THE EFFECT OF SHEAR SPAN-TO-DEPTH RATIO AND TEST SET-UP ON THE BEHAVIOR OF FIBRE COMPOSITE SANDWICH STRUCTURE

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ABSTRACT
The shear strength of the core material is a critical parameter and is an important consideration when designing a composite sandwich structure in construction application. In this paper, the shear behaviour of a new generation composite sandwich panel made up of glass fibre composite skins and phenolic core was investigated under three-point loading short beam (SB) and asymmetrical beam shear (ABS) tests. The effect of the shear span-to-depth ratio (a/D) was examined on the shear strength and failure behaviour of the fibre composite sandwich beams. The results showed that the shear behaviour of the beams is affected strongly by the a/D ratios. The beams with a lower a/D ratio failed at a higher load compared to the beams with larger a/D ratio. In general, the sandwich beams tested under ABS failed at a significantly higher load than that of the sandwich beams tested under SB for the same a/D ratio. The results also showed that the behaviour of the fibre composite sandwich beams is governed by the strength of the phenolic core material. In all the tested sandwich beams, the failure of the core occurred under the loading point where the shear force and bending moment are maximum.

KEYWORDS
Fibre composites; sandwich beams; shear; shear span-to-depth ratio; short beam; asymmetrical beam.

INTRODUCTION
Fibre composite sandwich structures are increasingly used in applications requiring high bending stiffness and strength, combined with low weight. Their usage is mainly in the aerospace, aircraft and marine industries because of their fuel efficiency in transportation vehicles, but at present, there is a strong interest in the development and applications of sandwich structures for civil and building material systems (Bakis et al. 2002). Recently, a new generation composite sandwich panel made up of glass fibre composite skins and modified phenolic core has been developed in Australia (Van Erp and Rogers 2008). Manalo et al. (2010a) have evaluated the flexural behaviour of this sandwich structure which indicates their high potential for structural applications. Similarly, the higher in-plane shear strength of the sandwich structure due to the presence of vertical fibre composite skins showed that this composite material can be used for shear webs of a structural beam (Manalo et al. 2010b). Furthermore, gluing these composite sandwich panels together resulted in a more stable and stronger section for structural glue-laminated fibre composite sandwich beam (Manalo et al. 2010c). However, a detailed understanding on the behaviour of sandwich structure under different loading conditions is a fundamental requirement before they can be used effectively in construction and building applications.

Under service loads, most sandwich construction fails due to shear failure of the core material (Kampner and Grenestedt 2007). In particular, the shear strength of the core is a critical parameter and is an important consideration when designing composite sandwich structure. These important aspects had to be addressed in order to advance the use of sandwich structures in civil engineering applications. Until recently, the failure mechanisms in thick composite sandwich structures were not well understood and very limited work has been reported on the shear behaviour of sandwich structure (Aviles et al. 2011). Similarly, there still exists a problem to describe accurately the true shear behaviour of composite sandwich structure due to lack of an accurate test method. Thus, a more in-depth understanding on the shear behaviour of fibre composite sandwich structures will help fill the knowledge gap that currently exists in civil infrastructure.

In this paper, the shear behaviour of the structural fibre composite sandwich beams was evaluated under two simple shear test methods, namely short beam and asymmetrical beam shear tests. The effects of the shear span-to-depth (a/D) ratio on the strength and failure behaviour of the sandwich beams were analysed.
MATERIALS AND METHOD

Material properties

The structural composite sandwich panel used in this study is made up of glass fibre composite skins co-cured onto the modified phenolic core material using a toughened phenol formaldehyde resin. The panel has a nominal thickness of 20 mm. The fibre composite skin is made up of 2 plies of bi-axial (0/90) E-CR glass fibre fabrics with a chopped strand mat and has a total thickness of 3.0 mm. The modified phenolic foam core material is made primarily from natural plant products with a proprietary formulation of CarbonLOC Pty. Ltd., Australia. The effective mechanical properties of the skin and the core material of the fibre composite sandwich panel were determined from testing of coupon specimens in earlier studies by Manalo et al. (2010a) and are listed in Table 1.

Table 1. Mechanical properties of the skin and core of the composite sandwich panel

<table>
<thead>
<tr>
<th>Test</th>
<th>Property</th>
<th>Skin</th>
<th>Core</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flexure Modulus (GPa)</td>
<td>12.82</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>Peak stress (MPa)</td>
<td>317.37</td>
<td>14.32</td>
</tr>
<tr>
<td></td>
<td>Tensile Modulus (MPa)</td>
<td>15.38</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Peak stress (MPa)</td>
<td>246.80</td>
<td>5.97</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
<td>0.25</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Compression Modulus (MPa)</td>
<td>16.10</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Peak stress (MPa)</td>
<td>194.77</td>
<td>22.99</td>
</tr>
<tr>
<td></td>
<td>Shear Modulus (MPa)</td>
<td>2.47</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>Peak stress (MPa)</td>
<td>23.19</td>
<td>8.80</td>
</tr>
</tbody>
</table>

Test specimen

The sandwich beam specimens were cut directly from the composite sandwich panels provided by the manufacturer. All specimens have a nominal thickness or depth, D and width, b of 20 and 50 mm, respectively. Sandwich beams with a/D ratios of 1 to 6 were examined to investigate its effect on the shear behaviour of fibre composite sandwich structure. Six replicates for each specimen type were prepared and tested. The descriptions of the test specimens are listed in Table 2. In this table, a and L represent shear span and span length of the sandwich beam, respectively while SB and ABS corresponds to the specimens tested under short beam and asymmetrical beam shear tests, respectively.

Table 2. Details of test specimen

<table>
<thead>
<tr>
<th>Shear span-to-depth (a/D) ratio</th>
<th>Shear span (a), mm</th>
<th>Test span (L₁), mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SB</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>3.5</td>
<td>70</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>--</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>240</td>
</tr>
</tbody>
</table>

Test set-up

Two simple types of shear tests were performed to evaluate the shear behaviour of fibre composite sandwich structure, namely short beam shear and asymmetrical beam shear tests (see Figure 1). Three-point bending test using short beam (SB) specimen is performed in accordance with ASTM C393 (2000). This test and involves loading a short sandwich beam under three-point bending to ensure shear failure of the core. On the other hand, the asymmetrical beam shear (ABS) test is conducted by eccentrically loading the specimen at two trisected points and the supports were applied at the remaining two points. This loading configuration generates a high shear stress and a nearly zero moment at the centre of the specimen. A steel spreader beam was used to transfer the single load applied by the loading machine to the specimen asymmetrically. In both test methods, the load was applied through a 100 kN electromechanical universal testing machine with a loading rate of 1.3 mm/min. An overhang length of 20 mm on both ends of the test specimens were provided to avoid slipping of the beam during testing. The loading pins and the supports had a diameter of 10 mm to prevent any indentation and crushing failure on the core of the fibre composite sandwich beams. All of the specimens were tested up to failure to determine the strength and failure mechanisms. The applied load and the crosshead displacement were measured and recorded using a material testing software TestWorks 4.
RESULTS AND OBSERVATIONS

Load and displacement behaviour

Figure 2 shows the load and the displacement of the machine crosshead during the entire test regime for fibre composite sandwich beams with different a/D ratios tested under SB and ABS. As indicated in the figure, the failure in the sandwich beam specimens is represented with a load drop in the load-crosshead displacement relation curve. For all tested specimens, the load increased linearly with the displacement of the crosshead until final failure. As expected, the longer beams deflected more than shorter beam specimens. A sudden load drop was observed which indicated the final failure of the beam. For composite sandwich beams tested under SB test and with a/D ratio higher than 4, there was a slight nonlinearity observed in the load-deflection curve before the final failure as shown in Figure 2a. This is due to the initiation of the compression failure of the top composite skin. It can be clearly noticed from the figure that the specimens tested under ABS failed at a higher load compared to SB. For beams with an a/D ratio of 1, there was no significant different in the slope of the load-deflection curve between SB and ABS. This is due to the dominant contribution of shear deformation in the behaviour of the beams. However, for a/D ratio of 2 to 6, the beams tested under SB deflected more than that of beams tested under ABS under the same level of applied load. This indicates the higher flexural stress experienced by the SB beams which resulted to a higher transverse displacement.

Failure behaviour

Figure 3 shows the typical failure behaviour of the fibre composite sandwich beams tested under SB and ABS methods, respectively. The results show that the sandwich beam specimens failed after the formation of the first shear crack in the core. In all the tests, shear cracks originates under the loading point and propagates towards the bottom of the sandwich beam. The inclination of shear cracks is approximately 45°. This failure is brittle and sudden which is accompanied by a loud noise after the appearance of the first shear crack. In both test methods, the specimens with a/D ratio of 1 and 2 failed due to shear failure of the core with minor debonding failure between the skin and the core at the bottom part of the beam (Figures 3a and 3b). For beam specimens with a/D
ratio of 3 to 6 and tested under SB (Figure 3c), the debonding failure between the fibre composite skin and the core at the bottom of the sandwich beam extended up to the edge of the beam which preceded after the shear cracking of the core. On the other hand, the debonding failure of the sandwich beam tested under ABS is confined in the region of maximum shear as shown in Figures 3d.

**DISCUSSIONS**

**Effect of a/D ratio on shear stress**

Figure 4 shows the average shear stress on the core of the fibre composite sandwich beams. In this figure, the average shear stress, \( \tau \) is estimated by dividing the shear force acting on the maximum shear region with the area of the sandwich beam section transformed into equivalent core using the ratio of the shear modulus of the skin and the core as given in equation (1).

\[
\tau = \frac{P}{2 \left( \frac{c + 2t}{G_s} \right) D} \tag{1}
\]

where \( t \) and \( c \) are the thicknesses of the skin and core and the skin, respectively, \( D \) is the depth or total thickness of the sandwich beam, and \( G_s \) and \( G_c \) are the shear moduli of the skin and core, respectively. In this prediction equation, the failure of the sandwich beam will occur when the shear strength of the phenolic core, \( \tau_c \), is reached.

![Figure 3. Failure behaviour of sandwich beams tested under SB method](image)

![Figure 4. Average shear stress of the sandwich beam with different a/D ratios](image)
The results indicate that the a/D ratio has a significant effect on the shear stress of the composite sandwich beams. In all the a/D ratios, shear cracking of the core was observed on the fibre composite sandwich beams at the region of maximum shear. This is expected as the coupling effect of the flexural stress increases with increasing a/D ratio which contributes to the initiation of failure in the core. Noticeably, the shear strength of the fibre composite sandwich beams tested under ABS is significantly higher than that of SB for the same a/D ratio. This is due to a higher bending moment exists on the specimens subjected to SB test than that of ABS specimens. This is also expected as the the maximum bending moment experienced by specimens with the same a/D ratio and tested under ABS is only half that of the SB specimens.

The maximum calculated average shear stress on the composite sandwich beams with a/D ratio of 1 tested under SB and ABS method is 5.3 and 7.2 MPa, respectively. This shear stress is 60% and 82% of the shear strength of the modified phenolic core. This decreases to 2.1 and 3.3 MPa for sandwich beams with a/D ratio of 6 tested under SB and ABS, respectively which are only 24% and 37% of the shear strength of the phenolic core. This result suggests that the flexural stress has played a major part in the overall behaviour of the sandwich beams especially for beams with large a/D ratios. Thus, it is important that the contribution of bending stress in the sandwich beams should be considered in the analysis and prediction of the sandwich beam behaviour.

Effect of a/D ratio on bending stress

The indicative bending stress in the skin and core of the sandwich beams with different a/D ratios is shown in Figure 5. The maximum flexural stress, \( \sigma_s \) carried by the outermost fibres of the skin for a composite sandwich beam is calculated as equation (2) while the maximum flexural stress, \( \sigma_c \) carried by the core is given in equation (3). In these equations, the bending moment \( M \) is determined based on the loads applied to the sandwich beam.

\[
\sigma_s = \frac{M(D/2)}{EI} E_s
\]

(2)

\[
\sigma_c = \frac{M(c/2)}{EI} E_c
\]

(3)

where \( E_s \) and \( E_c \) are the moduli of elasticity of the skin and core, respectively while \( EI \) is the flexural stiffness which is given as equation (4).

\[
EI = \frac{bh^3}{6} E_s + \frac{b(D-t)^3}{2} E_s + \frac{bc^3}{12} E_c
\]

(4)

As shown in Figure 5, the bending stresses in both the skin and the core increases with increasing a/D ratio. For beams tested under SB and with a/D ratio greater than 5, the maximum bending stress in the skin and the core is around 188.8 MPa and 13.9 MPa, respectively. These stress values are almost comparable to the compressive strength of the skin and the flexural strength of the core determined from coupon test. The results also indicated that even at an a/D ratio of 1, the specimen experiences bending stress which have influenced the failure mechanisms. Because of the combined stress condition, it is more likely that the failure caused by the bending moment for SB specimens with larger a/D ratio precedes the shear cracking of the phenolic core which leads to the final failure of the beam. On the other hand, the maximum bending stress experienced by the skin and core tested under ABS can be as low as 53.1 MPa and 3.9 MPa, respectively for a/D ratio of 1 and are only 145 MPa and 10 MPa, respectively for a/D ratio of 6. This result suggests that the beams tested under ABS are experiencing lower flexural stress that that of beams tested under SB. This indicates that a more representative shear strength of a fibre composite sandwich structure can be determined using the ABS test method.
Effect of a/D ratio on failure behaviour

The results of this study showed that the failure of the fibre composite sandwich beams tested either in SB or ABS occurred along the intended shear plane. As expected, the shear failure of the core for all the tested specimens was sudden and catastrophic. This can be explained by the brittle behaviour of the core wherein the shear failure occurred after the formation of the first shear crack. When shear failure of the core occurred, the sandwich beam lost its capacity to carry load instantly without any residual load-carrying capacity beyond the peak load. There was no observed indentation failure on all the tested specimens suggesting the high compressive strength of the core material and its suitability for civil engineering applications. This supports the observations by Sideridis and Papadopoulus (2004) wherein they have indicated that composite beams are expected to fail in shear at small a/D ratios while the mode of failure becomes flexural at large a/D ratio. However, they also indicated that there is an intermediate a/D ratio in which the behaviour is transitional, and the mode of failure can either be shear or flexure or a combination of both. For the structural composite sandwich beams investigated, this intermediate a/D ratio was found to be around 5. For specimens with a/D ratio of 5 or greater, the initiation of the compressive failure of the top skin was observed. This preceded shear failure, and in some cases, initiated shear failure of the core. The initiation of the compressive failure of the top fibre composite skin also explains the slight non-linearity observed in the load-deflection relationship curve.

CONCLUSIONS

The behaviour of structural fibre composite sandwich beams with different shear span-to-depth (a/D) ratios was evaluated using short beam (SB) and asymmetrical beams shear (ABS) test methods. The results showed that the shear strength of the fibre composite sandwich beams is affected strongly by the a/D ratios. The beams with lower a/D failed at a higher load compared to the beams with larger a/D. The shear strength of the sandwich beams decreases with increasing a/D ratios. On the contrary, the flexural stress increases with increasing a/D ratio. In general, the shear strength of the sandwich beams tested under ABS is significantly higher than that of the sandwich beams tested under SB for the same a/D ratio. The results also showed that the behaviour of the fibre composite sandwich beam is governed by the strength of the phenolic core material. In all the tested sandwich beams, the failure of the core occurred under the loading point where the shear force and bending moment are maximum. The fibre composite sandwich beams with lower a/D ratio failed due to shear failure of the core while the beams with a larger a/D ratio failed due to core shear with some initiation of compressive failure of the skin. Analysis showed that the shear stress in the core is more dominant than flexural stress when the a/D ratio is 1 for beams tested under SB and 1 to 3 for beams tested under ABS.

REFERENCES