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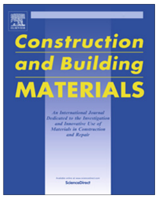

Flexural and shear behaviour of layered sandwich beams

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HIGHLIGHTS

- Flexural and shear behaviour of Layered Sandwich Beams (LSB) are investigated.
- Polymer coating can prevent wrinkling, buckling and indentation failure of panels.
- Horizontal LSB failed by core shear while the vertical LSB by skin shear.
- Vertical LSB had 50% higher shear strength but 7% lower modulus than horizontal LSB.
- Fundamental behaviour of LSB can be predicted reliably by finite element analysis.

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ABSTRACT

A new type of composite beam, referred to as Layered Sandwich Beam (LSB) is introduced in this study. The sandwich system consists of Glass Fiber Reinforced Polymer (GFRP) skins and Phenolic cores, and several layers of sandwich panels are bonded together with epoxy polymer matrix for manufacturing beams. To explore the suitability of this novel concept for structural applications, the flexural and shear behaviour of LSB have been investigated. Eight LSB, with four having layers horizontally oriented and the other four vertically oriented, have been tested under four-point bending and asymmetrical beam shear. A three-dimensional finite element model was developed using Strand7 to further understand the fundamental behaviour of the LSB. The results showed that the LSB has an increased sectional stability by preventing wrinkling and buckling of the composite skins and indentation failure. This improved the bending and shear strengths of the vertical LSB by 25% and 100%, respectively, compared with single sandwich beams in same orientation. While horizontal LSB provided a higher bending stiffness, the vertical beams exhibited higher shear strength due to the orientation of the skins. The finite element model can reliably predict the fundamental behaviour of the LSB in different orientations and loading configurations, within −10% to +14%.

1. Introduction

Composite sandwich panels are widely used in automotive and aircraft applications. The structural sandwich panels are generally composed of two thin but stiff skins that carry the majority of flexural loads, and are separated by a thick lightweight core that increases the shear capacity and moment of inertia of the section. These engineered composite systems are now receiving wider acceptance in the characteristically conservative infrastructure construction industry [1] due to their excellent durability, high strength-to-weight ratio, cost effectiveness, excellent fatigue and corrosion resistance, good impact resistance and design flexibility. Their current applications include structural roofs [2], floors [3], walls [4] and bridge decks [2].

In the last few years, a significant amount of research has investigated the behaviour of a wide range of fibre composite sandwich panels [5–8], but despite having great potential, their application in developing sustainable composite beams is limited. Recently, some studies were conducted on glue-laminated sandwich panels aiming to develop a possible alternative to timber beams. Awad et al. [9] investigated the behaviour of horizontally layered glue-laminated glass fibre reinforced polymer composite sandwich

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beams, and their study found that the shear and bending capacity of the glue-laminated beams reduced marginally from the single sandwich beam due to debonding failure of the internal sandwich layers. Manalo and Aravinthan [10] studied the behaviour of horizontally and vertically layered sandwich panels glued together with epoxy resin, and they concluded that the glue-laminated composite sandwich structures have stiffness and strength properties comparable to that of structural timber. However, the manufacturing process of these layered beams required applying and maintaining pressure to the sandwich panels until the resin is hardened and later removing the excess glue-lines, which was a labour-intensive process. A cost-effective manufacturing technology for this type of beam is to cast and coat the sandwich panels together using polymer matrix without applying external pressure. This method is similar to the casting of traditional reinforced concrete beams and relatively easier than the gluing process. However, the structural integrity and composite action of the layered sandwich panels bonded with polymer matrix which is important to satisfy the structural requirements for civil engineering applications are not yet fully understood. Therefore, an investigation on the structural behaviour of layered sandwich panels bonded with the polymer matrix is necessary for its safe use and widespread application as a composite beam. The outcome of this study aims at contributing to the scientific knowledge of understanding the behaviour of LSB in different sandwich orientations that can help to increase the confidence of this novel beam concept in civil engineering and construction including manufacturing bridge girders, structural beams, railway sleepers, and other similar applications [6,11,12].

2. Experimental program

This study investigated the structural behaviour of composite beams manufactured from layers of sandwich panels that are bonded together with the epoxy polymer matrix. The sandwich panels were bonded either in a horizontal or vertical orientation to compare the behaviour of LSB in the two orientations. Manalo and Aravinthan [10] indicated that the orientation of the sandwich laminations affects the structural behaviour of glued sandwich beams. On the other hand, the epoxy polymer matrix has excellent mechanical, thermal and durability properties [13], and can be used as a suitable binder for LSB. Similarly, the LSB were tested with different shear span-to-depth ratios to investigate the flexural and shear behaviour as many researchers [9,14,15] have indicated that this design parameter plays a significant role in the sandwich beam's structural behaviour. A recent study [8] on the single sandwich panel has shown that the sandwich beam fails in shear, a combined effect of shear and bending, and bending for shear span-to-depth ratios of 2 or less, between 2 and 6, and 6 or more, respectively. Therefore, this study considered shear span-to-depth ratios of approximately between 1 and 6 to capture the behaviour of LSB transitioning from shear to flexure.

2.1. Materials

The beams were manufactured using sandwich panels bonded with epoxy polymer matrix. The details of these materials are described in the succeeding sections.

2.1.1. Sandwich panel

The sandwich panels were made up of GFRP skins and phenolic core (Fig. 1a). The thickness of each skin was 1.8 mm with fibre volume fraction of 45% while the core was 16.4 mm thick. In each skin, the fibres were oriented in the longitudinal ([0°], 4 layers), transverse ([90°], 2 layers) and diagonal ([±45°], 2 layers in each) directions according to the following stacking sequence [0/90/0/+45/−45/+45/−45/0/90/0]. The bio-based phenolic core came from non-food based natural plant products derived from vegetable oils and plant extracts [16]. The sandwich panel density was approximately 990 kg/m^3 which is comparable to the hardwood red gum timber [17]. The properties of the GFRP skins and phenolic core [8] are provided in Table 1.

2.1.2. Polymer matrix

The polymer matrix was prepared by mixing resin and filler. A previous study by the authors [18] has suggested that the optimal polymer matrix can be obtained by mixing 40% filler with 60% resin (by volume) when maintaining a good balance between performance and cost. The two main constituents of resin systems were a DGEBA type epoxy resin (Part-A) and amine-based curing agent (Part-B), as shown in Fig. 1(b), with three different filler materials a Fire Retardant Filler (FRF), Hollow Microsphere (HM) and Fly Ash (FA). This study used Alumina Trihydrate (ATH) and E-Spheres as FRF and HM, respectively. The diameters of the round shaped filler were 75 to 95 μm for FRF, 20 to 300 μm for HM, and 0.1 to 30 μm for FA. Some relevant properties of the polymer matrix are given in Table 2, and the detailed investigation can be found in [13,18].

2.2. Specimen preparation

The sectional details of the LSB and casting method are provided in Fig. 2. Two different sectional configurations were considered in this study. The fibre composite sandwich panels, which were the main reinforcing elements of the beam, were placed either horizontally (Fig. 2a) or vertically (Fig. 2b). The horizontal LSB were 90 mm wide, and 105 mm deep whereas the width and depth of the vertical LSB were 105 mm and 90 mm, respectively. The purpose of selecting this dimension is to make the depth and width of the section as equal as possible. While there is a dimensional variation between horizontal and vertical LSB due to the 5 mm gap between sandwich panels, the total amount of reinforcement remains the same (i.e. four panels in both orientations). The 5 mm thick bond line and the coating were adopted to eliminate voids as determined in [18]. Spacers made of GFRP composite materials of dimension 25 mm × 10 mm × 5 mm were attached inside the formwork to achieve the required cover and gap between the panels. They were placed at two ends of each beam in order to be outside of the test span.

The beams were cast in the plywood formwork, and non-stick papers were laid-up in the interior surface of the mould for easy removal of the hardened specimens (Fig. 2c). Approximately 30% of the volume of the formwork (estimated based on sectional dimensions) was filled with the polymer matrix before placing the sandwich panels in it. The sandwich panels were laid vertically into the matrix and consequently an upward flow of matrix filled up the empty space in the formwork. This casting method minimised the void formation as the air bubbles escape out during the upward flow of matrix. After placing the panels into the matrix, the two ends of the beam were repressed to ensure the vertical alignment and position of the panels. The beams were cured at normal room temperature with an approximate humidity of 50%, and the specimens were removed from the mould after 7 days of casting. Six beams were prepared for the four-point bending test and the other two for asymmetrical beam shear test. All eight beams have the same properties, however, the test set-up and the orientation of the beams were different for each.

2.3. Test setup and procedure

A total of six LSB, three of which were horizontally layered and the other three vertically layered, were tested in simply supported condition under four-point bending (FPB) with a span of 1400 mm as shown in Fig. 3(a). The load was applied at shear spans of 600 mm, 400 mm and 200 mm which provided shear span-to-depth (a/d) ratios of approximately 6, 4 and 2, respectively. Two strain gauges were attached to top and bottom surface of the beam at midspan while another three gauges were attached vertically, horizontally and diagonally on the 45° line drawn from the loading point as shown in Fig. 3(a). Depending on the shear span, both flexural and shear failures were observed in the horizontal LSB, however, all three LSB in the vertical orientations failed in flexure with no observed shear failure. Therefore, the other two LSB were tested under asymmetrical beam shear (ABS) loading to generate a zero-bending point and ensure a shear failure of the specimens and have a better understanding of the shear behaviour of the horizontal and vertical LSB. The shear spans were fixed at 100 mm ($a/d = 1$, approximately). The beams under ABS test were eccentrically loaded at two trisected points, and the supports were applied at the other two points (Fig. 3b). Only three strain gauges were attached on the 45^0 line drawn from the load point at vertical, horizontal and diagonal directions to measure the shear strain as shown in Fig. 3(b).

The load was applied through a spreader beam using a hydraulic jack. To prevent the occurrence of abrupt failure due to load fluctuation, based on recommendations from previous studies, a moderate loading speed of approximately 5 mm/min was considered for FPB test [10] and 1 mm/min for ABS tests [19]. The displacement of the beams under FPB test was measured at midspan with a laser sensor. The applied load and displacement were recorded continuously by a System-5000 data acquisition system. Only one specimen was tested for each case due to the large size of the beams. This is rational as shown by the previous studies [13] that the properties of the materials are reasonably consistent and the beam manufactured with the same materials would give results within an acceptable margin of error. The details of the tested beams are provided in Table 3. In the specimen designation, the first letter indicates the orientation of the sandwich layer, i.e. 'H' or 'V' for horizontal and vertical orientation, respectively. The second letter 'F' or 'A' corresponds to the test configurations (FPB or ABS, respectively), and the third letter 'A' represents the shear span and the associated subscript number indicates the length of shear span in mm, i.e. A_{600} means a shear span of 600 mm.