STUDY ON FUNDAMENTAL MECHANICAL PROPERTIES OF INNOVATIVE COMPOSITE SANDWICH STRUCTURES AND THEIR ENGINEERING APPLICATION

W. Q. LIU*, H. FANG, Y. FANG, J. WANG, Y. J. QI, and L. WAN

College of Civil Engineering, Nanjing University of Technology, China

ABSTRACT

Innovative composite sandwich structures have attracted great fundamental and industrial interests because they can be used partly instead of steel and concrete using for structural engineering and construction. In this work, the fundamental mechanical properties and engineering applications of the innovative composite sandwich structures were investigated. At first, the mechanical properties of the innovative FRP sandwich composite structures in tension, compression, bending, shear, and torsion conditions were investigated. Furthermore, three interfacial reinforcement methods were employed to enhance the interface of the composite sandwich structures, including groove reinforced, perforate reinforced, and web reinforced methods. Among these, web reinforced method is critical to this novel structure. Additionally, the node connection of the composite sandwich structures is the key and difficult of design and application. Adherence I-shaped steel joints were used for node connection. Importantly, the engineering products of the innovative composite sandwich structures in civil engineering were exploited, including composite pavement matting, composite sheet piles, composite truss bridges, composite floating structures, composite collision avoidance facilities, and so on. With the additional advantages of light-weight, high strength, and corrosion resistance, this new structure can be exploited as an alternative method for manufacturing large structures using in civil engineering field.

Keywords: Fiber reinforced polymer (FRP), composite sandwich structure, mechanical property, engineering application.

1. INTRODUCTION

Fiber reinforced polymer (FRP) which is a composite material made of a polymer matrix reinforced with fibers has attracted great fundamental and industrial interests because of their advanced functions and properties (Schimanski et al. 2012; Jin 2002; Karpat et al. 2012; Sakamoto and Hanai et al. 2012). Up to now, numerous applications of FRP have been widely applied in aerospace industry, wind power generation areas, and structural reinforcement in traditional civil engineering areas. However, as a practical point of view, it seems to be difficult to produce high performance

* Corresponding author: Email: wqliu@njut.edu.cn

FRP structure using for structural reinforcement mainly due to the interface easy to peel off and difficult to anchor. To solve this problem, the innovative fiber composite structures (Tekalur et al. 2009; Fang et al. 2010) employed composite structure type and are made of FRP combined with the traditional materials (e.g. Paulownia wood, foam, concrete, metal, and so on).

This paper mainly investigates innovative sandwich composite structures, including their mechanical properties, interfacial reinforcement mechanism, and the node connection of composite structures. With the innovative structure and the additional advantages of light-weight, high strength, and corrosion resistance, this new structural material can be exploited as an alternative material for manufacturing large structures in civil engineering field like sheet piles, floating bridges, bridge collision avoidance system, and so on.

2. PROPERTY RESEARCHES OF SANDWICH COMPOSITE STRUCTURES

The large-scale/unusual composite structures can be manufactured by vacuum infusion molding process (VIMP) which is low cost and fast molding (Sun et al. 1998; Lacy et al. 2000). The composite sandwich construction having cores and fabrics with resins in the skin can reach the perfect structural performances including strength, stiffness, fatigue and impact behavior. This sandwich structure has the characteristics of light-weight, corrosion-resistant, and electromagnetism-shield. The innovative fiber composite structures have been designed and prepared as grooved perforation sandwich (GPS) fabricated by VIMP.

2.1. Mechanical Properties of Sandwich Composite Structures

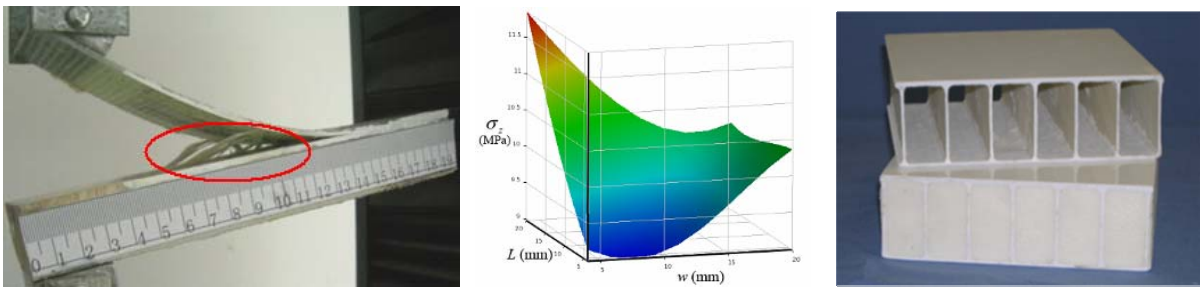
As seen in Figure 1a, the tensile property of the innovative composite sandwich structures was tested, and the results indicate that the composite sandwich behaves good tension strength. The flatwise compression and sidewal compression properties of the innovative composite sandwich structures were investigated (Figure 1b, c). Additionally, the there-point flexural testing of composite sandwich beams with three different spans (150, 300, and 450 mm) is performed. The failure mode of sandwich beams with the short span of 150 mm is core shear, while that with the span of 300 and 450 mm is face yield. (Figure1d).

(a) Tensile test (b) Flatwise compression (c) Sidewal compression (d) there-point flexural test

Figure 1: Mechanical properties of Innovative FRP composite structures.

2.2. Interfacial Reinforcement of Sandwich Composite Structures

The composite structures in practical engineering applications will be inevitably subject to various shocks. Under impact loading, varying degrees of damage destruction will be happened in the panel and core material, and interfacial delamination will occur (Fig. 2a), thus affecting the bearing capacity and durability of the composite structures. The improvement from pure resin columns on the interface was little and unstable, while the ERRs (Energy Release Ratio) of sandwiches with fiber/resin columns would be twice more than hand layup ones (Zhou et al. 2008). The reinforcing mechanism has been concluded as follows: The stresses between facesheet and core would be reduced by the columns, when the interfacial crack propagates through the columns (seen in Fig. 2b). As the extending of the interfacial crack, the fibers merged with the facesheet continuously prevent it from being separated until the fibers fail. The fracture of the fibers can significantly enhance the ERR of interface. Thus, functional gradient treatment will be done on the interfacial adhesion layer based on the basis of preliminary studies including core-grooved reinforced, perforated core reinforced, and web reinforced interface enhanced technology (Figure 2c).



(a) Interfacial debonding (b) Effect of delamination on tensile stress (c) Web-reinforced structures

Figure 2: Interfacial experiment and theory.

2.3. Node Connection of Sandwich Composite Structures

Node connection is key and difficult to design and application of sandwich composite structures. For the composites engineering structures, the node must have the reliable connection strength and a certain degree of deformation capacity. The forms of node connection of the composite sandwich structures can be divided into three types, including metal gasket joints, I-shaped steel joints, and I-shaped composite joints (Figure 3). The effect of inside declining angle of the I-shaped steels on failure modes of node connection was investigated. The results show that the joints can satisfy the loading-capacity requirement corresponding to the deformation limit of building structures, and be applied to sandwich composite structures. The effect of inside declining angle on the connecting strength was slight.

(a) Metal gasket joints **(b) I-shaped steel joints** **(c) I-shaped composite joints**

Figure 3: Node connection methods of sandwich composite structures.

3. ENGINEERING APPLICATION OF SANDWICH COMPOSITE STRUCTURES

Because of the characteristics of corrosion resistance, eco-friendly, and good designable, the innovative composite sandwich structures can partly take place of traditional steel or reinforced concrete with high energy consumption and resources type. The innovative composite structures can be used in pavement engineering, truss bridge, ship-bridge collision avoidance, ocean structure engineering, and so on. This new composite structure provides a green structural material with high-performance and multi-function for engineering structure.

3.1. Composite Pavement Matting & Bridge Decks

Composite pavement matting for rapid construction and repairment is a composite sandwich plate with high strength-to-weight ratio, which can not only be used for rapid construction of temporary road, landing field and ground, but also can be used for rapid repairment of destroyed airport and roadway. This matting is reusable and environmentally safe, which is especially suitable for usage in national defense engineering. Using wide grained balsa wood as core and E-glass fabric as panel, the light-weight high-performance sandwich composite matting (Figure 4) was fabricated by VIMP. The research focuses on a series of tests for this composite matting, such as fatigue test, ground vehicle test, and other tests for physical and chemical properties. It is noted that after 30-ton vehicle rolling back and forth 200 times the interface of the composite pavement matting is not stripped and it can still work. The composite matting can be assembled to the road, airport, the work site, emergency repair and construction.

Figure 4: Composite pavement matting.

3.2. Composite Sheet Piles

Composite sheet piles were investigated due to the advantages of FRP, such as their resistance to chemical erosion and electrical-chemical erosion, good corrosion resistance and better durability, both in law maintenance cost and in easy construction. The composite sheet piles do not produce chemical substances and impact minimally on the ecological environment. There are two types, including composite cantilever sheet pile and frame type composite revetment. The composite cantilever sheet pile structure system is composed of U type or Z type composite pile by locking laterally connected together. And the beams are set along the pile length. The structure has the advantages of small occupation area and convenient construction. The frame type composite revetment is composed of sparse pile, continuous sheet pile wall and beam. Composite sheet piles were manufactured in Fig. 5, and the connection form of composite sheet piles was as "hand-in-hand" style. This connection form can connect sheet piles tightly. The piling machine which can pile the steel sheet piles was employed to pile composite sheet piles, and the same method as piling the steel sheet piles was used. Additionally, the composite sheet piles can be pulled and not damaged. And composite pile directly bear the soil pressure and water-stop effect. The structure has the advantages of low cost, reliable stress, shorten time limit for a project. The composite sheet piles could be widely applied for sheet pile wharf, channel revetment, retaining walls, breakwaters, diversion dike, foundation reinforcement, bridge abutments, embankment protection, and other permanent structures.

Figure 5: Composite sheet piles.

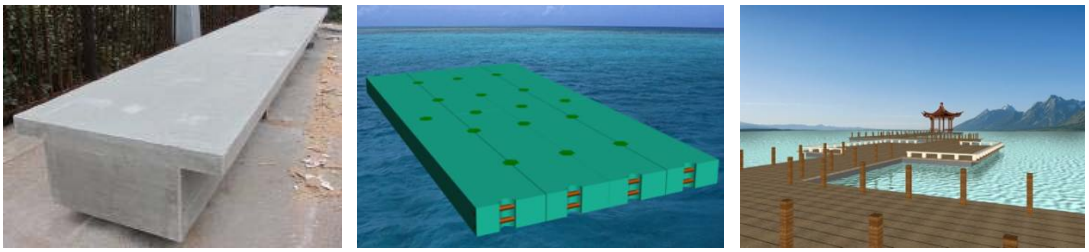
3.3. Composite Truss Bridges

FRP also can be applied in composite truss bridges. As seen in Figure 6, the total size is 6 x 1.6 m, and bridge's net width is 1 m. Dead weight is only 2.4 kN. Design carrying capacity is 3.5 kN/m^2. The loading test on the bridge is carried out using sand bags to give force gradually at mid-span and layout strain gauges to critical parts, and putting displacement meters under the mid-span to measure displacement value. The experimental result indicates that the light truss bridge has good flexibility and deflection quickly recovered after unloading. The vertical maximum deflection of mid-span is 22.3 mm. the deflection regeneration of mid-span is 4 mm. FRP truss bridges as working boat docks have been successfully working for Yangshan Port.

Figure 6: Composite truss bridge and its loading test.

3.4. Composite floating structures

Innovative FRP sandwich composite structures can be used for floating structures. This structure is molded overall (Figure 7a). The composite floating structures could be widely applied for offshore platform, floating bridge, and other traditional areas (Figure 7b, c). Moreover, the composite floating structures also have the potential applications, for instance, offshore helicopter landing fields, large water entertainment platform, floating crane island platform, and other heavy floating structure fields.



(a) Composite floating structure units **(b) Offshore platform** **c) Floating bridge**

Figure 7: Composite floating structure.

3.5. Composite ship-bridge collision avoidance facilities

There were many ship-bridge collision accidents in China. Guangdong Jiujiang Bridge was hit by ship in 2007. The bridge was collapsed, and 200 meters of the bridge deck was broken and fall into the river. Since that accident, the collision avoidance special rectification activities were launched. Expect bridge collapse, ship-bridge collision accidents caused other serious consequences, such as, ship damaged, polluted water, and so on. The ship-bridge collision accidents become an important factor of the bridge damaged. Thus, we need to do something to prevent the accidents. For new bridge, collision avoidance facilities can be installed. And for old bridge, the bearing capacity and strengthen the ability against collision should be reviewed. There are some bridge collision avoidance methods, including sand cofferdam protection method, fender pier piles method, artificial island method, buffer materials facilities method, buffer facility engineering method, steel cofferdam and fixed steel box method, steel rope rubber ring method, floating steel sleeve box for energy dissipation method, and so on. These traditional collision avoidance methods exist some problems. First, the traditional collision avoidance facilities are easily damaged, and can not be used repeatedly. Also, the ship hit the collision avoidance made of steel just like diamond cut diamond,

thus the ship is vulnerable to injury. More importantly, steel is easy to rust in alternating wet and dry environment, so it needs high maintenance cost.

Figure 8: Fuzhou Wulong River Bridge composite collision avoidance facilities.

In order to solve the above problems, our group investigates new-type ship-bridge collision avoidance facilities using a combination of the materials and structures. The outer shell is glass fiber reinforced composite which can relax compact for its elastic deflection. The inside spatial grid reinforced foam core has good compression capability which can dissipate energy. The large structure can be fabricated by VIMP. Composite collision avoidance facilities can prolong compact time, dissipate compact energy, and effectively protect ship damage. There are three types of composite collision avoidance system: self-floating type, fixed type, and cylinder-shaped. More than 100 design projects were completed, among them four projects have been completed, such as Fuzhou Wulong River Bridge (Figure 8), The North Bridge of Runyang Bridge (Figure 9), Changzhou Xinmengge Bridge, and Guangzhou-Shenzhen High-speed Way along the Yangtze River Bridge: Shenzhen Section (Figure 10).

Figure 9: The North Bridge of Runyang Bridge composite collision avoidance facilities.

(a) Changzhou Xinmengge Bridge **(b) Guangzhou-Shenzhen High-speed Way Bridge**

Figure 10: Typical composite collision avoidance facilities.

4. CONCLUSIONS

The innovative composite sandwich structures and the application of these structures to the major civil infrastructure were investigated. Fundamental mechanical properties of the structures including tension, compression, bending, shear, and torsion conditions indicate that these structures meet the requirements of the mechanical properties of major civil infrastructure. Furthermore, the interface reinforcing investigation indicates that grooves in the core could improve the interlaminar behavior of sandwich composites effectively. Both the process and interfacial structure would be benefit. The energy release ratio would be promoted as the increase of the resin groove width and decrease of the groove distance. Additionally, note connection was investigated, indicating that the joints can satisfy the loading-capacity requirement corresponding to the deformation limit of major structures. Importantly, the novel composite structures were applied in engineering projects, such as pavement matting, sheet piles, truss bridges, floating structures, and ship-bridge collision avoidance facilities.

5. ACKNOWLEDGMENTS

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