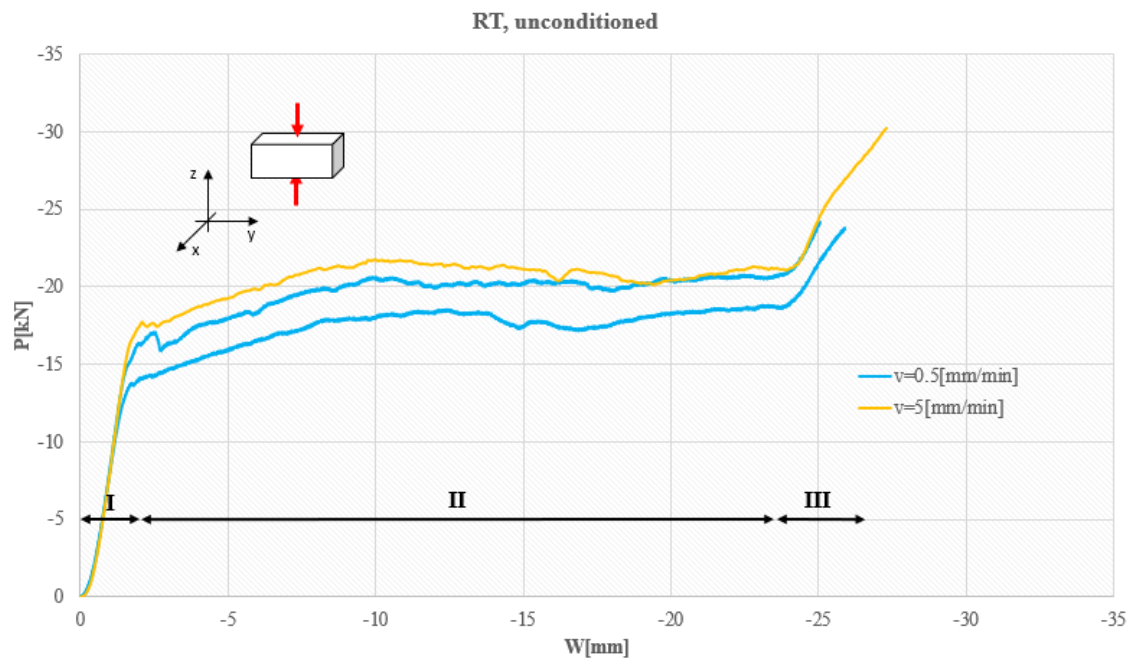
Number of valid tests:

- Room Temperature: two tests at $v=0.5\text{mm/min}$, one test with $v=5\text{mm/min}$.
- $T=50^{\circ}\text{C}$: two tests with $v=0.5\text{mm/min}$, one test with $v=5\text{mm/min}$.

4.4.2 Results

The results from the compression tests on AIREX® T10.170 PET foam, conducted according to the ASTM C365 standard, are instrumental for assessing the material's compressive strength and modulus in various conditions. These tests are meticulously executed with detailed setup under specified environmental conditions, including room temperature and elevated temperatures of 50°C . Once again, the diverse testing environments help illuminate how temperature variations impact the mechanical properties of the foam.

About the force-displacement curves, the initial part of both of them is marked by a clear stabilization phase of the test system, during which the plate applying the load settles and comes into full contact with the specimen. Having made this preliminary observation, the



results illustrate a typical three-stage compression behavior of polymeric foams. Initially, there is a quasi-linear elastic behavior where the cell walls bend and the cell faces stretch. This stage is critical for determining the initial modulus of elasticity. The precise values of the compressive modulus are indeed derived from the gradient of the stress versus strain in the elastic region, providing a quantitative measure of the foam's stiffness. This is followed by a horizontal plateau, indicative of either plastic bending, elastic buckling, or brittle fracture. The final stage is densification, where the cells collapse completely and the material begins to compact.

Notably, these stages exhibit variations in response to temperature changes. At room temperature, a sharp load drop was observed, indicating highly localized cell deformations. At elevated temperatures, such as 50°C, the material showed a softer load drop, suggesting an increase in the material's ductility due to thermal softening. Furthermore, the force-displacement curves reveal a nonlinear compressive response that intensifies with temperature. The densification phase occurred at smaller strains at higher temperatures, indicative of the polymer's thermal softening.

It's fair to note from the progressively captured images during the test the formation of

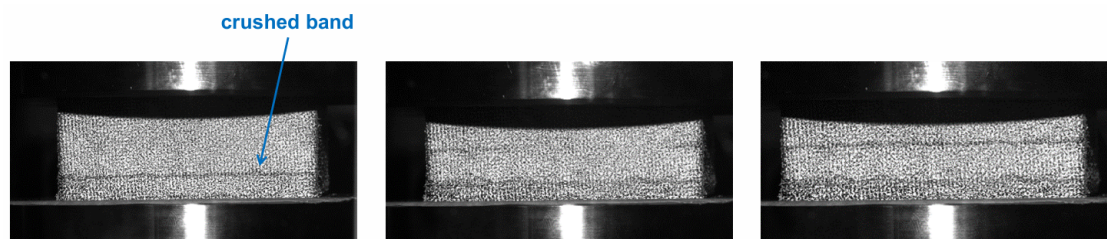


Figure 4.13: Formation of crushed bands during compression tests.

crushed bands (Fig.4.13) where the PET foam cells collapse, initiating a "compaction" process of the specimen starting from these bands. The position where these failure initiation bands form and propagate appears to be random, and it's conjectured that any weaknesses caused during the cutting phase of the specimens might partly influence this phenomenon.

About the stress-strain curves (Fig. 4.14), in the initial slope the load increases linearly and then follows the trend shown in both figures. This is graphically obtained by ignoring initial data, where the test setup is stabilizing.

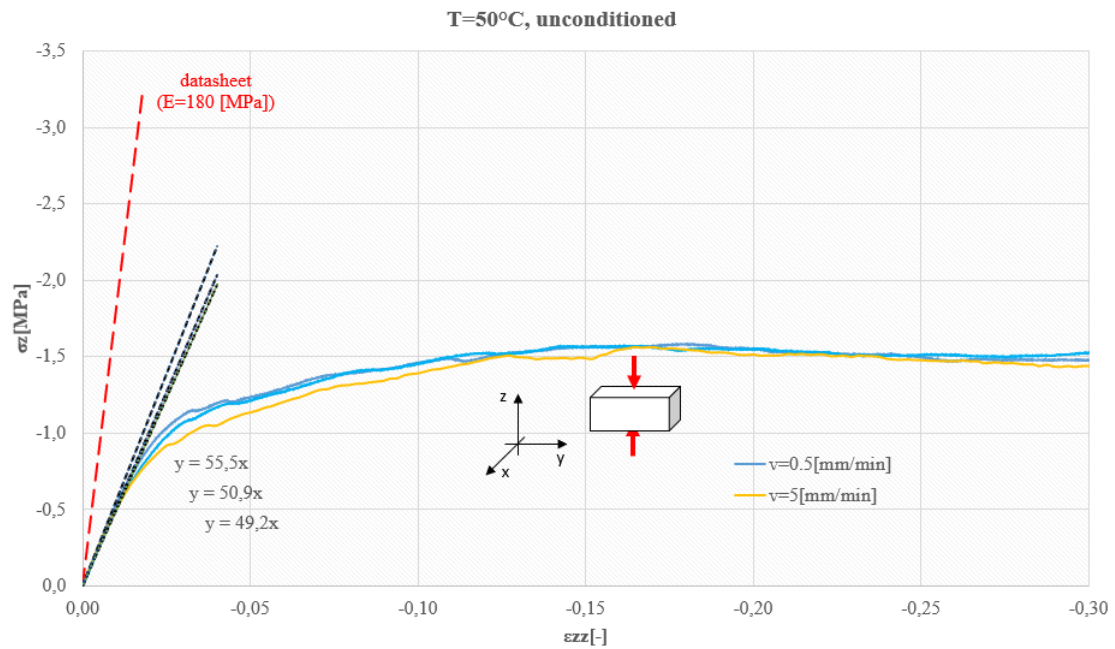
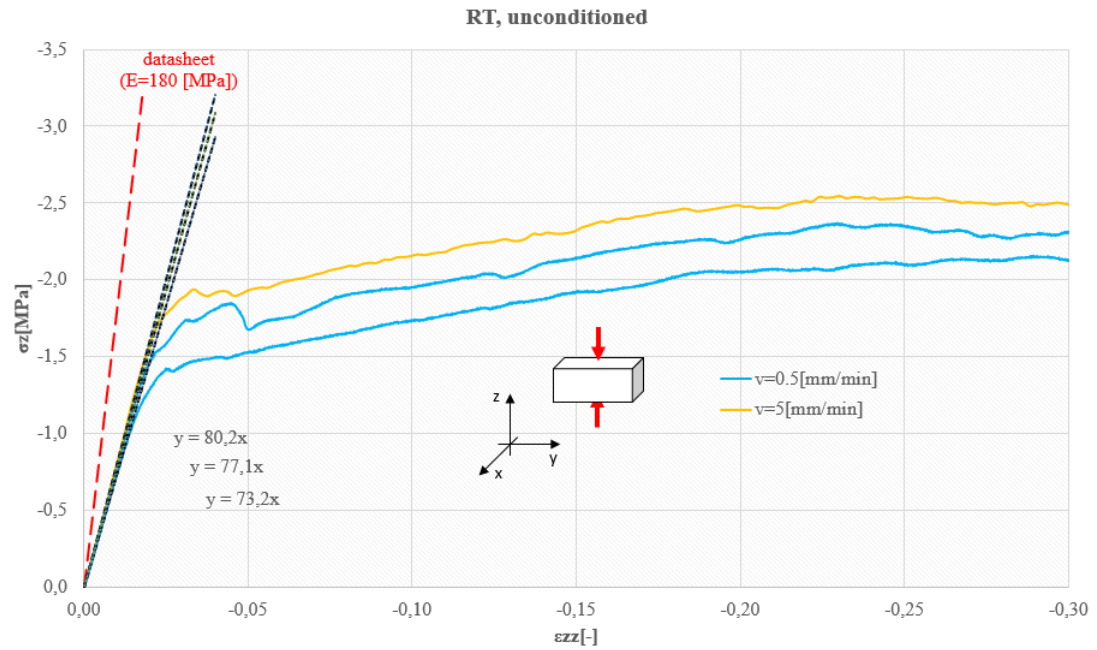


Figure 4.14: Stress-strain curves overview.

The values of compressive modulus and compressive strength are therefore reported (Fig.4.15), and here too, they are compared with the values listed in the material's datasheet.

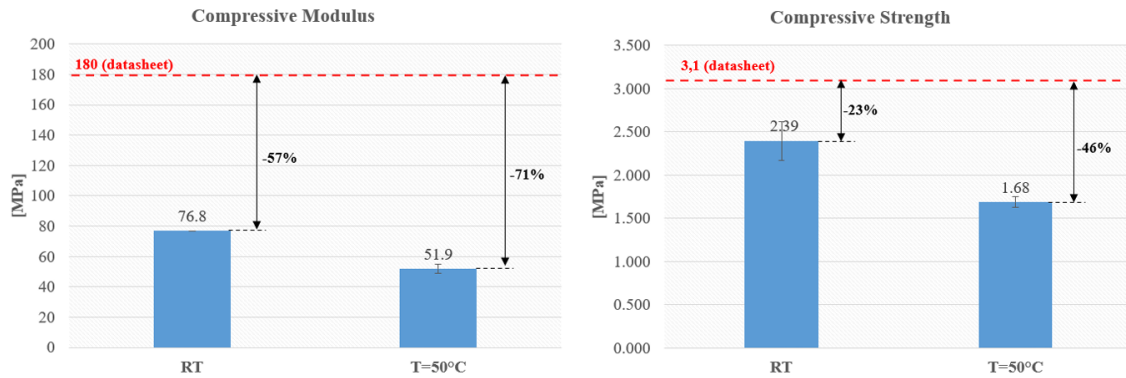


Figure 4.15: Compressive properties overview.

4.4.3 Investigation

The performance obtained, both in terms of compressive modulus and compressive strength, is noticeably lower than what is stated in the datasheet. Once again, it becomes necessary to verify the accuracy of the measurements made using DIC by conducting tests with LVDTs (Linear Variable Differential Transformers, see Appendix B) this time. This approach aims to compare DIC and LVDTs to identify any discrepancies in the recorded values.

First of all, the results of an initial test using the LVDTs measurement technique are compared with those obtained from the testing machine, to ensure that the setup is correctly installed and configured (Fig.4.16). The results obtained using LVDTs are perfectly comparable to those previously obtained with DIC, confirming the accuracy of the measurements.

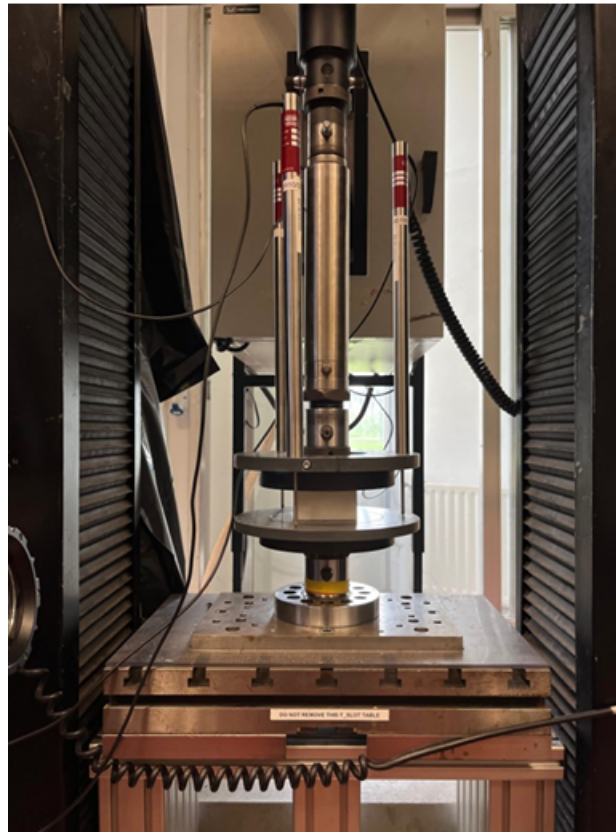


Figure 4.16: Measurement setup with LVDT's.

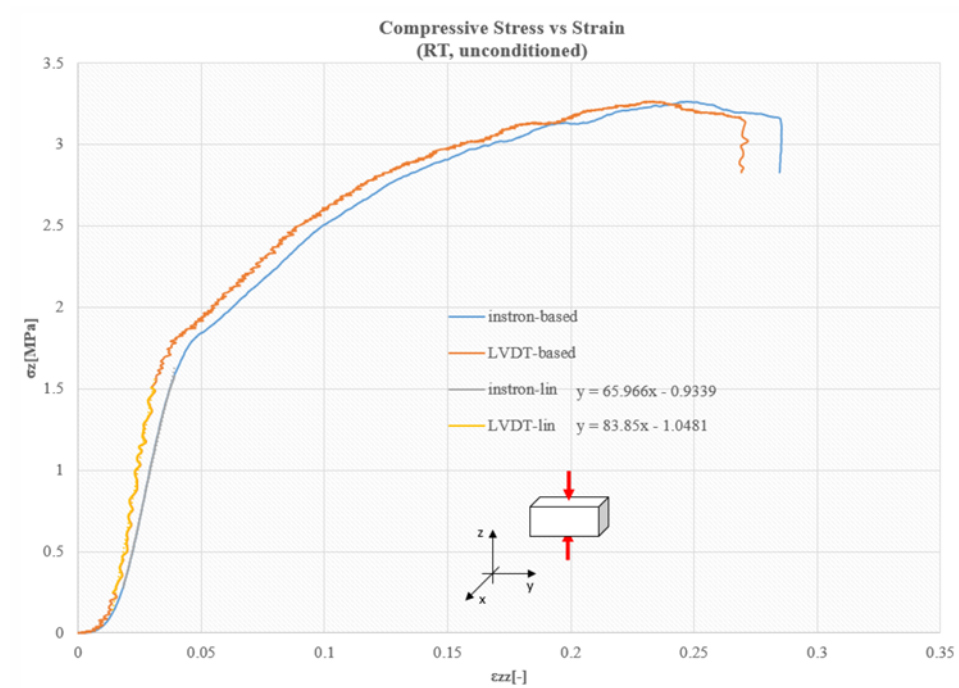


Figure 4.17: Comparison between LVDT's data and Instron Machine data.

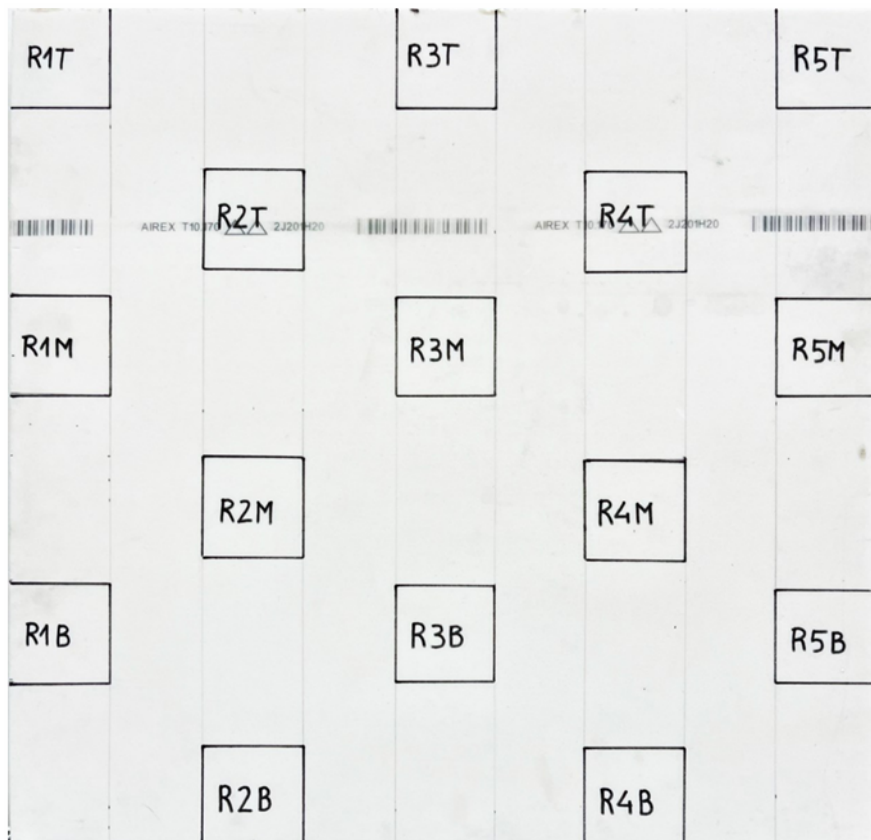
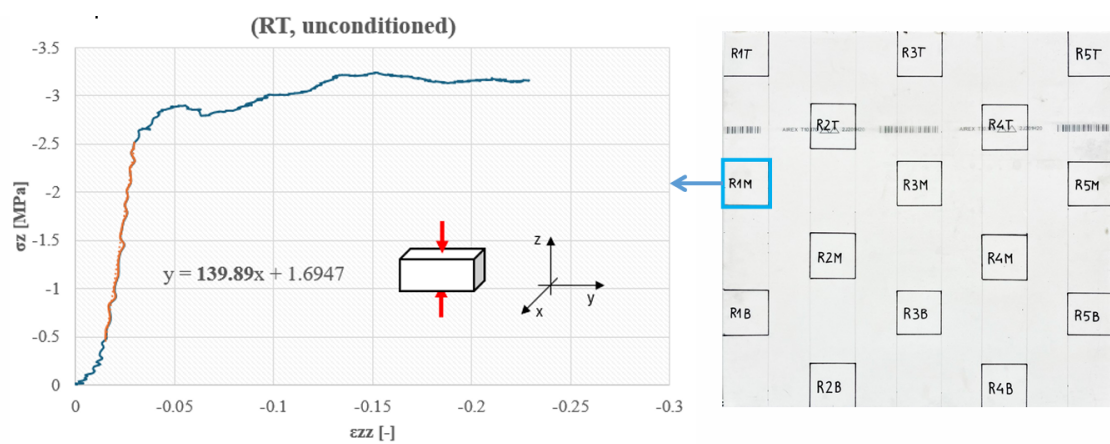


Figure 4.18: Specimens Mapping over the whole panel's area



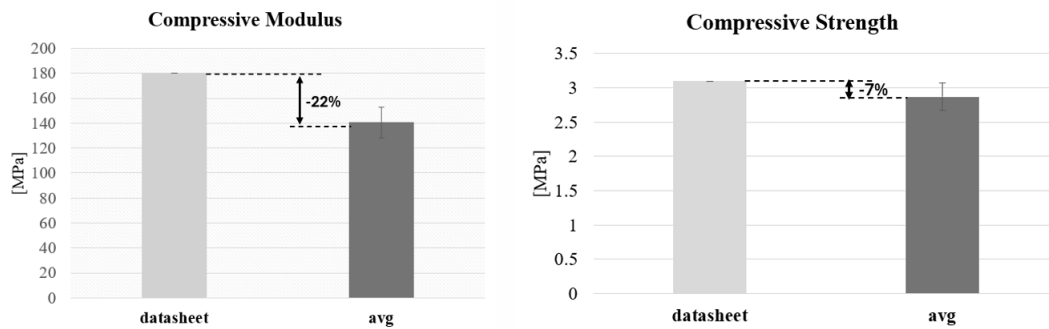
Therefore, a new investigative approach is required to explain the discrepancy between the experimental results and the datasheet values. The proposed strategy involves an intensive testing campaign using an entire panel of PET foam from which a series of 15 specimens will be derived, mapping their positions (Fig.4.18) to explore a potential topological correlation. This aims to link the performance of the material to the absolute position of the sample, hypothesizing a possible inhomogeneity in the foam's properties depending on the area from which the specimen is taken. The tests were conducted at room temperature, at a test speed of 10 mm/min (to speed up the procedure) and using LVDT's as displacement's measurement method. Every specimen is also accurately measured and weighed, allowing for the calculation of its density.



Figure 4.19: Results Mapping over the panel

The findings reveal that there is indeed a dependency between the elastic modulus and the specimen's extraction position. However, this dependency is not related to variations in foam density within the panel, as might be hypothesized. For completeness, a comprehensive comparison between the datasheet and the average values of the experimental results is provided, where a lower but considerable discrepancy between the two is clearly

confirmed.



4.5 Impact of Material Quality

To provide a comprehensive overview of the situation, the results obtained so far for the materials constituting the sandwich panel are reported (Fig.4.20). In particular, the variation in performance compared to the values declared in the datasheets of the individual materials is shown, both at room temperature and at $T=50^{\circ}\text{C}$. This approach further highlights the impact of manufacturing quality on the materials' performance and logically suggests that this quality will also reflect on the bending performance of the entire panel. It should be noted, however, that while the presence of voids in the composite matrix directly and indisputably affects its overall mechanical response, the initial results concerning the PET foam are as alarming as they are not truly representative of the foam's response. This is confirmed by the series of results obtained through the investigative campaign on the same material, which showed average performances higher than the initial tests. However, this does not diminish the still poor reliability of the PET foam, as its performance is strongly dependent on the position from which each specimen is taken from the entire panel.

To conclude, the effect of temperature, which was initially the main focus of the investigative campaign, has proven to be present but not predominant. Instead, the impact of manufacturing quality is far more evident and will undoubtedly take center stage in the results of the bending tests on the sandwich panel, to an extent that will be interesting to evaluate in the next step of the characterization currently underway. The focus of the

2/2 TWILL GLASS FIBER REINFORCED PA6						
		EXPERIMENTAL RESULTS		DATASHEET VALUES	PERFORMANCE VARIATION	
		RT	T=50°C	RT	RT	T=50°C
TENSILE STRENGTH [MPa]	t=2mm	317	289	468	-33%	-38%
	t=3mm	414	351	468	-12%	-25%
TENSILE MODULUS [GPa]	t=2mm	14,8	13,9	21,4	-31%	-35%
	t=3mm	17,9	17,1	21,4	-17%	-20%
SHEAR MODULUS [GPa]	t=2mm	0,67	0,54	2,26	-70%	-76%
	t=3mm	1,84	0,9	2,26	-19%	-60%

AIREX T10.170 PET FOAM						
		EXPERIMENTAL RESULTS		DATASHEET VALUES	PERFORMANCE VARIATION	
		RT	T=50°C	RT	RT	T=50°C
COMPRESSIVE STRENGTH [MPa]		2,4	1,7	3,1	-23%	-46%
COMPRESSIVE MODULUS [MPa]		76,8	51,9	180	-57%	-71%

Figure 4.20: Panel's constituent results overview

experimental campaign, aimed at understanding the causes of the issues encountered by the company during true scale testing, is inevitably shifting away from the thermoplastic nature of the materials used toward the quality of their manufacturing. This observation will be revisited in the concluding parts of this research work.

Chapter 5

Mechanical Characterization of the Thermoplastic Sandwich Panel

5.1 Flexural Testing at Ambient and Elevated Temperature

5.1.1 Specimen and Test summary

Reference standard:

- ASTM C393, ASTM D7250.

Specimen geometry:

- Rectangular, 300x100 [mm], t=46 [mm].

Specimen Preparation:

1. Cutting of specimens with a circular saw;
2. Surface polishing with a manual polisher (Fig.5.1), to get a smooth finishing;
3. Application of white paint on the target surface, using spray can;
4. Application of the speckle pattern, using spray can;

Test setup:

- 5800 Electromechanical Instron, 100 kN load cell;
- Instron Enviromental Chamber.
- Bending setup (supports, steel bars), steel rods, clamping rings and pins.

Measurement Setup (DIC):

- AVT cameras;
- VicSnap Triggerbox;
- Acquisition PC;
- Cambo UST studio stand (tripod);
- Hedler Profilux 1000 (additional light).

Speed of test:

- 5 [mm/min], according to ASTM C393.

Number of valid tests:

- Room Temperature: three tests.
- $T=50^{\circ}\text{C}$: three tests.

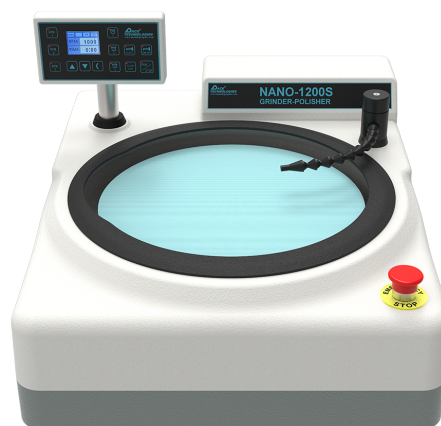
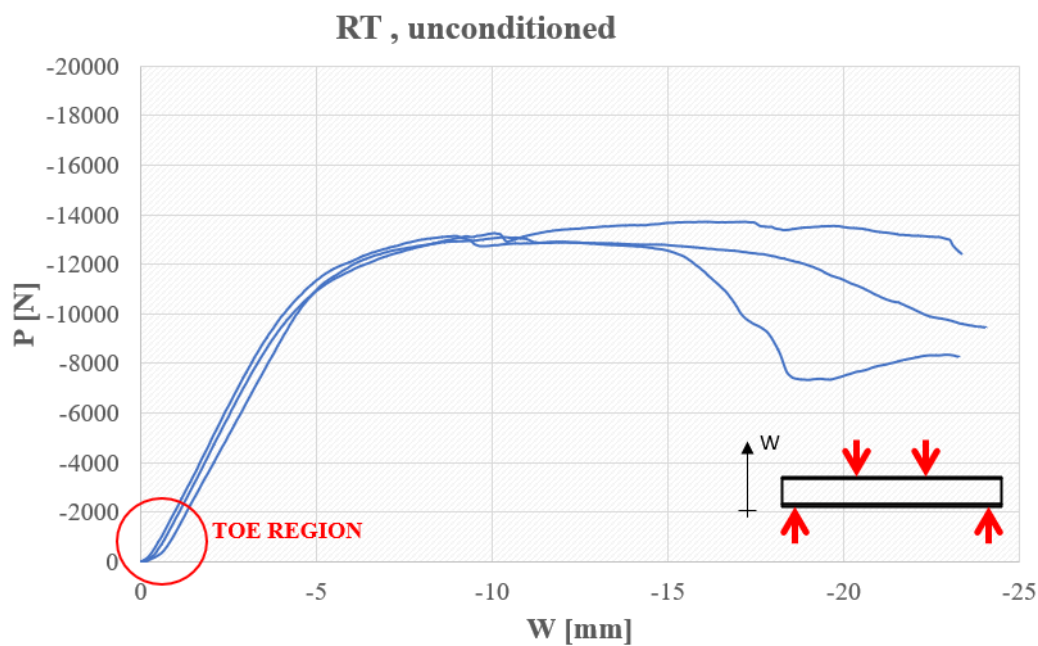
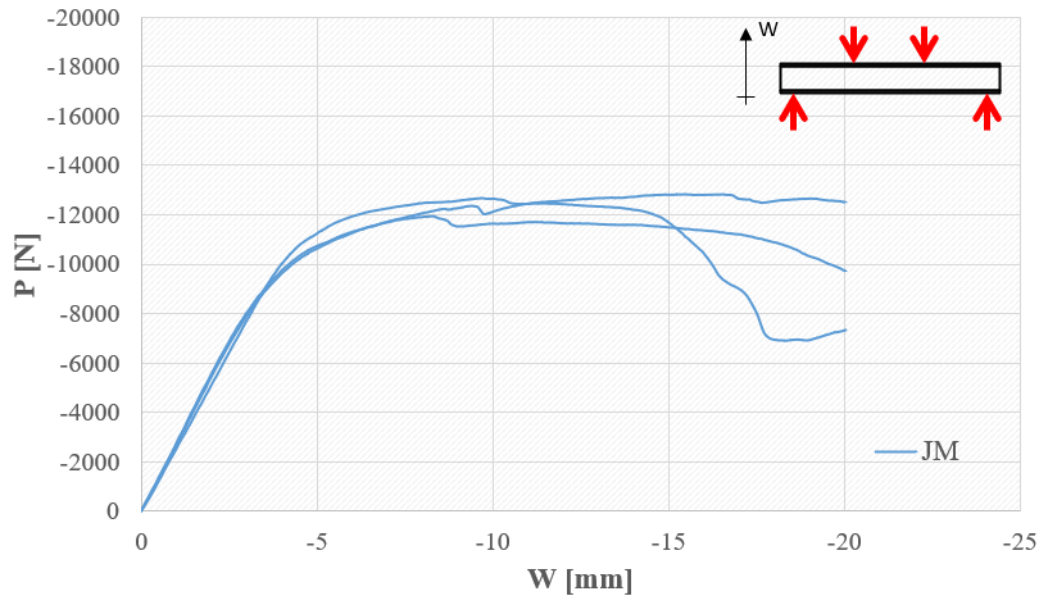
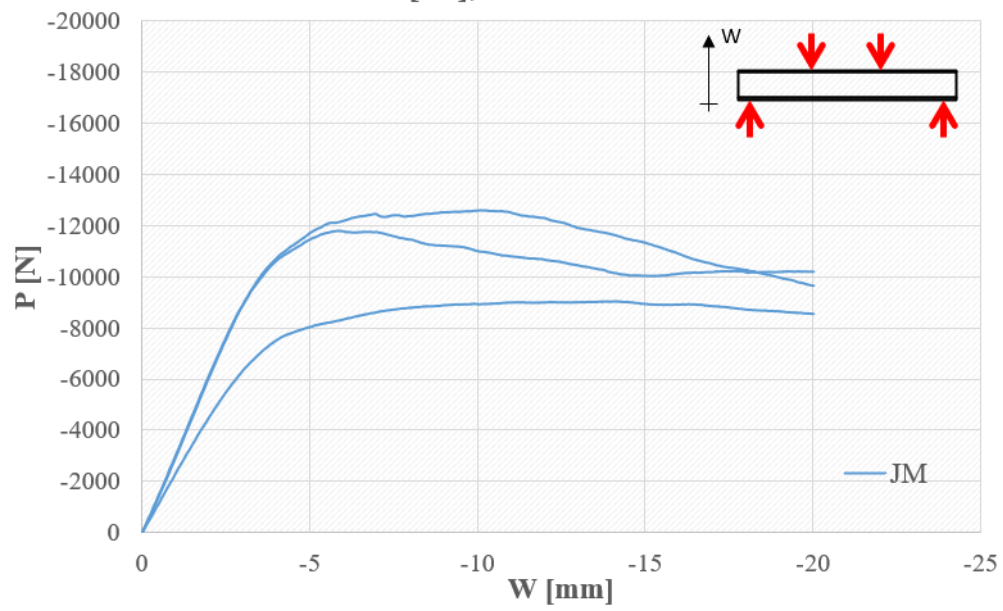


Figure 5.1: Manual polisher.

5.1.2 Results

The four-point bending tests on the sandwich panel, performed in accordance with ASTM C393, provide crucial insights into the panel's flexural behavior. This standard specifically addresses how sandwich constructions react to bending forces, focusing on determining the flexural response. The results from these tests are instrumental in assessing the structural integrity and load-bearing capabilities of the panel. These findings are vital for the panel's application in environments where bending stresses are predominant. The comprehensive analysis from the four-point bending tests not only enhances our understanding of the material's mechanical properties but also its performance under practical operating conditions. This chapter will present the detailed outcomes of these bending tests, illustrating the panel's behavior under flexural loads and the intrinsic properties that dictate its performance.



RT, unconditioned**T=50 [°C], unconditioned**

In a typical force-displacement curve, the initial toe region (Fig.5.1.2) does not reflect the material's intrinsic properties but results from slack take-up and specimen alignment. To ensure accurate slope measurements, this artifact must be adjusted to establish the true zero point on the displacement axis. For sandwich materials demonstrating linear behavior, extending the linear portion of the curve back to the zero-force axis identifies the corrected zero displacement point. All subsequent displacements should be measured from this adjusted starting point.

The flexural stiffness is then calculated using the formula provided in the ASTM standard

$$D = \frac{E(d^3 - c^3)b}{12} \quad (5.1)$$

where:

- E is the facing modulus, measured in MPa;
- c is the core thickness, $c = d - 2t$, measured in mm;
- d is the total thickness of the panel;
- t is the thickness of the facing;
- b is the width of the panel.

These tests indicate a notable similarity in the material's response under both temperature conditions, suggesting that the composite is largely stable across a moderate temperature range. Analyzing the force-displacement curves across the different environmental conditions, it becomes evident that the panel maintains similar flexural stiffness and strength at room temperature and 50°C. This similarity underscores the effectiveness of the fiber-dominated structure of the composite, which helps maintain mechanical integrity despite thermal stresses. However, a significant dispersion in the results was noted, indicating variability in performance even under identical testing conditions. This suggests that while the composite structure is designed to perform consistently, factors such as variations in manufacturing quality or material inhomogeneities may influence the specific outcomes of individual tests.

These observations are critical for understanding the operational reliability of the panel,

even in applications where environmental temperatures can vary. The minimal impact of temperature change on the mechanical properties provides a positive indication of the material's robustness; despite this, the wide variability in the results obtained confirms the impact of the not entirely sufficient quality of the composite, which does not allow ensuring the overall reliability of the sandwich panel as a whole.

5.1.3 Failure Modes and Mechanisms

The high variability in the flexural response of the panel is also visibly confirmed by the different failure modes observed in various tests. The failure modes observed (Fig.5.2)

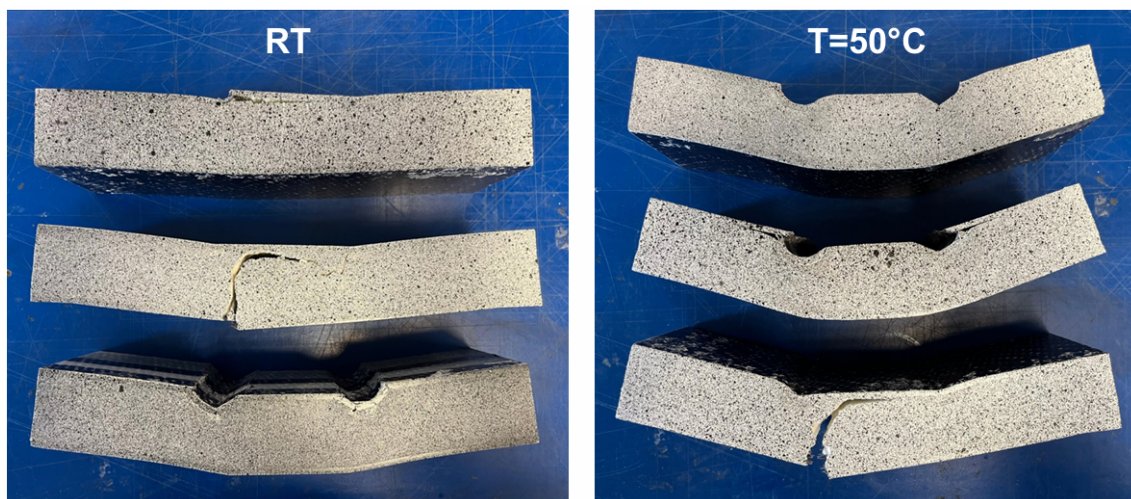


Figure 5.2: Different failure modes, both at room and elevated temperature.

are as follows:

- Face failure, where the compressive composite skin is the first to give way. This typically occurs when the outer layer of the composite, subjected to the maximum compressive stress, reaches its strength limit before the core or the opposite face skin;
- Core failure, where the shear failure of the PET foam is evident. This type of failure happens when the shear stresses within the core material exceed its shear strength, leading to a sliding failure along the planes parallel to the loading direction;
- Wrinkling and indentation, noted by the rippling and buckling of the core precisely at the points where the steel bars transfer the load to the specimen. Wrinkling

occurs when the face sheets crumple due to compression or buckling instabilities, and indentation is observed when localized pressure from the loading bars causes the core material to collapse or dent inward.

Under the same environmental conditions, the panel does not break in a uniform manner; instead, it fails in ways that likely depend on the local properties of the materials constituting the panel where the specimen is derived. Even in the failure modes, temperature does not have a significant influence (as was already evident from the force-displacement curves): in both scenarios, the failure behavior demonstrates randomness and is essentially unaffected by temperature changes. Thus, the flexural response varies both topologically and statistically, with the latter consideration including the presence of voids in the composite matrix.

5.2 Results of Weightsaver Sheets Panels manufactured with GFR PA6 from a second supplier

Given the rather alarming results obtained in the early stages of characterization, particularly from the tensile tests on the composite skins of the sandwich panel, the company involved in this research has started to explore the possibility of replacing the organosheets with a material from a different supplier. This move aims to definitively verify if the 2x2 twill GFR PA6 was indeed the main cause of the unexpectedly poor (negative) results from the true scale tests of the panel, which was being tested as the floor of a container being studied by the company itself. It should be noted that these true scale tests were the initial spark for the entire research effort, aimed at identifying the causes and solutions to the problem, and managing to revalidate the idea and feasibility of a line of lightweight, environmentally sustainable containers.

5.2.1 Material description

The material designated to replace the current organosheet is a composite that uses the same Glass Fibre for reinforcement and PA6 for the matrix, but with a different architecture, and thus inevitably a different production process involving a consolidation phase

for the plate. The new material is designated as W8SVR® Woven PA6-GF - the acronym stands for Weight Saver - and features a reinforcement content of 60% by mass and a weave style corresponding to an unconventional plain weave (Fig.5.3), where the fiber bundles, and thus the yarns, are particularly wide and thin in this configuration (they call this configuration "spread-tow"). This setup allows for a higher fiber content in the composite compared to the organosheet. W8SVR Woven is indeed a consolidated composite

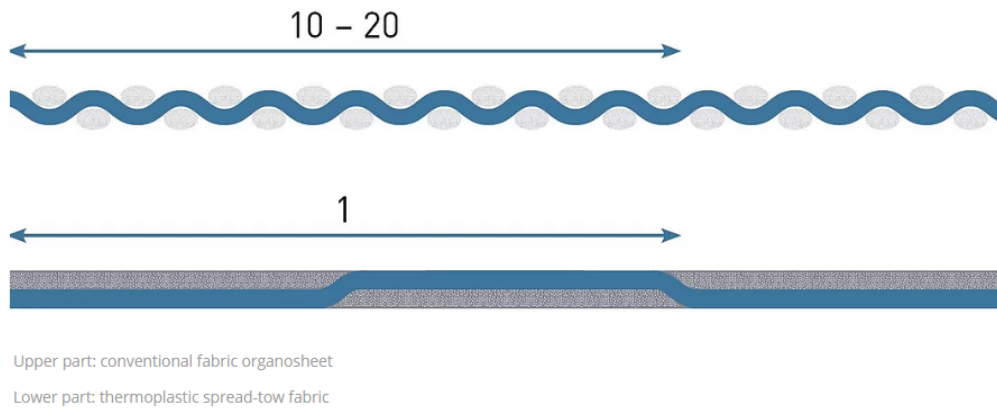


Figure 5.3: Comparison between a conventional organosheet and a spread-tow fabric

material made from thermoplastic UD-Tape fabric, which offers a significant advancement over traditional organosheets. As described in W8SVR website [24], its straight, twist-free fiber orientation and full fiber impregnation maximize load transmission, making it ideal for function-integrated components. The fabric's low crimp and flexible weave types enhance its drape properties, reducing wrinkling and fiber distortion in complex geometries. W8SVR Woven is aesthetically appealing and available in various widths and laminate thicknesses, suitable for efficient serial production due to its extremely high heating rates. The material features a plain weave with a density of 1.7 g/cm^3 and a thickness per layer of 0.5 mm. It has impressive mechanical properties with a tensile modulus of 18.5 GPa and strength of 350 MPa, alongside a flexural modulus of 21 GPa and strength of 505 MPa. Therefore, the material presents itself differently compared to the organosheet previously analyzed, as visible in Fig. 5.4. The company, having identified a suitable replacement for the existing skins, quickly supplied a new sandwich panel. This panel retains the same PET core but incorporates skins made from the new Weight Saver panel, allowing for the finalization of characterization with a successful new solution for con-

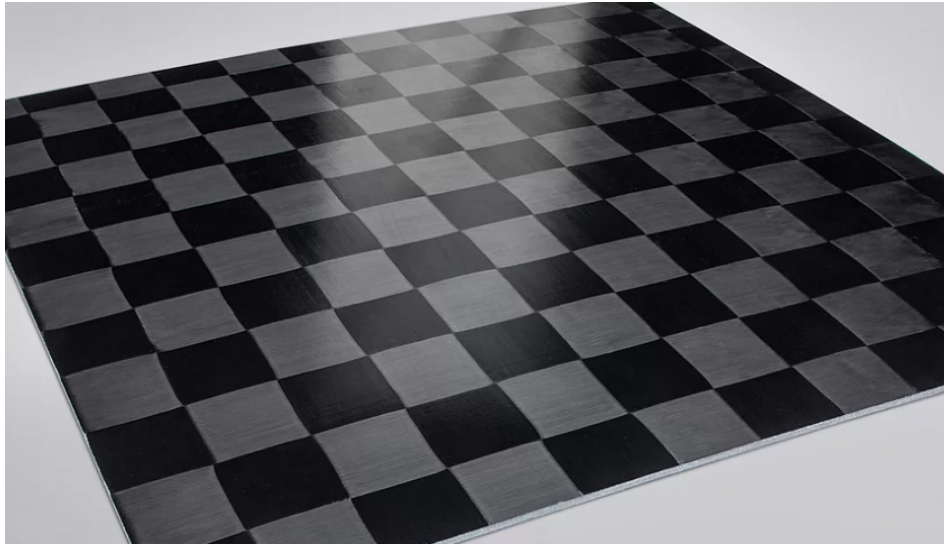
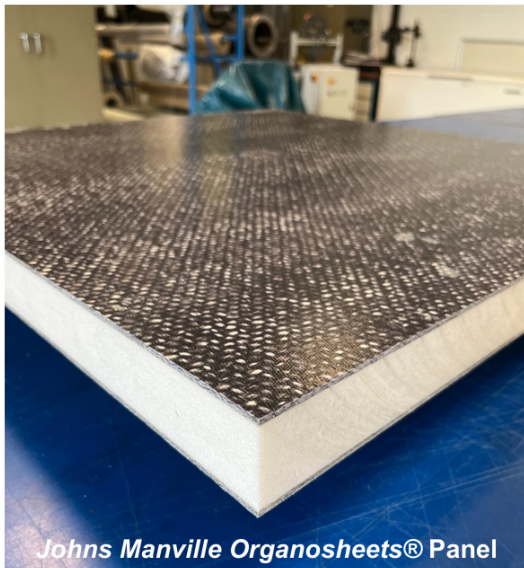
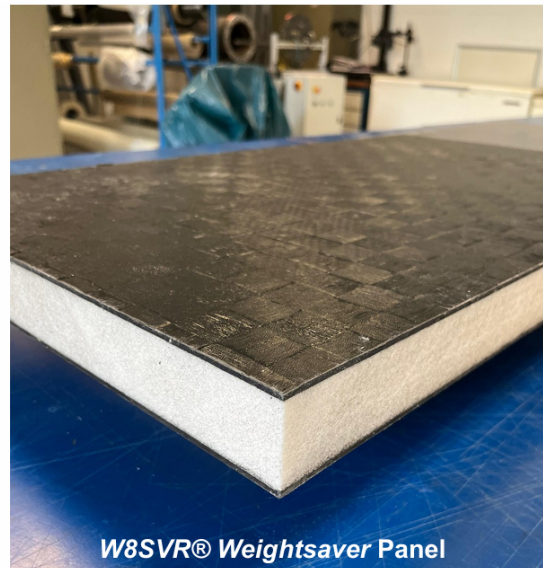


Figure 5.4: W8SVR Woven.



Johns Manville Organosheets® Panel



W8SVR® Weightsaver Panel

Figure 5.5: Comparison between the two panels analyzed.

tainers. The image provided (Fig.5.5) offers a visual comparison between the "old" and "new" panels.

5.2.2 Results

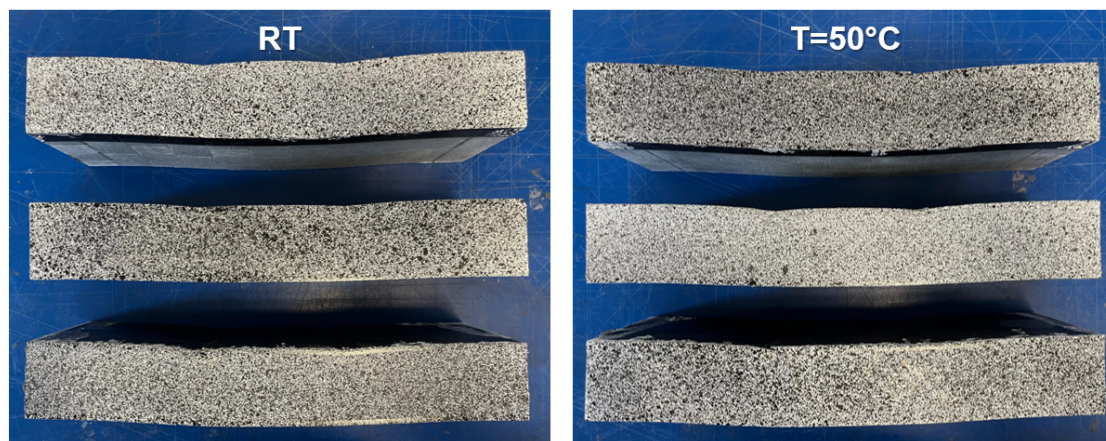
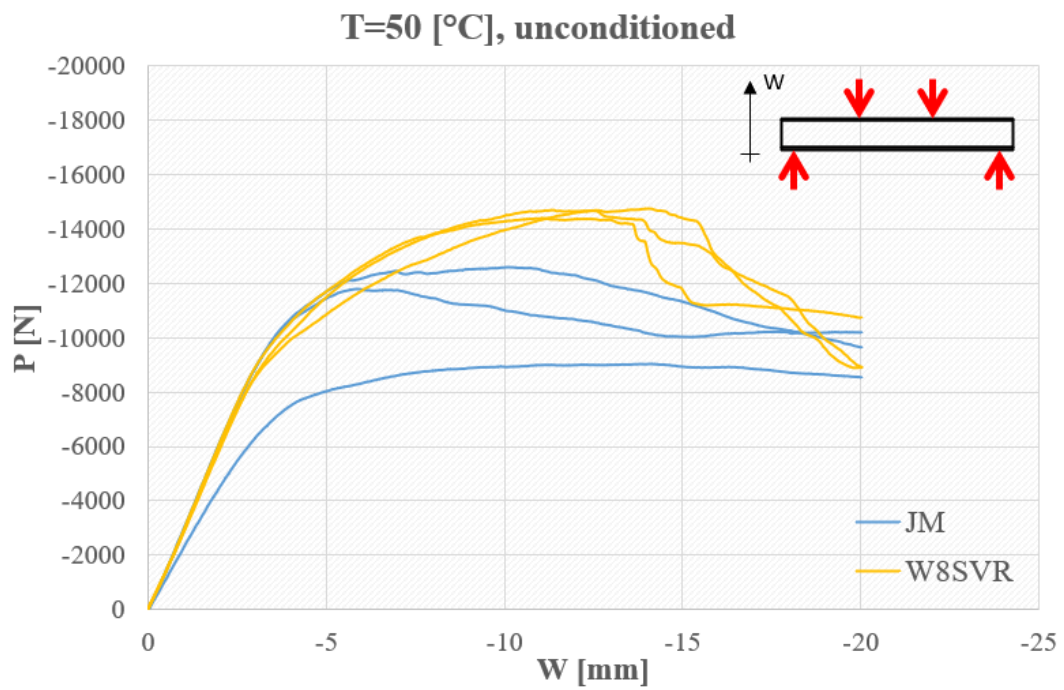
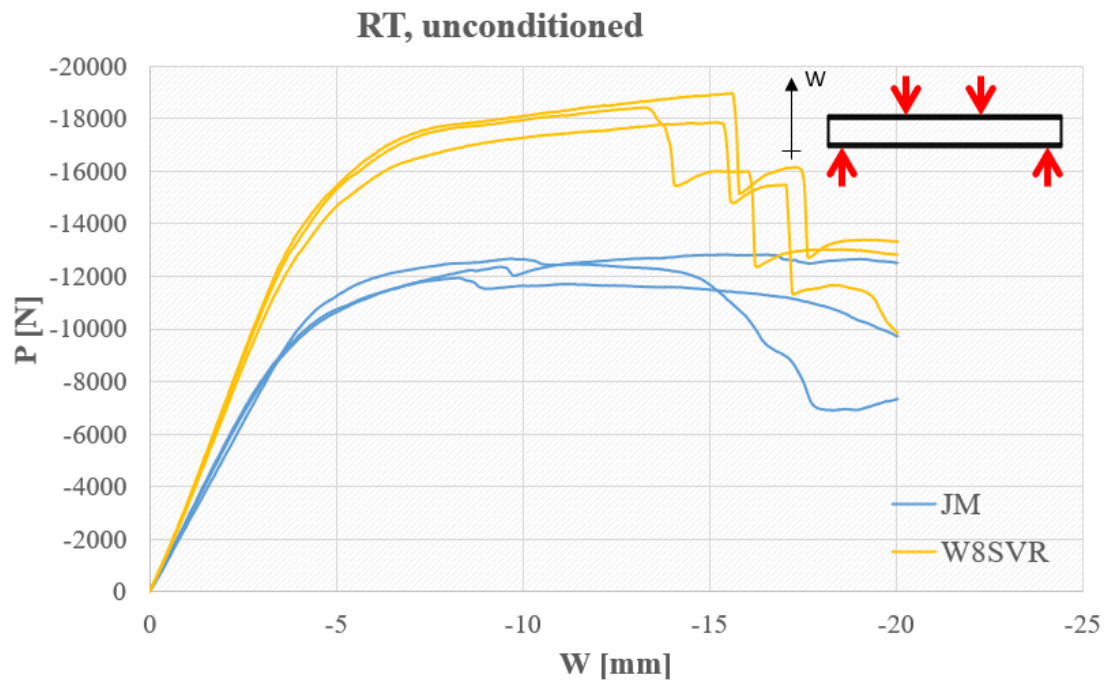


Figure 5.6: W8SVR failure modes, both at room and elevated temperature.

From the broken specimens, it is observed that failure occurs solely through compressive breaking of the skins, indicating that the material's response is much less influenced by statistical variation, suggesting greater reliability. Additionally, the impact on the specimens is less catastrophic compared to the sandwich panel with organosheet skins, showing notably less plastic deformation of the components. This demonstrates that the flexural behavior of the W8SVR panel is strongly influenced by the more performant skins, a point that is further underscored by the force-deflection curves to be discussed next. The force-deflection curves for the new sandwich panel are presented alongside those previously obtained to enable a direct comparison between the two. The loading configuration, as outlined by ASTM C393, remains unchanged (4-point bending, third point loading). This allows for a consistent evaluation of the panel's performance under the same test conditions.

The test results from the four-point bending tests firstly underscore the differing responses of the Johns Manville Organosheets® and W8SVR® Weightsaver panels to temperature changes. The W8SVR panel is notably more sensitive to temperature than the JM organosheet panel. However, at room temperature, the W8SVR panel outperforms the JM panel, exhibiting higher flexural stiffness and load-bearing capacity. This enhanced



performance is attributed to an optimized woven architecture and superior manufacturing quality of the W8SVR panel, which compensates for its temperature sensitivity. These findings highlight again the critical role of material quality and selection in the performance of sandwich panels.

Chapter 6

Analytical Model for Flexural Behavior

Of the two approaches discussed in Chapter 2 on literature research, the second approach titled "Alternative Theoretical Evaluation of the Flexural Response: Allen-Gibson-Timoshenko" is chosen. This method is selected for its direct relevance and representativeness of the flexural analysis conducted thus far, particularly in terms of the loading configuration used. Starting with the properties of the sandwich panel's constituents, the theoretical procedure for estimating the panel's flexural behaviour is presented.

6.1 Validation of Analytical Model with Experimental Results

6.1.1 Summary of the material properties used in the analysis

- Skin Material:

Property	Value
Tensile Modulus E_{st} [MPa]	17900
Compressive Modulus E_{sc} [MPa]	10200
Tensile Strength σ_{st} [MPa]	414
Compressive Strength σ_{sc} [MPa]	236
Shear Modulus G_s [MPa]	1800

Table 6.1: Skin Material Properties

- Core Material:

Property	Value
Compressive Modulus E_c [MPa]	141
Shear Modulus G_c [MPa]	43
Compressive Strength σ_{cc} [MPa]	2.8
Shear Strength τ_{zx} [MPa]	2

Table 6.2: Core Material Properties

- Sandwich Panel Properties:

Property	Value
Flexural Stiffness EI [Nmm^2]	2908760000
Shear Stiffness GA [N]	172000

Table 6.3: Sandwich Panel Flexural Properties

$$EI = \frac{Bt_s^3 E_{sc}}{6} + \frac{Bd^2 t_s E_{sc}}{2} + \frac{Bt_c^3 E_c}{12} \quad (6.1)$$

To determine the flexural stiffness, it is necessary to know the compressive properties of the skins. Lacking experimental data, the approach is as follows: considering the difference between the tensile and compressive strength of the composite (-43%) from the datasheet, a similar reduction is assumed for the compressive modulus. Thus, by reducing the experimental tensile modulus (at room temperature) $E_{st} = 17.9GPa$ by 43%, a compressive modulus of $E_{sc} = 10.2GPa$ is estimated, providing a fairly accurate value for subsequent calculations. Same procedure is used to determine the compressive strength from the experimental tensile strength. A value of $\sigma_{sc} = 236MPa$ is obtained.

Thus, using the formula (6.1) a flexural stiffness value of $EI = 2908760000Nmm^2$ is obtained.

6.1.2 Model Accuracy

The total deflection at the mid-span under four-point bending, considering both bending and shear contributions, is:

$$\Delta_{total} = \frac{23PL^3}{1296EI} + \frac{PL}{6GA} \quad (6.2)$$

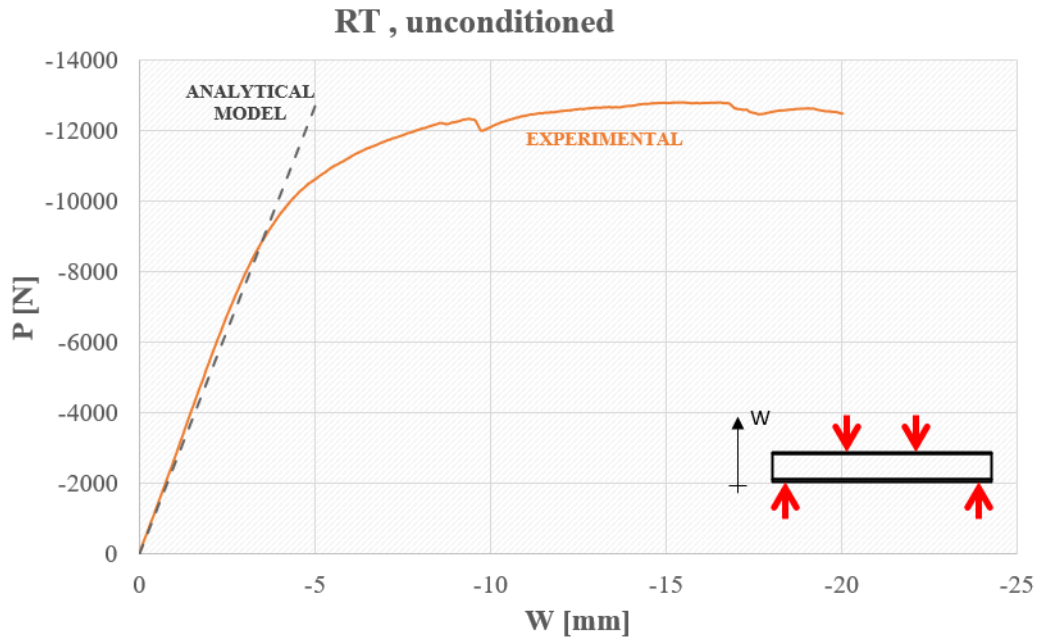


Figure 6.1: Comparison between experimental results and analytical model.

The GA is estimated as $GA = G_c t_c B \approx 172000N$. This equation is used to display the theoretical force-deflection curve and compare it with the experimental one.

The theoretical analysis aligned quite well with the experimental curve's initial slope (the discrepancy can be attributed to the fact that not all material property values are derived from experimental tests; those not available were estimated, which can affect the final accuracy of the model). As the applied load increased toward failure, a substantial divergence between the experimental and theoretical responses is noted. This discrepancy is attributed to the assumption of linear elastic behavior in the constituent materials, which does not accurately reflect their actual responses, with complex interactions and material non-linearities at higher loads.

6.1.3 Failure Mode Selection

Considering the failure modes observed in the experimental four-point bending tests of the panel, two distinct scenarios are taken into account:

- Compressive or tensile failure of the skins in sandwich panels occurs when axial stress exceeds the material's maximum strength. It's noted that the skins typically have higher tensile than compressive strength, leading to an expectation that failure

often results from compressive failure of the top skin. Classical sandwich panel theory, akin to Euler-Bernoulli beam theory, assumes linear variation of axial strain across the beam's cross-section, allowing prediction of peak strength under four-point bending:

$$F_s = \frac{12EI\sigma_{sc}}{LE_{sc}D} \quad (6.3)$$

A peak force $F_s \approx 70227N$ is obtained, which is very high compared to the experimental value. The result obtained by assuming compressive failure of the skins as the failure mode turned out to be imprecise, significantly overestimating the failure load.

- Shear failure in composite sandwich panels typically arises when the shear strength of the core material is exceeded. This failure usually occurs along the neutral axis, which lies between the top and bottom surfaces of the panel. This condition leads to a peak load, which can be determined through a specific calculation:

$$F_{cs} = \frac{2\tau_{zx}GI}{\left(\frac{G_{sc}t_s d}{2} + \frac{G_c t_c^2}{8}\right)} \quad (6.4)$$

The GI term is calculated with the same relation of the flexural stiffness, using shear moduli instead of compressive moduli. A value of $GI \approx 522973333Nmm^2$ is achieved.

A peak shear strength $F_c \approx 16775N$ is obtained. This value is significantly closer to the experimental results compared to previous estimates, which considered the rupture of the composite skins. This indicates that shear failure is the primary mode of failure that actually characterizes the behavior of the panel in question.

The occurrence of skin failure in some tests is likely due to the tests being extended too long, beyond the initial failure, which probably occurred in the core of the sandwich panel. After this initial core failure, the skins lacked the support of the intact PET foam. This compromised the structural integrity locally, leading to excessive deformation and eventual rupture of the thin skins. While this rupture is noticeable, it is not the failure mode that compromises the panel's functionality, which had already occurred.

Chapter 7

Conclusions and Future Work

7.1 Summary of Key Findings

This thesis has provided an in-depth analysis of the performance characteristics of sandwich panels under various environmental conditions, focusing on the influence of temperature and manufacturing quality. Extensive testing and comparison of materials have illuminated key areas affecting the structural integrity and utility of sandwich panels in industrial applications.

- **Temperature Effects on Materials:** This thesis provides a comprehensive analysis of how temperature variations impact the mechanical properties of thermoplastic sandwich panels, particularly focusing on Glass Fiber Reinforced Polyamide 6 (GFR PA6) and PET foam. It explores the temperature responsiveness in different configurations—fiber-dominated and matrix-dominated for GFR PA6, while also critically assessing the thermal behavior of PET foam.

The response of GFR PA6 to temperature greatly depends on its configuration. In setups where glass fibers primarily determine the mechanical properties (fiber-dominated), the material maintains relatively consistent performance across temperatures due to the inherent thermal resistance of the fibers. However, in scenarios where the polyamide 6 matrix significantly contributes to the properties (matrix-dominated behaviour), there is a noticeable reduction in mechanical strength with increasing temperature. This reduction is due to the thermal softening of the PA6

matrix, which compromises its load-bearing capacity, highlighting a critical area of vulnerability in temperature-sensitive applications.

Contrary to earlier assessments of stability, PET foam also exhibits a distinct temperature dependence. Although it should perform consistently under moderate temperature variations, it shows mechanical property degradation when exposed to investigated thermal stresses. This degradation indicates intrinsic material limitations where the foam may soften and provide reduced structural support under prolonged exposure to high temperatures.

The combined insights from the study of GFR PA6 and PET foam underline the need for careful consideration in the design and material selection for sandwich panels used in transport applications. The variable temperature sensitivities between the face materials and the core highlight also potential risks like structural weakening due to differential thermal expansion and contraction.

In conclusion, the findings emphasize the importance of accounting for temperature effects in the design and selection of materials for sandwich panels. They suggest that ensuring all materials (both fiber and matrix components, as well as core materials like PET foam) are appropriately selected and tested for temperature resistance is crucial to developing reliable, durable, and safe transportation solutions. Enhanced manufacturing processes and continuous material innovations are advocated to cater to the specific demands of environments experiencing significant temperature fluctuations, as in the transportation sector. Future research should aim to explore advanced thermoplastic materials and composites that could offer better thermal stability and performance, expanding the application of sandwich panel technologies across various industries.

- **Impact of Manufacturing Quality:** This thesis underscores the substantial role that material quality plays in determining the structural integrity and functional capabilities of thermoplastic sandwich panels utilized in transportation. Throughout the investigative phase, empirical evidence indicated that the manufacturing quality of these materials is critical to their performance under operational stresses.

Mechanical characterizations revealed that the initial composite material supplied

exhibited deficiencies in tensile, compressive, and flexural properties, which were particularly pronounced under varying thermal conditions. These deficiencies were largely attributed to suboptimal manufacturing processes, characterized by uneven fiber distribution and insufficient resin impregnation, leading to increased porosity and diminished mechanical performance.

Subsequent testing of materials sourced from an alternative supplier demonstrated significantly enhanced mechanical properties. This comparison not only validated the hypothesis that manufacturing quality directly influences material performance but also highlighted the potential for material improvements to enhance the overall efficacy of sandwich panels in their intended applications.

The implications of these findings are profound, suggesting that stringent quality control in manufacturing processes is paramount. Enhancing material properties through improved manufacturing techniques could significantly increase the reliability and functionality of sandwich panels, thereby extending their applicability in critical structural components within the transportation sector.

- **Comparative Analysis of Face Materials:** This comparison between the traditional Organosheet and the more recent W8SVR composite primarily focuses on the impact of manufacturing quality and the response of these materials to environmental temperature changes. The analysis reveals that the primary limitation of the Organosheet lies not in its intrinsic material properties but in the consistently low manufacturing quality observed across different batches. This poor quality manifests in uneven distribution of resin and inappropriate composite lay-up and fiber alignment, which collectively degrade the mechanical performance and reliability of the panels. Such manufacturing inconsistencies compromise the structural integrity and longevity of the panels, making them less suitable for structural applications, where uniform performance is critical.

On the other hand, the W8SVR composite demonstrated superior attributes across all tested parameters. Manufactured with advanced control, the W8SVR panels exhibited uniformity in material distribution and quality. This high manufacturing standard translates into enhanced mechanical properties, greater durability, and

more robust performance under environmental stresses. Furthermore, the W8SVR composite distinguishes itself not only through superior manufacturing quality but also through its unique fiber weave architecture, which plays a pivotal role in its enhanced performance characteristics. This advanced material utilizes a specially designed twill weave pattern that optimizes the alignment and distribution of glass fibers within the Polyamide 6 matrix.

The twill weave pattern used in W8SVR is engineered to enhance the mechanical interlocking and load transfer capabilities of the fibers. Unlike traditional plain weave patterns that can exhibit crimping and stress concentrations, the twill weave in W8SVR allows for more uniform distribution of stress across the fabric. This reduces the likelihood of failure points and improves the overall mechanical performance of the panel. The twill pattern also provides increased drapeability and conformability during the manufacturing process, facilitating better adhesion between the fibers and the resin, and resulting in a composite with fewer voids and defects, as mentioned before.

In conclusion, this study advocates for a shift towards using materials like W8SVR that combine high-quality manufacturing processes with advanced material properties. This approach not only ensures enhanced performance and reliability but also aligns with the needs of modern applications that require materials to withstand diverse and challenging environments. The findings support the ongoing evolution of material science in the sandwich panel industry, highlighting the important role of manufacturing excellence in achieving superior material functionality.

7.2 Recommendations for Manufacturing Improvement

Although this thesis does not focus strictly on the manufacturing methods of the tested materials, since these are provided directly by established manufacturers, the clear influence of the production process quality on the performance of the materials themselves prompts some brief considerations on possible interventions that could help improve the quality and repeatability of the manufacturing process. Without delving too deeply into specifics, only a few points are mentioned, which can simply be seen as possible sugges-

tions, being the result of critical issues actually observed "in the field" rather than purely theoretical concerns.

Based on the findings, and not knowing the precise techniques used by the composite supplier, the suggestions offered are as follows:

1. **Controlled Lay-up Procedures:** Precision in the lay-up process can be achieved through automated fiber placement (AFP) or automated tape laying (ATL) systems. These technologies allow for exact control over fiber orientation and placement, which is crucial for maintaining symmetry and order in the lay-up. Automated systems can consistently replicate the desired fiber orientation across production runs, reducing variability and enhancing the structural integrity of the panels.
2. **Vacuum and Pressure Techniques:** Applying vacuum bagging or utilizing autoclaves during the cooling and solidification process helps compress the material layers, forcing out trapped air and volatiles that can create voids. These techniques also promote better consolidation of the composite layers, ensuring that the resin binds effectively with the fibers and reduces the likelihood of delamination or structural weaknesses.
3. **Quality Inspection Using Advanced Imaging:** Non-destructive testing methods, such as computed tomography (CT) scanning, are invaluable for inspecting composite materials during and after production. These techniques allow for a detailed analysis of the internal structure of the composites, identifying inconsistencies like voids or misaligned fibers without damaging the material. Regular inspections help maintain quality standards by ensuring each batch meets specified criteria.
4. **Material Handling and Storage:** Proper management of composite materials before processing is crucial. This includes maintaining controlled environments to avoid moisture absorption or contamination and handling materials with care to prevent any pre-processing damage. These practices ensure that the fibers and resins are in optimal condition before entering the manufacturing process, reducing the risk of introducing defects during fabrication.

7.3 Contributions to Knowledge

This research enhances the field of composite material mechanics by providing a detailed analysis of the mechanical properties of thermoplastic sandwich panels, particularly focusing on GFR PA6 and PET foam. Through rigorous experimental testing and analytical evaluations, this work has explored the substantial impacts of manufacturing quality and environmental temperature on the structural performance of these materials. Moreover, the comparison between traditional organosheets and the newer W8SVR panels under various conditions has contributed novel insights into the potential and limitations of these materials in transportation applications. This research not only bridges a crucial gap in our understanding of thermoplastic composite behavior under varying temperatures but also provides practical insights into how enhanced material quality and textile design can boost performance. This can lead to the development of more reliable materials for structural applications.

7.4 Recommendations for Future Research

Future studies should explore:

- Explore the impact of moisture on the thermoplastic composite, knowing from the literature that glass transition temperature of PA6 is influenced by relative humidity;
- Long-term durability studies under cyclic loading conditions to mimic real-world usage more closely.
- Longitudinal studies on the aging of materials under harsh environmental conditions to predict long-term performance;
- Development of more refined analytical models that incorporate the viscoelastic behavior of thermoplastics.
- The integration of smart sensor technologies within panels to actively monitor health and predict maintenance needs;

- Expansion of the material database to include newly developed composites, providing a broader basis for selecting materials suited to specific application needs.

Appendix A - VRO Calibration

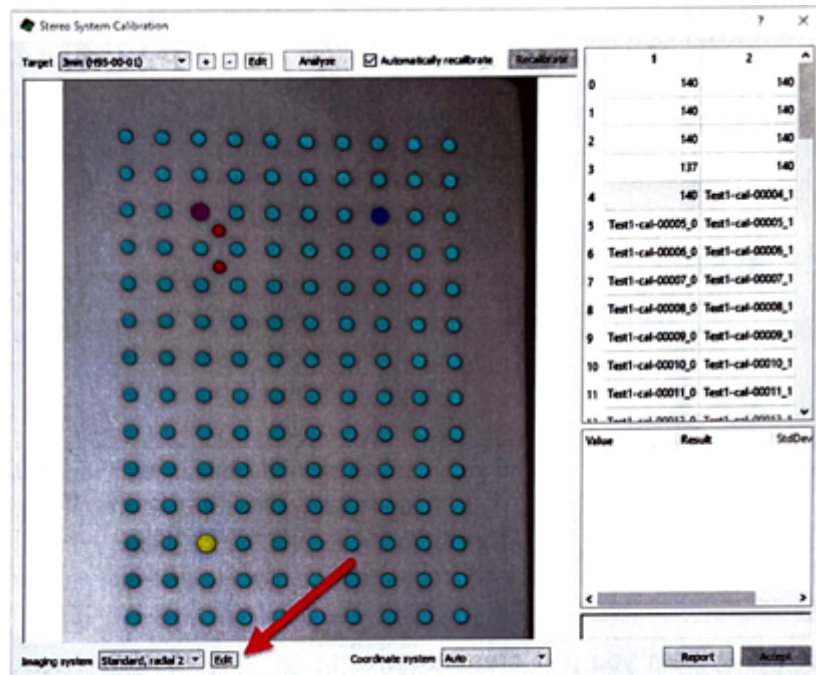
Traditional pinhole calibration models operate under the assumption that light rays follow a direct path from the specimen to a singular, unified camera origin. This assumption can introduce significant inaccuracies when a refractive interface is part of the optical pathway. With the introduction of version 8, Vic 3D has integrated more sophisticated calibration models that allow for each pixel to have its own unique camera origin. These models are known as Variable Ray Origin (VRO) models.

Previous technical documentation from Correlated Solutions suggested that calibration could be performed without a window, followed by an adjustment for the window using an "External Orientation Calibration" (EOC). This method is now considered obsolete with the advent of VRO calibration models. The obsolescence is evident when comparing outcomes from EOC and VRO methods and has been further confirmed by Correlated Solutions through recent communications.

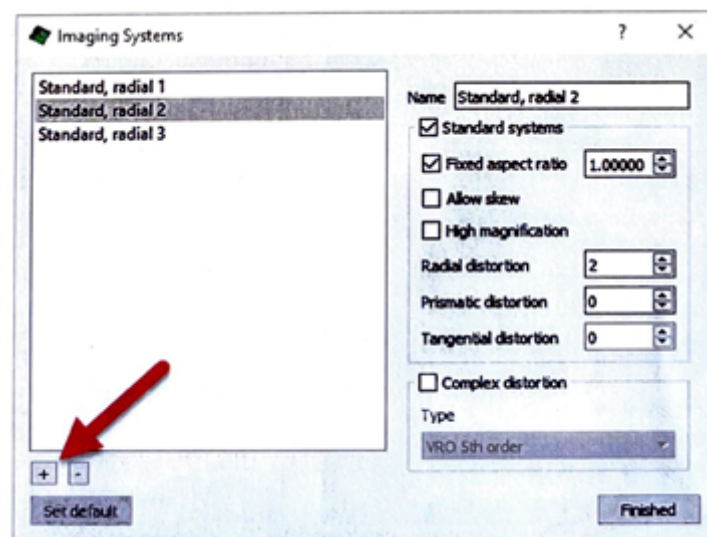
As VRO models are complex and have many parameters, quality and completeness of the set of calibration images are essential to building an accurate model of the volume of interest, even more than with the standard pinhole calibrations.

Calibrating in the software request to follow these instructions:

1. Acquire calibration images with the target in the same location as the test specimen will be. Any windows/liquids/etc. should be present as they will be during the test. Make sure there is no debris or air bubbles on any surface of the calibration target. Be especially careful of reflections that can be reaching the cameras. Acquire at least 30 images pairs with a good range of tilt of the calibration target.
2. Import the calibration image in Vic 3D , and click on the "Calibrate" button;
3. Click "Edit" at the lower left to edit the imaging systems;

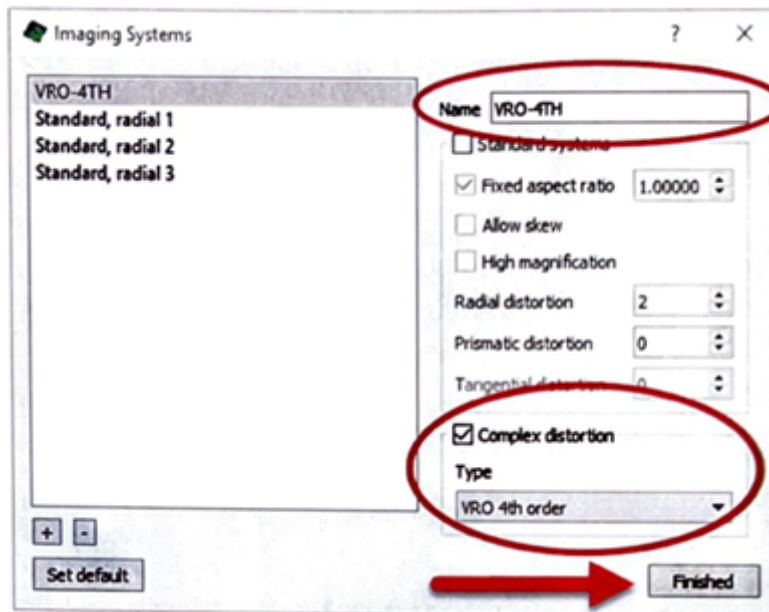


4. Click the "+" to add a new imaging system; Name the new image system, for ex-



ample "VRO-4th". Check the box labelled "Complex Distortion" and select "VRO 4th order". Click "Finished". It is advisable to use the 4th order as much as possible, because fewer variables are required to optimize the model. This model works for most steps. The 5th order may be used if the setup is more complicated, such as viewing through multiple refractive interfaces (e.g. camera-air-glass-water-glass-air-specimen).

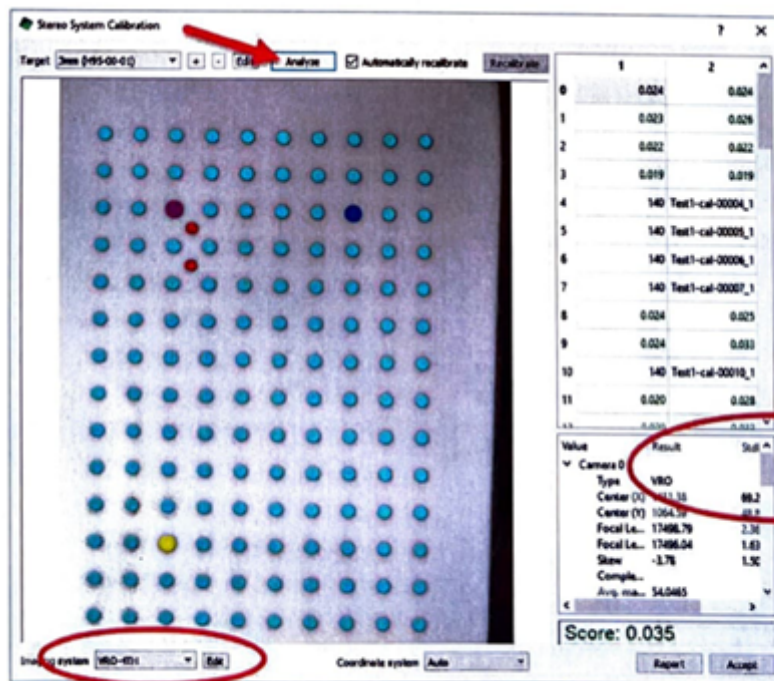
5. Select the system you just created from the imaging system drop-down. Select the



appropriate calibration target in the top left and click "Analyze".

6. With VRO calibration, getting an acceptable calibration score (≤ 0.1) does not guarantee a successful calibration. It is vital to check speckle images (as described in Chapter 3). If you see clear patterns that stay at a fixed location in the image (i.e., do not move with the specimen), these may indicate distortions not captured by the calibration. A certain degree of distortion is unavoidable when viewing through a window (especially if made up of several panels), so use common sense and experience to judge. When it comes to displacements and strains specifically, moreover, you should only see noise, because it is a rigid motion. If you see bands/patterns in the displacement and/or strain field, and especially if you see strain values higher than noise, there is definitely something wrong with the calibration. In that case, all you can do is recalibrate.

If you are unsure about the 3D shape or the contours you are looking at, you can always do a conventional calibration without the glass (don't forget to set the imaging system back to "Standard, radial 2") and take images of a RBM without the glass. This should be way faster and not give any problems. The processed images will be your benchmark to evaluate the VRO images.



Appendix B - Linear Variable Differential Transducer (LVDT)

A Linear Variable Differential Transducer (LVDT) is a widely used passive device in industries for measuring displacement, favored for its simplicity and reliability.

An LVDT comprises a primary coil, two secondary coils, and a movable magnetic core. Both the primary and secondary coils are encased within a barrel, through which a movable magnetic core rod is inserted. The LVDT operates on the principle of mutual induction, involving a primary and two secondary windings. Displacement is detected based on the movement of a core, which alters the mutual inductance between the primary and the secondary windings, directly affecting the output voltage. This voltage variation across the secondary windings, arranged in series opposition, reflects the displacement measured. The core's position relative to the windings is crucial, as it dictates the output voltage and, consequently, the displacement measurement.

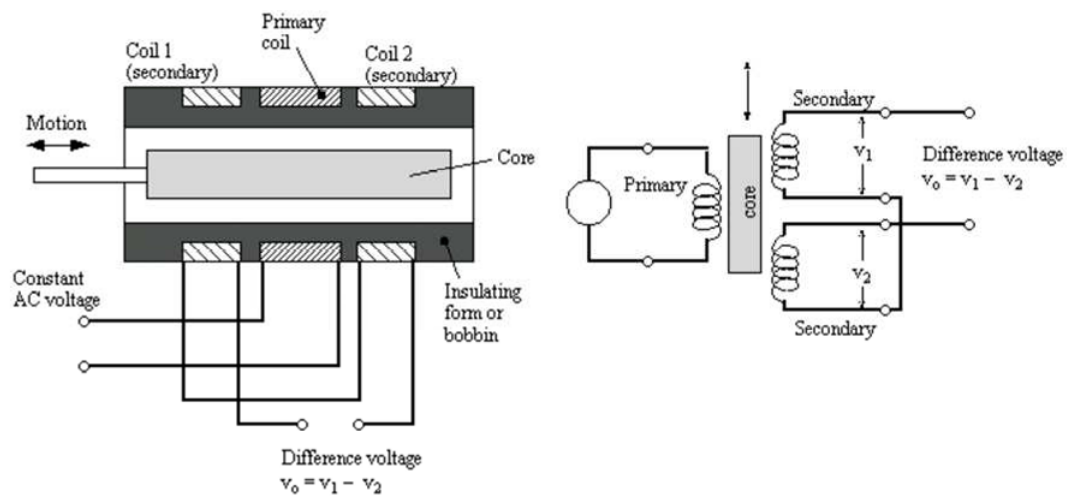


Figure 7.1: Construction of an LVDT and its circuit diagram.

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