A comparison of the shear behaviour of a fibre composite sandwich structure in the transverse and in-plane directions

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ABSTRACT: This paper presents the shear behaviour of a composite sandwich structure made up of glass fibre reinforced polymer skins and high strength phenolic core material with a view of using this material as a shear loading component in a structural beam. The shear behaviour of this sandwich structure in the transverse and in-plane directions is determined using an asymmetrical beam shear test. The presence of the vertical fibre composite skins on both sides of the phenolic core material when the composite sandwich beam is loaded in-plane direction resulted in a higher shear strength and a more ductile failure behaviour than the beam loaded in the transverse direction. However, the sandwich beam is more prone to indentation failure when loaded in this direction than in the transverse direction. The results of the numerical simulations using the mechanical properties of the skin and the core materials are in good agreement with the experimental results.

1 INTRODUCTION

A composite sandwich panel made up of glass fibre composite skins and a modified phenolic foam core material for structural applications has been developed in Australia (Van Erp & Roger 2008). The satisfactory performance of this sandwich panel in several building and bridge deck projects has shown the high possibility of using this material for structural beam application. Investigation conducted by Manalo et al. (2010a) showed that this fibre composite sandwich structure has excellent flexural behaviour in the flatwise and in the edgewise positions. However, before this sandwich panel can be used for structural beam application, a thorough understanding of its shear behaviour is necessary as the shear strength is an important consideration when designing composite sandwich construction.

In a number of sandwich structures, the main design criterion is the shear strength of the core material. It has been demonstrated that, under service loads, most sandwich constructions failed due to shear failure of the core material (Kampner & Grenestedt 2007). The brittle nature of the core material causes a sudden collapse of the composite sandwich structure after the formation of the first shear crack. In structural applications, this is more critical as thicker and higher density core material is required for composite sandwich beams to transfer the shear between the top and bottom skins compared to other industrial applications (Styles et al. 2007). Hence, the premature failure of the core material will have an adverse effect on the structural performance of composite sandwich beams and may be the limiting factor in designing such structures. It is essential therefore to eliminate this type of failure to be able to use fibre composite sandwich construction efficiently in structural applications.

In this paper, attempts to improve the structural performance of the composite sandwich structures by making the fibre composite skins carry some of the loads usually carried by the core have been made. No significant material development investigation was conducted and existing composite sandwich structure was used. In order to attain this, the composite sandwich beams were loaded in the transverse and in-plane directions. With the introduction of the vertical fibre composite skins on both sides of the core material, it is anticipated that the shear resistance of the composite sandwich beams will improve as the vertical skins might carry part of the shear load. This innovative concept could lead towards the improvement of the structural performance of composite sandwich structures while maintaining the simplicity of the production process. An experimental investigation using asymmetrical beam shear test is therefore conducted to understand the behaviour and failure mechanisms of the fibre composite sandwich panel when loaded in the transverse and in-plane directions. Finite element simulations were also performed to verify the shear behaviour of the composite sandwich beams using the effective mechanical properties of its constituent materials.

2 EXPERIMENTAL PROGRAM

2.1 *Material properties*

The composite sandwich panel used in this study is manufactured by LOC Composites Pty Ltd., Australia. This sandwich panel is made up of glass fibre composite skins co-cured onto the core material using a toughened phenol formaldehyde resin. The fibre composite skin is made up of two plies of stitched bi-axial ($0^o/90^o$) E-CR glass fibre fabrics and has a total thickness of 1.8 mm. The modified phenolic core material is made primarily from natural plant products with a proprietary formulation by the manufacturer. The composite sandwich panel has a nominal thickness of 20 mm. The mechanical properties of the fibre composite skin and the modified phenolic core material were determined in an earlier study conducted by Manalo et al. (2010a, b) and are listed in Table 1.

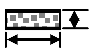
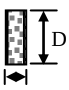
Table 1. Properties of skin and core of sandwich panels.

Test	Property	Skin	Core
Flexure	Modulus (MPa)	14,284	1,326
	Peak stress (MPa)	317	14
	Strain at peak (%)	2.29	1.22
Shear	Modulus (MPa)	2,465	528
	Peak stress (MPa)	22.82	4.25
	Strain at peak (%)	3.11	0.81

2.2 *Test specimen*

The specimens for shear testing were cut into required dimensions from the sandwich panels supplied by the manufacturer. In all tests, the span for maximum shear is held constant at 80 mm. Five replicates for each specimen type were prepared and tested with only 3 replicates from each type were provided with strain gauge. The details of the specimen for shear test are listed in Table 2. In this table, the sandwich beam loaded in the transverse (flatwise) direction is designated as specimen AS-SW-F while the sandwich beam loaded in the in-plane (edgewise) direction is designated as AS-SW-E.

Table 2. Details of specimen for asymmetrical beam shear test.

Specimen	Illustration	Number of specimens	B (mm)	D (mm)
AS-SW-F		5	50	20
AS-SW-E		5	20	50

2.3 *Test set-up and procedure*

The shear behaviour of composite sandwich beams was determined following the asymmetrical beam shear test. In this test method, the specimen was eccentrically loaded 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. The test-set-up for the asymmetrical beam shear test is illustrated in Figure 1. The load was applied through a 100 kN servo-hydraulic universal testing machine with a loading rate of 1.3 mm/min. Resistance strain gauges oriented at $\pm 45^o$ to the loading axis were attached on the surface along the middle line at mid-height of the sandwich beam specimen to evaluate the shear response during the entire loading regime. The applied load and strains were obtained using a System 5000 data logger. All specimens were tested up to failure to determine the shear strength and the mode of failure.

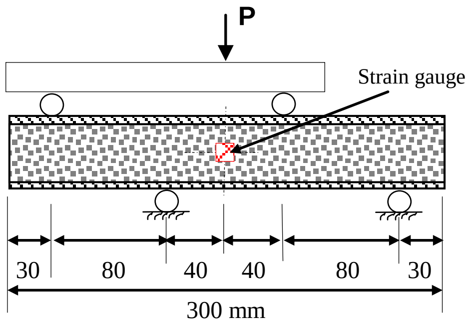


Figure 1. Illustration of asymmetrical beam shear test.

3 RESULTS AND DISCUSSION

In this section, a comparison between the shear behaviour of the composite sandwich beams when loaded in the transverse and in-plane directions under asymmetrical beam shear test is made.

3.1 *Failure load*

Table 3 summarises the load at first shear crack of the core and the maximum load carried by the composite sandwich beams when loaded in the transverse and in-plane directions. For specimen AS-SW-F, the load at first crack is also the maximum load as the specimen failed immediately after the formation of the first shear crack in the core material. A comparison of the failure load showed a higher load for specimen AS-SW-E than specimen AS-SW-F. Similarly, the load when the first crack in the core material was observed in specimen loaded in-plane is significantly higher than the failure load recorded for specimen loaded in the transverse direction.

Table 3. Failure load of composite sandwich beams.

Specimen	Load at 1st crack (kN)	Failure load (kN)
AS-SW-F	10.52	10.52
AS-SW-E	16.56	17.61

3.2 *Load-strain behaviour*

An initial check was conducted to determine if the asymmetrical beam shear test creates a pure shear for composite sandwich structures at the location of maximum shear. If the shear strain is pure, both tensile and compressive strains should be equal and opposite in sign, which can be checked with the strain gauge responses attached to the specimen. Thus, the diagonal tensile (+45^o) and compressive (-45^o) strain gauge measurements were plotted against the applied load during the entire test regime. The results show that both tensile and compressive strain values from the asymmetrical beam shear test are very close throughout the test, suggesting the presence of a reasonably pure field of shear strain at the mid-depth and midspan of the sandwich beam specimen. This result further confirms that the asymmetrical beam shear test is capable of characterizing the shear behaviour of composite sandwich structures with high strength core material.

The shear stress-strain relationship of the sandwich beam specimens provided with strain gauge is shown in Figures 2 and 3. The shear stress of the composite sandwich beam is calculated by dividing the shear force with the transformed area of the composite sandwich section. For specimen AS-SW-F, the cross section of the composite sandwich structure was transformed into an equivalent core material while the specimen AS-SW-E into an equivalent skin material. This approximation makes the contribution of the core and the skin equal because they will have the same properties. This assumption was based on the observed failure mode of sandwich beams under asymmetrical beam shear test which is described in the next section. The shear strain is determined from the indicated normal strains of the $\pm 45^o$ strain gauges attached to the specimen.

Figure 2 shows that the shear stress of specimen AS-SW-F behaved almost linearly with strain up to failure. As illustrated in the figure, the sandwich beam specimen failed at a shear strain between 7800 and 8400 microstrains. This level of strain is comparable to the maximum shear strain recorded in the core material from the coupon tests. However, the slightly higher shear strength of the sandwich beams at failure compared to the shear strength of the core material could be due to the contribution of the fibre composite skins in carrying the shear.

Figure 3 shows that the shear behaviour of specimen AS-SW-E. The stress-strain curve shows a linear response at a relatively low amount of strain and then started to behave non-linearly with increasing stress until final failure. The non-linearity was amplified after tensile cracking of the core. Similarly, a slight decrease in shear stress was observed after reaching the ultimate shear capacity. This could be due to the total shear failure of the core material. However, the fibre composite skin is still holding the failed core material. The maximum shear stress recorded for composite sandwich beam is around 23 MPa with strains of around 30000 microstrains. It is interesting to note that this strength is comparable to the maximum shear strength of the skins established from coupon testing. This also showed that the contribution of the vertical skins when loaded in the in-plane direction has a dominant effect on the shear behaviour of composite sandwich beam.

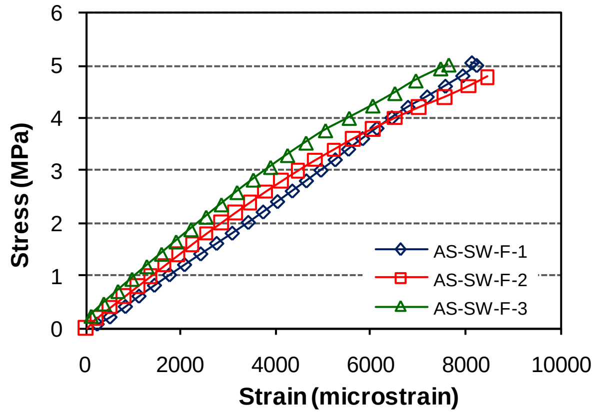


Figure 2. Shear stress-strain behaviour of specimen AS-SW-F.

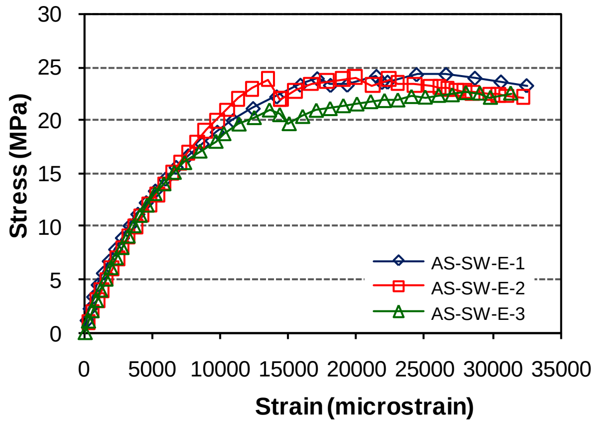


Figure 3. Shear stress-strain behaviour of specimen AS-SW-E.

3.3 *Failure behaviour*

The results of the experiment showed that the composite sandwich beams under asymmetrical beam shear test failed in a brittle manner due to shear failure of the core followed by the successive debonding between the skin and the core when loaded in transverse direction (Figure 4). The shear failure of the core material occurred at the location of maximum shear. This lacks of reinforcement through the thickness direction of the core material results in relatively lower shear strength for specimen AS-SW-F. For all the tested specimens, the composite sandwich beams failed after the formation of first shear crack in the core material. In this position, a diagonal shear crack of approximately 45^o propagates through the core at the location of maximum shear. This failure is brittle and sudden which is accompanied by a loud noise after the appearance of the first crack.

Figure 5 shows the failure mode of specimen AS-SW-E. In this position, the specimen exhibited more ductile failure mode under shear loading than the sandwich beam loaded in transverse direction.

The presence of the vertical fibre composite skins inhibits the development of cracks in the core material. When the shear crack in the core was observed, a drop in the shear stiffness was noticed. The vertical skins prevented the crack width from increasing and did not cause failure. Shear cracking of the fibre composite skin was then subsequently observed. With increasing load, the shear failure became obvious due to the scaling of the resin at the fibre composite skins. Furthermore, the cracking on the skins were contained within the location of the maximum shear, close to the pure shear region. The different failure behaviour of the composite sandwich beam when loaded in-plane can be explained by the geometry and position of the fibre composite skins. Based on these observations, it can be concluded that the vertical fibre composite skins increase the shear capacity of the sandwich beams by preventing the widening of cracks in the core thereby increasing the ultimate load of the specimens.

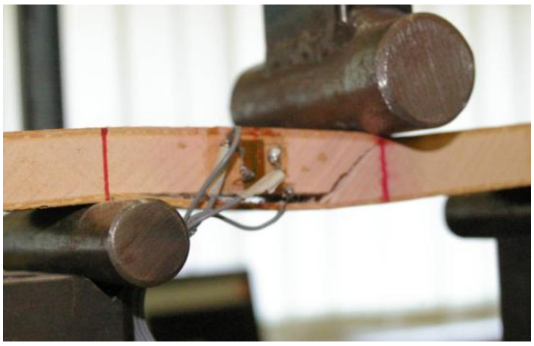


Figure 4. Failure behaviour of specimen AS-SW-F.

Figure 5. Failure behaviour of specimen AS-SW-E.

3.4 *Effect of width of steel plate on shear behaviour*

The shear strength of the composite sandwich beams when the load is applied in-plane is expected to be higher than that of beams loaded in the transverse direction. This higher load could result in compression or indentation failure under the load rollers and the supports. In an attempt to minimise the effect of load concentration, the influence of the beam support conditions, specifically, the width of the steel plate to distribute the load at the loading points and supports is investigated. Different width of steel plates (with thickness of 3 mm) were provided under the load rollers and the supports to determine the minimum size of the steel plates that can be used during the test to prevent compression and indentation failure without changing the overall behaviour of the composite sandwich beam. The results of this investigation are summarised in Table 4.

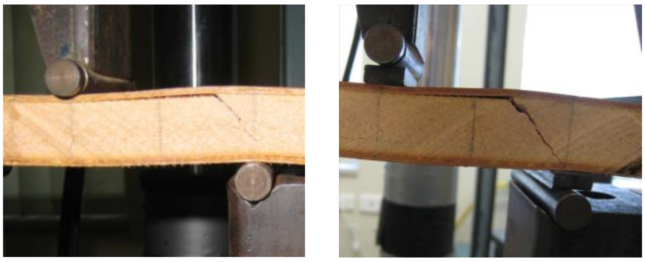
Table 4. Failure load of specimens with different plate widths.

Plate width (mm)	Failure load (kN)	
	AS-SW-F	AS-SW-E
0	10.78	7.58
10	10.75	9.23
20	10.85	15.89
30	10.63	17.60
40	11.16	17.46
50	10.69	18.51

The results show that for all the sandwich beams loaded in the transverse direction, the failure load under asymmetrical beam shear test is nearly equal for the all the plate widths investigated. All the specimens failed at an applied load of around 11 kN. Within the results of the experiment, the sandwich beams loaded in the in-plane direction obtained a slightly higher failure load for wider steel plates. However, there is no significant increase in the failure load of sandwich beams with plate width of 30, 40 and 50 mm. This suggests that the provision of steel plates on the loading points and the supports improves the load distribution on the specimen.

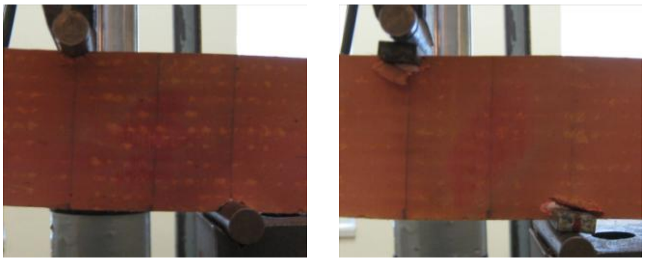
Figure 6 shows the failure mode of sandwich beams loaded in the transverse direction with different plate widths. Even without steel plates under the loading points and at the supports, there is no any skin indentation failure or local core crushing observed on sandwich beams loaded in the transverse directions. This could be due to the presence of the stiffer fibre composite skins throughout the width of the sandwich beam which spreads out the compressive stresses under the loading area to the lesser stiff core material preventing any localised failure. All specimens failed due to shear failure of the core oriented at approximately 45^{o} to the beam axis, then immediately followed by core-skin debonding.

Figure 7 shows that the sandwich beams when loaded in-plane are more prone to local crushing and indentation failure due to its high shear strength. Excessive compressive failure under the loading points and the supports was observed for specimens tested without and with 10 mm width steel plates. Signs of localised failure were still noticeable for specimens tested with 20 mm width steel plates but none were observed for specimens with 30 mm width steel plates. This result suggests that a 30 mm width steel plate is sufficient to prevent local indentation and compressive failure in the composite sandwich beams. This has provided the basis for using this width of steel plate in the asymmetrical beam shear test of sandwich beams when loaded in-plane.

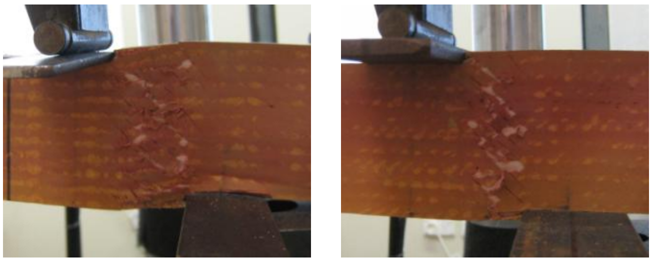


(a) no plate (b) 10 mm plate

Figure 6. Failure of AS-SW-F with different plate width.



(a) no plate (b) 10 mm plate



(c) 20 mm plate (d) 30 mm plate

Figure 7. Failure of AS-SW-E with different plate width.

4 FEM SIMULATION AND COMPARISON WITH EXPERIMENTS

Finite element model (FEM) simulations were carried out to verify the behaviour of sandwich beams under asymmetrical beam shear test loaded in the transverse and in-plane directions. The results of the numerical simulation and comparison with the experimental results are presented in this section.

4.1 *FEM of composite sandwich beam*

Simulations of the asymmetrical beam shear test of the composite sandwich beams using Strand7 finite element program have been performed to determine if the behaviour and the ultimate capacity of the composite sandwich beams could be predicted using the material properties established from test of coupons. The FEM was carried out simulating the specimen and the loading set-up in the actual experimental conditions to have a reliable result. Due to symmetry, only one-half of the composite sandwich beams was modelled to reduce the computational time. The skin and the core material were modelled as 20-node hexahedron (Hexa20) brick elements with aspect ratios between 1.1 and 1.4. The number of brick elements and nodes used to develop the FE model for composite sandwich beams under asymmetrical shear test and the computational time are listed in Table 5.

Table 5. Summary of the FEM simulation for sandwich beams.

Specimen	Hexa20 bricks	Nodes	CPU time (s)
AS-SW-F	13380	62942	1858.3
AS-SW-E	15528	72103	2073.6

4.2 *Failure load*

Using the maximum strain where the skin and the core materials will fail in shear, the FEM analysis was successful in the prediction of the failure load of the composite sandwich beams tested under asymmetrical beam shear. Based on the FEM model, the shear failure of the core of specimen loaded in the transverse direction occurred at a load of 10 kN while the shear cracking of the core material for sandwich beam loaded in-plane occurred at a load of 15 kN and shear failure of the fibre composite skins occurred at a load of 17 kN. In both directions, failure of the composite sandwich beams occurred at the region of maximum shear.

4.3 *Stress-strain behaviour*

The shear stress-strain relationship of the composite sandwich beams predicted numerically and the result of the asymmetrical beam shear test are shown in Figures 8 and 9. In these figures, the shear stress-strain behaviour based on FEM when loaded in the transverse and in-plane directions are designated by FEM (F) and FEM (E), respectively. When loaded in the transverse direction, the shear-stress strain behaviour is almost similar up to failure of the specimen. When loaded in-plane, a good agreement with the experimental results was observed only at the initial linear portion of the shear stress-strain curve. This could be due to using only the shear modulus value at the linear behaviour of the skins in the FEM simulations while the fibre composite skin behaved non-linearly at higher strain values. Results of the FEM simulations also showed that the slope of shear stress-strain curve for specimen AS-SW-F is equal to the shear modulus of the phenolic core material while that of specimen AS-SW-E to the shear modulus of the fibre composite skin.

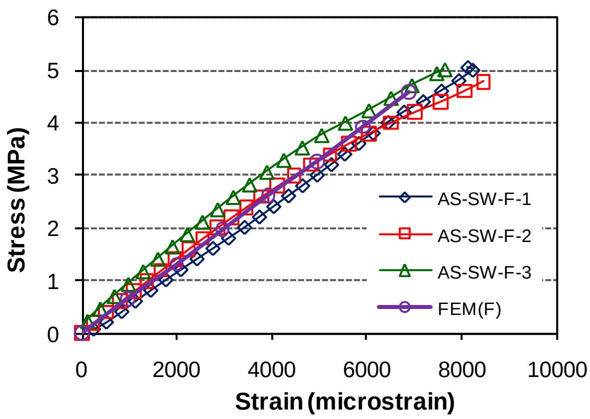


Figure 8. FEM and experimental shear stress-strain behaviour of specimen AS-SW-F.

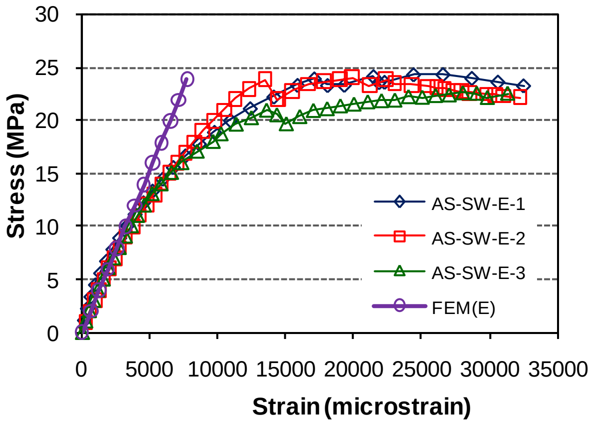


Figure 9. FEM and experimental shear stress-strain behaviour of specimen AS-SW-E.

4.4 *Failure behaviour*

The failure mechanisms of the composite sandwich beams under asymmetrical beam shear test based on the numerical simulations are shown in Figures 10 and 11. The result of the FEM analysis showed a good agreement with the experimental results. In both specimens AS-SW-F and AS-SW-E, the failure mechanisms predicted from the FEM simulations are similar to the failure mechanisms observed in the experimental investigation (Figures 4 and 5). These results further show that using the material properties determined from the coupon tests, the numerical models have provided results in good agreement with the experiment. The FEM simulations also verify that there is no localised failure in sandwich beams even without steel plate for load applied in the transverse direction while a 30 mm plate width minimises the compressive and indentation failure of sandwich beams when the load is applied in-plane.

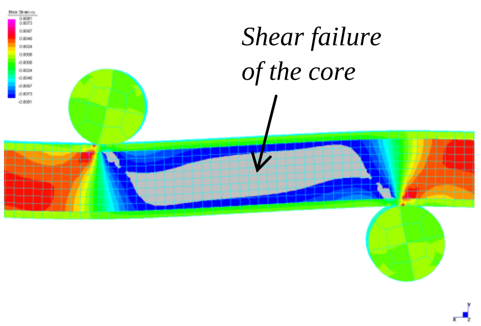


Figure 10. Predicted failure of AS-SW-F at a load of 10 kN.

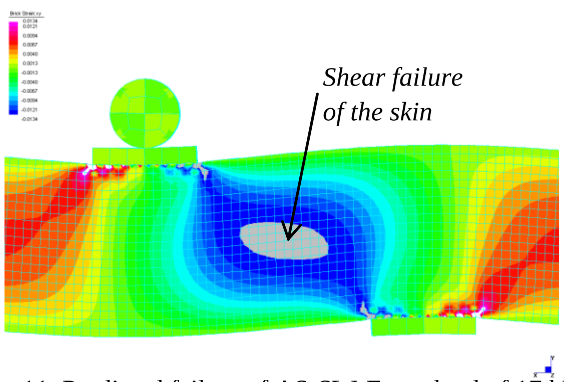


Figure 11. Predicted failure of AS-SW-E at a load of 17 kN.

5 CONCLUSION

The shear behaviour of a sandwich structure made up of glass fibre composite skins and modified phenolic core when loaded in the transverse and in-plane directions was determined using asymmetrical beam shear test. Based on the results of the investigations, the following conclusions can be drawn:

- The shear behaviour of the composite sandwich beams loaded in-plane is significantly influenced by the fibre composite skins while the behaviour of the sandwich beams when loaded in the transverse direction is governed by the core material.

- The sandwich beam loaded in the transverse direction is less prone to indentation and crushing failure due to the presence of the stiffer fibre composite skins to distribute the applied load.

- The FEM simulations predicted successfully the failure load and mechanisms of the beams but showed a good agreement with experiment only at the linear portion of the shear stress-strain curve.

- Significant improvement on the shear strength can be attained when sandwich panels are positioned in-plane. The increase in strength with the introduction of the vertical skins suggests the high potential of its utilization as a shear loading component in a structural beam. The presence of vertical skins also leads to more ductile failure behaviour.

6 ACKNOWLEDGEMENT

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