An Innovative Hybrid FRP-Concrete Bridge System

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Synopsis: An innovative corrosion-free system for short- and medium-span bridges consisting of precast prestressed concrete truss girders and cast-*in-situ* concrete deck has been developed. Advantages of the new system include reduced self-weight and enhanced durability. The girders consist of top and bottom concrete flanges connected by precast vertical and diagonal members made of fiber reinforced polymer (FRP) tubes filled with concrete. Glass FRP dowels and corrosion-resistant steel stud reinforcement are used, respectively, to connect the vertical and diagonal members to the concrete flanges. The flanges are pretentioned with carbon FRP tendons. The deck slab is reinforced with corrosion-resistant steel bars in the bottom transverse layer and with glass FRP bars in the bottom longitudinal and the top layers. The girders may be post-tensioned with external carbon FRP tendons to balance the slab weight and to provide continuity in multi-span bridges. The general details of the system and an experimental evaluation of its critical components, namely, the FRP tubes and the truss connection, are presented. Three types of FRP tube and four types of connection are investigated. The results of testing eight connection specimens under static loading are presented. The tests have shown superior performance of the connection when filament wound tubes and continuous double-headed studs are used.

Keywords: bridges; concrete-filled tubes; corrosion-free; deck slab; durability; fiber-reinforced polymers; headed studs; innovative; prestressing; truss girder

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INTRODUCTION

Over the past decade, there has been a significant increase in the application of fiber reinforced polymers (FRPs) for strengthening and rehabilitation of aging and deteriorated infrastructure. However, the use of these innovative materials in new construction has not reached its full potential, mainly because of their high cost in comparison with other conventional construction materials such as concrete and steel. The advantages of FRPs, such as the high strength, light weight, easy handling, enhanced durability and low maintenance, can be more realized when FRPs are used as load-carrying structural elements. Reduction of construction costs can be achieved when the design offers reduced amounts of materials, simplified fabrication and construction procedures, lighter weight and shorter construction time. The use of FRP in new structures, particularly bridges, can be limited if all the structural components are made of FRP, mainly due to its relatively small rigidity. This limitation can be eliminated when the structural system combines FRPs with other conventional materials in a hybrid form.

A few researchers around the world have attempted to develop new bridge systems that employ FRP structural components as load-carrying elements. In Japan, for example, a new composite concrete-FRP prestressed box-girder bridge system has been proposed (Gossla and Yoshioka 2000; Niitani et al. 2001). In this system, the heavy concrete web of conventional box girders is replaced with pultruded glass FRP panels. In the United States, two modular bridge systems have been developed: one is made of FRP box sections supporting conventional concrete slab cast on stay-in-place FRP deck panels (Seible et al. 1998; Cheng et al. 2005), and one consists of carbon fiber shells filled with concrete and used as primary flexural members connected in the span direction along their length to a conventional reinforced concrete slab by means of steel or special FRP dowel connectors

(Zhao et al. 2001a). This latter system was used in construction of the 20 m long Kings Stormwater Channel Bridge on California State Route 86 (Zhao et al. 2001b).

The concrete-filled FRP tube system utilizes the best characteristics of both the FRP and the concrete. Under compression, the tube provides confinement to the concrete core and, hence, increases its compressive load carrying capacity. The concrete on the other hand provides local stability to the thin-walled tube and, hence, prevents premature local buckling (Fam 2000). Under tension, when properly bonded to concrete, the FRP provides corrosion-resistant tensile reinforcement. Use of concrete-filled tubes primarily as flexural members is, however, less efficient than their use as axially-loaded tension or compression members. Fam (2000) has shown that for concrete-filled FRP tubes used as flexural members, the shear strength provided by the tube is small, unless filament-wound tubes with fibers mainly oriented in the circumferential direction are used. Also, the confining effect of the tube on concrete in the compression zone of flexural members is insignificant as compared to that of similar members under pure axial compression. The FRP tubes, however, serve as stay-in-place formwork for the concrete, protect it from the environment, and enhance its durability.

This paper is concerned with the development of a system for short- and medium-span bridges. In the proposed system, the superstructure is built entirely from materials that are not vulnerable to corrosion. The system consists of precast prestressed concrete truss girders and cast-*in-situ* concrete slab (Fig. 1). Each girder has top and bottom concrete bulbs (flanges) connected by precast vertical and diagonal truss members. In addition to concrete, the materials used are FRP and stainless or any other type of corrosion-resistant steel, which are utilized as described in the following section. In addition to being immune to corrosion, the new system is light in weight and durable. The light weight reduces the load on the supports and allows for longer spans, resulting in reduction in the size of the substructure and in the number of supporting piers in multi-span bridges and, hence, reduction in the initial cost. The improved durability reduces the maintenance cost and extends the life span of the structure.

DESCRIPTION OF THE BRIDGE SYSTEM

The Truss Girders

Each truss girder consists of top and bottom concrete bulbs (flanges) connected by precast vertical and diagonal members (Fig. 2a). The concrete bulbs are pretensioned with carbon FRP tendons and provide the flexural resistance of the girder. The bulbs are provided with stainless steel stirrups and non-prestressed glass FRP longitudinal bars at the stirrup corners (Figs. 2b and c). The vertical and diagonal truss members, resisting the shear forces, are made of hollow glass FRP tubes filled with high-strength concrete. The verticals are predominantly in compression and the diagonals are mainly in tension. The diagonals are optimally set at 45 degrees. Both the verticals and the diagonals are produced prior to the bulbs. Glass FRP dowels protrude from the ends of the verticals to connect them to the bulbs (Figs. 2a and b). Stainless steel headed studs (straight bars with anchor heads at one or both ends) connect the diagonals to the bulbs (Figs. 2a and c). Alternatively, the diagonals can be pretensioned with FRP flexible tendons (e.g., Carbon Fiber Composite Cables, known as CFCC, produced by Tokyo Rope, Japan). The pretensioning will provide the diagonals with a reserve tensile capacity in case the FRP tubes are damaged, for example, by fire. The tendons protrude from the ends of the diagonals and are bent to serve as dowels connecting the diagonals to the bulbs.

Single or double-headed studs are selected for this project because of their superior anchorage properties. With an area of the head 9 to 10 times the cross-sectional area of the stem, the full yield strength of the studs can develop immediately behind the head, without the need for development length as required in conventional reinforcement (Ghali and Dilger 1998).

For ease in production, it is preferable to cast the bulbs in a rotated position, while the verticals and the diagonals lie on a horizontal surface. In case of damage by fire, the FRP tubes can be easily replaced by wrapping the concrete diagonals and verticals with FRP sheets or jackets. Stainless steel double-headed studs are used to connect the deck slab to the girders (Fig. 2b).

After casting the deck slab the precast truss girders can be post-tensioned by external carbon FRP tendons (CFCC) to counterbalance the slab weight and to provide continuity in multi-span bridges. An external tendon can be harped (held down) to the bottom bulb at one or two points within the span and held up to the top bulb at one point near the intermediate supports in continuous bridges. No deviators are required at the harping points. The horizontal parts of the tendons between the harping points pass through ducts placed inside the bottom bulb, in a single-span bridge, or inside both the top and bottom bulbs in a continuous bridge. Deviation of the tendons from the horizontal is done at the location of the truss joints. The ducts can be left ungrouted for easy replacement of the tendons, or can be grouted to achieve bond between the horizontal parts of the tendons and the concrete bulb(s). Research has shown that partially bonded external tendons enhance both the strength and ductility of externally prestressed concrete members (Hindi et al. 1996).

The Deck Slab

Particular attention is given to the bridge deck slab as it represents an important component that considerably affects the overall cost and quality of the structure. Reinforcement of the deck slab can all be glass FRP bars. Alternatively, the FRP bars can be used in both the transverse and longitudinal directions for the top reinforcement, whereas the bottom reinforcement can be composed of stainless steel bars in the transverse direction (to act as ties in the arch action) and glass FRP in the longitudinal direction (Figs. 2b and c). The glass FRP reinforcement at the bottom longitudinal and top layers is only for crack control and should be of minimum amount.

EXPERIMENTAL PROGRAM

The initial phase of this research involved computer modeling and analysis of the proposed bridge system in order to determine the optimum design of the truss girder in terms of its depth for different ranges of span and loading, dimensions of the top and bottom bulbs, amount and placement of prestressing, size of the truss elements, and number and size of the stud reinforcement required. An extensive experimental program is currently in progress at the University of Calgary to investigate performance of the various components of the bridge system and to verify the optimum design. The experimental program includes the following:

1. Axial compression tests on samples of different types of concrete-filled FRP tube.
2. Tests on bond between the FRP tube and the concrete.
3. Static and fatigue loading tests on different types of connection between the truss elements and the top and bottom bulbs.
4. Tests on large-scale truss girder specimens covered with or without a concrete slab under static and fatigue loading and long-term effects.

Details of the tests of items 1 to 3 above (except for fatigue loading) are given below.

Compression Tests on Concrete-Filled FRP Tubes

As previously mentioned, under compression, an FRP tube confines the concrete core and increases its load carrying capacity. Tests were conducted on three different types of available glass FRP tubes to determine the enhancement of the compressive resistance that could be achieved and, hence, the most suitable type for the vertical (compression) members of the proposed truss girder. One type of pultruded glass FRP tube and two types of filament-wound tubes were used. The pultruded tube contained approximately 80% of the fibers oriented in the longitudinal direction and 20% in the circumferential direction. One type of the filament-wound tube contained approximately 70% circumferential fibers and 30% longitudinal fibers. The other type contained fibers wound in the diagonal direction at approximately 45 degrees.

The pultruded tube specimens were of 80, 100, and 150 mm nominal inner diameters. All filament-wound tubes were of 85 mm nominal inner diameter. The height of all specimens was set at twice the concrete core diameter. Two groups of specimens were tested. In Group 1, the FRP tube was 10 mm shorter in height than the concrete core. This was achieved by cutting a 5 mm ring from each end of the tube. In this manner, only the concrete core would be in direct contact with the loading plate and the pure confining effect of the tube could be assessed. In Group 2, both the tube and the concrete core had the same height and the compression load was applied on both the concrete and FRP. Table 1 gives nominal dimensions of all the tested specimens. Some specimens of the filament-wound tube were also tested with a rough inner surface consisting of sand mixed with resin adhesive to obtain bond between the concrete and the tube. Plain concrete specimens, with target compressive strength between 30-35 MPa, were also tested for comparison. All specimens were instrumented with strain gauges attached in both the vertical and transverse (circumferential) directions. Figure 3 shows elevations and cross-sections of typical specimens of Groups 1 and 2.

Bond Tests on Concrete-Filled FRP Tubes

Three groups of concrete-filled pultruded tubes were tested to examine means of better bond between the concrete and the tube. In the first group (Type S), the inner surface of the tube was left without treatment for bond and was used as control specimens. In the second group (Type A), the inner surface was coated with a 50 mm wide circumferential strip of sand mixed with resin adhesive. In the third group (Type R) shear connectors were provided in the form of two 60 x 150 mm GFRP strips glued to the inner surface and fixed in position by means of rivets. Figure 4 gives dimensions of both the tubes and the concrete core. All specimens were tested under vertical load applied to the top of the concrete core.

Connection Tests

The most important component of the truss girder is the connection of the vertical and diagonal elements to the concrete bulbs. Tests were therefore carried out to examine the behavior and efficiency of different types of connection and to determine the best type to be used. Specimens of a single section of truss consisting of one vertical and one diagonal member connected to portions of the top and bottom bulbs were fabricated (Fig. 5). The specimens were sized based on a prototype design for a pedestrian bridge spanning 45 m. The bottom bulb was fixed to the strong floor and a horizontal load was applied to the top bulb to produce a compressive and tensile force in the vertical and diagonal elements, respectively.

Four different reinforcing types were used to connect the diagonal to the concrete bulbs:

1. Unbonded post-tensioned tendon passing through the centre of the diagonal and anchored outside the top and bottom bulbs (Fig. 6a).
2. Long double-headed studs with the heads embedded in the top and bottom bulbs and the stems extending through the length of the diagonal (Fig. 6b).
3. Short double-headed studs at the upper and lower ends of the diagonal, with one head embedded in the top or bottom bulb and the other head embedded in the concrete inside the FRP tube (Fig. 6c).
4. Pairs of single-headed studs, one at each end of the diagonal, with the head embedded in the top or bottom bulb and the stems spliced inside the FRP tube with deformed steel bar of the same diameter as the stem of the stud (Fig. 6d).

A total of eight specimens, two for each connection type, were fabricated and tested under static loading. The first four specimens were built using pultruded FRP tubes of 3 in. and 5 in. nominal diameters for the vertical and diagonal elements, respectively. The inner diameter and wall thickness were, respectively, 80 mm and 4.5 mm for the vertical, and 126 mm and 3.5 mm for the diagonal element. The tensile strength and modulus of elasticity of the FRP tube were, respectively, 400.5 MPa and 25.3 GPa in the longitudinal direction, and 40.8 MPa and 10.15 GPa in the circumferential direction.

In the second four specimens, filament-wound FRP tubes with 70% circumferential fibers and 30% longitudinal fibers were used for the truss elements. Tubes of 3 in. and 4 in. nominal diameters were used for the vertical and diagonal elements, respectively. The inner diameter and wall thickness were, respectively, 84 mm and 1.9 mm for the vertical, and 110 mm and 1.9 mm for the diagonal element. Nominal diameter of 5 in. was not available in this type of tube. Adequate concrete consolidation was achieved and tensile resistance was not affected with the 4-in. tube. The tensile strength and modulus of elasticity of the tube were, respectively, 240 MPa and 20.6 GPa in the longitudinal direction, and 480 MPa and 29.0 GPa in the circumferential direction.

Figure 7 shows the stud reinforcement used in this project. The double-headed studs had plain stem, whereas the single-headed studs had deformed stems. Four studs of 12.7 mm diameter were used in the diagonal of each specimen. Deformed 10M (11.3 mm diameter) were used to splice the single-headed studs. Material properties of the studs and the splice bars are given in Table 2. A single 15 mm 7-wire strand (A_{ps} = 140 mm^2) was prestressed to 0.6 F_{pu} in the specimens with post-tensioned diagonal element.

The compressive strength of concrete used in all specimens was 55 MPa, with 14 mm maximum aggregate size in the flanges, and 10 mm maximum aggregate size in the truss elements in order to obtain complete consolidation of concrete in the tubes. Figures 8 and 9 summarize the fabrication process. The studs were placed in position inside the diagonal tube, with one end of the studs extending from either end of the tube. The truss elements were then precast and placed in position in the connection specimen formwork. The flanges were then cast embedding the studs to connect the truss elements to the flanges. The bottom flange was then post-tensioned with four dywidag threadbars.

During the test, the specimen was bolted to the laboratory strong floor within the loading frame shown in Fig. 10. A horizontal load was applied through an MTS system with two 1.5 MN rams in displacement control. Displacement and rotation transverse to the load direction were prevented by means of lateral supports bearing against Teflon sheets on each side of the top flange allowing free movement only in the load direction (Fig. 10). Loading was applied until failure occurred or the stroke limit of the rams was reached. Loading the specimens with post-tensioned diagonal continued until the tendon reached 85% of its ultimate tensile strength

TEST RESULTS

Compression Tests on Concrete-Filled FRP Tubes

Table 1 summarizes all compression test results. Figure 11 depicts the failure modes of the three types of concrete-filled FRP tubes. In Table 1, the strength of confined concrete, f'_{cc}, is defined as the load carried by the concrete core divided by its cross-sectional area. For Group 2 specimens, this load is calculated from the total measured load less the contribution of the FRP tube in the axial direction. The load carried by the tube is calculated from the measured axial strain in the FRP times its modulus of elasticity in the load direction multiplied by the tube cross-sectional area. Effective confinement is defined as the ratio f'_{cc}/f'_c of the strength of confined concrete to the strength of unconfined plain concrete cylinder.

As can be seen from Table 1, the pultruded FRP tubes provide low effective confinement to the concrete core varying from 15 to 40%. This is mainly due to the small percentage of fibers oriented in the circumferential direction. The confinement is less effective in larger diameter specimens since the tube circumferential stiffness is proportional to $1/R$, where R is the tube radius (Fam 2000). However, the concrete-filled pultruded tubes can be more efficient in carrying compression load when both the concrete and the tube are in direct contact with the load (Group 2). In this case, the longitudinal fibers share the load with the concrete. Because of the small percentage of the circumferential fibers, specimens Group 1 failed by splitting of the tube over its height, whereas specimens Group 2, with both the core and the tube directly loaded, failed by buckling combined with splitting.

The two types of filament wound tubes (FWC and FWD) offer a significant increase in the strength of confined concrete as opposed to the pultruded tubes, even though the tube thickness is much smaller, raising the effective confinement ratio to approximately 3-4.5. This is due to the higher percentage of the circumferential or diagonal fibers. The results also indicate greater increase in strength in specimens with just the concrete core loaded (Group 1) than in specimens with both the concrete and the tube loaded (Group 2). This confirms the findings of Fam (2000) and Mirmiran and Shahawy (1997).

Specimens made of the filament-wound tubes, FWC and FWD, exhibited similar modes of failure (Figs. 11b and c), with fibers splitting along a diagonal line over the tube height. Failure of the specimens of FWD type, with diagonal fibers, was drastic and very brittle, with all fibers along the tube length rupturing, blowing out the crushed concrete core and allowing no residual load to be taken. On the other hand, failure of the FWC specimens, containing 30% longitudinal fibers, was less drastic (Fig. 11b) and the tubes continued to offer some confinement and load carrying capacity after the ultimate load was reached. Therefore, of the two types of filament-wound tubes, the FWC type was selected to build the connection specimens of the truss as described above.

Bond Tests on Concrete-Filled FRP Tubes

Table 3 shows results of the bond test carried out on the concrete-filled pultruded FRP tubes. As expected, the shear connectors made of FRP strips fixed to the inner surface by epoxy and rivets provided bond strength between the concrete and the tube higher than the sand/adhesive coating applied to the tube surface. Figure 12 shows failure of the two types of specimens. The increase in strength, however, was only 11%. It was therefore decided to use adhesive coating in the tubes of the truss connection specimens described above.

Connection Tests

Figure 13 compares the load-displacement behavior of the four different connections when pultruded tubes were used. Figure 14 shows the comparison for specimens built with filament-wound tubes. The displacement was measured in the direction of the applied load, at the centre of the top flange, by two transducers located on each side of the flange at the intersection of the truss elements. Failure modes of the connections are shown in Figs. 15-19.

As can be seen, the specimens built with filament-wound tubes showed better performance, particularly in terms of ductility. The maximum load that each connection type sustained was comparable for specimens of each tube type. However, the filament wound tube specimens continued to sustain load under larger horizontal displacement. This is attributed mainly to the increase in concrete strength due to better confinement.

The post-tensioned specimens performed quite similarly. The tendon in both specimens yielded at approximately the same load and displacement. The specimen with filament-wound tubes experienced more displacement after the tendon yielded, and reached a slightly higher applied load under the same tensile force in the tendon.

The connection with long double-headed studs showed the best performance in both types of specimens, with much higher ductility than the other three types of connection. The specimen with pultruded tube ultimately failed due to buckling and premature rupture of the tube of the vertical compression member (Fig. 17). The studs in the diagonal member did not reach their ultimate tensile strength. The specimen with filament-wound tube showed much better performance and continued to sustain load at displacements well beyond the pultruded tube specimen (Fig. 14). In fact, the test was stopped because the stroke limit of the rams was reached when the horizontal displacement of the specimen was approximately 85 mm. Rupture at the bottom of the vertical tube under compression was also observed.

The connection with spliced single-headed studs sustained a slightly higher load, but exhibited much less ductility and failure was caused by fracture of the studs (Fig. 18). This is possibly because the single-headed studs have deformed stems, whereas the double-headed studs have plain stems. The single-headed studs could develop bond with the concrete and share part of the load with the tube resulting in localized yielding and failure at the connection to the flange. The double-headed studs, on the other hand, developed little bond and were free to yield over a longer length (Fig. 16).

The short double-headed stud connections failed well below their yield strength. In the pultruded specimens, the FRP tube cracked longitudinally in the diagonal member, most likely due to circumferential stress induced from the transfer of force from the stud head. In the filament-wound tube specimens, the tube was able to withstand the circumferential forces and no failure in the tube took place. However, the concrete inside the tube cracked at the end of the head and the core ultimately slipped from the tube (Fig. 19). The series of peaks and drops in the load-displacement curve (Fig. 14) was due to successive failure of bond between the concrete and the tube at the locations of the sand-adhesive coating of the tube inner surface.

SUMMARY AND CONCLUSIONS

An innovative corrosion-free bridge system that combines precast prestressed hybrid FRP-concrete truss girders and a cast-*in-situ* concrete deck has been developed. The web members of the truss girders are made of concrete-filled FRP tubes connected to the prestressed concrete top and bottom flanges of the truss by means of single- or double-headed studs. Compression tests were performed on small FRP tubes filled with concrete in order to examine the effect of confinement on the truss compression members. Tests were also carried out on a single section of the truss in order to investigate the performance of different types of connections. It has been shown that filament wound GFRP tubes with fibers oriented in the circumferential direction perform extremely well in confining concrete in the truss compression members, and create a ductile connection that continues to take load well beyond yielding. Because of their excellent anchorage properties, continuous double-headed studs or spliced single-headed studs can be used efficiently to connect the truss tension members to the flanges. The studs have shown better performance than post-tensioned tendons. The studs can resist the required tensile forces and provide much more ductile connections. It is concluded that the proposed bridge system can be an efficient and more economical superstructure for short- and medium-span bridges.

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REFERENCES

Cheng, L., Zhao, L., Karbhari, V.M., Hegemier, G.A., and Seible, F., (2005), "Assessment of a Steel-Free Fiber Reinforced Polymer-Composite Modular Bridge System," ASCE *Journal of Structural Engineering*, V. 131, No. 3, March 2005, pp. 498-506.

Fam, A., (2000), "Concrete-Filled Fibre-Reinforced Polymer Tubes for Axial and Flexural Structural Members," Ph.D. Thesis, University of Manitoba, August 2000, 261 pp.

Ghali, A., and Dilger, W.H., "Anchoring with Double-Head Studs," *Concrete International*, V. 20, No. 11, November 1998, pp. 21-24.

Gossla, U. and Yoshioka, T., (2000), "FRP for Shear Walls of Box-Girder Composite Bridges," Proceedings of the Third International Conference on *Advanced Composite Materials in Bridges and Structures*, ACMBS-III, Ottawa, August 15-18, 2000, pp. 87-94.

Hindi, A., MacGregor, R., Kreger, M.E., and Breen, J., (1996), "Effect of Suplemental Bonding of External Tendons and Addition of Internal Tendons on the Strength and Ductility of Post-Tensioned Segmental Bridges," ACI Special Publications SP-160, on "Seismic Rehabilitation of Concrete Structures," 1996, pp. 169-189.

Mirmiran, A. and Shahawy, M., (1997), "Behavior of Concrete Columns Confined by Fiber Composites," ASCE *Journal of Structural Engineering*, V. 123, No. 5, May 1997, pp. 583-590.

Niitani, K., Yoshioka, T., Abe, H. and Gossla, U., (2001), "The Use of FRP Shear Panels in PSC Bridge Design," Proc. of the 5th International Conference on *Fibre-Reinforced Plastics for Reinforced Concrete Structures*, FRPRCS-5, Cambridge, July 16-18, 2001, pp. 1123-1131.

Seible, F., Karbhari, V.M., Burgueno, R. and Seaberg, E., (1998), "Modular Advanced Composite Bridge Systems for Short and Medium Span Bridges," Proceedings of the Fifth International Conference on *Short and Medium Span Bridges*, SMSB V, Calgary, Alberta, July 13-16, 1998, pp. 431-441.

Zhao, L., Karbhari, V.M., Seible, F., Brostorm, M., La Rovere, H., and Burgueno, R., (2001a) "Design and Evaluation of Modular Bridge Systems Using FRP Composite Materials," Proceedings of the Fifth International Conference on *Fibre-Reinforced Plastics for Reinforced Concrete Structures*, FRPRCS-5, Cambridge, July 16-18, 2001, pp. 1143-1151.

Zhao, L., Karbhari, V.M., and Seible, F., (2001b), "Development and Implementation of the Carbon Shell System for the Kings Stormwater Channel Bridge," Proceedings of the International Conference on *FRP Composites in Civil Engineering*, CICE 2001, Hong Kong, China, December 12-15, 2001, pp. 1299-1306.