FLEXURAL BEHAVIOR OF HYBRID FRP GIRDER WITH CONCRETE DECK

H. Mutsuyoshi ¹, T. Aravinthan ², S. Asamoto ¹, A.C. Manalo ¹* and K. Suzukawa ³

¹ Department of Civil and Environmental Engineering, Saitama University, Japan. Email: engr_manalo@yahoo.com
² Faculty of Engineering and Surveying, University of Southern Queensland, Australia
³ Toray Industries, Incorporated, Japan

ABSTRACT

An innovative hybrid composite girder is being developed in Japan consisting of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). The innovative feature of this girder is the optimum use of CFRP and GFRP in flanges to maximize structural performance while reducing the overall cost by using only GFRP in the web section. The flexural behavior of such hybrid FRP composite girders was investigated. Preliminary tests revealed that hybrid FRP girder failed due to local buckling and separation of laminates in the compression flange with the tensile strain much lower than the expected maximum strain. In view of improving its structural performance and practical application, concrete deck was provided on top of the hybrid FRP composite girder to avoid local brittle failure and to fully utilize the superior characteristics of the FRP materials. Different types of shear connection were trialed to provide composite action between the hybrid FRP girder and concrete deck. This paper will discuss the results of the experimental investigation on the combined section of concrete deck and hybrid FRP composite girder focusing mainly on issues related to the composite action of such girders.

KEYWORDS

Hybrid FRP composite girder, CFRP, GFRP, concrete deck, composite action, shear connection.

INTRODUCTION

There has been an increasing interest in the use of Fiber Reinforced Polymer (FRP) composites for civil engineering applications. FRP composite materials are extensively being applied for retrofitting structural members and have been an accepted reinforcement for concrete. The use of FRP as stay-in-place bridge deck panel has been explored for a number of years (ACI 2006). In addition, FRP tubular forms filled with concrete were already used for structural beams and columns. The high tensile strength, light weight, non-corrosive properties, rapid and economical construction make a FRP attractive for bridge construction. However, due to its high cost, the advantages of FRP material can only be realized when new design concepts and structural systems with improved durability, reduced life-cycle costs and short construction period are developed.

Recently, the authors have undertaken studies on the flexural behavior of hybrid FRP composite girder which optimizes the combined use of CFRP and GFRP. Initial investigation showed that the hybrid FRP girder failed without utilizing the material tensile strength fully (Mutsuyoshi et al. 2007). Similarly, separation of laminates between the GFRP and CFRP and local buckling in the compressive flange caused a sudden failure of the FRP girder. According to Bank (2006), the ultimate strength of the FRP material is not realized when local buckling or delamination occurs. These failure modes are likely to control the design of structures. Thus, further improvement and development are needed to increase the capacity of the hybrid FRP section.

Many problems in FRP composite beams are associated with poor performance of the thin compression flange. Barbero (1999) suggested that the compression flange of FRP composite girder has to be supported or restrained by a firmly attached flooring system to prevent local buckling. Different lay-ups can also be used to improve the property of the FRP section (Bank 2006). Thus, it is conceived that placing concrete deck on top of FRP composite girder to carry the compressive force will prevent local failure at the thin compression flange. This is an economical solution when compared to thickening the compression flange with more glass or carbon fibers.
In future bridge projects, it is likely that FRP composites will be used as a main girder to support concrete bridge decks. This combination of hybrid FRP girder and concrete deck is appropriate for developing the composite action to fully utilize the superior characteristics of each material. Composite construction allows two structural elements to carry loads and deflect as a unit when integrally connected (Nilson et al. 2003). This type of construction consisting of composite girder and deck has been conducted in the region other than Japan. In England, concrete-FRP composite bridge deck with steel girders wrapped in protective enclosures was constructed (Keller 2003). Gurtler (2004) studied the composite action of FRP bridge deck adhesively bonded to steel girder. Van Erp (2005) developed a FRP box beam with an integral concrete compression flange to control serviceability deflection. Zhao et al. (2000) investigated the flexural behavior of FRP bridge deck adhesively bonded to steel girders with reinforced concrete bridge deck and pultruded hybrid FRP rectangular girders with polypropylene fiber reinforced concrete deck. Connection between the FRP composite girder and concrete deck was accomplished by embedding shear connectors or providing carbon snap-in stirrups for horizontal shear transfer. The concrete aid in carrying compressive forces and stabilized the thin walled carbon shell against buckling.

The addition of concrete deck will result in an upward shift in the location of the neutral axis to exhibit higher tensile capacity on the hybrid FRP girder and lead to effective utilization of its strength. In FRP-reinforced concrete, the design for a composite section allows concrete compression failure and FRP tensile failure occur simultaneously. This requires that the neutral axis be higher because of the large strain to failure the FRP in tension relative to the crushing of the concrete (Bank 2006).

Previous studies suggested that the investigation of hybrid FRP composite girder with concrete deck is necessary. In this paper, the flexural behaviour of hybrid FRP girder with a compositely acting concrete deck is investigated. It is anticipated that the addition of concrete deck will prevent local deformation on the thin compression flange and will lead to utilization of the superior characteristics of FRP materials. Similarly, an effective connection between the FRP girder and concrete deck is investigated since it is anticipated that shear failure in the interface between concrete and FRP can easily occur.

**MATERIALS AND METHOD**

An appropriate shear connection between the interface of FRP girder and concrete deck is important to develop a composite structure. Similarly, the failure mechanism of a suitable shear connection should not be catastrophic. In literature, only a few examples can be found on this topic. Most studies on deck-to-girder connections involved FRP deck and girder made from conventional materials. Hence, initial investigation on the behavior of hybrid FRP girder with two differently bonded and compositely acting concrete decks was conducted.

Adhesive bonding, an adopted connection method for girder and deck system, and a combination of mechanical fasteners and adhesives to prevent delamination failure were used in this study. FRP girder with an overlying precast concrete deck bonded with epoxy only (FRP-conc 1) and FRP girder with cast-in-place concrete deck bonded with epoxy and steel u-bolts (FRP-conc 2) were subjected to three point loading test. Two 1.5 m long FRP composite girders with 1.0 m loading span were used as test specimens. The concrete deck was 75 mm thick and 275 mm wide with a small amount of steel reinforcement (3 pieces 6 mm diameter) to facilitate casting. Epoxy resin adhesives with the help of 8 pieces 10 mm diameter bolts were used to connect the precast concrete deck. On the other hand, u-shaped bolts made of high-strength steel with 10 mm diameter were used as shear studs as well as epoxy resins with gravel chips to developed full composite interaction between the FRP girder and cast-in-place concrete deck. The top flange of the FRP composite girder was sandpapered and cleaned with acetone to give a rough bond surface before the application of epoxy adhesives. Figure 1 shows the shear connection for both specimens.
Subsequently, four point loading test on hybrid FRP girder with compositely acting concrete deck was conducted. Specimen FRP-conc 3 represents FRP composite girder with cast-in-place concrete deck bonded with epoxy and steel u-bolts. The top and bottom flanges of FRP composite girder were comprised of CFRP and GFRP with 14.0 mm thickness and GFRP of 9.0 mm thickness in the web. The modulus of elasticity of CFRP and GFRP were 113,000 MPa and 35,000 MPa, respectively. Metal box stiffeners spaced at 333.33 mm on center were installed in the web to prevent premature failure and ensure that only tensile failure will occur in the FRP girder. Stiffeners were bonded to FRP specimen using epoxy adhesives. U-shaped bolts made of high-strength steel with 10 mm diameter as well as epoxy resins with gravel chips were used as shear connection. The concrete deck was 100 mm thick and 400 mm wide with steel reinforcement (5 pieces 16 mm diameter bars) to provide additional compressive force on the concrete section. In addition, 5 pieces 16 mm diameter bars were used as bottom reinforcement for delaying the formation of tension cracks and limit the crack width on the concrete deck. Lateral steel ties were installed to provide confinement of concrete. The concrete has a mean cylinder strength of 32 MPa obtained from compression test at 14 days (at the same age of testing the specimen). The dimensions and details of the specimen are shown in Figure 2.

The test set-up and instrumentation are shown in Figure 3. The beam was simply supported with angle bars attached near the support to prevent lateral collapse of the beam. Load was applied manually by hydraulic jack and the deflection, strains and failure mode were recorded during loading and until failure of the specimens.

RESULTS AND DISCUSSIONS

Shear Connection

A suitable connection between the interface of hybrid FRP girder and concrete deck is discussed firstly. Results of the initial test showed that the adhesive bond provided by epoxy and the mechanical anchorage by steel u-bolts enabled a smooth load transfer from FRP girder to the concrete deck. The stiffness of both specimens was the same before cracking of the concrete as shown in Figure 4. However, FRP-conc 2 behaved slightly stiffer than FRP-conc 1 after cracking of concrete until failure. FRP-conc 1 failed due to total debonding of epoxy which caused separation of the FRP girder and concrete deck. On the other hand, when debonding of epoxy occurred in FRP-conc 2, the load suddenly dropped but increased again. This indicates that the u-bolts started
contributing to the shear anchorage between FRP girder and concrete deck. The concrete flowed in the open holes created by the u-bolts forming dowels might have provided the shear resistance. Similarly, reinforcement bar placed in the open holes with the surrounding concrete improved the transfer of horizontal shear forces between FRP girder and concrete deck. Failure of the composite girder occurred due to shear failure of concrete with the concrete deck still attached to the FRP girder. Figure 5 shows the failure mode of both specimens.

Figure 4. Load and mid-span deflection relationship of FRP-conc 1 and FRP-conc 2

Figure 5. Failure mode of initial test on hybrid FRP girder with concrete deck

Analytical Result

Fiber Model Analysis or FMA (Park and Paulay 1975) was conducted to determine the moment curvature and strength capacity of the combined FRP girder and concrete deck. The moment-curvature and load-strain relationships of the FRP girder and concrete deck based on FMA and result of the four-point loading test is shown in Figure 6. The FMA shows almost a linear moment-curvature relationship and makes a good agreement with the experimental result up to final failure of the specimen. Based on the result, a simple FMA enables to predict the strength capacity of a hybrid FRP girder with compositely acting concrete deck. This also showed that a complete interaction between the FRP girder and concrete deck was achieved using steel u-bolts and epoxy resin as shear connection. Furthermore, the assumption of compatibility of strains throughout the depth of the section, and equilibrium of force resultants at any points along the member is valid.
Load-deflection Relationship

In this section, the behaviour of FRP girder with an overlying concrete deck was compared with the result of the four-point loading test conducted on FRP girder alone. Figure 7 shows the load deflection of the FRP girder with and without concrete deck. FRP-1 represents a load deflection relationship of the hybrid FRP girder only. Based on the figure, the load capacity of FRP-conc 3 increased linearly with deflection until an applied load of 246 KN and a decrease in stiffness was observed until final failure. The reduced stiffness may be caused by the development of diagonal cracks within the shear spans which contributed to the downward deflection of the beam. Before ultimate failure, there was widening of cracks in the concrete deck and an increased amount of deflection even without an increase in the applied load. At an applied load of 427 KN with a mid-span deflection of 73.9 mm, the composite beam failed due to crushing of the concrete at the shear span followed by shear failure of the top flange and web of the FRP girder. On the other hand, FRP-1 behaved linearly with no signs of damage before final failure. FRP-1 failed at a much lower load and exhibited large amount of displacement. Consequently, result of the experimental investigation showed that composite action from a concrete deck could overcome deflection limitations inherent in FRP composite girder and a higher load carrying capacity at final failure could be attained.

![Figure 7. Load and mid-span deflection relationship of hybrid FRP girder with and without concrete deck](image)

Failure Mode

Figure 8 shows the failure mode of FRP composite girder with concrete deck. Development of diagonal cracks within the shear span started at a load of 246 KN. The crack width started to increase with the continuous application of load and lead to the compression failure of concrete deck near the loading point followed by shear failure on the top flange and web of FRP composite girder. Shear failure in the top flange of FRP girder may be due to stress concentration in the holes provided for the u-bolts. This was not the expected mode of failure as the composite beam was designed to fail by rupture of the FRP to determine the strain level where FRP girder will fail in tension. However in actual design, this may be a preferred failure mode because cracks in the concrete deck will give an adequate warning of failure to the structure.

![Figure 8. Failure mode of hybrid FRP girder with concrete deck](image)
Load Strain Relationship of Hybrid FRP Girder

The load strain relationship of the top and bottom flanges of FRP girder tested with and without concrete deck is shown in Figure 9. In both tests, hybrid FRP girder behaved linear elastic until final failure. The composite action resulted to a stiffer and higher load capacity with higher tensile strain in the FRP girder. The maximum tensile strain measured for FRP-conc 3 was 9,050 microns compared to only 6,245 microns for FRP-1. Similarly, there is a significant decrease in the compressive strain in the top flange of the FRP girder preventing the separation of laminates and sudden failure of the beam. This shows that the superior characteristics of the FRP material was efficiently utilized with the addition of concrete deck in the thin compression flange. Composite construction eliminates the need for expensive CFRP in the upper flange of the hybrid FRP girder as this is subjected only to minor stresses.

CONCLUSIONS

The flexural behavior of hybrid FRP girder with concrete deck was investigated. A complete interaction at the interface of FRP girder and concrete deck was achieved using steel u-bolts and epoxy resin. The predicted strength based on a simple FMA was in good relationship with the experimental result. The composite action resulted to a higher stiffness and strength with the FRP girder exhibited high tensile strain before final failure. The composite beam failed due to crushing of the concrete in the shear span followed by shear failure in the top flange and web of FRP girder. Lastly, the superior characteristics of FRP girder can be efficiently utilized if a stiffer material such as concrete is provided on the top flange which can form a part of the bridge deck.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the MLIT grant-in-aid for scientific research of construction technology. The assistance of Mr. Nguyen Duc Hai and Ms. Ikumi Yamamoto in conducting the experiment is likewise acknowledged.

REFERENCES