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State-of-the-Art Review on FRP Sandwich Systems for Lightweight Civil Infrastructure

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Abstract

Fiber reinforced polymer (FRP) sandwich systems as primary load-bearing elements are relatively new concepts in lightweight civil infrastructure. These systems offer a combination of light weight, high strength, thermal insulation for some types, and service-life benefits. Recent developments and applications have demonstrated that these composite systems have emerged as a cost-effective alternative, especially when each material component is appropriately designed. Still, some issues and challenges need to be addressed if FRP systems are to gain widespread use in civil infrastructure. This paper provides an overview of the state-of-the-art research, development, and applications of FRP sandwich systems. It also identifies the challenges and future opportunities for the broad use of these advanced systems in civil engineering and construction.

Authors keywords: Sandwich systems; Fiber reinforced polymer; civil engineering; developments; challenges; opportunities.

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Introduction

Fiber reinforced polymer (FRP) sandwich systems are special form of a laminated composite fabricated by attaching two thin skins to a thick lightweight core (ASTM C274-99). These systems are increasingly used in applications requiring high bending stiffness and strength, combined with low weight (Belouettar et al. 2009). FRP sandwich systems have been widely used in the aerospace, aircraft, and marine industries because of their many advantages such as improving the efficiency in transportation vehicles (Bakis et al. 2002). Such systems have also drawn considerable interest in the construction industry and are now emerging as effective alternatives for use in niche civil infrastructure applications (Keller et al. 2007). The low weight of FRP sandwich systems facilitates handling during assembly, while reducing installation and transportation costs. This can significantly speed up construction, especially rebuilding in disaster areas and in highly populated areas to reduce traffic interruptions. These systems also offer benefits in structures built in rural and regional areas where relatively light construction and lifting equipment are used. Moreover, the high insulating capacity of some FRP sandwich systems is of great interest for energy-efficient buildings. In addition, the construction industry's need for durable, cost-effective civil infrastructure has generated significant research into developing new and innovative FRP sandwich systems.

The material combination coupled with the geometry of FRP sandwich systems, makes it possible to optimize designs for specific applications. FRP skins are commonly used due to their lightweight and high tensile strength. A great variety of core materials have been used, such as balsa wood, polymeric foam core, honeycomb, and trussed core. Similarly, the bond between the skin and core interface must be adequate in order to make the best use of the effective mechanical properties of the skin and core materials. The evolution of FRP sandwich systems through research and development has provided an opportunity to expand the engineering application of these advanced material systems.

Recent developments in FRP sandwich systems have been very valuable in terms of research and applications. The feasibility and potential of FRP sandwich systems in civil engineering and construction have been successfully demonstrated for various applications including structural roofs (Keller et al. 2008), floors (Van Erp and Rogers 2008), walls (Sharaf and Fam 2011), and bridge decks (Keller et al. 2014) as well as composite railway sleepers (Manalo and Aravinthan 2012a; Van Erp and McKay 2013), bridge beams (Primi et al. 2009; Van Erp and McKay 2012), and floating and protective structures (Qiao et al. 2008; Liu et al. 2013). The potential of these systems has yet to be fully explored despite engineers having access to a wide range of sandwich composites. This paper reviews the state-of-the-art research, innovations, and developments related to FRP sandwich systems, including field implementation in lightweight civil infrastructure. Challenges in using these emerging composite systems are discussed and future prospects are presented to pave the way in improving confidence in using FRP sandwich systems for civil infrastructure.

Components of FRP Sandwich Systems

This section describes the materials commonly used in manufacturing (as well as the production methods) and joining FRP sandwich systems.

Top and Bottom Skins

The top and bottom skins are largely responsible for the system's flexural strength and stiffness. Steel, stainless steel and aluminium often serve as skin materials and have been extensively studied and used in aerospace, automotive, and marine applications while FRP have emerged as an excellent alternative skin material for structural engineering applications (Mathieson and Fam 2014a). The high specific strength and stiffness of FRP significantly reduce the weight of sandwich composites. According to the ACI recommendations for reinforcement of concrete members using FRP materials, the fibres used in that important civil engineering application can be glass, carbon or aramid bonded with epoxies, polyester, vinyl esters, or phenolics (ACI 440R 2007). The same type of fibres can be used in the skins of sandwich panels.

Glass fibers are the most commonly used due to their relatively lower comparative cost. The use of basalt (Torres et al. 2013) and bio-based fibers is now also being explored for FRP sandwich systems. Mak et al. (2015a) published results indicating that FRP sandwich systems with three layers of flax fiber skins provide equivalent structural performance to composites comprising a single layer of glass fibers skins. Interestingly, the sandwich composites with flax fiber skins exhibited a more flexible failure than the glass fibers. Indeed, using these new fiber types for the skins may result in more cost-effective and environmentally-friendly FRP sandwich systems.

According to Barbero (1999), the strength and stiffness of FRP skins depend largely on fiber amounts and the direction the fibers were laid. In general, skins fail by face yielding in either tension or compression, face wrinkling, buckling due to core compressive failure or adhesive-bond failure, and by dimpling in the case of sandwich systems with cellular cores. Borsellino et al. (2004) and Belouttar et al. (2009) however indicated that the nature of the core influences more the fracture mechanism of FRP sandwich systems than the different skin arrangements. Gdoutos and Daniel (2008) suggested that core usually fails by shear cracking, crushing, core indentation, and flexural tensile cracking. Thus, research and development have focused more on developing effective core material systems so as to boost the performance of FRP sandwich systems.

Core Materials and Systems

The lightweight core material of unreinforced cores provides the shear rigidity and strength of FRP sandwich systems. Traditionally, sandwich composites consist of a simple foam core, as shown in Fig. 1a. The two of the most commonly used materials are polyvinyl chloride (PVC) foam in densities ranging from 30kg/m^3 to 400kg/m^3 and rigid polyurethane (PU) foam in densities ranging from approximately 21 kg/m^3 up to 400 kg/m^3. While structurally inferior to denser cores, lower density PU foam core is desirable for its higher thermal insulation (Mathieson and Fam 2014a). Another big advantage of PUR foams is their relatively low cost. Polyethylene terephthalate (PET) foam is also increasingly being used for FRP sandwich systems and is very interesting by being thermoplastic and recyclable. Balsa wood (Fig. 1b) is another common core material because of its lightweight and good mechanical properties (Grenestedt and Bekisli 2003). Usually, small blocks of balsa wood are glued together side by side to form sheets of the so-called end-grain balsa, in which the grain is oriented parallel to the thickness. As a core material, end-grain balsa improves sandwich panel resistance to local indentation and face-sheet wrinkling (Kepler 2011). Furthermore, balsa has positive shear properties and contributes significantly to bending stiffness (Keller et al. 2014). Table 1 provides the mechanical properties of the balsa wood and foam core commonly used for FRP sandwich systems as reported by Beckwith (2008) and Manalo et al. (2013a).

Honeycomb and truss cores have received much attention in recent years to meet the through-the-thickness compression requirements of FRP sandwich systems. Honeycombed core FRP sandwich systems (Fig. 1c) may be low-density polymeric or metallic (aluminium) honeycomb core (He and Hu 2008). FRP sandwich systems with a honeycomb core can perform better than foam core in compression and shear at equivalent weight. On the other hand, sandwich composites with trussed cores (see Fig. 1d) are highly efficient from a weight standpoint and deliver good compression performance (Wicks and Hutchinson 2001). However, trussed cores are very hard to produce properly, guaranteeing fibre continuity between truss members and face sheets is challenging, and this type of solution if often poor from a cost-effectiveness stand-point.

While various core materials are available, the nature of those in common use limits their application in FRP sandwich systems for civil infrastructure. Fam and Sharaf (2010) indicated that FRP sandwich systems with lightweight foam cores usually fail due to core indentation and shear and that their low shear stiffness leads to early skin-core delamination failure. Open-cell foam cores tend to absorb and retain moisture and have very low fire resistance (Marsh 2007). The major problem with balsa wood is its susceptibility to water penetration leading to swelling, debonding, and rotting (Grenestedt and Bekisli 2003). Similarly, the closed cells in the honeycomb core are susceptible to entrapping moisture which can lead to core and skin delamination (Kooistra and Wadley 2007). On the other hand, FRP sandwich systems with truss cores are weak at bearing concentrated loads and very difficult to join (Demelio et al. 2001). The presence of cavities between the skins of honeycomb and truss core materials reduces the capacity of sandwich composites to hold mechanical connectors. Moreover, the continued high cost of the honeycomb and truss core materials has restricted their applications predominantly to the aerospace industry (Reis and Rizkalla 2008). Thus, the evolution of FRP sandwich composites with lightweight and high-strength core materials will help increase the use of these systems for civil engineering and construction.

Production Methods for FRP Sandwich Systems

The adequate joining of the fibre composite skins and the core is one of the most difficult aspects to achieve in the manufacturing of sandwich composites (Lee et al., 2004). In fact, many of the failure modes of the FRP sandwich systems are closely related to the integrity of the adhesion between the face and the core. Thus, strict quality control is required during their production process to achieve a good adhesion. A description of the commonly used production methods in manufacturing sandwich composites are presented in this section.

- *Adhesive bonding*

Adhesive bonding is a conventional method of manufacturing FRP sandwich systems wherein composite faces are prepared and separately bonded to the core (Grunewald et al. 2015).

Adhesive layers are introduced between the faces and the core and the whole stack is subjected to pressure using weights or a hydraulic press. For high-performance applications, the pressure can be achieved using a vacuum bag and an autoclave. In this production method, it is normally necessary to prepare the surfaces to be bonded in order to achieve a good enough bond. While a time and labor intensive process, adhesive bonding is suitable for short production series of small to medium-sized sandwich components for civil infrastructures.

- *Wet lay-up*

Wet lay-up is one the most commonly used methods to manufacture sandwich components with composite faces (Zenkert 1995). During the wet lay-up process, the dry top and bottom fibres are impregnated with a resin and laid out on the core. The wet-layup may be performed either by hand lay-up or spray-up. Airborne volatile organic compounds (VOCs) content is very high during this type of open mould production, which may pose safety and health concerns, forcing workers to use appropriate protection gear. In case of vacuum assisted wet layup, the core is placed in between the top and bottom fiber composite skins whereupon the vacuum is applied to remove the excess resin. Rolling on top of the vacuum bags is common in order to minimise voids in the skins and to produce a better surface finish. This method is very flexible yet labor intensive and thus the method best suited for especially large and/or complex structures.

- *Vacuum assisted resin transfer moulding*

Vacuum assisted resin transfer moulding (VARTM) is a low cost manufacturing process that has been employed to manufacture large sandwich structures such as turbine blades, boats, rail cars and bridge decks since early 1980s (Mohamed et al. 2015). VARTM is capable of producing geometrically complex sandwich structures in relatively short time, without creating an unhealthy work environment since the process uses closed moulds. In this method, the dry fibers are placed in the mould together with the core. Moreover, not only cores, but also inserts and fasteners are easily integrated into the reinforcement of the core before impregnation. After the mould is closed, the resin is introduced into the mould to impregnate the reinforcement under vacuum. Sandwich composites manufactured through VARTM are characterized by good to excellent mechanical properties due to low void contents in the skins and consistent laminate quality.

- *Resin transfer moulding*

A two-sided mould is used for the Resin Transfer Moulding (RTM) (Barbero 1999). This manufacturing method is different from VARTM wherein a top and rigid mould is used instead of a flexible vacuum bag to form a vacuum-tight seal. Once the dry fibre composite skins and the core are preformed and placed in the mould, the mould is closed and the resin is injected into cavity. The two-sided mould permits the production of sandwich composites with good surface finish on both sides. While this method is suited for high production volumes, the necessity for top and bottom moulds prohibits its production to very large size sandwich panels.

- *Vacuum infusion*

The Vacuum Infusion (VI) process uses vacuum pressure to drive resin into a laminate (Zenkert 1995). In this manufacturing method, the dry fiber composite skins and the core materials are placed in a mould. A vacuum is then applied through a flexible cover or vacuum bag tightly sealed over the top of the mould. From that point, resin is infused using vacuum pressure. As the VI process starts with none and pushes resin in, any excess resin that is introduced will eventually be sucked out into the vacuum line. As a result, only the minimum amount of resin is introduced producing a sandwich structure with a low weight and high strength. This manufacturing method is well suited to large sandwich components in low to medium production volume.

- *Co-curing*

Co-curing is a production method wherein the composite faces and the core are simultaneously cured during the manufacturing (Lee et al. 2004). In this method, the dry fibres for the top and bottom skins are infused with resin at the same time. The bottom skin is then laid in a mould, the core is then placed, and finally the top skin. The assembled materials are then cured in one operation ensuring a good bond between the skins and the core. Most of the co-curing methods uses forming pressure and temperature in manufacturing and curing sandwich components. The expansion of the foam core with temperature increase helps increase pressure within the mould. Thus, the deformability and thermal expansion of the core especially the foam core material systems are critical as their properties are known to decreased significantly at high curing temperature.

Joining Techniques for FRP Sandwich Systems

In civil engineering applications, connections are inevitable due to limitations on shape size and the requirements of transportation and installation. For FRP sandwich systems, this requires the consideration of connections between sandwich composites themselves as well as joints between them and other structural components. Zhou and Keller (2005) reviewed the joining techniques for FRP bridge decks in component, panel and structure levels. They indicated that adhesive bonding has been widely used in component level connections as it is easier to design and provides higher strength values than the bolted connections. Similarly, splicing–bonding connections are well adapted for panel-to-panel connections. The splicing-bonding connections is a type of connection wherein splice plate is fixed into the grove in the top and bottom of the sandwich composites using an adhesive (Fig. 2a). Reising et al. (2004) reported that the individual panels in the bridge decks that they have installed and evaluated were interconnected using adhesively bonded tongue and groove systems, as it provides a more effective load transfer and failure resistant capability than mechanical fixing. All-adhesive connections (Fig.

2b) are also preferable for deck-to-support connections when the supports are wide and flat because their installation is simple and gives an even distribution of stresses in the joint (Zhou and Keller 2005). In adhesively-bonded connections, however, the quality during on-site installation and the fatigue and durability of the adhesive layer should be carefully ensured.

Recent studies presented other joining techniques for FRP sandwich systems. Dawood and Peirick (2013) published their development work on connections for FRP sandwich systems made of GFRP face skins and fiber reinforced foam core. They concluded that bonded connections are more suitable for sandwich systems with a low-density foam core to effectively utilise the high strength of FRP skins while bolted connection is more preferred for high-density foam cored sandwich systems to achieve a higher capacity joint. Garrido et al. (2015a) developed and investigated the behavior of a Z-shaped adhesive joint for connecting adjacent sandwich deck panels (Fig. 3a). This connection is integrated into the sandwich panels during production, and adhesively bonded on-site. These same authors also demonstrated the effectiveness of angular steel sections as node connectors for sandwich composites with stiff core materials such as balsa wood (Garrido et al. 2016). Manalo (2013) also presented a connection systems that is composed of exterior studs with a grove for the shear key to connect the adjacent prefabricated sandwich wall panels (Fig. 3b). The studs and the shear key are made up of glass fiber reinforced rigid polyurethane (PU) foam. The results of the in-plane shear test demonstrated that the rigid PU foam shear key provided a reliable attachment to connect two adjacent panels. While some joining techniques are available, this issue has received comparatively little research attention especially for FRP sandwich systems in load bearing structures.

Recent Developments in FRP Sandwich Systems

Several researchers have contributed to the research and development of FRP sandwich systems for structural purposes. These researchers have focused on enhancing core materials either through cellular manipulation (CM), corrugated face (CF), fiber reinforcement (FR), geometric arrangement (GA), introduction of an intermediate layer (IL) or hybrid (H) systems to manufacture sandwich composites with higher performance. Table 2 provides a summary of these developments as a companion to the detailed information presented in this section.

Cellular Manipulated Solid Core material

Marsh (2007) suggested that cellular manipulation could be used to produce a sandwich panel with a high-strength solid core. Accordingly, Van Erp and Rogers (2008) chemically modified the plant-based phenolic resin to produce a lightweight but high-strength core material. The solid phenolic core is consists of a proprietary lignin resin containing approximately 50% bio-content. It was purposely designed for high compressive and shear strength to carry the concentrated loads typical in bridges and other structural elements. It can be noted from Table 1 that the phenolic resin is twice as heavy as the heaviest PET or PUR foams. Extensive characterisation of the mechanical properties of this novel core material was conducted and reported by Manalo et al. (2013a). Investigation of the flexural (Manalo et al. 2010a) and shear behavior (Manalo et al. 2010b) of the FRP sandwich systems with this core material indicated that its strength and stiffness were suitable for civil engineering and construction. This FRP sandwich panel has been used in several building and residential projects in Australia and its use has already been explored for bridge infrastructure.

Corrugated Facing Sandwich Panels

Kampner and Grenestedt (2007) introduced sandwich composites with corrugated skin and foam core to improve shear capacity and reduce weight. The corrugated skin also increased the wrinkling strength of compression-loaded sandwich composites. As a result, the corrugated sandwich beams showed similar strength but weighed 10% to 20% less than their plain counterparts.

Fiber Reinforced Core Material Systems

Karlsson and Astrom (1997) suggested that reinforcing through thickness with fibers can potentially significantly improve the structural integrity of sandwich composites. Thus, Reis and Rizkalla (2008) developed a 3-D fiber reinforced composite sandwich panel (Fig. 4) which increased the shear modulus and through-the-thickness compressive strength of the foam core but caused a decrease in the tensile strength and stiffness of the skin due to the waviness created by the stitched fibers.

Geometrically Arranged Core Material

A number of developments have focused on enhancing the structural performance of FRP sandwich systems by geometrically modifying the arrangement of the core material. Grenestedt and Bekisli (2003) analysed the behavior of a sandwich core with a new arrangement of balsa blocks. This core consisted of an assembly of complex-shaped balsa blocks with the grains oriented 30^o to 60^o with respect to the longitudinal direction and was predicted to have a 70% higher average effective shear stiffness than that of end-grain balsa. Experimental verification by Bekisli and Grenestedt (2004) of the behavior of the new balsa core with a grain orientation of 45^o showed a 30% higher average effective shear modulus while evidencing similar shear strength to the end-grain balsa. Kepler (2011) provided a simpler concept for improving the shear stiffness of balsa elements in which small strips of balsa wood were glued together at alternating grain angles (see Fig. 5a). An approximately four-fold increase in the shear stiffness was achieved when the grains were oriented at 45^o compared to 90^o with the failure strength varying only moderately between the specimens.

Another approach to increasing performance in carrying applied loads is to modify the geometrical orientation of FRP sandwich panels (Fig. 5b). Due to limitation in thickness of the mass produced FRP sandwich systems with a phenolic core, Manalo et al. (2010c, 2013b) have extensively investigated the behavior of glue-laminated beams made by bonding the sandwich panels in the horizontal and vertical positions. They found that the beams laminated in the vertical position were found to possess 25% higher bending strength (Manalo et al. 2010c) and achieved over 200% higher shear strength (Manalo et al. 2013b) than in the horizontal position suggesting a more effective use of the composite material. The introduction of the vertical fiber composite skin inhibits the development of flexural and shear cracks in the core making the FRP sandwich systems exhibit ductile failure behavior, which is important from the civil engineering perspective.

Osei-Antwi et al. (2013; 2014a) optimised the load-bearing behavior of an FRP sandwich deck by introducing multilayer core materials involving balsa with different densities, i.e. structurally graded cores. In their concept, a high-density end-grain balsa was provided at the upper face of FRP sandwich systems to prevent indentation and wrinkling and to provide sufficient strength and stiffness in the deck's support region. Low-density balsa was used in the less-stressed zones to minimize overall weight. Intermediate arch-shaped FRP laminates (Fig. 6) were then provided between the core layers to further increase the stiffness and strength. The effectiveness of this core configuration was also assessed for FRP sandwich decks in bridge construction (Onsei-Antwi et al. 2014b). They found a maximum span of approximately 19 m long could be achieved with balsa-core sandwich-slab bridges with a deflection limit of span/500, if a carbon FRP arch was integrated into the balsa core.

Intermediate Layer

The performance of FRP sandwich systems may be improved for specific applications by introducing an intermediate layer between the top and bottom skins and the core material. Mamalis et al. (2008) produced sandwich beams with an intermediate plywood layer between the skin and the PVC foam core to improve the system's impact resistance (Fig. 7a). Fang et al. (2015) developed sandwich beams containing an intermediate bamboo layer between the GFRP skins and the wood core. In investigating the flexural behavior, they found that increasing the thickness of the bamboo and GFRP layers significantly increased the system's stiffness and ultimate load due to the good bonding of the intermediate bamboo layer to the GFRP skin and paulownia wood core.

Hybrid Core Systems

Hybrid core involves combining two or more different core materials to improve the structural performance of FRP sandwich systems. Using this approach, Keller et al. (2008) combined PU foam core of three different densities and strengths reinforced with orthogonal GFRP webs to increase the shear strength of an FRP sandwich roof. Fam and Sharaf (2010) explored the feasibility of fabricating and improving the performance of FRP sandwich systems with low-density PU foam cores by providing internal and/or exterior GFRP ribs in the longitudinal direction connecting the core and GFRP skins. They found that, depending on the rib configuration, the flexural strength and stiffness of the sandwich panel could be increased by 44% to 140% compared to panels without ribs. Sharaf and Fam (2012) further estimated that an increase in strength of up to 220% could be achieved if the ribs had an optimal spacing of 2.93 times the panel thickness, indicating the high potential of these sandwich composites for structural applications. More recently, Mohamed et al. (2015) manufactured sandwich panels made from PU foam core and E-glass fiber skins. Three types of sandwich panels with different stiffeners and stitching orientations shown in Fig. 7b, i.e. closed cell (Type 1), trapezoidal shape (Type 2), and web-core boxes (Type 3) were investigated. Their results showed that the sandwich panel with trapezoidal shape stiffeners represents a feasible design for full scale bridge decks.

Case Studies and Field Applications of Sandwich Composites in Civil Engineering

FRP sandwich systems have been effectively and economically applied for civil infrastructure demonstrating their light weight and efficient load-carrying capacity. This section presents case studies and several field applications of FRP sandwich composites.

Housing and Construction

FRP sandwich composites offer promising material properties suitable for housing and construction. A function-integrated GFRP sandwich roof structure for a main gate building (Fig. 8) was designed and built in Switzerland by Keller et al. (2008). The face sheets of this sandwich structure have thicknesses of 6 to 10.5 mm GFRP while the core is constructed using up to 600 mm thick PU foam of three different densities in which a system of crossing GFRP webs is inserted. The sandwich integrates structural, architectural and building physics functions (thermal insulation, waterproofing and sound insulation). The prefabrication of large and lightweight panels enabled easy transportation and rapid installation. Keller et al. (2010) have furthermore proven the feasibility of encapsulating photovoltaic cells into almost transparent GFRP skins, thus also providing energy supply functions.

The GFRP sandwich systems with ribs (Fig. 9) developed by Fam and Sharaf (2010) were found to be applicable not only for thermal insulation but also as a structural cladding for buildings. Their experimental investigation using large-scale sandwich panels (9.145 m high, 2.440 m wide, and 78 mm thick) under transverse loading showed that the sandwich composites failed at 7.5 kPa or 2.6 times the factored design pressure for the windiest region in Canada (Sharaf and Fam 2011). Furthermore, the deflection under the design wind pressure did not exceed span/360.

Bridge and Pedestrian Decks

The inherent advantages in strength and stiffness per unit weight as compared to traditional steel-reinforced concrete decks make FRP sandwich decks a good alternative. As a result, several variants of sandwich bridge decks, spanning transversely or longitudinally between supporting elements (such as concrete, steel and timber beams) have been developed.

Keller et al. (2007) presented a new concept for a lightweight hybrid-FRP deck. This deck had GFRP for the tensile skin, lightweight concrete for the core, and a thin layer of ultra-high performance reinforced concrete for the compressive skin. Similarly, SAMPE (2010) reported the first use of balsa cored FRP sandwich bridge deck (Fig. 10a) in Louisiana, USA. In developing this bridge deck, high tensile strength steel reinforcement was combined with bi-axial GFRP skins to achieve the required flexural stiffness. The core was then made up of end-grain balsa wood with embedded fiber-optic strain gauges to monitor the long-term performance of the deck. Composite Advantage LLC installed its FiberSPAN™ FRP bridge deck on a new three-span steel superstructure at Wolf Trap National Park for the Performing Arts in Virginia (United States). The deck was a moulded sandwich construction consisting of thick GFRP top and bottom skins and a foam core with fiberglass shear webs in which the fibers were oriented at ±45° angles (Reeve, 2013).

FRP sandwich decking also provides the opportunity to upgrade a bridge's load carrying capacity. An FRP sandwich composites deck was used to replace the deteriorated concrete slab on a bridge over Bennet's Creek in Steuben County, New York (Aref et al. 2005). Keller et al. (2014) developed and installed the first GFRP-balsa sandwich bridge deck in Switzerland, across the Avançon River in Bex. The new lightweight two-lane bridge replaced a one-lane concrete bridge without increasing the total load on the stone abutments. The sandwich deck was composed of three panels of 22-mm-thick GFRP face sheets and a 241-mm-thick balsa-wood core, see Fig. 10b, manufactured with the vacuum infusion process. The balsa-wood fibers in the core were oriented perpendicular to the face sheets to provide the required resistance against indentation and shear. The panel-to-panel and deck-to-girder connections were manufactured on site through an adhesive infusion process.

Bridge Beams

The development of structural beams from FRP sandwich systems is gaining interest. Canning et al. (1999) proposed a hybrid box section for beam application. The web of the beam is made up of sandwich construction to prevent buckling with an upper layer of concrete in the compression side. A similar structural concept was used by Primi et al. (2009) to build a new

FRP bridge in Spain wherein the beam's webs consisted of sandwich panels with polyurethane core and glass-fiber skins produced by hand lay-up process. Likewise, the girders of the Asturias Bridge in Spain have a trapezoidal cross-section and built by wrapping carbon fiber prepreg around a stay in place polyurethane mould, thereby producing FRP sandwich bridge systems (Hurtado et al., 2012). Each girder had been split in two trunks and was successfully joined at the site using adhesive bonding.

Bridge beams made of FRP sandwich panels were developed in Australia for the replacement of deteriorating timber girders (Van Erp and McKay, 2012). These beams incorporated the sandwich panels oriented in the vertical position to provide the general shape, shear strength and structural core of the girder, while the hybrid modules consisting of steel reinforcing bars cast in pultruded FRP tubes provided additional flexural strength and stiffness (Fig. 11). Furthermore, a solid glue-laminated sandwich panel was used mainly in the ends of this beam for the drilling and installation of the fixing rods and to resist the high compressive/crushing force at this location.

Floating and Protective Structures

The low weight, high-strength, and corrosion resistance of FRP sandwich systems make them suitable for the development of floating and impact resistant structures. In China, floating and energy absorptive elements made of FRP sandwich systems were developed for a collision-avoidance structure. The outer shell of the sandwich structure is a thin GFRP skin while the inside is a fiber-reinforced foam core (Liu at el. 2013). Theoretical investigation and full-scale testing showed that the anti-collision structure around a bridge shown in Fig. 12a could reduce the ship impact force by 40% (from 19.95MN to 13.16MN). There were more than 50 completed design projects, such as Fuzhou Wulong river bridge, Changzhou Xinmengge bridge, Guangzhou-Shenzhen high-speed way along the Yangtze river bridge (Shenzhen section), which used this structure. The concept of a floating collision-avoidance structure is similar to the collision-protection/scarifying I-Lam system for concrete bridge girders shown in Fig. 12b developed by Qiao et al. (2008). This system uses sandwich composites with a crushable core. The system has smart sensors and actuators for remote sensing, triggering and monitoring. Numerical simulations and full-scale impact tests on reinforced concrete beams showed that about 60 to 70% of the kinetic energy was absorbed by crushing of the aluminium core in the I-Lam system. 20 I-Lam panels were installed on the sides of a slab concrete bridge (DEL-23-12.99) in Delaware, Ohio in 2006.

Railway Sleepers

A number of railway sleeper technologies have been developed using glued FRP sandwich panels and combinations with other materials (Manalo and Aravinthan 2012a; Van Erp and McKay 2013). These technologies are suitable for replacing and maintaining deteriorating timber sleepers, including existing timber lines, turnouts, and transoms. One significant advantage of FRP sandwich systems as railway sleepers is that they can be engineered to have similar flexural stiffness to structural timber and to deform at the same magnitude as the existing railway sleepers, which is very important in the sleeper maintenance works.

The timber-replacement sleeper made of glued FRP sandwich panels in the edgewise position with top and bottom glass fiber reinforced polymer (GFRP) plates and coated with epoxy-based polymer (Fig. 13a) was specifically designed to conform to the loading conditions for mainline applications in which the sleeper is only loaded in two distinct locations (at the rails) and does not need the same strength along its length. These sleepers can be drilled on site similar to timber sleepers. Fifty units of this new sleeper have been installed in 2014 and are in service on the standard railway line on the Queensland Rail Line (Australia). Sleeper technologies with glue-laminated FRP sandwich panels as the main structural component were also developed for railway turnouts and transoms. These sleepers have a prismatic rectangular shape (Fig. 13b) and are reinforced with 2 layers of GFRP laminates at the bottom to enhance flexural strength and stiffness. The composite transom sleepers are FRP sandwich panels combined with steel reinforcement bars similar to the bridge beam concept in Fig. 11 to make the sleepers exhibit ductile behavior when overloaded. This creates a very reliable structural element that gives ample warning of failure. Australian Rail Track Corporation (ARTC) installed twenty-two of these transoms in November 2007 on a railway bridge in the Hunter Valley, Australia (Prasad, 2008). To date, the sleepers have been subjected to approximately 80 million load cycles and have been performing extremely well. They were recently approved for general use on the ARTC rail network.

Challenges and Opportunities

While sandwich systems have emerged as a suitable solution in civil infrastructure, barriers still need to be overcome for their continued acceptance and growing use. This section discusses the emerging issues of FRP sandwich systems and presents future developments and opportunities to accelerate their application in civil engineering and construction.

Core Material Development

Belouttar et al. (2009) highlighted that the failure modes of the FRP sandwich systems depend largely on the nature of the core material. As presented in Table 1, the commonly used foam cores have low strength and modulus in shear and compression. As a result, many researchers have dedicated significant efforts to develop and/or modify core material to produce sandwich systems with higher performances (see Table 2). The localised strengthening and the introduction of fibers to improve the properties of foam core involve a complex process such as weaving or injection technology, which may further increase the production cost. It also increases the amount of resin pickup during moulding, which adds to the panel’s weight. Similarly, the intermediate layer increases the amount of material used, which increases cost. Furthermore, the increased stiffness in using a complex core structure is obtained at added machining cost, and wasted materials. This approach also produces a core that is not geometrically perfect, creating mismatches between blocks (Kepler, 2011). These important aspects have to be addressed in developing new core materials in order to advance the use of FRP sandwich systems in civil engineering applications.

The priority should be focusing on exploiting the potential of the core material for the demanding requirements in civil infrastructure. Moreover, improving some aspects of the properties in developing or modifying core material should not compromise the competitive advantages of FRP sandwich systems. Attention should be paid to optimising core material characteristics for stronger, lighter, more competitive, and more effective FRP sandwich systems. For example, the effective use of existing core materials can be achieved by strategically placing the high-strength core in locations where stress levels are high and low-strength core in areas where stress levels are low. Similarly, different core material systems can be combined together to achieve the desired stiffness and strength characteristics. Better performing sandwich composites can be achieved even using simple concept and manufacturing method but with some manipulation of the existing core material systems. From the recently developed core material systems, the solution with the most promise seems to be the use of FRP ribs/webs (hybrid cores) – it is cost effective and allows using cheaper and lower strength core materials that are already available. These methods of core improvement can result in FRP sandwich systems with higher structural performance while maintaining the simplicity of the production process.

Effective Joining Systems for FRP Sandwich Composites

The design and manufacture of reliable joining systems is recognized by many researchers as the major challenge in the development of FRP composite structures. This problem also exists for FRP sandwich systems. Garrido et al. (2015a) highlighted that a significant part of the current sandwich panel connection technology has been developed for non-structural or secondary structural sandwich panels. While tongue and groove combined with adhesive bonding is proven effective as panel-to-panel connection for pultruded FRP decks, Reising et al. (2004) indicated that this can be an issue for FRP sandwich systems manufactured by VARTM and hand lay-up process due to higher dimension tolerances. Moreover, this joining technique may not be suitable for FRP sandwich systems with soft flexible foam cores and with low shear properties as the adhesive needs to be applied to the contact surfaces between the joints. Similarly, when joining adjacent sandwich panels with different core materials, Osei-Antwi (2014c) highlighted the importance of appropriately joining core materials of different properties to minimize material discontinuities and stress concentrations. For these applications, node connections between sandwich panels are necessary. Similarly, FRP sandwich systems with foam and balsa wood cores cannot directly support mechanical joints such as bolts and rivets due to their low strength if they are to be connected to bridge girders or other systems. In these cases, insert materials such as metal, stiffer foam core, wood patches or polymeric materials can used for local reinforcement (Zenkert 1995) to adequately transfer the load to the FRP skins. Currently, only a few published works focus on inserts and primarily on FRP sandwich systems in automobile and aerospace structures (Bozhevolnaya and Lyckegaard 2005). Likewise, the corner joints in lightweight honeycomb sandwich structures for aerospace design presented by Heimbs and Pein (2009) can be adopted in panel-to-panel connections for FRP sandwich systems used in structural walls. Clearly, the development of reliable joining systems for FRP sandwich in civil engineering is important as they are subjected to high load levels and their behavior should be determined to ensure the integrity of the entire structure. Research activities in this area should be conducted to verify the efficiency of shear transfer and constructability of inserts in FRP sandwich systems for civil infrastructure. Moreover, investigation on the global behavior of sandwich composites with node connections made of FRP sections shown in Fig. 14 should be assessed to determine reliable connection systems between adjacent sandwich panels and at the corners. These connection techniques should be adaptable for curved/free-form FRP sandwich panels for roof and facades, with varying skin thickness and skew angles for bridge decks.

Acoustic and Thermal Insulation Properties

FRP sandwich systems are widely employed for sound absorption in various structural applications including aircraft, spacecraft, automotive, and wind-turbine blades. When used in building and construction, the sound and thermal insulation of sandwich composites are also desirable (Patinha et al. 2015). However, information on the sound propagation of FRP sandwich systems for civil engineering and construction are limited even though these materials are already dominating in the commercial market (Zhu et al. 2014). This is because of the natural difficulty in measuring this property both experimentally and numerically.

Patinha et al. (2015) indicated that FRP sandwich systems have superior noise reduction capacity and have clear advantage over conventional panels and plasterboard materials of the same weight due to their increased thickness. Zhu et al. (2014) identified the materials of the core and skin, and the density, thickness and topology of the core as important design parameters that determine the sound transmission loss in sandwich composites. While there is an increasing attention on this topic, D'Alessandro et al. (2013) highlighted that the core configuration is the most investigated parameter because it highly influences the acoustic behavior. These authors further mentioned that the sound absorption coefficient of sandwich composites increase as the density of the core material becomes higher. Similarly, the thickness and the density of the core play a major role in the thermal insulation properties of FRP sandwich systems. Kawasaki and Kawai (2006) indicated that insulation materials must be of sufficient thickness and low density to provide high thermal resistance. These researchers found that moderate (340 kg/m^3) to high density (410 kg/m^3) fiberboard core materials have high warmth-keeping properties. The thermal conductivity of these sandwich panels are only 0.070 and 0.077 W/m°K, respectively, which are suitable for building construction. Moreover, the

Federation of European Rigid Polyurethane Foam Associations (2006) reported that PU foam is one of the most efficient, high performance thermal insulation materials. This material has a thermal conductivity of around 0.023 W/m°K. In fact, they suggested the use of sandwich panels with PU foam in buildings can cut average energy consumption by more than 50%. Moreover, the results of their 15-year tests showed very minimal decrease in the thermal insulation properties of PU foam.

Sound transmission and heat insulation may not be a significant issue for FRP sandwich systems used in civil infrastructure as in this application, high density and thick core materials are normally utilised for high load-bearing capacity. However, the lightweight of FRP sandwich systems with low density foam core is a drawback as it results in poor acoustic performances and may have negative effects on physiological and psychological health of building occupants. This is also a concern for resin rich FRP sandwich systems as the sound absorption behavior of the resin systems is low. As large variety of FRP sandwich systems arising from different materials and geometrical combinations becomes available, the acoustic properties cannot be neglected when designing them for use in housing and building construction. Similarly, comprehensive evaluation of the thermal properties of the current variety of core materials should be conducted to open up a broad field of applications for FRP sandwich systems.

Time Dependent Behavior

FRP sandwich systems in civil infrastructure will support significant permanent loads as well as will subject to repetitive loads. However, the creep performance and fatigue behavior of FRP sandwich systems for civil infrastructure has received limited attention to date.

Barbosa (2014) indicated that the structural form of sandwich composites makes them susceptible to creep. The primarily reason for this is the nonlinear viscoelastic behavior of polymeric foams especially at higher levels of load. They suggested that PET sandwich panels will exhibit lower creep deformation than PU sandwich panel due to their lower viscoelastic properties. Jeon et al. (2014) found that sandwich beams with foam core and GFRP skins, wherein the fibers are oriented mostly in the longitudinal (0°) direction experience lesser creep deformation than sandwich beams with skins oriented in 45° and 90° due to the dominating response of polymeric constituents. Similarly, Garrido et al. (2013) noted a 65% increase in the deflection due to creep of the sandwich beam with PU core and GFRP skins after 5 months under an applied load of 5.2 kPa (or a load level inducing 20% of the core shear strength). Moreover, they highlighted the importance of considering the shear deformation in the creep behavior of sandwich composites as it contributes up to 70% of the total deformation. Thus, understanding the response of sandwich structures for a prolonged loading in time is critical as the design of FRP for civil infrastructure is normally governed by serviceability rather than strength. Moreover, simple models to account for the long-term effect of creep in the deformation of FRP sandwich systems are needed.

Fatigue is a critical design concern in response to repetitive loads (Osgood 1982), but only a few studies have investigated the behavior of FRP sandwich systems under fatigue. Dawood et al. (2010) found that sandwich composites with stiffer cores under fatigue loading generally evidenced greater degradation than those with lighter cores due to the higher induced shear stresses at the same level of applied shear strain. Mathieson and Fam (2014a) indicated that the fatigue life of sandwich composites with GFRP skins and a polyurethane foam core was significantly short under full unloading and fully reversed loading. This also occurred with the addition of internal ribs (Mathieson and Fam 2015a). Moreover, a reduction of up to 25% in flexural stiffness of the sandwich composites was observed when 45% of the failure load was applied for 2M cycles of fatigue loading (Mathieson and Fam 2014b). Consequently, the authors recommended that the maximum applied load should not exceed 35% and 21% of the ultimate static strength for FRP sandwich systems with ribs (Mathieson and Fam 2015a), and 30% and 45% for those without ribs (Mathieson and Fam 2014a, Mathieson and Fam 2014b) under full unloading and under fully reversed loading, respectively, in order to achieve a fatigue life of 2M cycles. The fatigue tests on full-scale GFRP-balsa beams, including an adhesive lap joint at mid-span, for the Avançon bridge under a quasi-static load varied between 21 kN and 118 kN, which are 10% and 60% of the failure load, respectively (Keller et al., 2014) returned reassuring results by showing no signs of damage during 5 million cycles. This corresponds to the bridge's 100-year service life. These results highlight the importance of understanding the property retention and failure behavior performance of emerging FRP sandwich systems under fatigue loading for simulating and designing structures subjected to moving loads, wind pressure and suction, and hydraulic forces.

Durability

Primary load-bearing FRP sandwich systems are a relatively new technology in civil engineering applications. As a result, their performance history is relatively short compared to more conventional construction systems utilising hardwood, concrete or steel. Hollaway (2010) identified elevated temperature, fire resistance, ultraviolet-light, and ingress of alkalis or other liquid as some of the most important in-service properties that should be considered when using FRP composite materials in civil engineering applications. A number of researchers showed that glass, carbon and basalt fibers perform reasonably well in harsh environmental conditions (Benmokrane et al. 2015). Most studies conducted to investigate the durability performance of FRP sandwich systems have been, however, related to aerospace and naval applications. Li et al. (2014) confirmed that the incidence of face yield in sandwich composites increased as did the temperature. Similarly, moisture uptake in moist environments affects the mechanical behavior of sandwich composites. Foam shrinks at high temperature, while face sheets delaminate from the inner core as a result of moisture uptake (John et al. 2011). Yin et al. (2015) also observed a considerable decrease in modulus with an up to 45% decrease in flexural strength for polymethacrylimide (PMI) foam-core sandwich composites immersed in seawater at 70ºC. In probably one of the first attempts at using bio-fibers in sandwich composites for structural applications, Mak et al. (2015b) found that the tensile strength retention of flax-FRP skins after 300 days of exposure in saltwater was 81%. Based on the Arrhenius model, it was estimated that these skins would retain 60% of their tensile strength after 100 years at an annual mean temperature of 10ºC. In a case involving actual field conditions, Reising et al. (2004) found delamination of the top skin of a FRP sandwich bridge deck exposed to direct sunlight and harsh winter conditions as a result of the small, relatively fragile connection between the face and honeycomb core.

As in most civil engineering applications, FRP sandwich systems are likely to be subjected to fire and elevated temperature. Bai et al. (2014) strongly recommended that the structural adequacy and integrity shall be satisfied in order to successfully implement FRP composites in structures subjected to relatively high in-service temperature. It is well known that under high temperature, FRP composites may undergo a decrease in stiffness and strength as the resin/matrix binding the fibers will soften resulting in functionality loss of the structure (Mouritz and Gibson 2007). Specifically, FRP composites undergo significant changes at a temperature higher than the glass transition temperature, T_g. Van Erp (2008) reported that depending on the cure schedule, the T_g of the matrix is between 60°C and 110°C for epoxy; 60 and 120ºC for vinylester; and 85 and 125ºC for polyester. Significant degradation of most polymeric foam core's properties occurs at much lower temperature than the T_g of fiber composites which can result in loss of stiffness and strength of FRP sandwich systems even at a temperature within the in-service condition. Taher et al. (2013) reported a 50% decrease in the compressive strength and modulus of PVC foam when exposed to 85ºC. Moreover, Garrido et al. (2015b) found a considerable reduction in shear modulus in PET and PU foams used in FRP sandwich systems. At 80ºC, the PET foam with density of 94 kg/m^3 and PU foam with density of 68 kg/m^3 only retained 24% and 66%, respectively of their shear moduli from ambient temperature. Adding to this issue, Taher et al. (2013) highlighted that there exist limited and incomplete information about the temperature dependence of the core properties for FRP sandwich composites.

The information from the above studies can be used as a preliminary indication of the durability performance of sandwich systems when used in civil infrastructure. Nevertheless, the performance of FRP sandwich systems under the actual and simulated conditions that are expected for such types of structures should be continuously investigated to ensure that these systems perform satisfactory during their service lives. There is also a great need to ascertain the thermal degradation behavior of the existing and emerging FRP sandwich systems when subjected to combined thermal and structural loads if they are to be used in load-bearing applications. A detailed understanding of how these factors affect the long-term durability of FRP sandwich systems is very important, since it will provide the guidance for their effective design and use in developing sustainable infrastructure. These issues are being addressed and the current pace of development means that solutions are rapidly being found and there is no doubt that sandwich composites will be suitable systems for lightweight civil infrastructure.

Design Oriented Analysis

Bakis et al. (2002) pointed out that without an established design method and data, it is unlikely that FRP-based materials will be used as a construction material beyond the scope of research and demonstration projects. While the Queensland Government (2009) has made an effort to promote composite materials in various industry sectors by providing an introductory guide, the application of sandwich composites in construction has been limited. Currently, there are no Australian Standards and provisions in the Building Code Australia on the strength and performance requirements for FRP sandwich systems. In contrast to this, designers and builders in Europe have started to use sandwich composite panels in structural systems, due to the availability of design guidelines. An example is the document 'European Recommendation for

Sandwich Panels, Part I: Design' (Davies, 2000) which has been developed for the design of sandwich composites with metal faces and various types of foam core. Thus, Manalo and Aravinthan (2010b; 2012b) proposed simplified analysis methods to describe the approximate flexural and shear behavior of FRP sandwich systems consisting of GFRP skins and a phenolic core. Similarly, Fam and Sharaf (2010) and Mathieson and Fam (2015b) invested significant efforts in developing simplified analytical tools for sandwich composites with GRFP skins and polyurethane cores. In their proposed model for sandwich composites under in-plane bending, a stiffness-based approach incorporating both flexural and shear rigidities of the core was adopted to establish the load-deflection response while skin wrinkling criterion was used to establish ultimate load. The flexural and shear stiffness of the soft core were also considered in calculating the critical buckling load under axial load for sandwich composites with various slenderness ratios and cross-sectional configurations (Mathieson and Fam 2015c). The comparison and validation of the simplified analytical models showed good agreement with experimental results.

The simplified methods described above have been suggested as very useful for scientific research and engineering calculations. Moreover, they are straightforward and easy for designers and engineers to use, but with the capability of reasonably predicting the structural performance of sandwich composites. The suitability of simplified design approaches should therefore be validated for sandwich composites with other core material systems and geometries before these methodologies can be adopted/and or modified for the general design of FRP sandwich systems. Moreover, these simplified approaches can be used to develop failure-mechanism maps as proposed by Gibson and Ashby (1988) by calculating the active collapse mode based on a given geometry and material systems combination. Several researchers (Steeves and Fleck 2004; Gdoutus and Daniel 2008; Kazemahvazi et al. 2009) have used this approach and developed collapse mechanism maps for sandwich composites with different material systems. These maps allow appropriate design criteria to be developed as a function of the design variables critical for sandwich composites, such as loading conditions, face and core dimensions, overall sandwich dimensions, and the skin and core properties, which can be used handy by designers and engineers. However, unique design challenges specific to FRP sandwich systems including significant shear deformations and the evolution of new characteristic modes of failure should not be neglected in the development of simplified design and analysis tools. In many cases, the failure of a sandwich structure involves delaminations, debonding, and disintegration of the layered panel. Another group of failure modes is governed by geometrical nonlinearity, evolution of instabilities, and wrinkling or buckling of the compressed face sheet followed by global failure of the panel. A third group of failure modes is involved with cracking of the core. In all cases, those modes of failure are typically brittle, sudden, and abrupt and they are significantly different than the classical ductile modes of failure attributed to steel or well detailed reinforced concrete structures. The formation of such characteristic and, in many cases, undesirable modes of failure have to be reflected by design procedures and partial safety factors. Moreover, the environmental degradation, fatigue loading, temperature effect, and the level of maintenance and inspection of in-service structures should be accounted in developing design methods and analytical procedures.

Systems Proof and Performance Evaluation

More typical infrastructure prototypes need to be built to demonstrate practical applications, increase acceptance, and build a market volume of new and emerging FRP sandwich systems. Reising et al. (2004) highlighted the importance of demonstration projects in gaining a better understanding of particular installation issues, connection details, and construction techniques as well as of the long-term performance of composite structures. Moreover, Keller et al. (2008) indicated that the safety factors could be adapted or reduced during the different design stages, from the preliminary to the project execution, based on the results of small-scale materials testing. This approach would be very helpful in achieving a more widespread use of FRP sandwich systems, as the tendency in the industry is to design to suit particular applications, often relying on past experience and guidance from the results of the comprehensive design, experimental programs, and field performances. For new and emerging FRP sandwich systems, the confirmation testing of assemblies' representative of the actual structure would also be an important step in ensuring their compliance with existing design requirements and specifications. Keller et al. (2008) and Keller et al. (2014) have satisfactorily shown that experimental validation of the concept and design in compliance with existing codes for FRP will result in the successful implementation of infrastructure projects, even given the lack of design standards for sandwich composites. Furthermore, load testing and long-term monitoring will help ensure the satisfactory in-service performance of sandwich composites, verify all design assumptions, improve detailing and field installation techniques, and help optimize the product in future applications. This would also help to physically demonstrate to asset owner and other interested parties the effectiveness and suitability of FRP sandwich systems in carrying the design load and complying with the deflection requirements. Inspection programs covering such aspects as dimension tolerances, presence and extent of defects/delaminations, curing of the installed system, adhesion, plate thickness, fiber alignment, and material properties should be put into place. The information that will be obtained from performance evaluation testing would be also helpful in developing design specifications. The availability of these documents will give professional engineers and contractors more confidence in designing and field implementing FRP sandwich systems in civil engineering and construction.

Conclusions

FRP sandwich composites provide an effective alternative in lightweight civil infrastructure when the need for corrosion resistance, high strength, reduced weight, thermal insulation, or fast installation is a driver for the system. Their flexibility in design allows innovative structural developments from these composite systems to suit various structural applications. Based on a comprehensive state-of-the-art review, the following conclusions have been drawn with the aim of expanding the application of FRP sandwich systems in civil infrastructure:

- The structural behavior of FRP sandwich systems results from the combination of their parts. FRP materials have emerged as excellent alternatives to metallic skins for sandwich composites in structural engineering applications. The key to the system's success is the core stiffness and arrangement.
- The evolution of FRP sandwich systems with enhanced core material provides an opportunity to expand the application of these systems in civil infrastructure. Cellular manipulation, fiber reinforcement, modification of the core geometry, introduction of an intermediate layer between the skin and the core, and hybrid core materials were found to be effective methods in improving the core structure and enhancing the structural performance of FRP sandwich systems.
- FRP sandwich systems have been successfully used for or have a strong potential to be applied in multi-functional roofs, cladding and roofing systems for buildings, footbridges and bridge decks, railway sleepers, bridge beams, and floating and protective structures. These innovative applications exploit the many advantages of FRP sandwich systems and can provide the construction industry with more durable and cost-effective infrastructure.
- Reliable and adaptable joining techniques for connecting FRP sandwich component, panel and structure are important to ensure the integrity of the entire structure. The connection method should provide a high-strength and durable joint that is easy to install and maintain.
- Performance testing of FRP sandwich systems under actual and simulated conditions should be continuously carried out to ensure that they will satisfactory perform during

their service lives. Understanding acoustic, creep, fatigue, thermal and degradation performance of existing and emerging FRP systems especially those consisting of bio-based materials is critical if they are to be used in load-bearing applications.

- Design procedures which account for environmental degradation, creep, fatigue loading, temperature effect, and the level of maintenance and inspection of in-service structures will help gain wider acceptance of FRP sandwich systems in various engineering applications. Unique design challenges specific to these systems include the significant shear deformations that should not be neglected as in conventional structures, and the brittle mode of failure. Moreover, systems proof and performance evaluation will ensure satisfactory in-service performance of FRP sandwich systems, improve detailing and field installation techniques, connection details, and help optimize these systems in other civil engineering applications.

Such an approach could expedite the implementation of FRP sandwich structures in new design and construction of lightweight civil infrastructure through a more functional and economical design.

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Table Click here to download Table CCENG-1709R1_Tables.docx

List of Tables

Table 1. Properties of balsa wood and foam core material systems

Core Material	**Density, kg/m^3**	**Shear Strength, MPa**	**Shear Modulus, MPa**	**Compressive Strength, MPa**
End-grain balsa wood	96 - 250	1.85 - 4.94	108 - 312	6.5 - 26.6
PU foam	21 - 400	0.15 - 3.1	1.55 - 104	0.2 - 0.35
PVC foam	30 - 400	0.35 - 4.5	8.3 - 108	0.3 - 5.8
PET foam	70 - 200	0.5 - 1.8	13 - 50	0.75 – 3.6
Phenolic foam	855	8.8	530	21.3

Table 2. Recently developed sandwich composites

Category	Existing Core	Modification	Enhanced Properties	Manufacturing method	Researchers
CM	Phenolic foam	Chemically modified	Shear, tension, and compression	Co-curing	Van Erp and Rogers (2008); Manalo et al. (2013a)
CS	PVC foam	Corrugated skin	Shear	Wet lay-up	Kampner and Grenestedt (2007)
FR	Foam	3-D fibre stitch	Shear and compression	VARTM	Reis and Rizkalla (2008)
GA	Balsa wood	Complex shape	Shear	Wet lay-up	Grenestedt and Bekisli (2003); Bekisli and Grenestedt (2004)
	Balsa wood	Alternate grain angles	Shear	Wet lay-up	Kepler (2011)
	Phenolic core	Sandwich orientation	Shear and flexure	Adhesive bonding	Manalo et al. (2010); Manalo et al. (2010b); Manalo et al. (2010c)
	Balsa wood	Multi-layer and mixed densities	Shear	VARTM	Osei-Antwi et al. (2013); Osei-Antwi et al. (2014a)
IL	PVC foam	Intermediate plywood layer	Impact	Adhesive bonding	Mamalis et al. (2008)
	Paulownia wood	Intermediate bamboo layer	Bond strength	VARTM	Fang et al. (2015)
H	PU foam	Mixed densities with orthogonal GFRP webs	Shear	VARTM	Keller et al. (2008)
	PU foam	Internal ribs	Flexure	VARTM	Fam and Sharaf (2010)
	PU foam	Stiffened core	Shear	VARTM	Mohamed et al. (2015)

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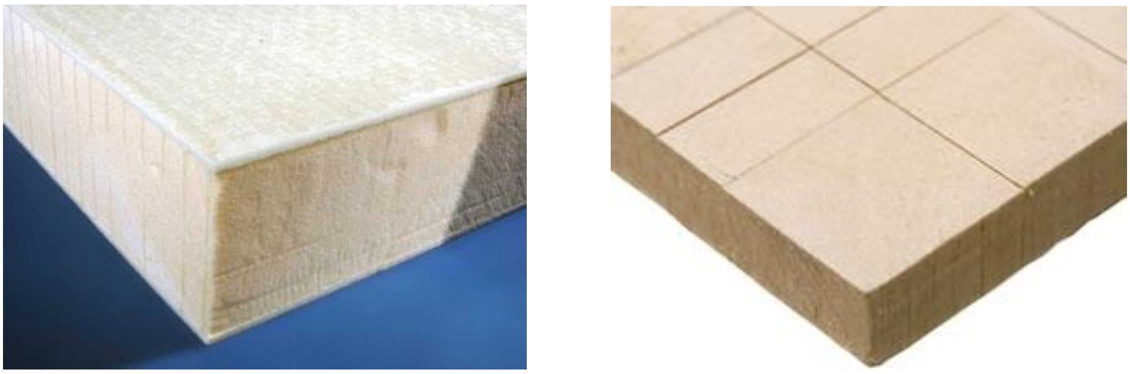
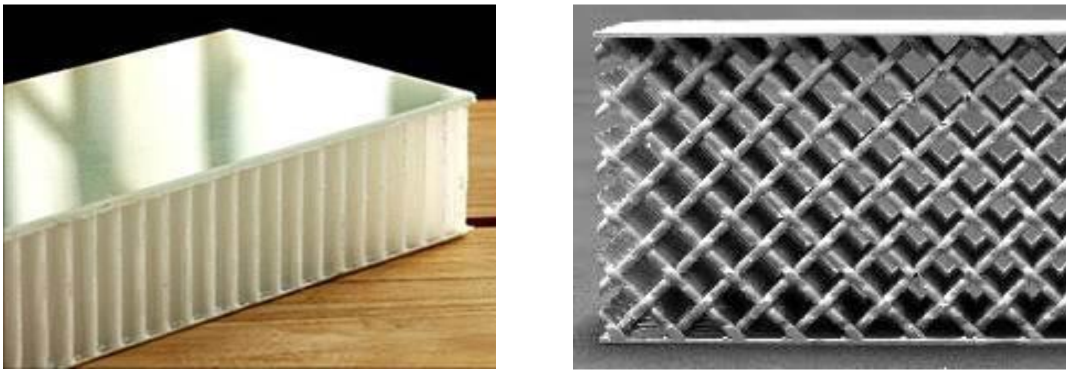


(a) Foam core (b) Balsa wood



(c) Honeycomb core (d) Trussed core

Fig. 1. Commonly used core material systems

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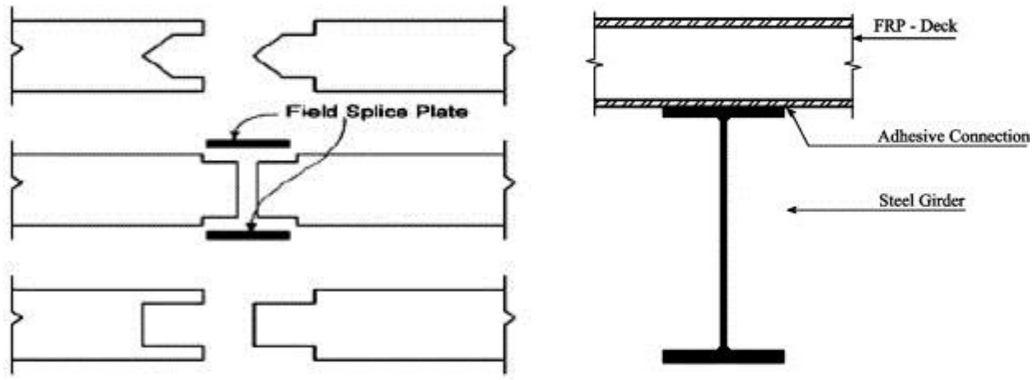

(a) Panel-to-panel (b) Deck-to-girder

Fig. 2. Joining techniques for FRP decks (Zhou and Keller 2005)

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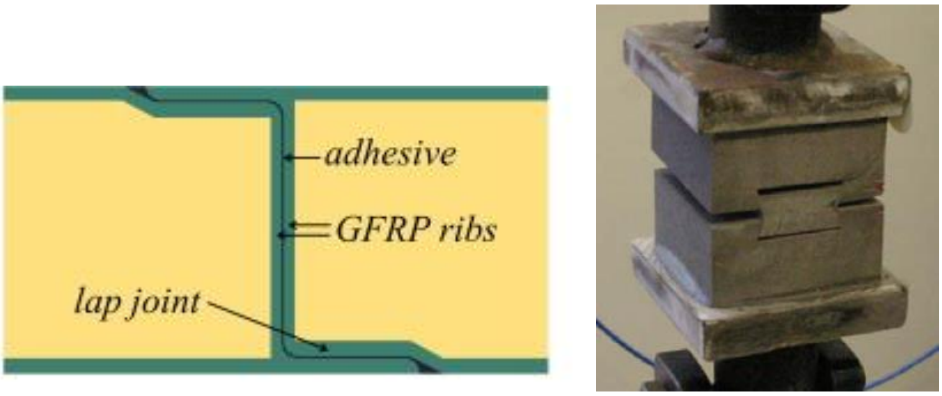

(a) Z-shaped adhesive joint (Garrido et al. 2015)   (b) Shear key (Manalo 2013)

Fig. 3. Joining systems for adjacent sandwich panels

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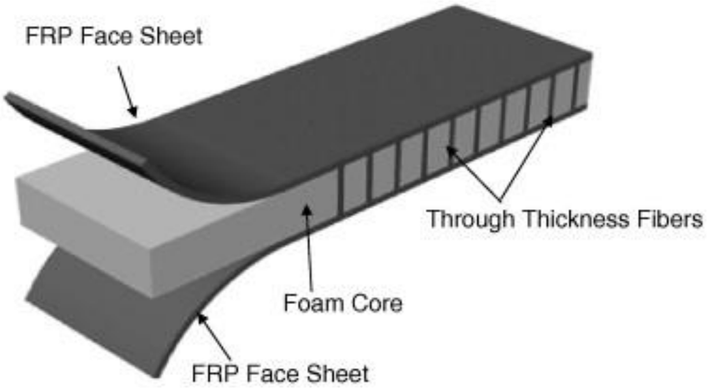

Fig. 4. Fiber reinforced core material systems (Reis and Rizkalla, 2008)

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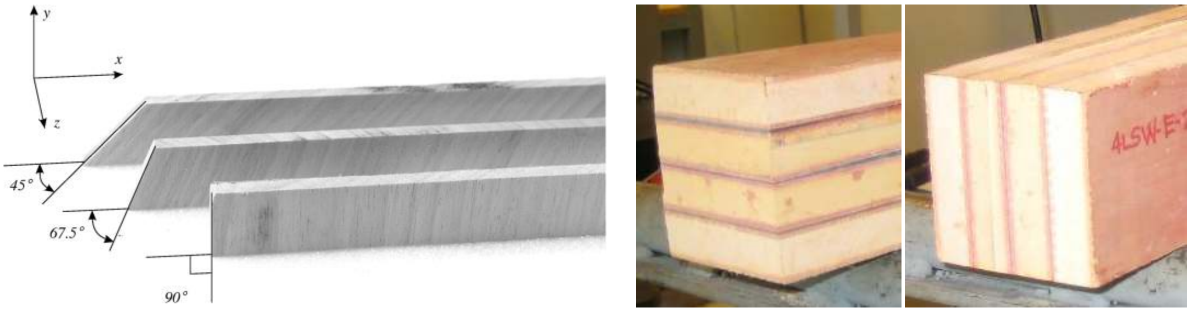

(a) Alternating grain angles (Kepler 2011) (b) Glued sandwiches (Manalo et al. 2010c)

Fig. 5. Geometrically arranged core material

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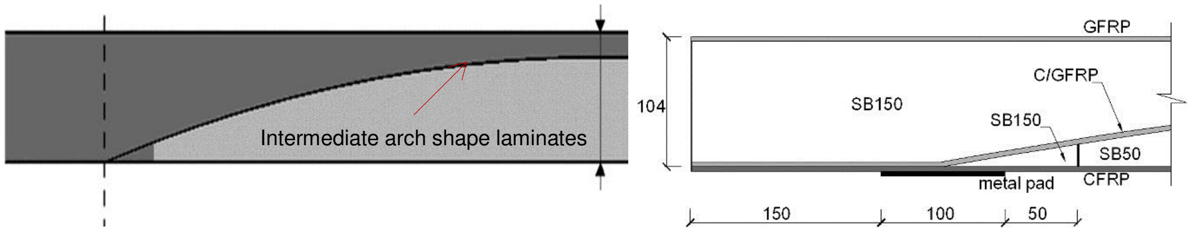

Fig. 6. Sandwich beam with intermediate arch-shaped FRP laminates (Osei-Antwi et al. 2013)

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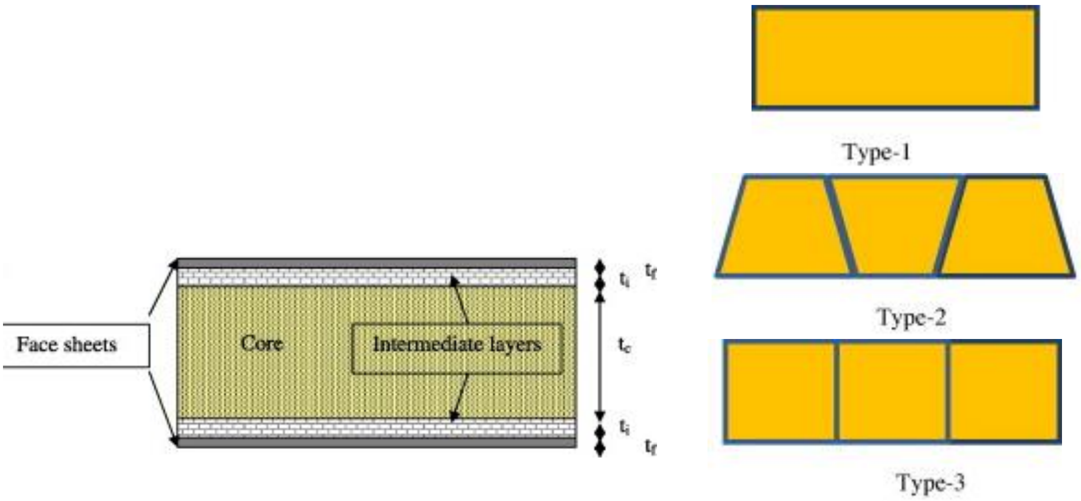

(a) Intermediate layers (Mamalis et al. 2008)   (b) Core stiffeners (Mohamed et al. 2015)

Fig. 7. FRP sandwich system with intermediate layers and hybrid core systems

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Fig. 8. Lightweight GFRP sandwich roof (Keller et al., 2008)

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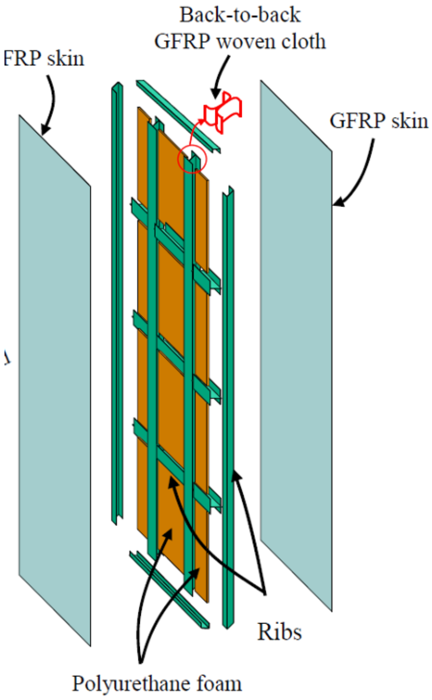

Fig. 9. FRP sandwich walls with ribs (Fam and Sharaf, 2010)

Figure_10 Click here to download Figure CCENG-1709_Figure_10.pdf

(a) balsa cored sandwich (SAMPE, 2010) (b) GFRP-balsa sandwich (Keller et al., 2014)

Fig. 10. FRP sandwich bridge decks

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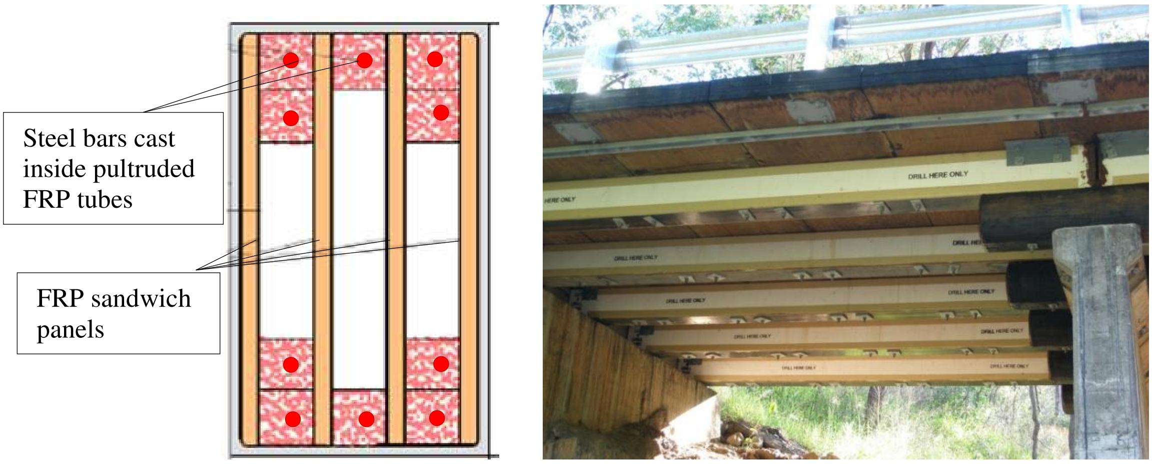

Fig. 11. FRP sandwich bridge beams (Van Erp and McKay, 2012).

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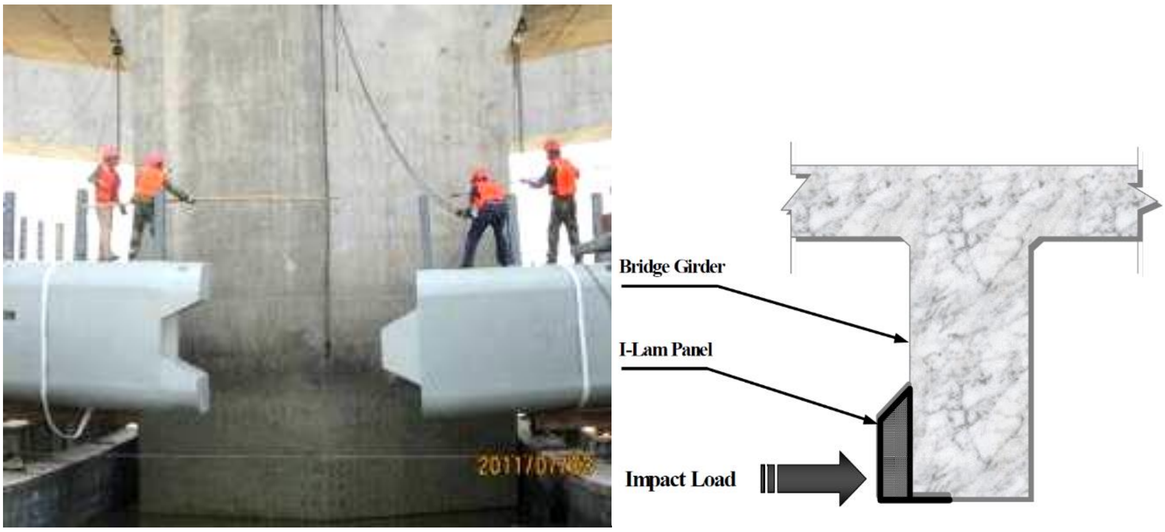

(a) Collision-avoidance system (Liu et al., 2013) (b) I-Lam system (Qiao et al. 2008)

Fig. 12. Floating and protective structures using FRP sandwich systems

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(a) Timber replacement sleeper (b) Turnout sleepers

Fig. 13. Railway sleeper technologies using FRP sandwich panels

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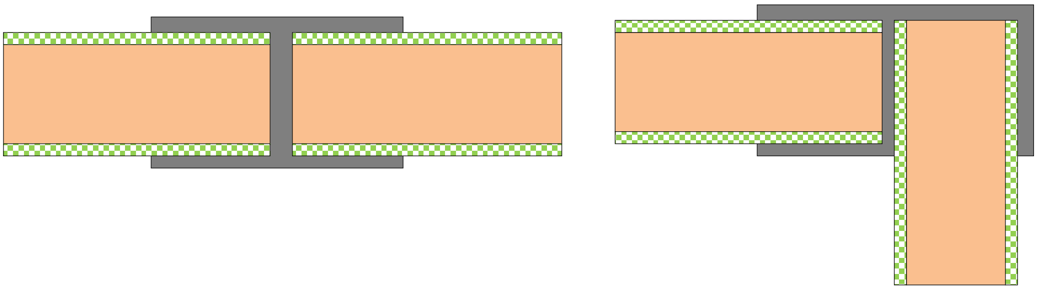

(a) Adjacent sandwich panels (b) Corner joints

Fig. 14. Design concepts for FRP sandwich node connections

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