Fabrication and Analysis of Nanoparticle-Infused Natural Fibre Honeycomb Core in Sandwich Structures

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Abstract

This study investigates the feasibility of employing natural fibre materials to fabricate honeycomb core structures, addressing concerns over the environmental impact associated with conventional cores composed of aluminium, Nomex, and petroleum-based materials. The research process involves the fabrication of honeycomb cores utilizing a 3D printed moulding technique, followed by the adhesion of these cores to flax and glass fibre facings, thereby augmenting structural durability. Through the incorporation of cellulose and nanoclay as additives to the adhesive, the investigation reveals a substantial enhancement in flexural strength and impact resistance, surpassing the performance of structures bonded solely with epoxy. However, a notable reduction in compressive strength is observed upon the introduction of these additives to the adhesive.

Quantitatively, the study demonstrates that the addition of 3wt% cellulose to the epoxy adhesive results in a remarkable 7.43% increment in flexural strength, a 4.09% increase in yield stress, a 0.17% rise in flexural modulus, a 6.45% enhancement in core shear ultimate strength, a 7.17% increase in facing bending stress, and a 7.94% elevation in absorbed energy. Similarly, the addition of 3wt% nanoclay to the epoxy leads to a significant enhancement, with a 10.48% rise in flexural strength, a 4.09% increase in yield stress, a substantial 20.92% augmentation in flexural modulus, a 10.75% improvement in core shear ultimate strength, a 10.5% increase in facing bending stress, and an elevated absorbed energy by 14.37%. Furthermore, in out-of-plane oriented structures, ultimate compressive strength experiences an increase of 7.32% and 20.1% for cellulose and nanoclay additives, respectively, while compression modulus rises by 6.6% and 29.65%. Nevertheless, it is noteworthy that the structures bonded with nanoclay-filled epoxy exhibit the most favourable overall performance, boasting an ultimate compressive strength of 7.72 MPa and a compression modulus of 7.77 MPa, outperforming their in-plane counterparts due to the larger compressive area of the out-of-plane samples.

In terms of tensile properties, the study establishes that hybrid face sheets display an impressive 33.65% higher ultimate tensile strength compared to plain flax fibre samples. Additionally, the hybrid face sheets manifest a 69.45% increase in tensile strength and a substantial 58.73% enhancement in yield stress and Young's modulus, respectively, in contrast to exclusively flax fibre facings. Moreover, the research indicates that hybrid face sheets lead to significantly reduced moisture absorption, with structures employing solely flax fibre face sheets experiencing a mass increase of 11.88% after 168 hours of exposure, while structures utilizing hybrid face sheets encounter a substantially lower mass increase of 6.31%. This corroborates the effectiveness of hybrid face sheets in enhancing the water resistance properties of the composite.

In summation, the study underscores the potential of natural fibre honeycomb composite structures to perform comparably to traditional honeycomb materials such as Nomex and aluminium, while being constructed from environmentally sustainable materials. The integration of an efficient additive manufacturing process further bolsters the prospects of these structures, enabling customization and scalability for diverse applications across industries, including aerospace, automotive, and marine sectors.

Declaration

I, *Sumeshan Govender*, hereby declare that the work presented in this dissertation/thesis is my own original work and has not been submitted for a degree at any other university. Any sources used in the preparation of this dissertation/thesis have been fully acknowledged and cited in accordance with academic conventions. The only prior publication of any part of this dissertation/thesis was in the form of conference papers and/or journal articles, which are listed in the bibliography section of this document.

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Sumeshan Govender

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1 Introduction

The use of composite materials has been increasing in various structural applications due to their unique combination of properties. However, traditional composite materials such as fiberglass and carbon fibre have a significant impact on the environment and economy. While they offer high strength-to-weight ratios, corrosion resistance, and design flexibility, their production process is energy-intensive, generating greenhouse gas emissions and using toxic chemicals that are harmful to human health and the environment. Additionally, their disposal at the end of their life cycle can release harmful substances and negatively impact the environment. Therefore, researchers and manufacturers are exploring alternative fibres, such as natural fibres like hemp, flax, and bamboo, that are renewable, biodegradable, and recyclable or biodegradable matrix materials, to create more sustainable composite materials.

One such natural fibre is flax, which has low environmental impact and mechanical properties comparable to traditional composite materials. In recent years, researchers have studied flax fibre for use in various applications, such as the automotive, aerospace, and marine industries. A well-known drawback common among natural fibres are their heredity poor properties in the presence of moisture, which limits their application and durability.

Honeycomb core structures, known for their high strength-to-weight ratio and energy absorption, are extensively used in composite materials as a core between outer facings to form sandwich structures which have been adopted in various industries. However, fabrication methods for such cores have limitations, including difficulty in producing complex shapes and sizes which results in a restricted variety of materials used, most commonly; Nomex and aluminium.

To overcome these challenges, the study utilized 3D printing moulds needed to produce honeycomb cores using flax fibres bonded to hybrid flax and glass fibre facings, using a cellulose/nanoclay based adhesive system, resulting in a sustainable alternative material. The resulting structures displayed high levels of strength, durability, and resistance to moisture absorption. These structures could serve as a sustainable and durable alternative in structural applications and provide a basis for further research and development.

1.1 Research Motivation

The motivation of the research was to investigate the potential of flax fibre honeycomb sandwich structures as a sustainable and durable alternative to traditional composite materials in structural applications. The use of flax fibres as the core material and hybrid flax and glass fibres as the face sheets makes the composite structure highly sustainable as it utilizes a renewable resource and reduces the environmental footprint. The use of 3D printing technology in the production process enabled precise control of shape and size, making it suitable for mass customization. The study aimed to investigate the mechanical properties of the composite structures, and to evaluate the potential of flax fibre honeycomb sandwich structures as a sustainable and durable alternative in structural applications.

1.2 Research objectives and scope

The scope of this research is to investigate the potential of flax fibre honeycomb sandwich structures as a sustainable and durable alternative to traditional composite materials in structural applications. The study will focus on the following areas:

- To produce flax fibre honeycomb sandwich structures using hybrid flax and glass face sheets and a flax fibre honeycomb core, with a nanoclay and cellulose-filled adhesive used for bonding. 3D printed moulds will be utilized for precise control of shape and size.

- To evaluate the mechanical properties of the composite structures, including tensile strength, flexural strength, impact resistance, compression, and water absorption and compare the properties of the flax fibre honeycomb sandwich structures with various traditional materials.

- To analyse the properties of the honeycomb structure, such as stiffness and strength.
- To evaluate the potential of flax fibre honeycomb sandwich structures as a sustainable and durable alternative structure.

The research can be used as a foundation for future studies in the field of natural fibre based cellular bio-nanocomposite sandwich structures and the use of 3D printing technology in the fabrication of moulds for cellular structures and composites.

1.3 Research design

The purpose of this study was to investigate the potential use of cellular bio-nanocomposite sandwich structures as a sustainable and durable alternative in various structural applications. The research design for this study was a laboratory-based experimental design using hybridized flax and glass fibre face sheets, a constructed flax fibre core, and a cellulose-nanoclay-filled bio-based adhesive for bonding. The research design consists of the following components:

- Research question: How do the mechanical properties and durability of sandwich structures made with hybridized flax and glass fibre facings, a flax fibre honeycomb core, and cellulose/nanoclay-based adhesives compare to those of traditional sandwich structures?
- Research approach: The research approach was an experimental design, utilizing laboratory-based tests to investigate the mechanical properties of the composite materials.
- Sampling strategy: The sampling strategy used hybridized flax and glass fibre face sheets, a flax fibre core, and a cellulose-nanoclay-filled bio-based adhesive for bonding.

The samples were fabricated using 3D printing technology to control the shape and size of the honeycomb structures.

- Data collection methods: The data collection methods consisted of laboratory-based tests to investigate the mechanical properties of the composite materials, including tensile strength, flexural strength, impact resistance, compression, and water absorption.
- Data analysis methods: The data collected was analysed using statistical analysis to determine the significant differences in mechanical properties and durability of the composite materials.
- Ethical considerations: There are no ethical considerations involved in this research.
- Limitations: One limitation of this study is the potential for the results to be specific to the materials and methods used in this study. Additionally, the study was limited to laboratory-based testing, and further research may be necessary to investigate the performance of the materials in real-world applications.

In conclusion, this research design provides a detailed investigation into the potential use of these structures as a sustainable and durable alternative in various structural applications. The use of hybridized flax and glass fibre face sheets, a flax fibre core, and a cellulose-nanoclay-based adhesive for bonding, along with 3D printing technology to control the shape and size of the honeycomb structures, was the focus of the experimental design. The result of the study provides valuable insights into the mechanical properties and durability of the composite materials, which can be used as a basis for future research and development in various structural applications.

1.3 Outline

The work begins with an introduction that provides background and motivation for the research, as well as outlining the research objectives and scope, and the outline. The literature review covers various aspects of natural fibres, specifically flax fibres, and their properties, as well as honeycomb sandwich structures, flax fibre-reinforced composites and the mechanics of honeycomb sandwich structures. Materials and methods describe the preparation of flax fibres, fabrication of honeycomb core and sandwich panels, characterization of materials and testing methods used in the study. The results and discussion section present the material characterization results, testing results and data analysis, comparative analysis with other honeycomb sandwich structures and a discussion on the influence of process parameters on mechanical properties. The conclusion summarizes the research findings, its implications and future work, and provide a conclusion. The thesis is completed by referencing the literature used and appendices that include detailed testing procedures, additional data and figures, and any other relevant information.

2 Literature Review

The literature review provides an overview of natural fibres and their properties, specifically focusing on flax fibres and their comparison with other natural fibres. Additionally, it will examine honeycomb sandwich structures, including the types of cellular core materials, advantages and disadvantages, and applications. The review will also explore natural fibre-reinforced composites, including manufacturing methods, mechanical properties, and applications. In addition, the literature review will focus on the mechanical characteristics and analysis methods of honeycomb sandwich structures, as well as the properties and applications of nanofillers, specifically cellulose and nanoclay, and the use of 3D printing in the fabrication of moulds for fibre-reinforced composite structures.

2.1. Honeycomb structures

The honeycomb structure is a shell material made up of many interlinked cells and is known for its lightweight and high specific strength. It is manufactured according to ASTM C297-94 standards, where the cell shape, size, and arrangement are defined. The properties of the honeycomb are influenced by cell size, material thickness, and strength [1].

Honeycomb structures can be made from materials such as cardboard, ceramic, fibreglass, Kraft paper, Nomex®, plastic, steel, thermoplastics, and aramid fibre. Aluminium honeycomb structures are particularly noteworthy for their specific strength, energy absorption, heat transfer, and electromagnetic shielding properties. They are cost-effective due to their thin walls and smooth surface, which make them easy to machine. The lightweight honeycomb core is sandwiched between two thin panels to create a structure that combines the advantages of lightness and strength. While each component may be weak and flexible, the overall structure is stiff and durable when combined into a sandwich panel. The models for Aluminium, Kraft and Nomex honeycomb core Figure 1 and honeycomb sandwich structure Figure 2 were created using the Autodesk Inventor (version 2022) software.

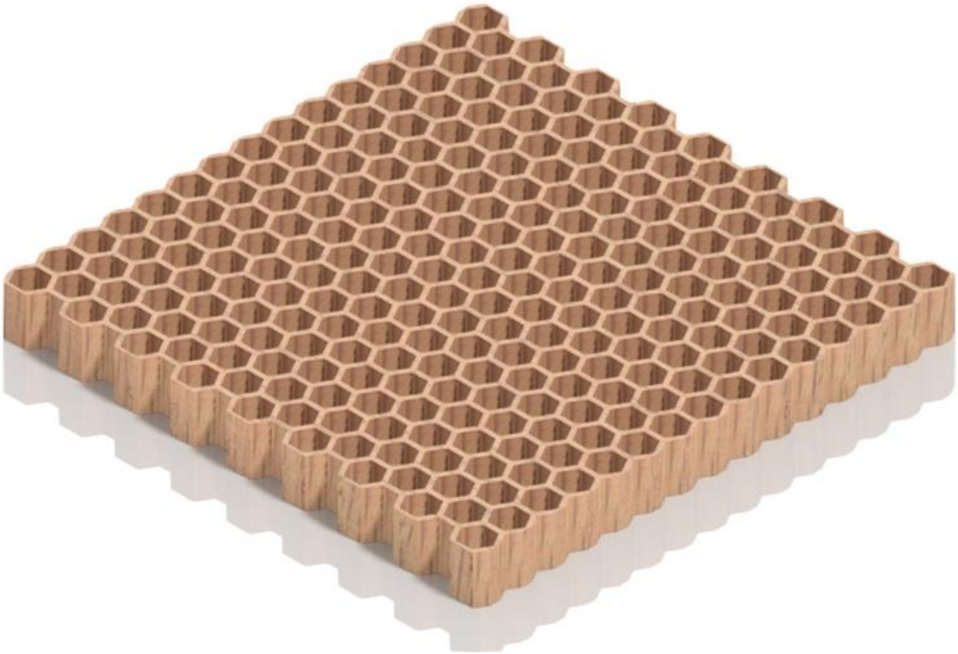


Figure 1 Model of honeycomb core

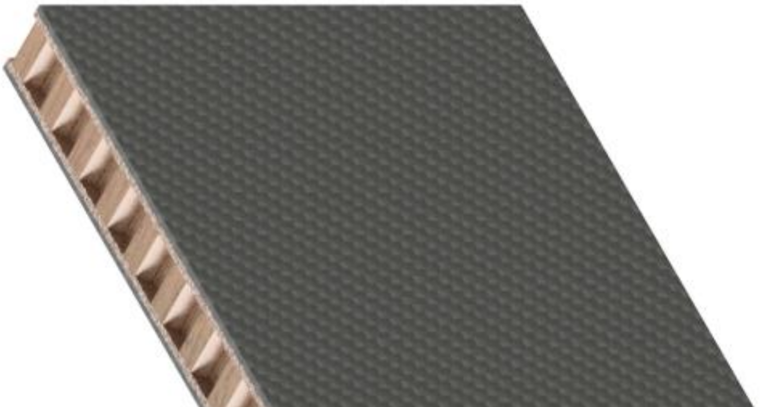


Figure 2 Model of honeycomb sandwich structure

2.1.1 Types of Honeycomb Cores

Honeycomb cores are a lightweight and strong material used in a wide range of applications, from everyday household items like interior doors to high-load aeronautical structures. They have the ability to be formed into flat or curved shapes, including those with complex curves, without requiring excessive force or heat. The method of creating honeycomb cores may vary based on the chosen material. For instance, thermoplastic honeycombs are made through extrusion and slicing, while paper and aluminium honeycombs are produced through a multi-step process that includes the application of adhesive stripes and a press that applies heat.

The characteristics of honeycomb cores are influenced by various factors, such as cell size, the thickness of the web material, and material strength. They are often combined with high-performance resin systems to secure proper bonding with the laminate skins. However, it's crucial to note that aluminium honeycombs are prone to corrosion in saltwater environments, and caution should be taken when using them in marine structures. Also, aluminium honeycombs don't have a "mechanical memory" and can permanently deform upon impact, potentially weakening the structure. Another option is Nomex honeycombs, made of aramid fibres, used in specific applications, though it is more costly than aluminium honeycombs [2].

2.1.2 Manufacturing process of honeycomb cores

Five key techniques are employed in the production of honeycomb structures: adhesive bonding, thermal fusion, brazing, resistance welding, and diffusion bonding. Adhesive bonding is the most frequently utilized method, accounting for nearly 95% of honeycomb production. The remaining techniques, however, are often reserved for the production of cores that will be subjected to high temperatures or extreme conditions and are typically more costly to manufacture. The two techniques used to turn sheet material into a honeycomb are the expansion process and the corrugation process. Adhesively bonded cores are usually created using the more streamlined expansion process, while metallic cores are treated with a corrosion-resistant coating, imprinted with adhesive lines, cut, stacked, and then cured under pressure and high temperatures. For non-metallic honeycombs, the process is a bit different, as the shape is not retained after expansion and must be secured in a rack. The adhesive lines at the nodes can be printed crosswise or inline, with the latter method restricting the length of the core in the L direction. Despite being labour-intensive, the corrugation method is still employed for producing high-density metallic and non-metallic cores [2].

2.2 Additive Manufacturing

2.2.1 Review of additive manufactured moulds for hand-laid fibre-reinforced composites

Fibre-reinforced composite materials have become increasingly important in the creation of lightweight and high-performance products. In order to effectively produce limited-volume composite parts through rapid prototyping, companies must be able to create highly representative prototypes, plugs, and moulds quickly and efficiently [3-5]. To achieve this, computer-aided manufacturing processes like stereo lithography can be utilized [3]. Nevertheless, the accuracy of the resulting mould and plug is largely dependent on the experience of the artisan worker. To address these limitations, additive manufacturing (AM) has emerged as a promising solution. AM is a process of constructing a part by adding multiple layers [6, 7]. With AM, parts can be designed using CAD tools and sliced into layers for processing using specialized software. This provides more flexibility for complex geometric patterns and designs than subtractive manufacturing methods like machining [6]. While some studies have explored the use of AM in rapid prototyping by printing a plug and coating it in silicone to create a soft mould [7, 8], and companies like John Deere have utilized AM to print sand-casting moulds [9], no studies have investigated the direct printing of moulds or plugs for hand layup or vacuum resin transfer of composite materials, due to limitations such as small print beds and slow deposition rates in traditional 3-D printers.

2.2.2 The FDM Process

The Fused Deposition Modelling (FDM) process, first patented by Stratasys in the 1990s, allows for constructing three-dimensional plastic objects without the use of a mould. The components are built up layer by layer using extruded thermoplastic filaments that typically come on spools [10]. This is currently the most widespread form of additive manufacturing (AM) because of the wide range of thermoplastic material options it offers, from readily available PLA [11] to engineering-grade Nylons [12]. The FDM process has been shown to be capable of producing solid objects with intricate shapes and geometries, as exemplified by the works of SAVU et al. [13] and Turner et al. [14]. Despite some challenges associated with AM, such as low efficiency, subpar surface quality, dimension instability, and internal anisotropy that affects the mechanical properties of the final products [15], the FDM process is well-suited for producing end-use parts and small-scale production runs [16, 17].

2.2.3 3D printing and component manufacturing

The FDM 3D printing technique is an affordable way of producing objects from thermoplastic materials, which is partially due to the straightforward hardware setup compared to other technologies. Unlike the Selective Laser Melting (SLM) method, FDM doesn't necessarily require a closed and heated chamber. The filaments used in FDM are easy to produce, as they are made from polymer granules, and there is a large selection of thermoplastic polymers available from various manufacturers. FDM also has some safety benefits, as it doesn't require personal protective Equipment like powder-based technologies do, and fumes generated during printing can be effectively filtered out. However, the surface quality of components produced with FDM can be lower compared to other 3D printing technologies such as SLM, Stereolithography (SLA), and Multi Jet Fusion from HP [18, 19]. Surface noise caused by spikes and peaks during modelling may affect print quality [20], and the difficulty in predicting residual stresses and deformations of printed components has limited the use of FDM for structural components, requiring several trials before obtaining the desired quality [21]. Despite this, FDM printing can be useful as a support procedure for creating other components, particularly for small batches or prototypes [22]. One example is using FDM to manufacture metal components using the lost wax casting technique [23] with low-melting thermoplastic polymers such as PLA or ABS [24], which reduces costs by avoiding the need for a metal mould. Another example is using FDM for creating moulds for silicone components [25], which offers similar benefits.

2.2.4 Moulds for bio-fibre composites

The process of traditional mould production, which often involves materials like metal or fibreglass, can be quite expensive. To construct a fibreglass mould, a starting model is necessary, which is often made using CNC on wood or high-density polyurethane foam. After the model is complete, it is treated with a release agent, such as Polyvinyl Alcohol, or wax. The surface is then given a glossy, homogeneous appearance through the application of a gel coat. To ensure rigidity and consistency in the mould, fibres are infused with either epoxy or a thermosetting resin. As the process is typically carried out by experienced operators manually, it is challenging to automate. This can result in high costs for creating single prototypes made from natural fibre composite, as the mould must be made from a single piece. In light of these challenges, the authors of this research explore the use of 3D printing technology as a solution.

2.3 Fabrication

The fundamental components of a sandwich panel, as depicted in Figure 3, consist of metallic or non-metallic facings, a core made of honeycomb, and an adhesive to bond them together. The metallic skins, such as titanium, steel, or aluminium, must undergo thorough cleaning prior to adhesion. Non-metallic facings like carbon, Kevlar, or fibreglass can either be bonded with a similar adhesive to the metallic facings, or in the case of composite prepregs, the resin can bond the reinforcement fibres to the core.

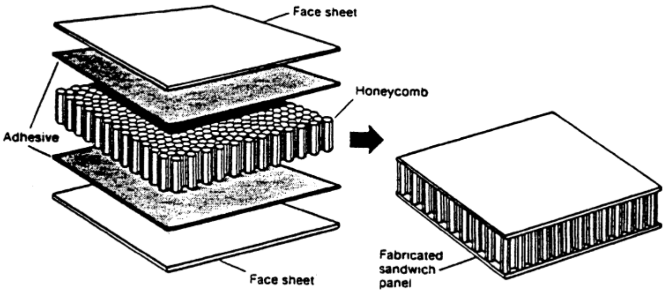


Figure 3 Basic components of the sandwich panel

There are two primary techniques of bonding the panel, which are by means of autoclaves and presses. Autoclaves are employed to produce curved shapes while presses are typically used for flat panels. Sandwich panels are constructed in clean rooms where the temperature and humidity are regulated, and personnel wear white cotton gloves. Aerospace industry relies on autoclaves and presses, however, there are alternatives such as vacuum bagging and curing the panel in an oven or using a homemade solar oven.

A typical cure cycle for a composite laminate, as seen in Figure 4, in an autoclave requires a temperature of either 121°C or 177°C for about 1 hour, after a heat-up rate of 1.1-2.2°C per minute, with a pressure of around 0.48 MPa. The cure cycle for honeycomb panels with composite or metallic facings is similar, but with a typical pressure of 0.31 MPa employed by most companies.

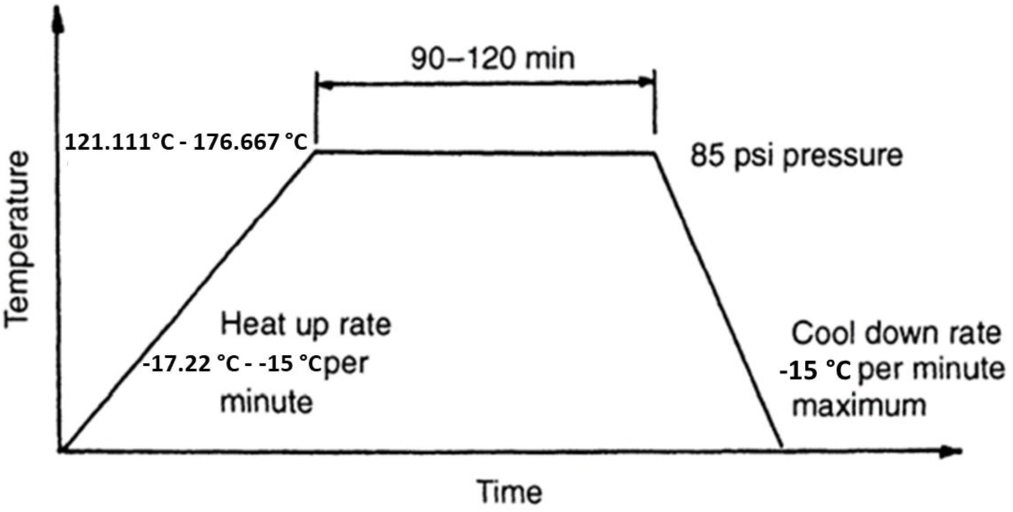


Figure 4 Typical laminate cure cycle.

2.3.1 Facings

The composition of the facings in a sandwich panel can vary, ranging from plywood to composites made of carbon tape fibres. The mechanical properties of some common materials are listed in Appendix H, and the choice of facing material is determined by factors such as strength, stiffness, damage tolerance, environmental factors, appearance, and cost. In designing the panel, it is ideal for the specific strength or modulus to be high, as this will result in a lighter panel, particularly if bending stress or panel deflection are significant design considerations.

It is noteworthy that the specific strength of carbon and Kevlar tape in tension is significantly higher than other materials. Kevlar has limited compressive strength, with a compressive specific strength of 0.166 MPa/kg/m^3, making it best suited for tension applications. On the other hand, carbon tape is the preferred material when stiffness is the main concern, as it produces a stiff and lightweight honeycomb sandwich. Steel, though heavy with a density of 7680 kg/m^3, has a specific modulus comparable to lighter aluminium, thanks to its modulus that is three times that of aluminium, making it cost-effective in certain situations.

For sandwich panels that need to endure damage, the thickness and material of the facings will depend on the type and density of the honeycomb. Aluminium facings are easily damaged, so if the panel will be subjected to rough handling or objects falling on it, a facing thickness of 0.81 mm or greater is advisable. Steel facings might have a minimum thickness of 0.51 mm, while fibreglass, Kevlar, and carbon facings could go down to 0.51 mm thickness, depending on the severity of impacts. In general, fibreglass facings on Nomex honeycomb create a tough and durable sandwich that can withstand substantial abuse.

2.3.2 Adhesives

Lightweight properties are a key factor in the use of honeycomb sandwiches, so it's crucial to make the panel as light as possible. The weight of the adhesive used to bond the facings to the core is often overlooked, it can still have a significant impact on the total weight of the sandwich panel. In order to reduce the added weight, the use of composite skins that are cured to the honeycomb can eliminate the need for adhesives. Another solution is to apply roller coats to the core or use film adhesives that are lighter in weight.

In the past, sandwich panels were made using thin facings made from wood, plywood or metal that were bonded to balsa wood cores. However, the adhesives used at the time were not suitable for honeycomb panels as they would not adhere to the cell walls. In the 1940s, advancements in adhesive technology allowed for the creation of all-aluminium honeycomb sandwiches by changing the rheology of the adhesives so that they would remain on top of the honeycomb cells during the cure process. However, the adhesives used at the time also gave off a significant number of volatiles, which required the aluminium honeycomb to be perforated to prevent the core from exploding or the skins from not bonding properly.

Nowadays, adhesives that are 100% solid and do not release volatiles are available. Most honeycomb is produced without perforations and a corrosion protection coating is applied. The facing is bonded to the honeycomb cell walls mainly on the sides, which is referred to as the adhesive fillet. This is crucial for achieving a strong bond, as the bond strength is higher when the fillet depth is sufficient. To ensure a strong bond, the adhesive must be able to wet the surfaces and have a higher strength and modulus of elasticity than the materials being joined.

In conclusion, the choice of adhesive for bonding facings to the honeycomb core must take into consideration factors such as weight, strength, and compatibility with the materials being joined. Advances in adhesive technology have provided solutions that minimize added weight and improve the bond strength of the joints.

2.4 Bio-Fibres and Their Utilization

Scientists worldwide are working towards protecting the atmosphere and biodiversity by promoting sustainable and eco-friendly products. The use of natural fibres has seen a resurgence as an alternative to synthetic and hazardous materials, due to their bio-renewable properties and eco-friendly behaviour. While natural fibres do have some drawbacks, such as biocompatibility and hydrophilic properties, these can be addressed through various surface modifications and chemical treatments. These fibres have been used effectively in a range of applications, including composite materials, textiles, biomedical, biopolymer, biosensors, and smart packaging, despite their lower density when compared to glass fibres. The use of natural fibres can help to reduce pollution issues such as waste, landfill, toxicity, and greenhouse gas emissions [26-28].

Fibres are defined as elongated and slender materials that are easily bent. They can be sorted into three categories based on their origin: natural and synthetic. Natural fibres, which are plentiful and cost-effective, have several advantages including reduced energy consumption and density, sustainability, lack of skin irritation, improved strength-to-weight ratio, a high aspect ratio (L/D of around 100), and increased strength and elastic modulus. As a result, these fibres have found widespread use in a variety of human needs and industrial applications such as textiles, paper production, accessories, bio-composites, and arts and crafts [29].

The botanical classification system is a widely used method for categorizing natural fibres. According to Rowell (2014) [30], five distinct categories of natural fibres are identified using this method: (1) bast fibres, including jute, flax, hemp, ramie, and kenaf, (2) leaf fibres, such as banana, sisal, agave, and pineapple, (3) seed fibres, including coir, cotton, and kapok, (4) grass and reed fibres, such as those found in wheat, maize, and rice, and (5) all other types of fibres, including roots and wood. It's worth noting that certain crops can produce more than one type of fibre, such as jute, flax, hemp, and kenaf which yield both bast and core fibres. Other crops, such as agave, coconut, and oil palm, have both fruit and stem fibres, and cereal grains have both stem and hull fibres [31].

Natural fibres in their raw state have some challenges when it comes to being used with polymers. These limitations stem from the presence of hydroxyl and other polar groups, dead cells, wax, oil, and low fire resistance, which can lead to the formation of aggregates and poor interface strength when compared to composites made from glass or carbon fibres. Additionally, natural fibres are highly absorbent, and this can further decrease their strength. To create eco-friendly composite materials, it is crucial to have a thorough understanding of the fundamental properties and components of natural fibres. Furthermore, when using natural fibres as textiles, factors such as length, flexibility, and strength should be taken into account, with the most critical property being the length-to-width ratio.

To address these challenges, various techniques such as stretching, calendaring, and producing hybrid yarns can be used to modify the physical properties of natural fibres. Furthermore, fibres such as abaca and biduri have substantial potential for use in the textile industry due to their strength, resistance to humidity, mildness, and hydrophobic characteristics.

The water retting method is utilized to extract fibres from plants by allowing the plant matter to decompose in water, but it has some downsides, such as the emission of pollutants and high-water consumption. Researchers are exploring alternative methods, such as mechanical, chemical, and enzymatic retting, as more sustainable alternatives.

Overall, natural fibres have great potential as raw materials across several industries, particularly in composite materials and textiles. Nevertheless, to fully tap into this potential, it's important to have a thorough understanding of their properties and limitations, and various modifications and alternative methods can be employed to overcome these challenges.

The use of natural fibres in composites has been proposed as a possible alternative to more traditional composites made from materials such as glass, aramid, and carbon [32]. The performance of natural fibre composites is strongly influenced by the type of natural fibre being used. For example, bast fibres have been found to have excellent flexural strength, while leaf fibres are known for their impressive impact resistance [33]. Flax fibres in particular have been found to display high bending and impact strength when combined with an epoxy matrix [34]. The form of the natural fibres also plays a role, with factors such as aspect ratio and the presence of yarn, bundles, or individual fibres impacting mechanical properties [35]. Other variables such as fibre content, temperature, humidity, fibre modification, storage methods, and type of fibre can all affect the mechanical properties of natural fibres [36]. However, there are also challenges to using natural fibres in composites, such as their hydrophilic nature, low durability, and difficulty in achieving good fibre-matrix adhesion [37]. This can result in lower efficiency in stress transfer and overall durability. Surface modification may be used to mitigate issues such as thermal degradation and improve the overall performance of natural fibre composites by improving interfacial adhesion [37].

The use of bio-fibres in sandwich structures has garnered attention as a substitute for traditional materials like aluminium, Nomex and glass for various industries such as aerospace, automobiles, civil engineering, and marine applications [38]. Natural fibre composites can be manufactured through various methods such as hand lay-up, compression moulding, and vacuum bagging.

The use of natural fibre composites has gained significant traction in the automotive sector, where they are often integrated into various interior components like door panels, dashboard parts, parcel shelves, seat cushions, backrests, and cable linings [39-41]. Pineapple fibres and fibre composites have found applications in the textile and transportation industries due to their impressive initial modulus [42, 43].

2.4.1 Flax Fibre Properties

The bio-fibre, Linum usitatissimum, better known as Flax, has a long history of use dating back to ancient Egypt over 5000 years ago [44]. Even earlier, evidence of its utilization has been found in the Dzudzuana Cave in Georgia, where it is believed that hunter-gatherers used twisted wild flax fibres for cordage, weaving, and sewing over 30,000 years ago [45]. This highly valuable crop is grown as cultivars specifically for fibre or linseed oil [46]. Canada leads the world in flax production and exports, with 60% of its output going to the EU, 30% to the US, and 4% to Japan. Other significant producers include France, Belgium, and the Netherlands, with nearly 130,000 acres under cultivation annually, and the EU producing 122,000 tonnes of flax fibres in 2007.

Fine, long flax fibres are commonly spun into yarn for high-quality linen textiles such as bed linens, furnishings, and interior decor. Meanwhile, shorter fibres produce heavier yarns that are ideal for products like kitchen towels, sails, tents, and canvas [46]. Lower-grade flax fibres are used as reinforcement and filler in composite materials, including automotive interiors and furniture [46]. The versatility of flax and the increasing demand for linen worldwide make it a valuable cash crop, with a growing cycle of only 100 days between sowing in March and harvesting in July in Western Europe. The rich history and continued use of flax as a bio-fibre highlights its versatility and importance.

2.4.2 Hybridisation

Composite materials have garnered much attention in both research and industry due to their unique characteristics and affordable manufacturing costs. They consist of a blend of fibres or fillers and a polymer matrix, which can be adjusted by combining various fibres with the matrix. The primary aim of using fibres is to enhance the strength of the composite. The properties of the fibres can be influenced by factors such as length, orientation, shape, and material. Fibres can be obtained either naturally or through synthetic means. Natural fibres, sourced from plants, animals, or cultivated materials, such as jute, ramie, sisal, hemp, coir, grewia optiva, silk, and bamboo, are environmentally friendly, renewable, cost-effective, non-toxic, and easily obtainable. However, their mechanical properties tend to be weaker compared to synthetic fibres. Additionally, their hydrophilic nature can hinder good bonding with the matrix. Synthetic fibres, including carbon and Kevlar, on the other hand, are man-made and tend to exhibit hydrophobic qualities, resulting in strong bonding with polymers. In some cases, a hybrid of natural and synthetic fibres is used to take advantage of both types, a practice referred to as hybridization, leading to enhanced mechanical and tribological properties of the final composite. The properties of the composite are also impacted by factors such as the type and size of fibre, fibre concentration, polymer type, processing methods, and chemical treatments. This discussion will delve into the various natural and synthetic fibres available, their effect on the composite, the modification of natural fibres chemically, and the applications of both natural and synthetic fibres.

2.4.3 Hybrid fibre-based polymer composites

The technique of combining two or more fibres to create a single matrix, referred to as hybridization, has been a topic of significant research in the field of composite materials. This process, also known as the integration of fillers into fibre polymer composites, has been utilized for centuries and has been observed to positively impact various properties such as physical, mechanical, and thermal, through increased fibre-fibre and fibre-matrix adhesion. The addition of natural fibres to synthetic fibre polymer composites can reduce production costs but may also lower the overall strength of the composite.

A variety of hybrid composite forms have been developed, including core-shell, sandwich-type, laminated, two-by-two, and intimately type composites. For instance, combining oil palm and epoxy fibres leads to substantial improvements in mechanical, thermal, and dynamic properties [47]. The addition of natural fibres, such as jute or glass, to synthetic fibre composites, such as oil palm or polymer, has been found to increase tensile and flexural strength [47]. However, it should be noted that hybridization does not always result in enhanced properties and can also result in trade-offs.

The majority of hybridization research has centred around the combination of natural and synthetic fibres, such as the hybridization of sisal with glass fibres that results in an improvement in tensile and flexural modulus [47]. Similarly, the addition of hemp fibres to glass fibres reduces production costs while also improving the mechanical and physical properties of the composite [47]. Natural fibres like flax and jute, which have been used for centuries, can also be hybridized with synthetic fibres to enhance the tensile strength of the composite [47].

Moreover, hybridization also holds great potential in improving the properties of green composites, such as enhancing the fracture toughness of bamboo-cellulosic fibre-based PLA composites [47].

2.4.4 Applications

The use of synthetic fibre polymer composites has been increasing, but there is a rising interest in replacing these materials with natural fibres for various applications due to the benefits of natural fibres [47]. However, natural fibres also have some limitations, and as a result, combining both types of fibres into one component have become a solution. This has led to the creation of hybrid composites, which have various uses.

In recent years, the use of hybrid fibre composites has grown in the automotive industry. Components such as door panels, instrument panels, armrests, headrests, seat shells and parcel shells are now being produced using these composites. Additionally, the passenger car's under-floor protection chamber has been successfully designed and developed using banana fibre polymer composites for safety purposes. The use of natural fibre composites has also extended to mirrors, visors of two-wheelers, billion seat covers, indicator covers, L-side covers, and nameplates, which are now being manufactured using sisal fibre polymer composites. The combination of different fibres has also made it possible to produce cost-effective components, such as the bumper of a car that is made using a combination of kenaf and glass fibres. Composites made from glass and sugar palm fibres are now being utilized in the production of small boats and ships.

Natural and synthetic fibre-based composites have proven to be ideal materials for structural applications. Hybrid composites made from jute fibres and concrete are being developed for the purpose of constructing structural composites. These applications include building panels, roofing sheets, door frames, door shutters, transport containers, packaging, geotextiles, chipboards, absorbent cotton, storage devices, furniture, transportation Equipment, household accessories, and biodegradable shopping bags. Coir-based polymers and ceramic composites are also being used in building panels, flush door shutters, roofing sheets, storage tanks, packing materials, helmets, post-boxes, mirror casings, paperweights, projector covers, voltage stabilizer covers, seat upholstery filling, brushes and brooms, ropes and yarns for nets, bags, and mats, as well as mattress and seat cushion padding.

Natural fibre polymer composites can also be used in the creation of materials that need fire-resistant properties. This is because the porous microstructures of natural fibres provide fire-resistant properties [47].

2.5 Properties of honeycomb

The mechanical characteristics of honeycombs that are usually measured encompass unstabilized and stabilized compressive strength, stabilized compressive modulus, and L and W plate shear strengths and moduli. For applications that necessitate energy absorption, the crush strength is also calculated. Table 1 displays some of the mechanical characteristics of generic honeycomb at room temperature. The thickness of metallic honeycomb for testing is standardized at 15.9mm, that of non-metallic core at 12.7mm, and commercial-grade Kraft paper at 25.4mm. The compressive properties and shear moduli do not significantly fluctuate with thickness; however, shear strengths tend to decrease as the thickness increases. A honeycomb with hexagonal cells is orthotropic, meaning that the L or ribbon direction has almost twice the shear strength and modulus compared to the W direction. When the core is overexpanded, the L and W shear strengths tend to become similar, and the W shear modulus tends to be almost twice the L shear modulus.

Table 1 Mechanical properties of honeycomb [2]

Core		**Compression**		**L shear**		**W shear**	
	Density	*Strength*	*Modulus*	*Strength*	*Modulus*	*Strength*	*Modulus*
	kg/m^3	*MPa*	*MPa*	*MPa*	*MPa*	*MPa*	*MPa*
2024 Aluminium	44.85	2.21	275.79	1.38	289.58	0.83	131
	152.18	17.24	3309.48	7.93	1172.11	4.48	441.26
3003 Aluminium	20.82	0.48	110.32	0.38	96.53	0.28	48.26
	76.89	4.34	1020.42	2.31	434.37	1.48	213.74
0º-90ºfiberglass Phenolic	35.24	1.24	89.63	0.83	41.37	0.41	20.68
	192.22	17.37	1792.64	6.79	330.95	4.31	193.05
45º fiberglass Phenolic	32.04	1.17	117.21	0.79	103.42	0.41	34.47
	128.15	12.07	889.42	4.0	337.84	2.34	165.47
45º fiberglass Polyimide	51.26	2.14	186.16	1.34	131	0.66	55.16
	128.15	8.34	868.74	4.83	379.21	2.9	151.67
Nomex Phenolic	24.03	0.69	41.37	0.52	20.68	0.28	13.79
	144.17	14.48	620.53	3.55	124.11	2.07	75.84
45º Graphite Phenolic	80.09	0.59	586.05	4.07	648.11	2.41	275.79
	160.18	1.17	1172.11	7.31	1482.37	5.24	620.528

2.6 Applications of honeycombs

Honeycomb is commonly utilised in construction projects for its high stiffness-to-weight and strength-to-weight ratios. Its light weight makes it a favoured material when weight reduction is necessary. The following section explores the typical and unique applications of honeycomb in the construction field [2]

2.6.1 Aircraft

Honeycomb cores are widely used in modern airplanes, particularly in Boeing commercial jets. Honeycomb usage has increased from the Boeing 707 to the current 757 and 767 aircraft. The wetted surface area of planes has also grown. Airlines focus on reducing weight to minimize the impact of fuel prices on their finances. Honeycomb is used in various parts of the aircraft structure, such as leading edges, flaps, spoilers, elevators, rudders, and cowling, to decrease weight. Honeycomb is also employed in radomes, which protect radar equipment, and is found in aircraft like the Beech Starship and Voyager. The military extensively uses honeycomb in their fighter aircraft, bombers, and helicopters. Honeycomb sandwich construction is commonly used in helicopter rotor blades. The Lockheed SR-71 Blackbird, built in 1965 and still holding the world record for speed and altitude, incorporates honeycomb components. The use of honeycomb in aviation enhances aircraft efficiency and helps reduce environmental impact.

2.6.2 Aerospace

Even a small weight reduction of 0.45 kg in the aircraft industry can lead to significant cost savings ranging from $500 to $1000. In space vehicles, the cost savings from weight reduction can be even higher, potentially in the tens of thousands of dollars. Space shuttles utilize honeycomb and composite facings extensively to minimize weight due to the high cost of launching into space. The Jet Propulsion Laboratory (JPL) and Hexcel are collaborating on a space telescope made from aluminium Flex-Core honeycomb with carbon skins arranged in a hexagonal panel. The telescope's surface must be curved and smooth for coating with gold, silver, or aluminium vapor. It must also maintain its shape across temperature changes and have a low coefficient of thermal expansion. The telescope, weighing only 12% of an equivalent glass lens, is set to be launched into space in the late 1990s.

2.6.3 Transportation

Honeycomb sandwich panels and honeycomb structures are being recognized for their value in the transportation sector. Weight reduction has become crucial, and Europe is leading in the development of lightweight rail cars featuring honeycomb doors and floors. Ongoing research in France focuses on a rail car made entirely of honeycomb. Some rapid transit trains in New York and the San Francisco Bay Area, as well as Disneyworld monorail cars, use honeycomb for ceilings and floors.

In 1974, Hexcel built an aluminium honeycomb truck van that weighed 1361kg less than a typical van, although the concept was not widely adopted due to higher costs. Race cars and unlimited hydroplane racing boats benefit from honeycomb sandwich constructions for their rigidity and low weight. Honeycomb is also used in sailboats, motorboats, and America's Cup sailboats to reduce weight and improve performance.

The United States Navy employs honeycomb panels in bulkheads to enhance stability and manoeuvrability. Honeycomb is also used for energy absorption and flow control in General Motors fuel-injected cars, where it optimizes mass airflow and fuel injection. Truck-mounted crash cushions filled with aluminium honeycomb protect highway workers without causing harm to car occupants. Honeycomb knee restraints and Tube-Core energy absorbers are being tested for vehicle safety, including protection during crashes and impact absorption in aircraft tail sections.

2.6.5 Building construction

Honeycomb made from commercial Kraft paper is affordable and commonly used in applications like doors, walls, recreational vehicles, and signs. It offers cost-effectiveness and can be used instead of plywood in construction. Specification-grade Kraft paper, treated with phenolic resin for improved water resistance and strength, is utilized in portable military shelters and aircraft repair hangars. These lightweight structures can be easily transported to remote areas. A military shelter and aircraft repair hangar are examples of such applications. In addition, a lightweight honeycomb water flume was created for Pacific Gas & Electric, and a unique approach in Ireland involved bonding honeycomb panels to marble slices, resulting in a lightweight marble curtain wall for buildings.

Honeycomb integration in sports has been common since the 1970s. Noteworthy applications include lightweight and agile snow skis using aluminium honeycomb cores, as well as tennis rackets, platform tennis paddles, running shoes, and canoes that utilize honeycomb to absorb shocks and reduce weight. There are also patented ideas for incorporating honeycomb into various sports gear, including bicycle seats, body Armor, helmets, and back scrubbers. However, certain sports equipment, like Ping Pong paddles, have restrictions and guidelines that require honeycomb to be composed mostly of wood.

2.7 The mechanics of honeycombs

The honeycomb design, characterized by its repeating geometric pattern of prismatic cells, serves as a model for two-dimensional cellular solids. This concept can be extended to both natural honeycombs found in bees, as well as to man-made materials like polymers, metals, and ceramics that are used in applications such as core materials for sandwich panels, energy-absorbing devices, and high-temperature processing Equipment. It is also possible to examine natural materials like wood through the lens of honeycombs. The examination of honeycombs not only provides a deeper understanding of these materials, but it also offers a simpler approach to comprehending the mechanics of three-dimensional foams. Research has shown that when a honeycomb is subjected to in-plane compression, the cell walls initially bend before collapsing through processes such as elastic buckling, plastic yielding, creep, or brittle fracture. When the honeycomb is placed under tension, the cell walls bend, with brittle materials resulting in fracture, while those with plasticity will exhibit significant deformation. When loaded out-of-plane, the cell walls undergo extension or compression and exhibit larger moduli and collapse stresses. This section focuses on the analysis and comparison of in-plane and out-of-plane deformation and failure of honeycombs with experimental data, particularly with regards to the mechanics of hexagonal cells.

2.7.1 Deformation mechanism in honeycombs

The hexagonal structure of honeycombs is a commonly found pattern in both nature and industry. When considering the direction parallel to the cell walls (X1-X2 plane), the mechanical properties of the honeycomb are relatively weak, as it requires the bending of the cell walls. In contrast, the properties perpendicular to the cell walls (X3 direction) are much stronger, as they require the cell walls to undergo axial extension or compression. This chapter aims to differentiate the in-plane and out-of-plane properties of the honeycomb and analyse them accordingly. The examination of in-plane properties will focus on understanding the deformation and failure mechanisms of cellular solids. The out-of-plane analysis, on the other hand, will provide information on the additional stiffness required for the design of sandwich panels and the comprehensive understanding of natural honeycomb-like materials such as wood [48].

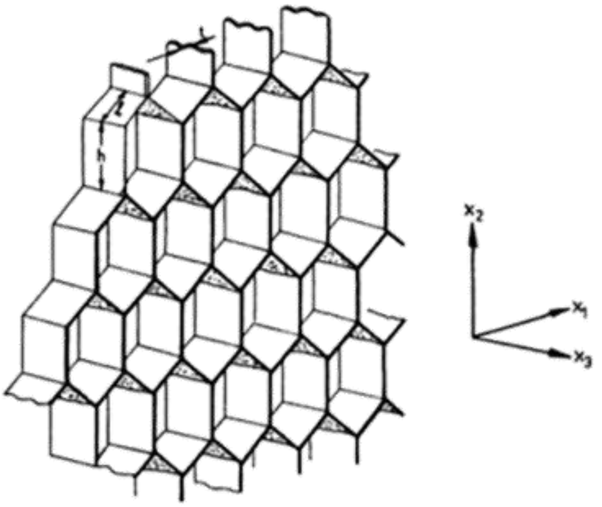
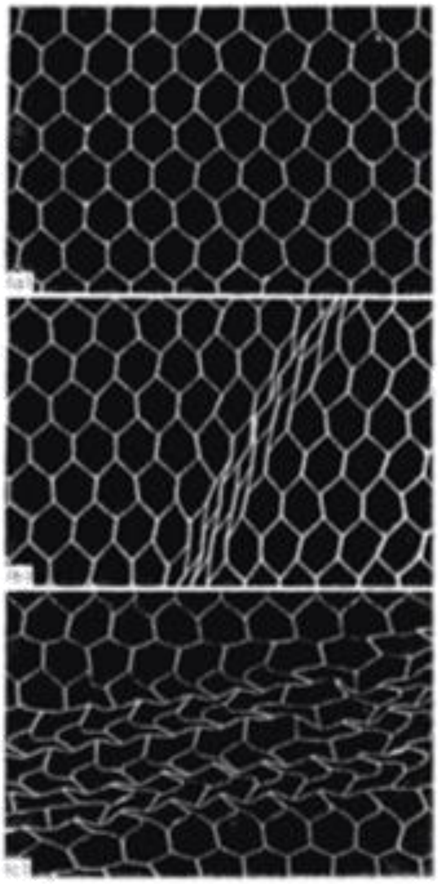


Figure 5 A hexagonal honeycomb. The in-plane properties relate to loads applied in the X1-X2 plane. The loads normal to the face to X3 are referred to as out-of-plane properties. [49]

2.7.1.1 In-Plane Deformation

The stress-strain curves for three types of honeycombs are displayed in Figure 6, a rubber-based elastomeric honeycomb, a metal-based elastic-plastic honeycomb, and a ceramic-based elastic-brittle honeycomb. Despite having similar shapes, the reasons for these similarities differ. During compression, all three honeycombs display a linear elastic stage followed by a period of nearly constant stress, ultimately resulting in a steep increase in stress. The various stages of deformation can be recognized by loading and capturing images of model honeycombs, seen in Figure 7 and Figure 8. Initially, the cell walls bend which results in linear elasticity if the cell wall material is linear elastic. Upon reaching a critical stress, the cells begin to collapse. In the case of elastomeric materials, collapse occurs through elastic buckling of the cell walls and can be reversed. In plastic materials, collapse happens through the formation of plastic hinges in areas



of maximum bend, which is not recoverable. In brittle materials, the collapse is due to brittle fracture of the cell walls and is also irreversible. Finally, as the cells collapse further and opposing cell walls touch, further deformation compresses the cell wall material leading to the steeply rising portion of the stress-strain curve called densification. An increase in relative density of a honeycomb leads to thicker cell walls, resulting in increased resistance to cell wall bending and collapse, and thus a higher modulus and plateau stress. The stage of densification starts earlier and at a lower strain. Figure 9 summarizes the mechanisms for compressive deformation of honeycombs and how the stress-strain curve changes with relative density or t/l. Tensile deformation can be distinct shown in Figure 6. Initially, cell walls bend which results in linear elastic deformation with the same slope as in compression. However, elastomeric honeycombs do not buckle in tension. Instead, the cell walls rotate towards the tensile axis, increasing stiffness. Plastic honeycombs behave similarly in tension as they do in compression, forming plastic hinges, and allowing for substantial deformations at nearly constant plateau stress. The only difference is the change in geometry, typically pushing the tensile curve above the compressive one. Brittle honeycombs fail abruptly under tension at a stress that is usually lower than the true crushing strength. The propagation of the largest defect (a crack, notch, or cluster of damaged cells) in a brittle solid is controlled by fracture mechanics methods and determines the failure in tension. Increasing relative density has a similar impact in tension as it does in compression, increasing elastic moduli, plastic yield stress, and brittle fracture stress.

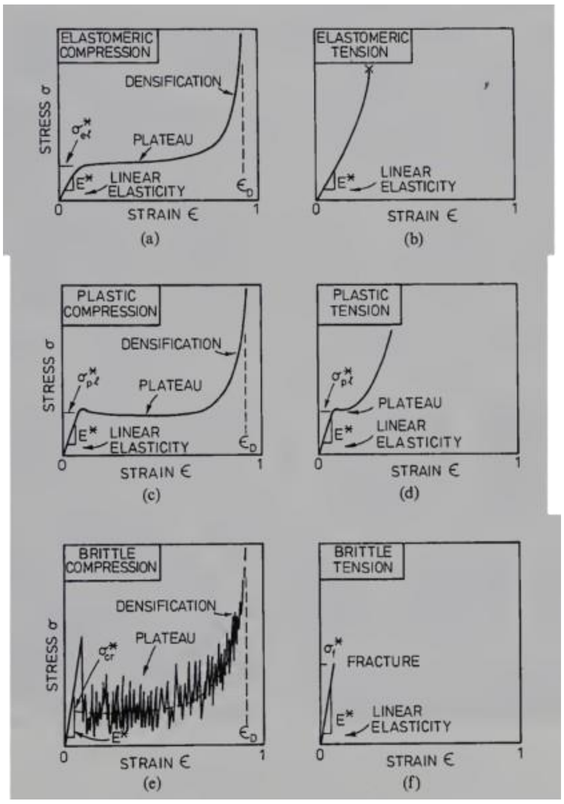


Figure 6 Compressive and tensile stress-strain curves for honeycombs: a) and b) an elastomeric honeycomb; c) and d) an elastic-plastic honeycomb; e) and f) an elastic-brittle honeycomb. [49]

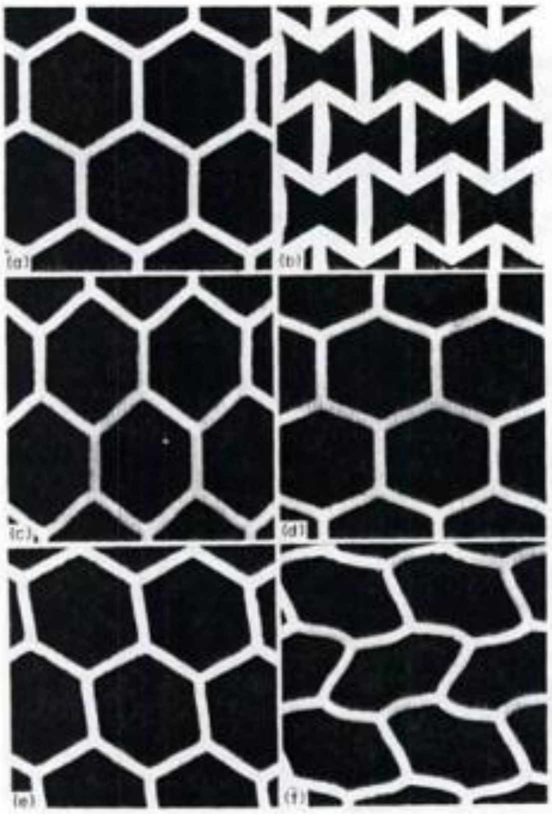


Figure 7 In-plane mechanisms of deformation in elastomeric honeycombs: a) an undeformed rubber honeycomb with regular hexagonal cells; b) an undeformed rubber honeycomb with inverted cells; c) the cell wall bending caused by uniaxial compression in X_1 direction; d) the cell wall bending caused by uniaxial compression in the X_2 direction; e) bending of the cell walls in shear; f) elastic buckling of the cell walls from compression in the X_2 direction. [49]

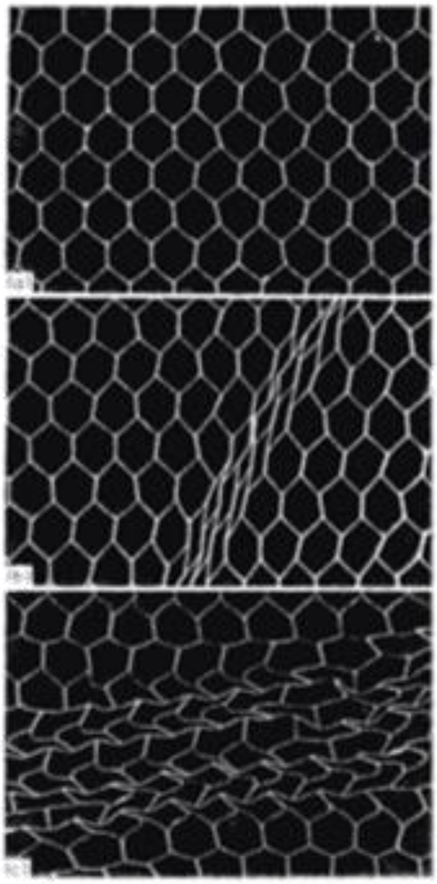


Figure 8 In-plane mechanisms of deformation in elastic-plastic honeycombs: a) an undeformed aluminum honeycomb; b) plastic yielding of the cells walls loaded in compression in the X_1 *direction; c) plastic yielding of the cell walls loaded in compression in the* X_2 *direction. [49]*

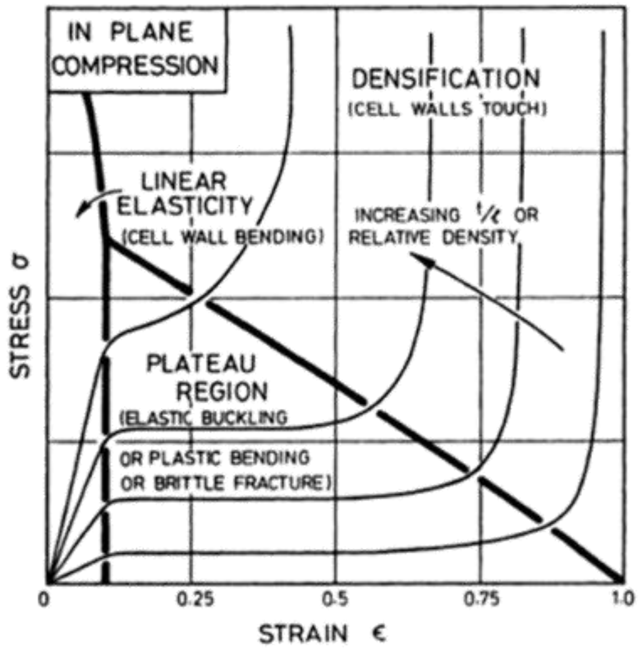
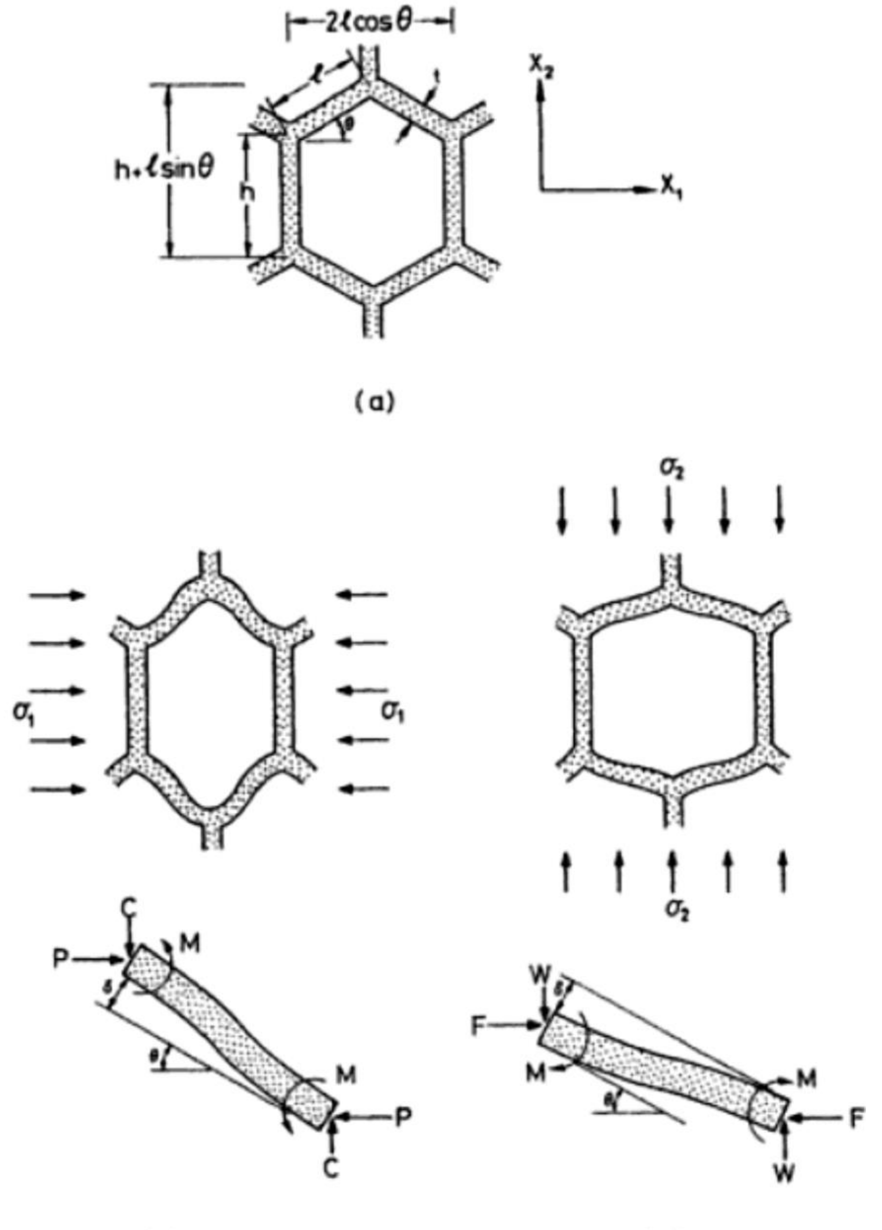


Figure 9 Honeycomb loaded in compression in the X1-X2 plane, showing the linear elastic, collapse and densification regimes, and the way the stress strain curves changes with t/l. [49]

2.7.2 The in-plane properties of honeycombs: uniaxial loading

In
Figure 10, a unit cell of a hexagonal honeycomb is depicted, and its reaction to loads applied in the X1-X2 plane is analysed. If the hexagon is symmetrical (Equal sides and angles of 120°) and the cell walls have consistent thickness, the properties are isotropic and do not vary based on direction. This structure exhibits two independent elastic constants (such as Young's modulus E* and shear modulus G*) and a single plateau stress value, a*. Conversely, if the hexagon is asymmetrical or the cell wall thickness varies, the properties become anisotropic, necessitating the use of four moduli (E*, E*, G2 and v2, where v* is Poisson's ratio) and two plateau stress values (a* and a%) to fully describe the in-plane properties. The evaluation of moduli and collapse stress for a general honeycomb, with unequal h and l and arbitrary cell wall angle, 6, is also explored. The isotropic results can be derived from these results, assuming that the honeycomb has low relative density, p*/ps, so that t/l is small. The relation between p*

and t/l can be found through simple geometry and is given as: p*/ps = t/l (h/l + 2) cos 6(h/l + sin 9), which simplifies to p*/ps = 2 t/l when the cells are regular (h = l; 6 = 30°). Additionally, it is assumed that deformations are minor enough that changes in geometry can be ignored. Further refinements to account for larger deformations or t/l values greater than 1/4 can be added [49], though these are more complicated and only necessary for strains exceeding 20%.



(a)

(b)

(c)

Figure 10 Cell deformation by cell wall bending, giving linear-elastic extension or compression of the honeycomb: (a) the undeformed honeycomb; (b) and (c) the bending caused by loads in the X1 and X2 directions. [49]

The behaviour of a honeycomb structure when subjected to loading in the X1 or X2 direction is characterized by linear-elastic deformation, leading to bending of the cell walls (Gibson and Ashby, 1997). The properties of the structure can be represented using five moduli, including two Young's moduli (E1 and E2), one shear modulus (G12), and two Poisson's ratios (v12 and v2*). However, these five moduli are interrelated through a reciprocal relationship, which reduces the number of independent moduli to four. These four moduli are the same for both tension and compression and can be calculated as indicated:

$E *_1 \, \upsilon *_{21} = \, E *_2 \, \upsilon *_{12}$

A general hexagonal with an arbitrary cell wall angle. The isotopic properties can be easily obtained from the results for the case of a general hexagon. Simple geometry analysis gives relative density [p*/ps], as below:

$$\frac{\rho^*}{\rho_s} = \frac{\frac{t}{l}(\frac{h}{l}+2)}{2cos\theta(\frac{h}{l}sin\theta)} \quad \text{Relative density}$$

Which reduces to:

$$\frac{\rho^*}{\rho_s} = \frac{2}{\sqrt{3}}\frac{t}{l} \quad \text{For regular hexagons}$$

When the cells are regular (h=l; O=30*). For the theoretical approach, it is also assumed that the deformations are sufficiently small that changes in geometry can be neglected.

Solid cell wall properties: $\rho_s, E_s, \sigma_{ys}, \sigma_{fs}$

Cell geometry: $\frac{h}{l}, \theta$

Many commercial honeycombs are made by expanding strip-glued sheets. Then each cell has four walls of thickness t and two which are doubled and have a thickness of 2t. The doubling of this pair of cell walls does not change the values of the in-plane young’s moduli calculated below.

Linear elastic deformation

The honeycomb's linear-elastic response is a result of bending in the cell walls. Each wall is considered as a beam with a thickness of t, depth of b and Young's modulus of E s. The beam formulas outlined by Timoshenko (1955) are utilized, disregarding the shear deformation and axial extension or compression of the beams, and on the premise that the strains are minimal to the point that there are no significant alterations in geometry. Although, a more comprehensive examination that takes into account all these factors, as outlined by Gibson et al. [50], can be performed but is only required when dealing with high-density honeycombs.

Elastic Buckling (non-linear deformation)

In cellular materials, elastic buckling of the cell walls enables substantial bending while keeping the applied force constant. Our observations from experiments on elastic models revealed the buckling pattern displayed in Figure 11. Owing to its symmetrical nature, all of the joints bend at the same angle, and the beam's central point, labelled as D, experiences no bending moment as it acts as a point of inflection.

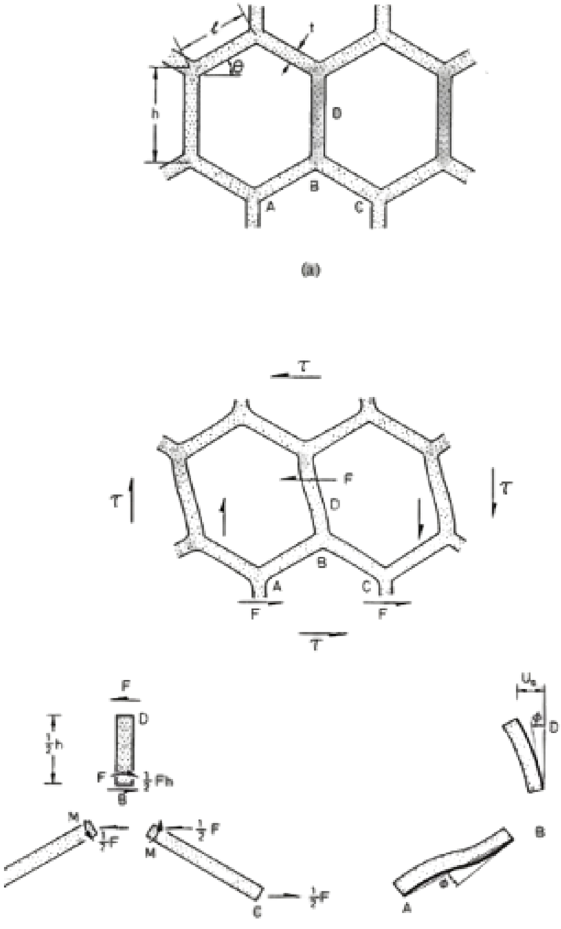


Figure 11 Cell deformation by cell wall bending and rotation, giving linear-elastic shear of the honeycomb: (a) the undeformed honeycomb; (b) the loads, moments, displacements and rotations caused by a shear stress. [49]

Plastic behaviour, Plastic Collapse

The plastic collapse of a cellular material occurs when the cell wall material surpasses its yield point and the structure experiences plastic deformation from the bending moment exceeding the fully plastic moment. The plastic collapse stress of the foam can be calculated by evaluating the amount of work performed by the force during a plastic rotation of the four plastic hinges (A, B, C, D) as depicted in Figure 12. This represents an upper limit of the plastic collapse stress when loading occurs first in the X1 direction, as shown in Figure 12.

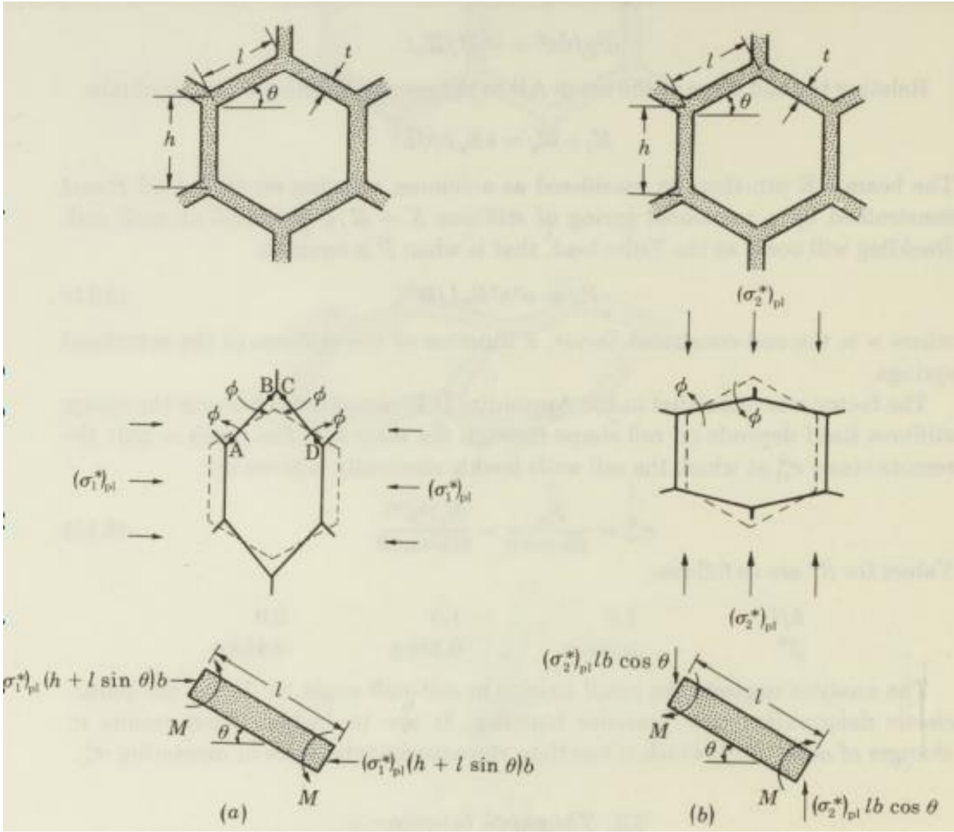


Figure 12 Cell deformation by plastic collapse: (a) the undeformed honeycomb; (b) and (c) the rotations, forces and moments for loading in the and X2 directions. [49]

2.7.1.2 Out of plane deformation

The stiffness and strength of honeycombs are more pronounced when subjected to load in the direction of the cell axis (X3 direction), and in the out-of-plane shear, as observed in sandwich panels undergoing bending. The initial linear-elastic deformation in these scenarios involves a noticeable amount of axial or shear distortion of the cell walls. The stress-strain curve in the case of compression shows buckling followed by tearing or crushing, as depicted in Figure 13. Tension causes the honeycomb to exhibit elastic behaviour until it fails through tearing, yielding plastically, or fracturing. The stress-strain curves for honeycombs with varying relative densities also form a pattern, as seen in Figure 14.

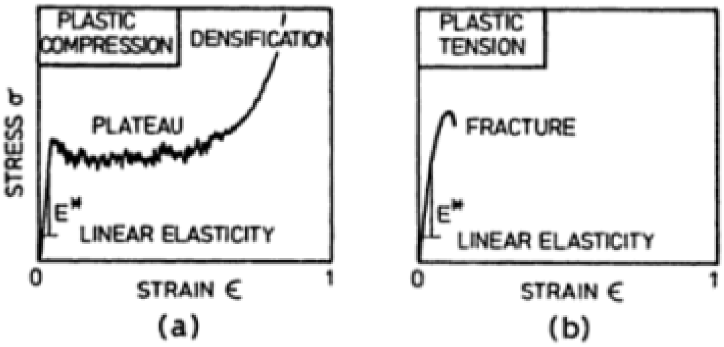


Figure 13 Stress-strain curves for the axial (X3) loading of a honeycomb, in (a) compression and (b) tension. [49]

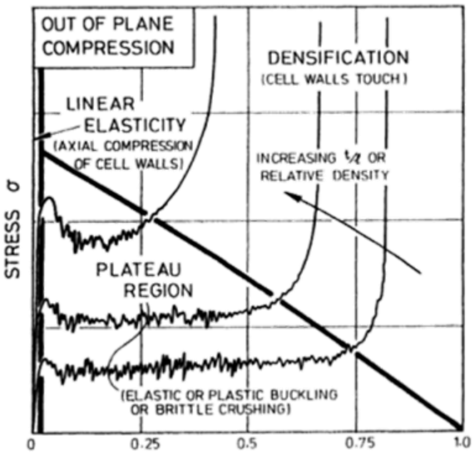


Figure 14 A schematic diagram for honeycombs loaded in the axial (X3) direction, showing regimes of linear elasticity, collapse and densification, and the way in which the stress-strain curve changes with t/l. [49]

Linear-elastic deformation

Honeycombs are commonly utilized as cores in sandwich panels due to their lightweight and rigid structure. This design is commonly seen in skis, aircraft, and space vehicles. In Chapter 9, sandwich panels are thoroughly discussed. It is noteworthy that the honeycomb core's role is to support normal, and shear loads in planes that contain the axis of the hexagonal prisms, also known as the X3 direction in Fig. 4.27. In this direction of loading, the cell walls undergo extension or compression, as opposed to bending, resulting in moduli that are significantly greater for hexagonal honeycombs compared to those calculated for in-plane loading in Section 4.3. The plastic collapse strengths are also higher due to the involvement of axial deformations in addition to bending. It is assumed that the density is low and t«l, and the thickness of all the walls is identical. The extension of the honeycomb to walls of varying thickness is straightforward. A total of nine moduli are required to describe the honeycomb's complete properties, including five additional moduli for out-of-plane deformation.

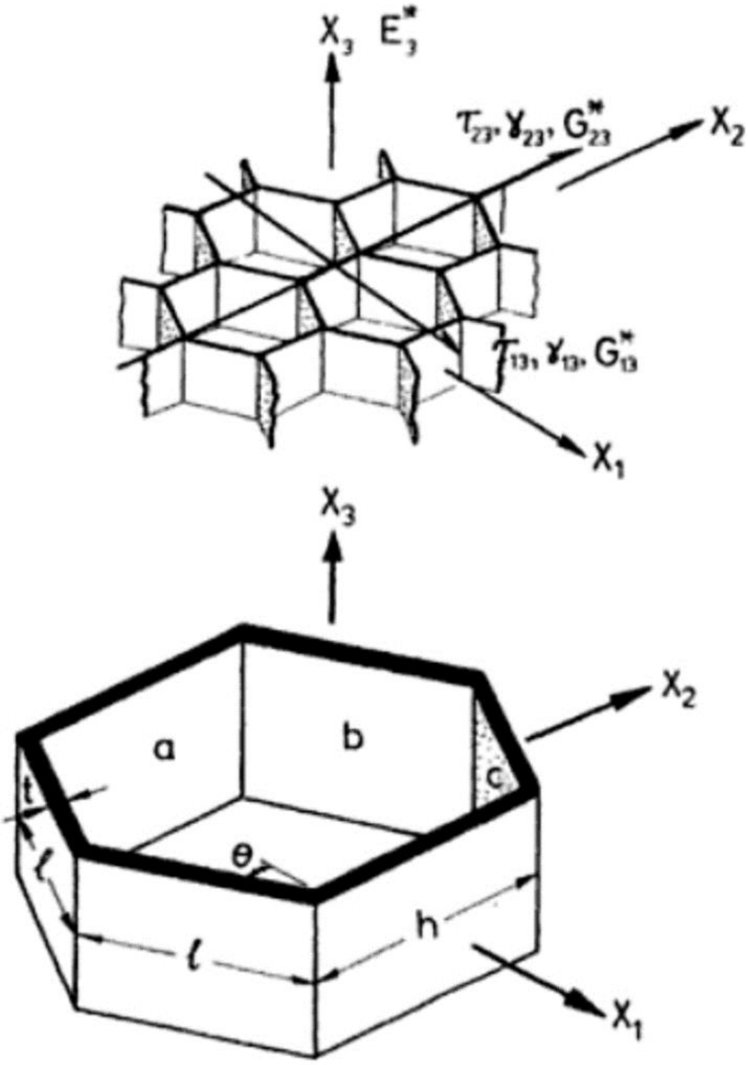


Figure 15a) A honeycomb carrying loads on the face normal to X3; b) one cell showing the walls a, b and c. [49]

Non-linear elasticity: elastic buckling

Currently, little research has been conducted on the remaining out-of-plane properties. However, tests with rubber models have shown that an elastomeric honeycomb, when compressed in the X3 direction, will eventually buckle, with the cell walls bulging periodically as depicted in Fig. 4.29. Buckling of a panel (i.e., the cell wall) that is constrained along the two edges parallel to the loading direction is a standard problem, as documented in Timoshenko and Gere's 1961 publication. The buckling load is dependent on the width (l or h) of the panel, as well as the second moment of inertia of the wall, but not on the height (b).

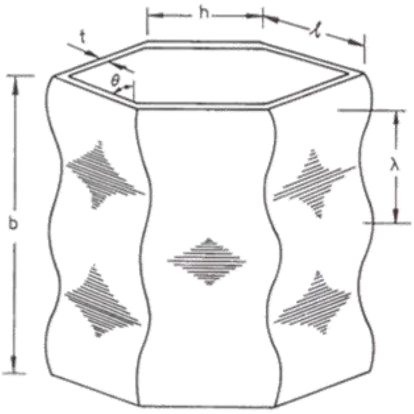


Figure 16 The axial buckling of a hexagonal cell. [49]

Plastic collapse

The function of the honeycomb core is to carry normal, and shear loads in planes containing the axis of the hexagonal prisms. When loaded in this direction, the moduli and plastic collapse strengths of hexagonal honeycombs are much larger than those calculated for in-plane loading. The current understanding of the out-of-plane properties of honeycombs, assumes a low density and uniform wall thickness.

The plastic collapse strengths of hexagonal honeycombs are larger than those calculated for in-plane loading because axial deformations are involved in addition to bending deformations.

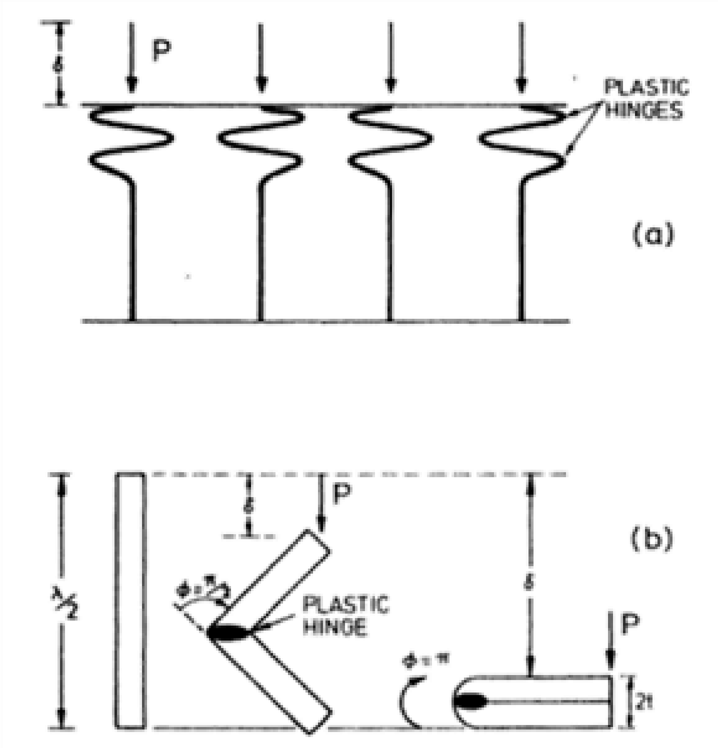


Figure 17 a) Schematic of the plastic buckling of a honeycomb, loaded in the X3 direction: the walls fold in a periodic way; b) the work done by the load Up on one wall in a displacement ((λ/2-2t) is dissipated in the plastic hinge. [49]

2.8 Research Gap

2.8.1 Introduction

This chapter aims to identify the research gaps within the field of natural fibre-reinforced polymer composites and their integration into honeycomb structures. While extensive research has been conducted in this area, several gaps remain to be addressed. By identifying these gaps, this study aims to contribute to the existing knowledge and pave the way for further advancements in the field.

2.8.2 Moisture Performance of Natural Fibre Composites

Previous studies have focused on exploring the utilization of natural fibres in honeycomb structures, primarily using short fibres and basic shapes [51-60]. However, the performance of natural fibre composites in the presence of moisture remains a challenge. Natural fibre composites have been found to perform poorly when exposed to moisture, affecting the morphology of the fibres, crack propagation, and sliding surface reaction. Further investigation is needed to understand and mitigate the impact of moisture on the mechanical properties and long-term performance of natural fibre composites.

2.8.3 Hybridization of Natural Fibres

Hybridization, which involves combining different types of fibres, has shown promising results in overcoming the inferior mechanical properties of natural fibres. Flax fibres, in particular, have gained popularity as a sustainable and eco-friendly reinforcing agent [61-67]. However, there is a lack of research on hybrid composites that combine flax fibres with other fibres, such as glass. Such hybrid composites have the potential to enhance strength and stiffness while protecting the inner hydrophilic layers reinforced with flax fibres, thus extending the material's service life. Investigating the mechanical properties and durability of these hybrid composites is essential to further advance their application in various industries.

2.8.4 Cost-Effective Mould Fabrication for Honeycomb Structures

The corrugation manufacturing process has been widely used for cost-effective production of honeycomb cores. Additionally, 3D printing techniques, such as Fused Deposition Modelling, offer the potential for low-cost and efficient mold fabrication for fibre-reinforced composites. However, further research is needed to develop cost-effective and efficient strategies for mold fabrication specifically tailored to fibre-reinforced composites. Exploring innovative techniques and materials for mold fabrication can significantly impact the manufacturing process and overall cost-effectiveness of composite structures.

2.8.5 Nanoparticle Reinforcement in Polymer Matrices

Infusing polymer matrices with nanoparticles, such as cellulose and nanoclay, has been shown to enhance the thermal, mechanical, and moisture barrier properties of nanocomposites [68-76]. While previous research has focused on inorganic nanofillers, there is a growing trend towards using cellulose nanocrystals or nanofibrils as strengthening agents. However, the optimal concentration and dispersion techniques of these nanoparticles in the modified epoxy-based adhesive system for honeycomb structures remain to be determined. Further investigation is needed to understand the ideal concentration and dispersion methods that can achieve significant improvements in the properties of nanocomposites.

2.8.6 Industrial Implications

The potential implications of composite structures integrating natural fibre composites and honeycomb cores in various industries, such as automotive, aerospace, and construction, are significant. However, there is a need for further research to understand the specific requirements and challenges faced by these industries when adopting these composite structures. Investigating the performance, durability, and manufacturing considerations in real-world scenarios will provide valuable insights into the practical implications of these composites and facilitate their widespread adoption.

2.8.7 Conclusion

This chapter has identified key research gaps within the field of natural fibre-reinforced polymer composites integrated into honeycomb structures. Addressing these gaps will contribute to advancing the mechanical properties, moisture performance, hybridization techniques, cost-effective mold fabrication, and nanoparticle reinforcement of polymer matrices. Furthermore, understanding the industrial implications and challenges will facilitate the successful implementation of these composite structures in various sectors. The present study aims to bridge these research gaps and contribute to the knowledge in the field, ultimately leading to the development of more sustainable and high-performance composite materials.

3 Material and methods

This chapter describes the methodology used in the study to investigate the potential use of honeycomb sandwich structures as a sustainable and durable alternative in various structural applications. The chapter discusses the research approach, sampling strategy, data collection methods, data analysis methods, ethical considerations, and limitations.

3.1 Research question

The research question for this study is: What are the mechanical properties and durability of cellular bio-nanocomposite sandwich structures using hybridized flax and glass fibre face sheets, a flax fibre core, and a cellulose-nanoclay-filled bio-based adhesive for bonding?

3.2 Research approach

The research approach for this study was an experimental design. This approach was used to investigate the mechanical properties of the composite materials. The use of laboratory-based tests helped to provide quantitative data that can be used to compare the mechanical properties of the composite materials.

3.3 Sampling strategy

The sampling strategy for this study used hybridized flax and glass fibre face sheets, a flax fibre core, and a cellulose-nanoclay-filled bio-based adhesive for bonding. The samples were fabricated using 3D printing technology to control the shape and size of the honeycomb structures. This sampling strategy ensured that the mechanical properties of the composite materials are tested under standardized conditions.

3.4 Data collection methods

The data collection methods for this study consists of laboratory-based tests that investigate the mechanical properties of the composite materials. The tests include tensile strength, flexural strength, impact resistance, compression, and water absorption. The laboratory-based tests were conducted in accordance with standard test procedures to ensure the accuracy and consistency of the results.

3.5 Data analysis methods

The data collected from the laboratory-based tests were analysed using statistical analysis. The statistical analysis provides quantitative data that can be used to compare the mechanical properties of the composite materials. The results of the statistical analysis are presented in tables and graphs to provide a clear understanding of the results.

3.6 Ethical considerations

There are no ethical considerations involved in this research. The use of laboratory-based tests to investigate the mechanical properties of the composite materials does not involve any human or animal subjects. All necessary safety precautions were taken during the laboratory-based tests to ensure the safety of the researchers and the environment.

3.7 Limitations

One limitation of this study is the potential for the results to be specific to the materials and methods used in this study. The use of hybridized flax and glass fibre face sheets, a flax fibre core, and a cellulose-nanoclay-filled bio-based adhesive for bonding, along with 3D printing technology to control the shape and size of the honeycomb structures, may limit the generalizability of the results. Additionally, the study has been limited to laboratory-based testing, and further research may be necessary to investigate the performance of the materials in real-world applications.

This chapter has described the methodology used in this study to investigate the potential use of cellular bio-nanocomposite sandwich structures as a sustainable and durable alternative in various structural applications. The use of hybridized flax and glass fibre face sheets, a flax fibre core, and a cellulose-nanoclay-filled bio-based adhesive for bonding, along with 3D printing technology to control the shape and size of the honeycomb structures, is the focus of the experimental design. The results of this study provide valuable insights into the mechanical properties and durability of the composite materials, which can be used as a basis for future research and development in various structural applications. The limitations of the study and potential future research directions have also been discussed.

Fibreglass and metal moulds are expensive, and their fabrication requires extensive time and labour. The entirety of this fabrication process is also difficult to automate and requires experienced personnel to carry out. Hence, additive manufacturing was chosen to fabricate polymer moulds layer-by-layer using ABS filament by fused deposition additive manufacturing technique to obtain a high surface finish for better composite samples.

The corrugation process for the honeycomb core first requires the modelling of the desired geometry in a CAD package. Autodesk inventor was used for modelling the required honeycomb core geometry. A model of the matched moulds was formed using the core geometry as a reference. The mould models were exported to UP Studio, a 3D printing software where it undergoes slicing and transfer to the UP MINI 2 3D printer, where the final moulds were fabricated using FDM. ABS plastic filament was used as the material of choice due to its ease of use and is readily available. A hand layup process was used to layer the flax fibre plies within the mould and a compression force was applied as seen in Figure 18.

3.8 Sample Fabrication

Matched moulds were additively manufactured to form corrugated honeycomb layers through a compression moulding process.

3.8.1 Matrix Material

LR30 epoxy resin and LH30 fast hardener system were used as a matrix for the fibre reinforcements. The diglycidyl ether of bisphenol-A (DGEBA) based epoxy resin (LR-30) and cyclic aliphatic amine-based epoxy hardener (LH-30) were purchased from AMT Composites, South Africa. All other chemicals used were obtained from Merck Chemicals, South Africa.

3.8.2 Core and Face Sheets

The core compromises two plies of flax fibre orientated at 0° and the face sheet comprises a single inner ply (primary) of flax fibre and a single outer ply (secondary) of glass chopped strand mat. By utilising this stacking sequence, the outer glass layer prevents moisture from compromising the flax fibre component. 300 GSM, 2X2 twill bidirectional flax fibres were used to construct the core as well as the primary ply of the face sheets. 450 GSM, glass fibre chopped strand mat was used as the secondary outer ply for the face sheets.

3.8.3 Fabrication Process

LR30 epoxy resin and LH30 fast hardener system were used as adhesives for bonding the core and face sheets. The epoxy resin system was used as an adhesive, bonding the corrugated layers to form the desired cellular honeycomb core. Cellulose extracted from banana fibre through an acid hydrolysis process was considered as a filler for the resin adhesive. Cloisite 93A nanoclay was also considered as an adhesive filler. The additives used were 3wt% of the epoxy.

The printed moulds inclose 2 plies (2.5g/ply) of the flax fibre fabric that’s impregnated with the resin, in between plies of vacuum bag to prevent the composite from adhering to the mould and ensure a flawless surface. A compression force of 55N was applied to the moulds and left to cure for 16 hours. The corrugated layers, once cured, were adhered together to form the honeycomb core. The surfaces being bonded were cleaned and lightly sanded down to improve adhesion and remove surface impurities. The type of adhesive was varied using plain epoxy resin, cellulose-filled epoxy-resin or nanoclay-filled epoxy-resin. The process can be seen in Figure 18, illustrating in detail the steps of fabricating the corrugated layers.

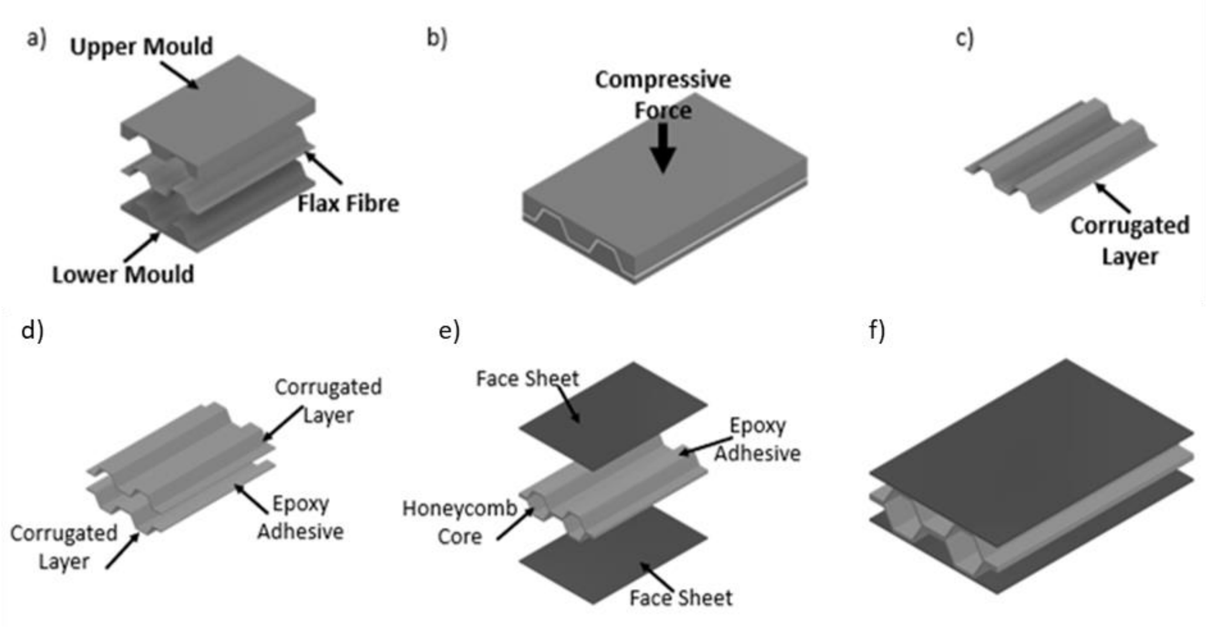


Figure 18 The corrugation process, a) flax fibre impregnated with resin was placed into the mold, b) compression force was applied to the mold, c) the corrugated layer of the sandwich structures; d) individual components, e) bonded honeycomb core, and f) the fabricated honeycomb core sandwich structure.

The honeycomb cores were formed into sandwich structures by adhering to hybrid composite skins, constructed by primarily a ply (2.5g) of the flax fibre fabric, with an outermost ply (2g) of glass fibre chopped strand mat in epoxy resin. The adhesives varied and were the same as those used for bonding the layers of the core. Figure 18 illustrates the sandwich structure fabrication process.

Cellulose, for the adhesive filler, was extracted from banana fibre through sequential chemical and mechanical treatment processes, an alkaline treatment, bleaching, mechanical stirring and acid hydrolysis. The processed fibre and extracted cellulose can be seen in Figure 19. The banana fibre was ground and cut up to obtain an initial mass of 25g. 5*w/v*% Sodium hydroxide (NaOH), which measured 25g, was diluted in a beaker with 500 ml of distilled water to form an alkali solution. The banana fibre was added to the mixture and left to soak for a duration of approximately half an hour. Thereafter, the content was strained and dried in the oven at 60˚C. The alkali treatment was repeated for a total of three treatments. During alkaline treatment, hydrogen bonds in the fibre were broken down and wax, lignin and oils were removed from the fibre surface [37]. The fibres were then ground up, and the final mass measured 10,8g. Sodium hypochlorite (NaOCl) was used at a 3,5*v/v*% ratio to form a bleaching solution. Approximately 17,5 ml of NaOCl was added to 500 ml of water forming the bleach solution. The fibre obtained from the alkali treatment was added to the bleach solution and left to soak for 30 minutes. The fibre was then strained and dried in the oven at 60 ˚C. The bleaching treatment has been repeated a total of times and the final mass was recorded as 8,5g. Bleaching is a critical step in the extraction process, it degrades cellulose, removes stains and gives the fibre a white appearance.

The dried fibres obtained after the bleaching treatment was further cut, ground up, placed into a beaker with approximately 200ml of water, and aggitated for 2 hours. The fibres were then placed into a beaker with 490ml distilled water and 2v/v% (10 ml) sulphuric acid (H_2SO_4) solution, to undergo acid hydrolysis. This solution was then agitated for a duration of 2 hours. The disordered regions of cellulose were disintegrated by the hydrolysis process, and the highly ordered cellulose segments remained, with different degrees of crystallinity. Thereafter, the content was strained, dried, and sifted to obtain cellulose in a powdered form, to be used as the additive in the adhesive. The final mass was measured as 7,9g.

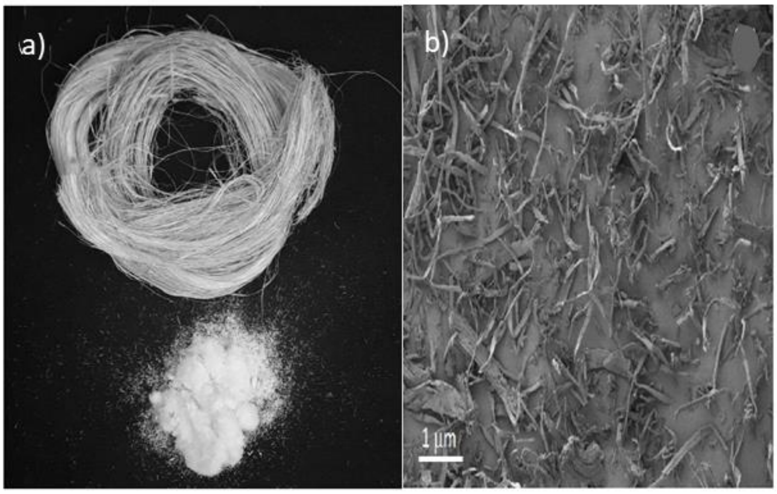


Figure 19 Fibre and cellulose images show a) a photography image of raw banana fibre and extracted cellulose and; (b) an SEM image of cellulose fibrils. [72]

3.9 Charactarization of materials

3.9.1 Honeycomb core properties

3.9.1.1 Density

The density was calculated according to ASTM C271, the standard test method for the density of sandwich core materials. The samples were conditioned, and their mass and volume were recorded, which were used to calculate the density of the core. Equation 1 was used to calculate the core density [77].

$$d = \frac{100000 \times w}{v} \qquad (1)$$

Where d is the density of the sample is (kg/m^3), w is the final mass of the sample after conditioning (g) and v is the final volume of the sample after conditioning(mm^3) [77].

3.10 Testing methods

3.10.1 Adhesive

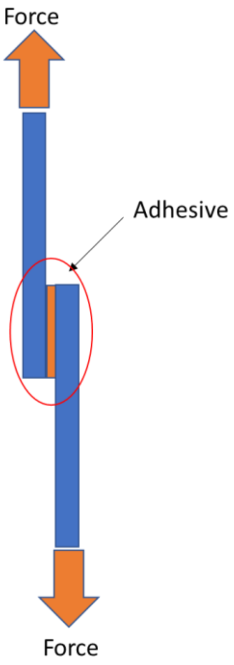


Figure 20 Schematic of lap shear test

The lap shear test was conducted as part of the methodology for this research to evaluate the performance of different types of epoxy adhesives, filled with cellulose and nanoclay as illustrated in Figure 20. The test was conducted using thin sheets of steel bonded with the adhesive and tested on an MTS universal testing machine at a test rate of 0.01mm/s. The objective of the test was to measure the lap shear strength of the adhesive, which represents the maximum load that the adhesive can withstand before failure.

To conduct the test, the steel sheets were first cleaned with isopropyl alcohol to remove any contaminants that could affect the bonding strength. The adhesives were then prepared and applied to the steel sheets in a thin and uniform layer. The second steel sheet was then placed on top ensuring the adhesive-covered bonding area of the sheet and pressure of 60N was applied to ensure good contact between the adhesive and the steel. The adhesive was allowed to cure for the recommended time and temperature, and the samples were conditioned at room temperature for 24 hours before testing.

The lap shear test was conducted using an MTS universal testing. The sample was loaded in the fixture and the test was conducted at a test rate of 0.01mm/s. During the test, the load and displacement data were recorded, and the maximum load was determined. The lap shear strength of the adhesive was then calculated by dividing the maximum load by the bonded area.

The lap shear strength of the different types of adhesives was then compared to evaluate their performance. The lap shear test was a critical component of the methodology for this research paper as it provided valuable data on the performance of different types of epoxy adhesives, filled with cellulose and nanoclay, which can be used to inform future adhesive selection and design in various industries.

3.10.2 Quasistatic 3-Point Flexural Test

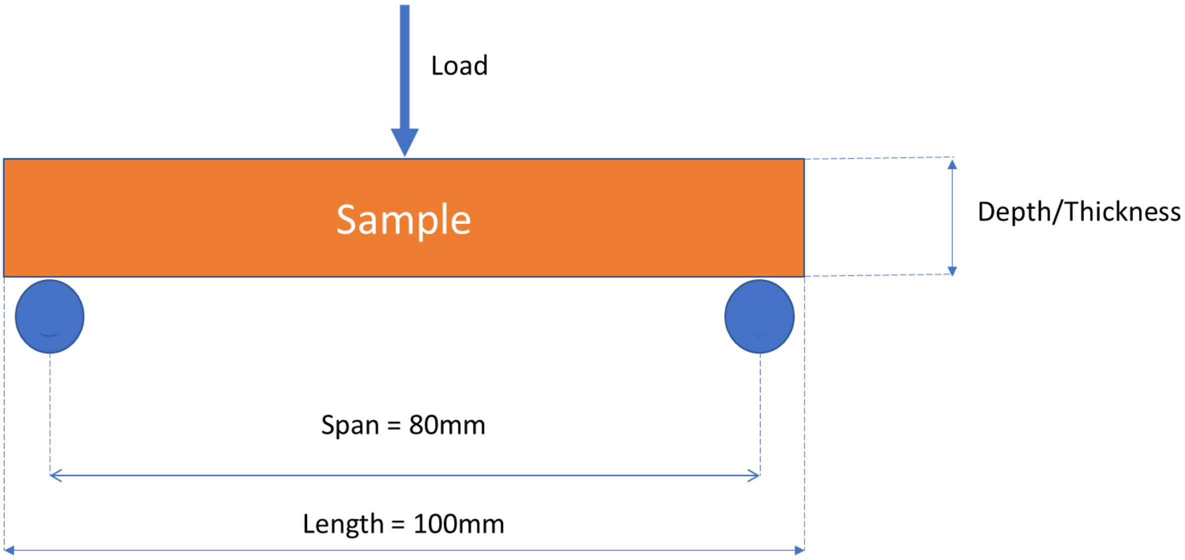


Figure 21 Schematic of three-point flexural test

Three-point bending tests study the bending behaviour of the honeycomb structures. Tests were conducted according to ASTM C393, the standard test method for flexural properties of sandwich constructions at a test rate of 0.03 mm/s. This test method was used to determine the properties of flat sandwich constructions subjected to flatwise flexure in such a manner the applied moments produce curvature of the sandwich-facing planes as illustrated in Figure 21 [78]. All tests were run at room temperature using MTS Criterion (Model 43), an electronic universal testing machine with a load cell capacity of 30 kN. The bend fixture used was set to a span length of 80 mm. The samples were placed into the test fixture and loaded until failure occurred. The load applied and the corresponding displacement was recorded for plotting load-displacement curves. Flexural stress and strain were calculated from the corresponding load-displacement data, to plot stress-strain curves. The sample deformation was photographed throughout testing.

The dimensions of the samples can be seen in Figure 24. Flexural stress, flexural strain, and flexural modulus were calculated [78]. Eq 2 and Eq 3 were used to calculate the core ultimate shear stress and facing bending stress, respectively [78].

$$\tau_{cs} = \frac{P}{(d+c)b} \tag{2}$$

$$\sigma_{fb} = \frac{PL}{2t(d+c)b} \tag{3}$$

where τ_{cs} is the core shear stress (MPa), d is the sandwich thickness (mm), c is the core thickness (mm), b is the sandwich width (mm), σ_{fb} is facing bending stress (MPa), t is the facing thickness (mm) and L is the span length (mm) [78]. The energy absorbed is calculated using Eq 4.

$$EA = \int_0^d F(\delta)d\delta \tag{4}$$

where EA is the energy absorbed (J), d is the collapse distance (mm) from displacement data obtained during three-point flexural test and $F(\delta)$ is the instantaneous force.

3.10.3 Charpy Impact Test

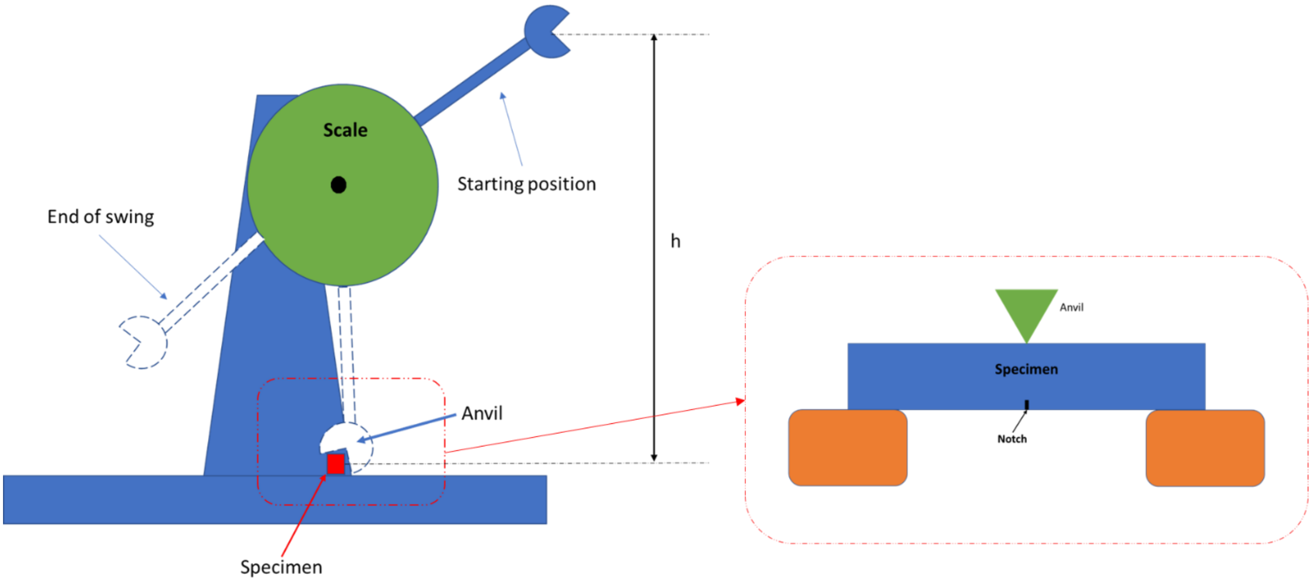


Figure 22 Schematic of Charpy impact test

Charpy is an industry-standardized high-strain rate test used to determine the energy absorbed by a material during fracture. The test measures energy absorbed by a standard notched specimen while breaking under an impact load as illustrated in Figure 22 [79]. The samples were easy to prepare, and tests can be run quickly at a low cost. Figure 24 shows an illustration of the Charpy impact test sample dimensions.

3.10.4 Quasistatic Tensile Test

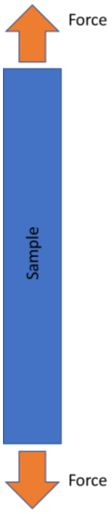


Figure 23 Schematic of tensile test

Tensile testing is a common destructive mechanical testing technique used for composite materials. It helps determine how strong a material is and how much it can extend before failure. Yield strength, ultimate tensile strength, ductility, Youngs modulus and Poisson's ratio of a material can be determined through tensile testing. Tensile testing was performed on samples of flax fibre composite and hybrid flax-glass composite in the form of tension testing according to ASTM D3039, the standard test method for tensile properties of polymer matrix composite materials, at a test rate of 0.03mm/s. This test method determines the in-plane tensile properties of polymer matrix composite materials reinforced by high-modulus fibres as illustrated in Figure 23[80]. The testing was conducted using MTS Criterion, Model 43, an electronic universal testing machine with a load cell capacity of 30kN with tensile grips. Ultimate tensile strength and tensile stress and strain, and the Youngs modulus were calculated [80].

3.10.5 Water absorption

Natural fibres are prone to water absorption due to their cellulose-rich chemical composition and hydrophilic nature. An increase in cellulose content tends to increase water absorption due to the increase in free hydroxyl groups within the fibre. Water absorption was measured according to ASTM C272, the standard test method for water absorption of core materials for sandwich constructions. This test method determines the relative amount of water absorption when immersed in water. It consists of exposing sandwich core specimens to a defined moisture condition and determining the amount of water absorbed by measuring the mass increase in the specimen [81]. Figure 24 illustrates the dimensions of the water absorption samples. Eq 5 was used to calculate the increase in mass [82].

$$Increase\ in\ mass, \% = \frac{W_i - D}{D} \times 100 \tag{5}$$

where W_i is the specimen weight after immersion (g) and D is the pre-immersion mass (g) [82].

3.10.6 Water Contact Angle

The water contact angle is a crucial parameter in the evaluation of the wetting and adhesion properties of fibre-reinforced composites. The American Society for Testing and Materials (ASTM) has specified a standard test method, D7334, for determining the water contact angle on fibre-reinforced composites. An Ossila, Contact Angle Goniometer was used to test and observe the contact angle for a time frame of 10 secs, these results were recorded and used in further calculations to characterise the material. The test was conducted using a 25 microlitre droplet of distilled water with a radius of 10 mm.

The following Eq 6 is used in the calculation of the water contact angle according to ASTM D7334.

$$\theta = \frac{L\theta + R\theta}{2} \tag{6}$$

Where, θ = Average contact angle, L θ = Left contact angle and R θ = Right contact angle.

3.10.7 Quasistatic Compression Tests

Compression testing was carried out on samples according to ASTM C365, the Standard Test Method for Flatwise Compressive Properties of Sandwich Cores. The test was conducted at a test rate of 0.5mm/min. According to this method, core compressive strength can be calculated and, the core compressive modulus (E) is expressed in Eq 7:

$$E = \frac{St}{A} \tag{7}$$

where $S = \frac{dP}{du}$ is the slope of the initial linear portion of the load-deflection curve (N/mm), u is the displacement of the loading block and t is the core thickness (mm) [83].

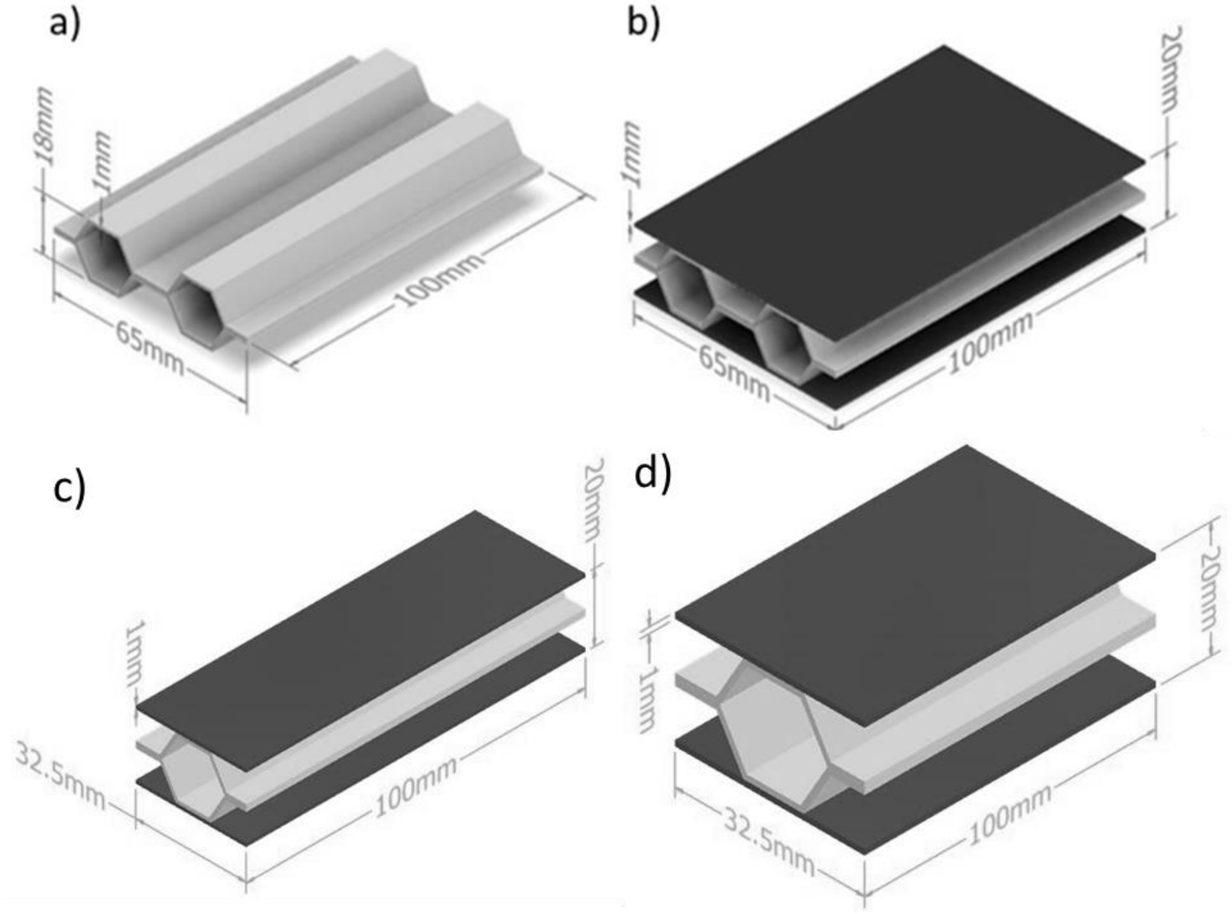


Figure 24 Dimensions of a) honeycomb core, b) honeycomb sandwich structure dimensions for flexural and compression testing, c) Charpy impact sample dimensions and, d) water absorption specimen.

4 Results and discussion

4.1 Material characterisation

4.1.1 Density

The sandwich core densities are presented in Table 2 and Table 3.

Table 2 Densities of in-plane orientated sandwich structure cores.

Sample Adhesive	**Average Mass**		**Average Density**
	g	*SD*	*kg/m^3*
Epoxy	26.116	0.658	22.32
Epoxy-3wt% Cellulose	27.062	0.503	23.13
Epoxy-3wt% Nanoclay	26.866	0.397	22.964

Table 3 Densities of out-of-plane orientated sandwich structure cores.

Sample Adhesive	**Average Mass**		**Average Density**
	g	SD	*kg/m^3*
Epoxy	9.623	0.358	25.16
Epoxy-3wt% Cellulose	9.832	0.330	25.35
Epoxy-3wt% Nanoclay	9.876	0.269	25.26

The epoxy-bonded sandwich structure cores have a slightly lower density. This is possibly due to human error during the layup process, additionally, the quantity of resin expelled was difficult to control as the spacers used to control wall thickness allows the resin to escape during the curing process.

4.1.2. Quasistatic Tensile Results

The samples were constructed out of purely flax fibre and flax-glass fibre were subjected to tensile testing. The load vs displacement curves can be seen in Figure 25, Flax-Flax denotes samples of sole flax and Glass-Flax denotes the hybrid samples.

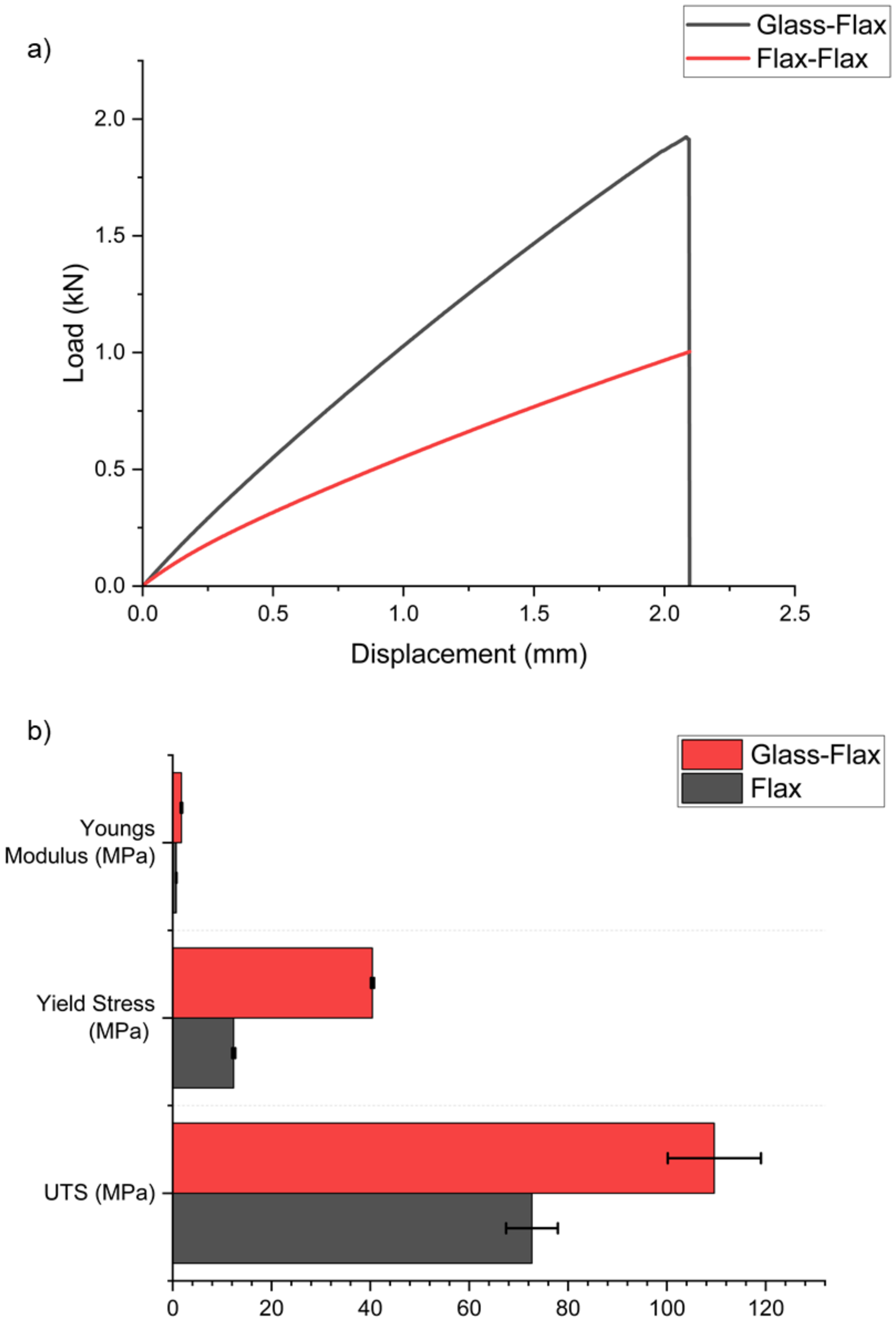


Figure 25 a) Load vs Displacement curves of flax and hybrid samples in tensile and b) average tensile properties

The sample's ultimate tensile strength, yield stress and Young’s modulus were shown in Figure 25. From the results, the use of the hybrid face sheet constructed of flax fibre and glass fibre has significantly improved tensile properties compared to just flax fibre alone. The average tensile performance can be seen in Figure 25.

The hybrid face sheets were found to have superior mechanical properties compared to plain flax samples. Specifically, ultimate tensile strength was increased by 33.653%, while yield stress and Young's modulus improved by 69.446% and 58.731%, respectively. This suggests that choosing hybrid face sheets as the bottom layer that undergoes tension is a better option than using a sole flax fibre face sheet, as the former will perform better. It is worth noting that the peak ultimate strength is not achieved by the plain flax samples, unlike the hybrid samples. In summary, hybrid face sheets are preferred due to their superior mechanical properties over plain flax fibre samples.

4.1.3 Quasistatic 3-Point Flexural Results

The data obtained was used to plot the load vs displacement curves shown in Figure 26.

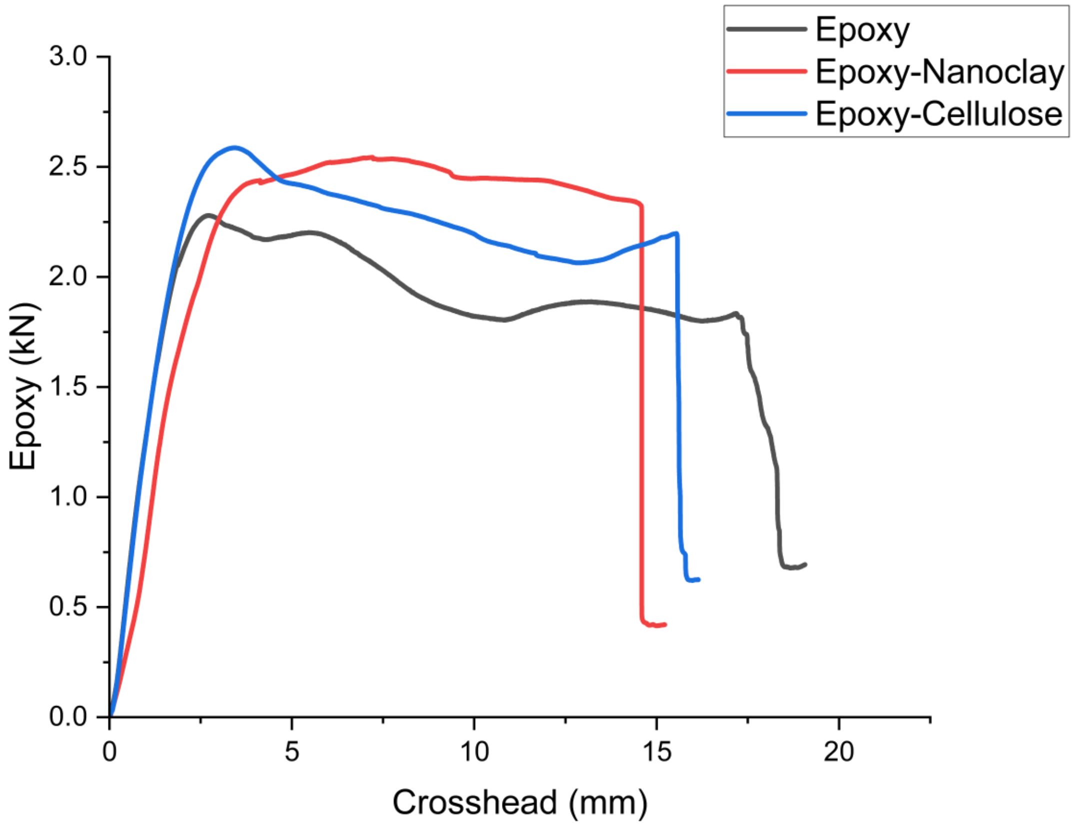


Figure 26 Load-Displacement curves for in-plane sandwich structures

Table 4 Average flexural performance of in-plane sandwich structures.

	Epoxy-3wt%Nanoclay		Epoxy-3wt%Cellulose		Epoxy	
		SD		SD		SD
Flexural Strength (MPa)	11.677	0.671	11.354	0.395	10.569	0.735
Yield Stress (MPa)	8.9	0.319	8.9	0.429	8.55	0.922
Flexural Modulus (MPa)	86.37	4.301	71.55	2.944	71.43	3.377
Core Shear Strength (MPa)	1.03		0.99		0.99	
Facing Bending Stress (MPa)	81.99		79.52		74.2	
Energy Absorbed (J)	44.38	4.05	41.89	6.223	38.808	6.12
Maximum Deflection (mm)	16.924	1.882	16.502	1.998	19.82	3.195

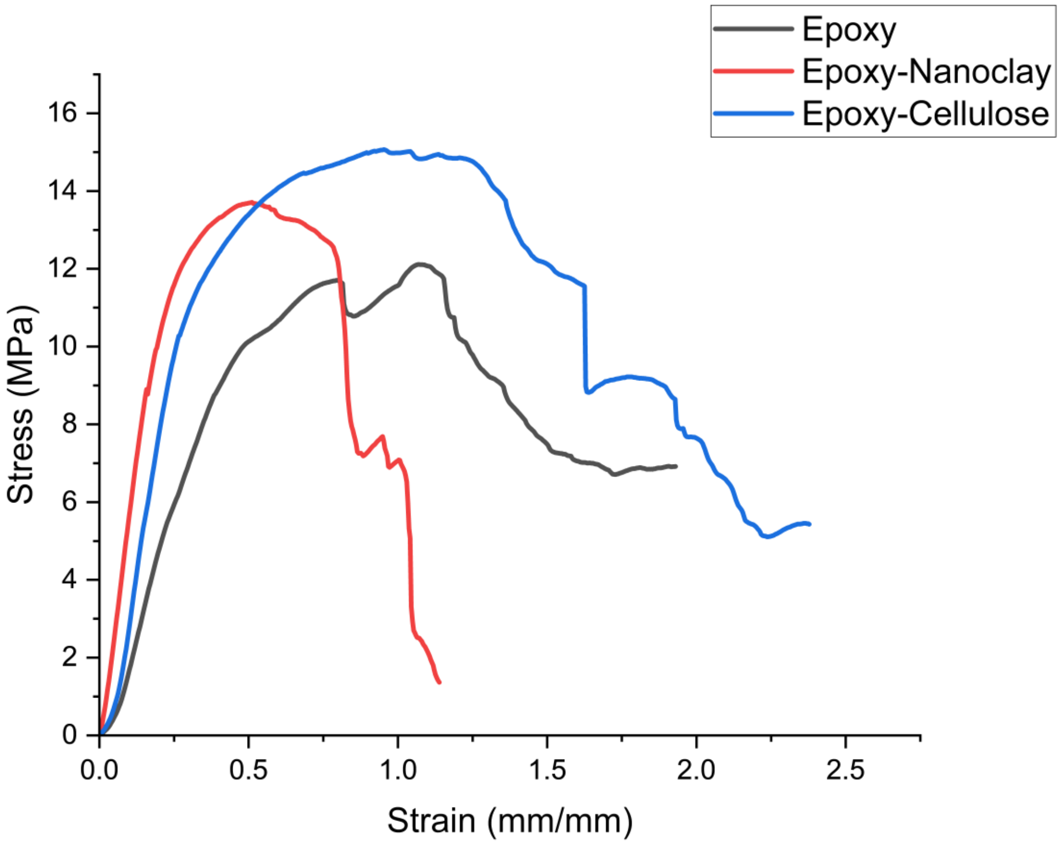


Figure 27 Stress Strain Curve out of plane flexural

Table 5 Average flexural performance of out-of-plane sandwich structures.

	Epoxy-3wt%Nanoclay		Epoxy-3wt%Cellulose		Epoxy	
		SD		SD		SD
Flexural Strength (MPa)	15.21	0.59	14.55	0.36	13.08	0.28
Yield Stress (MPa)	10.72	0.83	9.56	1.18	9.11	0.80
Flexural Modulus (MPa)	48.87	5.28	39.72	4.66	27.98	4.82
Core Shear Strength (MPa)	1.70		1.63		1.46	
Facing Bending Stress (MPa)	0.05		0.05		0.04	
Energy Absorbed (J)	20.31	7.78	25.98	3.06	20.51	3.66

The in-plane maximum load, yield stress, flexural modulus, core shear ultimate strength, facing bending stress and energy absorbed for the sandwich structures were calculated and displayed in Figure 26.

Sandwich structures bonded with virgin epoxy adhesive showed flexural strength of 10.569 MPa, a yield stress of 8.55 MPa, a flexural modulus of 71.43 MPa, a core shear ultimate strength of 0.93 MPa, and an energy absorption of 38.81 J. However, the addition of 3wt% cellulose or 3wt% nanoclay to the epoxy adhesive resulted in improved performance, with both showing increased flexural strength, yield stress, flexural modulus, core shear ultimate strength, facing bending stress, and absorbed energy compared to the virgin epoxy-adhered samples. Figure 26 displays the average flexural performance of the sandwich structures, with the main form of failure observed at the lower face sheet undergoing tension as seen in Figure 28. It's worth noting that while the improved performance of filled adhesives may be due to the type of adhesive used, the samples using adhesives with fillers consist of slightly denser cores compared to the virgin epoxy-adhered samples as shown in Table 2. Overall, the sandwich structures using filled adhesives demonstrated improvement in all properties, with 3wt% cellulose showing an average flexural strength of 11.35 MPa, yield stress of 8.9 MPa, a flexural modulus of 71.55 MPa, the core shear ultimate strength of 0.99 MPa, facing bending stress of 79.52 MPa, and energy absorbed of 41.89 J, while 3wt% nanoclay resulted in improved flexural strength of 11.677 MPa, yield stress of 8.9 MPa, flexural modulus of 86.37 MPa, the core shear ultimate strength of 1.03 MPa, facing bending stress of 81.99 MPa, and absorbed energy of 44.38 J.

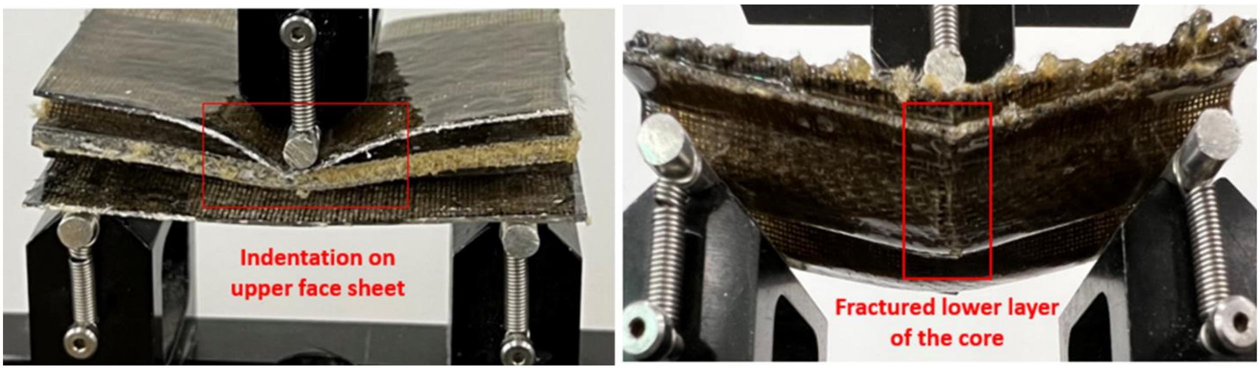


Figure 28 Failure of the sample under three-point loading.

The out-of-plane sandwich structures bonded with 3wt% cellulose and nanoclay improved flexural strength by 10.61% and 15.03%, respectively. Similarly, yield stress, flexural modulus, core ultimate strength and facing bending strength were all improved with the addition of fillers to the adhesive.

Three-point bending and energy absorption were found to be largely influenced by the structural parameters of the honeycomb core and not by the skin thickness [84].

4.1.4. Adhesive lap shear

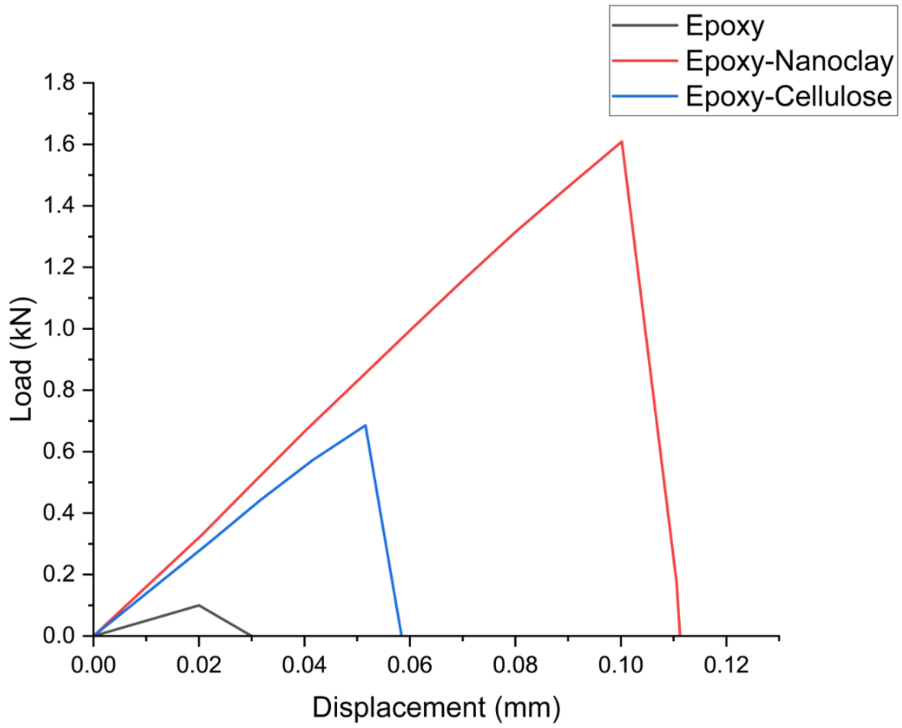


Figure 29 Adhesive lap shear load vs displacement curve

As shown in Figure 29**,** the use of cellulose and nanoclay as an additive in the adhesive resulted in increased adhesive lap shear strength of the bond as compared to the unfilled epoxy adhesive. The results indicate that the fillers have a positive effect on adheison. Notably, the use of nanoclay as a filler performing the best amongst all the samples due to the increase in adhesive properties when used as a filler in the adhesive system.

4.1.5. Quasistatic Compression Results

The load and displacement results obtained from the compression testing were plotted in Figure 30.

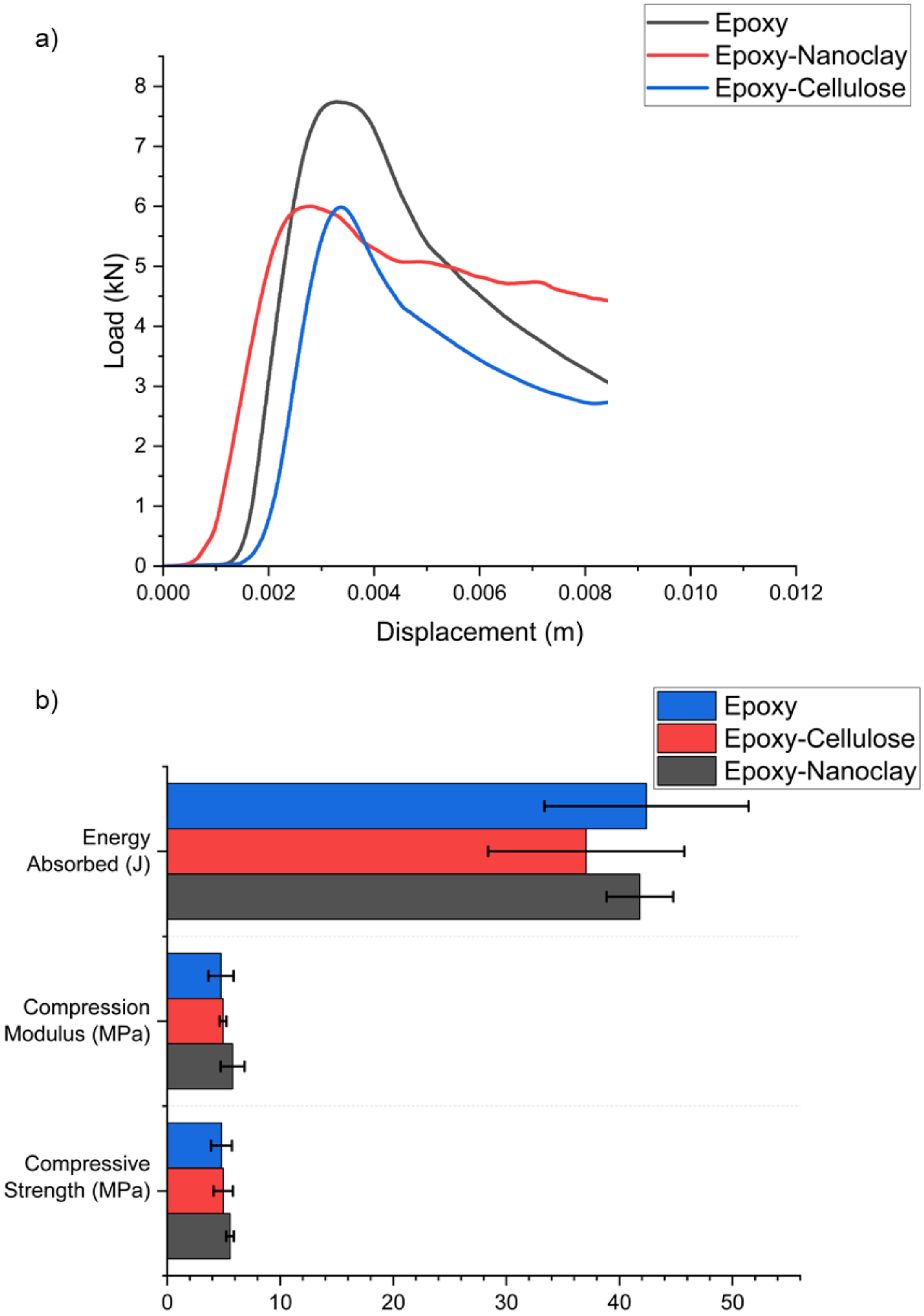

a)
Epoxy
Epoxy-Nanoclay
Epoxy-Cellulose
Load (kN)
0
1
2
3
4
5
6
7
8
Displacement (m)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
b)
Epoxy
Epoxy-Cellulose
Epoxy-Nanoclay
Energy Absorbed (J)
Compression Modulus (MPa)
Compressive Strength (MPa)
0
10
20
30
40
50

Figure 30 Load-Displacement curve for in-plane sandwich structures under compression and average in-plane orientated compressive properties.

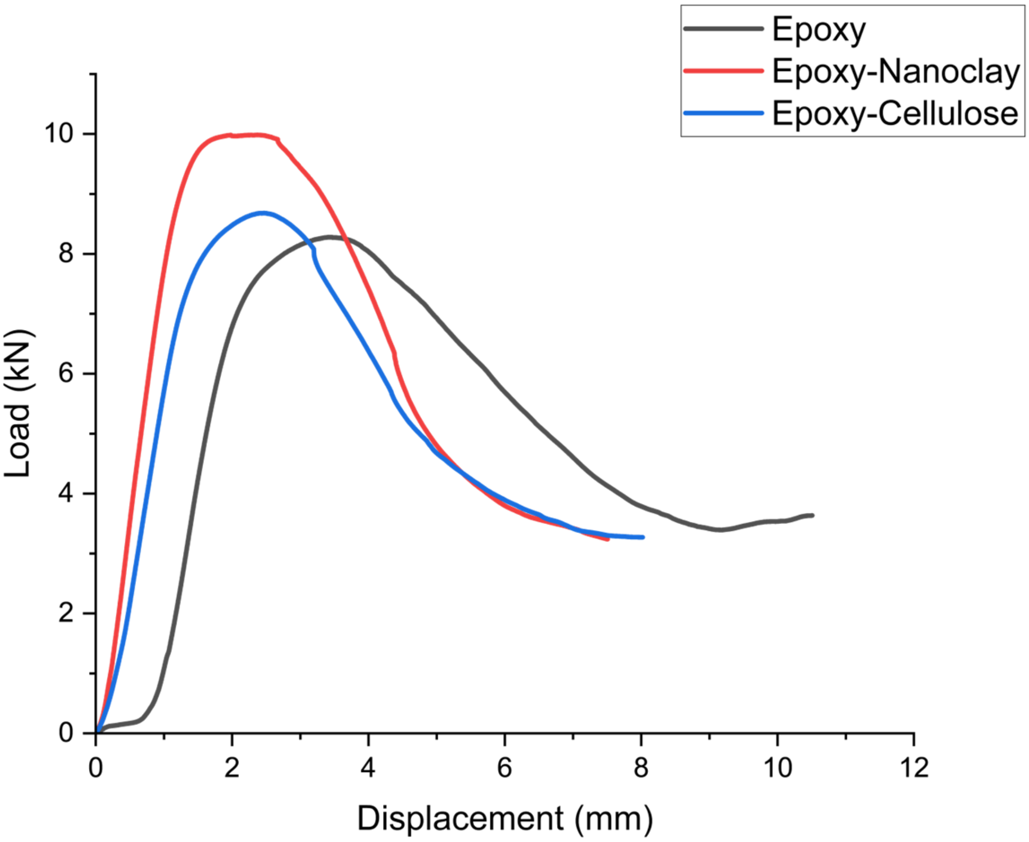


Figure 31 Load-Displacement curve for out-of-plane sandwich structures under compression

Table 6 Average out-of-plane compressive properties

	Fmax		Compressive Strength		Modulus		Energy Absorbed	
Sample Adhesive	kN	SD	MPa	SD	MPa	SD	J	SD
Epoxy	8.36	0.59	6.43	0.59	5.99	1.711	53.27	2.82

Epoxy-3wt%Cellulose	8.97	0.76	6.90	0.76	6.38	1.25	41.08	4.30
Epoxy-3wt%Nanoclay	10.04	0.50	7.72	0.50	7.77	1.23	61.14	10.25

The sample's ultimate compression strength and compression modulus were illustrated in Figure 30.

Based on the results, the in-plane orientated sandwich structures bonded with virgin epoxy as an adhesive displayed the highest ultimate compressive strength and compression modulus. However, the addition of cellulose or nanoclay into the adhesive resulted in a reduction of these properties. The ultimate compressive strength decreased by 12.18% and 15.19% for cellulose and nanoclay, respectively, while the compression modulus decreased by 17.23% and 21.56%. Despite these decreases in compressive strength, it is worth noting that the structures bonded with virgin epoxy showed the best overall performance, with an ultimate compressive strength of 5.56 MPa and a compression modulus of 5.79 MPa.

The out-of-plane orientated structures showed an ultimate compressive strength increase by 7.32% and 20.1% for cellulose and nanoclay, respectively, while the compression modulus increased by 6.6% and 29.65%. Despite these decreases in compressive strength, it is worth noting that the structures bonded with nanoclay filled epoxy showed the best overall performance, with an ultimate compressive strength of 7.72 MPa and a compression modulus of 7.77 MPa, outperforming their in-plane counterparts due to the increase in compressive area of the out-of-plane samples.

4.1.6. Charpy Impact Results

Notched samples of the sandwich structures were subjected to Charpy impact testing, with the results shown in Figure 32. The in-plane orientated samples bonded solely with epoxy adhesive displayed an average impact strength of 32.88J. The addition of cellulose or nanoclay to the adhesive resulted in increased impact strength, with the structures using cellulose and nanoclay absorbing impacts of 35.73J and 35.81J, respectively. To normalise the effect of the samples' area, the impact strength was normalized, resulting in average strengths of 11.80 J/mm^2, 12.32J/mm^2, and 12.7424 J/mm^2 for epoxy, epoxy-cellulose, and epoxy-nanoclay, respectively.

The out-of-plane samples bonded solely with epoxy adhesive displayed an average impact strength of 42.13J. The addition of cellulose or nanoclay to the adhesive resulted in increased impact strength, with the structures using cellulose and nanoclay absorbing impacts of 42.3J and 46.33J, respectively. To negate the effect of the samples' area, the impact strength was normalized, resulting in average strengths of 12.96J/mm^2, 13.01J/mm^2, and 14.25J/mm^2 for epoxy, cellulose-epoxy, and nanoclay-epoxy, respectively.

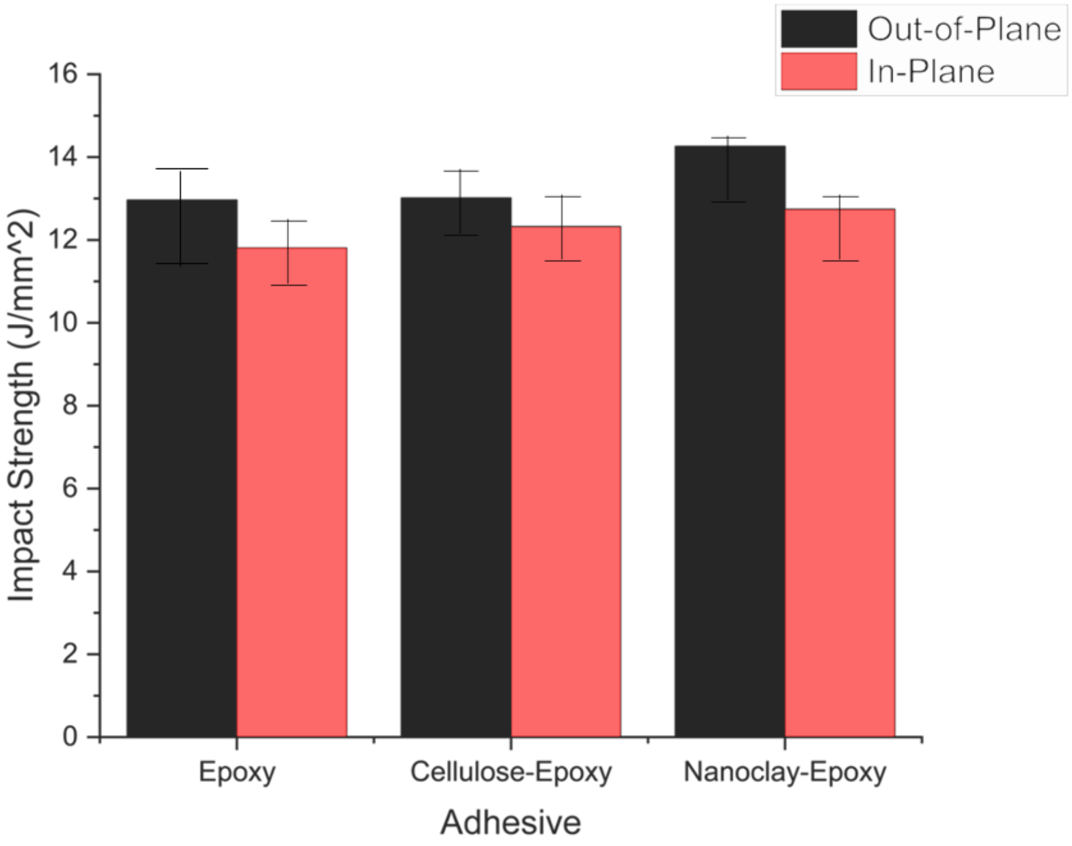


Figure 32 Impact properties of the sandwich structures.

The results indicate the addition of cellulose and nanoclay has improved the impact absorbed by the structure.

4.1.7. Water Absorption Results

The increase in the mass of the sample is displayed in Figure 33.

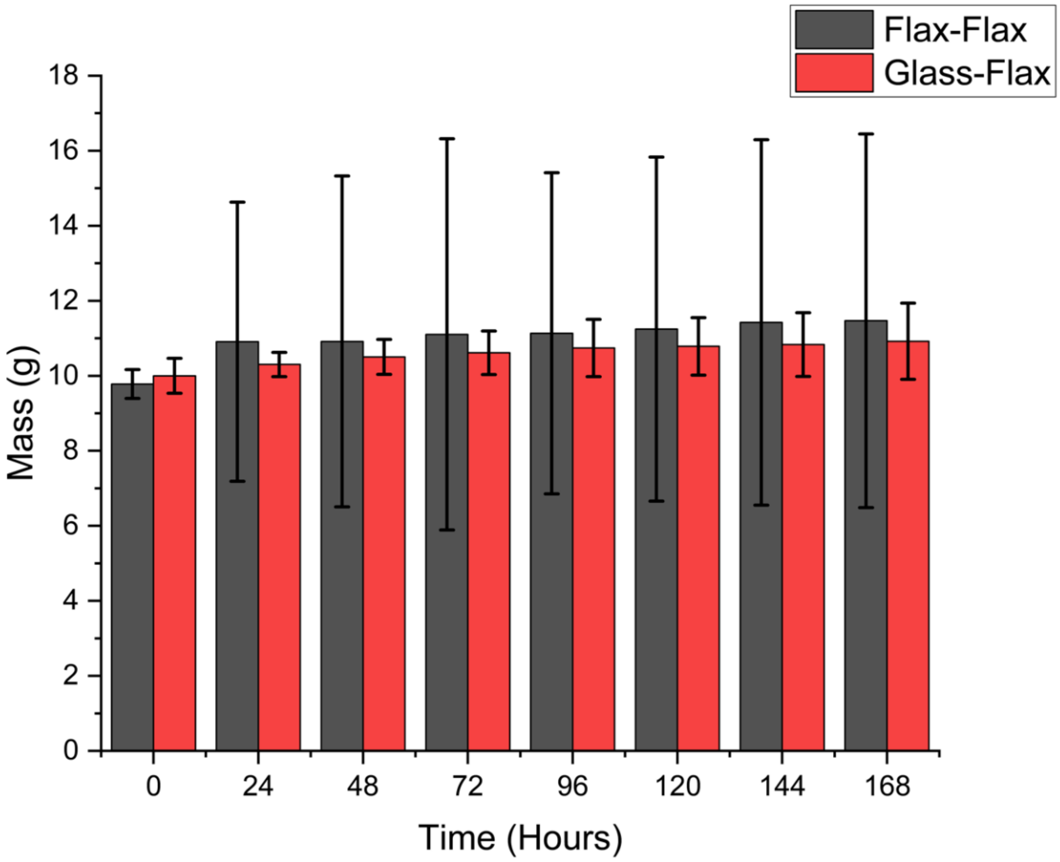


Figure 33 Water absorption for 24hr intervals

Figure 33 shows that the sole flax sandwich structures experienced an average increase in mass of 11.88% over 168 hours, while the hybrid face sheet sandwich structures showed an average increase in mass of 6.31%. This indicates that the use of a hybrid face sheet, which includes an outer ply of glass fibre, was successful in providing moisture resistance for the natural fibre sandwich structures. The water resistance properties of the sandwich structures were evaluated, and the results demonstrate that the mass of the sandwich structures using solely flax fibre face sheets increased by 11.88% after 168 hours of exposure. In contrast, the hybrid face sheets led to a mass increase of 6.31%. Thus, the hybrid face sheets proved to be an effective solution for improving the composite's resistance to water.

4.1.8. Water Contact Angle Results

In this study, both the flax and hybrid flax-glass skins exhibited hydrophilic behaviour, indicating their affinity for water. Both variations behaved hydrophobically since their measured contact angles exceeded 90°. However, the study revealed that the sole flax skin's average contact angle fluctuated significantly over time, indicating a change in its hydrophilic behaviour. Conversely, the hybrid skin demonstrated more consistent values in its average contact angle, with an increase in values occurring later in the test. This implies that the hydrophilic behaviour of the hybrid skin was more stable and uniform than that of the sole flax skin. The flax facing had an instantaneous contact angle of 116.74°, and the hybrid glass and flax facing had a contact angle of 91.31°.

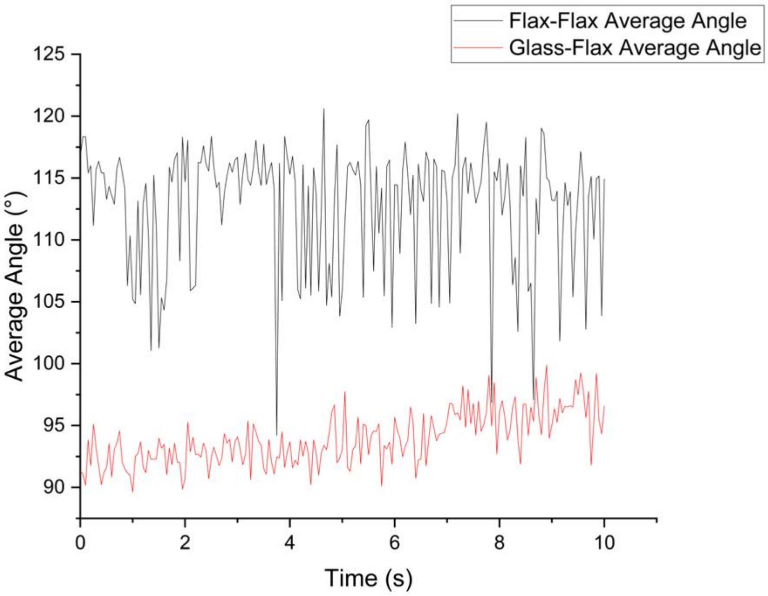


Figure 34 Average water contact angle vs time

4.1.9. Strength-to-Weight Ratio

The strength-to-weight ratio of honeycombs refers to the relationship between the mass of a honeycomb structure and the weight it can support. Honeycomb structures are known for having an exceptional strength-to-weight ratio, due to their geometric shape, which provides a balance between structural integrity and material usage. It was observed that the use of cellulose and nanoclay as an adhesive additive improved the strength to weight of the structures in flexural and compression loading. However, a negative effect was observed in compression for in-plane samples, while improved in out-of-plane samples.

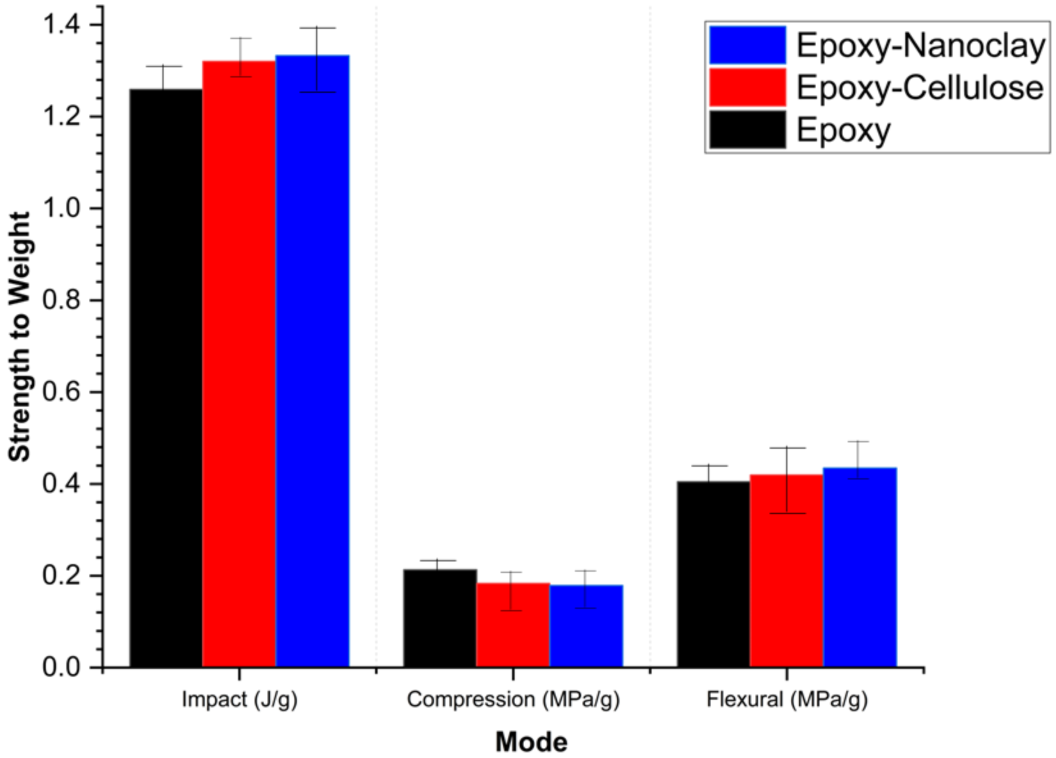


Figure 35 Strength to weight in-plane

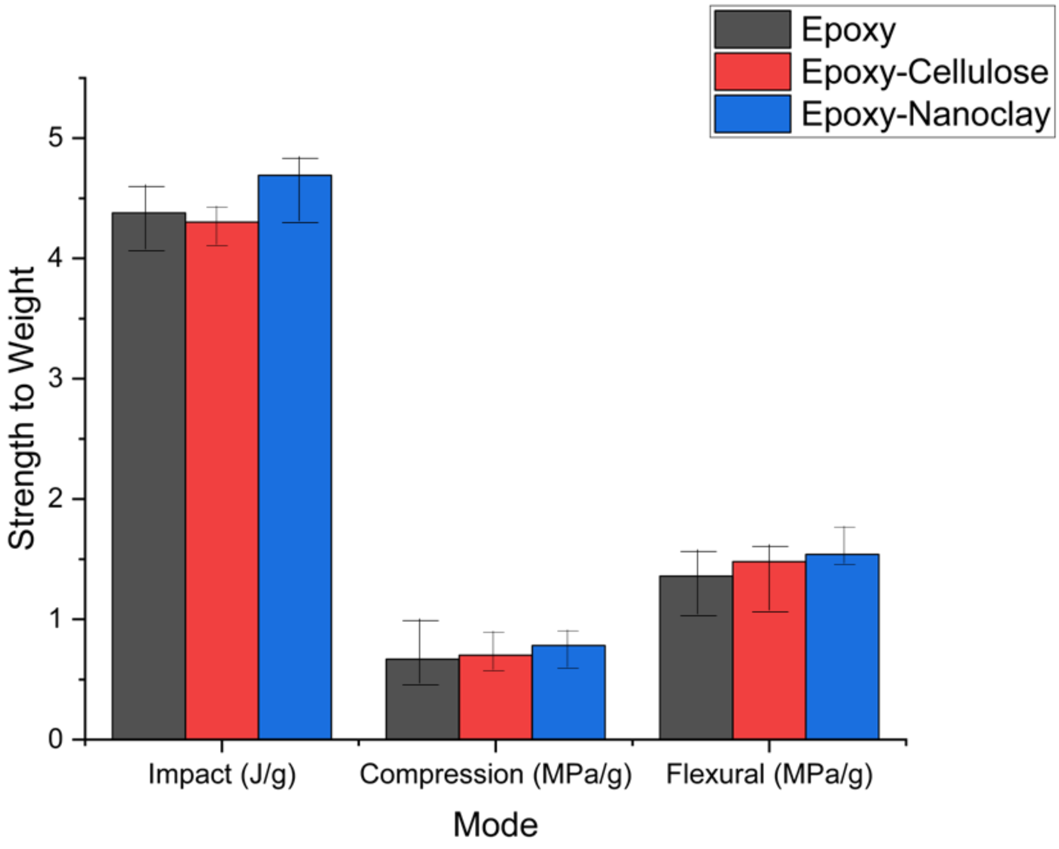


Figure 36 Strength to weight out-of-plane.

Strength-to-weight characteristics of the sandwich structures, as seen in Figure 35 and Figure 36. Overall, the strength of the structures performs comparatively to traditional honeycomb materials such as Nomex and aluminium, while being constructed of sustainable flax.

4.2. Comparative Analysis of Core Materials

The comparative analysis of the flax fibre honeycomb core structures was performed against Nomex and aluminium honeycomb cores, as well as paper and Kevlar honeycomb cores. The results revealed that the flax fibre honeycomb core structures had comparable performance to the other honeycomb cores tested. Specifically, the flax fibre structures demonstrated 20.77% higher max flexural stress than Nomex honeycomb cores [85], and 2.86% higher max flexural stress than aluminium honeycomb cores [86]. Furthermore, the flax structures showed 214.29% higher normalised impact strength compared to paper honeycomb cores and face sheets [87], and 123.89% higher normalised impact strength compared to Kevlar honeycomb cores [88]. Based on these results, it can be inferred that the flax fibre honeycomb core sandwich structures bonded with cellulose-nanoclay as the adhesive performed excellently under flexural and impact loading.

4.3. Discussion on the influence of process parameters on mechanical properties

The study found that flax fibre honeycomb core structures provide a sustainable alternative to traditional honeycomb core structures made of aluminium and Nomex. Additionally, additive manufacturing was demonstrated as a viable method for forming moulds for fabricating cellular structures. The flax fibre honeycomb cores were transformed into sandwich composite panels by bonding the cores to hybrid flax and glass fibre face sheets. The resulting in-plane sandwich structures, bonded with virgin epoxy, showed a flexural strength of 10.57 MPa, yield stress of 8.55 MPa, a flexural modulus of 71.43 MPa, core shear ultimate strength of 0.93 MPa, facing bending stress of 74.20 MPa, and absorbed energy of 38.81 J. The addition of 3wt% cellulose to the epoxy resulted in a 7.43% increase in flexural strength, a 4.09% increase in yield stress, a 0.17% increase in flexural modulus, a 6.45% increase in core shear ultimate strength, a 7.17% increase in facing bending stress, and a 7.94% increase in absorbed energy. The addition of 3wt% nanoclay to the epoxy increased flexural strength by 10.48%, yield stress by 4.09%, flexural modulus by 20.92%, the core shear ultimate strength by 10.75%, facing bending stress by 10.5%, and absorbed energy by 14.37%. The out-of-plane sandwich structures bonded with 3wt% cellulose and nanoclay improved flexural strength by 10.61% and 15.03%, respectively. Similarly, yield stress, flexural modulus, core ultimate strength and facing bending strength were all improved with the addition of fillers to the adhesive. The in-plane sandwich structures also showed an average impact strength of 32.88 J for the unfilled epoxy bonded structures after Charpy impact testing. The cellulose and nanoclay filled adhesive absorbed 35.73J and 35.81J, an improvement over the solely epoxy bonded structures by 8.67% and 8.91%. The out-of-plane samples bonded solely with epoxy adhesive displayed an average impact strength of 42.13J. The addition of cellulose or nanoclay to the adhesive resulted in increased impact strength, with the structures using cellulose and nanoclay absorbing impacts of 42.3J and 46.33J, respectively. To negate the effect of the samples' area, the impact strength was normalized, resulting in average strengths of 12.96J/mm2, 13.01J/mm2, and 14.25J/mm2 for epoxy, cellulose-epoxy, and nanoclay-epoxy, respectively. However for in-plane, the compression testing revealed that the additives had a negative effect on the properties. The structures bonded with virgin epoxy showed the best performance, with an ultimate compressive strength of 5.56 MPa and a compression modulus of 5.79 MPa. The addition of cellulose reduced the ultimate compressive strength by 10.79% and compression modulus by 14.7%, while the addition of nanoclay reduced the ultimate compressive strength by 13.6% and compression modulus by 17.74%. The out-of-plane orientated structures showed an ultimate compressive strength increase by 7.32% and 20.1% for cellulose and nanoclay, respectively, while the compression modulus increased by 6.6% and 29.65%. Despite these decreases in compressive strength, it is worth noting that the structures bonded with nanoclay filled epoxy showed the best overall performance, with an ultimate compressive strength of 7.72 MPa and a compression modulus of 7.77 MPa, outperforming their in-plane counterparts due to the increase in compressive area of the out-of-plane samples. The tensile strength of plain flax fibre and hybrid flax-glass fibre was evaluated. The results showed that the hybrid face sheets exhibited 33.65% higher ultimate tensile strength compared to the plain flax fibre samples. Additionally, the hybrid face sheets displayed 69.45% increase in tensile strength and a 58.73% improvement in yield stress and Young's modulus, respectively, when compared to solely flax fibre. Thus, the choice of hybrid face sheets was deemed preferable. The water resistance properties of the face sheets in sandwich structures were also assessed. The results indicated that the mass of sandwich structures using solely flax fibre face sheets increased by 11.88%

after 168 hours of exposure, while the structures using hybrid face sheets experienced a mass increase of 6.31%. This confirms that hybrid face sheets are an effective solution for improving the composite's water resistance properties.

The strength-to-weight ratio of honeycombs refers to the relationship between the weight of a honeycomb structure and the amount of weight it can support before collapsing. Honeycomb structures are known for having an exceptional strength-to-weight ratio, due to their geometric shape, which provides a balance between structural integrity and material usage. It was observed that the use of cellulose and nanoclay as an adhesive additive improved the strength to weight of the structures in flexural and compression loading. However, a negative effect was observed in compression.

Strength to weight characteristics of the sandwich structures undergoing flexural and impact has improved with addition of cellulose and nanoclay in the adhesive, respectively. However, in compression, the structures with cellulose and nanoclay added to the adhesive performed worse than the unfilled adhesive bonded structures, respectively. Overall, the strength of the structures performs comparatively well to traditional honeycomb materials such as Nomex and aluminium, while being constructed of a sustainable flax.

4.4. Comparison with traditional honeycomb sandwich structures

Comparative analysis revealed that the flax fibre honeycomb core structures had comparable performance to Nomex and aluminium honeycomb cores. The flax fibre honeycomb core structures demonstrated 20.77% higher max flexural stress compared to Nomex honeycomb cores [85], and 2.86% higher max flexural stress compared to aluminium honeycomb cores [86]. The flax structures also showed 214.29% higher normalised impact strength compared to paper honeycomb cores and face sheets [87] and 123.89% higher normalised impact strength compared to Kevlar honeycomb cores [88]. The results suggest that the flax fibre honeycomb core sandwich structures bonded with nanoclay as the adhesive performed best under flexural loading. The choice of hybrid face sheets was preferred for their improved tensile strength, water barrier properties, and overall flexural performance.

5 Conclusions

5.1 Summary of research findings

This study used natural fibre-reinforced polymer composite samples infused with nanofillers, namely, cellulose and nanoclay, to improve the mechanical properties. The use of additive manufacturing to construct moulds to be used in the production of natural fibre-reinforced honeycomb cores has been proven viable.

1. The corrugated process for fabricating honeycomb cores has revealed promising mechanical properties, demonstrating the viability of utilizing additively manufactured moulds. This approach results in the production of composites with a high-quality surface finish.

   The study has shown that the corrugated process for fabricating honeycomb cores has the potential to yield composites with good mechanical properties, thanks to the utilization of additively manufactured moulds.
2. The results showed that the addition of fillers to the adhesive had a significant impact on both the flexural and impact properties of the structures. The addition of cellulose and nanoclay to the epoxy adhesive led to an increase in flexural strength by 7.43% and 10.48%, respectively. Under impact loading, the structures using cellulose and nanoclay in the adhesive absorbed 8.67% and 8.91% more impact energy than those bonded solely with epoxy.

   On the other hand, the addition of cellulose and nanoclay to the adhesive resulted in a decrease in compressive strength by 10.79% and 13.6%, respectively. The improved impact and flexural properties can be attributed to the improved interfacial adhesion due to the improved surface interlocking during the bonding process. However, in compression, the main form of failure occurred at the plastic hinges of the honeycomb structure without any effect on the bonding locations.

The results of this study demonstrate that the addition of fillers to the adhesive can have a significant impact on the performance of honeycomb core sandwich structures, affecting both the flexural and impact properties. Further research is needed to optimize the use of fillers and balance the trade-off between the positive effects on flexural and impact properties and the negative effects on compressive strength.

3. The study evaluated the performance of glass and flax hybrid facings as compared to solely flax facings in terms of their hydrophobicity and barrier properties. The results showed that the use of hybrid facings improved the performance of natural fibre composites under tension and as a moisture barrier. The hybrid facings showed to be hydrophobic, leading to a reduction in water uptake compared to solely flax facings. The tensile strength of the structures using hybrid facings was found to be 69.45% higher than those using solely flax facings. Additionally, the water absorbed by structures using hybrid facings was reduced by 46.89%.

   The findings of this study highlight the impact of hybridization on the moisture barrier performance of natural fibre composites. The use of glass and flax hybrid facings was found to be hydrophobic and offered improved performance under tension and as a moisture barrier, with reduced water uptake compared to solely flax facings. These results demonstrate the potential for the use of hybrid facings to improve the performance of natural fibre composites in moisture-prone environments.

In conclusion, the study of woven flax fabric fibre-reinforced polymer composites as honeycomb cores for sandwich structures, with a focus on the use of cellulose and nanoclay as adhesive fillers, holds significant implications for the development of more versatile and sustainable materials for a wide range of applications. The utilization of cellulose and nanoclay as green-fillers has the potential to enhance the bonding and performance of these composites, making them more suitable for use in various applications such as construction, transportation, and packaging. Furthermore, the use of the corrugation manufacturing process, particularly through the use of Fused Deposition Modelling (FDM) or 3D printing, provides a low-cost, flexible, and efficient method for producing high-quality moulds for fabricating natural fibre honeycomb cores, using the corrugation method.

This highlights the significance of understanding the relationship between the composition and processing of fibre-reinforced composites and their final properties, and the potential of cellulose and nanoclay as effective adhesive fillers. The findings of this research could inform the development of cost-effective, efficient, and sustainable materials for various applications, thereby contributing to the advancement of the field of composites.

5.2 Implications and future work

The findings of the study on the fabrication and analysis of cellular bio-nanocomposite sandwich structures have profound implications for the future of sustainable and durable construction materials. By utilizing natural fibres, cellulose-nanoclay filled bio-based adhesive, and 3D printing technology, this study presents an environmentally friendly alternative to conventional synthetic composite materials.

One major implication of this research is the broad range of potential applications for these structures, including construction, packaging, and aerospace industries. The structures exhibit exceptional strength, durability, and resistance to water absorption, making them ideal for demanding applications. Additionally, the incorporation of natural fibres enhances their sustainability and reduces environmental impact compared to traditional synthetic composites.

Furthermore, the study highlights the significant role of 3D printing technology in fabricating moulds for honeycomb structures. The precise control over shape and size offered by 3D printing enables the creation of structures with tailored properties, opening up new possibilities for sustainable and durable construction materials. This innovative approach has the potential to revolutionize the design and fabrication processes, ushering in a new era of sustainable construction.

The use of cellulose-nanoclay filled bio-based adhesive in these structures is another noteworthy implication. This adhesive provides robust bonding and improved durability, crucial characteristics for their implementation in demanding applications. Moreover, the utilization of cellulose-nanoclay filled bio-based adhesive further enhances the structures' environmental friendliness, adding to their overall sustainability.

Lastly, the integration of artificial intelligence (AI) in the future development of these structures holds immense potential. AI can analyse the study's findings and contribute to the advancement of fabrication and analysis techniques for these structures. By optimizing mechanical properties and overall performance, AI-driven improvements can make the structures even more suitable for demanding applications, further solidifying their value in sustainable construction.

In conclusion, the study on cellular bio-nanocomposite sandwich structures sheds light on the immense potential of sustainable and durable construction materials. The use of natural fibres, cellulose-nanoclay filled bio-based adhesive, and 3D printing technology holds great promise for the future of environmentally friendly construction materials. Moreover, the integration of AI in the future development of these structures offers exciting possibilities for their utilization in various applications.

5.3 Concluding remarks

In conclusion, this study has successfully achieved its aims by investigating the potential of flax fibre honeycomb sandwich structures as a sustainable and durable alternative in structural applications. The results have shown that the use of 3D printing technology to fabricate moulds for the honeycomb structure is viable and provides precise control over the shape and size of the structure. The use of cellulose and nanoclay as fillers in the adhesive has improved the mechanical properties of the structures, while the use of hybrid flax and glass face sheets has provided better performance under tension and moisture resistance. The findings of this study highlight the potential of flax fibre honeycomb sandwich structures as a sustainable and durable alternative in structural applications and provide valuable insights for future studies in this field. The results also demonstrate the importance of core density in the performance of the structures. Overall, this study has made a significant contribution to the development of sustainable and environmentally friendly construction materials and has the potential to have a significant impact on the future of the construction industry.

5.4 Publications based on this thesis

Peer-reviewed journal papers:

1. Govender S, Mohan TP,Kanny K. Effect of nanoclay-cellulose adhesive bonding and hybrid glass and flax fiber face sheets on flax fiber honeycomb panels. Polym Compos.2023;1-12. doi:10.1002/pc.27450

Peer-reviewed book chapters

1. S. Govender, T.P. Mohan, K. Kanny. Chapter 6, Surface modification and its effect on interfacial properties. Book title: Bast Fibers and Their Composites, Springer Series on Polymer and Composite Materials. Pp. 95-122, 2022. Editors: G. Rajesh Kumar, G.L. Devnani, Shishir Sinha, M. R. Sanjay, Habil Suchart Siengchin, Springer Nature, Singapore. ISBN 978-981-19-4865-7 (Hardback). DOI: 10.1007/978-981-19-4866-4

2. Sumeshan Govender, TP Mohan, K Kanny. Nanofillers: A review of their fabrication and application. Handbook of Nanofillers. Springer Nature Singapore Pte Ltd. (Submitted: 15 May 2023)

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[1] L. Wahl, S. Maas, D. Waldmann, A. Zürbes, and P. Frères, "Shear stresses in honeycomb sandwich plates: Analytical solution, finite element method and experimental verification," *Journal of Sandwich Structures & Materials,* vol. 14, no. 4, pp. 449-468, 2012.

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