Low Strain Rate Mechanical Performance of Balsa Wood and Carbon Fibre-Epoxy-Balsa Sandwich Structures

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Low strain rate mechanical performance of balsa wood and carbon fibre-epoxy-balsa sandwich structures

Mertol Tüfekci [a,*], Vehbi Öztekin [b], İnci Pir [b,*], Murat Alioğlu [b], Can Dikicioğlu [b], Adnan Dikicioğlu [b], Ekrem Tüfekci [b]

[a] Department of Mechanical Engineering Imperial College London, Exhibition Road, London SW7 2AZ, United Kingdom
[b] Istanbul Technical University, Faculty of Mechanical Engineering, 34437 Beyoglu Istanbul, Turkey

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ABSTRACT

The focus of this study is the experimental assessment of the mechanical behaviour of balsa wood and its sandwich structures, where balsa serves as the core, supported by carbon fibre-epoxy skin layers. A comprehensive characterisation is conducted on the mechanical behaviour of balsa wood and carbon fibre-epoxy balsa core sandwich structures subjected to a range of low strain rates. Initially, the study undertakes a consistent procedure for sample preparation. Subsequently, the characterisation of the manufactured composite structures is performed experimentally. A stereo microscope is employed for a detailed visual inspection of the internal structure of the balsa wood and the sandwich structures. Furthermore, the mechanical characterisation is carried out with three-point bending tests at a range of strain rates from 0.1 % to 6 % strain per minute. This research reveals key findings about balsa wood and its sandwich structures, highlighting their performance and their sensitivity even under low strain rates.

1. Introduction

New materials are developed to meet the diverse needs of ever-evolving industrial sectors. Composite materials, characterised by their highly customisable properties, hold significant potential in this field. According to the requirements of the engineering system where composites are intended to be employed, it is quite simple to modify their properties. Composite materials are used in numerous engineering disciplines, ranging from the marine industry and construction to home appliance manufacturing and space technology [1]. In parallel, the growing need for material resources has led to a significant shift towards sustainability, driven by pressing global issues related to environmental conservation and resource management. Balsa wood is emerging as a promising candidate among the wide variety of sustainable materials. Known for its lightweight characteristics, strength-to-weight ratio, and natural abundance, balsa wood is recognised as a sustainable material suited to plenty of applications in engineering and industry.

Even though the field of composite materials seems to have appeared in the last few decades, the first examples date back to ancient times [2]. The first examples of composite material emerged through interventions made in materials found in nature for military use [3–5]. Since prehistoric times, people have attempted to strengthen, stiffen and toughen certain structures by adding fibres and/or particles as reinforcements into brittle materials. However, the introduction of the concept of composite material as a subject of modern engineering occurred only in the early 1940s [6]. In time, the use and development of composites accelerated rapidly, and many sorts of materials, like polymers, ceramics and metals, are employed to build up composite structures. Later in the progress of the industrialisation of composites, sustainability emerged as a significant problem, leading to using more natural and sustainable materials in design problems [7,8].

Nowadays, sandwich structures are one of the most commonly used types of composites. In sandwich structures, foams, honeycombs, cellular structures and various kinds of lightweight materials like wood are preferred as core materials [9]. These structures cost less day by day due to new manufacturing techniques development. Materials such as carbon fibre, aramid, and glass fibre are used as reinforcements for the surface of the sandwich structure due to their stiffness [10]. They are usually preferred for their superior structural performances, particularly their capacity to absorb impact energy and vibration alongside their lightweight, especially where high specific strength and stiffness are desired [11].

* Corresponding authors.
E-mail addresses: m.tufekci17@imperial.ac.uk (M. Tüfekci), pirin@itu.edu.tr (İ. Pir).

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Balsa wood, a tropical hardwood, stands out as a widely used lightweight material in various industries. Its exceptional growth rate makes it one of the fastest-growing wood. However, what sets balsa apart is its extraordinary low density, making it one of the lightest commercial timber available. This unique combination of rapid growth and minimal weight has made balsa wood a choice for a wide range of applications. Its high strength-to-weight ratio makes it ideal for some structural components, while its versatility in shaping and bonding simplifies manufacturing processes. Furthermore, balsa's natural damping properties enhance its utility in applications requiring vibration reduction. When combined with responsible harvesting practices and cost-effectiveness in the long run, balsa wood emerges as an eco-friendly, high-performance material that inspires innovation in various fields.

Balsa is an example of a natural wood used in composite materials alongside being a green material [12]. It is one of the lightest commercial timbers, which presents low density (60–380 kg/m^3) and good mechanical properties and performance, which are an effective combination for wind turbine blades, sports equipment, and marine and aircraft industries [13]. The first attempts at engineering applications of balsa woods are seen aircraft industry in the 1940s [14]. Since then, balsa wood has been preferred as a core material of sandwich composites for wind turbine blades, aircraft, and boats [15]. More information related to the areas of application of balsa wood is presented in Table 1. Based on this information, it is possible to state that balsa is predominantly used for static and/or low-strain-rate applications.

The first works aimed to characterise balsa wood regarding wood fibre directions and environmental effects on the material in the 1960s and 1970s [16,17]. The balsa fibre orientation angle is one of the dominant properties influencing the sandwich composites' mechanical properties. In their study, Grenestend and Bekisli investigated the anisotropic mechanical properties of balsa wood with numerical and experimental methods, and they found that improved shear properties are obtained with balsa wood with 45° fibre orientation [18,19]. In another study, to investigate the effect of the core material on the shear properties of balsa sandwich structures, an appropriate transverse layup sequence is applied, and the sandwich structure is modelled using basic laminate theory and validated through experiments [20]. To understand the suitability of balsa wood as a core material for sandwich structures, fracture properties in different fracture modes of balsa are evaluated experimentally. As a result, the toughness of balsa wood is found to be sufficient for sandwich composite core material and greater than other compared core materials [21].

Comparisons between different sandwich structures are also evaluated in the literature. Dynamic properties of balsa wood sandwich composites with varying densities are compared using a modified Kolsky (split Hopkinson) pressure bar [22]. In another study, the impact responses of balsa wood and PVC core are compared [23]. On the other hand, a four-point bending test is applied to the glass fibre-balsa sandwich structure manufactured in different sizes and damage analysis is performed to characterise the fatigue response of glass fibre-balsa sandwich beams [24].

Temperature-related studies of sandwich structures are also conducted in the literature. A study explores the fire resistance of E-glass/vinyl ester balsa wood core sandwich panels used in marine applications, revealing that exposure to high-temperature flames significantly reduces the panels' impact response, structural integrity, and energy absorption with fire [25]. Moreover, the operating temperatures at which different mechanical properties of the glass fibre-balsa sandwich samples reach their optimum are determined [26]. Another study states that the temperature should not be exceeded $200^\circ - 250\ ^\circ C$ to prevent permanent heat damage to balsa wood [27]. Therefore, the fire behaviour of the glass fibre-balsa sandwich structure is modelled. In this direction, fire simulations are prepared, and the thermochemical properties of the component materials are examined [28].

Table 1
Examples of applications of sandwich structures with balsa cores [9].

Application	Components with balsa core
Windmills/Wind Turbines	Turbine blades, spinners, nacelle covers
Bridges	Decking
Buildings	Insulation, flooring
Automobile	Body panels, interiors, floor, walls,
Aircraft	Floor panels, interior partitions
Boats	Hulls, decks, superstructres and interiors
Packaging	Cargo pallets
Storage	Storage tanks
Sports Equipments	Skis and snowboards

The mechanical properties of composites can be evaluated in several scenarios. There are studies about the mechanical behaviour of the composites regarding hygrothermal conditions. In these studies, the mechanical behaviour of the polymeric matrix composites is evaluated with tensile testing in wet and dry conditions. The elasticity modulus and elongation at break values of the composite change concerning its condition [29,30]. In another study, to investigate the mechanical conditions of fibre-structured composites under hygrothermal effects, carbon fibre reinforced-polymer (CFRP) laminate dry and wet specimens are subjected to static and dynamical loading at $-50\ ^\circ C$, room temperature and $80\ ^\circ C$ [31].

Balsa is combined with bamboo, fibre-reinforced polymer, and glass fibre resin in sandwich structures [32–34]. There are studies in the literature related to balsa-carbon fibre structure as follows: Ballistic effect analysis of sandwich structure with balsa core material and carbon fibre surface material is investigated [35]. The three-point bending and torsion of the balsa carbon fibre sandwich structure are studied. The study mainly focuses on combining the different numbers of carbon fibre layers with different orientations [36].

In this study, an in-depth analysis is performed on the mechanical behaviour of balsa wood and manufactured carbon fibre-epoxy balsa core sandwich structures under low strain rates considering that the majority of the applications of balsa wood are intended for either static loading or loading that leads to low deformation rates. A consistent manufacturing strategy is followed for sample preparation, where balsa wood and carbon fibre are cut and aligned based on their fibre orientations. These samples undergo a series of experimental characterisations, employing a stereo microscope for a closer inspection of their internal structure and mechanical characterisation via a three-point bending test under strain rates of up to 6 % strain per minute. The results and subsequent discussion section of the paper thoroughly analyse and interpret findings from the microscopic evaluations and mechanical characterisation. The novelty of this study resides in the thorough characterisation of balsa wood and its combination with carbon fibre-epoxy in a sandwich structure. The findings indicate that these materials are notably strain rate-dependent and behave as orthotropic materials. Despite this study solely exploring the mechanics of these structures/materials under a lower range of strain rates, significant variations are observed even with minimal changes in the strain rates.

2. Material preparation and experimentation

2.1. Preparation of balsa samples

Balsa is provided in large rectangular plates, and the samples are cut with dimensions 100 mm length, 30 mm width, and 10 mm thickness. To investigate the orthotropic behaviour of balsa, specimens are prepared to have specific angles relative to the direction of fibre orientation. These angles are chosen 0°, 30°, 60°, and 90°. Accordingly, the balsa board is cut to have fibre angles of 0°, 30°, 60°. Some samples with different fibre orientations are shown in Fig. 1.

2.2. Manufacturing of the sandwich structure samples

To investigate the mechanical properties of balsa core carbon fibre

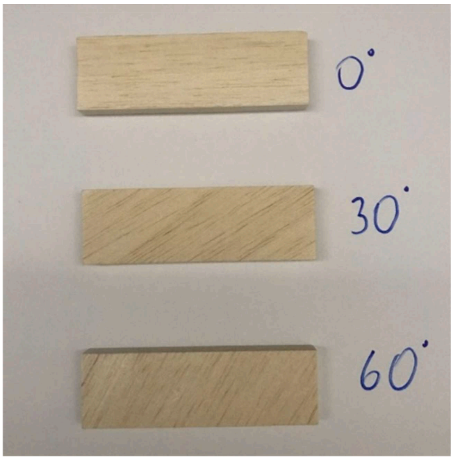

Fig. 1. Balsa samples with different orientation angles.

epoxy sandwich structures, samples are prepared by utilising balsa wood presented earlier and a standard carbon fibre epoxy composite. Dimensions of the sandwich structures are chosen as the same as the plain balsa wood samples for consistency, which are 100 mm in length, 30 mm in width, and 10 mm in thickness. Fibre orientation angles of both the core and skin materials are arranged as presented in Table 2.

Given the sensitive nature of the materials involved, particularly the balsa core and carbon fibre epoxy composite, the manufacturing process demands special attention to detail. Due to the delicate characteristics of these materials, control over the pressure applied to create the cohesive zones and temperature to cure the epoxy is essential. Even though there are several methods to manufacture composites, in this study, the hand-laying technique is employed for its ability to offer finer control over these parameters.

The carbon fibre epoxy layers are prepared with heat-resistant nylon. Then, a mixture of resins, named LOCTITE EA 9390 AERO, Two-Component Epoxy Adhesive, is prepared for application to the carbon fibre, adjusting the epoxy-carbon fibre ratio to 40 %–60 %. The resin is hand-laid onto the carbon fibre and then cut into the desired dimensions. The properties of the carbon fibre epoxy composite layers prepared are given in Table 3.

The resin-soaked carbon fibre samples are then attached to the balsa. The resultant samples are organised on an aluminium plate (Fig. 2) and shielded with a heat-resistant layer to prevent the thermal interaction between the samples and the mould. The samples are left for curing in an incubator at 90 °C for 4 h. Fig. 2 displays some of the manufactured samples, and Fig. 3 shows a closer view of the sandwich sample.

2.3. Internal structure visualisation

The internal structure of composites significantly influences the mechanical properties of materials. For a precise examination of the manufactured composite sandwiches' surfaces, the Nikon SMZ800 stereo microscope equipped with a camera is utilised. With a stereo microscope, an exploration of the specimens under magnifications ranging from x20 to x120 can be performed. Also, details about the surface characteristics and structural details and complexities of the samples can be identified using the stereo microscope. The image of the microscope is given in Fig. 4.

Table 2
Fibre orientation angles of the core and skin materials.

Balsa Orientation [°]	0	0	0	30	30	30	60	60	60
Carbon Fibre Orientation [°]	0	30	60	0	30	60	0	30	60

Table 3
Mechanical properties of carbon fibre epoxy laminates.

Property	Value	Units
Laminate Thickness	0.327	mm
Laminate Weight	438	g/m^2
Average Distance Between Fibres	2	mm
Fibre Diameter	7	μm
Density	1.76	g/cm^3
Longitudinal Elastic Modulus (E_1)	141	GPa
Transverse Elastic Modulus (E_2)	8.7	GPa
Shear Modulus ($G_{12,13}$)	5.6	GPa
Shear Modulus (G_{23})	3.7	GPa
Poisson's Ratio (V_{12}, V_{13})	0.3	–
Poisson's Ratio (V_{23})	0.4	–
Longitudinal Tensile Strength	1925	MPa
Transverse Tensile Strength	76	MPa
Longitudinal Compressive Strength	1725	MPa
Transverse Compressive Strength	228	MPa
Out-of-Plane Shear Stress	70	MPa

Fig. 2. Manufactured samples.

Fig. 3. Detailed image of the sandwich sample.

2.4. Three-point bending tests

2.4.1. Balsa wood characterisation

In order to investigate the mechanical behaviour of the manufactured composite structure concerning strain rate, the material samples undergo three-point bending tests at various strain rates ranging from 0.1 % up to 6 % strain per minute, namely 0.1 %, 3 %, 4 %, 5 %, 6 % strain per minute. The selection of the strain rate range is determined by considering the capabilities of the equipment and the limitations of the materials under investigation. So, it is ensured that the experimental data gathered can be reliably compared and analysed. The tests are conducted based on the ASTM standard ASTM-C393 [37].

Manufactured samples are subjected to three-point bending testing for characterisation. Three-point bending tests are performed on Shimadzu AG-IS 50 kN universal test machine. All tests are conducted in ambient conditions. Each test is repeated five times. Specimens and test setup are shown in Fig. 5. The flexural moduli of the tested samples are calculated using Eq. (1). This equation relies on the applied force and dimensions of the tested sample as well as the deformation of the sample.

$$E = \frac{F \times l^3}{4 \times w \times b \times h^3} \quad (1)$$

Here, F denotes the applied force to the specimen, and l represents

Fig. 4. The image of the stereo microscopy setup.

the span between supports whilst *w* represents the deflection and *b* and *h* indicate the dimensions of the test specimen, which are width and height, respectively.

Balsa wood samples are tested under various strain rates ranging from 0.1 % to 6 % strain per minute. To recognise anisotropic characteristics, specimens with four fibre orientations (0°, 30°, 60°, and 90°) are evaluated, and tests are conducted with these four orientations. In total, three-point bending tests are applied to 20 balsa wood specimen types. Relevant testing parameters are explained in Table 4.

2.4.2. Balsa core carbon fibre-epoxy sandwich structure characterisation

Whilst balsa wood samples are tested for various strain rates, only test with a 0.1 % strain per minute strain rate are applied to balsa core – carbon fibre composites since the focus here is on the impact of the fibre orientations on the mechanics of the sandwich structures. Different balsa wood orientations and carbon fibre orientations are combined. In total, three-point bending tests are applied to 9 balsa core–carbon fibre composite specimen types/groups. Each test is repeated five times. The summary of the testing and specimens is given in Table 5.

3. Results

3.1. Internal structure visualisation

Fig. 6 presents four images, each indicating different orientations and combinations of the balsa-carbon fibre composites. Fig. 6a) displays the balsa wood with a fibre orientation of 0°, and Fig. 6b) shows the balsa wood with a 30° fibre orientation. Fig. 6c) provides a cross-section view of the 0° balsa fibre orientation. The orientations of the balsa fibres are distinctly visible in Fig. 6a) and b). Fig. 6c) exhibits the inherent voids within the balsa wood. Interestingly, Fig. 6d) reveals no major structural flaws between the balsa wood and the carbon fibre layers, highlighting the successful integration of these two components of the sandwich structure. The visual characteristics of the balsa wood point

Table 4
Tensile test conditions of balsa wood.

Orientation [°]	Strain rate [%strain per minute]
0	0.1
0	3
0	4
0	5
0	6
30	0.1
30	3
30	4
30	5
30	6
60	0.1
60	3
60	4
60	5
60	6
90	0.1
90	3
90	4
90	5
90	6

Table 5
Balsa – carbon fibre composite test conditions.

Balsa orientation [°]	Carbon fibre orientation [°]	Test speed [%strain per minute]
0	0	0.1
0	30	0.1
0	60	0.1
30	0	0.1
30	30	0.1
30	60	0.1
60	0	0.1
60	30	0.1
60	60	0.1

Fig. 5. Three-point bend tests for balsa and sandwich samples.

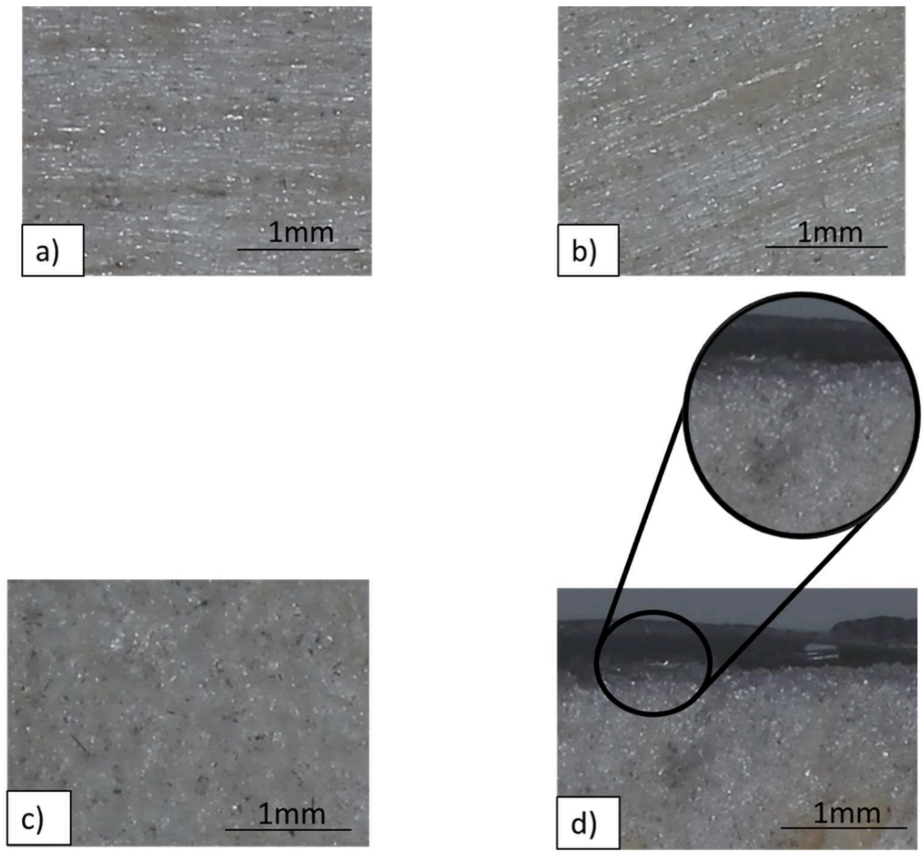

Fig. 6. a) Balsa wood with fibre orientation of 0°, b) balsa wood with fibre orientation of 30° balsa fibre orientation, c) cross-section of the balsa wood with fibre orientation of 0°, d) combination of balsa wood with fibre orientation of 0° and carbon fibre with fibre orientation of 30°

out no significant concerns and expose the fibrous structure of the balsa wood. Although, the gaps between the fibres are known to weaken the wood/material, it significantly reduces the weight, which primarily explains why balsa is considered a lightweight material.

Finally, Fig. 6d) displays a combination of balsa wood with a fibre orientation of 0° and carbon fibre with a fibre orientation of 30° The representative visual of the balsa wood and carbon fibre-epoxy combination shows no separation/non-bonded region between the balsa and carbon fibre-epoxy layers. It is important to note that an infusion region is observed where the epoxy penetrates the balsa wood, which is expected to affect the composite's overall mechanical properties, particularly stiffness, debonding and strength. The thickness of the infusion region is measured as 0.36 mm. While determining this value, three measurements are recorded, and the average of these measurements is taken. The presence of this region indicates the complexities involved in the manufacturing and performance of this sandwich structure. The manufacturing process should be tailored so that this infusion happens to a level which improves the mechanical properties of the composite. In the literature it is shown that the integration of the different phases in a composite is heavily influential on the overall performance of composites particularly the performance of the sandwich structures [38].

3.2. Three-point bending tests

3.2.1. Orientation and strain rate sensitivity of balsa

In order to examine the effect of the fibre orientation and strain rate on the flexural properties of balsa, various fibre-orientated models are tested under differing strain rates from 0.1 % to 6 % strain per minute. A set of stress–strain curves for various orientation angles of balsa wood under 0.1 % strain per minute is shown in Fig. 7. The resultant parameters (flexural modulus, flexural strength, and elongation at break) are presented in Table 6 and Figs. 8 and 9. The results in Table 6 and Figs. 8 and 9 are the averaged values of the repeated tests considering the parameters of strain rate sensitivity and balsa fibre orientation. The variability of the results is also presented alongside the averaged values in Table 6. It is observed that the variability among these tests remained around a relatively stable 5 % for these parameters, lending confidence in the reliability and repeatability of the results. This also reinforces the reliability of the obtained results. These results also suggest that the mechanical performance of balsa wood is sensitive to strain rate and fibre orientation.

Examining the effect of fibre orientation on the flexural modulus of balsa wood, it is clearly seen that both flexural modulus and flexural strength decrease with increasing angles of fibre orientation. This can be seen as evidence that an orthotropic material model is appropriate for describing balsa wood's mechanical behaviour. In the orthotropic model, the properties and responses of a material are predominantly controlled by the orientation of the material's structure. More

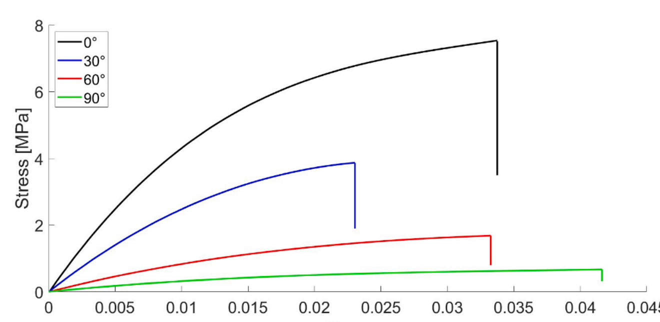

Fig. 7. Stress–strain curves of balsa wood under 0.1 % strain per minute.

Table 6
Flexural modulus of the balsa wood due to balsa orientation and strain rate.

Test speed [ε/min]	0° balsa orientation			30° balsa orientation			60° balsa orientation			90° balsa orientation		
	Flexural modulus [MPa]	Flexural strength [MPa]	Elongation at break	Flexural modulus [MPa]	Flexural strength [MPa]	Elongation at break	Flexural modulus [MPa]	Flexural strength [MPa]	Elongation at break	Flexural modulus [MPa]	Flexural strength [MPa]	Elongation at break
0.1	433.48 ± 20.83	7.55 ± 0.063	0.034 ± 0.0013	257.45 ± 12.21	3.74 ± 0.073	0.023 ± 0.00098	76.96 ± 3.19	1.59 ± 0.068	0.033 ± 0.00057	29.49 ± 1.28	0.63 ± 0.031	0.041 ± 0.00015
3	453.96 ± 22.45	7.63 ± 0.029	0.031 ± 0.0003	259.52 ± 11.56	3.92 – 0.044	0.021 ± 0.00058	83.56 ± 4.34	1.67 ± 0.073	0.029 ± 0.00045	32 ± 0.87	0.67 ± 0.025	0.039 ± 0.00012
4	491.95 ± 24.18	7.66 ± 0.079	0.027 ± 0.0009	288.05 ± 14.25	3.93 ± 0.086	0.019 ± 0.00086	103.57 ± 5.14	1.72 ± 0.046	0.023 ± 0.00046	39.41 ± 1.91	0.68 ± 0.027	0.035 ± 0.00018
5	503.52 ± 20.61	7.74 ± 0.061	0.024 ± 0.0012	298.57 ± 13.87	4.11 ± 0.052	0.018 ± 0.00074	110.61 ± 4.89	1.75 ± 0.057	0.023 ± 0.00049	42.75 ± 2.12	0.71 ± 0.019	0.030 ± 0.00014
6	551.39 ± 22.37	7.82 ± 0.032	0.021 ± 0.0009	304.57 ± 14.02	4.32 ± 0.061	0.016 ± 0.00081	125.74 ± 6.21	1.79 ± 0.081	0.019 ± 0.0005	49.81 ± 2.04	0.72 ± 0.008	0.027 ± 0.00011

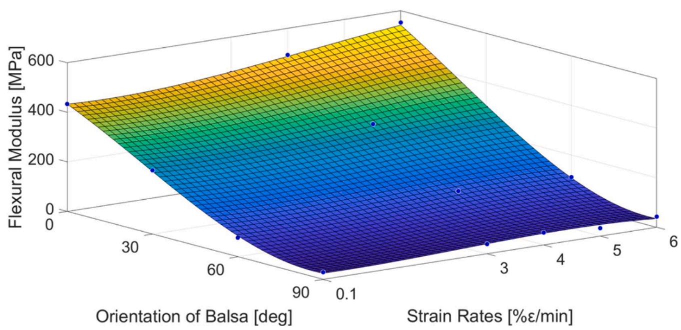

Fig. 8. Flexural modulus variation of balsa according to strain rate and balsa angle.

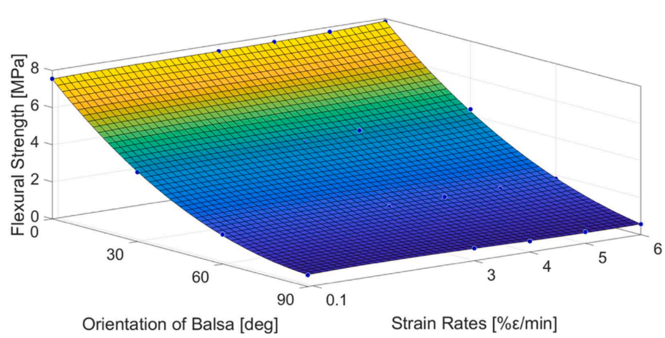

Fig. 9. Flexural strength varies according to strain rate and balsa angle.

specifically, for instance, at the test speed of 0.1 % strain per minute, the flexural modulus goes from 433.48 MPa at 0° to 76.96 MPa at 60° orientation, pointing out a significant fall of approximately 82.25 %. The same trend is observed at higher strain rates as well. For the test speed of 6 % strain per minute, the flexural modulus drops from 551.39 MPa at 0° to 110.61 MPa at 60° orientation, indicating a noticeable reduction of approximately 79.94 %.

Apart from the fibre orientation, the flexural modulus is affected by the strain rates. As seen in Table 6, the flexural modulus gradually increases for each fibre orientation as the strain rate progresses from 0.1 % to 6 % strain per minute. This change suggests that the balsa wood behaves in a strain rate-sensitive manner. For instance, in the case of 0° balsa orientation, the flexural modulus increases from 433.48 MPa at 0.1 % strain per minute to 551.39 MPa at 6 % strain per minute. Similar patterns can be observed in the other orientations as well, with the flexural modulus increasing from 257.45 MPa to 298.57 MPa for 30° orientation, from 76.96 MPa to 110.61 MPa for 60° orientation, and from 29.49 MPa to 42.75 MPa for 90° orientation.

Investigating the flexural strength values, at the strain rate of 0.1 % strain per minute, the flexural strength is reduced from 7.55 MPa at 0° to 0.63 MPa at 90° orientation, demonstrating a significant loss of strength of roughly 91.66 %. Similar tendencies are observed at other strain rates.

The flexural strength of the balsa wood also shows a noticeable dependency on the strain rate. Analysing the data in Table 6, it is observed that a generally rising trend in the flexural strength as the strain rate increases for each orientation. In the case of 0° balsa orientation, the flexural strength increases from 7.55 MPa at a strain rate of 0.1 % strain per minute to 7.82 MPa at 6 % strain per minute. Similar upward trends for other orientations are noted, from 3.74 MPa to 4.32 MPa at 30°, 1.59 MPa to 1.79 MPa at 60°, and 0.63 MPa to 0.72 MPa at 90°.

Toughness, indicative of a material's ability to absorb energy, can be assessed by examining the area under the stress–strain curve. Notably, the elongation at break, the material's ability to deform until failure, is among the primary indicators of ductility, which can correlate to toughness. Therefore, elongation at break should be assessed alongside toughness. A clear correlation between the toughness of the material and fibre orientation can be observed.

From the testing equipment, force and displacement data are obtained. These data are processed based on Eq. (1) and stress-strain curves of the samples are plotted. As illustrated in Fig. 7, the stress–strain curves are significantly influenced by the orientation angle of the balsa wood. Indeed, the area under the stress–strain curve, and hence the toughness, varies with changing orientation and strain rate.

For example, for the 0° balsa orientation, the elongation at break is approximately 3.4 % on average over all the test speeds, contributing to a larger area under the curve and thereby implying a greater toughness. However, as the balsa orientation shifts from a 0° to 90° position, the toughness, similar to flexural strength and modulus, decreases. This decrease can be attributed to a reduction in the elongation at break, which drops to about 2.3 % at 30° orientation, the lowest recorded. At 60° and 90° orientations, the elongation at break measurements show rise to around 3.3 % and 4.1 %, respectively, therefore leading to smaller areas under the curve, which are still less than that at 0° orientation. Consequently, it can be deduced that the sample with 0° balsa orientation possesses the highest toughness among all.

Furthermore, Figs. 8 and 9, respectively, visualise the flexural modulus and flexural strength variations due to the strain rate and balsa angle using surfaces that fit the data extracted from experiments. Collectively, these figures provide an enhanced understanding of the strain rate sensitivity and fibre orientation sensitivity of balsa wood.

3.2.2. Orientation sensitivity of carbon fibre-epoxy balsa sandwich structures

The results of the three-point bending test performed on the sandwich structures represent the homogenised/effective flexural modulus and strength of the composite. The data given in this section represent average results from five separate experiments. The variability between these experiments is found to be under 5 % for these parameters, which points out the accuracy and reproducibility of the results. The variations in these properties in response to different orientation angles of each component highlight the composite's characteristic behaviour as a sandwich structure.

In Fig. 10, stress–strain curves of sandwich structures with 0° balsa orientation and 30° and 60° carbon fibre orientations are given. From this figure stress–strain relationship with respect to carbon fibre orientation can be examined. With increasing orientation angle, the flexural modulus and flexural strength of sandwich structures decrease. In the legend of Fig. 10, numbers represent the orientation of fibre angle, b represents "balsa", and cf means "carbon-fibre."

In order to analyse the mechanical behaviour of sandwich structures with respect to balsa orientation, in Fig. 11, stress–strain curves of sandwich structures with respect to balsa orientation are given. A decline in the flexural strength and modulus of sandwich structures is also observed with changing orientation angles. Similar to Fig. 10, in the legend of Fig. 11, numbers represent the orientation of the fibre angle, b represents "balsa", and cf means "carbon fibre."

Unlike the previous section concerning the results of the balsa wood, elongation at break values for carbon fibre-epoxy balsa sandwich structures are not available as only the balsa exhibits failure, but the carbon fibre epoxy components do not fail during the three-point bending test, and therefore the determination of the elongation at break has not been possible. Therefore, it is difficult to comment on the ductility and/or toughness of the sandwich structures as a complete failure cannot be observed.

Tables 7 and 8 present data that suggest a more complex behaviour/interaction between balsa orientation, carbon fibre orientation, and the composite's flexural strength and modulus. Here, as expected, the highest flexural modulus and flexural strength are detected at a fibre orientation of 0° of both balsa and carbon fibre-epoxy, and they decrease as the fibre orientations shift to 90°. Even though the fibre orientations for both materials seem to impact the flexural modulus and strength significantly, the fibre orientation of balsa appears to be more dominant. This is because the balsa layer is much thicker compared to the carbon fibre-epoxy layers composing the structure.

To visualise the results, Figs. 12 and 13 use surfaces fitted to the data collected from three-point bending test results to represent the differences in the flexural modulus and flexural strength caused by the carbon fibre and balsa angle, respectively.

To summarise, it can be understood that the situations 0° fibre orientations of balsa and carbon fibre have the most optimal toughness and flexural properties. This phenomenon can be attributed to the anisotropic behaviour of balsa wood and carbon fibre.

In the literature, balsa is also combined with different materials while building sandwich structures, for example, glass fibre-epoxy and polyethylene terephthalate (PET). When the results of this study and the results in the literature are compared, it is seen that carbon fibre provides a higher flexural modulus. As a result, carbon fibre epoxy balsa sandwich structure can be an alternative to these ones [39,40].

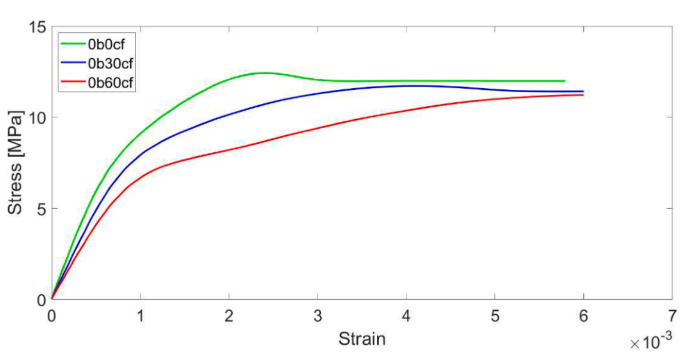

Fig. 10. Stress–strain relationship with varying carbon-fibre orientations (numbers represent the orientation of fibre angle, b represents "balsa", and cf means "carbon fibre").

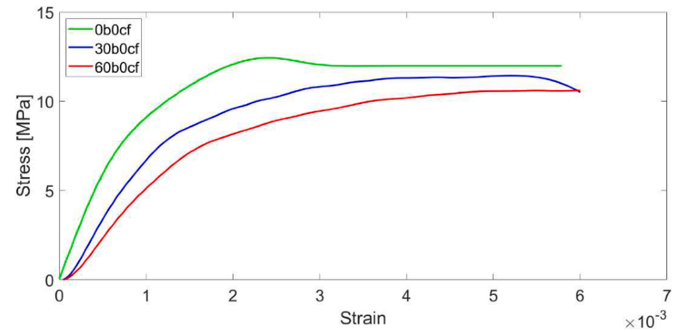

Fig. 11. Stress–strain relationship with varying balsa orientations (numbers represent the orientation of fibre angle, b represents "balsa", and cf means "carbon fibre").

Table 7
Flexural modulus of the composite due to balsa/carbon fibre orientation and strain rate.

Balsa/Carbon fibre orientation	Flexural modulus [MPa] 0°	30°	60°
0°	8520 ± 404.29	7290.5 ± 142.27	6289.73 ± 232.76
30°	6807.06 ± 144.48	5346.09 ± 207.74	4500.25 ± 175.31
60°	4350.48 ± 93.25	3701.08 ± 86.94	2437.68 ± 82.59

Table 8
Flexural strength of the composite with different balsa/carbon fibre orientations.

Balsa/Carbon fibre orientation	Flexural strength [MPa] 0°	30°	60°
0°	12.51 ± 0.56	11.73 ± 0.12	11.13 ± 0.45
30°	11.37 ± 0.33	10.07 ± 0.23	9.85 ± 0.21
60°	10.68 ± 0.25	9.07 ± 0.38	8.96 ± 0.007

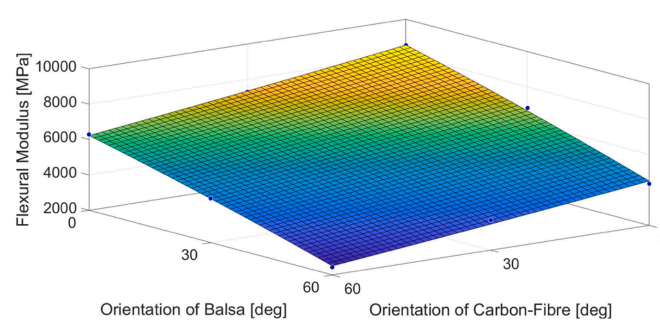

Fig. 12. Flexural modulus variation of the composite according to strain rate and balsa angle.

4. Discussion

The fibre orientation sensitivity and strain rate sensitivity of the composite material further underscores the need for an orthotropic and viscoelastic material model, reaffirming the conclusions drawn from the

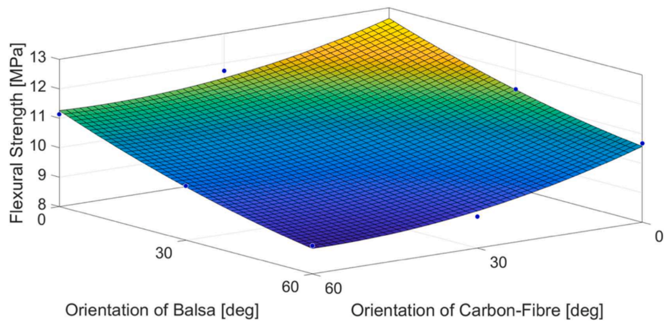

Fig. 13. Flexural strength variation of the composites according to strain rate and balsa angle.

initial mechanical behaviour analysis. This model would provide a more accurate representation of the material's behaviour under various conditions, enabling more precise predictions and better design capabilities for such composite structures. The orthotropic material model assumes different properties in different directions, which is consistent with the observations for the composite material in this study.

These results clearly elucidate the orthotropic nature of balsa wood, where the mechanical properties, including toughness and elongation at break, differ along different axes, contingent on factors such as fibre orientation and strain rate. Therefore, a thorough understanding of these characteristics is pivotal in harnessing the optimal performance of balsa wood in various applications.

These observations underline the significant role of strain rate on the flexural modulus of balsa wood, indicating that balsa wood and its sandwich structures are not just orthotropic but also strain rate-dependent materials. Such insights into the behaviour of these materials under different strain rates provide essential data for the design and analysis of structures in various engineering and architectural applications.

These results clearly point to the strain rate-dependent nature of balsa wood's flexural strength. The ability to modulate strength through strain rate manipulation could have significant implications for the design and application of balsa-based materials in engineering and architectural contexts. It offers an additional degree of control to tailor the material's performance as per specific requirements.

It's important to note, however, that with the increase in strain rate, there's a slight rise in flexural strength for each orientation. This indicates that balsa wood's strength properties, much like its flexural modulus, exhibit strain rate sensitivity. Understanding these variations in strength across different strain rates and orientations is crucial, as it enables a more accurate prediction of the material's performance under various operational conditions. The ability to anticipate and control these factors is essential when employing balsa wood in engineering and architectural applications, particularly where the material will be subjected to different levels of strain.

Even though this study reveals that the mechanical behaviour of the balsa wood and balsa core carbon fibre epoxy sandwich structures considerably change with slight changes in strain rates, the findings remain limited to lower strain rates. It would be difficult to make accurate predictions using the results of this study for the mechanics of thos materials under higher strain rates and impact loadings.

5. Conclusions

This study critically examines the mechanical behaviour of balsa wood and its composite structure with carbon fibre-epoxy under various low strain rates. The results emphasise the strain rate sensitivity of both the stiffness and strength of balsa wood. Contrary to common assumption that balsa wood is isotropic, instead this study offers a complex view of the mechanical performance of balsa wood.

Through a methodical examination, it has been established that the orientation of balsa wood has a significant effect on the mechanical properties of the composite, indicating the presence of anisotropic properties. The relationship between the relative orientation of carbon fibre and balsa wood of the flexural modulus and strength are clearly seen and it offers significant implications for the engineering applications of this sandwich structure.

Therefore, this study emphasises the potential of balsa wood as a multidirectional, sustainable, and lightweight material. More importantly, it highlights the need for a comprehensive study on the material's anisotropic properties due to its potential in various industries and its importance. Future researches could focus on the examination of these properties under different environmental conditions and the investigation of other potential improvements to balsa-based composite materials.

The results of this study would be valuable for future research to explore how balsa wood and carbon fibre-epoxy sandwich structures perform under higher strain rates and in various environmental conditions, like extreme temperatures or moisture levels. Also, a deeper understanding of how these materials perform in real-world situations could be investigated. Future research could focus on investigating the interface performance of balsa wood composites. Additionally, the anisotropic behaviour of these composites could be further explored using varying combinations of fibre orientations and strain rates in optimisation studies of their mechanical properties for specific applications. Studies focusing on the impact resistance and long-term durability of these materials could also be investigated and are recommended. Lastly, due to sustainable properties of balsa wood, further research into its life cycle analysis could provide insights into the environmental benefits of using this material rather than other less sustainable alternatives. The insights derived from such studies will greatly contribute to the development of more efficient, sustainable, and versatile composite materials.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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