Behaviour of fibre composite sandwich panels under uniformly distributed loading

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ABSTRACT: Sandwich composites are widely used in various industries such as aeronautical, mechanical, automotive, marine and others. However, most of the existing sandwiches are not suitable and cost effective for applications in civil infrastructure. An innovative fibre composite sandwich panel made of glass fibre reinforced polymer skins and a modified phenolic core material was developed for building and other structural applications. The behaviour of this new generation sandwich panel was studied to assist the technical persons and the construction crews in better understanding its properties for an efficient use in flooring applications under different loading conditions. If a fibre composite sandwich panel is placed not in the main fibre direction, an adverse effect on its performance may occur. This paper discusses an experimental investigation on this innovative sandwich for its one and two-way spanning floor applications under uniformly distributed loading. The experimental result showed that the stiffness of the sandwich is affected by the fibre orientation of the sandwich skins. Also, no major effect was observed for variation of fixity between slab and joist.

1 INTRODUCTION

Composite materials have been utilised in a variety of engineering fields such as marine, aeronautical and automotive industries (Corigliano et al. 2000, Davalos et al. 2001, Khan 2006). Composites have only just recently been utilised in civil engineering practices (Karlsson & Astrom 1997). The use of sandwich panels as a civil construction material has been overlooked to traditional materials such as concrete and steel. These traditional materials are relatively cheap and readily available. The advantages of sandwich panels over traditional building materials though are starting to become apparent (Karbhari 1997, Burgueno et al. 2001, Keller 2006).

Sandwich panels are light weight, strong, water resistant and fire resistant making them a very viable alternative for civil construction (Reis & Rizkalla 2008, Van Erp & Rogers 2008). A major area where sandwich panels are beneficial is flooring systems. Due to their light weight and strength properties, the use of sandwich panels proves a much better alternative to traditional wooden or concrete flooring (Karbhari 1997). The reduced dead weight of the floor results in reduced overall load and hence smaller supporting members.

An innovative fibre composite structural sandwich panel has recently been developed for various civil applications (Van Erp & Rogers 2008). This new generation sandwich panel has potential to applications in floors, bride decks, walls, roofs, etc. The behaviour of sandwich panels in flooring systems and one and two-way slabs have not yet been fully researched.

This paper presents the experimental results on one and two-way spanning sandwich panels applying uniformly distributed load (UDL) and varying fibre orientation and panel fixity with the joists. The behaviour of one and two-way slabs was investigated to provide more knowledge into the behaviour of sandwich panels as flooring systems.

2 THE SANDWICH PANEL UNDER STUDY

The fibre composite sandwich panel under study is made up of glass fibre composite skins co-cured onto the modified phenolic core material using a toughened phenol formaldehyde resin (Van Erp & Rogers 2008, Manalo et al. 2010). The fibre composite skin consists of 2 plies of stitched bi-axial (0/90) E-CR glass fabrics manufactured by Fiberex and has a total thickness of around 1.8 mm. The 0° fibres and the 90° fibres of the skin contain 400 gsm and 300 gsm respectively. The core has a density of 850 kg/m^3. The improved compressive strength and rigidity of this new composite sandwich structure together with its higher density core make this material suitable for structural applications. The combined density of the overall sandwich panel is around 990 kg/m^3, similar to that of hardwood timber. The average strengths of the skin in flexure, tension, compression and shear are 317, 247, 202 and 23 MPa respectively for 0° fibre orientation and 135, 208, 124 and 22 MPa respectively for 90° fibre orientation. The average skin modulus in flexure, tension, compression and shear are 14285, 15380, 16102 and 2466 MPa respectively for 0° fibre orientation and 3664, 12631, 9949 and 2174 MPa respectively for 90° fibre orientation. The core consists of average strengths in flexure, tension, compression and shear of 14, 6, 21 and 4 MPa respectively and modulus of 1154, 980, 2571 and 747 MPa respectively (Manalo et al. 2010).

3 EXPERIMENTAL PROGRAM

3.1 *Test specimens*

The prototype slabs were designed and constructed to replicate one and two-way slab systems in a typical floor structure adopted from the Particleboard Structural Flooring Design Manual (1996) published by the Australian Wood Panels Association Incorporated. The one-way slab was restricted on two opposite sides to simulate a two-edge supported slab system. The two-way slab was restricted on all four sides to replicate a four-edge supported slab system. The tests were carried out on 900 mm x 900 mm square panels. For one-way slab system, the specimens were tested at 0° and at 90° main fibre orientations. The orientation of the main fibre for two-way slab does not matter as the panel was square. The joists used were 45 mm x 145 mm hardwood timber. A list of variables for specimen preparation is given in Table 1.

Table 1. List of variables for preparing specimens for uniformly distributed load testing.

Support condition	Main fibre orientation at 0°	Main fibre orientation at 90°
One-way	Screw only	Screw only
One-way	Screw and glue	Screw and glue
Two-way	Screw only	
Two-way	Screw and glue	

Sikaflex®-221 was used as glue for fixity between slab and joist. For screw fixity, the screws with 10G x 40 mm specification were placed with a spacing of 285-300 mm to each other depending on the length of the joist. In case of fixity with screw and glue, the glue was placed first and then the slab was screwed before curing of the glue. The screws were countersunk into the top of the slab.

3.2 *Test set-up and procedure*

The tests were conducted using a high pressure airbag. The airbag was 0.95 m square. When the air pressure increases, a uniformly distributed load (UDL) is placed on the sandwich panel. The air bag was continually pressurised until failure occurred.

The slabs were placed on a base plate that was connected to four load cells as shown in Figure 1. A large steel metal plate was then fixed to the upper cross arm of the apparatus to prevent the upward movement of the airbag. The airbag was then placed in between the steel plate and the slab where the increase in the height of the airbag was restricted as shown in the figure. The airbag was inflated through pressurised air along yellow tubing going into the airbag. Once the airbag was inflated, it caused UDL onto the slab specimen. The four load cells located under the base plate then measure the loading on the slab.

A draw-wire displacement transducer (string pot) was placed under the centre of the specimen to get the deflection of the panel under loading. The string pot was attached by wire to a bracket located at the centre of the panel. Two strain gauges were placed in the centre of each panel (at bottom surface of the panel) perpendicular to each other to record the strain in the 0° and 90° fibre orientations to understand the strain levels in the varying fibre orientations. Testing was undertaken on the one and two-way slab specimens with varying main fibre orientations of 0° and 90°. The fixities were varied to determine their behaviour under a different loading condition. As the slabs tested were 900 mm x 900 mm and supported on all four sides, the fibre orientation for two-way slabs is always the same.

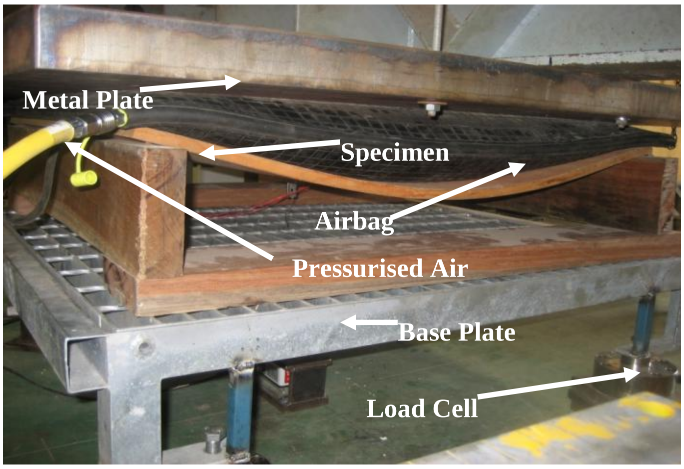


Figure 1. Uniformly distributed load (UDL) testing set-up.

4 RESULTS AND DISCUSSION

The test results for uniformly distributed loading are discussed under this section, with similar emphasis on load-deflection relationship, strain variation and ultimate failure.

4.1 *UDL-deflection relationship*

Figure 2 demonstrates the distributed load versus deflection relationship of the varying fibre orientations and fixities in a one-way slab system. The initial stiffness for the 0° fibre orientation found to be greater than the 90° fibre orientation. The initial stiffness of the combined screw and glue fixity was also greater until the glue peeled off and the panel behaved as a screw only fixity. The panels however did not fail but deflected greatly before the joists supporting the panel failed as shown in Figure 3.

The two-way slab specimens behaved similarly to the one-way slabs, however the joists did not fail. The initial stiffness for the 0° fibre orientation was greater than the 90° fibre orientation as shown in Figure 4 as similar to one-way slab system. It should be noted that the deviation in the two-way screw and glue line in the figure is not a failure but letting the load off the slab.

Table 2 shows the deflection of the one and two-way slabs with varying fibre orientations and fixities at different uniformly distributed loads. The 2 kPa, 3 kPa and 5 kPa loads are focused importantly as per the Australian/New Zealand on Structural Design Actions, Part 1 (AS/NZS 1170.1: 2002). The slabs with screw and glue fixity deflected less in comparison to the screw only. On the other hand, the 90° fibre orientation deflected more than the 0° fibre orientation except for one-way screw only under all loading situations. This may be because the readings shown in the table were mostly at low loading, so the differences were very small although they are higher. However, once a higher loading of 20 kPa, for example, was reached the 0° fibre orientation slab deflected less than the 90° fibre orientation one.

As per the Particleboard Structural Flooring Design Manual (1996), the maximum span length recommended for UDL is 700 mm where the deflection limit is "Span/300" for 19 mm thick particleboard under 2 kPa UDL. However, the 15 mm thick sandwich panels were tested with the span length of 855 mm. Therefore, the deflection criteria can not be compared with a standard.

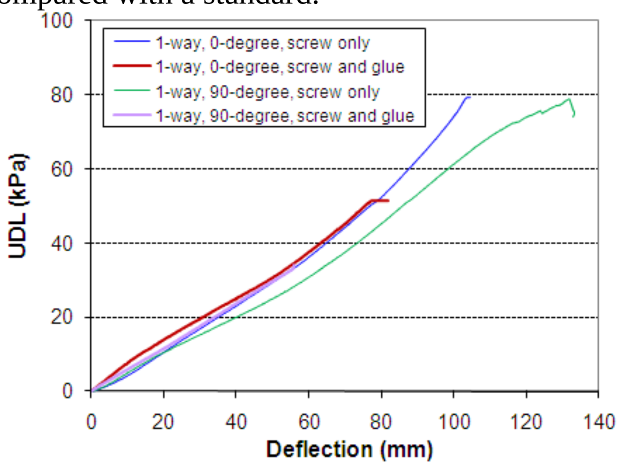


Figure 2. Uniformly distributed load (UDL) versus deflection diagram for one-way slabs.

(a) (b)

Figure 3. Joist failure of one-way slab under UDL.

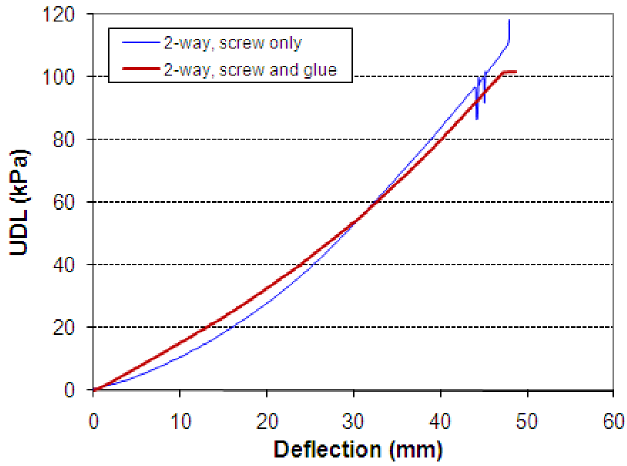


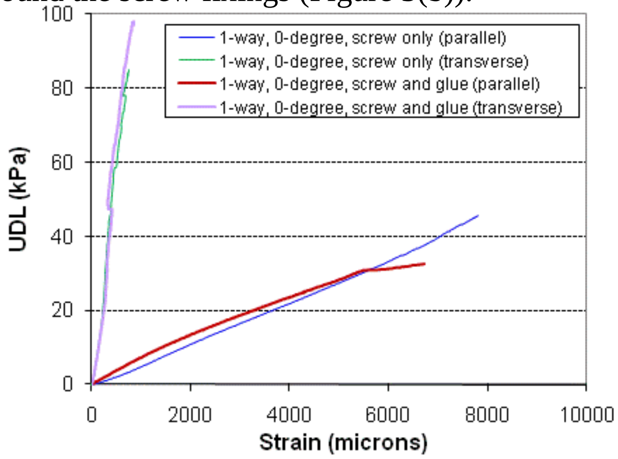
Figure 4. UDL versus deflection diagram of two-way slabs.

Table 2. Deflections at different loads at mid-span of the slabs for different fixities under UDL.

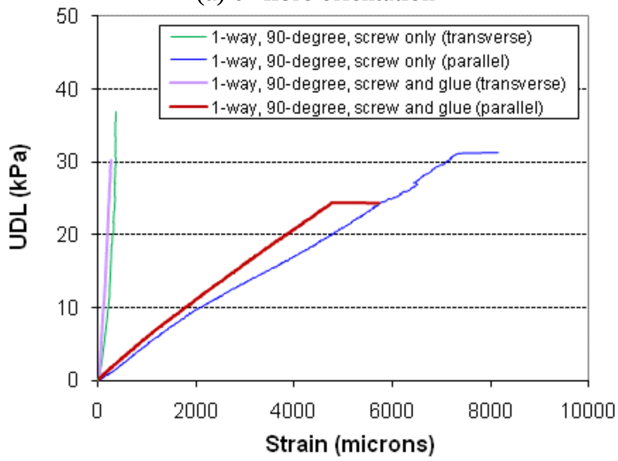
Edge support	Slab fixity	Main fibre orientation	Deflect. at mid-span at 2 kPa (mm)	Deflect. at mid-span at 3 kPa (mm)	Deflect. at mid-span at 5 kPa (mm)
One-way	Screw only	0°	4.94	7.25	11.31
		90°	4.38	6.34	9.87
One-way	Screw & glue	0°	2.53	3.89	6.67
		90°	3.01	4.64	8.41
Two-way	Screw only	-	2.54	3.73	5.64
	Screw & glue	-	1.51	2.23	3.52

4.2 *UDL-strain relationship*

Figure 5 shows the load (UDL)-strain relationship of the one-way slabs for the two varying directions of strain gauges that were placed under the centre of the panel. The graphs show the comparison between the screw only and combined screw and glue fixity for both 0° and 90° fibre orientations (Figures 5(a) and 5(b)). As shown in each graph, the two relationships are very close showing the fixity not having any major effect on the behaviour of the slab. The strain gauge parallel to the main fibre orientation experienced a higher strain from a lower UDL until the strain gauge failed. This shows that the main strain of the panel was taken by the main directional fibres running from span to span for the one-way slab. This was expected as the UDL increased across the panel, the main strain incurred was from span to span. The fibre running transverse to the main fibre orientation experienced a much smaller strain under higher loading. On the other hand, for the one-way 0° screw and glue specimen, as the strain keeps increasing the load plateaus. This was due to the joists starting to buckle inwards and the panel still deflecting greatly without failing. The connection between the joist and bearer failed resulting in the inward buckling of the joists (Figure 3(a)). The joist itself also failed in some cases with the timber cracking around the screw fixings (Figure 3(b)).



(a) 0° fibre orientation



(b) 90° fibre orientation

Figure 5. Load (UDL) versus strain diagram in varying direction of one-way slabs.

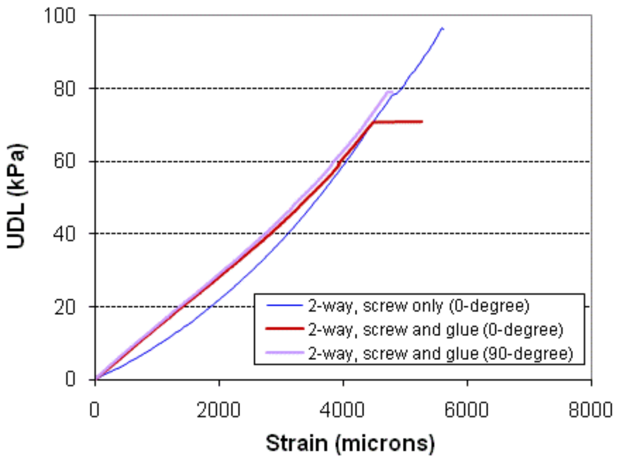


Figure 6. Load (UDL) versus strain diagram in varying direction of two-way slabs.

Figure 6 shows the relationship between load and strain for two-way slab specimens under UDL. The strain gauges were placed along the 0° and 90° fibre orientations under the centre of the panel. The strain was distributed evenly between the fibre orientations. The majority of the strain of the panel was taken by the fibre that ran from span to span of the slab system. In the two-way slab system this was in both directions, hence the strain was distributed evenly between the fibre orientations. As it can also be seen in the graph, the specimens with screw and glue took a higher initial loading for the amount of strain occurred due to the glue providing initial strength before peeling off. This was evident in the load strain relationship but had no significant effect on the overall performance of the panel. It should be mentioned that the strain gauge of the 0° screw and glue specimen broke at 72 kPa load and hence no more data could be obtained from it. Also, in the case of "Screw only (90°)", no useful readings were taken from the strain gauge because of a fault found in it.

4.3 *Ultimate UDL carrying capacity*

Almost all the cases, the one and two-way slab systems were not loaded until their ultimate failure. The loading on the one-way spanning slabs were required to stop before their ultimate deflection when the mid-span were about to touch the bottom or joists were about to fail (Figure 3). For the two-way spanning slabs, the loading was stopped when the based plate started to deflect. However, based on the observation from the diagrams for load-deflection relationship shown in Figures 2 and 4, the ultimate load carrying capacity of the slabs under UDL is higher than 80 kPa.

4.4 *Failure mode under UDL*

Figure 3 shows bucking and cracking as the typical failure modes of the joist for one-way slabs under UDL. However as mentioned before, the panels did not fail but deflected greatly. The strain of the one-way specimens was taken by the fibre that ran from span to span. Therefore, in the 0° fibre orientation, the 0° fibre orientation took the majority of the strain. The same case happened for the 90° fibre orientation where the 90° fibre orientation took the majority of the strain. The strain of the panel was distributed almost evenly between the fibres for the two-way slab system due to the same span lengths in each direction, although a slight variation was noticed probably due to variation in fibre content in two directions. These results were consistent with the results from the one-way slabs. The joists on the one-way slab system failed before the panel could with the joists buckling inwards and the timber cracking at the fixity of the panel. The two-way slab systems did not fail either, but deflected greatly. At high loading, the base plate began to deflect with the slab specimen and failure could not occur. It should be noted that the highest possible deflections observed during testing were usually at above 60 kN load (or around 80 kPa UDL) when no failure was noticed in the panel for UDL (Figures 2 and 4). However, in other investigation (Islam et al. 2009) when the panels were tested with the similar situation under point load, the core failed in shear at only around 20 kN. So, UDL is less critical than the point load for sandwich panel failure.

5 CONCLUSIONS

The behaviour of the structural fibre composite sandwich panels was investigated experimentally by developing prototype one and two-way slab systems. Various test variables were considered to determine the effects of varying the sandwich skin fibre orientation, the fixity between slab and joist and the slab edge support on the slab properties under uniformly distributed load (UDL). Experimental investigation suggests that fibre composite sandwich panels as slab systems behave similarly under UDL no matter the fixity, fibre orientation or slab edge support.

It was found that the fixity of the slabs did not have a major effect on the behaviour of the panels, only the initial deflection being reduced as in the point load tests. The 90° fibre orientation deflected more than the 0° fibre orientation due to the higher stiffness of the 0° fibre orientation panel. None of the panels however, no matter the fixity, fibre orientation or slab system failed. None of the one and two-way spanning panels failed under UDL but great deflections were observed in both. For the two-way slab system, the span length was equal in both directions hence the strain was distributed evenly between both fibre directions.

Overall, the results were consistent and the information recorded was highly valuable in determining the behaviour of fibre composite sandwich panels for slab system applications. However, there is need to investigate the behaviour of such composite sandwich panels analytically and conduct a parametric study to have a better understanding of its behaviour in flooring systems.

6 ACKNOWLEDGEMENT

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