All FRP and FRP-Concrete Hybrid Components for Bridges: Experiments, Theories and Case Study

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ABSTRACT

The experimental and theoretical research on FRP bridge is being conducted at Tsinghua University which aims at innovating high-performance FRP components and solving the emerging problems of FRP bridges. Three typical components, Outside Filament-wound Reinforced (OFR) FRP deck, Optimized Corrugate-skin Sandwich (OCS) FRP deck, and FRP-concrete hybrid beam are presented. The innovative configuration of OFR layer restricting the failure modes of delamination, in-plane shear failure, and debonding makes FRP more efficient used. The OCS FRP decks are optimized for moving load in simple supported condition as so to obtain the ultra-light FRP. Different hybrid beams using the pultruded FRP profiles are studied by experimental tests and theoretical analysis. The shear effect in hybrid beam is explained. Then, overall comments about FRP bridge components design are summarized. Based on the research of Tsinghua, four FRP pedestrian bridges are designed, including one cable-stayed bridge, one arch bridge, one girder bridge, and one suspending bridge. Three of them have been completed. The configurations and the structural behaviors of them are explained and summarized. This paper mainly discusses the rationale and advantages of FRP for bridges by different FRP components and application cases. These studies form part of a major on-going research programme at Tsinghua University.

KEYWORD

bridge deck, sandwich panel, shear connector, FRP-concrete hybrid beam, pedestrian bridge
1. INTRODUCTION

Bridges are the pivotal part in transportation system to dominate traffic capacity and efficiency, supporting traffic loads and being exposed in natural environment. With the development of human society and economy, higher requirements for bridges are put forward, such as the fast construction with less traffic disruption, reliability in expected long service life, chemical resistance, fatigue resistance and overload recoverability. These coincide with the period when fiber reinforced polymer (FRP) composite materials making their headway into the civil and bridge infrastructures. FRP is a promising high performance and innovative material for enhancing bridge’s performance.

By now, the development of FRP application for bridges can be reduced to three phases. The initial phase was from 1970s to 1980s. FRP was recognized by sophisticated civil engineers to be used to construct bridges, such as the Miyun Bridge in Beijing [1], the first all FRP traffic bridge in the world. Many prospective imaginations of FRP bridges have been presented in this period. For example, Meier proposed using carbon fiber reinforced polymer (CFRP) to build the Strait of Gibraltar Bridge [2], which has a span of over 10,000 meters long. The second phase started from 1991, when Ibach Bridge in Switzerland was strengthened with CFRP [3]. After it, FRP strengthening concrete structure was successfully applied in numerous structures, as well as a large amount of researches on this technique were carried out in various countries. Then, the guidelines or codes [4-9] of FRP strengthening concrete structures were published successively in UK, Japan, Canada, Europe, USA, and China. By the middle of 2000s, FRP had been known from the new structural material to the familiar one by most of civil engineers gradually. Besides strengthening structures, FRPs were also used tentatively in various forms for new bridges, including rebar, deck, cable, tendon, and profile. More than one hundred FRP bridges and more bridges with FRP components were completed [10]. But most of them were tentative projects.

Now is in the third phase. FRP is turning into an extensive used structure material for bridges in various forms because of its advantages including light weight, no corrosion, modular construction, environmentally friendly, and less maintenance.

However, the simple substitution of traditional materials by FRP may not benefit bridge, because it is a definite new material in term of its properties, such as high specific strength but brittleness, light weigh but low stiffness, no corrosion but thermal sensitivity, and tailorability but anisotropy. Furthermore, selection of fiber and resin and manufacture process must be considered integratively with structure design. Hence, the design concepts should be modified for FRP structural components. The core idea is to utilize FRP appropriately and efficiently according its properties by innovative design. From the perspective of the whole structure of bridges, FRP implementation causes some emerging difficulties in design, including deflection dominant, pedestrian's comfort of bridge vibration, and ultimate load capacity of structure cooperated FRP.

The experimental and theoretical research on FRP bridge is being conducted at Tsinghua University which aims at innovating high-performance FRP components and solving the new problems of FRP bridges. Three typical components, Outside Filament-wound Reinforced (OFR) FRP deck, Optimized Corrugate-skin Sandwich (OCS) FRP deck, and FRP-concrete hybrid beam are presented here. The OFR FRP deck is developed and investigated in experiments and numerical analysis. In this type of bridge deck, the failure modes, including delamination, in-plane shear failure, and debonding, which do not utilize the full strength in fiber direction, are avoided and the failure modes using FRP more efficiently are the control modes. Therefore, high-performance of OFR FRP bridge deck is obtained. The mechanism of OFR system is also demonstrated by finite element analysis (FEA). The OCS FRP deck is the designed result of ultra-light bridge deck, which is optimized for moving load in simple supported condition. The minimum weight of the bridge deck to satisfy flexural, shear and deflection limitations is the target. Two generation of OCS FRP decks are investigated by experimental tests and numerical analysis. An ultra-light OCS FRP deck is obtained. Different hybrid beams using the pultruded FRP profiles are studied. The shearing effect, including shear deflection, shear force distribution, shear connections in hybrid beam is investigated. Based on experimental tests and theoretical analysis, a hybrid beam is designed appropriately, which has the failure mode of FRP rupture in compressive and concrete crush so as to provide the significant deformability and bearing capacity. Shear failure which is quite often but lower bearing capacity is
eliminate. Overall comments about FRP bridge components design are provided.

Based on the research at Tsinghua University, four FRP pedestrian bridges are designed, including one cable-stayed bridge, one arch bridge, one girder bridge, and one suspending bridge. The former three have been completed. The configurations and the structural behaviors of them are explained and summarized in this paper.

2. OFR FRP DECKS

2.1 OFR Configuration

The OFR configuration was invented for enhancing the loading capacity of FRP decks. The fiber filaments, which are dipped in resin, are wound around the whole FRP deck as the core in the cross-angle ±θ. The filaments are tensioned before they are wound around. Thus, the performance of FRP decks which are confined by OFR is greatly improved. FRP decks have a tendency to disperse and swell, including transverse cracking, bubbling, and debonding. These failure modes cause the low loading capacities of FRP bridge decks. All of them can be significantly constrained by OFR treatment. Three different types of FRP decks with and without OFR as listed in Table 1 were studied. Their cross sections are shown in Fig.1.

![Table 1 Tested OFR FRP decks](image)

2.2 FRP Decks with OFR

SP is a GFRP modular pultruded profile deck for footbridges. It is formed with E-glass roving, continuous strand mat, and unsaturated polyester resin. An SP deck was wound with the filament around its cross section, which was called SPW. The E-glass roving and epoxy resin compose 2.2mm thick filament wound layer. The winding angle is ±80° and the fiber volume fraction is 0.55. The deck for highway bridges, named FD deck was the first generation product. It is combined with pultruded GFRP profiles and lay-up face plates. The pultrusions are composed of E-glass roving, continuous strand mat and unsaturated polyester resin. The plates are laid up with E-glass strand mat and unsaturated polyester resin. Epoxy resin bonds them together. An FD deck was treated with the same OFR layer as SPW, named FDW. The second generation FRP deck product for highway bridges was named HD deck. HD deck is composed of two pultruded GFRP face plates and four filament-wound square tubes bonded with epoxy adhesive. The plates, which are 12mm thick, are composed of roving layers, fabric layers, and mat layers. The tubes are made of E-glass and epoxy resin. Their average wall thickness is 8mm. The gaps and the filleted corner are filled with resin mortar. Two HD decks were treated with different thickness OFR: 3mm and 5mm, which were named as HDW3 and HDW5, respectively.

2.3 Experimental Results

All decks were loaded on simple supported. There were three loading conditions, of which the central point simulates the wheel load. The results[11] are following.

The load was applied on SP and SPW gradually to avoid sudden collapse. Some clacks began to appear for SP when the load reached 30kN, while it was at 40kN for SPW. It was noticed however that there was no sound emitted when the load reached the same level in the second loading after unloading from the evaluated maximum load. It can be concluded that the clacks are the signal of damage developing. With continuous increase in load, denser clacks were heard. SP reached its ultimate load by sounding loudly during failure, a crack along the top edge of the section occurred on one side, and the top plate delaminated and buckled. The thickness of the delaminated layer was about 3mm and the crack length was about 480 mm. Moreover, there was a crack on the other edge of the decks. For SPW, it had exhibited similar behavior as loading increased except that
the ultimate load was much higher than SP and resulted in a different failure mode. At the ultimate failure point, a longitudinal crack appeared on each inner web. The cracks extended from the span center to one support end in one half of the span only. Under the distributing beam at the center loading position, there was a vertical crack on the outside wound layer. Both SP and SPW displayed linear behavior throughout the loading history, as illustrated in Fig.2. Compared with SP, the failure mode of SPW has been changed; the ultimate load of SPW increased 59% with 12.7% increase in stiffness.

![Fig.2 Load-deflection curves of SP and SPW](image)

FD and FDW were loaded at the center of decks through a 200mm*200mm rubber pad. With the load increasing, the phenomena of the cracks were similar to that with SP and SPW. For FD, the first crack load was 50kN and the behavior was linear until the ultimate load of 256kN. However, the behavior of FDW was different as the pseudo-ductility appeared. Their load-deflection curves are shown in Fig.3. On the curve of FDW, the point at 276kN load and 12.8mm deflection can be defined as the nominal yield point, the ultimate deflection is 29.1mm and the maximum load is 299kN. The ductile behavior was not provided by the plastic deformation of material because FRP is a linear elastic material, but actually by fraction and sliding of the interface between components. The deflection of FDW was recoverable with unloading as shown in Fig.3. FD’s failure mode was debonding between the assembled profiles and the bottom plate. FDW’s failure mode was changed, due to OFR, which effectively confined the assembled profiles and the plates. The ultimate failure was caused by the cracks on the two webs under the loading patch. The loading patch obviously was sunken. And there was a slippage between the profiles and the bottom plate. Compared with FD, the maximum load of FDW increased 16.8% with a little increase in stiffness. It is the most significant effect that the deformability of FDW was more than doubled and had a yieldable characteristic.

![Fig.3 Load-deflection curves of FD and FDW](image)

The decks in HD group were loaded in two cases: four-point bending to estimate the stiffness and central point loading to simulate the wheel load. HD0 and HDW3 loaded to failure under Case 2. For HD0, the debonding between tubes and bottom plate occurred suddenly when the central load reached 485kN. HDW3 had a little ductile failure process due to the punching failure under the load position. It started from the load of 590kN. The maximum load reached 618kN. Comparing HDW3 and HD0, the load capacity had a 26.4% increase. HDW5 didn’t fail when the load went over the maximum value of the other two in Case 2. The load-deflection curves are compared in Fig.4. HDW5 was loaded to failure at 1737kN in Case 1. Before failure, the deck deformed obviously as shown in Fig.5(a). The deck was broken in bending, and the tubes were crushed as shown in

![Fig.4 Load-deflection curves of decks in Case 2](image)

![Fig.5 Failure of HDW5](image)
Fig. 5(b). In this mode, FRP was utilized effectively although it failed brittlely. Comparing three specimens, it can be concluded that the ultimate strength increases with the thickness of the OFR layer.

2.4 Failure Process Simulation and Mechanism

As the debonding failure between core and face plate in test was restricted by the use of OFR, which is its most considerable effect, this failure mode was simulated with ANSYS. The pre-crack method was used. There was a preset rectangle crack between core and bottom plate in the FEA model before loading. The depth of the crack was defined as \( c \), and the width of the crack was \( 2c \). It expended from one side to the other while \( c \) increased step by step under a certain load. Fig. 6 shows the failure process in Case 2. The stiffness and the deformation were investigated at each step.

![Fig.6 Debonding failure simulation of HDW](image)

![Fig.7 Shear stress in OFR](image)

The ideal bonds were considered under lower load. In Case 2, the transverse strain in OFR can be picked up. It can be found that there are peak strains at the corners, the edge of the loading patch, and the joint of face and rib. In the FEA of pre-cracked HDW, there is an obviously high shear stress area near the crack as shown in Fig. 7. The plate and the core can work together with the OFR layer to transfer the shear force. From the strain distribution of OFR, it is concluded that there are two actions mainly: bearing the shear force released from the crack and enhancing the local properties in transverse.

From the above studies, some conclusions can be drawn as below: OFR is an effective configuration for improvement of FRP deck’s behaviors in the loading capacity and the deck’s ductility; the changing of failure modes is the exhibition of OFR effect on mechanics as the failure mode corresponding with lower loading capacity is avoided; and OFR layers bear the shear force released from the crack and strengthen the local area in transverse direction in the FRP decks. The rational configuration like OFR is crucial to FRP structural component, which must be designed according to FRP’s characteristics.

3. OCS FRP DECKS

3.1 Design Concept of OCS FRP Decks

For the traditional sandwich deck, there are four major failure modes: core shear, indentation, face microbuckling, and face wrinkling. For the simply supported deck bearing a moving load, the maximum shear force occurs at the moment of load close to the support, which may cause core shear failure. However, the maximum bending moment appears when the load is located at the middle of the span, which is critical state for face microbuckling and wrinkling. A flat sandwich bridge deck with uniform section cannot be utilized sufficiently to bear a moving load. Hence, the corrugated skin for sandwich panel, an innovative configuration, is presented to achieve an ultra-light bridge deck. For the sandwich bridge decks, the top skin corrugated slightly may prevent the failures of bulking, indentation and wrinkling, the bottom skin curved and corrugated may improve the shear resistance near the supports. Certainly, the corrugation shape must be optimized to ensure that the deck meets the deflection requirement and has an adequate safety margin in strength.

The light weight sandwich decks made of GFRP skins and PVC foam core were studied and developed. The integration technique of digital design and digital manufacture was exploited for this deck. The shape of corrugated skin was analyzed and optimized by FEA program, which was saved and spread in code format. The foam core was cut to the complicated shape by a large CNC router as the code. Then, the fiber sheets were laid up to the surfaces of the foam core. Finally, FRP skins were attached on the core tightly as the shape after the resin infused by
vacuum aid system was gelled. All procedures are illustrated in Fig. 8.

Fig. 8 Integration technique of digital design and digital manufacture for OCS FRP deck

3.2 GI
The one-directional simply supported sandwich bridge decks were studied. The deflection limit of span/500 was required. The Divinycell H30 foam and H100 foam were used as the core and the bearing layer, respectively. The FRP skin was made of the OCTM Knytex glass fiber fabrics WR24-5*4 and Derakane 8084 resin. (a) Cross section (b) Comparison of bottom skins

Fig. 9. Shape of GI deck

Based on this design concept, GI (generation I) corrugated skin sandwich deck was designed. The cross section is illustrated in Fig. 9. The top skin in transverse direction is corrugated as quarter circles. The bottom skin is corrugated in two directions, cap-shaped in transverse direction and parabola in traffic direction, which is a smooth surface. Between them, hard foam layer and soft foam core are machined to the appropriate shape by CNC mill. In the middle of span, where the bending moment is the largest, the deck section close to a rectangle has greater flexural stiffness and greater bending moment resistance. Near the supports, the curved bottom skin can provide greater shear stiffness and capacity. The skins have the uniform thickness, and the section is changed in one direction. Based on the conceptual design, section shape parameters, thickness of skins and width of caps were optimized to get the minimum weight of the deck by ANSYS, where the maximum stress ratio and the maximum deflection were controlled in the acceptable range. As the result, GI deck's weight is much lower than the flat sandwich deck because the FRP skin is utilized efficiently.

A one eighth scaled specimen of GI deck was made by vacuum-aided resin infusion. It was loaded to failure at 12.5kN as a shear crack in the soft foam at the quarter span occurred, as shown in Fig.10. Based on the FEA results, the skins in GI deck with uniform thickness are too curved to be exploited efficiently. More optimizations for OCS deck are needed.

(a) GI (b) GII

Fig. 10 Failure of tested OCS decks

3.2 GII
Two-stage optimization was employed for OCS deck. In the first stage, the longitudinal curve was optimization by FEA. Then, the different skin thicknesses, section shape parameters, width of caps were optimized in one program. Finally, a curved surface for bottom skin as shown in Fig.11 was obtained.

(a) GI (b) GII

Fig. 11 GII deck

The scaled specimen of GII deck was loaded to failure as a shear crack between soft foam and hard foam occurred. The ultimate strength and stiffness of GII are 3.5% and 16.1% higher than those of GI, respectively. However, its weight is only 78.6% of GI deck. The load-deflection curves are shown in Fig. 12. Obviously, the optimization
is very effective. Through this work, an ultra-light bridge deck was achieved.

Fig.12 Load-deflection curves of GI and GII

Based on tests and FEA, the mechanical behaviors of corrugated skin sandwich panel were investigated. Comparing with the flat skin in sandwich panel, the corrugated skin can share shear force and provide shear stiffness. However, these contributions are more efficient near the supports. From the above studies on OCS decks, it can be seen that the shape and layup affect the structural behaviors obviously. The optimization for FRP components is an imperative for design.

4. FRP-CONCRETE HYBRID BEAMS

4.1 Three Types of FRP-Concrete Hybrid Beam

Many FRP-concrete hybrid beams with different configuration have been studied from 1990s [12]. They can be sorted into three types according to the intention using FRP: FRP composited with concrete by using shear connectors, FRP permanent formwork or protection for concrete, and FRP confine concrete, as shown in Fig.13. Some can be taken account into two different types. Type I and type II are studied at Tsinghua.

Fig.13 Three types of FRP-concrete hybrid beams

4.2 Type I

The first type hybrid beams have higher stiffness and more economical than all FRP beam, and have the advantage of corrosion resistance compared to the steel-concrete composite beams. Because of its higher elastic modulus, pultruded profiles are used mainly for this type of elements. However, in the most of FRP-concrete hybrid beams, FRP can not be utilized sufficiently as premature shear failure in FRP profiles or shear connector failure, which are unwanted.

Six FRP-concrete hybrid beams are fabricated and tested, which are composed of I-shaped pultruded GFRP beams and concrete. They are connected with the combination of stainless steel bolts and epoxy adhesive. The effects of concrete thickness, loading pattern, shear connector are investigated. The horizontal shear cracking on the web of FRP profile and the shear connector failure as shown in Fig.13 were observed in the experimental tests.

(a) web shear failure          (b) connector failure

Fig. 13 Failure of FRP-concrete hybrid beams

Based on the results of experimental tests and FEA, shear strength and shear stiffness of type I FRP-concrete hybrid beam were investigated. It is found that the shear strength linearly correlates to the depth of concrete. The shear deformation occupies 10-20% of total deformation of a normal hybrid beam. Furthermore, different shear connectors’ bearing capacities were determined by experimental tests. Finally, the theoretically reasonable configuration, which minimized the shear effect in pultruded FRP-concrete hybrid beam, was proposed.

Fig. 14 Improved FRP-concrete hybrid beams

A new FRP-concrete hybrid beam (250mm wide and 560mm high) was designed and fabricated as shown in Fig. 14. It has two ribs for shear connection, two horizontal stiffeners in the box beam and concrete depth to beam height ratio of 1/8. In the test, shear failure and connector failure were eliminated. It had a very large bearing capacity and deformability, as show in Fig.15(a). Its ultimate bending moment was 720 kN.m, and the ultimate deformation was about 1/45 span length. Even more important is that the beams’ failure was crush of concrete and top part of FRP, as shown Fig. 15(b). The measured maximum compressive strain was over 5000με. Obviously, the FRP in this beam was utilized sufficiently.
4.2 Type II
The type II hybrid beam is to mainly utilize corrosion resistance of FRP, which is expected in the strong corrosive environment, such as coast, chemical plant, and sewage treatment plant. The high durable FRP-RC hybrid member was designed as shown in Fig.16. FRP enclosure as the permanent formwork protects the concrete and embedded steel bars. It can also increase the strength of the members.

The high durable FRP-RC hybrid members were tested comparing with RC beam in laboratory and field. The load-deflection curves of tested hybrid beam and reference RC beam in lab are shown in Fig.17. A long-term exposure test is undertaking. Ten pairs of beam have been placed on a coastal beach and been exposed in natural environment in Hainan (an island in South China Sea) for 30 months, where the annual average temperature is 23.8 °C and ultraviolet intensity is high. By now, the debonding between the concrete and FRP, and the surface cracks have been seen in the hybrid beams without loading. Corrosive medium will get into the gap between FRP and concrete. The long-term behavior of type II hybrid beam should be investigated more, although the mechanical performance of hybrid beam is acceptable.

5. DISCUSSIONS
It can be found from above that FRP structure components are definitely different to the traditional RC members and steel members, especially in the following aspects: (1) an appropriate mode selected from many failure modes should be chose, designed and achieved; (2) local failure caused by stress concentration should be averted; (3) shear effects including shear failure and shear deformation need to be paid much attention; (4) optimization is an imperative for design; (5) long-term behavior of interface between FRP and other materials is critical for hybrid members. The advantages of FRP will not benefit bridge structures if these are neglected.

6. APPLICATION CASES
Four FRP pedestrian bridges were designed, three of them have been constructed. It should be noted that deflection and vibration may control the structure design in these cases.

6.1 Cable-Stayed Bridge
A demonstration cable-stayed pedestrian bridge was constructed in Jinzhou, and then moved to Miyun, Beijing, as shown in Fig.18(a). It has three spans of 5m, 24m, and 4.1m, respectively, and has 32 cables totally. Cables, beams, stair and railing are made of pultruded GFRP. The tower is steel. The deck consists of twenty four 500mm-high beams (cross section as shown in Fig.18 (b), and the cable has a diameter of 32mm. The girders are composed of large cross-section pultruded profiles made with glass fiber and vinyl resin.

In this cable-stayed bridge, the most concerned
issue is the prominent vibration under human-induced load, which refer to comfort level of pedestrian. This phenomenon is caused from low stiffness and light weight of FRP. Generally there are two methods in design codes to control vibration: minimal natural frequency limit and maximal acceleration limit. Nevertheless, acceleration is recognized as key factor that directly affect human’s comfort level. From the initial analyzing results, it was found that the natural frequency was 3.13Hz (higher than Chinese code minimal limit 3.0Hz), while the maximal deflection was $L/300$ (higher than Chinese code maximal limit $L/600$, $L$ for span length). To meet the service limit state (SLS), an additional layer of concrete was proposed to pave on the surface of bridge. After then, the natural frequency was decreased to 2.72Hz and the maximal deflection was decreased to $L/435$. However, the significant improvement is that the maximal acceleration under human-induced forced vibration load was profoundly suppressed to 45%. Thus the cable-stayed bridge can meet the actual SLS after the improvement. In situ tests have been executed to fully validate the effect of this improvement. Besides, the structural performance of railing systems and the safety design of railing systems were fully investigated in this case study.

6.2 Arch Bridge
An arch bridge was constructed in Hebei Province, which has been in normal use, as shown in Fig.19. It has three spans of 9m, 27m, 9m, respectively, with steel arch in the main span. Similarly, components are made from pultruded GFRP, except some joints with steel. The deck also consists of seventeen 600mm-high hybrid beams as shown in Fig.14. With the experience from the demonstration cable-stayed bridge, this arch bridge is paved a concrete layer.

The initial design shown that the arch bridge can fully meet the ultimate limit state (ULS) and service limit state (SLS), with natural frequency of 6.11Hz and maximal deflection of $L/1470$. After completion of construction, the actual natural frequency is 6.88Hz while the damping ratio is 3.3%. 110 volunteers were chosen to walk on the bridge to evaluate the vibration status, including group walking, randomly walking, jumping and runing. A survey from these volunteers shows that this bridge has a high level of vibration comfort, and few people can perceive the vibration. Time history of acceleration was also recorded when volunteers were moving with different patterns, and the maximal acceleration was $0.00789 \text{ m/s}^2$ (much lower than the maximal acceleration limit of $0.7 \text{ m/s}^2$ in Europe code). Thus, this first applied FRP bridge shows a good behaviour both in static and dynamic.

![Fig.19 Arch bridge with FRP beams](image1)

6.3 Panel Bridge
A bridge was constructed in Hebei Province, which is close to the arch bridge, as shown in Fig.20. It has two separate spans of 8m and 16m with a cable-stay system, which is not pre-stressed in the cables and thus the system is just for decoration purpose. The deck also consists of seventeen 600mm-high hybrid beams.

The initial design result can also fully meet the ULS and SLS, with natural frequency of 5.51Hz and maximal deflection of $L/1227$. After completion of construction, the actual natural frequency is 7.16Hz while the damping ratio is 4.1%. The same procedure to evaluate the vibration status by volunteers were conducted and the maximal acceleration was $0.00668 \text{ m/s}^2$. The arch bridge and the beam bridge have both validated the feasibility of FRP bridge.

6.4 Suspension Bridge
A suspension bridge shown in Fig.21 is currently being designed, which will be constructed in Beijing. It has three spans of 12m, 28m, and 12m, respectively. The suspension system has five steel circle pipes suspended by cables in the main span. The tower consists of 500mm diameter concrete filled steel pipes. The stainless steel cables are
pre-stressed. The deck is a composite beam with GFRP and concrete.

In this bridge, load carrying capacity, internal forces, shearing resistance, interfacial performance of the beam are all analyzed and designed. In this design stage, the natural frequency is 3.45Hz and the maximal deflection is L/690. The approach to control the deformation and the natural frequency is investigated, which can provide reference for the design of FRP suspension bridges.

7. CONCLUSIONS

Selected ongoing research at Tsinghua University on FRP components for bridges has been presented herein, including the experimental studies and numerical analysis of OFR deck, OCS deck and two types of FRP-concrete hybrid beams. The innovative concepts for improved the FRP components performance are illustrated. Meanwhile, the difficulties from the difference of FRP to traditional material are summarized, needs for appropriate mode, local failure caused by stress concentration, shear effects imperative optimization and long-term behavior of interface.

Four FRP pedestrian bridges, including one cable-stayed bridge, one arch bridge, one girder bridge, and one suspending bridge, have been introduced herein. The configurations and the structural behaviors of them are explained. Deflection and vibration will be more critical than strength in the design.

Looking ahead, to utilize FRP appropriately and efficiently according its properties by innovative design is expected, which will realize the widespread implementation of FRP bridges.

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