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The State of the art review on Concrete Sandwich Panels

M. Raga Sudha [1,*] and A. Muthadhi [2]

[1] Research scholar, Department of Civil Engineering, Puducherry Technological University, Puducherry, India
[2] Assistant Professor, Department of Civil Engineering, Puducherry Technological University, Puducherry, India

*Corresponding author email: ragasudha.m@ptuniv.edu.in, Tel. : +91 7598246810

ABSTRACT

Concrete sandwich panels (CSPs) are composites, consisting of three main parts the skin, core and adhesives/connectors. Skin faces comprise two top and bottom concrete wythes, which are thin, stiff and strong; whereas the middle core part was thick, light and made up of weaker material, characterized by high thermal resistance which is boned or fixed together with adhesives or connectors. CSPs can be manufactured either cast in situ or precast and affixed to any type of structural frame. It can function dually by transmitting load and insulating the structure. Hence, it was thermally efficient and used as replacement cladding for renovation works. Nowadays most studies on CSP report on its structural testing, which focus mainly on the load transfer mechanism between concrete wythe skin and core material by composite and/or non-composite action to the attached structural component. Sandwich panels may also be intended to carry the self-weight of the buildings and critical studies from various pieces of literature focused on the structural performance of sandwich panels are reviewed herein.

This critical review also focuses on the latest advancements in the development of textile-reinforced concrete sandwich panels with various types of mesh reinforcement that achieve excellent flexural and impact strength properties. But still, there is a need for further studies on different types of adhesives and connectors used between concrete wythe and core material of concrete sandwich panels and thermal validation of novel CSPs.

Keywords - Sandwich panel, Concrete Wythe faces, Textile reinforced concrete, Adhesives and Connector.

1. INTRODUCTION

Sandwich panels are stacked structures composed of two or more materials with exclusive properties. The different layers are usually bounded together by some sort of adhesive or connectors. This type of structure has many advantages, combining the properties of each material and resulting in a final structure with superior properties [1].

The ASTM defines a sandwich structure as follows: *A structural sandwich is a special form of a laminated composite comprising a combination of different materials that are bonded to each other to utilize the properties of each separate component to the structural advantage of the whole assembly.*

Concrete sandwiches are composed of three main components as illustrated in Fig.1 (a). Two thin, stiff, and strong faces of concrete wythes (layers) are separated by a thick, light, and weaker core layer of rigid foam insulation. The faces are adhesively bonded to the core to obtain a load transfer between the components [2].

One of the concrete wythes may be a standard shape, such as a flat slab, hollow-core section, double tee, or any custom architectural concrete section. In place, sandwich wall panels can provide the dual function of transferring load and insulating the structure. They may be used solely for cladding, or they may act as beams, bearing walls, or shear walls. Concrete sandwich wall panels are used as exterior and interior walls for many types of structures. These panels may readily be attached to any type of structural frame, including structural steel, reinforced concrete, pre-engineered metal, and concrete. Panels generally span vertically between foundations and floors or roofs to provide the permanent wall system but may also span horizontally between columns. In this report, concrete sandwich wall panels will be referred to as sandwich panels. They are most typically used in low-rise industrial buildings but increasingly in a wider range of building typologies including mid to high-rise residential and commercial buildings [1,2]. However, traditional CSPs are heavy and often favoured for low rise buildings where panels are simply tilted up into place [2].

Typically constructed of steel-reinforced concrete, CSPs often have thicknesses that exceed 300 mm [3] and associated weights of ~500 kg per m^2 of wall area. To expand their applicability to a wider range of buildings the weight and thickness of CSPs need to be reduced and hence a number of recent projects [4,5] and studies [6–8] have focused on designing thinner sections.

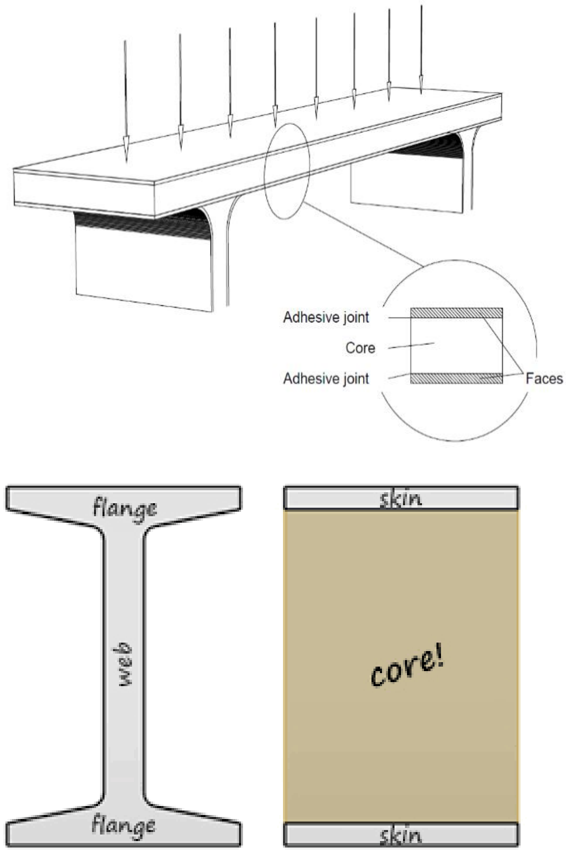


Figure 1. (a) Schematic of a structural sandwich panel [2] & (b) Comparison of I-beam with sandwich panel.

In case of sandwich beams, the skin faces take the role of the flanges and the core material act as the web as shown in Fig 1 (b). The difference is that the core of a sandwich is of a different material from the faces and it is spread out as a continuous support for the faces rather than concentrated in a narrow web. The faces will act together to form an efficient stress couple or resisting moment counteracting the external bending moment. The core resists shear and stabilizes the faces against buckling or wrinkling. The bond between the faces and the core must be strong enough to resist the shear and tensile stresses set up between them. The adhesive that bonds the faces to the core is thus of critical importance. In Sandwich elements, faces usually consist of thin and, high-performing material while the core material is thick, light but relatively low performing. The choice of constituents depends mainly on the specific application and the design criteria set up by it. The design of a structural sandwich will not be one of geometry only but an integrated process of geometrical design and materials selection [1,3]. This paper critically reviews the types and components of sandwich panels.

Sandwich panel types:

The sandwich panels are of three types namely non-composite, composite and partially composite [3].

1. Non-composite: A non-composite sandwich panel is analysed, designed, detailed, and manufactured so that the two concrete wythes act independently. Generally, there is a structural wythe and a non-structural wythe, with the structural wythe being the thicker of the two.

2. Composite: Composite sandwich panels are analyzed, designed, detailed, and manufactured so that the two concrete wythes act together to resist applied loads. The entire panel acts as a single unit in bending. This is accomplished by providing full shear transfer between the wythes.

3. Partially Composite sandwich panels have shear ties connecting the wythes, but the connectors do not provide full composite action. The bending stiffness and strength of these panel types fall between the stiffnesses and strengths of fully composite and non-composite sandwich panels.

2. COMPONENTS

2.1 FACE MATERIALS

Any structural material which is available in the form of thin sheet may be used to form the faces of a sandwich panel [1]. The properties of primary interest for the faces are;

I) High stiffness giving high flexural rigidity II) High tensile and compressive strength, III) Impact resistance, IV) Surface finish, v) Environmental resistance (chemical, UV, heat, etc.) and vi) Wear resistance. The commonly used face materials can be divided into two main groups; metallic and non-metallic materials. The former group contains steel, stainless steel, aluminium alloys, etc. Non- metallic materials include materials such as plywood, cement, veneer, reinforced plastic, fibre composites, etc. [10]. This paper discusses concrete wythes faces with fiber composites in sandwich panels.

2.1.1 Concrete Wythes Faces

The concrete wythes are the structural part of the concrete wall panels and form the inner and outer surfaces, made of Normal Concrete, Foamed Concrete, Self-Compacting Concrete, High-Performance Fibre Reinforced Concrete, Textile reinforced concrete (TRC), etc. Concrete with compressive strengths ranging from 8

MPa for lightweight foamed concrete [13] to 193 MPa for UHPC [14] have been reported. In order to achieve high rigidity, composites are more often sandwiched with a light core material. Textile-reinforced concrete can also be made with hybrid fibre in different forms as shown in Fig.2, thus having the potential to result in higher impact resistance due to synergic effect [16]. Scarce amount of research has been done to study the textile- reinforced concrete with hybrid fibre mesh reinforcement as concrete wythe faces.

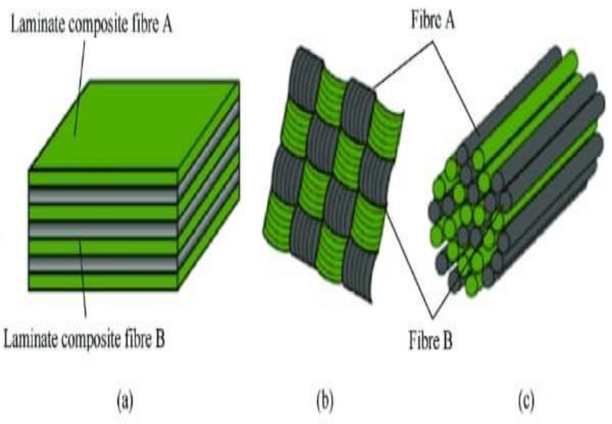


Figure. 2 Different forms of hybrid fibres
(a) hybrid fibre inter-layer (b) hybrid fibre intra-layer
(c) hybrid fiber intra-yarn [17]

The material constituents of fiber composites, which are the most widely used type of non-metallic face materials in sandwich constructions are classified into natural and synthetic or man-made fibers.

The two groups of synthetic fibers are:

1. Fibers that have a **moduli** value lesser than the cement matrix. Examples are: Nylon, cellulose and polypropylene
2. Fibers that have a **greater moduli** value than cement. Examples are glass, steel, asbestos fibers etc. [18]

Type-1 fibers are said to increase the strain performance of the concrete, while the type-2 fiber has greater modulus than cement and provides greater strength performance for the concrete. In Table.1, a list of typical fiber data is presented.

In many non-load bearing Precast CSPs, the wythe thickness is determined by the required cover to the reinforcement, rather than the structural requirements. To overcome this, a number of studies have proposed the use of non-corrosive Textile Reinforced Concrete (TRC) as the wythes of their CSP designs [6, 22, 23]. Different textile materials have been used and tested throughout the Concrete sandwich panel, each offering different advantages.
The influence of yarn alignment, geometry and orientations of fibers imparts the mechanical properties of the fiber composites. Textile reinforced concrete (TRC) is one which fulfils both Fiber reinforced concrete (FRC) and Reinforced concrete (RC) features, as in FRC the fibers are arranged in a discrete manner that can be placed according to the tensile stresses in the structures similar to conventional RC [32, 33] and behave pseudo ductile in nature because of its mesh or fabric form. The weaving techniques are listed in table 2. The textile reinforcements are classified as two-dimensional planar or conventional (2D) and three-dimensional (3D) as shown in Fig.3.

Table 1: *Comparison of most common man-made and natural fibers [19].*

Types of Fibers	**Diameter range (μm)**	**Density (kg/m3)**	**Tensile Strength (GPa)**	**Advantages**	**Disadvantages**
Man-made					
AR-glass	9 to 27	2800	1.4	Very good adhesion	Low tensile strength, Low cost
Carbon	7 to 15	1800	2 to 5	Superior tensile strength, Flame resistance	Expensive, Poor adhesion than AR glass
Aramid	10 to 15	1400	3	Flame resistance, Good Impact resistance	Expensive, Hygroscopic
Polypropylene	50 to 500	900 to 950	0.14 to 0.96	High chemical resistance, Hydrophobic	Poor bonding, Poor fire resistance
Polyvinyl Alcohol	10 to 670	1300	0.88 to 1.9	More durability	Hydrophilic
Ceramic	10	2200 to 3300	2.8 to 3.6	High temperature resistance	High brittleness

Natural					
Hemp	66 to 80	1480	0.55 to 0.9	Low cost, Biodegradable	Hygroscopic, Low tensile strength, Low melting point, Degrade at more than 2000C
Flax	10 to 20	1400	0.8 to 1.5	Low cost, Biodegradable	Hygroscopic, Low tensile strength, Low melting point, Degrade at more than 2000C
Sisal	50 to 300	1330	0.6 to 0.7	Low cost, Biodegradable	Hygroscopic, Low tensile strength, Low melting point, Degrade at more than 2000C
Jute	40 to 75	1460	0.4 to 0.8	Low cost, Biodegradable	Hygroscopic, Low tensile strength, Low melting point, Degrade at more than 2000C

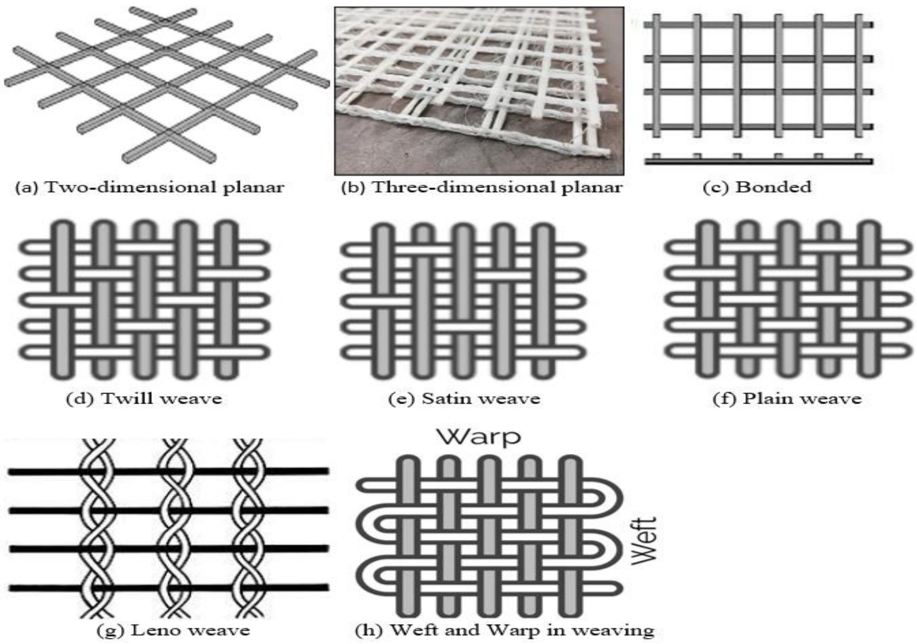


Figure 3. Different forms of weaving techniques

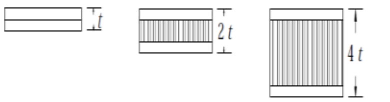
Table 2: *Comparison of fiber yarn weaving.*

Style of weaving	Properties and uses		Complications
Plain weave	High dimensional stability, High shear resistance		Wrinkle more, Lower tear strength, Preclude in a composite application, Low reinforcing efficiency
Leno weave	Dimensional stability, Strong, Lightweight, Durable, Ideal for cement-based composites		Very poor drape
Twill weave	Easily stretched		Less reinforcing due to high curvature, Low dimensional stability

Satin weave	High structural stability, Possible to make mesh structure		Low bending properties
Bonded	Suitable for cement-based composite applications		---

3. INSULATION CORES

The idea of sandwich construction has become increasingly popular because of the development of manmade cellular materials as core materials. The separation of the skin by the core increases the moment of inertia of the panel with little increase in weight, producing an efficient structure for resisting bending and buckling loads. Table 3 shows illustratively the flexural stiffness and strength advantage of sandwich panels compared to solid panels using typical beam theory with typical values for skin and core density. By splitting a solid laminate down the middle and separating the two halves with core materials, the result is a sandwich panel. The new weighs a little more than the laminate, but its stiffness and strength are much greater, by doubling the thickness of the core material, the difference is even more striking.



Relative Bending Stiffness	1	7.0	37
Relative Bending Strength	1	3.5	9.2
Relative Weight	1	1.03	1.06

Table 3. Structural efficiency of sandwich panels in terms of thickness [35].

Thus sandwich panels are popular in high-performance applications where weight must be kept to a minimum. To minimize weight, the cores used are in the form of foams, honeycombs or with corrugated constructions as shown in Fig 4. As well as mechanical requirements, core materials may also be selected based on their fire resistance or thermal properties [36-38]. Compared to honeycomb and corrugated cores the foam core is less likely to delaminate and is highly used in sandwich panels. Some core materials studied to date combined with cement matrix are Expanded Polystyrene (EPS), Aerated Aerocon concrete, and Foamed Concrete. Colombo et. al., [39] studied EPS as a core with FRC skins in the sandwich panels for energy retrofitting purposes. In the later context of sandwich construction, Gypsum and calcium silicate is used as insulation in various constructions, and integrating them in the TRC sandwich panel is studied by Gopinath et. al., [40] to understand the bending response. The Calcium silicate board resulted in an increased shear transfer, toughness value and residual strength and has a controlled failure when compared to the gypsum core.

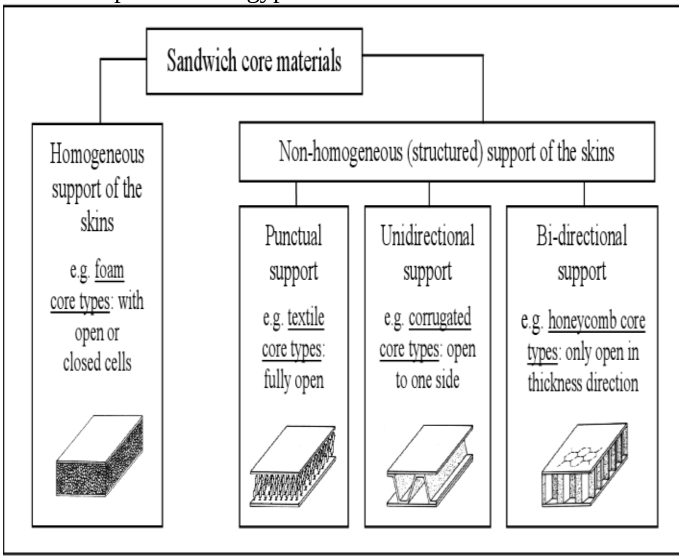


Figure 4. Classifications of sandwich core materials.

4. CONNECTORS & ADHESIVES

4.1 CONNECTORS

The connectors join the structural concrete wythe and core material layer together. Connectors help in transferring lateral shear forces between the two concrete layers to achieve composite action. The degree of behaviour of composite action is dependent on the type of connector used [21]. Traditionally, steel connectors are used but they cause mould problems and thermal bridges in sandwich concrete panels. Then in early precast CSPs, metal and plastic ties are commonly used. The size and material of the connector are the reason for tie bridges in the insulation layer creating a thermal bridge and the challenge is to provide structural shear transfer while minimizing the thermal bridge.

Two concrete wythes of a sandwich panel were connected with continuous ribs or discrete concrete passed through the insulation layer was also studied [41]. These concrete ribs [42,43] or solid concrete [44] enhanced composite behaviour. All these concrete connectors compromise the thermal resistance of the sandwich panel. To reduce the area of insulation bridged metallic connectors in the form of trusses, tubes or plates [47,48,49,50,51], or in the form of discrete pin connectors [52,53,54] was studied [Fig.5]. Hegger et al.

[55] use the connectors only around the edges and minimize the use of metallic connectors in their panel designs. Metallic connectors show higher thermal conductivities [11,56] so the same can be replicated using non-metallic connectors to lower thermal conductivities [57].

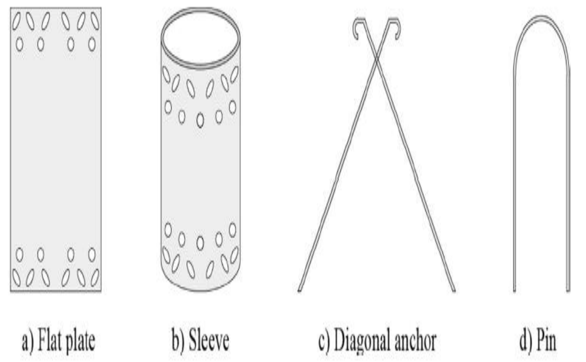


Figure 5. Different forms of metallic and non-metallic connects [57].

4.2 ADHESIVES

The choice of adhesive is primarily focused on finding an adhesive that satisfies the mechanical requirements of the structure of providing a good bond between the material components in the environment that the structure is to work, and considerations like fatigue, heat resistance, strength, ageing and creep are of primary interest. Health considerations, manufacturing technique, curing time, curing temperature, special tooling requirements, etc., can also decide the choice of adhesive system.

4.2.1 *Epoxies* are usable with almost every type of core material. Epoxies are commercially available in various forms such as paste, powder, films, or as solid adhesives. They generally have good mechanical properties with a shear strength of about 20-25 MPa at room temperature [58].

4.2.2 *Toughened epoxies* are similar as common epoxies but mixed with synthetic rubber, like polysulfide elastomers, which greatly improves the peel resistance. The greater the portion of
elastomers the more excellent ductility but the creep tendencies increase correspondingly as well and the heat resistance decreases. Other modifications are the inclusion of Nylon to improve filleting and control flow [59]. These types are, however sensitive to humidity. By mixing the epoxy with nitrile instead of Nylon the same advantages are gained but with maintained resistance to humidity. These are the most common of the toughened thermoset adhesives and are usually limited to approximately 150°C service temperature. The shear strength of toughened epoxies approach values of about 35 MPa. Toughened epoxy adhesive films are the most common material used when bonding honeycomb sandwich parts.

4.2.3 *Phenolic* adhesives have excellent strength, high-temperature mechanical properties and durability. The main drawbacks are that they give off some water when curing making venting essential. The out-gassing makes phenolic unsuitable for use in bonding sandwich constructions [59].

4.2.4 *Polyurethane* (PUR) adhesives are probably the most widely used adhesive for bonding sandwich elements. This is because they provide excellent adhesion to most materials. They can be used as paste or liquid in a wide range of viscosities, may have long or short cure times and can be made fire-retardant and water-resistant [60]. PUR adhesives contain virtually no solvents and are thus environmentally friendly and the least toxic of the resins mentioned herein. There exist two different types of PUR adhesives; one-component moisture-cured and two-component systems. One-component PUR adhesives are in short pre-reacted, two-component adhesives which continue to cure when exposed to moisture. Two-component PUR adhesives consist of various polyols, water scavengers, catalysts, fire retardants, fillers, etc. The curing agent is usually polymeric methylene-di-phenyl-di-isocyanate, which is the least volatile of all isocyanates. PUR adhesives are mainly used in the bonding of foam or balsa core sandwich structures.

4.2.5 *Urethane acrylate* is a resin that is compatible with polyesters and vinyl esters. Acrylates are so compatible that they can be incorporated in laminate. Urethane acrylates are very tough and exhibit almost no curing volume shrinkage. A way to drastically increase the face-to-core bond in foam core GRP-sandwich structures is to use urethane acrylate resin for the first reinforcing layer [61], that closest to the core. The rest of the laminate can then be laminated wet, using for example polyester resin on top of the acrylate layer and still provide a perfect inter-laminar bond.

5. CONCLUSIONS

This review paper addresses the different types of materials used in various components of concrete sandwich panels. In the face concrete wythe of the sandwich panel, the use of non-corrosive Textile Reinforced Concrete (TRC) have additional advantages. The influence of weaving technique (including yarn alignment, geometry and orientations) and coating of fibers affects the mechanical properties of the fibre mesh composites. Calcium silicate board used as core material in concrete sandwich panels resulted in an increased shear transfer due to its increased core thickness and has a controlled failure because of its effective bond with the skin when compared to the gypsum core. Different types of connectors and adhesives used for concrete sandwich panels are also discussed. However, still, there is a need for further studies on novel CSPs with hybrid TRC faces and thermal insulating core material with different adhesives or connector types, tested for mechanical performance, thermal variation and durability characteristics.

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