FLEXURAL BEHAVIOUR OF A BIO-BASED SANDWICH STRUCTURE MANUFACTURED BY LIQUID RESIN INFUSION

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ABSTRACT

This work summarizes the results of quasi-static and dynamic flexural tests performed on a bio-based sandwich structure. The skins are made of an innovative liquid thermoplastic resin reinforced with flax fibres and balsa wood panels are used as core. Sandwich plates are manufactured within a single-step liquid resin infusion process. First, the quasi-static flexural behavior of sandwich beams was investigated. Three point bending tests were conducted with different span lengths to determine the mechanical properties of the skins and core. Moreover, failure modes were analysed and explained by an analytical approach based on the implementation of a failure mode map. Finally the structure was tested in fatigue with different loading ratios to study its dynamic flexural and shear properties.

1 INTRODUCTION

Bio-based composites appear to be very promising alternatives to traditional composites [1]. As a matter of fact, the use of natural fibres as reinforcement reduces the environmental impact of these materials and their specific properties are significantly increased [2]. Flax, hemp, jute, ramie and sisal fibres are probably among the most studied vegetal fibres used by the composite industry. Most of the time, the choice of the kind a fibre to use is a compromise between its mechanical properties and its local availability and price. In Europe and particularly in France, flax and hemp fibers have been used for centuries for the manufacturing of textiles, ropes, etc. As a consequence, these fibres are currently widely studied for a composite usage [3].

Bio-based sandwich structures also appear to be interesting material candidates to face further environmental and industrial challenges. There are made up with a light core inserted between stiff and resistant skins. This increases the quadratic moment of the structure and improves its flexural stiffness and strength. Several authors have already studied bio-based sandwich structures [4-7]. For example, le Duigou et al. [8] described the manufacturing and the mechanical properties of a sandwich made up with PLLA skins reinforced with flax fibres and a balsa core. This material, completely biodegradable, exhibits interesting specific properties. Moreover a life cycle analysis revealed a reduced environmental impact. Indeed, balsa wood is often mentioned as a good core candidate. It is among the natural material exhibiting the highest compressive and shear specific properties. Due to its cellular microstructure, balsa wood also exhibits other interesting physical properties such as fire retardancy [9], sound or vibration damping [10], etc.

In this context, this work focuses on the manufacturing and the flexural properties a bio-based sandwich made up with thermoplastic skins reinforced with flax fibres and a balsa wood core. This structure, produced by a liquid resin infusion process, brings new perspective in the field of bio-based and potentially recyclable thermoplastic composites.
2 MATERIALS AND MANUFACTURING

2.1 Sandwich components

The reinforcement used is a tape of unidirectional continuous flax fibres with a surface mass of 200 g.m\(^{-2}\) manufactured by LINEO [11]. A key feature of this product is that the fibres are held together without any twisting or weft yarn by a process consisting in reactivating the external pectin cements on the surface of fibre bundles. This allows, among other things, the manufacturing of very aesthetic composite parts.

The fibres are associated with an innovative liquid thermoplastic resin (ELIUM RT 150) produced by ARKEMA. It is an acrylic resin activated by peroxide (2% of CH50x). This resin has a very low viscosity. As a consequence, it can be used with manufacturing processes such as liquid resin infusion (LRI) or resin transfer molding (RTM) usually used for the production of thermosetting composites.

Balsa wood panels provided by BALTEK are used as core with a nominal density of 150 kg.m\(^{-3}\). This product is an assembly of several rectangular elementary blocks of wood (50mm x 25mm x 15.9mm) maintained together by a thin mesh grid. This configuration allows the manufacturing of curved panels. Moreover, the gaps between the blocks facilitate the resin infusion and migration from the upper to the lower faces. However, the pieces of wood composing the panels are coming from different trees. As a consequence, local dispersion of the core properties should be observed. To verify this, several elementary blocks were randomly extracted from the panels, measured and weighted. The average volume mass measured was equal to 150 kg.m\(^{-3}\). However, a high standard deviation (\(\sigma = 27\)) was measured.

2.2 Manufacturing process

Sandwich plates are produced within a single step liquid resin infusion process. The dry materials (fibres and balsa) are drought in a ventilated oven at a temperature of 110°C for one hour. This step is necessary to remove a part of the water trapped in these natural materials and poorly compatible with the acrylic resin used. Then, a flat glass mold is prepared with a release agent. The dry fibres constituting the lower skin are laid out with the desired stacking sequence. Then, the dry balsa core is placed over the fibres and covered by the flax plies constituting the upper skin. A peel ply is added as well as an infusion complex composed of a micro perforated film and an infusion mesh to facilitate the resin migration. Finally, the dry preform is covered by an impermeable film attached to the mold with an adhesive sealer. This vacuum bag contains a resin inlet initially closed and an outlet connected to the vacuum pump. The vacuum quality is controlled by mean of an ultrasonic leak detector and a pressure manometer to make sure that a quasi-constant vacuum can be maintained for at least one hour. Then maximum vacuum is applied for at least one hour to remove the air trapped in the materials.

Finally, the vacuum is set to -0.5bars and the resin inlet is opened to start the infusion. Several steps of this process are illustrated in Fig.1. Preliminary trials have revealed that this method is very efficient for small core thicknesses (max 12mm). Despite the very low viscosity of the resin, the impregnation of the lower face for thicker balsa cores is not always satisfying. As a consequence, an additional infusion complex can be used between the mold and the lower face for the thickest sandwiches. This ensures a correct impregnation and skin/core adhesion of both upper and lower faces. When the materials are completely infused, the resin inlet is closed. The vacuum in maintained until the exothermic peak is observed approximately 45 minutes later. The sandwich plates are demolded 24 hours later.
3 EXPERIMENTAL PROCEDURE

To study the flexural behavior of this material, rectangular (300mm x 40mm x 20mm) beams were cut in the sandwich plates with a diamond circular saw. The samples were held in the laboratory conditions at room temperature and humidity before being tested.

2.1 Three point bending tests

First, quasi-static three point bending tests were performed according to the test method ASTM D7250M. An Instron machine equipped with a 10 kN force sensor was used. The deflection of the beam was measured with a displacement sensor (LVDT). The experimental setup is presented in Fig. 2. The tests were conducted with a speed of testing equal to 5 mm.min⁻¹. Two types of sandwich beams were tested. The first one, labelled [0]₅-150-15.9 was made up with faces composed of five unidirectional flax plies and a 15.9mm thick balsa core with a nominal density of 150 kg.m⁻³. At least five samples were tested to take into account the statistical spread of the results due, among other things, to the use of natural materials. Moreover, to focus on the flexural and shear behavior and failure modes of [0]₅-150-15.9, specimens were tested with five different span lengths: d=80mm, d=100mm, d=150mm, d=200mm and d=250mm. In addition, a second type of sandwich beam with faces made up with flax plies with a [0/90]₅ stacking sequence and labelled as [0/90]₅-150-15.9 were tested with a span length d=250mm.
Fatigue tests were performed with the experimental setup described previously and for [0/90], -150-15.9 sandwich specimens. The tests were displacement-controlled with various loading ratios $r$ defined by:

$$r = \frac{D_{\text{max}}}{D_f}$$

with $D_{\text{max}}$ and $D_f$ respectively the maximal displacement applied during the fatigue tests and the average displacement at failure measured during quasi-static tests. For every beam, the average displacement $D_m$ was set equal to 50% of $D_f$. The loading ratio $r$ was modified by changing the amplitude of displacement $A$. To analyse the flexural and shear responses of the sandwiches, the beams were tested with two different span lengths ($d=250\text{mm}$ and $d=110\text{mm}$). The different experimental conditions are summarized in Tab 1. At least three samples were tested for every experimental configuration.

<table>
<thead>
<tr>
<th>Span length</th>
<th>$d = 250 \text{ mm}$</th>
<th>$d = 110 \text{ mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amplitude (mm)</strong></td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>$r$ (%)</strong></td>
<td>60</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 1: experimental conditions for fatigue tests

The tests were performed with a frequency of 5Hz. Some authors have proven that this frequency is not likely to cause a significant increase of temperature in the materials used [12-13].
4 RESULTS

4.1 Elastic properties of the sandwich components

In three point bending, the relation between the applied load $P$ and the deflection measured $W$ is given by:

$$\frac{W}{P} = \frac{d^3}{48D} + \frac{d}{4N} \iff \frac{W}{Pd} = \frac{d^2}{48D} + \frac{1}{4N}$$

where $D$ and $N$ are respectively the equivalent flexural and shear stiffness of the sandwich beam. Moreover, according to the sandwich beam theory and assuming the thin faces and weak core approximations, the expressions of $D$ and $N$ (per unit of width) are [14]:

$$D = \frac{E_f t_f h^2}{2} \quad \text{and} \quad N = \frac{G_c h^2}{2}$$

with $E_f$ the Young modulus of the composite, $t_f$ and $t_c$ the thickness of the faces and core, $G_c$ the shear modulus of the core and $h = t_f + t_c$. Based on this analytical background, the equivalent flexural and shear stiffness $D$ and $N$ were deduced form the slope and intercept of the curves presented in Fig. 3.

Figure 3: evolution of the ratio $W/(Pd)$ with the square of the span length

Then, according to Eq. 3, the Young modulus $E_f$ and the shear modulus $G_c$ were deduced for both kind of sandwich beams. The results are presented in Tab. 2.

<table>
<thead>
<tr>
<th></th>
<th>$E_f^{[0]}$</th>
<th>$E_f^{[0/90]}$</th>
<th>$G_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>GPa</td>
<td>GPa</td>
<td>MPa</td>
</tr>
<tr>
<td>Average</td>
<td>24</td>
<td>11</td>
<td>225</td>
</tr>
<tr>
<td>Standard Dev</td>
<td>1.3</td>
<td>1.4</td>
<td>48</td>
</tr>
</tbody>
</table>

Table 2: Elastic properties of the sandwich components

The Young modulus of the faces obtained for both sandwich configurations are very close from the Young modulus of unidirectional and [0/90], Flax/Elium composites with a fibre volume fraction of 35-40% measured by tensile tests in previous studies [15-16]. However, the shear modulus of the core appears to be 25% higher than the modulus provided by the manufacturer and measured according to ASTM C273 test method. This may be explained by the contribution from the skins’ shear properties, as well as a contribution of a certain amount of resin trapped in the core, particularly in the gaps.
between adjacent balsa blocks, increasing core shear stiffness. Moreover, a high standard deviation is observed, probably due to the local dispersion of wood density discussed in paragraph 2.1.

4.2 Quasi-static failure analysis

In addition, an experimental and analytical analysis of the failure modes was performed for the sandwich beams [0]_s-150-15.9.

First, the failure modes were analysed for every span length. The results are presented in figure 4. It appears that for the shortest span lengths, core shear failure is the predominant damage mode. On the other hand, compressive failure of the upper skin is the main failure mode noticed for the longest span lengths. However, for the span length d=150mm, the sandwich beam can break in an unstable manner. Both failure modes are randomly observed. This seems to indicate that this particular boundary condition corresponds to the transition between core shear failure and compressive failure of the upper skin.

![Figure 4](image-url)

**Figure 4**: a) experimental failure modes observed for different span length: b) compressive failure of the upper face and c) core shear failure

To verify this, a failure mode map based on sandwich beam theory \([14,17]\) was implemented. It consists in equating the failure loads corresponding to the major failure modes observed. For example, the critical load corresponding to the compressive failure of the faces is:

\[
P = \frac{\sigma_t}{k_t} \frac{t_f b h}{L}
\]  

(4)

Moreover, the critical load corresponding to the core shear failure is:

\[
P = \frac{C_T \rho_c b h}{k_T}
\]  

(5)

In addition, local buckling of the upper face can be predicted by:

\[
P = \frac{t_c b h}{2k_m L} \left( E_f C_E C_G \rho_c^{2n} \right)^{\frac{1}{3}}
\]  

(6)
where \( \rho_c \) is the density of the core, \( t_f \) the thickness of the faces, \( b \) the width of the beam, \( L \) the span length, \( h = t_f + t_c \), \( k_m \) and \( k_f \) constants depending on the boundary conditions. Moreover, \( C_E, C_G, C_\tau, m \) and \( n \) are constants determined experimentally, based on the assumption that the core properties depends on the core density. Thus:

\[
E_c = C_E \rho_c^m \\
G_c = C_G \rho_c^n \\
\tau_c = C_\tau \rho_c^{m n}
\]

with \( E_c \) the Young modulus of the core, \( G_c \) its shear modulus and \( \tau_c \) its shear strength. Balsa wood as a cellular material has been widely studied in literature. As a consequence, these constants were determined based on the works of several authors [18-20]. All the material properties used in this analytical study are synthetized in Tab. 3.

<table>
<thead>
<tr>
<th>( C_E )</th>
<th>( C_G )</th>
<th>( C_\tau )</th>
<th>( E_f )</th>
<th>( \sigma_f )</th>
<th>( K_M )</th>
<th>( K_T )</th>
<th>( m )</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>1.4</td>
<td>0.02</td>
<td>23 GPa</td>
<td>120 MPa</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3: Material properties used of the failure mode map implementation

Then, equating the critical load expressions of different failure modes results in the equations of the borders between these modes. Thus, the transition between the compressive failure of the skins and the shear failure of the core is given by [14]:

\[
\log(\rho_c) = \frac{1}{m} \log \left( \frac{\sigma_f k_T}{k_M C_\tau} \right) \left( \frac{t_f}{L} \right)
\]

Moreover, the transition between the local buckling of the upper skin and the face failure is given by:

\[
\log(\rho_c) = \frac{3}{2n} \log \left( \frac{\sigma_f^2}{\sqrt{E_f C_E C_G}} \right) \left( \frac{t_f}{L} \right)
\]

Then, the transition between the local buckling of the upper skin and the core shear failure is given by:

\[
\log(\rho_c) = \frac{3}{3m - 2n} \log \left( \frac{k_T}{2k_M C_\tau} \right) \left( \frac{E_f C_E C_G}{t_f} \right)
\]

The failure mode map implemented with this method is presented in Fig. 5. The core density is set to the y axis and the ratio \( t_f/L \) is set to the x axis. The beams tested with the five span lengths are located on the map by the circular plots. As observed experimentally, the beams tested with the longest span lengths are expected to fail by compression of the upper skin, whereas the beams tested with the shortest span length are expected to fail in the core. The particular span length \( d = 250 \text{ mm} \) is located at the vicinity of the border between these failure modes. Moreover, as explained in paragraph 2.1, the core is composed of several pieces of wood coming from different trees and exhibiting different densities and so different mechanical properties. Thus, the standard deviation of core density was reported on the failure mode map presented in Fig. 5.
This clearly shows that for the span length $d=150\,\text{mm}$ the beams tested can fail randomly in the upper skin or in the core. As a conclusion, this analytical approach appears to be in good accordance with the experimental results observed.

### 4.3 Fatigue properties

Fatigue tests were conducted for $[0/90]s$-150-15.9 beams. To analyse the behaviour of the beams under flexural and core shear loadings, the tests were performed with two different span lengths $d=250\,\text{mm}$ and $d=100\,\text{mm}$. Fig. 6 presents the end of life diagrams of the beam tested according to an end of life criterion $N_{10}$. This criteria is achieved when a decrease of 10% of the mechanical properties is noticed.

The results indicate that under the severe loading conditions applied, the $N_{10}$ criterion is met during the first 1000 cycles. Moreover, the criterion is met earlier for the sandwich beams tested with a span...
length $d=110\text{mm}$. This indicates that the beams are more severely damaged when the core is subjected to shear.

### 4.4 Damping analysis

Finally, the evolution of the dynamic loss factor $\eta$ with respect to the number of cycles was studied for both span length $d$ and for every load ratio $r$. The loss factor $\eta$ is defined by:

$$\eta = \frac{E_d}{2\pi E_p}$$

where $E_d$ is the energy dissipated by the material and $E_p$ the potential energy. These energies were calculated by mean of a trapezoidal rule applied on the hysteresis cycles. The results obtained are presented in Fig. 7. In both cases, the loss factor initially decreases with the first cycles. This decrease seems to be more pronounced for the highest loading ratios. Then, the loss factor seems to stabilize with the number of cycles, and finally slightly increases. This phenomenon may be explained by an increase of the number of damage mechanisms, dissipating energy by friction. However, additional investigations are required to fully understand the role of the different components (skins and core) and damages in the evolution of the loss factor.

![Figure 7: evolution of the fatigue loss factor with the number of cycles for beams tested with a span length : a) $d= 110\text{mm}$ and b) $d=250\text{mm}$](image)

### 5 CONCLUSIONS AND PERSPECTIVES

This study focuses on the development of a new bio-based sandwich structure made up with thermoplastic skins reinforced by flax fibres and a balsa core. The structure is manufactured within a single step liquid resin infusion technique. This opens new perspectives in the development of potentially recyclable thermoplastic composites. First, quasi static flexural tests were performed on sandwich beams. The main elastic properties of the components (skins and core) were determined. Moreover, the failure modes were analysed and the influence of the span length was discussed. An analytical approach based on the implementation of a failure mode map was used to explain the scattering observed. This approach takes into account the local dispersion of density (and mechanical properties) of the balsa wood cores. The analytical results appeared to be well correlated with the experimental observations, indicating that such methods could be suitable for sizing structures made with this bio-based materials. Finally, preliminary fatigue tests were performed to discuss the fatigue
flexural behavior of this sandwich structure. However, additional investigations are required to compare this structure to other equivalent non-bio-based materials and to discuss whether or not it could be suitable for semi structural applications.

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REFERENCES


