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Structural Sandwich Panels: A State of the Art Review

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Abstract

Known for their structural efficiency, sandwich panels have evolved with advances in materials science. These panels are now used extensively in many fields including the construction industry to take advantage of their light weight and ease of construction. Metals and timber-based products, especially oriented strand board, have continued to be the facing materials of choice. However, plastic, polymer and concrete or other cementitious facings reinforced with glass, steel, carbon, natural fibres or textiles are finding increasing use. Core materials now include balsa and other types of wood, expanded polystyrene (EPS), rigid foams, and foamed or lightweight cements and concretes. Some cores incorporate various lattice, truss or pyramid-type structures while others have honeycombs. Such assemblies are fabricated using materials ranging from paper to aluminium and steel. The current review surveys structural sandwich panels with non-profiled faces and a range of innovative core composites and configurations. Specifically, it examines the properties that make them particularly suitable for their respective applications as well as any inherent weaknesses or peculiarities that require due consideration in design. Structural response under bending and compression, and typical failure modes are also considered.

Keywords: Sandwich panel, Structural insulated panel, Bending, Compression

1. INTRODUCTION

A *sandwich panel* is comprised of a thick internal layer of low density material, referred to as the *core*, which contributes to flexural stiffness, out-of-plane shear and compressive behaviour, and externally bound thin, stiff and fairly dense material, referred to as the *facings* or *face sheets*, which generally carry bending and in-plane loads (Figure 1). The methods of manufacturing sandwich panels are numerous, and depend on the materials and required shapes or configurations. Examples of these methods include injection moulding, air bubble-free resin vacuum infusion process, the seeman composites resin infusion moulding process (SCRIMP), which is a more economical vacuum-assisted resin transfer moulding (VARTM) process, vacuum bag technology, investment casting method, and hot-melt impregnation process. The structural applications of sandwich panels are as many and as diverse as the materials and the configurations used in their fabrication.

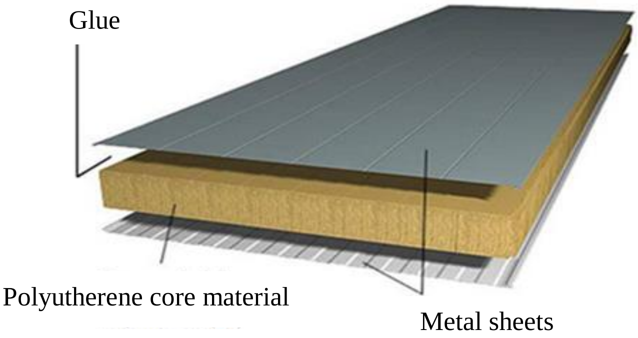

Figure 1 Typical sandwich panel (http://www.sovereignbd.com/sandwich-panel.html)

2. FACE SHEETS

It has been estimated by the Federation of American Scientists (2009) that metals are the most extensively used face sheets and make up approximately 50% of the market while wood, particularly oriented strand board, follows at approximately 42%. All other materials make up the remainder. The commonly used metals are steel (Szyniszewski et al (2012)) and aluminium (Ramakrishnan and Kumar (2016)), due to their relatively thin face sheets, which can be lightweight and non-flammable (Panjehpour et al (2013)). Oriented strand board, on the other hand is highly flammable, but tends to be much cheaper than metals (Panjehpour et al (2013)). Also in literature are concrete and other cement-based facings, such as precast concrete wythes, which are connected by concrete webs or steel connectors (Benayoune et al (2006)) and cellulose-fibre cement board (Dundu and Bukasa (2013)). Typically cement board is fire-resistant, but has the drawback of exhibiting brittle failure, especially in compression (Panjehpour et al (2013)). One group of materials that is now being used widely, as reflected in the growing body of research literature, is the fibre-reinforced polymers or plastics (FRP). A survey of literature reveals that the types of fibre ranges from Kevlar (Borsellino et al (2004)), fibreglass (Mamalis et al (2002)), electrical glass or E-glass (Borsellino et al (2004) and Abdi et al (2014)) to carbon fibres (Borsellino et al (2004) and Cartié and Fleck (2003)).

3. CORE MATERIALS

According to Daniel (2009), the core material properties have the greatest influence on failure initiation and failure mode, and this seems to be backed up by the huge range of materials that have been investigated. Balsa, which has a relatively high density of up to 150kg/m^3 (Avilés and Carlsson (2006)), and has been used in boat hulls and flooring over a long period of time has been found to have a static strength that is greater than polyvinyl chloride (PVC) foams (Ramakrishnan and Kumar (2016)). Today, this material is used as the core of modern facing materials, such as FRP (Avilés and Carlsson (2006)). However, PVC foams appear to enjoy the most widespread use, and this has been ascribed to their superior insulation properties (Ramakrishnan and Kumar (2016)). They can be found in densities ranging from 48kg/m^3 to 200kg/m^3 (Avilés and Carlsson (2006), Bezazi et al (2007) and Mamalis et al (2005)), depending on their intended use. Several researchers have investigated the effect of different types of foam and foam density on the structural properties of sandwich panels (Table 1). Other core materials found in literature include polyurethane (PUR) of densities ranging from 32kg/m^3 (Tuwair et al (2015)) up to 139kg/m^3 (Abdi et al (2014)), expanded polystyrene (EPS) (Borsellino et al (2004), and Mousa and Uddin (2011)), polymethacrylimid (PMI)(Mamalis et al (2005)), and syntactic phenolic foam(Mamalis et al (2002)).

Increasingly, these foams are being reinforced in various ways in order to improve their load-carrying capacity. A broad range of materials from simple fibres (Dawood et al (2010), and Cartié and Fleck (2003)) and pins (Abdi et al (2014)) to tubes (Mamalis et al (2002)), pyramidal shapes (Cartié and Fleck (2003)) or trusses (Benayoune et al (2006)) and honeycombs (Daniel (2009)) have been investigated in order to determine whether they are of structural benefit. Fibres extending from one facing to the other increased the shear strength, stiffness and flat-wise compression of the panel (Dawood et al (2010)). The problem of delamination was also dealt with to a certain extent (Abdi et al (2014)). It was found that cylindrical pins, made of glass-fibre/polyester resin laminate and encased in a polyurethane foam (69.5kg/m^3), and rigidly connected to the top and bottom sandwich faces increased the resistance to debonding and delamination. The pins also eliminated core crushing (Abdi et al (2014)). In one study (Cartié and Fleck (2003)), titanium alloy or carbon fibre pins were inserted into foam cores, at an angle of 30° to the sandwich panel mid-plane, resulting in a pyramidal structure. In another study (Mamalis et al (2002)), a phenolic foam core had additional reinforcement in the form of tubes made of the same material as the fibreglass facings. Located at the corners of the specimen, the axes of four of the tubes were aligned perpendicular to the plane of the facings, as shown in Figure 2. A fifth tube was positioned such that its axis was parallel to the facings and during edgewise compression test this tube was either vertical or horizontal (Mamalis et al (2002)). One conclusion drawn from the results was that the usefulness of such tubes as reinforcement was somewhat dictated by their orientation in relation to the loading direction (Mamalis et al (2002)).

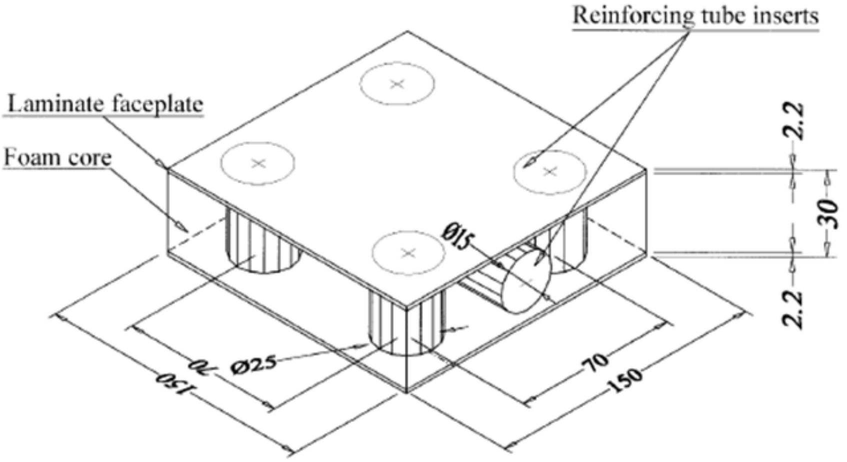

Figure 2 Schematic diagram showing tube orientation in foam core (Mamalis et al (2002))

4. STRUCTURAL RESPONSE OF PANELS IN BENDING

Flexural tests, in three or four-point bending, have been conducted on various combinations of facing and core materials. The deflections and ultimate loads sustained, and the failure modes were shown to be influenced by the choice of facing and core materials. A comparison between facings made up of several layers of either woven Kevlar, glass or carbon fibres with epoxy resin and hardener as the matrix (Borsellino et al (2004)) revealed that higher modulus of the carbon fibre facing translated into a slightly higher flexural strength when compared to the other two facing materials, but the maximum loads sustained by all three panels still remained within 10MPa of each other. The failure mode for all panels was wrinkling of the top facing (compression face) due to crushing of the underlying core. This was followed by a fracturing failure of that face, and this usually occurred under the load position. The failure of the Kevlar facing was found to be less sudden, a behaviour that was ascribed to its ability to absorb energy (Borsellino et al (2004)). In the same study, comparisons between two different densities of EPS foam (15kg/m^3 and 18kg/m^3) showed a 51% increase in elastic modulus and a 108% increase in ultimate flexural stresses for the higher density foam, compared to the one with the lower density (Borsellino et al (2004)). Similar results were obtained by Bezazi et al (2007). Specimens with the less dense core failed by upper facing rupture and indentation under the load position, while the denser core specimens experienced shear failure and delamination of both facings (Bezazi et al (2007)). In general, core failures occurred faster when compressive forces and shear stresses were working together than when either one is working in isolation. Indentation frequently occurred where the soft cores were subjected to concentrated loads. In such cases, the top facing deformed into the core (Daniel, (2009)).

Where the core had additional reinforcement in the form of pins, results showed that flexural stiffness and ultimate strength were increased by the presence of the pins. In fact, increasing the pin diameter was found to increase strength and stiffness (Abdi et al (2014)). When compared to plain foam core sandwich specimens, the samples reinforced with 2mm and 3mm diameter pins experienced an increase in the failure load-to-weight ratio of 44.9% and 48.6%, respectively, while the corresponding deflections increased by 98% and 42.6%, respectively. In addition, the maximum flexural stresses sustained by the 2mm and 3mm pin sandwich specimens were 77.2% and 97% higher, respectively (Abdi et al (2014)). In the plain foam core specimens, failure of the top face sheet resembled local buckling, at the load position, with no observable failure of the core (Figure 3 (a)). However, in the pin-reinforced specimens, the first sign of failure was cracking of the pins near the load position. The cracks happened at the top facing-core interface, propagated outwards towards the supports, and eventually traversed the core to the bottom interface, as illustrated in Figure 3 (b) (Abdi et al (2014)).

(a) Plain foam core panel (b) Pin reinforced foam core panel

Figure 3 Failure of the foam core material (Abdi et al (2014))

Truss cores were found to carry greater ultimate loads than similar tetrahedral cores (Wang et al (2003)). The failure mode was shearing of the core which took the form of tensile rupture of the core members. The compression members experienced yielding and no buckling. It was surmised that some of the truss member rupture was due rather to material imperfection which affected ductility (Wang et al (2003)).

Concrete and other cementitious composites have also been tested in four-point bending. Sandwich panels with FRP facings and polymer-concrete filled corrugated cores exhibited composite action and sustained greater ultimate shear and flexural loads when compared to equivalent conventional reinforced concrete wall panels (Wattick and Chen (2017)). The panels also exhibited greater stiffness and ductility than their conventional equivalents. At failure, the panels first experienced debonding between the core and facings and then finally failed in shear (Wattick and Chen (2017)). There was no evidence of such debonding or delamination of fibres of the face sheet in full scale panels made of cellulose fibre-cement board facings and EPS cement cores. Although the panels were found to be more than adequate in sustaining typical service loads, they experienced sudden catastrophic failure. The panels sustained very little deflection (Dundu and Bukasa (2013), and Bukasa and Dundu (2014)).

5. STRUCTURAL RESPONSE OF PANELS IN COMPRESSION

The behaviour of sandwich panels under compressive loads was examined either from tests on full-scale panels or from edge-wise or flat-wise compression tests of smaller specimens. Researchers investigated the effects of different cores on the compressive behaviour of sandwich specimens (Boyle et al (2001) and Daniel (2009)). Boyle et al (2001) examined the buckling and post-buckling behaviour of full scale panels with similar facings (glass/ vinylester FRP) and either PVC (69.5kg/m^3) or balsa (150kg/m^3) cores. With a panel aspect (length to width) ratio of 2, the specimens with balsa cores buckled in two half-sine waves, while those with PVC cores buckled in a single half-sine wave (Boyle et al (2001)). In addition, the failure load of the balsa core specimens was 1.75 times larger than the theoretical buckling load, compared to only 1.35 times for the PVC core. Face sheet delamination and subsequent shear failure of core were observed at failure for the balsa core panels (Boyle et al (2001)). In Daniel (2009)'s investigation panels with FRP facings and either aluminium honeycomb, 100kg/m^3 density PVC foam or 250kg/m^3 density PVC foam were tested. The specimens with aluminium honeycomb cores failed by compressive failure of the face sheet rather than by face sheet wrinkling. Theoretical equations had predicted that face sheet wrinkling would be the most likely failure at a stress of around 2850MPa but the panels actually failed at a stress of 1550MPa in compression. This ultimate compressive load was much lower than the critical wrinkling stress (Daniel (2009)). Both sandwich specimens with the PVC foam cores failed due to wrinkling of the facing, at stresses that were close to the theoretical values. Similarly, the effects of different facing materials have been investigated. In Borsellino et al (2004)'s study, panels with similar core material (EPS bounded by an outer layer of PVC foam)and FRP facings, reinforced with either Kevlar (aramid), glass or carbon fibres were subjected to either edgewise or flatwise compression tests. In edgewise compression, Kevlar was found to have lower strength than either glass or carbon (Borsellino et al (2004)).

Panels with circular or square debonds on one facing were tested under compressive loading (Avilés and Carlsson (2006)). The debonds were placed centrally and the core material was again varied (PVC foam (48kg/m^3, 100kg/m^3, 200kg/m^3) and Balsa (150kg/m^3)) while the facing material was kept constant. For the majority of panels, initial failure occurred by local buckling of the facing at the location of the debonds. After that the region of debonding spread as the load increased until compressive failure of the face sheet occurred (Avilés and Carlsson (2006)). A unique sandwich panel made up of solid steel face sheets and foamed steel core was the subject of an analytical study (Szyniszewski et al (2012)), to assess the local buckling strength of such an arrangement. It was shown that when between 30 and 90% of the initial solid steel plate thickness was foamed, the resulting bending rigidity was greater than that of both the solid plate and fully foamed plate. In fact, indications were that when only the central 30% of the panel was foamed strength increased by up to 200%. This assessment was based on a comparison with a solid steel panel of similar mass. However the effective modulus and yield decreased (Szyniszewski et al (2012)).

6. CONCLUSION

Sandwich panels have been in use for several decades and their behaviour is generally well understood. However, as advances continue to be made in manufacturing, and new materials and composites are developed and subsequently incorporated into sandwich panel design, there is an ongoing need to test their adequacy in carrying typical loads.

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