FLEXURAL BEHAVIOUR OF LAMINATED FIBRE COMPOSITE SANDWICH BEAMS

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ABSTRACT

A new generation composite sandwich made up of glass fibre reinforced polymer skins and lightweight but high strength core material has been developed in Australia. Experimental investigation was conducted to determine the behaviour of this composite sandwich with a view of using this material for structural beam. As these sandwiches are produced in limited thicknesses, the structural beam section could be attained by gluing a number of sandwiches in the flatwise (horizontal) or edgewise (vertical) positions. Characterisation of the behaviour of individual sandwiches as well as beams with 2, 3 and 4 composite sandwiches glued together was conducted. The results showed that the composite sandwiches in the edgewise position has a 9% lower effective modulus of elasticity in bending than in the flatwise position. However, it failed at a 20% higher load with a different failure mode. The specimens in the edgewise position failed with greater ductility due to progressive failure of the fibre composite skins while the specimens in the flatwise position failed in a brittle manner due to core shear failure followed by delamination between the skin and the core. These initial results are very encouraging. With further investigation, the development of structural beams from these fibre composite sandwiches could be realised.

KEYWORDS

Composite sandwiches, laminated sandwich beams, bending, flatwise, edgewise.

INTRODUCTION

A structural sandwich is a special form of a laminated composite fabricated by attaching two thin but stiff skins to the lightweight but thick core. This material has been identified as a very interesting alternative to traditional construction materials because of its many advantages. The main benefit of using the sandwich concept in structural components is its high bending stiffness and high strength to weight ratios (Belouettar et al. 2008). In addition, sandwich constructions are preferred over conventional materials because of its high impact strength and high corrosion resistance (Russo and Zuccarello 2007). With its many advantages, composite sandwich structures have been widely used in the automotive, aerospace, marine and other industrial applications (Bakis et al. 2002). This material also draws a lot of interest in the construction industry and is now beginning to be in use for civil engineering applications (Keller, 2006).

Recent applications have demonstrated that fibre composite sandwiches can be effectively and economically used in the civil infrastructures. However, very limited attempt has been made so far to use these materials for structural beam applications although engineers have access to a wide range of composite sandwiches. The main reason could be that most of the currently used core materials are not appropriate for this type of applications. The commonly used foam core and balsa wood are soft and will crush under high compressive loads (Borsellino et al. 2004). Honeycomb and trussed core structure have high compressive strength (Kooistra and Wadley 2007) but the presence of cavities in these core materials reduces the capacity of sandwiches to hold mechanical connections. The development of composite sandwich with lightweight, high strength core material and good holding capacity for mechanical connections could be an alternative material for structural beam elements.

Recently, a new generation fibre composite sandwich has been developed in Australia (Van Erp and Rogers 2008). The satisfactory performance of this innovative composite sandwich in several building and residential projects has shown a high possibility in using this material in the development of structural beams. As this composite sandwiches are produced in limited thicknesses, a structural beam section from this material could be attained by gluing a number of sandwiches either in the flatwise or edgewise positions. This concept is similar to laminated veneer lumber used in timber engineering where several smaller pieces of wood are horizontally or vertically laminated (either by nailing or gluing) to produce a single large structural member to support a greater...
load (Bougthon and Crews 1998). Similarly, Lopez-Anido and Xu (2002) developed a structural system based on the concept of sandwich construction with strong and stiff FRP composite skins bonded to an inner glulam panels. In addition, most currently available commercial FRP decks are constructed using assemblies of adhesively bonded FRP pultruded shapes (Bakis et al. 2002). These examples show that the concept of gluing a number of composite sandwiches to form a structural beam is highly practical.

This paper presents the results of the preliminary investigation on the behaviour of laminated composite sandwiches in the flatwise and edgewise positions to determine its application for structural beams. Initially, the mechanical response of individual composite sandwiches was determined. Experimental investigation was then conducted to determine the flexural behaviour of a number of composite sandwiches bonded together. The load-deflection behaviour, strength and failure mechanisms of composite sandwiches glued together are reported. The effect of the number and orientation of laminations on strength and stiffness is also discussed.

MATERIALS AND METHOD

Test specimen

The composite sandwiches tested in this study are made up of a modified phenolic core material bonded to the bi-axial glass fibre composite skins using a plant based resin. The effective mechanical properties (in the main direction) of the fibre composite skin and the core material determined from coupon tests are listed in Table 1. The description of the test specimens is listed in Table 2. The composite sandwiches were laminated using structural epoxy adhesives and post-cured to attain a good bonding between the composite sandwiches.

<table>
<thead>
<tr>
<th>Property</th>
<th>Skin</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s modulus (MPa)</td>
<td>14280</td>
<td>1150</td>
</tr>
<tr>
<td>Maximum tensile stress (MPa)</td>
<td>242</td>
<td>14</td>
</tr>
<tr>
<td>Maximum compressive stress (MPa)</td>
<td>211</td>
<td>21</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1.92</td>
<td>16.16</td>
</tr>
</tbody>
</table>

Table 2. Description of specimen for flexural test of composite sandwiches

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Illustration</th>
<th>Number of specimens</th>
<th>t, mm</th>
<th>b, mm</th>
<th>Length L_T, mm</th>
<th>Support span, L</th>
<th>Orientation of testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1LSW-F</td>
<td></td>
<td>5</td>
<td>20</td>
<td>50</td>
<td>500</td>
<td>400</td>
<td>Flatwise</td>
</tr>
<tr>
<td>1LSW-E</td>
<td></td>
<td>5</td>
<td>50</td>
<td>20</td>
<td>500</td>
<td>400</td>
<td>Edgewise</td>
</tr>
<tr>
<td>2LSW-F</td>
<td></td>
<td>2</td>
<td>40</td>
<td>50</td>
<td>500</td>
<td>400</td>
<td>Flatwise</td>
</tr>
<tr>
<td>2LSW-E</td>
<td></td>
<td>2</td>
<td>50</td>
<td>40</td>
<td>500</td>
<td>400</td>
<td>Edgewise</td>
</tr>
<tr>
<td>3LSW-F</td>
<td></td>
<td>2</td>
<td>60</td>
<td>60</td>
<td>1400</td>
<td>1200</td>
<td>Flatwise</td>
</tr>
<tr>
<td>3LSW-E</td>
<td></td>
<td>2</td>
<td>60</td>
<td>60</td>
<td>1400</td>
<td>1200</td>
<td>Edgewise</td>
</tr>
<tr>
<td>4LSW-F</td>
<td></td>
<td>2</td>
<td>80</td>
<td>80</td>
<td>1400</td>
<td>1200</td>
<td>Flatwise</td>
</tr>
<tr>
<td>4LSW-E</td>
<td></td>
<td>2</td>
<td>80</td>
<td>80</td>
<td>1400</td>
<td>1200</td>
<td>Edgewise</td>
</tr>
</tbody>
</table>
Test set-up and procedure

The static 4-point bending test of composite sandwiches was performed in accordance with the ASTM C393-00 standard. The load was applied at 0.4 and at 0.6 of the span through a 100 kN universal testing machine with a loading rate of 5 mm/min. Figure 1 shows the actual test set-up and instrumentation for the static flexural test of composite sandwiches. The applied load and displacement were recorded using a data logger. The test was discontinued after the failure in the composite sandwich was observed.

RESULTS AND DISCUSSION

Load-deflection behaviour

The load and midspan deflection behaviour of composite sandwiches under 4-point static bending test is shown in Figure 2. Figure 2a shows that the deflection of specimen 1LSW-F increased linearly with load up to final failure. The specimen failed at an applied load of around 4550 N with a midspan deflection of 24 mm. The load capacity of specimen 1LSW-E increased linearly with deflection but showed a reduction in stiffness at a load of around 5000 N due to the tensile cracking of the core. The specimen then continued to carry load until 5500 N at a deflection of 8 mm. Before the final failure, there was an increased amount of deflection even without an increase in the applied load due to the progressive failure of the non-horizontal skins. The figure also shows that the load capacity of specimen 2LSW-F increased linearly with deflection. This linear behaviour was observed until a load of 6000 N and a deflection of 7 mm. After this load, a non-linear response was observed until failure. This non-linear response could be due to the development of tensile cracks in the core which decreased the stiffness of the beam. When the depth of cracks reached the fibre composite skins, a significant drop in the load was observed. The load capacity increased again up to a level similar to the initial failure load (around 9000 N). The specimen then failed due to shear failure of the core followed by delamination between the skin and the core. When tensile cracks occurred in specimen 2LSW-E at an applied load of almost 11000 N, a slight drop in the load was observed. As the loading continued, there is a gradual decrease in the bending stiffness due to the progressive failure of the fibre composite skins. After compressive failure of the skins, a gradual decrease in bending stiffness was observed but the beams were still able to carry load until 13770 N. The load then decreased but showed a large deformation capacity. In the elastic region, specimens 1LSW-F and 2LSW-F deflected less than specimens 1LSW-E and 2LSW-E under the same level of applied load. This is expected as the second moment of area of composite sandwich in the edgewise position is higher than in the flatwise position. Similarly, a higher load capacity was observed in the edgewise position than in the flatwise position.

![Figure 1. Test set-up and instrumentation of flexural test for composite sandwich](image)

![Figure 2. Load and midspan displacement relationship of composite sandwich specimens](image)
Similar behaviour was observed in specimens with 3 and 4 laminations (Figure 2b). The load deflection curves for specimens 3LSW-F and 4LSW-F is almost linear until the development of flexural cracks in the core material. A decrease in stiffness was then observed until failure of the specimen. A decrease in stiffness was also observed in specimens 3LSW-E and 4LSW-E when tensile cracks of the core occurred. Even after compressive failure of the skins was observed, the specimens 3LSW-E and 4LSW-E continued to carry load until tensile failure of the fibre composite skins. In both 3 and 4 composite sandwich laminations, the specimens in the flatwise positions behaved slightly stiffer than specimens in the edgewise position. However, the composite sandwiches in the edgewise positions failed at a higher load than specimens in the flatwise position. Finally, the load-deflection curve indicated that the composite sandwiches tested in the flatwise position failed in a brittle manner while the composite sandwiches in the edgewise beams failed in a ductile flexural mode. This could be due to the difference in the failure mode which will be discussed in the next section.

Failure mode

Experimental investigation showed that composite sandwiches exhibited different failure behaviour in the flatwise and in the edgewise positions. The failure mode of the composite sandwiches are shown in Figure 3. Tension cracks in the core were observed at the bottom of specimen 1LSW-F but these cracks did not cause immediate failure. Figure 3a shows that the specimen 1LSW-F failed due to compressive failure of the fibre composite skin followed by delamination between the core and the skin. Tensile core cracks were also observed in specimen 1LSW-E. However, the presence of the non-horizontal skins in the edgewise position prevented the premature failure of the core and made the composite sandwich beams to fail in a ductile failure mode. The specimen 1LSW-E failed due to progressive compressive failure of the skin followed by tensile failure of the skins (Figure 3b). For laminated composite sandwiches tested in the flatwise position, flexural cracks were observed on the core of the bottommost sandwich. These cracks originated at the top of tensile skin and progressed with the applied loads. When the depth of the flexural cracks reached the level of the skin, the crack width increased and a significant drop in the load was observed. The cracks then started to propagate horizontally which lead to the delamination failure between the bottom skin and the core followed by compressive failure of the skin (Figure 3c). The non-horizontal skin prevented the tensile cracks in the core of the laminated composite sandwich tested in the edgewise position from widening and delayed the failure of the specimen until the fibre composite skins failed. As more cracks developed, the damage of the specimen increased, thereby decreasing the stiffness, and subsequently increasing the deflection. The specimen continued to carry load even after compressive failure of the skin was observed. In some specimens, compression buckling on the top fibre composite skin near the loading points was also observed as the skin was delaminated from the core. The specimen then failed due to tensile failure of the fibre composite skins (Figure 3d). These different failure modes have affected the strength capacity of the composite sandwiches which will be discussed in the following section. Furthermore, the results of the experiment showed that the structural epoxy adhesives provided a highly efficient glue joint between the composite sandwiches. No delamination or slipping was observed on the glue lines which suggested that the full capacity of the composite sandwiches was attained.

(a) specimen 1LSW-F
(b) specimen 1LSW-E
(c) specimen 2LSW-F
(d) specimen 2LSW-E

Figure 3. Failure modes of composite sandwiches
Effect of glue lamination on the stiffness of composite sandwich beams

Initial evaluation on the effect of gluing on the stiffness of the composite sandwich beams was conducted. The flexural stiffness, \( EI \) of the glue laminated sandwich beams was calculated using the elastic properties of the fibre composite skins and core material in Table 1 and simple sandwich beam theory. Calculations were made assuming that no interlayer slips occurred and the laminated sandwiches acted as a solid beam with perfect bonding. The contribution of the epoxy adhesives in the flexural stiffness is also neglected. The flexural stiffness in the flatwise position was estimated using Eq. 1 and in the edgewise position using Eq. 2.

\[
(EI)_{\text{flat}} = \sum \left( \frac{Bt^3}{12} + Bt_i d_i^2 \right) E_i + \left( \frac{Bt^3}{12} + Bt_i d_i^2 \right) E_c
\]

\[
( EI )_{\text{edge}} = \frac{nD^3}{6} \left( t_i E_i + \frac{l_i^2 E_c}{2} \right)
\]

(1)

(2)

where \( t_i \) is the thickness of the skin, \( t_c \) is the thickness of the core, \( B \) is the width of the sandwich, \( d_i \) and \( d_c \) are the distances from the centre of the skins and core to the neutral axis of the glued section, respectively, \( D \) is the depth or thickness of the sandwich while \( E_i \) and \( E_c \) are the modulus of elasticity of the skin and core, respectively, and \( n \) is the number of glued composite sandwiches.

The effective bending stiffness, \( (EI)_{\text{eff,exp}} \) of the composite sandwiches (which considers the combined effect of bending and shear deformations) was determined from the result of the experimental investigation. Using the initial linear elastic portion of the load-midspan deflection curve (Figure 2), \( (EI)_{\text{eff,exp}} \) was calculated based on a simply supported beam test shown in Figure 1 using the relation:

\[
(EI)_{\text{eff,exp}} = \frac{99}{3,000} L \left( \frac{\Delta P}{\Delta v} \right)
\]

where \( (\Delta P/\Delta v) \) is the slope of the load-deflection curve. The apparent bending modulus of elasticity, \( E_{\text{app}} \) of the composite sandwiches was then computed by dividing \( (EI)_{\text{eff,exp}} \) by the second moment of area of the homogenised cross-section. The predicted \( EI \) and the calculated stiffness, apparent bending modulus and the maximum load, \( P_{\text{max}} \) and moment, \( M_{\text{max}} \) capacities of the composite sandwiches obtained from the experiment is reported in Table 3.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( EI ) (x10^7), Nmm²</th>
<th>( (EI)_{\text{eff,exp}} ) (x10^7), Nmm²</th>
<th>( E_{\text{app}} ), N/mm²</th>
<th>( P_{\text{max}} ), N</th>
<th>( M_{\text{max}} ), N-m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1LSW-F</td>
<td>234</td>
<td>237</td>
<td>3,880</td>
<td>4,554</td>
<td>364</td>
</tr>
<tr>
<td>1LSW-E</td>
<td>743</td>
<td>774</td>
<td>3,848</td>
<td>5,560</td>
<td>444</td>
</tr>
<tr>
<td>2LSW-F</td>
<td>1,298</td>
<td>1,210</td>
<td>4,200</td>
<td>9,472</td>
<td>757</td>
</tr>
<tr>
<td>2LSW-E</td>
<td>1,396</td>
<td>1,360</td>
<td>3,440</td>
<td>13,772</td>
<td>1,102</td>
</tr>
<tr>
<td>3LSW-F</td>
<td>4,772</td>
<td>5,077</td>
<td>4,274</td>
<td>9,318</td>
<td>2,236</td>
</tr>
<tr>
<td>3LSW-E</td>
<td>4,102</td>
<td>4,259</td>
<td>3,868</td>
<td>11,247</td>
<td>2,699</td>
</tr>
<tr>
<td>4LSW-F</td>
<td>14,024</td>
<td>15,114</td>
<td>4,173</td>
<td>20,869</td>
<td>5,008</td>
</tr>
<tr>
<td>4LSW-E</td>
<td>12,566</td>
<td>13,375</td>
<td>3,814</td>
<td>28,086</td>
<td>6,260</td>
</tr>
</tbody>
</table>

The results show that for individual composite sandwiches, shear deformation has no significant effect on the bending stiffness in both flatwise and edgewise positions as the predicted \( EI \) is almost equal to the result of the experiment investigation. On the other hand, the \( (EI)_{\text{eff,exp}} \) for the 2 sandwiches bonded together is 3-7% lower than the predicted values. This suggests that the shear deformation could have contributed to the total deformation due to the decreased span to depth ratio. However, for longer beams and with 3 and 4 laminations, the \( (EI)_{\text{eff,exp}} \) is higher than predicted. The increased bending stiffness observed in the test is attributed to the friction effects between the laminations provided by the epoxy adhesives. The difference between the predicted \( EI \) and \( (EI)_{\text{eff,exp}} \) slightly increased with increasing laminations. However, the difference in the bending stiffness is slightly higher in the flatwise position than in the edgewise position. In general, both \( EI \) and \( (EI)_{\text{eff,exp}} \) in the flatwise position is lower than that in the edgewise position for specimens with 3 and 4 laminations.

The results also showed that the \( E_{\text{app}} \) of the laminated sandwiches in the flatwise position is lower than that of the individual sandwiches. The decrease in \( E_{\text{app}} \) when the composite sandwiches were laminated in the flatwise position is expected as the skins near the neutral axis of the section did not contribute as much stiffness as the outermost skins. Interestingly, the \( E_{\text{app}} \) of the composite sandwiches for 2, 3 and 4 laminations are almost the same. For 3 and 4 laminations, the apparent bending stiffness in the flatwise position is 9% higher than in the edgewise position. Finally, the \( E_{\text{app}} \) of the individual sandwiches in the edgewise position is almost equal to that of the glued sandwiches. This clearly shows that the modulus of elasticity in the edgewise position is not affected by the number of laminations as the shear stresses induced by the flexure are not carried across the glue lines.
Effect of glue laminations on the strength of composite sandwich beams

The experiment showed the strength capacity of the composite sandwiches (listed in Table 2) that are glued together is higher in the edgewise than in the flatwise position. Gluing the composite sandwiches in the edgewise position resulted to an increase of at least 20% in strength. In the edgewise position, the non-horizontal skins prevented the widening of the tensile cracks in the core, thus preventing premature failure. Even after compressive failure of the fibre composite skins at the outer sandwiches, the beam continued to carry load until tensile failure of the skins. This could be due to the reinforcing effect of the epoxy adhesives which prevented the compressive failure and buckling of the non-horizontal skins at the glue lines. The result also showed that the strength capacity increases with increasing number of laminations. This further confirms that in multiple composite sandwiches in the edgewise position, the failure on one sandwich might be compensated by the stronger adjacent sandwiches. The glue lines acted as a load-distributing element and hold the composite sandwiches together. Furthermore, the load-deflection behaviour of the composite sandwiches tested in the edgewise position suggests that in this position, the specimen will fail in a ductile manner due to progressive failure of the skin. The higher load capacity and the progressive failure of the non-horizontal skins of the laminated composite sandwiches in the edgewise position suggest a further increase in the safety of the structure. In the flatwise position, the strength capacity is not affected by the presence of gluelines. For all composite sandwich beams tested in the flatwise position, failure occurred in a brittle manner due to shear failure of the core followed by the simultaneous compressive failure and delamination of fibre composite skins.

CONCLUSIONS

The flexural behaviour of laminated composite sandwiches was determined through experimental investigation. The results suggest that using the same amount of material, the composite sandwiches in the edgewise position have higher strength but with slightly lower bending stiffness than in the flatwise position. The progressive failure of the non-horizontal skins in the edgewise position resulted in a more ductile failure. In the flatwise position, the failure is governed by the mechanical properties of the core, thus resulting in brittle failure. Finally, the results of the investigation suggest a high possibility of developing a structural beam from glue-laminated sandwiches. Currently, research is being conducted into the problem of bonding together composite sandwiches in flatwise and edgewise positions with the objective of developing an optimised structural beam section.

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REFERENCES