GLUE-LAMINATED COMPOSITE SANDWICH BEAMS FOR STRUCTURAL ENGINEERING AND CONSTRUCTION

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ABSTRACT

The Centre of Excellence in Engineered Fibre Composites (CEEFC) at the University of Southern Queensland, Toowoomba, Australia has played a significant role in research and development of innovative fibre composite structures suitable for replacement of structural timber elements. Recently, a new generation fibre composite sandwich panel made up of glass fibre reinforced polymer skins and phenolic foam core has been developed and found to have strength and stiffness similar with that of hardwood timber. As these composite sandwich panels are produced in limited thicknesses, a structural beam is manufactured by gluing several of these sandwich panels together.

This paper presents the recent developments and successful applications of glue-laminated sandwich beams for structural engineering and construction. These include fibre composite railway sleepers, composite walers, and fibre composite replacement bridge girders. Future research and development on this innovative structural system are also discussed. A number of barriers that need to be overcome and the potential solutions for the continued growth and wide acceptance of glue-laminated sandwich beams in civil infrastructure and construction are also presented.

Keywords: Sandwich structure, glue-laminated beams, bridges, railway sleepers, decking.

1. INTRODUCTION

A large number of timber structures such as road and rail bridges, railway sleepers and marine and fender piles remain in service in Australia (Dutton and Cartwright, 2001). Important components of these timber structures have deteriorated to a point where they are no longer considered safe and needs immediate replacement. Managing timber structures is very challenging as it has been increasingly difficult to get large section of good quality hardwood in quantities to replace these deteriorating timber components. To address this concern, researchers and asset owners in Australia have been actively seeking long-term solutions for the repair and rehabilitation of deteriorated timber civil infrastructures. Fibre reinforced polymer (FRP) composites is now becoming a viable alternative to replace deteriorating timber elements as this material can be engineered based to behave like hardwood timber, are more environmentally sustainable than steel and concrete, and promising results as long-term solutions for maintenance of existing timber infrastructure.

FRP composites, in the form of a sandwich structure, are one of the most efficient types of construction system. The main benefit of using a sandwich concept in structural components is its high bending stiffness and high strength-to-weight ratio. Using fibre composites, this type of construction offers a corrosion resistant infrastructure that makes them suitable for several civil engineering applications. This structure is composed of a lightweight and thick core attached between two stiff but thin skins producing a configuration with increased second moment of area without an increased in its self-weight.

Earlier studies have focused onto the improvement of the mechanical properties of the core material system to enhance the performance of sandwich structures and realize their application in civil infrastructure. These studies include manipulating the cellular structure of the core material (Marsh 2007), reinforcing the core with titanium dioxide (TiO_2) nanoparticles (Mahfuz et al. 2004) and fibres (Flores-Johnson et al. 2012), to achieve the desired stiffness and strength of the composite sandwich structure. Other studies suggested the introduction of through-thickness fibre stitching of core materials (Lascoup et al. 2006) thereby improving its mechanical performance. As a result, several studies have proven the suitability of composite sandwich construction in the fabrication of structural elements such as bridge and pedestrian decks, walls and prefabricated trusses.

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 (Van Erp and Rogers, 2008). The significant improvement in strength of the core of this sandwich structure presents an ideal opportunity to increase the use of this material for civil engineering applications. As these composite sandwich panels are produced in limited thickness, structural beam sections are manufactured by gluing several sandwich panels together. This paper presents the recent research, developments and successful applications of glue-laminated composite sandwich beams for the replacement of structural timber elements. A number of barriers that need to be overcome and the potential solutions for the continued growth and wide acceptance of glue-laminated sandwich beams in civil infrastructure and construction are also presented.

2. R&D ON GLUE-LAMINATED COMPOSITE SANDWICH STRUCTURES

Extensive research and development of the state-of-the-art composite sandwich structures have been conducted to meet the need of the construction industry for stronger and highly sustainable infrastructure. In this section, earlier studies that utilized glue-laminated elements for structural beam applications are presented. Investigation on the mechanical behaviour of the novel fibre composite sandwich panel as well as its constituent materials and its behaviour when glue-laminated together to form a structural beam beams are also presented.

2.1. Early application of sandwich construction for structural beam application

The idea of using sandwich structure for beam application was pioneered by Canning et al. (1999) who proposed the use of composite sandwich shear web in an innovative hybrid box section (see

Figure 1). Similarly, Lopez-Anido and Xu (2002) 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 show that the concept of gluing a number of composite sandwich panels to form a structural beam is highly practical. However, very limited attempts have been done so far to use composite sandwich materials for this type of structural application although engineers have access to a wide range of composite sandwich panels. The main reason could be that most of the currently used core material systems are not appropriate for this type of structural application.

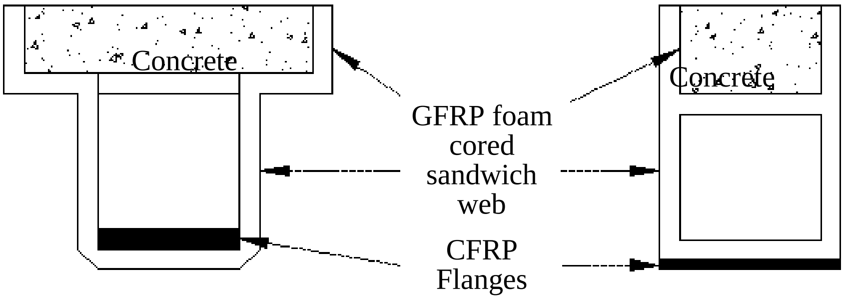

Figure 1: Hybrid box beam concept (Canning et al. 1999).

2.2. Novel sandwich panel for structural applications

In Australia, the CEEFC has played a significant role in research and development on innovative fibre composite structures suitable for replacement of structural timber elements. Recently, CarbonLOC Pty Ltd, in collaboration with CEEFC, has developed an environmentally sustainable fibre composite building panel with excellent structural and durability properties. The novel composite sandwich panel is composed of fibre composite skins, made up of 2 plies of stitched bi-axial [0/90] E-CR flass fibre fabrics, and modified phenolic foam core. The results of the extensive investigation by Manalo et al. (2010) indicated that the strength and stiffness of this composite sandwich panel is comparable with that of structural timber.

The novel composite sandwich panels are now being used in wet areas and in balcony construction as it was classified as Grade 1 waterproof membrane. Furthermore, because of its Class 1 fire resistant rating (Building Code of Australia), the panels are also utilized for walls, roofs, floors and fire doors. A number of infrastructure projects have also utilized this sandwich panel for bridge and pedestrian decks. Further application of the panels as structural beams is desired, thus, investigation of the strength and stiffness properties of this structural concept are performed.

2.3. Flexural and shear behaviour of glue-laminated sandwich beams

One limitation of the novel sandwich panel is that it is produced in limited thicknesses for reasons of cost effectiveness and efficiency. To address this problem, Manalo and Aravinthan (2012) adopted the concept of glue-laminated (glulam) lumber wherein several layers of composite sandwich panels are adhesively bonded together in flatwise and edgewise orientations to produce glue-laminated beams. Gluing a number of elements of limited dimension to manufacture large structural members in any shapes and sizes has been used many years in the construction industry. In timber engineering, several layers of suitably selected smaller pieces of lumber are horizontally or vertically laminated (either by nailing or gluing) to produce structural glue-laminated timber. Thus, an investigation on the flexural and shear behaviour of this innovative beam concept is performed to effectively use this system in civil infrastructure. The flexural and shear behaviour of the glue-laminated sandwich beams with flatwise and edgewise laminations are determined using a 4-point static bending test (Figure 2) and asymmetrical tests, respectively.

The results of the experimental investigations indicated that the apparent bending modulus, bending strength and shear strength of glue-laminated sandwich panels panels with increasing number of laminations. The results also showed that gluing the sandwich panels together resulted in a stronger and more stable beam section than individual sandwich panels alone. The glue-laminated sandwich beams with edgewise laminations exhibited higher flexural and shear strength and almost the same stiffness compared to sandwich beams glued in the flatwise position. More importantly, the presence of vertical skins in the edgewise position resulted in a more progressive failure behaviour. Finally, the strength and stiffness of the glue-laminated beams are comparable with that of structural timber. This result highly suggests the high feasibility of using the novel composite sandwich structures in manufacturing glue-laminated beams for several civil engineering infrastructures.

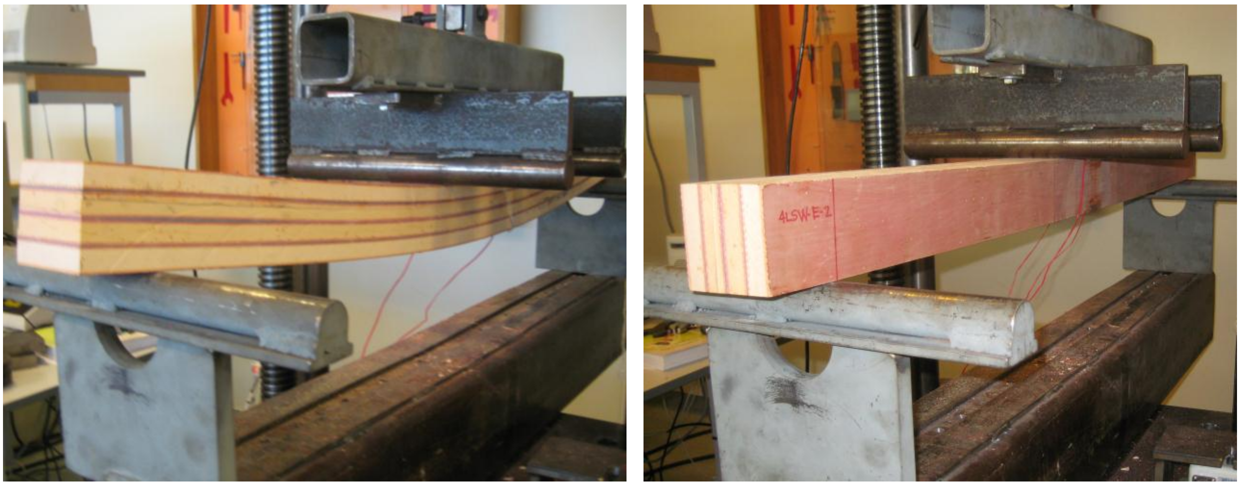

Figure 2: Static bending test of glue-laminated sandwich beam.

3. APPLICATIONS OF GLUE-LAMINATED COMPOSITE SANDWICH BEAMS

The glue-laminated fibre composite sandwich beams are found viable substitutes to structural timber elements. The current applications of sandwich beams are presented in this section.

3.1. Fibre composite railway sleeper

The railway industries in Australia are one of the major users of hardwood timber sleepers. Due to various environmental concerns, there have been a limited supply of hardwood timber sleepers to replace an increasing number of deteriorated railway sleepers. Thus, the structural behaviour of full-scale glue-laminated sandwich beams was verified through practical experimentation and was evaluated against technical and performance benchmarks for railway sleeper application as shown in Figure 3. The results suggest that the innovative glue-laminated fibre composite sandwich beam concept has strength and stiffness suitable for railway application. Evaluation against technical standards for railway sleepers have shown that this type of sleeper has mechanical properties greater than the minimum performance requirements for composite sleepers and that it has a comparable performance with the existing timber sleepers. A number of these sleepers are now being trialled on an actual railway bridge in Australia which verified that the fibre composite sleepers are performing to expectations and estimated that its serviceable life should be well in excess of 50 years.

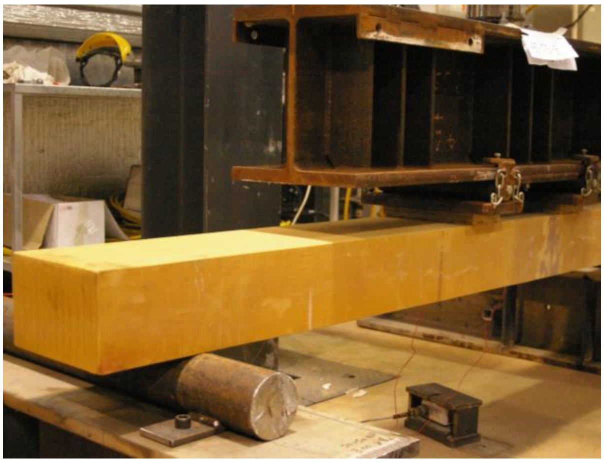

Figure 3: Glue-laminated fibre composite sandwich railway sleepers.

3.2. Composite waler

Timber and steel are the commonly used construction materials to fabricate waler that ties individual floating marinas and walkways together. However, these materials are exposed to aggressive marine environments and would require replacement every 10 to 15. 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 Figure 4) 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 (see Figure 11) where FRP reinforced polymer concrete was used (Van Erp et al. 2006).

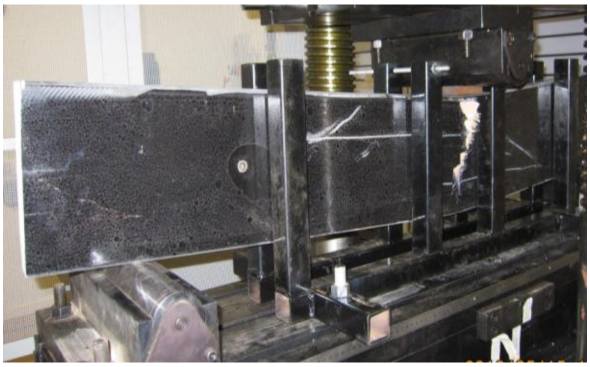

Figure 4: Flexural test of sandwich waler

Figure 5: Fibre composite reinforced waler

3.3. Fibre composite replacement bridge girder

The novel sandwich structure is used as shear webs of fibre composite replacement bridge girders (Figure 6). The FRP sandwich beam is stiffened with composite hybrid module that consists of steel reinforcing bars cast into a GFRP tube. Further, a solid glue-laminated sandwich structures are used mainly in the ends of this hybrid FRP bridge beam where drilling and installing the fixing rods are being undertaken and resist the high compressive/crushing force in this location. Bending, shear and fatigue tests conducted on these hybrid FRP beams satisfied the performance requirements for a bridge girder. 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 6: Glue-laminated fibre composite sandwich bridge girder.

4. RESEARCH AND DEVELOPMENT ON HYBRID SANDWICH BEAM SYSTEM

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 (see Figure 7) 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.

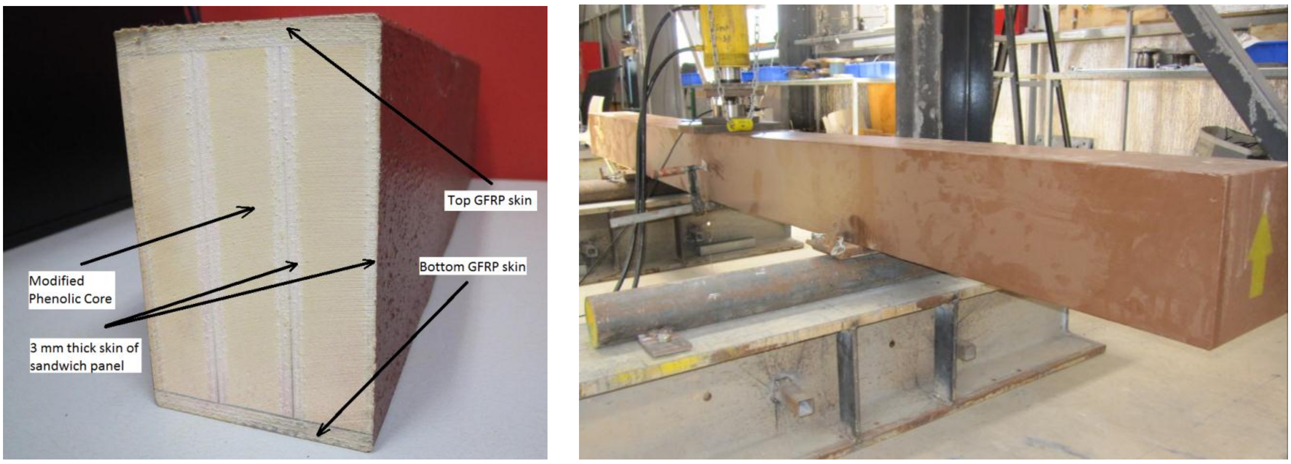

Figure 7: Hybrid glue-laminated fibre composite sandwich beam.

5. CHALLENGES AND SOLUTIONS

FRP composite sandwich structures are an acceptable alternative in constructing efficient and reliable structures. However, the full potential of this type of structure has not been fully explored. A number of barriers that need to be overcome and the potential solutions to advance the use of FRP sandwich structure in civil engineering applications are presented in this section.

5.1. Development of high strength and lightweight core material

The lower load carrying-capacity of FRP composite sandwich structures is mostly due to its core material having lower mechanical properties. The core of a sandwich structure plays an important role when used in structural application. Strong and thick core is needed to provide the necessary shear strength to resist the shear stress due to applied loads. Therefore, enhancement of the shear properties of core structure without an increase in weight will provide wider opportunities to increase the acceptance and utilisation of this type of construction in civil infrastructure.

5.2. Development of design standards

Designers and builders in Europe have extensively used composite sandwich panels due to the availability of design guidelines for fibre composite sandwich structure. However, the lack of design standards in Australia has limited the utilization of composite material for constructing efficient and reliable structures. This made fibre composites to be of less preferred material as compared to traditional construction materials such as concrete, timber and steel that already has established codes and standards in Australia. Design guidelines through collaborations with several institutions who have sufficient knowledge and experience on using composite materials should be established to encourage wider acceptance of sandwich structures in building and construction.

5.3. Innovation

The growth of FRP sandwich construction can be further realised by developing innovative structures which exploit its many advantages. For example, FRP sandwich structure will generally feasible when the need for corrosion resistant, high strength, reduced weight or fast installation is a driver for the system.

6. CONCLUSIONS

This paper presents the current research, development and application of glue-laminated fibre reinforced polymer composite beams. Studies have shown that the constituent materials of the glue-laminated sandwich beams are highly sustainable that are ideal to meet the environmental standards and/or requirements currently imposed in the construction industry. It also has properties comparable with hardwood timber and found suitable for structural engineering and construction. Currently, the composite beams are employed as structural element in several civil engineering infrastructures like railway sleepers, composite waler and bridge girder. Further research is being conducted to fully maximize the application of the novel composite sandwich beams. Several challenges and issues are identified to realize the wider acceptance of the fibre composite sandwich beams in structural engineering and construction.

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