Fibre reinforced polymer composites sandwich structure: Recent developments and applications in civil infrastructure

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RATIONALE
Fibre composites, which typically consist of strong fibres embedded within light polymer matrix, have become the new generation of material to be used in civil infrastructure. The Centre of Excellence in Engineered Fibre Composites (CEEFC) at the University of Southern Queensland (USQ), Australia is recognised worldwide for its track record in implementing numerous research and development projects in the area of fibre composites for civil infrastructure. Recently, a new type of composite sandwich panel made up of glass fibre-reinforced polymer skins and a modified phenolic core material has been developed for structural applications. This paper presents the recent research, developments and successful applications of this innovative fibre composite sandwich. A number of barriers that need to overcome and the potential solutions for the continued growth and wide acceptance of this innovative technology in civil engineering and construction are also presented.

OBJECTIVES
This paper aims to present a review of the recent developments and initiatives on fibre composite sandwich structures, focusing on its application in civil infrastructure. This paper also aims to give an overview of the on-going research and development on an innovative composite sandwich structures developed at CEEFC, USQ.

METHODOLOGY
On-going research, development and applications of fibre composite sandwich structures in Australia and around the world are reviewed and presented. The recent research, developments and initiatives conducted by the author focusing on a novel composite sandwich panel made up of glass fibre-reinforced polymer skins and a modified phenolic core material are highlighted. A number of barriers that need to be overcome for the continued growth and wide acceptance of this construction system in civil infrastructure are also presented and the potential solutions have been identified for fibre composites sandwich structures to become a more competitive construction material and advancing its potential in civil infrastructure.

RESULTS
This paper demonstrates the high possibility of using fibre composites sandwich as an innovative and effective material system in civil engineering and construction. The recent developments and applications of fibre composites sandwich include structural panels for roofs, floors, walls, and bridge decks. In addition, the innovative sandwich structure is now being used in the development of composite railway sleepers, bridge beams and composite walers. Overcoming challenges and lessons learned in the implementation of fibre composite sandwich construction in civil infrastructure are also identified.

CONCLUSIONS
The recent development and applications of fibre composite sandwich structure in civil infrastructure taking place in Australia and around the world are highlighted in this paper. Several new and innovative structural systems have shown that the construction of a more durable and cost-effective infrastructure is possible using fibre composite sandwich structures.

KEYWORDS

Sandwich structures, fibre composites, civil engineering, construction.

1. INTRODUCTION

Fibre composite sandwich has become the new generation of material used in civil infrastructure in the last decade. A structural sandwich is a special form of a laminated composite fabricated by attaching two thin but stiff skins to the lightweight but thick core [1]. Because of this special feature, the sectional area is increased and consequently an increase in its flexural rigidity. The strength of this type of construction results from the combination of properties from the skin, core and interface. In a sandwich structure, the strong and stiff skins carry most of the in-plane and bending loads while the core mainly bears the transverse shear and normal loads [2]. Fibre composites are now commonly used for the top and bottom skins due to its high mechanical performance and low density. On the other hand, the core provides a sandwich construction with high flexural stiffness and strength with a relatively lightweight structure [3]. The interaction of the inherent properties of these constituent materials makes composite sandwich construction an efficient structural system.

Over the last few years, the development in fibre reinforced polymer (FRP) composite sandwich structures has been very exciting in volumes as well as in applications. Their usage is mainly in the aerospace, aircraft and marine industries because of their fuel efficiency in transportation vehicles. The evolution of sandwich structures with enhanced material systems provided an opportunity to expand the application of this material in civil infrastructure. At present, there is a strong interest in the development and applications of fibre composite sandwich structures for civil engineering and construction. The light weight of sandwich composites facilitates handling during assembly, and reduces installation and transportation costs. They also offer corrosion resistant structures requiring less maintenance. In Australia, fibre composite sandwich structures are now being used as structural panels in residential and industrial buildings, boardwalks, bridge decks, and timber replacement girder in a number of infrastructure projects. Its application for a railway sleeper is also now trialled.

This paper presents an overview of the recent developments and initiatives on fibre composite sandwich structures, which have been evolving and have become a viable construction material in civil engineering and construction. The on-going research, development and applications of a novel composite sandwich panel made up of glass fibre-reinforced polymer skins and a modified phenolic core material at the Centre of Excellence in Engineered Fibre Composites (CEEFC) at the University of Southern Queensland (USQ) are also highlighted.

2. RECENT R&D ON COMPOSITE SANDWICH STRUCTURES

Composite sandwich structure has been identified as a very interesting alternative to traditional construction materials. Consequently, several researchers have contributed towards the research and development of composite sandwich for structural and construction purposes. Daniel and Abot [4] suggested that the desired stiffness and strength of a composite sandwich structure can be modified by varying the materials for the skin and the core. It is also indicated that the nature of the core material system greatly influences the behaviour of sandwich structures.

In recent years, there have been considerable attempts to improve the performance of core materials for composite sandwich structure. Marsh [5] suggested that cellular manipulation can be made to achieve a high strength core. Accordingly, Daniel and Abot [4] filled the cells of a honeycomb core with epoxy to prevent premature shear failure at the load application. In another study, Mahfuz et al. [6] improved the performance of a sandwich structure under flexure by infusing titanium dioxide (TiO_2) nanoparticles into the parent polyethylene foam material. A 53% and 26% increase in the flexural stiffness and strength, respectively was attained by infusing 3% loading of TiO_2 nanoparticles in the core compared to neat polyurethane foam.

Another approach to improve the performance of sandwich structure is to reinforce the core with fibre composites. Karlsson and Astrom [7] suggested that three-dimensional reinforcing fabrics that integrate the faces and the core have the potential of significantly improving structural integrity of composite sandwich structures. Lascoup et al. [8] found out that stitching the top and bottom skins of the composite sandwich panels with glass fibres prevented the delamination failure and enhanced the mechanical performance. Reis and Rizkalla [9] developed a 3-D fibre reinforced polymer sandwich panel with the top and bottom skins connected with through-the-thickness unidirectional glass fibres to overcome delamination problem (Fig. 1). Increasing the quantity of 3-D fibres resulted in a significant increase in the shear modulus and compressive strength of the panel. However, there was a decrease in the tensile strength due to the waviness created by the stitched fibres. Kampner and Grenestedt [10] found that the introduction of corrugated skin improves the shear capacity and offered weight savings in a composite sandwich structure (Fig. 2). The corrugated skins also increase the wrinkling strength in compression and make the panels weigh 10-20% lighter than their plain counterparts.

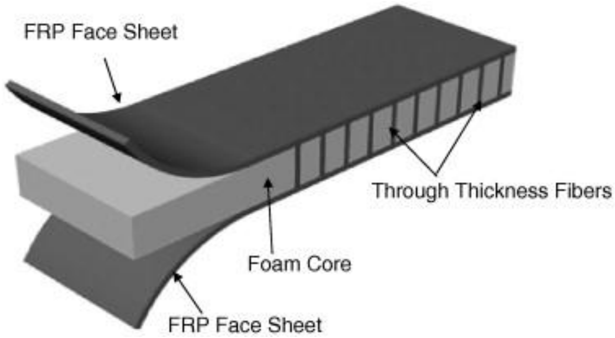

Figure 1. 3-D FRP sandwich panels [9].

Figure 2. Sandwich panels with corrugated skin [10].

CarbonLOC Pty. Ltd. in Toowoomba, Australia is now producing a novel fibre composite sandwich panel with lightweight but high-strength core material (Fig. 3). This highly sustainable sandwich structure is made up of bi-axial (0/90) E-CR glass fibre composite skins co-cured onto the modified phenolic core using a toughened phenol formaldehyde resin [11]. The application of this composite sandwich structure has been demonstrated in several building and residential projects within Australia and its use have already been explored for bridge and railway infrastructure. Studies have shown that the enhancement of the mechanical properties of the skin and core materials significantly improved the performance of the composite sandwich structures. These developments also presented an ideal opportunity to increase the use of composite sandwich structures for civil infrastructure.

Figure 3. The novel fibre composite sandwich panel.

3. APPLICATIONS OF COMPOSITE SANDWICH STRUCTURES

Research efforts in Australia and throughout the world are continuously aiming toward the development of new and innovative sandwich structures utilising fibre composites to address the need of the construction industry for more durable and cost-effective infrastructure. In this section, several applications of fibre composite sandwich structures are presented.

3.1 Bridge and pedestrian decks

One important application of sandwich construction in civil engineering is the sandwich bridge deck. The inherent advantages in strength and stiffness per unit weight as compared to steel reinforced concrete decks make the composite sandwich bridge decks a good alternative. Several variants of composite bridge decks comprise sandwich profiles, spanning transversely or longitudinally between supporting elements or suspended from tension cables have been developed. Kumar et al. [12] reported the development of an all-composite bridge deck made of pultruded GFRP tubes bonded together using epoxy adhesive to build a four-layered tube bridge deck assembly. Fibre composite sandwich profiles for highway bridge deck systems [13] and temporary bypass roadways have also been developed.

SAMPE [14] in New Jersey, USA has reported the application of first balsa cored composite bridge deck installed in Louisiana (Fig. 4). In the development of the composite sandwich bridge deck, layers of Hardwire® high-tensile strength steel reinforcements were used in conjunction with conventional biaxial glass fibre in the structural skins to achieve the required stiffness. The core material was a BALTEK® end-grain balsa containing Single-Walled Carbon Nanotubes. In addition, fibre optic strain gauges were installed in the bridge panels to monitor the long term performance of the composite bridge deck. Hulsey et al. [15] reported the development and testing of new and integrated Smart honeycomb fibre-reinforced polymer (S-FRP) sandwich materials for highway bridge decks in cold regions (Fig. 5). The novelty of sandwich bridge deck integrates advanced polymer composite materials with smart piezoelectric sensors and actuators to form smart structures, and along with advanced material technologies and proposed damage identification algorithms. With this, the structure is capable of improving construction speed in cold climates and self-monitoring structural conditions in remote sites.

Figure 4. Balsa-cored composite bridge deck [13].

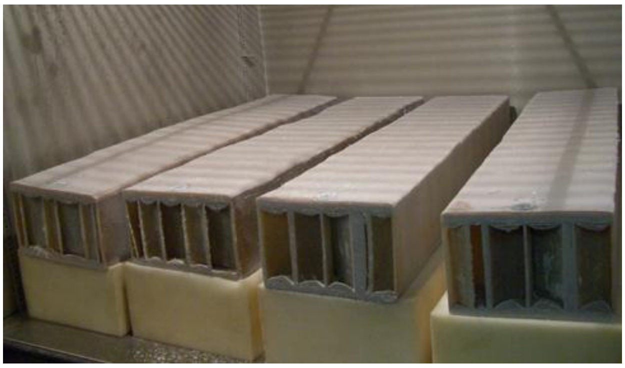

Figure 5. S-FRP sandwich bridge beck [14].

Composite sandwich decks also provided the opportunity to upgrade the load carrying capacity of existing bridges. A composite sandwich deck was used to replace the deteriorated concrete slab on a bridge over Bennet's creek in Steuben County, New York [16]. Prior to this, Kalny et al. [17] developed a bridge deck system made up of sandwich panels with a honeycomb core which is now installed in bridges in several states in the US including Kansas, Missouri and West Virginia.

Pedestrian bridges and walkway structures with fibre composites sandwich bridge decks (Fig. 6) are now common all across Australia. Due to their unique characteristics to withstand the harshest environments while providing a low maintenance, fibre composite sandwich structure in combination with pultruded FRP sections are now the preferred materials in the construction of bridges and walkways near to costal, marine, and environmentally sensitive areas such as tidal flood plains, protected mangrove swamps and corrosive mining facilities. An example of a composite sandwich boardwalk is shown in Fig. 6. As the area is subject to harsh environmental condition, fibre composite solution was sought by the council.

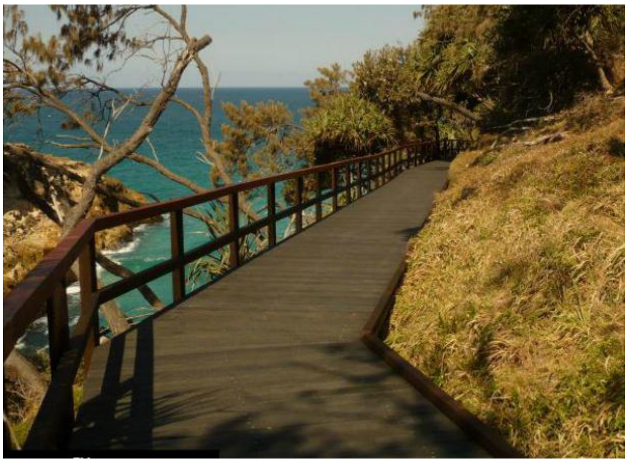

Figure 6. Composite sandwich boardwalks.

3.2 Structural beams

The development of structural beams from fibre composite sandwich structures is now gaining interest. Canning et al. [18] proposed an innovative hybrid box section for beam application (Fig. 7). 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. [19] in the construction of a new FRP bridge in Spain. The webs of this hybrid fibre composite bridge beam are sandwich panels with polyurethane core and glass-fibre skins. Similarly, Lopez-Anido and Xu [20] developed a structural system based on the concept of sandwich construction with strong and stiff fibre composite skins bonded to an inner glulam panel. The glulam panels were fabricated with bonded eastern hemlock laminations. These studies showed that the concept of gluing a number of composite sandwich panels to form a structural beam is highly practical.

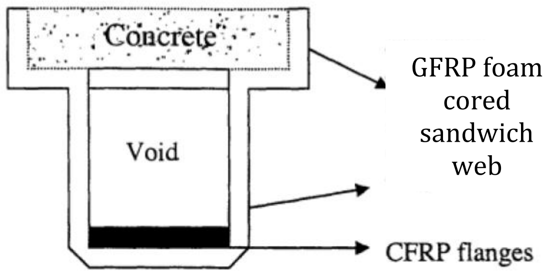

Figure 7. Hybrid box beam concept [18].

One technological development in Australia was the construction of a prototype bridge at USQ using fibre composite sandwich structures. This new generation of composite bridge using the fibre composite sandwich panels (Fig. 8) could potentially increase the span by two folds. This new technology has been realised through the partnership with Queensland Department of Transport and Main Roads and CanbonLOC Pty

Ltd, who patented the innovative sandwich panel technology. Further, the novel fibre composite sandwich structure is used as shear webs of fibre composite replacement bridge girders (Fig. 9). The FRP sandwich beam is stiffened with composite hybrid module that consists of steel reinforcing bars cast into a GFRP tube. A solid glue-laminated sandwich structure is used mainly in the ends of this hybrid FRP bridge beam where drilling and installing the fixing rods are being undertaken and in resisting the high compressive/crushing force in this location. Bending, shear and fatigue tests conducted on these hybrid FRP beams satisfied the performance requirements specified by the Department of Transport and Main Roads. Destructive bending test conducted showed that the combination of materials has made the hybrid FRP sandwich beams to exhibit a pseudo-ductile failure behaviour. This is very important from the structural point of view as the large deflection provides significant warning prior to final failure of the structure.

Figure 8. FRP sandwich bridge beams at USQ.

Figure 9. Glue-laminated sandwich bridge girder.

3.3 Innovative truss systems

The recent applications have demonstrated that composite sandwich construction can be effectively and economically used in the development of fibre composite truss systems. A unitary construction or "monocoque" fibre composite truss in Fig. 7a which uses two planer skins that contain the fibre separated by a core material was designed and developed by Humpreys et al. [21]. Omar [22] developed a deployable shelter using modular composite truss panel as the main structural system. The diagonal members of the truss are made of composite sandwich structures as shown in Fig. 10.

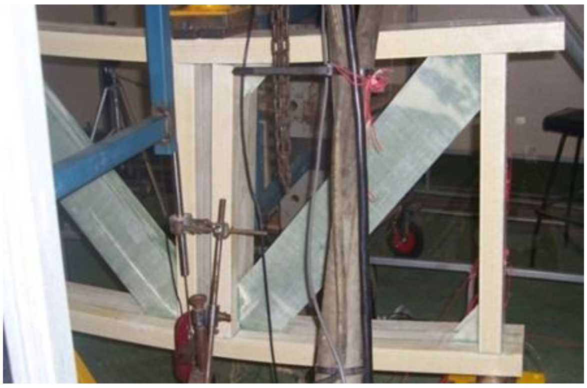

Figure 10. Modular composite truss panel [22].

3.4 Housing and construction

Composite sandwich structure has numerous advantages in housing and construction. The light weight of sandwich composites facilitates handling during assembly, and reduces installation and transportation costs. This can significantly speed up construction, especially in the rebuilding of structures in calamity-affected areas. Consequently, an increasing range of fibre composite sandwich structure is now available like roof, wall, floor, and subfloor system for housing and construction.

The Advanced Composite Construction System (ACCS), undertaken by Maunsell Structural Plastics, London, made from pultruded FRP composite with polyethylene foam core was developed for use in walls and floors of a two-storey building structure [23]. A function integrated GFRP sandwich roof structure (Fig. 11) for a main gate building was designed and constructed in Switzerland by Keller et al. [24]. Thermal insulation, waterproofing and acoustics were integrated into the system during the prefabrication of the sandwich roof structure enabling easy transportation and rapidly installation. Currently, the CEEFC is collaborating with Urban Moments Design, a company based in Rockhampton in Queensland in the development of a housing technology made from all fibre composite materials (Fig. 12). The fibre composite sandwich wall panels of this new technology are now being produced to determine the structural performance and practicality of this construction system.

Figure 11. Lightweight GFRP sandwich roof [24]

Figure 12. All FRP modular houses.

3.5 Railway sleepers

The CEEFC at USQ, in collaboration with the different railway industries in Australia, has been involved in a number of research and development projects involving innovative fibre composite railway sleepers. One of these developments is the fibre composite railway turnout sleeper made from novel composite sandwich structure developed by CarbonLOC Pty. Ltd. The composite railway turnout sleeper is produced by gluing layers of fibre composite sandwich structure together in flatwise (horizontal) and in edgewise (vertical) orientations. The strength and stiffness properties as well as the resistance to hold screw spikes of these glue-laminated composite sandwich beams are suitable for turnout sleeper application. This fibre composite railway sleeper also has better mechanical properties than most of the commercially available sleepers and showed comparable properties with the existing timber turnout sleepers. Railway sleepers made from glue-laminated sandwich structures are now being trialled on an actual railway bridge in Australia as shown in Fig. 13 where it was verified that the fibre composite sleepers are performing to expectations and estimated that its serviceable life should be well in excess of 50 years.

Figure 13. Composite sandwich railway sleepers

3.6 Sandwich waler

On the coastline of Australia, boardwalks, jetties, pontoons, and marine structures operate in a very corrosive environment. This results in serious durability problems for steel and reinforced concrete. Hardwood has traditionally been used to overcome some of these problems. However, when exposed to aggressive marine environments, timber waler would require replacement every 10 to 15 years. The composite waler made from glue-laminated sandwich structure is a viable substitute for this application because of its excellent corrosion resistance and durability properties. The flexural test (see Fig. 14) indicated that the strength and stiffness of a sandwich waler are suitable for this application. The presence of vertical fibre composite skins in the sandwich waler resulted in a higher resistance to mechanical connections than that of hardwood timber. The sandwich structure is now planned to be used as waler in a floating structure similar to that at the Brisbane Floating Riverwalk where FRP reinforced polymer concrete was used.

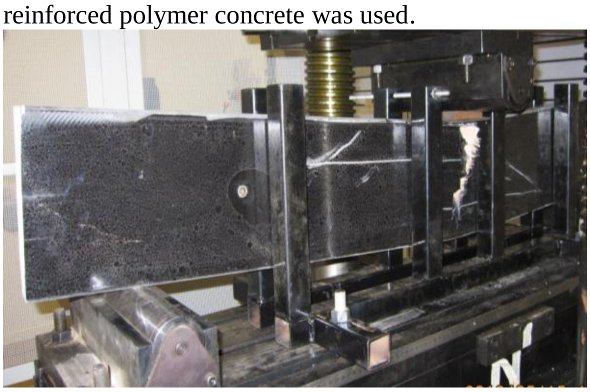

Figure 14. Flexural test of a sandwich waler

3.7 Hybrid glue-laminated sandwich beam

A hybrid fibre composite sandwich beam composed of glue-laminated sandwich panels oriented in edgewise position at the middle with top and bottom glass fibre reinforced polymer (GFRP) skin plates as shown in Fig. 15 are now being developed. The mechanical behaviour of this beam is currently investigated in CEEFC and with this configuration, it is expected that the beam will have an improved shear strength due to the vertically oriented sandwich panels and an improved bending and compressive strength due to GFRP skin plates. The potential application of this hybrid beam is for railway transom or sleepers used in a railway bridge.

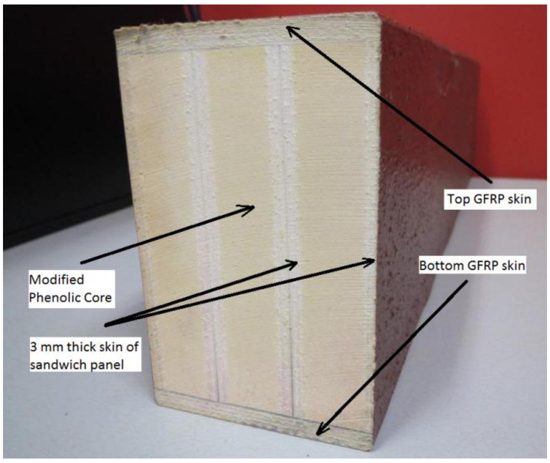

Figure 15. Hybrid glulam composite sandwich beam

4. CHALLENGES AND ISSUES

A number of issues contributing to the slow uptake of composite sandwich structures in civil infrastructure have been well documented. These important aspects have to be addressed in order to advance their use of sandwich structures in civil engineering applications.

4.1 Core material development

The low load-carrying capacity of most sandwich construction is due to the nature of the commonly used core materials. Unlike in aerospace and automobile applications, the core of the sandwich structures for building and construction needs to be reasonably strong to withstand high concentrated and impact loads. Moreover, a thicker composite sandwich panel is usually used in structural than in industrial applications where the shear strength of the core is a critical parameter to efficiently transfer the shear between the top and bottom skins. In fact, Styles et al. [25] indicated that the shear cracking of the core is the dominant failure mode for a sandwich structure with a thick core. Thus, it is anticipated that the evolution of composite sandwich structure with lightweight, high-strength core and with good capacity for mechanical connections could provide wider opportunity to increase the acceptance and utilisation of this type of construction in civil infrastructure. However, the method of enhancement of the core structure should not involve a complex manufacturing process and increase the cost of production.

4.2 Design guidelines

The poor understanding of the overall behaviour of fibre composite sandwich structures is commonly claimed to place them at a disadvantage when considered against traditional construction and building materials. This problem, combined with the lack appropriate design codes and standards, is recognised as a significant barrier to broad utilisation of these materials in civil engineering. Bakis et al. [26] pointed out that without an established design method and data, it is unlikely that structures utilising fibre composites will be used beyond the scope of research and demonstration projects.

While the Queensland Government has made an effort to promote fibre composites in various industry sectors by providing an introductory guide, the application of composite sandwich structures in construction has been limited. Designers and engineers are still searching for design guidelines that can be used for this type of construction. In contrast to this, designers and builders in Europe have extensively used composite sandwich panels in many structural systems, due to the availability of design guidelines. An example is the document 'European Recommendation for Sandwich Panels, Part I: Design' [27]. Similar design method should therefore, be developed so that fibre composite sandwich structures could gain wider acceptance in civil infrastructure. New and simple analysis techniques should be able to analyse the overall behaviour of composite sandwich structures within acceptable levels of confidence.

4.3 Innovations

Fibre composite sandwich panel is an acceptable alternative material in building efficient and reliable civil infrastructures. They are now being used for floors, roofs, walls, bridge decks, and other innovative structural applications. However, this limited application also shows that the potential of this type of construction has not been fully explored yet despite engineers have access to a wide range of fibre composite sandwich panels.

The growth of composite sandwich construction in civil infrastructure can be further realised by developing innovative structures which exploit its many advantages. Fibre composite sandwich structures will generally feasible in infrastructure when the need for corrosion resistance, high strength, reduced weight, or fast installation is a driver for the system. As seen by the recent development of innovative composite sandwich bridge decks, this effort is driven by the need to replace the heavy weight and corrosion prone reinforced concrete decks and the opportunity to upgrade the load carrying capacity of the existing bridge. Such composite structures are needed in order to address the need in the construction industry for more durable and cost-effective infrastructure. Moreover, typical infrastructure prototypes need to be developed to demonstrate its practical application, increase its acceptance and to build a market volume.

5. CONCLUSION

This paper presented the recent developments and applications of composites sandwich construction into civil infrastructure. The many advantages of fibre composite sandwich structure support the development of a low weight, high strength and more durable infrastructure. The development of a high strength core material presented an opportunity to increase the use of fibre composite sandwich panel in civil infrastructure. Several new and innovative structural systems have shown that the construction of a more durable and cost-effective infrastructure is possible using fibre composite sandwich structures. Further research is being conducted to fully maximize the application of the novel composite sandwich structures. A number of barriers that need to be overcome for the continued growth and wide acceptance of this construction system in civil infrastructure are also presented and potential solutions have been identified for fibre composites sandwich structures to become more competitive construction material and harness its potential in civil infrastructure.

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