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A B S T R A C T

The aim of this paper is the fabrication and mechanical testing of entangled sandwich beam specimens and the comparison of their results with standard sandwich specimens with honeycomb and foam as core materials. The entangled sandwich specimens have glass fiber cores and glass woven fabric as skin materials. The tested glass fiber entangled sandwich beams possess low compressive and shear modulus as compared to honeycomb and foam sandwich beams of the same specifications. Although the entangled sandwich beams are heavier than the honeycomb and foam sandwich beams, the vibration tests show that the entangled sandwich beams possess higher damping ratios and low vibratory levels as compared to honeycomb and foam sandwich beams, making them suitable for vibro-acoustic applications where structural strength is of secondary importance, e.g., internal paneling of a helicopter.

Keywords:
Entangled sandwich materials
Mechanical testing
Vibration testing
Damping

1. Introduction

Sandwich structures are commonly used in aerospace and automobile structures, since they offer great energy absorption potential and increase the flexural inertia without significant weight penalties. The purpose of the core is to maintain the distance between the laminates and to sustain shear deformations. By varying the core, the thickness and the material of the face sheet of the sandwich structures, it is possible to obtain various properties and desired performance [1–4]. Examples of widely used laminate materials are glass reinforced plastic (GRP) and carbon fiber. There are many wide varieties of core materials currently in use. Among them, honeycomb, foam, balsa and corrugated cores are the most widely used. Usually honeycomb cores are made of aluminum or of composite materials: Nomex, glass thermoplastic or glass-phenolic. The other most commonly used core materials are expanded foams, which are often thermoset to achieve reasonably high thermal tolerance, though thermoplastic foams and aluminum foam are also used. For the bonding of laminate and core materials, normally two types of adhesive bonding are commonly employed in sandwich construction, i.e., co-curing and secondary bonding.

Characterization of sandwich materials has been carried out in detail in scientific literature. The determination of the sandwich material behavior under crushing loads and the measurements of the ductile fracture limits is normally done with the help of compression tests [5,6]. Typically, cores are the weakest part of sandwich structures and they fail due to shear. Understanding the shear strength properties of sandwich core plays an important role in the design of sandwich structures subjected to flexural loading [7,8]. Therefore, three-point bending tests are often performed to find the flexural and shear rigidities of sandwich beams [9–11]. The vibration characteristics of sandwich materials have drawn much attention recently. The dynamic parameters of a structure, i.e., natural frequency, damping and mode shapes, are determined with the help of vibration testing which provides the basis for rapid and inexpensive dynamic characterization of composite structures [12]. Ewins [13] gave a detailed overview of the vibration based methods. A wide amount of literature is present related to vibration testing of composite sandwich beams [14–20]. The equations that explain the dynamic behavior of sandwich beams are also described extensively in the literature and notably in [21,22].

The importance of material damping in the design process has increased in recent years as the control of noise and vibration in high precision, high performance structures and machines has become more of a concern. In polymeric composites, the fiber contributes to the stiffness and the damping is enhanced owing to the internal friction within the constituents and interfacial slip at the fiber/matrix interfaces. At the same time, polymer composites researchers have focused more attention on damping as a design variable and the experimental characterization of damping in composites and their constituents [23,24]. A comprehensive review on the status of research on damping in fiber-reinforced composite materials and structures has been presented by Chandra et al. [25]. Their paper presents damping studies involving macro-mechanical, micro-mechanical and viscoelastic approaches;

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models for inter-phase damping, damping and damage in composites. In recent years, several investigators have considered a number of innovative ideas in order to improve the mechanical performance of sandwich structures. But the majority of these works present in scientific literature for example [26–29], are related with the improvement of the mechanical properties (in particular the longitudinal Young's modulus and the transverse shear modulus) and the impact toughness (energy absorption characteristics) of sandwich structures. However works related to the enhancement of damping in sandwich structures are relatively few in number as compared to enhancements in mechanical properties and impact toughness. A way of increasing damping in sandwich materials is by putting a viscoelastic layer as core between the two laminates [30,31]. Yim et al. [32] studied the damping behavior of a 0° laminated sandwich composite cantilever beam inserted with a viscoelastic layer. Gacem et al. [33] improved damping in thin multilayer sandwich plates having five layers composed of elastomer and steel. Afterwards they submitted the structure to shear vibrations under a compression preload. With the advancement of technology in electro-rheological (ER) materials, their applicability to sandwich structures has been increased significantly due to their merits such as variable stiffness and damping properties [34]. The vibration analysis of a sandwich plate with a constrained layer and electro-rheological (ER) fluid as core has been investigated by Yeh and Chen [35]. Jueng and Aref [36] also investigated the feasibility of a combined composite damping material system. In this new configuration, they used two different types of composite materials. One is a polymer honeycomb material and the other is a solid viscoelastic material. The honeycomb material is helpful to enhance the stiffness of the entire structure, and the solid viscoelastic will provide more energy dissipation properties in the multilayer panel systems when subjected to in-plane shear loading. These advanced polymer matrix composite (PMC) systems are also addressed for seismic retrofitting of steel frames [37]. Damping layer in sandwich structures can be made of any suitable material which provides the vibration damping function. Damping can be promoted in sandwich structures by using rubber-type cores made of butyl rubber or natural rubber, plastics such as polyvinyl chloride (PVC), adhesives of various polymer materials including epoxy-based materials, silicones, polyurethane, etc. [38,39]. A 3MTM VHBTM structural glazing tape is also used as damping layer in sandwich structures [40].

These advancements have led to the need for developing materials possessing better damping characteristics. Entangled sandwich materials can be used as potential dampers and sound absorbers in specific applications like the inner paneling of a helicopter, where structural strength is not the primary requirement. Entangled materials are made from natural materials (wool, cotton, etc.) as well as artificial ones (carbon, steel, glass, etc.) and are quickly becoming of widespread use as sound absorbers [41]. Bonded metal entangled materials offer advantages for use as heat exchanger [42] or insulation [43]. These materials possess low relative density, high porosity and are cost-effective. Recently, a novel type of sandwich has been developed with bonded metallic fibers as core material [44–48]. This material presents attractive combination of properties like high specific stiffness, good damping capacity and energy absorption. Entangled materials with carbon fibers have also been studied as core material [49]. Entangled materials with cross-linked carbon fibers present many advantages as core materials, i.e., open porosity, multifunctional material or the possibility to weave electric or control cables on core material. Mezeix et al. [50] studied the mechanical behavior of entangled materials in compression. Mechanical testing has also been carried out on specimens made of wood fibers [51], glass fibers [52] and various matted fibers [53]. There are also some works in the literature related to 3D modeling of wood based fibrous networks based on X-ray tomography and image analysis [54]. Unfortunately, only a few works can be found in the scientific literature devoted to the mechanical testing of entangled sandwich materials, and no scientific literature can be found related to the vibration testing of entangled sandwich materials or even simple entangled materials.

The type of sandwich structures considered in this article consist of two thin but relatively stiff sheets bonded to each side of a 10 mm thick light-weight core in a symmetrical configuration with the help of co-curing process. The proposed entangled sandwich specimens are currently in the phase of research and are not a finished article as yet. Therefore the mechanical behavior of these sandwich materials are compared for now with standard sandwich beams with honeycomb and foam cores only. Once further expertise is developed in fabricating entangled sandwich specimens, their mechanical behavior especially damping capability shall be compared with innovative sandwich specimens such as multi-layered sandwiches with viscoelastic cores, 3D fabric sandwich structures including glass fibers in the thickness directions, thermoplastic cored sandwiches, etc. Furthermore, compression and three-point bending tests are carried out to determine the compressive and shear modulus. Vibration testing is used to diagnose the quality of the fabrication process and also to verify the potential damping capabilities of the entangled sandwich specimens.

2. Experiments

2.1. Materials and specimens

Three types of sandwich beam specimens are fabricated and tested in this article with entangled glass fibers, honeycomb and foam as core materials. The skins for all the sandwich beams used are made of glass woven fabric 20823 supplied by Brochier. The sandwich beam specimens are fabricated using an autoclave and an aluminum mold. The skin and the core are cured simultaneously in order to have an excellent bond. The physical properties of the skin are given in Table 1. The glass woven fabric is impregnated with the help of epoxy resin. The epoxy resin SR 8100 and injection hardener SD 8824 are provided by Sicomin. The upper and lower skins consist of two 0.5 mm thickness plies containing 50% of resin by volume. The combined weight of the upper and lower skins is approximately 19 g for each of the three types of sandwich specimens.

The entangled sandwich beam cores consist of glass fibers that are made of a yarn of standard glass filaments. The properties of the glass fibers are presented in Table 2. The fibers are provided by the company PPG Fiber Glass Europe. The same epoxy resin is used as in case of the skins for the cross-linking of glass fibers. All the test specimens presented in the article are carefully weighed using a Mettler balance.

The honeycomb and foam cores can be selected from a wide range of metallic and non-metallic honeycomb cores and a variety of non-metallic foams. The honeycomb sandwich beams in this article are made of Nomex-aramid honeycomb core (HRH 10) supplied by Hexcel composites [55]. The honeycomb core has a nominal cell size of 6.5 mm and a core thickness of 10 mm. In case of the foam sandwich beams, the foam core has a thickness of 10 mm and is provided by Rohacell (51 A). Mechanical properties

Table 1
Properties of glass woven fabric.

Elastic modulus in the longitudinal direction (E_x)	23,000 MPa
Elastic modulus in the transverse direction (E_y)	23,000 MPa
Shear modulus (G)	2900 MPa
Poisson ratio	0.098

Table 2
Properties of glass fibers.

Type of glass fiber	Type E
Length of glass fiber	10 and 15 mm
Diameter of glass fiber	14 μm
Elastic modulus	73 GPa

of the honeycomb and foam cores are listed in Tables 3 and 4 respectively.

The fabrication of entangled sandwich specimens is often a tedious and complex process. These types of materials are mostly in the research phase, therefore standard fabrication processes do not exist. The fabrication procedure used in this article was developed by Mezeix et al. [50]. Two types of entangled sandwich beams are fabricated in this article having glass fiber lengths of 10 and 15 mm for the core using an aluminum mold (510 × 65 × 11 mm). A 200 kg/m^3 glass fiber density is chosen for the entangled sandwich core. The glass fibers are cut with the help of a fiber cutting machine. The fibers are then separated by a blow of compressed air. The mixture of resin and hardener is then sprayed on the separated glass fibers by a spray paint gun. The fibers impregnated by the resin are then placed in the mold between the two skins of impregnated glass woven fabric. To produce good quality sandwich beams reliably, the cure cycle is adopted as follows: 1 h from the ambient temperature to 125 °C, 1.5 h at 125 °C and 1 h from 125 °C to the ambient temperature. For the two types of entangled sandwich specimens (10 and 15 mm glass fiber length), the core contains 26 g of glass fiber and 7 g of epoxy resin. The same mold, cure cycle and skins are used for the fabrication of honeycomb and foam sandwich specimens. Two beams of dimensions (250 × 50 × 11 mm) are extracted from the mold for each sandwich specimen, having honeycomb, foam and entangled glass fibers as core (10 and 15 mm). Sandwich test specimens with honeycomb, foam and entangled glass fiber cores used for vibration testing are shown in Fig. 1.

After the vibration testing, one specimen of each type is cut into smaller specimens for compression and bending tests with the help of a diamond wheel cutter, following the ASTM D3039/D3470 standards. The specifications of the compression, bending and vibration test specimens are presented in Table 5.

2.2. Experimental procedure

Compression tests are carried out in order to calculate the compressive modulus for the sandwich honeycomb, foam and entangled specimens. The quasi-static compressive response of these specimens is measured in a 100 kN Instron machine. The specimen size chosen for the compression tests is 30 × 30 × 11 mm. The test specimens are placed between the moveable and the fixed plate as shown in Fig. 2. The displacement is measured by a LVDT sensor integrated in the Instron machine placed under the movable plate. The applied velocity of $v_0 = 2$ mm/min corresponds to a nominal strain rate of $\dot{\varepsilon} = 3 \times 10^{-3}$/s at the beginning of the test. The maximum applied load is 4 kN corresponding to 4.5 MPa. To analyze the experimental results, the following definitions for the true strain and stress are used:

Table 3
Properties of Honeycomb core (HRH-10).

Cell size	6.5 mm
Density	31 kg/m^3
Compressive strength	0.896 MPa
Compressive modulus	75.8 MPa
Shear strength in longitudinal direction (σ_{xz})	0.65 MPa
Shear modulus in longitudinal direction (G_{xz})	29 MPa
Shear strength in width direction (σ_{yz})	0.31 MPa
Shear modulus in width direction (G_{yz})	13.8 MPa

Table 4
Properties of Foam core (Rohacell 51A).

Density	52 kg/m^3
Tensile strength	1.9 MPa
Compressive strength	0.9 MPa
Elastic modulus (traction)	70 MPa
Shear strength	0.8 MPa
Shear modulus	19 MPa
Elongation at break	3.0%

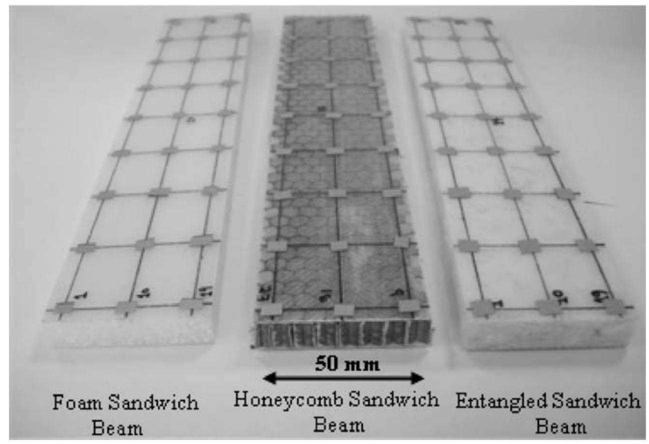

Fig. 1. Sandwich test specimens with honeycomb, foam and entangled glass fibers as core used for vibration testing.

Table 5
Dimensions of the compression, bending and vibration test specimens

	Compression test	Bending test	Vibration test
Length (mm)	30	140	250
Width (mm)	30	20	50
Core thickness (mm)	10	10	10
Skin thickness (mm)	1	1	1

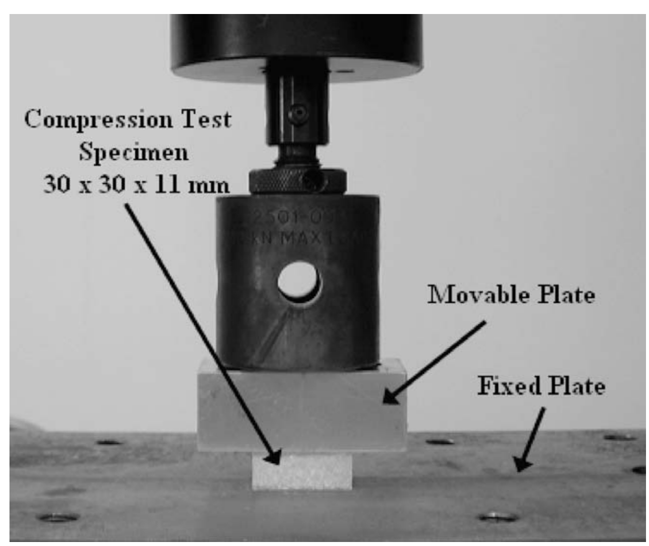

Fig. 2. Test Specimen between the fixed and moveable plate during compression test.

$$\text{Strain}, \ \varepsilon = \ln\left(\frac{h}{h_0}\right) \quad (1)$$

$$\text{Stress}, \ \sigma = \frac{F}{S} \quad (2)$$

where h is the height during compression, h_0 is the initial height of the sample, S is the area during compression, S_0 is the initial area and F is the applied force. In our case, the area S varies very little and no barreling is noted during the compression tests, so it is assumed that $S = S_0$.

A three-point bending test is performed in order to measure the out-of-plane shear modulus for the honeycomb, foam and entangled sandwich specimens on a 10 kN Instron machine. The dimension of the bending test specimens are 140 × 20 × 11 mm and the distance between the two supports is 80 mm. The applied velocity is v_0 = 1 mm/min. Round steel bars or pipes are used as supports having a diameter of 6 mm which is not less than one half the core thickness (5 mm) and not greater than 1.5 times the sandwich thickness as per ASTM standards [7]. The three-point bending test is shown in Fig. 3.

For the analysis of a sandwich beam under three-point bending, consider a sandwich beam of width b and length l, comprising two identical face sheets of thickness t_f and core of thickness t_c. Also, h is the spacing of the mid plane of the face sheets ($h = t_c + t_f$), as shown in Fig. 4.

The load P is applied at the center of the beam. The maximum deflection of the beam is due to both flexural and shear deformations. The shear deformation is dominated in the core and hence, the approximate expression for the elastic deflection can be expressed as [3]:

$$\text{Maximum deflection}, \ \delta = \frac{Pl^3}{48D} + \frac{Pl}{4S} \quad (3)$$

The bending stiffness D and the shear stiffness S are given by

$$\text{Bending stiffness}, \ D = \frac{E_s t_f h^2 b}{2} \quad (4)$$

$$\text{Shear stiffness}, \ S = bhG_c \quad (5)$$

where E_s is the elastic modulus of the skins, G_c is the shear modulus of the core and t_f is the thickness of the skin. The maximum deflection δ is calculated experimentally by the three-point bending test, the only unknown is the shear modulus G_c which is calculated by putting Eq. (5) in Eq. (3). The obtained equation is only valid for the beginning of the bending tests when the deflection is relatively small and in fact is used only to evaluate the shear modulus.

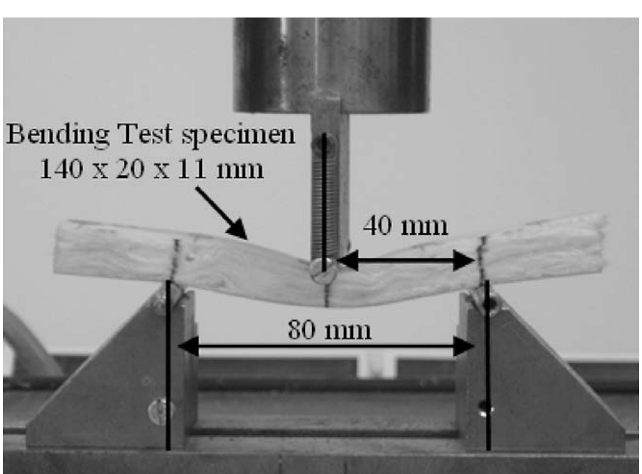

Fig. 3. Test specimen between the three supports during three-point bending test.

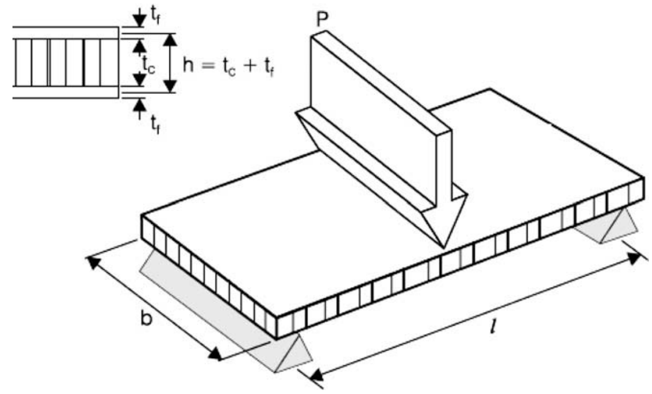

Fig. 4. Sketch of a sandwich beam under three-point bending showing geometrical parameters.

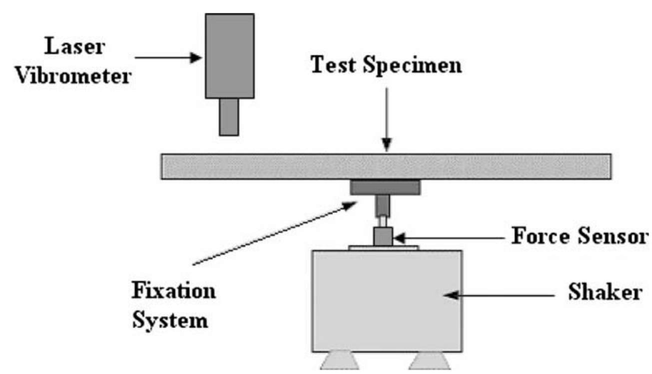

Fig. 5. Diagram of the experimental set-up for vibration testing.

Fig. 5 shows the experimental set-up used for vibration testing. The experimental set-up is that of a free–free beam excited at its center, based on Oberst method [56]. The Oberst method states that a free–free beam excited at its center has the same dynamical behavior as that of a half length cantilever beam. The test specimen is placed at its center on a B&K force sensor (type 8200) which is then assembled on a shaker supplied by Prodera having a maximum force of 100 N. A fixation system is used to place the test specimens on the force sensor. The fixation is glued to the test specimens with a HBM X60 rapid adhesive. The response displacements are measured with the help of a non-contact and high precision Laser Vibrometer OFV-505 provided by Polytec. The shaker, force sensor and the laser vibrometer are manipulated with the help of a data acquisition system supplied by LMS Test Lab.

The center of the test specimens is excited at Point 14 as shown in Fig. 6. A broadband excitation signal (0–3200 Hz) is used as a burst random excitation. The signal is averaged 10 times for each measurement point. Hanning windows are used for both the output and the input signals. The linearity is checked and a high frequency resolution (Δf = 0.25 Hz) for precise modal parameter estimation is used. Response is measured at 27 points that are symmetrically spaced in three rows along the length of the beam. The modal parameters are extracted by a frequency domain parameter estimation method (Polymax) integrated in the data acquisition system.

3. Results and discussions

Fig. 7 shows a typical stress–strain curve obtained from the quasi-static compression tests, carried out on the sandwich specimens with honeycomb, foam and entangled glass fiber cores

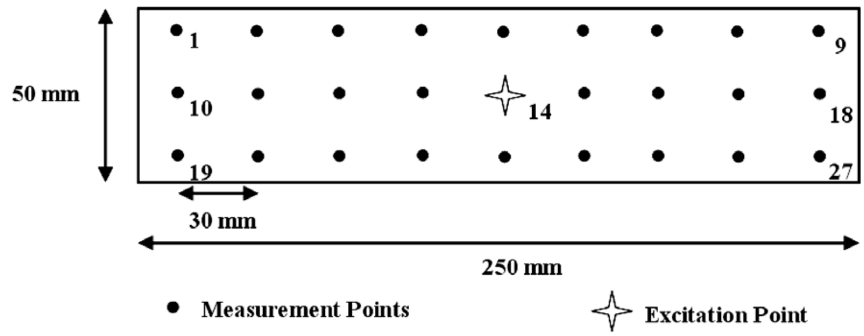

Fig. 6. Location of excitation and measurement points in sandwich beam for vibration test.

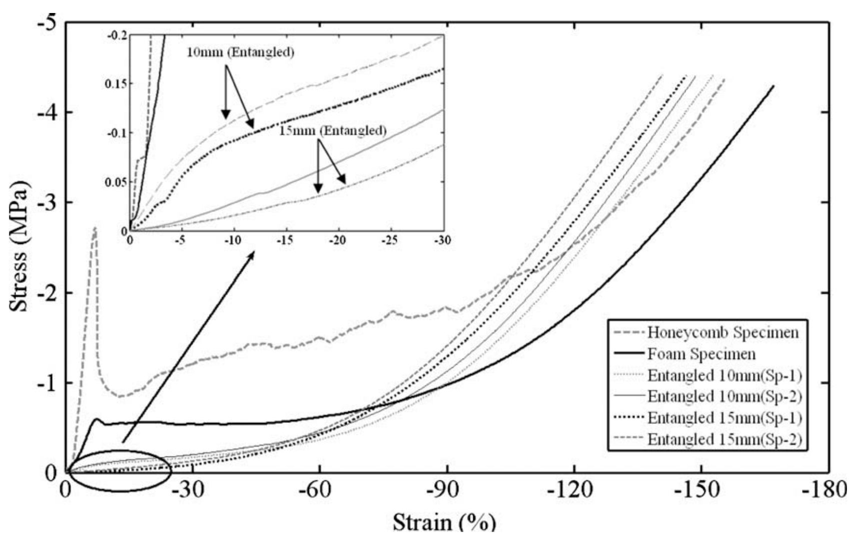

Fig. 7. Compression stress/strain curves for the entangled (10 and 15 mm fiber core length), foam and honeycomb sandwich specimens. The zoomed view shows the linear-elastic phase used for calculating the elastic modulus.

(10 mm and 15 mm fiber length). Three specimens of each type of sandwich material are tested but for the sake of clarity, we only present results for a single specimen in case of honeycomb and foam sandwich materials, and two specimens each in case of the entangled sandwich materials with 10 and 15 mm glass fiber lengths (Fig. 7). The compressive modulus is computed based on the linear-elastic phase by the method presented in [53]. In the case of honeycomb cores, the calculation of the compressive modulus is done without taking into account the open cells at the four ends of the $30 \times 30 \times 11$ mm specimen. These open cells buckle under loading and do not contribute to the compressive modulus [57]. Thus the calculations are carried out based on an effective area of approximately 25×25 mm^2 instead of the original area 30×30 mm^2. It can be seen that the overall behavior in compression is considerably identical for the two types of entangled sandwich specimens having glass fiber lengths of 10 and 15 mm. The densification for all the entangled specimens starts around the 60% strain mark. However if the curves are analyzed more closely (zoomed view in Fig. 7), it can be seen that an elastic-linear part exists in case of the 10 mm fiber length entangled sandwich specimens, but this elastic-linear part is non-existent in the case of entangled sandwich specimens with 15 mm length fibers in the core. The reason for this is the orientation of fibers in the specimen as shown in Fig. 8.

For the 10 mm fiber length entangled specimens, the fibers are situated in both the *x* and *y* directions, but in case of the 15 mm fiber length entangled specimens, glass fibers in the *y*-direction are very sparse. The reason may be that in an entangled core better fiber orientation occurs if the length of the fibers is equal to or smaller than the thickness of the core, as discussed in Ref. [53]. This is the main reason why fibers in the entangled core have a more multi-direction orientation in case of 10 mm fiber lengths as compared to 15 mm fiber lengths. As the load during the compression tests is applied in the *y* direction, it is evident that the compressive modulus for the 15 mm fiber length specimens is very hard to calculate (absence of linear-elastic phase), as the specimens have very low resistance in the y direction due to lack of glass fibers. The compressive modulus for the 10 mm fiber length entangled specimens calculated from the linear-elastic phase is 3 MPa. For the foam and honeycomb sandwich specimens, the linear-elastic phase is much more prominent when compared to the entangled sandwich specimens. The compressive moduli calculated from the compression tests are presented in Table 6. It can be seen that the compressive modulus for the entangled sandwich materials is much smaller than standard sandwich materials with honeycomb and foam

Table 6
Compressive modulus of the honeycomb, foam and entangled material cores calculated from the compression tests.

Compressive modulus for honeycomb core	64 MPa
Compressive modulus for foam core	43 MPa
Compressive modulus for 10 mm glass fiber length entangled core	3.0 MPa
Compressive modulus for 15 mm glass fiber length entangled core	–

cores. The compressive modulus calculated for the honeycomb specimen can be compared with that provided by the manufacturer in Table 3.

Fig. 9 shows a typical load–deflection curve obtained under static three-point bending (support span of 80 mm), on the three types of sandwich materials studied in this article. In case of honeycomb and foam sandwich materials, load–deflection curve for a single specimen is presented whereas in the case of entangled sandwich specimens, results are presented for two specimens for each 10 mm and 15 mm fiber core length entangled sandwich materials. An initial crushing phase occurs for all specimens up to a deflection of 1 mm due to skin thinness. In case of the foam sandwich specimen different key features can be clearly identified. The initial linear-elastic behavior (point ①) is followed by an elasto-plastic phase until a peak value is reached (point ②), after which the load decreases, initially markedly and then more smoothly (point ③ and ④); during this phase energy is mainly dissipated by indentation with the formation of hinges within the upper face adjacent to the indenter, and by compressive yielding of the underlying core. For the honeycomb sandwich specimen, the load loss after the peak value (point ①) is much more evident (point ②) due to core shear failure. Afterward (point ③ and ④) the load remains almost constant. In case of the entangled materials, the behavior is a bit different. For the four entangled sandwich specimens (two 10 mm fiber length and the two 15 mm fiber length specimens), the first damage in the skin occurs around 18 N. After this phase, the load increases up to the 4 mm deflection mark, and then it becomes constant due to the densification of the glass fibers in the core. The reason of this densification is the higher density of the glass fibers in the core of the entangled sandwich specimens (200 kg/m^3) as compared to that of honeycomb (30.5 kg/m^3) and foam (51.5 kg/m^3) sandwich cores. The shear moduli calculated from the three-point bending tests are presented in Table 7.

Table 7 shows that the standard sandwich specimens with honeycomb and foam core materials possess better shear strength when compared to the entangled sandwich specimens. In order to improve the shear modulus in case of the entangled specimens, a certain percentage of the glass fibers in the core should be placed in the ±45° direction, but unfortunately with the fabrication method proposed in the article, that is not possible. For the entangled sandwich specimens, we think that the shear modulus G is homogeneous in the plane (it remains to be verified), so we shall compare it with that of the honeycomb in the width direction only (G_{yz}) due to its smaller value (Table 3). As in the case of compression tests, the computed values of the shear modulus for the honeycomb and foam sandwich specimens show a good correlation when compared with those presented in Tables 3 and 4, provided by the manufacturers. However, the difference in the shear moduli between the two types of entangled sandwich specimens is also due to the orientation of fibers as discussed above and shown in Fig. 8.

Table 7
Shear modulus of the honeycomb, foam and entangled material cores calculated from three-point bending tests.

Shear modulus for honeycomb core (G_{yz})	12 MPa
Shear modulus for foam core	22 MPa
Shear modulus for 10 mm glass fiber length entangled core	9 MPa
Shear modulus for 15 mm glass fiber length entangled core	5 MPa

Vibration tests are then carried out on the three types of sandwich specimens studied in this article, i.e., honeycomb, foam and glass fiber entangled core materials with 10 and 15 mm fiber lengths. Two specimens of each type of material are tested. The modal parameters extracted from 27 high quality frequency response functions with the help of Polymax algorithm integrated in the LMS data acquisition system, are presented in Table 8 along with the specimen weights. The difference in weights observed between the specimens is due to the uneven distribution of resin in skins and in the core (in case of the entangled specimens).

Table 8 shows that the natural frequencies and damping ratios for the honeycomb and foam sandwich specimens are quite similar; the only exception is the damping ratios for the 1st and 4th bending modes. The compression and bending tests underlined that the 10 mm fiber length entangled sandwich specimens have higher compressive and shear moduli as compared to the 15 mm fiber length entangled sandwich specimens (Table 6 and 7). The better strength of 10 mm fiber length entangled sandwich specimens can also be proved with the help of vibration test results by comparing the natural frequencies of the 10 and 15 mm fiber length entangled sandwich specimens in Table 8. It can be seen that the 10 mm fiber length entangled sandwich specimens possess higher natural frequencies, thus proving that they are more rigid than the 15 mm fiber length entangled sandwich specimens. Furthermore, it can be observed from Table 8, that the entangled

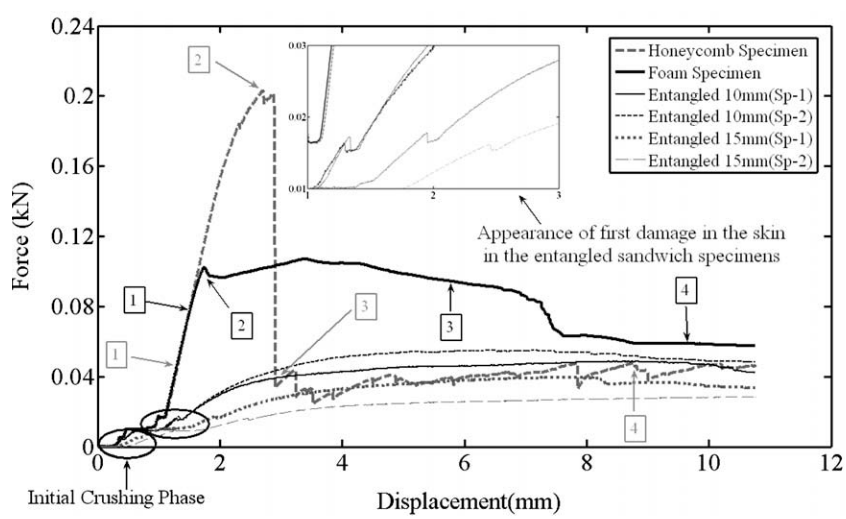

Fig. 9. Force-deflection curves measured under three-point bending tests for the entangled (10 and 15 mm fiber core length), foam and honeycomb sandwich specimens. The appearance of the first damage in the skins is indicated.

Table 8
Comparison of modal parameters for the honeycomb, foam and entangled sandwich specimens.

Type of specimen	Specimen No.	Specimen weight (g)	Damped natural frequencies (Hz)				Damping Ratios (%)			
			1st mode	2nd mode	3rd mode	4th mode	1st mode	2nd mode	3rd mode	4th mode
Honeycomb	1	22.6	552	1092	1974	2695	0.492	0.396	0.507	0.492
	2	23.4	560	1092	1994	2646	0.527	0.441	0.626	0.494
Foam	1	26.2	540	1025	1970	2607	0.368	0.556	0.503	0.769
	2	25.6	535	1023	1950	2622	0.355	0.464	0.560	0.744
Entangled	1	49.7	403	747	1201	1799	0.544	0.722	0.950	1.102
(10 mm)	2	51.6	407	759	1240	1826	0.560	0.832	0.790	0.898
Entangled	1	50.7	308	691	1166	1622	0.816	1.753	1.770	1.547
(15 mm)	2	49	306	724	1199	1678	0.838	1.892	2.152	1.806

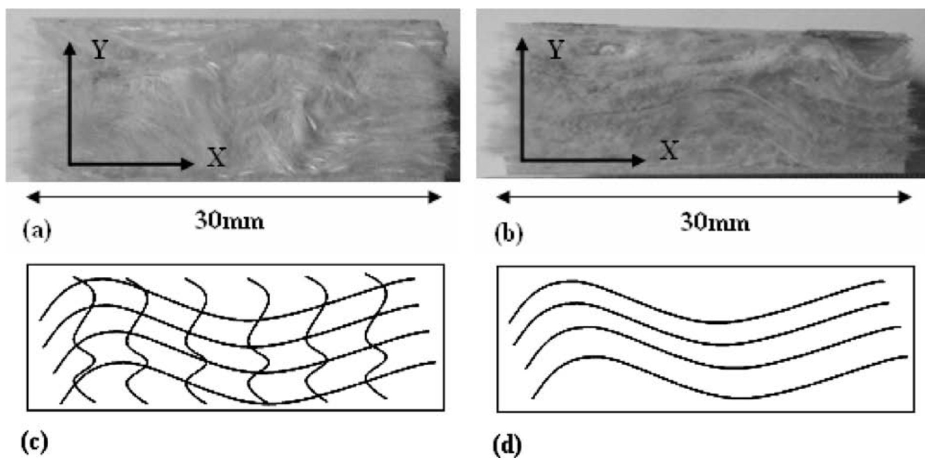

Fig. 8. Cross-section view of specimen showing the orientation of fibers: (a) 10 mm fiber length entangled sandwich specimen, (b) 15 mm fiber length entangled sandwich specimen. Schematic view explaining the orientation of fibers (c) 10 mm fiber length entangled sandwich specimen and (d) 15 mm fiber length entangled sandwich specimen.

sandwich specimens have higher damping ratios as compared to standard sandwiches with honeycomb and foam cores. However, it has to be clarified that enhanced sandwich structures with better damping characteristics exist as discussed previously, but this paper deals only with the static and dynamic characterization of glass entangled sandwich specimens and their comparison with standard honeycomb and foam sandwiches. Comparison with enhanced sandwich structures, e.g., honeycomb sandwiches with viscoelastic layer, etc. is not in the scope of this work and shall be duly considered in future works.

The vibration test results can be further analyzed by studying the changes in the damping ratios, average vibratory levels (AVL) and specimen weights. These changes for the entangled sandwich specimens (10 mm fiber length) and the foam and honeycomb sandwich specimens are calculated with the help of Eqs. (6)–(8) and the resulting values are shown in Table 9. The comparison between the other materials is carried out in similar fashion.

$$\text{Change in damping ratio, } \Delta\xi = \left(\frac{\bar{\bar{\xi}}_{E10} - \bar{\bar{\xi}}_{H,F}}{\bar{\bar{\xi}}_{H,F}}\right) \tag{6}$$

where $\bar{\bar{\xi}}_{E10}$ is the average damping ratio in case of the two 10 mm fiber length entangled specimens for the first four bending modes and $\bar{\bar{\xi}}_{H,F}$ is the average damping ratio in case of the two honeycomb and two foam sandwich specimens for the first four bending modes. The honeycomb and foam results are presented together in order to simplify the comparisons between the various types of materials presented in this article and also because their modal parameters and weights are quite similar (Table 8).

$$\text{Change in average vibratory level, } \Delta a = \bar{a}_{E10} - \bar{a}_{H,F} \tag{7}$$

where $\bar{a}_{E10}$ is the average amplitude in dB of the sum of the frequency response functions for the two 10 mm fiber length entangled specimens and likewise, $\bar{a}_{H,F}$ is the average amplitude in dB of the sum of the frequency response functions for the two honeycomb and two foam sandwich specimens.

$$\text{Change in weight, } \Delta W = \left(\frac{\bar{W}_{E10} - \bar{W}_{H,F}}{\bar{W}_{H,F}}\right) \tag{8}$$

where $\bar{W}_{E10}$ is the average weight (g) for the two 10 mm fiber length entangled specimens and likewise, $\bar{W}_{H,F}$ is the average weight (g) for the two honeycomb and two foam sandwich specimens.

The entangled sandwich specimens with 10 mm fiber length have (in average for all modes) a 60% higher damping ratio when

Table 9
Comparison of the vibrational levels, damping ratios and weights between the sandwich specimens with honeycomb, foam and entangled glass fibers as cores (+ sign shows an increase, while − sign shows a decrease).

	Change in damping ratio (%)	Change in vibrational level (dB)	Change in weight (%)
Entangled 10 mm versus (honeycomb, foam)	+60	−16	+96
Entangled 15 mm versus (honeycomb, foam)	+215	−24	+96
Entangled 15 mm versus entangled 10 mm	+97	−8	–

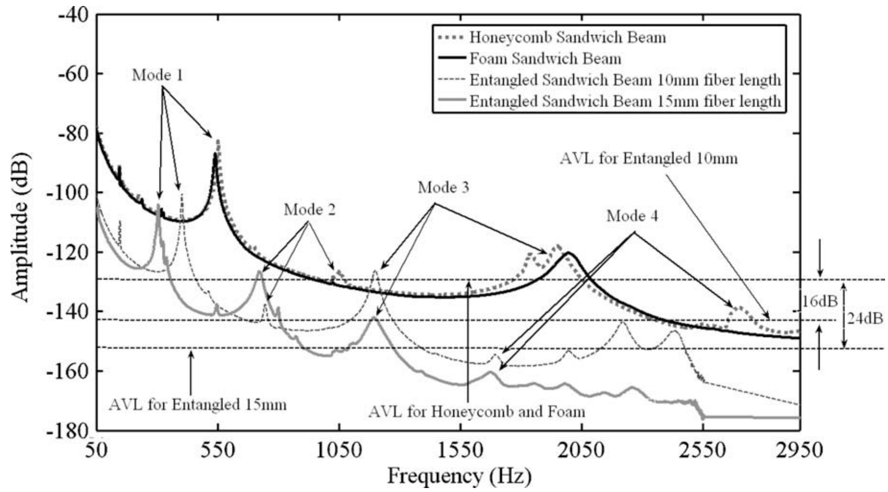

Fig. 10. Comparison of the Sum of frequency response function (FRF) for the honeycomb, foam and entangled sandwich specimens with the average vibratory level.

compared to honeycomb and foam sandwich specimens. In the case of the 15 mm fiber length entangled specimens, this increase in damping ratio is around 215% as shown in Table 9. On the other hand, the 15 mm fiber length entangled sandwich specimens have 97% higher damping ratios than the 10 mm fiber length ones. So it can be concluded that entangled sandwich specimens with relatively shorter fiber length (10 mm) in the core possess higher structural strength but have lower damping ratios as compared to entangled sandwich cores with comparatively longer fiber lengths (15 mm). Therefore, the entangled sandwich specimens can be manufactured according to the choice of the type of application, i.e., possessing higher rigidity or better damping characteristics. The major disadvantage of the proposed entangled sandwich specimens is that they are nearly two times heavier as compared to sandwiches with honeycomb and foam cores.

The comparison of modal parameters between the sandwich specimens can be further explained by comparing their sum of frequency response functions (FRF) as shown in Fig. 10. The sum of the frequency response functions can be compared for all vibration test specimens, as they have the same dimensions and the same number of measurement points (27), i.e., symmetry has been respected for all specimens. The average vibratory level for these sandwich specimens is also compared. The average vibratory level is computed by taking the average of the amplitude (in dB) of the sum of the frequency response function for each specimen.

It can be seen from Fig. 10 that the honeycomb and foam sandwich specimens have identical frequency response functions (FRF) which lead to relatively similar modal parameters as shown in Table 8. It can also be seen that the 10 mm fiber length entangled sandwich specimens have in average a 16 dB lower amplitude than the honeycomb or foam sandwich specimens. In case of the 15 mm fiber length entangled specimens, this difference in average vibratory level as compared to the honeycomb and foam specimens is 24 dB. Furthermore, Fig. 10 shows that the entangled sandwich specimens with longer fiber length (15 mm) in the core have lower amplitudes than those with shorter fiber length (10 mm). From the compression and bending tests, it is evident that the entangled materials have a low structural strength and are also heavier as compared to the standard sandwich materials (honeycomb or foam as core). But on the other hand, these materials possess higher damping ratios and low vibratory levels which make them suitable for damping suppression and sound absorption applications where structural strength is not the main requirement.

As previously discussed, enhanced sandwich structures with better damping characteristics exist, but this paper deals only with the static and dynamic characterization of glass entangled sandwich specimens and their comparison with standard honeycomb and foam sandwiches. Comparison with enhanced sandwich structures, e.g., honeycomb sandwiches with viscoelastic layer, etc. is not in the scope of this work and shall be duly considered in future works.

4. Conclusion

The aim of this paper is to manufacture and mechanically test glass entangled sandwich specimens in order to compare their performance with standard sandwich specimens having honeycomb and foam as core materials. The compression and bending test results show that the entangled sandwich specimens have a relatively low compressive and shear modulus when compared to honeycomb and foam sandwich materials. Vibration tests demonstrate the presence of high damping in the entangled sandwich specimens making them suitable for specific applications like the inner paneling of a helicopter cabin, even if the structural strength of this material is on the lower side. Furthermore, the vibration tests showed that entangled sandwich specimens possess in average 150% higher damping ratios and 20 dB lower vibratory levels than the honeycomb and foam sandwich specimens. The test results also proved that entangled sandwich specimens with shorter glass fiber lengths have high structural strength but on the other hand low damping ratios and higher vibratory levels when compared to entangled sandwich specimens with longer glass fiber length in the core. Thus, the entangled sandwich specimens can be fabricated according to the choice of the type of application, i.e., possessing higher rigidity or better damping characteristics.

Impact tests shall also be carried out on these sandwich materials in future with glass fibers, honeycomb and foam cores in order to study the variations of modal parameters with impact damage and to evaluate the impact toughness of entangled sandwich materials.

Acknowledgments

The authors gratefully thank Professor B. Castanié from Université de Toulouse for his technical support during the experimental work.

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