THE EFFECTS OF FIBRE WRAPS ON THE FLEXURAL BEHAVIOUR OF GLULAM COMPOSITE SANDWICH BEAMS

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Abstract: A novel composite sandwich structure made up of glass fibre composite skins and modified phenolic core material has been developed for civil engineering applications. The satisfactory performance of this composite sandwich material as structural panels in several building and residential projects has shown the possibility of using this material in the development of structural beams. As these composite sandwich panels are manufactured in limited thicknesses, the structural beam section could be attained by gluing a number of sandwich panels together in the flatwise or edgewise positions. An experimental study of the flexural behaviour of the glue-laminated (glulam) composite sandwich beams with different orientations of sandwich laminations was evaluated to determine the most effective use of this composite material for structural beam applications. The effects of wrapping the glulam sandwich beams with one-layer of tri-axial glass fibres on the flexural behaviour were also examined.

The glulam sandwich beams with edgewise laminations showed better structural performance compared to the beams with flatwise laminations due to the introduction of the vertical fibre composite skins. The glulam beams with edgewise sandwich laminations failed with 25% higher bending strength and almost similar bending stiffness than beams with flatwise laminations. The glulam sandwich beams with fibre wraps behaved slightly stiffer compared to the sandwich beams without wraps. In addition, the presence of fibre wraps prevented the immediate failure of the glulam beams which resulted in a higher strength and more ductile failure behaviour.

Key words: Sandwich structures, glulam beams, fibre composites, fibre wraps, flexure.

1 INTRODUCTION

The flexibility of composite sandwich construction allows novel structural developments from this material. Composite sandwich panels can be formed to carry loads that cannot be carried by individual sandwich structure. Composite sandwich structures can also be designed to a desired stiffness and strength with no additional weight to suit various structural applications. Recently, a novel composite sandwich structure made up of glass fibre composite skins and modified phenolic core material has been developed for civil engineering applications (Van Erp & Rogers, 2008). The satisfactory performance of this composite sandwich material as structural panels in several building and residential projects has shown the possibility of using this material in the development of structural beams. After evaluating the favourable characteristics of the individual sandwich structures (Manalo, 2010a, b), an innovative beam concept made completely from this composite sandwich structure has been developed to increase its use in civil engineering applications. As these composite sandwich panels are produced in limited thicknesses, a structural beam can be manufactured by gluing several sandwich panels together either in the flatwise (horizontal) or edgewise (vertical) positions.

The concept of gluing smaller elements to produce a single large, structural member to support a greater load has been used many years in the construction industry. In timber engineering, several layers of suitably selected smaller pieces of lumber are horizontally or vertically laminated to produce structural glulam timber (Boughton & Crews, 1998; Moody, Hernandez, & Liu, 1999). In the field of composite materials, Lopez-Anido and Xu (2002) developed a structural sandwich construction with strong and stiff fibre composite skins bonded to an inner glulam panel. Wagners CFT Manufacturing in Toowoomba, Australia has been producing boardwalks and road bridges using adhesively bonded pultruded fibreglass sections (Kemp, 2008). Similarly, most currently available commercial fibre composite decks are constructed using assemblies of adhesively bonded pultruded shapes (Bakis et al., 2002). These studies show that the concept of gluing a number of composite sandwich panels to form a structural beam is highly practical. However, before this system can be used effectively for civil infrastructure, an investigation on the flexural behaviour of this beam concept is necessary.

This paper presents the results of the experimental investigation on the flexural behaviour of glulam fibre composite sandwich beams. The effects of the orientation of sandwich laminations and fibre wraps on the strength, stiffness and failure behaviour are discussed.

2 EXPERIMENTAL PROGRAM

2.1 Materials under study

The structural sandwich panel is made up of 2-layers bi-axial glass fibre composite skins and phenolic core material produced by LOC Composites Pty Ltd., Australia. Fig. 01 shows the structural panels used in the development of the sandwich beams. A number of these composite sandwich panels were assembled and glued together to produce the glulam composite sandwich beams. The effective mechanical properties of the skins and the phenolic core material determined from coupon tests are summarised in Tab. 01.

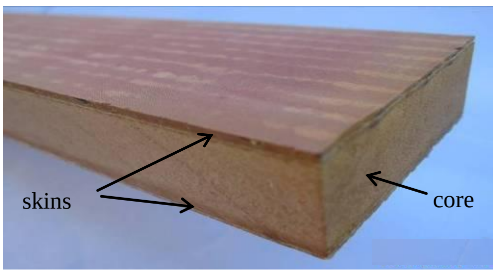


FIGURE 01: Cross-section of the novel fibre composite sandwich panel

TABLE 01: Mechanical properties of skin and core

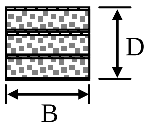
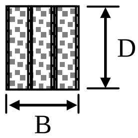
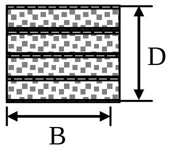
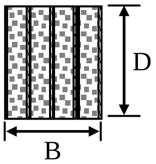
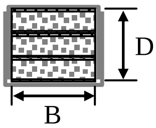
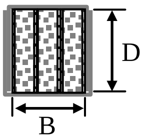
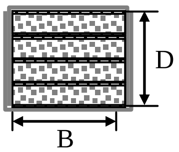
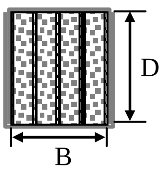
Property	Skin	Core
Young's modulus (MPa)	14,280	1,320
Maximum tensile stress (MPa)	246	6
Maximum compressive stress (MPa)	201	21
Thickness (mm)	1.8	16.4

2.2 Test specimens

Composite sandwich panels were assembled and glued together in 3 and 4 layers using Techniglue-HP R5 structural epoxy resin. The glued sandwich panels were then clamped for 24 hours to initially cure the epoxy and were removed from clamping to post-cure at 90°C for 8 hours. After curing, the glued panels were cut to the required specimen width. The descriptions of the test specimens are listed in Tab. 02. In this table, the *B* and *D* represent the width and depth of the beams, respectively while *L* denotes the test span. In the specimen designation, *F* and *E* represent the orientation of the laminations in flatwise and in edgewise position, respectively while the *W* corresponds for the specimens with fibre wraps.

The specimen with wraps were prepared by wrapping the beams with one layer of 750 g/m^2 tri-axial glass fibre composites (0/+45/-45). The fibre wraps were provided through hand lay-up process in two different stages covering the top and bottom with one layer and the sides with 2 layers of glass fibres. Hyrex 201 (Rogers, 2004) was used to impregnate and bond the wraps.

TABLE 02: Description of test specimens for glulam sandwich beams

Specimen	Illustration	No. of specimen	D , mm	B, mm	L, mm
3LSW-F		2	60	60	1200
3LSW-E		2	60	60	1200
4LSW-F		2	80	80	1200
4LSW-E		2	80	80	1200
3LSW-WF		1	60	60	1200
3LSW-WE		1	60	60	1200
4LSW-WF		1	80	80	1200
4LSW-WE		1	80	80	1200

2.3 Test set-up and procedure

The 4-point static bending test on glulam fibre composite sandwich beams was performed in accordance with the ASTM C393 (2000) standard. The load was applied at 0.4 and 0.6 of the span through a 100 kN universal testing machine with a loading rate of 5 mm/min. Fig. 02 illustrates the set-up for flexural test of glulam composite sandwich beams. Uni-axial strain gauges were attached to the specimen in both tests to evaluate the longitudinal strains during the entire loading regime. All of the specimens were tested beyond the peak load to determine the strength and failure mechanisms. The applied load, displacement and strains were recorded and obtained using a System5000 data logger.

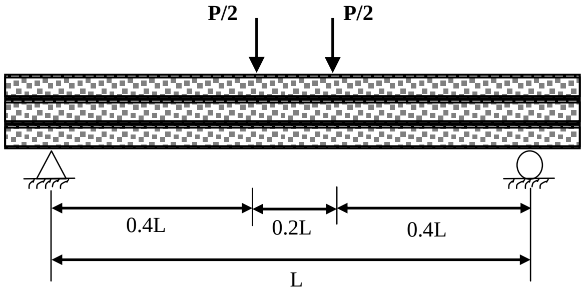


FIGURE 02: Set-up for flexural test of glulam sandwich beams

3 EXPERIMENTAL RESULTS AND OBSERVATION

The results of the experimental investigations on the flexural behaviour of the glulam fibre composite sandwich beams with and without fibre wraps are presented here. The strength and failure modes of the glulam composite sandwich beams with different orientations of sandwich laminations are also reported.

3.1 Failure load

Tab. 03 summarises the failure load of the glulam sandwich beams under 4-point static bending test. Based on the result of the experimental investigation, the glulam beams with sandwich laminations in the edgewise position failed at a higher load than the beams with flatwise sandwich laminations. As a general trend, the addition of fibre wraps resulted to a higher failure load than the glulam composite sandwich beams without wraps.

TABLE 03: Failure load of glulam composite sandwich beams

Specimen name	Failure load, N	
	Without wraps	With wraps
3LSW-F	9,318	11,065
3LSW-E	11,247	12,026
4LSW-F	20,869	29,828
4LSW-E	26,086	29,969

3.2 Load and midspan deflection behaviour

The comparison of the load and midspan deflection behaviour of glulam composite sandwich beams with and without fibre wraps under 4-point static bending is shown in Fig. 03 & 04. The figures show that the load deflection curves for specimens 3LSW-F and 4LSW-F are almost linear until the development of flexural tensile cracks in the core material. A decrease in stiffness was then observed until failure of the beams. A decrease in stiffness was also observed in specimens 3LSW-E and 4LSW-E when tensile cracks of the core material developed. As the loading continues, there is a gradual decrease in the bending stiffness due to progressive failure of the skins. Specimen 3LSW-E and 4LSW-E continued to carry load even after compressive failure of the outer fibre composite skins. The specimens then behaved non-linearly with a reduced stiffness up to failure.

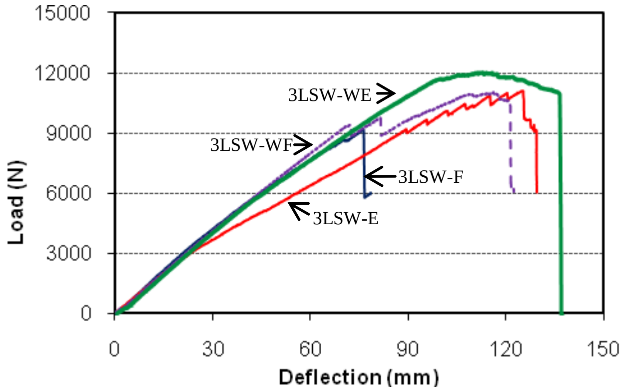


FIGURE 03: Load and midspan deflection of 3LSW and 3LSW-W

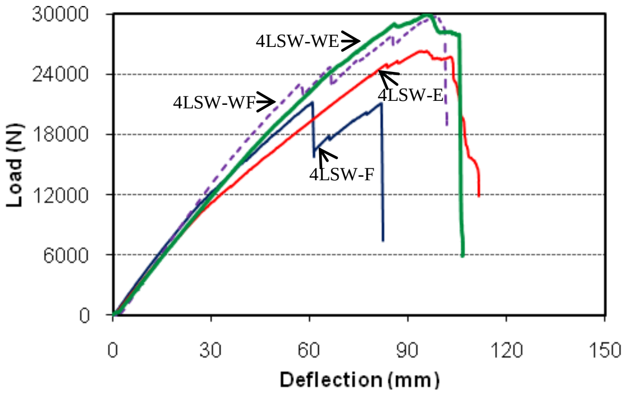


FIGURE 04: Load and midspan deflection 4LSW and 4LSW-W

In both composite sandwich beams with 3 and 4 laminations, the specimens in the flatwise position behaved slightly stiffer than specimens in the edgewise position. However, the glulam composite sandwich beams in the edgewise position failed at a higher load than the beams in the flatwise position. The load-deflection curve also indicated that the glulam sandwich beams tested in the flatwise position failed in a brittle manner while the sandwich beams in the edgewise beams failed progressively.

The load-deflection relation of glulam composite sandwich beams with fibre wraps shows that the initial load-deflection behaviour of all specimens was linear and became non-linear with a reduced stiffness up to failure. The behaviour of specimen with fibre wraps tested in the flatwise position is similar to the specimen without wraps before cracking of the core. In specimens 3LSW-F and 4LSW-F, a big drop in the load was observed when compressive failure of the skin occurred. On the other hand, compressive failure of the skins and cracking of the core in specimens 3LSW-WF and 4LSW-WF are represented by smaller load drops. Interestingly, the first load drop occurred at almost the same level of applied load and deflection for both wrapped and unwrapped specimens. As loading continues, the load starts to rise again but with a reduced stiffness as shown in the load-deflection curve. The wrapped specimen exhibited a higher deflection than the unwrapped specimens, thus more ductile. However, the results also showed that the fibre wraps could not prevent or delay the compressive failure of the skin. The fibre wraps only held the composite sandwich laminations together thereby preventing the separation between the skins and the core and increasing the failure strength.

In the edgewise position, the fibre composite wraps acted as a load distributing element which resulted to a more ductile load-deflection behaviour. For specimens 3LSW-E and 4LSW-E, the progressive failure of the fibre composite skin is represented by small load drops similar to a saw-tooth pattern. As a consequence of wrapping, the progressive failure of the fibre composite skins in specimens 3LSW-WE and 4LSW-WE is characterised by a decreasing capacity but with a smoother non-linear load-deflection curve. Similarly, the progressive failure of the fibre wraps did not create visible load drops due to small percentage of additional fibres (single wrap). The non-linear load-deflection response was terminated by a sudden drop in the load as a result of the composite sandwich beam failure. Noticeably, both the specimens with and without fibre wraps failed at almost the same amount of deflection. This result showed that the strength and ductility of the glue-laminated composite sandwich beams are controlled primarily by the composite sandwich beams and not that of the fibre wraps as the amount of wraps in small. Nevertheless, the fibre wraps provided additional load sharing mechanism amongst the bonded composite sandwich beams. The presence of fibre wraps prevented the compressive buckling and debonding of the outermost fibre composite skins. This resulted in a wrapped glue-laminated composite sandwich beams tested in the edgewise position to fail in a more ductile behaviour than the unwrapped specimens.

3.3 Failure behaviour

The different failure modes of the glue-laminated composite sandwich beams are shown in Figs. 05 to 08. Flexural tensile cracks were observed on the core material of the bottom most sandwich layers for flatwise specimens with 3 and 4 laminations. The cracks originated at the top of the tensile skin and progressed with the application of load. When the depth of the flexural cracks on the core reached the level of the next skin, the crack width increased and a significant drop in the load was observed. The presence of the fibre composite skins however prevented the immediate extension of the cracking of the core to the core of the next sandwich laminations. With increasing load, flexural cracks also developed on the core material of the upper sandwich laminations. The glued composite sandwich beams in the flatwise position failed due to the compressive buckling of the fibre composite skins followed by the debonding between the bottom skin and the core as shown in Fig. 05.

Tensile cracks of the core material were observed in the glulam sandwich beams with edgewise sandwich laminations at the early application of load. As more cracks developed on the core, the stiffness of the specimens decreased, and subsequently increasing the deflection. The continuous application of load caused the outermost compressive fibre composite skins to delaminate from the core material and cause the cracks to propagate horizontally at the region of constant moment. Splitting of the tensile fibre composite skins were then observed. This failure resulted to a decrease in lateral stability and eventually caused compression buckling of the detached skins. Final failure of the glued composite sandwich beams in the edgewise position was due to tensile failure of the skins followed immediately by simultaneous compressive failure of the skins and the crushing of the core (Fig. 06).

At the early stage of loading, the noise related to micro-cracking of the core was evident for glue-laminated sandwich beams with fibre wraps. Prior to failure, the cracking noise are more frequently heard. In all specimens, the failure of the sandwich beams with fibre wraps was initiated at the compressive part at the constant moment region. This failure mechanism is similar to what was observed in the specimens without fibre wraps. Also, the failure mechanisms of wrapped specimens indicated that very little confining effect was provided by the fibre wraps. After compressive failure of the skin was detected, progressive failure of

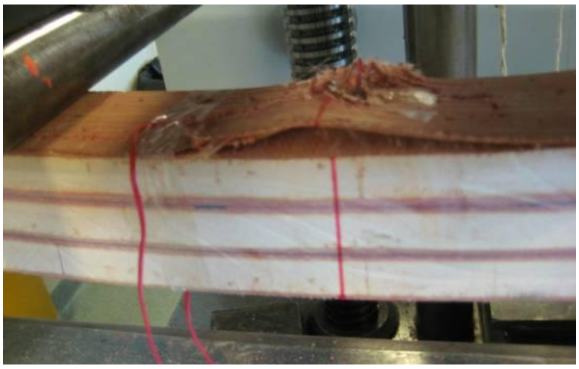


FIGURE 05: Failure of specimen 3LSW-F

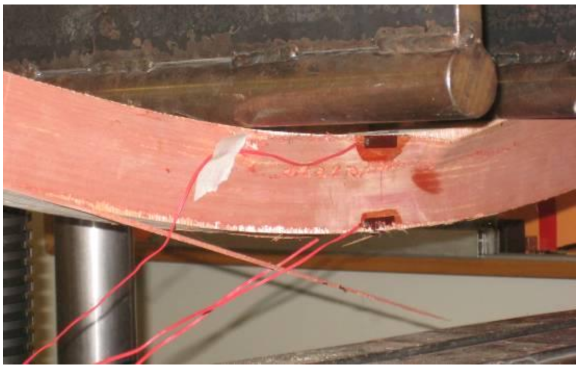


FIGURE 06: Failure of specimen 3LSW-E

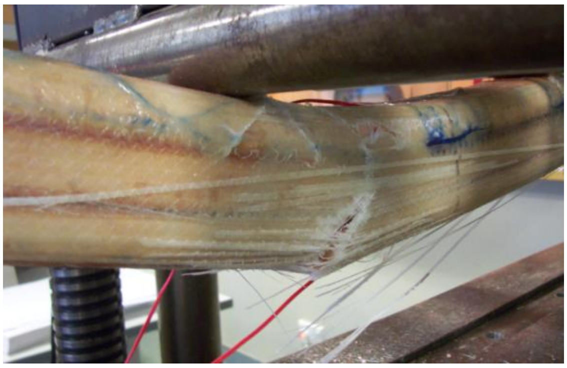


FIGURE 07: Failure of specimen 3LSW-WF

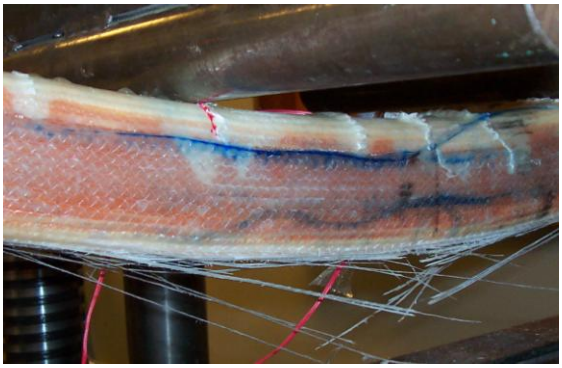


FIGURE 08: Failure of specimen 3LSW-WE

the fibre wraps immediately followed. Several points of debonding failure were observed between the fibre wraps and the specimens at the compressive side followed by splitting of the fibre wraps in tension as shown in Fig. 07 & 08. Thus, it was concluded that the failure of glulam composite sandwich beams is governed by the strength of the composite sandwich beams and not that of the fibre wraps. However, the wrapped specimen failed with more ductility than the specimen without wraps.

3.4 Displacement and longitudinal strain relationship

The displacement and longitudinal strain relationship of glue-laminated sandwich beams with 3 layers of sandwich laminations (specimen 3LSW) is shown in Fig. 09. In this figure, the longitudinal tensile and compressive strains are designated with (T) and (C), respectively, F and E for beams tested in flatwise and edgewise positions, respectively while W for beams with fibre wraps. The results showed that the strains in both tension and compression increased linearly with displacement at the early stage of load application. However, a slightly stiffer displacement-strain relation curve can be noted for specimens with flatwise (F) than with edgewise (E) sandwich laminations. In all the tested specimens, a higher longitudinal strain is measured in the tension than in compression. This further confirms that the fibre composite skins have a slightly lower modulus in tension than in compression as also observed in the test of coupons.

For specimens with fibre wraps, the strain gauge at the tension side of the specimen broke at a longitudinal tensile strain of around 6000 microstrains indicating the development of cracks in the core material. This level of strain is comparable with the failure strain of the phenolic core in tension established from the test of coupons. Non-linearity in the longitudinal compressive strain was then observed indicating the further development of cracks in the core material. The strain gauge on top of the specimen broke at a compressive strain of around 12400 microstrains which indicated the compressive failure of the topmost fibre composite skin. The value of longitudinal strain represents the strain at which the skins failed in compression as determined from the coupon tests. In this level of strain, the specimen in the flatwise position failed instantly while the specimen in the edgewise position continued to carry load and failed at a higher load than expected. The final failure of the edgewise specimens occurred only when the core crushed in compression followed by buckling of the inner skins.

A higher failure strain was measured for specimens with fibre wraps. In these specimens, the failure was initiated at a strain level of around 12000 microstrains due to the compressive failure of the fibre composite skins. It was also observed that the tensile cracking of the core was delayed by the fibre wraps due to some confining effects. The addition of fibre wraps also resulted in beams with a slightly stiffer displacement and longitudinal strain relation curve.

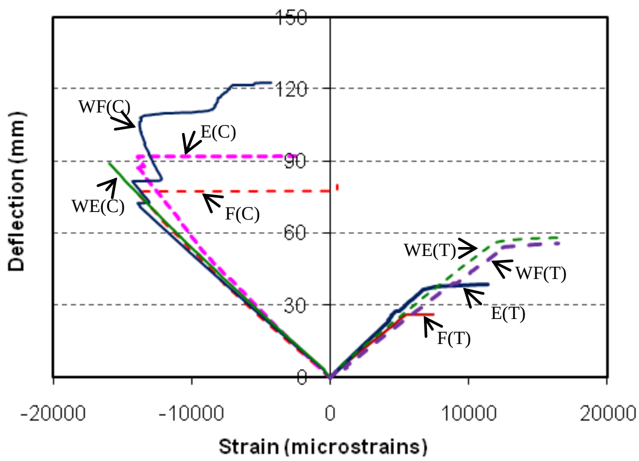


FIGURE 09: Displacement and strain relationship of specimen 3LSW

4 DISCUSSIONS

The effects of the orientation of sandwich laminations and the addition of fibre wraps on stiffness, strength and failure mechanisms of the glue-laminated composite sandwich beams under 4-point static bending test are discussed.

4.1 Effect of beam orientation on strength and stiffness

The effective bending stiffness, $(EI)_{eff}$ of the glulam composite sandwich beams (which considers the combined effect of bending and shear deformations) was determined from the linear elastic portion of the load-midspan deflection curve (Fig. 03 & 07) and was calculated based on a simply supported beam test in Fig. 02 using the relation (1):

$$(EI)_{eff} = \frac{59}{3{,}000} L^3 \left[\frac{\Delta P}{\Delta v} \right] \qquad (1)$$

where $(\Delta P/\Delta v)$ is the slope of the load-deflection curve. The apparent bending modulus of elasticity, E_{app} was then computed by dividing $(EI)_{eff}$ by the second moment of area of the homogenised cross-section of the glued sandwich beams. The effective bending stiffness, E_{app} and the maximum bending moment, M_{max} of the glulam sandwich beams with and without fibre wraps obtained from the experiment are reported in Tab. 04.

TABLE 04: EI_{eff}, E_{app} and M_{max} of glulam sandwich beams

Specimen name	EI_{eff} ($x\ 10^6$), Nmm^2	E_{app}, N/mm^2	M_{max}, N-m
3LSW-F	4,851	4,253	2,236
3LSW-E	4,270	3,969	2,699
4LSW-F	14,811	4,047	5,008
4LSW-E	13,196	3,988	6,260
3LSW-WF	4,764	4,187	2,656
3LSW-WE	4,756	4,126	2,886
4LSW-WF	15,564	4,234	7,158
4LSW-WE	14,715	4,189	7,193

The table shows that the apparent bending stiffness of the glulam composite sandwich beams with different orientations of laminations is almost similar for specimens 3LSW and 4LSW. On the other hand, the orientation of sandwich laminations has a remarkable effect on the maximum bending moment that the sandwich beams could carry. Gluing the composite sandwich beams together in the edgewise position resulted to an increase of at least 25% in bending strength. In the edgewise position, the vertical skins prevented the widening of the tensile cracks in the core. The structural epoxy adhesives have also provided some reinforcing effects which increased the buckling resistance of the bonded vertical skins, delaying its failure thereby increasing its strength. This shows that the glue lines acted as a load-distributing element and hold the glued sandwich beams together. This load sharing mechanisms led to the increased performance of the glue-laminated composite sandwich beams in the edgewise position. Similar to engineered timber products, the strength-reducing characteristics of glulam composite sandwich beams are dispersed within the sandwich laminations and have much less of an effect on strength properties in contrast with the individual sandwich beams.

4.2 Effect of beam orientation on failure behaviour

Most of the glulam sandwich beams tested in the flatwise position failed in a brittle manner due to compressive failure of the topmost fibre composite skin followed immediately by debonding between the skin and the core. The compressive failure of the skin caused a total collapse of the composite sandwich beams as the remaining materials are incapable of absorbing the released energy. This failure behaviour suggests that the flexural strength of the glued sandwich beams tested in the flatwise position depends largely on the compressive properties of the fibre composite skin.

In the edgewise position, the failure behaviour of the glulam composite sandwich beams suggests that in this position the specimens will fail in a ductile manner due to progressive failure of the fibre composite skin. Even after compressive failure of the skin at the outermost sandwich laminations, the beams continued to carry load until failure as the load was shed to the inner bonded sandwich laminations. This failure behaviour is significant as one of the most common concerns in designing fibre composite structures is its brittle failure behaviour. The staggering and progressive failure of the fibre composite sandwich beams when utilised in the edgewise position could provide early identification that the design load has been exceeded and an adequate warning of impending failure of the structures.

4.3 Effect of fibre wraps on stiffness and strength

As expected, the glulam sandwich beams with fibre wraps behaved slightly stiffer and failed at a higher load compared to the glulam sandwich beams without fibre wraps. The higher stiffness of the wrapped sandwich beam specimens became more apparent when cracking of the core occurs and until final failure. This could be due to the bridging effect provided by the fibre wraps on the local defects in the sandwich beam specimens. However, there were insignificant differences on the apparent bending stiffness between the composite sandwich beams with fibre wraps tested in flatwise position and the specimens in edgewise position due to the amount of the fibre wraps is small.

The wrapped specimens with flatwise sandwich laminations failed at 18-35% higher load than the unwrapped specimens. On the other hand, the increase in failure load of the glued sandwich beams in the edgewise position with fibre wraps is in the order of 10-15% compared to specimens without wraps. In general, the maximum load recorded for sandwich beams with fibre wraps were almost the same in the flatwise and edgewise positions. If the first initiation of damage (represented by a drop in the load) is considered as the failure, the sandwich beams in the flatwise position has a 20-25% lower capacity than the specimen in the edgewise position. This difference in strength between wrapped specimens in the edgewise and flatwise positions is similar to the unwrapped specimens. Finally, the increase in stiffness and strength is due to additional reinforcement provided by the fibre wraps and not the confining effect.

4.4 Effect of fibre wraps on failure behaviour

The addition of fibre wraps has some significant effects on the failure behaviour of the glulam composite sandwich beams. A more progressive failure was observed for the wrapped specimens compared to their unwrapped counterparts. The presence of fibre wraps prevented the immediate failure of the specimen as it held up the glue-laminated sandwich beams together which resulted to a higher strength before failure.

The test results have shown some positive effects of fibre wrapping on the flexural behaviour of glue-laminated composite sandwich beams. In all of the experimental cases, there was considerable amount of increase in the strength and a slight increase in stiffness of the wrapped sandwich beam specimens compared to specimens without fibre wraps.

5 CONCLUSIONS

The flexural behaviour of glue-laminated composite sandwich beams in the flatwise and the edgewise positions was determined through experimental investigation with a view of using this material for structural applications. The orientation of sandwich laminations has a significant effect on the flexural behaviour of the glued sandwich beams. In the flatwise position, the failure of the beams is governed by the compressive properties of the skin, thus resulting in a brittle failure. Using the same amount of material, the glued sandwich beams in the edgewise position could offer up to 25% increase in flexural strength compared to beams in flatwise position but with a slightly lower bending stiffness.

The addition of one layer of tri-axial glass fibre wraps resulted in up to 35% increase in the bending strength but only 5% in stiffness of the glulam composite sandwich beams. The addition of fibre wraps prevented the early cracking of the core resulting in more progressive failure behaviour. More importantly, the fibre wraps prevented the debonding of the fibre composites skin for beams with flatwise laminations and the buckling of the outermost skins for beams with edgewise laminations resulting in a higher failure load. The final failure of the sandwich beams with fibre wraps is due to compressive failure of the fibre composite skins followed by progressive failure of the fibre wraps. More effective results could be obtained on sandwich beams with more layers of fibre wraps. This could provide better confining effect leading to a different failure mode and much higher failure load. However, increasing the number of fibre wraps would definitely entail higher cost.

The results of the study point towards the high feasibility of using glue-laminated sandwich construction for structural beam in the civil engineering infrastructure. A case study on the suitability of this sandwich beam concept for a replacement timber railway turnout sleeper is now being conducted. The results of this study are currently being processed for publication in due course.

6 ACKNOWLEDGEMENTS

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