Mechanical Characterization of Natural and Synthetic Fibres using Sandwich Structures Under Bending

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Abstract: Fibre-reinforced sandwich panels are a well stablished design solution for applications that require high stiffness and low weight, but the high cost and enviromental impact of synthetic fibres have prompted the research for sustainable alternatives, such as natural fibres. While they offer potential for cost reduction and environmental sustaintalibity, their mechanical properties may compromise structural reliability. In this context, this work compares the equivalent stiffness of different composite sandwich panels under bending, using carbon, glass, linen, jute and cotton fibres as reinforcement. The specimens were produced using the Vacuum Assisted Resin Transfer Moulding (VARTM) and tested under four point bending conditions. Analytical methods were used for mechanical characterization, followed by Finite Element Method (FEM) validation. The results show that carbon fibre yields a greater stiffness-to-weight ratios followed by glass, jute, linen and cotton fibres. Sandwich panels with natural fibres reinforcement showed relative bending performances ranging from 19% to 35% of the carbon fibre ones.

Keywords: Composite Materials, Natural Fibres, Sandwich Structure, Finite Element Method.

1. INTRODUCTION

High-performance structures for aeronautical and naval applications have driven designers to overcome material limitations by combining two or more constituents in composite systems [1]. In this regard, continuous fibre-reinforced composites, such as carbon fibre, are widely adopted due to their higher strength-to-weight and stiffness-to-weight ratios [2]. Moreover, sandwich structures, formed by two fibre reinforced composites and a low-density core, offer excellent bending stiffness and strength while maintaining low overall weight [3]. As a cost-effective alternative to synthetic fibre reinforcements, natural fibres have gained visibility for structural applications. However, their use present challenges, primarily due to the inherent variability in their mechanical properties, which are less consistent than those of synthetic counterparts.

Sadeghian *et al*. [4] investigated the bending behaviour of sandwich composite beams with fibre-reinforced polymer (FRP) skins and lightweight cores, comparing natural and synthetic fibre. Glass and linen fibres were analysed, as along with cork and polypropylene honeycomb cores. The results showed that natural materials, such as linen and cork, exhibited promising structural performance, comparable to that of synthetics alternatives. Similarly, Blanchardt *et al*. [5] highlighted that although natural composites may not perform as well as conventional synthetic fibres, their low density and reduced environmental impact make them viable for secondary structural applications.

The geometry of the core plays a decisive role in the mechanical performance of sandwich panels, directly influencing parameters such as deflection, stiffness and stress distribution. For instance, trapezoidal core configuration, for example, show superior performance compared to those with a sinusoidal geometry, particularly in terms of deflection control and stress behaviour [6]. Tetrahedral cores structures, on the other hand, show significant mechanical anisotropy, which directly affects the stress-strain response under bending loads [7]. In recent studies, Thiagarajan & Munusamy [8] demonstrated that the combination of composite faces, such as carbon fibre sheets, with aluminium honeycomb cores can achieve tensile and flexural strengths of up to 444 MPa and 842 MPa, respectively. Manufacturing methods, such as hand lay-up or autoclave curing, also significant influence final properties, especially flexural strength and impact absorption [9]. Due to their high structural efficiency and ability to reduce weight without compromising performance, sandwich panels remain essential components in the aerospace and maritime industries. Ongoing research has focused on improving their mechanical behaviour, improving damage tolerance, and incorporating environmentally sustainable materials to meet increasingly stringent industry requirements [10-16].

Tensile testing remains a fundamental method for characterizing composite materials, providing key properties such as tensile strength, modulus of elasticity, and strain at failure. To ensure the standardization and reliability of these tests, standards

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such as ASTM D3039 are widely used [17]. Parallel to experimental methods, the Finite Element Method (FEM) has become an established tool for predicting properties such as equivalent Young's modulus in composites, enabling detailed simulations of their mechanical response under various loading conditions. Theoretical models, such as Halpin-Tsai equations, are often integrated into FEM analyses to relate elastic properties to microstructural parameters as, reinforcement volume fraction and the aspect ratio. These numerical approaches have been validated by experimental comparisons, confirming their ability to predict composite behaviour with good accuracy. Furthermore, the exploration of different reinforcement configurations in simulations contributes to a deeper understanding of the geometric effects on the overall performance of composites [18].

However, the application of FEA (Finite Element Analysis) can require unstructured meshes, and high computational resources, as well as presenting challenges in controlling parameters and boundary conditions, particularly in models based on representative unit cells [19]. In this context, analytical methods, such as those based on the Chamis and Tsai-Halpin equations, offer attractive alternative due to their simplicity and scalability in predicting properties such as modulus of elasticity and Poisson's ratio [20]. While these methods can show comparable accuracy to FEA in estimating longitudinal properties -, such as modulus in the direction of the fibre and Poisson's ratio, FEA remains more precise for predicting transverse properties, such as shear modulus and through-thickness elasticity [20]. Therefore, the integration of experimental results with numerical analysis increases the reliability of design processes in real-world designs such as medical applications [21].

In view of the growing global interest in sustainable materials for structural applications, this work aims to evaluate the mechanical properties of different fibres reinforcements within sandwich structure under bending loads. Both natural fibres, such as jute, linen, and cotton, and synthetic fibres, such as carbon and glass, were investigated. The sandwich specimens were manufactured using the Vacuum Assisted Resin Transfer Moulding (VARTM) process, ensuring uniformity and quality in the materials. Four-point bending tests were carried out on a universal testing machine, INSTRON EMIC 23-100, to characterize the mechanical performance of the samples. An analytical expression was used for equivalent bending stiffness tailored to sandwich structures composed of thin sheets of composite material and low-density core. In addition, a numerical model based on the Finite Element Method (FEM) was developed, incorporating a cohesive model to represent the interaction between the faces and the core of the sandwich structure, and a comparison between analytical and computational models was carried out. The analysis considered factors such as applied bending moment and specimen mass to assess the structural efficiency of each fibre type and explore their feasibility as sustainable reinforcement alternatives in composite sandwich.

This work presents an experimentally validated comparative study of stiffness to density performance in sandwich structures under bending loads, comparing natural to synthetic fibres. Results demonstrate that jute fibre achieves 35% of carbon fibre’s specific stiffness, while being a more cost effective and sustainable alternative, which makes it a viable option for applications where bending stiffness must align with cost and ecological constraints. It is also found that each fibre system’s dimensions could be tailored to increase natural fibres’ potential.

2. MATERIALS AND METHODS

2.1. Specimen Manufacturing

The specimens were manufactured using the Vacuum Assisted Resin Transfer Moulding (VARTM) process, as illustrated in Figure **1**.

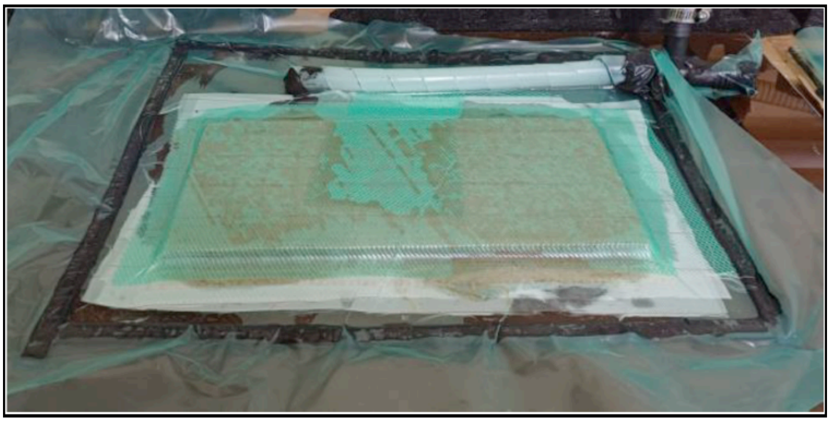

Figure 1: Fabrication of composite plates using VARTM.

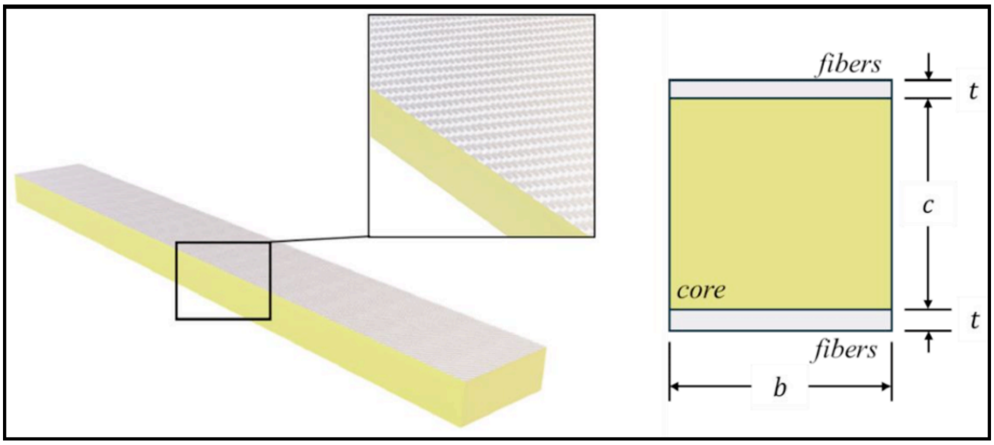

Figure 2: Sandwich structure model used.

The process consists of layering each ply with a pre-mixed epoxy resin and hardener, and subjecting the assembly to a vacuum under the flexible vacuum bag tooling. The Epoxy matrix was prepared by mixing *E-composites® AR720* resin and *AH723* hardener with 76% to 24% mass fractions, respectively.

The lay-up of the structure consisted of the sequential deposition of a single layer of the pre-impregnated fibres onto a flat glass mould. A 10 mm thick expanded PVC structural core plate (E-composites® Divinycell H45) was then placed over the fibres bottom skin layer. Subsequently, a second layer of impregnated fibre was applied on top the core, completing the conventional sandwich structure configuration Figure **2** shows the geometry of the sandwich panels, where the dimensions b, c and t representing the specimen's width, core thickness and face sheet fibre thickness, respectively.

To ensure proper resin flow infusion and aid the removal of the laminate after curing, a layer of peel ply and flow media were used over the outermost plies. The assembly was then sealed with a plastic bag attached to the glass mould with adhesive sealing tape, creating an airtight environment for vacuum application. The vacuum pump was connected to the system and operated continuously until a pressure of approximately 600 mmHg (around 80 kPa below atmospheric pressure) was reached. This pressure was maintained for a period of 6 hours to allow full impregnation. The initial curing of the resin occurred at room temperature and was completed within 24 to 48 hours. Following the curing stage, the specimens were cut using a circular saw to a final width of 28 mm, and none of the specimens showed any sign of delamination. They were later subjected to a thermal post- curing process in a controlled oven. The temperature was ramped at a rate of 1 °C/min until reaching 80 °C, which was maintained for 4 hours, in accordance with the resin manufacturer's specification.

For each different fibre, their respective specimens' sizes were compared, and their width, total thickness, and length maximum standard deviations were, respectively, 0.72%, 1.07% and 0.31%. In contrast, the specimens' face sheet thickness maximum standard deviation was 10.34%, which is expected due to manufacturing variability. Although this deviation is quite high, it shouldn't affect the results since every calculation done for each specimen considered their respective measurements.

2.2. Testing Set-Up

The specimens were tested under four-point bending using an INSTRON EMIC model 23-100 universal testing machine equipped with a high-precision 100 kN load cell, as displayed in Figure **3**. The tests followed the guidelines of ASTM D7249, which covers bending tests for sandwich structures with thick cores, and ASTM D7250, which specifies the structural properties of laminated composite materials.

The span between the lower supports was set at 190 mm, and the upper loading points were symmetrically positioned at 47.5 mm from each lower support, in accordance with the standard specifications. The crosshead displacement rate was maintained as at 6 mm/min, and load (N) and displacement (mm) data were acquired simultaneously throughout the tests.

2.3. Data Post Processing

Composite materials can exhibit anisotropic constitutive behaviour, with their mechanical response strongly dependent by the loading direction relative to the fibre's orientation. To enable structural analysis based on classical beam theory, it is common to adopt the concept of equivalent bending stiffness, which allows the structure to be treated as effectively homogeneous system [22]. Eq. 1 presents the equivalent stiffness coefficient for the sandwich core depicted in Figure **2**, defined as

Figure 3: four-point bending mechanical test used.

$$(EI)_{eq} = \sum_{i=1}^{N} E_i I_i = 2E_{fibre}\left(\frac{bt^3}{12} + bt\left(\frac{c+t}{2}\right)^2\right) + E_{core}\left(\frac{bc^3}{12}\right). \quad (1)$$

where E_i and I_i are the Young's moduli and area moment of inertia of each layer i ranging from 1 to N. For the geometry on Figure **2**, the equation relates geometrical parameters b, c and t with core and fibre elastic moduli E_{core}, E_{fibre}. For sandwich structure with thin reinforcement layers (t≈0) and lightweight, flexible cores ($E_{core} \ll E_{fibre}$), the equivalent bending stiffness can be approximated by the simplified expression, as found in [23], shown in Eq. 2, as

$$(EI)_{eq} = E_{fibre}\left(\frac{bt(c+t)^2}{2}\right). \quad (2)$$

This equation assumes a symmetric layup configuration, in which the neutral axis coincides with the centroid of the cross-section. For different layup configurations, the left-hand side of Eq. 1 must be used, with I_i representing the area moment of inertia with respect to the neutral axis.

The simplified expression captures the stiffness contribution of both the fibre reinforcement and the foam core. Once the equivalent bending stiffness is known, classical beam deflection solutions can be computed. Assuming Euler-Bernoulli beam theory under small displacements, the deflection at the load application point a, under four-point bending, according to [24], is given by Eq. 3, as.

$$v(a) = \frac{F(4a^3 - 3La^2)}{6(EI)_{eq}}. \quad (3)$$

In this equation, v(a) represents the deflection at the point of load application, F is the applied load at one of the contact points, and L is the total length of the beam. The distance a is the position of the applied load from one end of the beam with respect to the simple support.

The modulus of elasticity of the fibre material E_{fibre} can also be inferred from the equivalent bending stiffness. The relationship between the fibre modulus and the equivalent bending stiffness can be obtained by substitution of Eq. 2 into Eq. 3 and is displayed in Eq.4., as

$$E_{fibre} = \left(\frac{4a^3 - 3La^2}{3bt(c+t)^2}\right)\frac{F}{v(a)}, \quad (4)$$

where the fibre modulus is dependent on geometric parameters of the four-point bending test configuration and the experimentally determined ratio between load F and displacement v. The ratio between load and displacement can be interpreted as a stiffness value k for each beam. Additionally, the equivalent density of the composite section can be computed by averaging the structural mass over the complete volume, relating geometric parameters and densities for each material phase, resulting in Eq. 5, as

$$(\rho)_{eq} = \frac{M}{V} = \frac{2\rho_{fiber}t + \rho_{core}c}{(2t+c)}. \quad (5)$$

Thus, the combination of geometric, mechanical and physical parameters yields different bending performance with different associated equivalent densities. Therefore, the selection of the fibre reinforcement material should take both aspects in to account to enable, the design of high-performance, cost-effective, and sustainable structures.

2.4. Finite Element Model

Numerical model for the four-point bending test was developed using the Abaqus® finite element software, following the modelling guidelines proposed by Ramful [25]. The regions of load application and boundary condition were modelled using a general frictionless contact formulation to represent the experimental procedure. Due to the numerical nonlinearities associated with contact modelling, the analysis was carried out using the time dependent dynamic solver with explicit time integration solution scheme. Inertial effects were minimized, during the solution increments, by prescribing smooth step displacement functions at the load rollers. The three-dimensional geometry implemented in the model reproduces the dimensions of the tested specimens, as illustrated in Figure **4**, while the boundary conditions adopted can be seen in Figure **5**.

The properties of each material used are described in detail in Table **1** and Table **2**. Elastic properties of fibres were computed from experimental results using Eq. 4.

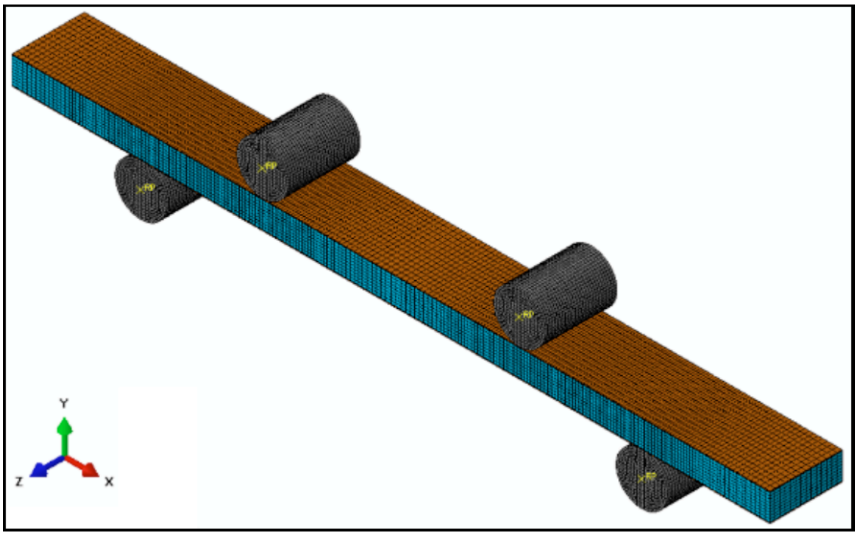

Figure 4: Finite element model used.

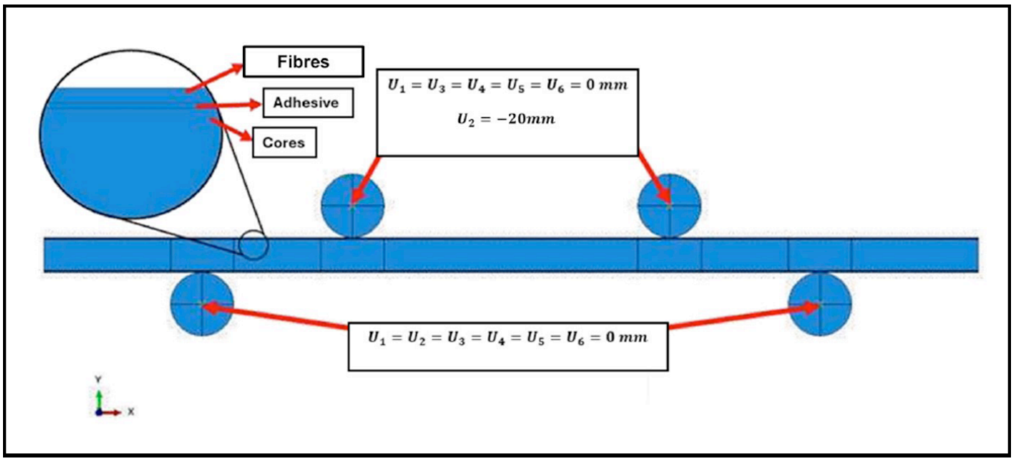

Figure 5: Boundary conditions used.

Table 1: Properties of the Materials used in the Numerical Model

	Carbon	Glass	Cotton	Linen	Jute	Core
$E_{xx} = E_{zz}$ (MPa)	13484.2	12494.7	1704.1	2620.0	1738.6	172.5
G_{xz} (MPa)	4000.0	3706.5	505.5	777.2	515.7	61.6
ν_{xz}	0.06	0.06	0.06	0.06	0.06	0.4

Table 2: Adhesive Layer Traction Separation Parameters [2]

E_{nn} (MPa)	2060	σ_{nn} (MPa)	21.63
E_{ss} (MPa)	770	σ_{ss} (MPa)	17.9
E_{tt} (MPa)	770	σ_{tt} (MPa)	17.9

To accurately represent the different components of the sandwich structure, various element types were used in the finite element model. The core material was modelled using three-dimensional hexahedral elements with reduced integration (C3D8R), which provide good numerical performance in nearly incompressible materials and avoid volumetric locking problems. This element choice also captures through-the-thickness deformations, which are often significant in core materials. The loading and supports rollers were represented as discrete rigid bodies (R3D4), ensuring that they remained undeformed during the simulation. An interface layer between fibres face sheets and the sandwich core was modelled using three-dimensional cohesive elements (COH3D8), allowing the simulation of interlaminar failures due to delamination if applicable. Finally, fibre layers were modelled using continuum shell elements (SC8R) with reduced integration, as the small thickness of sandwich faces allow for the plane stress condition under bending. The contact interactions between the rigid bodies and the test specimen were configured with rigid contact in the normal direction (hard contact) and frictionless tangential behaviour. The load application was performed by means of imposed displacement on the upper supports, while the lower supports were fully restricted in the vertical direction. Reaction forces and displacements at each loading points were continuously monitored throughout the analysis.

To ensure that the results from the finite element analysis are not dependant mesh density, a mesh independence study was conducted as shown in Figure **6**.

Three mesh configurations were evaluated: mesh 1 with 3 elements in the thickness direction of the foam, mesh 2 with 6 and mesh 3 with 9. The results show negligible variation between meshes, indicating mesh independence. Therefore, the decision was made to carry out all analysis with mesh 3.

3. RESULTS AND DISCUSSIONS

3.1. Experimental Results

The experimental load- displacement curves, for both synthetic and natural fibre systems, are plotted in Figure **7**. In these plots, displacement refers to the crosshead movement of the testing machine, while the load corresponds to the total force recorded by the load cell. Test results indicate that, as expected, synthetic fibres result in greater stiffness to the sandwich composite structure when compared to those reinforced with natural fibres.

The stiffness parameter k for each test was determined from the slope of the load vs. displacement curves, and the corresponding fibre Young's moduli using Eq. 4 a. In addition, the equivalent section stiffness $(EI)_{eq}$ was computed from Eq. 2, based on the average geometric parameters for each material

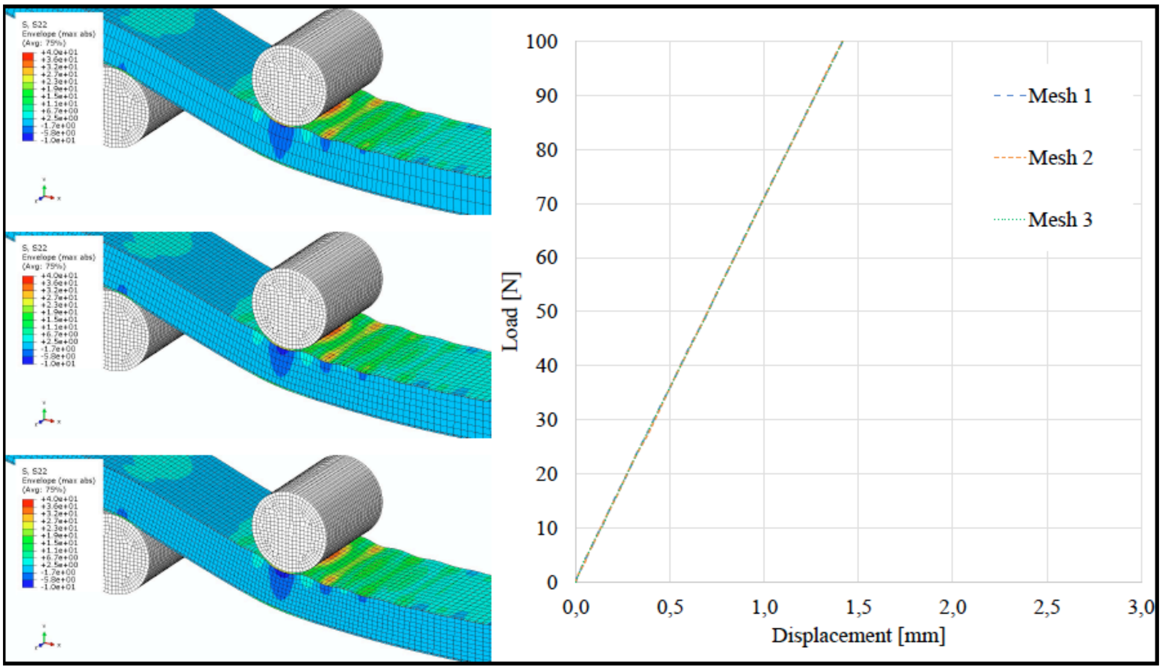

Figure 6: Mesh independence study.

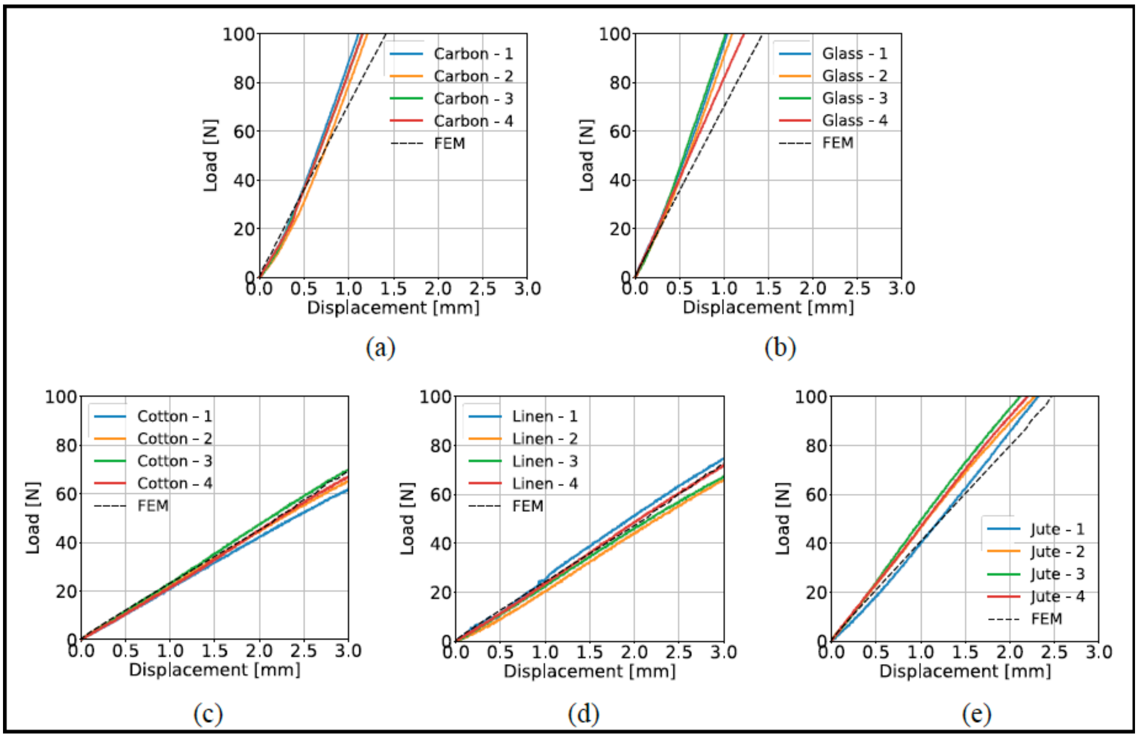

Figure 7: Experimental results. (**a**) Synthetic carbon fibres. (**b**) Synthetic glass fibres. (**c**) Natural cotton fibres. (**d**) Natural Linen fibre. (**e**) Natural jute fibres.

system. The equivalent densities of each structure were computed using Eq. 5, considering the total mass of the sandwich structure measured with a precision scale and the volume derived from the geometric dimensions. Table **3** summarizes the geometric parameters of each sandwich configuration, as along with the average experimental stiffness, fibre elastic modulus, equivalent density, and section stiffness values. The ratio of section stiffness to equivalent density is also displayed on the last column, highlighting the stiffness-to-weight efficiency under bending loads.

The results indicate that carbon fibre reinforcement resulted in the stiffer configuration, while cotton natural fibres provided the most flexible structure. Glass fibres composites, however, exhibited similar stiffness performance to those reinforced with carbon fibres. Among the natural fibre composites, jute fibres provided the highest stiffness values, reaching approximately 46 % of the stiffness observed for carbon fibre specimens.

In terms of Regarding the mass of the components, carbon fibre reinforced were the lightest among all tested materials, highlighting their superior structural efficiency when considering the stiffness-to-weight ratio. Although, glass fibre composite showed comparable stiffness to carbon fibre, they resulted in significantly heavier structures. The natural fibres composites displayed equivalent densities similar to the synthetic ones, with jute representing the heaviest and linen the lightest.

Regarding the bending efficiency, based on the ratio of section stiffness to density, synthetic fibres yielded the best overall performance. Nonetheless, jute fibres demonstrated a comparable bending efficiency, achieving around 40 % of the bending efficiency of glass fibre and 35 % of that of carbon fibre., These

Table 3: Stiffness and Density Results for Different Sandwich Structures

Fibre	Width (mm)	t (mm)	k (N/mm)	E (MPa)	ρ_{fiber} (g/mm^3)	$(EI)_{eq}$ $(MPa.mm^4)$	ρ_{eq} (g/mm^3)	$\frac{(EI)_{eq}}{\rho_{eq}}$ (MPa/g.mm)
Carbon	28,13	0,34	48,25	13484,21	1,79E-03	6,89E+06	1,59E-04	4,33E+10
Glass	29,10	0,34	46,25	12494,73	2,01E-03	6,61E+06	1,73E-04	3,83E+10
Cotton	28,75	0,58	11,13	1704,10	1,44E-03	1,59E+06	1,93E-04	8,23E+09
Linen	28,55	0,42	11,94	2620,02	1,76E-03	1,71E+06	1,81E-04	9,44E+09
Jute	28,60	1,04	22,05	1738,59	9,67E-04	3,15E+06	2,06E-04	1,53E+10

findings suggest that jute fibres could serve as a viable, cost-effective alternative to more expensive synthetic reinforcements.

3.2. Finite Element Results

The finite element models showed similar behaviour to the experimental data. Figure **8** presents the load vs displacement plots for each finite element model as dashed lines, while the solid lines represent the experimental data. From the figure, it can be seen that the finite element model shows that synthetic fibres display the highest stiffness values, while cotton and linen show the most compliant scenarios. Jute fibres fall in between, aligning with the trends observed in the experimental results.

Table **4** shows the predicted stiffness values for each face sheet reinforcement system compared to average experimental values. Firstly, results are compared until a small deflection of 0.4mm, resulting in a maximum deviation of 15% for the glass fibre reinforced beam. However, as displacement increases, the mismatch between experimental and predicted stiffness increases, as displayed in Table **4**, reaching 26% for a 3mm displacement. This difference is expected, as the bending of sandwich panels with soft cores are subjected to non-linear effects related to the indentation damage of the core and buckling due to compressive stresses on the faces. Furthermore, the interaction of non-linear effects with interfacial damage and different contact enforcement methods are directly related to the correlation of results. For the purpose of the proposed analysis, the FE model was sufficient to

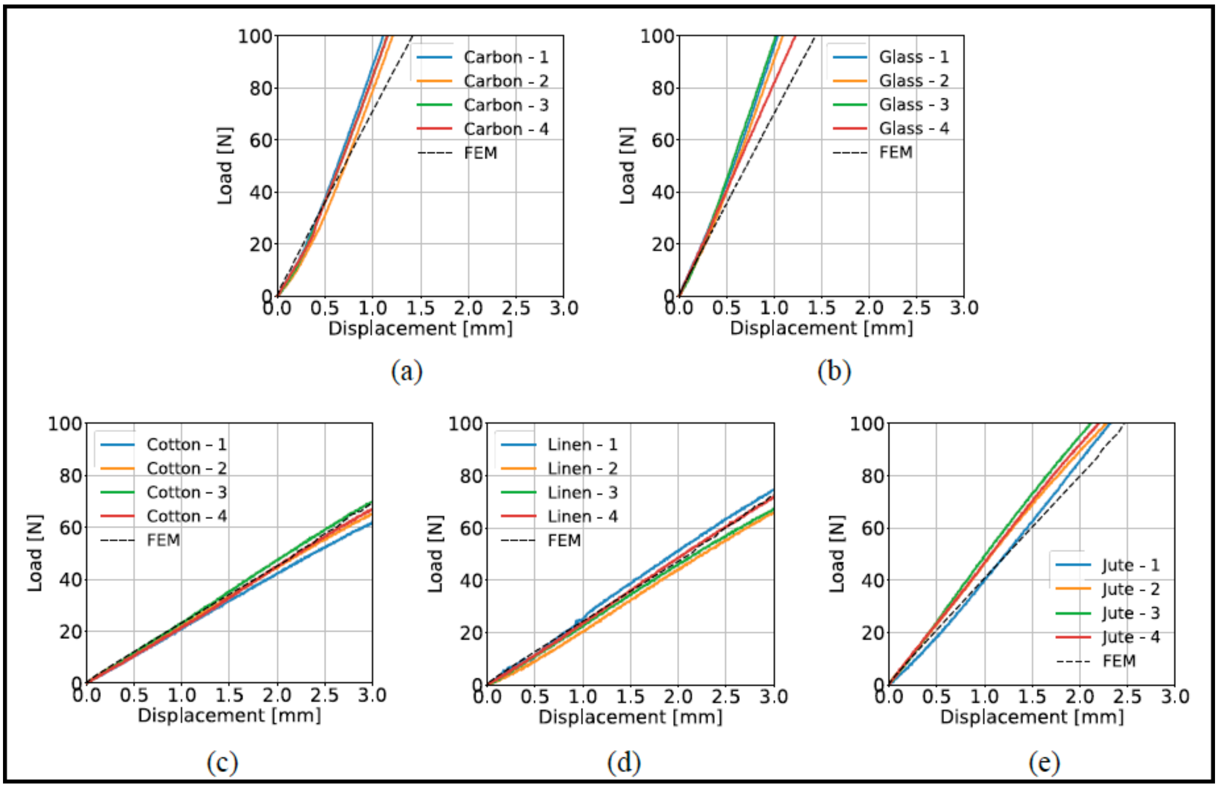

Figure 8: Finite element model results. (**a**) Synthetic carbon fibres. (**b**) Synthetic glass fibres. (**c**) Natural cotton fibres. (**d**) Natural Linen fibres. (**e**) Natural jute fibres.

Table 4: Comparisson between Experimental and FEM Stiffness

	3.0 mm displacement			**0.4 mm displacement**		
Fibre	k_{exp} **(N/mm)**	k_{FEM} **(N/mm)**	**Error [%]**	k_{exp} **(N/mm)**	k_{FEM} **(N/mm)**	**Error [%]**
Carbon	48.25	35.60	26.21%	33.59	35.60	5.99%
Glass	46.25	35.10	24.09%	41.33	35.10	15.06%
Cotton	11.13	11.54	3.72%	10.77	11.54	7.20%
Linen	11.94	12.09	1.32%	10.90	12.09	10.97%
Jute	22.05	20.45	7.25%	21.96	20.45	6.84%

represent the different characteristics for each core and face material combinations. In spite of these differences, the proposed model was able to accurately represent the stiffness of natural fibres throughout the complete displacement history.

Throughout all simulation runs, no interlaminar damage between sandwich panel faces and core were observed. However, due to the flexibility of the core material, through-the-thickness strains significantly influenced the stiffness result. Figure **9** shows the displacement and stress field variables at three different stages of the solution increments for the carbon fibre reinforced panels. At low displacement values, the deflection shape closely aligns with the expected solution from Euler-Bernoulli beam theory. However, as stresses increase, wrinkling of panel faces occurs, altering the deflection pattern. A similar effect was observed in the glass fibre panels.

This behaviour was also observed during the experiments with synthetic fibres. However, due to slits on the core foam, which were introduced to enhance the core's drapability, delamination occurred, as displayed in Figure **10**. Since the slits were not included in the numerical model, the simulation predicted wrinkling without any delamination damage. Figure **10b** shows bending stress numerical predictions where the curvature induced by wrinkling effects changes the local stress field distribution.

Natural fibres exhibited a more compliant structure, with no signs of wrinkling or delamination effects. Figure **11** shows the finite element displacement and stress fields at three different stages throughout the simulation increments. For natural fibres, the numerical deflection shape aligned more closely with classical beam theory solutions and the experimental data, as shown Figure **8**. Similar results were obtained for both linen and cotton fibres.

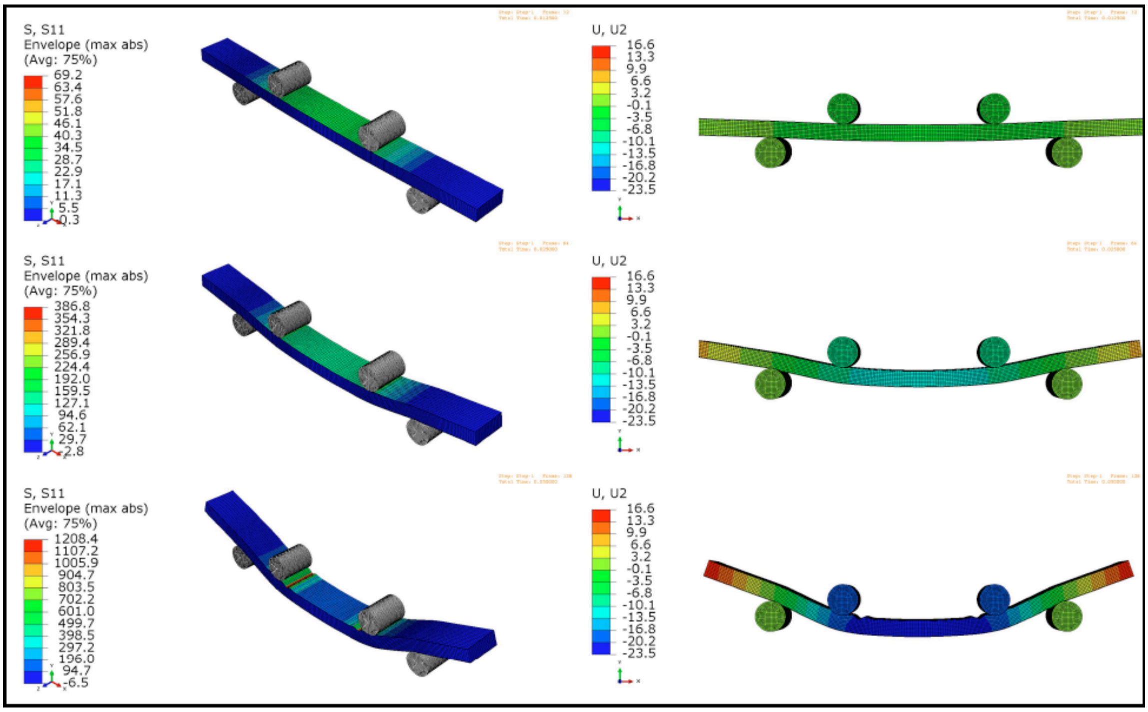

Figure 9: Carbon fibre reinforcement FEA.

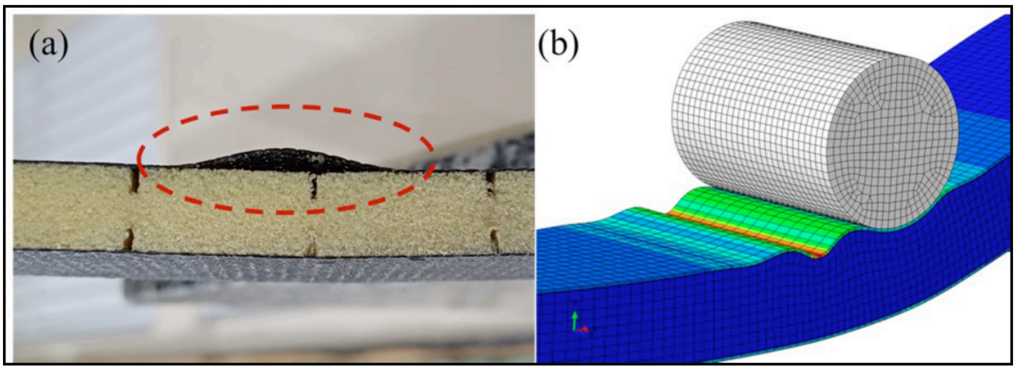

Figure 10: Failure mode of (**a**) tested beam and (**b**) simulated beam.

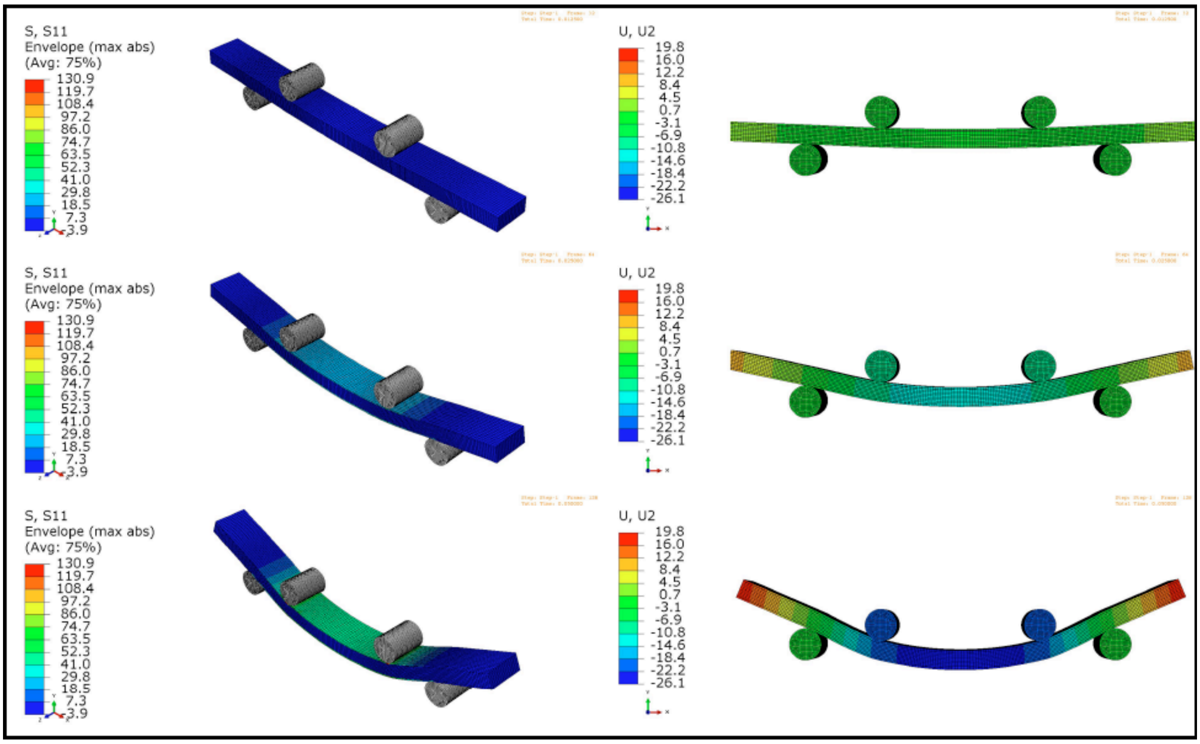

Figure 11: Jute fibre reinforcement FEM.

In view of the above discussed, synthetic fibres demonstrated superior resistance to normal stresses. However, due to the thickness of their faces, beams made with jute fibres exhibited a bending moment at failure very similar to that observed for carbon and glass fibres, making them a viable alternative in structural applications where mass reduction is not a primary requirement.

4. CONCLUSION

This study experimentally compared the efficiency of different sandwich panel reinforcement materials under static bending. Different structures were manufactured and tested, and the elastic moduli of the fibres were determined using analytical beam solutions. Finite element models were implemented, demonstrating the different interactions observed between fibre and core materials. The results indicate that although composites with synthetic fibres, such as carbon and glass, exhibit superior mechanical properties, natural fibres, especially jute, is a viable alternative, achieving 46% of carbon fibre's bending stiffness and 35% of it's specific stiffness without substantial mass penalties. This shows that jute fibre may be a sustainable, cost effective alternative for applications where moderate weight constrains coexist with environmental and economic considerations. Moreover, results also indicate that core indentation, face buckling and contact enforcement methods are relevant for FE with stiffer face materials, such as the synthetic fibres, and need to be accounted for the accurate analysis of sandwich panel strength. These conclusions underscore the importance of exploring alternative, cost-effective materials for structural applications, particularly given the growing demand for accessible and environmentally responsible solutions in engineering and industry.

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CONFLICTS OF INTEREST

All authors declare that they have no conflicts of interest.

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