RECTANGULAR FRP TUBES FILLED WITH CONCRETE FOR BEAM AND COLUMN APPLICATIONS

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This paper introduces an innovative concept of FRP/concrete hybrid structural member. This concept includes rectangular filament-wound glass fiber reinforced polymer (GFRP) tubes, totally or partially filled with concrete, and used as beams and/or columns. The paper presents the experimental program and results of three beams and five short columns tested with different eccentricities. Two of the beams were completely filled with concrete, while the third beam was partially filled to minimize the self-weight of the beam. This beam had a void within the cross-section, eccentric towards the tension side of the beam such that the remaining concrete was used to resist the internal compression and shear forces. Two of the columns were subject to zero eccentricity and the other three were subjected to various levels of eccentricity to study the combined effect of axial and flexural loading.

INTRODUCTION

The application of fiber reinforced polymers (FRP) in new concrete structures started with replacement of steel bars with FRP bars. Although this direct replacement philosophy was suitable at early stages, it doesn't necessarily utilize the full potential of FRP materials. It is, therefore, believed that FRP could be combined with concrete through more efficient structural concepts. The proposed system in this paper consists of concrete-filled rectangular filament-wound glass-FRP tube with several layers including fibers oriented at ± 45 and 90 degrees for shear resistance. The upper and lower flanges of the tube include additional uniaxial roving for flexural rigidity. The tube, which could be totally or partially filled with concrete, acts as lightweight permanent formwork and reinforcement, simultaneously. The concrete provides stability for the tube and compressive resistance. Research has been conducted on concrete-filled circular FRP tubes [1], however, no research has been reported on optimized concrete-filled rectangular filament wound tubes. Triantafillou and Meier [2] have studied hybrid rectangular sections with GFRP tubes supporting concrete flange above the section and a layer of carbon-FRP attached to the lower GFRP flange, however, premature failure occurred due to debonding of concrete.

EXPERIMENTAL PROGRAM

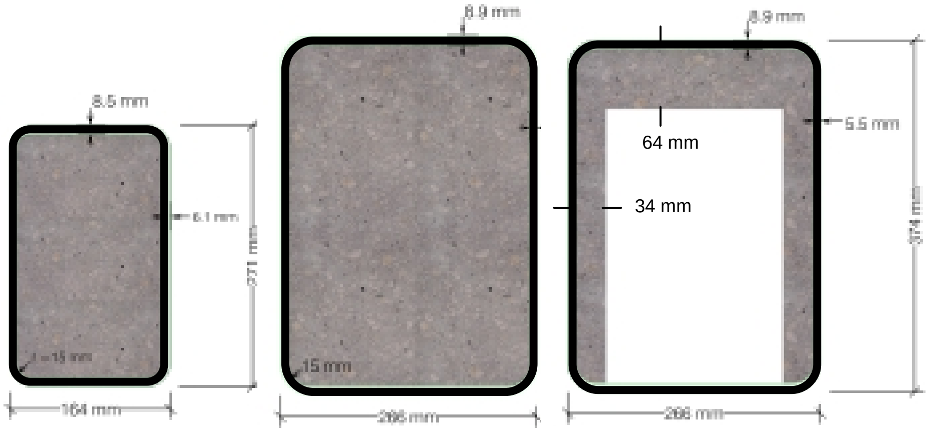
The objective of the experimental program is to determine the interaction of axial load and flexure behavior for rectangular GFRP concrete-filled tubes as well as to optimize the section by providing a central hole to reduce the self-weight of the beam. In this case, the concrete was cast with a void offset towards the tension side of the shell such that the concrete is optimally used for compression, shear and stability of the webs.

Composite Tubes

The GFRP composite shells used in this study were fabricated using a combined filament-winding and hand lay-up technique, where bi-directional glass fiber sheets were inserted into the top and bottom flanges, resulting in two longitudinal (zero degree) layers in both the tension and compression flanges of the rectangular shell. The remaining, non-zero degree laminae, were produced through conventional filament winding techniques. The final stacking sequences for the webs and flanges were [90, 45, -45, 90, 45, -45, 90] and [90, 45, -45, 0, 90, 0, 45, -45, 90] respectively. E-glass fibers used for the filament winding process have tensile strength between 1380 and 2070 MPa, and modulus of elasticity of 72.5 GPa. The E-glass fiber sheets used in the hand layup process have a tensile strength of 798 N/mm in the warp direction and 183 N/mm in the weft direction.

Hybrid Beam Specimens

The GFRP concrete-filled tubes used for the flexural tests were 2200 mm in length. No reinforcement was provided other than the outer GFRP shell was provided. Two different cross-section sizes were used. The smaller tube, with a height of 271 mm and a larger tube with a height of 374 mm as shown in Figure 1(a and b). The flange was thicker due to the addition of two layers of glass fiber sheets oriented in the longitudinal direction of the specimen. A second configuration was produced using the larger sized GFRP tube. In this case a void, offset towards the tension side of the member, was generated to minimize the self-weight of the member and to optimize the use of the concrete as shown in Figure 1(c). Concrete was used to carry the compressive and shear forces of the beam, in addition to providing stability for the thin GFRP webs. The cross sectional area of the concrete for the optimized beam was 40% of the totally filled tube. Considering the weight of the tube, the optimized beam has 44% of the weight of the totally filled tube.



(a) (b) (c)

Figure 1 Cross-section configurations of test specimens

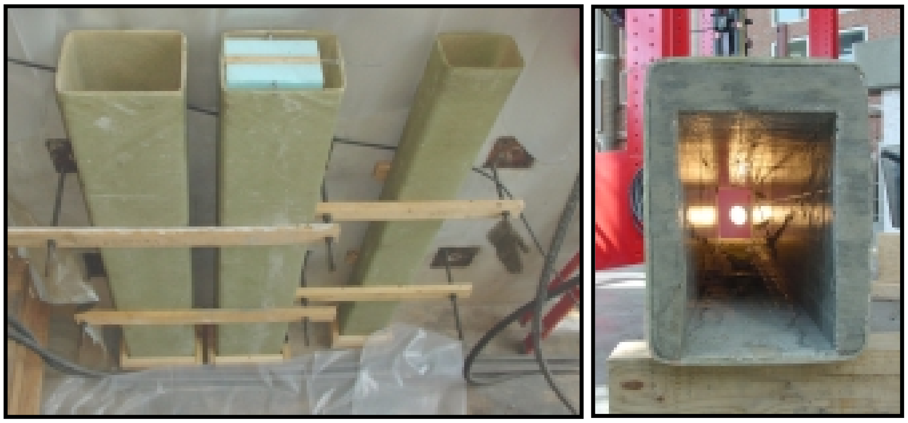
Short Column Specimens

The axial specimens tested were the same size as the small specimen used in the flexural tests, as shown in Figure 1(a). However, the length of the axial specimens was reduced to 680 mm, such that the length of the column was 2.5 times its width. In total, five compression specimens were fabricated. Three of these specimens were in their original state when tested and two were obtained from the shear spans of the flexural test of the small GFRP beam, far from the failure region.

Fabrication of Test Specimens

In order to enhance the bond between the GFRP tubes and the concrete fill, the inner surface of the GFRP tubes was coated with a layer of epoxy. A thin layer of coarse silica sand was then applied on the tacky epoxy in order to provide a rough texture. For the partially filled tube, which has a void inside the concrete core, a Styrofoam prism of the same size as the inner void was fabricated and inserted inside the tube. Later, after hardening of concrete, the Styrofoam core was removed. In order to facilitate casting concrete, the tubes were braced in a vertical position to a structural wall as shown in Figure 2(a), and were filled with 53 MPa concrete from the top end. Vibration of concrete was applied during the gradual filling of the tubes.

Once the specimens had cured, the Styrofoam core was removed, leaving the void. The cross-section of the optimized GFRP beam is shown in Figure 2(b). In order to prevent crippling of the thin web of the optimized beam above the supports, Concrete end blocks were cast, filling in the void over a length of 375 mm from each end.



(a) Setup used for casting the concrete into the tubes (b) Optimized beam

Figure 2 Fabrication of test specimens

Test Setup and Instrumentation of Beam Specimens

The three beam specimens were tested using four-point bending as shown in Figure 3. The span of the beams was 2100 mm and the distance between the loads was 300 mm. The beams were loaded using displacement control with a 500 kN capacity hydraulic actuator using displacement rate of 0.50 mm/min. The specimens were instrumented to record load, deflection and strain measurements. Longitudinal strains at midspan were measured using strain gauge type displacement transducers and electrical foil gauges attached directly to the GFRP surface at different levels along the depth of the beam. Transverse strains were also measured in the compression zone using foil strain gages. Two displacement potentiometers were used to measure the midspan deflection and another was used to measure the support settlement. Digital displacement gauges and potentiometers were also used to measure the slip between the concrete core and the GFRP tube on the tension side at both ends.

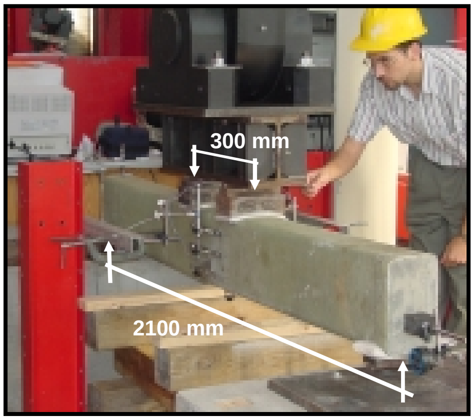


Figure 3 Test setup and instrumentation of test beams

Figure 4 Test setup and instrumentation of short columns

Test Setup and Instrumentation of Short Column Specimens

Compression specimens were subjected to concentric and eccentric axial loads applied at various eccentricities using a 9000 kN capacity testing machine as shown in Figure 4. The eccentricities considered were 0, 25 mm, 50 mm and 64 mm using a setup with free rotation allowed at the ends. Another concentric test was conducted on a specimen between fixed platens, without allowing end rotation. All specimens tested were 680 mm in length. A thin layer of gypsum plaster was used to distribute the load from the steel plates to the specimens. Specimens were loaded under stroke control at a displacement rate of 0.165 mm/min. Load, deflection and strain measurements were taken for the compression specimens. Strain was measured in the axial direction at opposite faces using electrical foil gauges and strain gauge type displacement transducers with a gauge length of 200 mm. Foil strain gauges were also used in the transverse direction to measure the transverse strains.

RESULTS OF THE EXPERIMENTAL PROGRAM

Beam Specimens

The load-deflection behaviours of the totally-filled small and large beams as well as the partially-filled beam are shown in Figure 5. The figure shows that the totally-filled beam and the partially-filled beam had similar flexural stiffness. This behaviour indicates that the size of the concrete in the compression zone of the optimized beam was quite efficient. The depth of concrete in the compression zone was determined based on location of the neutral axis using strain compatibility analysis of a totally-filled tube and the partially-filled beam was designed to eliminate the concrete below the neutral axis. The flexural strength of the optimized beam was however lower than that of the totally-filled beam by about 22 %. This is attributed to the different failure modes as will be discussed. The load-axial strain behaviour at the extreme tension and compression sides of the three beams is given in Figure 6. The behavior of the totally-filled large beam is very similar to that of the partially-filled beam. The small GFRP beam had the largest value of compressive strain, -0.0088. Both the totally-filled large beam and partially-filled beam had lower maximum compressive strains of –0.0049 before strain reversals occurred due to buckling of the GFRP, resulting in local bending stresses in the compression flange. Buckling resulted in debonding from the concrete and not only reduced the effectiveness of the compression flange in carrying compression force, but also eliminated any concrete confinement effect. Maximum tensile strains of 0.0267 are similar for the small beam and for the large beam where rupture of the GFRP tension flange was the cause of failure. The partially-filled beam, which failed due to compression failure, had a maximum tensile strain of only 0.0213. Hoop strains measured at midspan in the constant moment region indicate significant hoop stresses are developed during loading. Figure 7 shows the hoop strains for the totally-filled large beam and the partially-filled beam. It should be noted that the hoop strains are a result of the Poisson’s ratio effect of the tube, the confinement effect of concrete and the flange buckling. If all the strain were attributed to the buckling, it would be expected that the hoop strains would be very low initially, followed by a sudden increase when buckling occurred at the late stages of loading. This is true for the partially-filled beam, where confinement was expected to be insignificant due to the void. However, the behaviour and magnitude of the strains is greater for the large totally filled tube, indicating that a portion of the hoop strain may be attributed to confinement. The maximum slip measured between the concrete core and GFRP tube at the ends of the beams were 0.18, 2.5 and 0.01 mm for the small beam, the totally-filled large beam and the partially-filled beam respectively.

Test results indicate that the partially-filled beam could provide an optimized section considering the significant reduction of weight and cost of the materials.

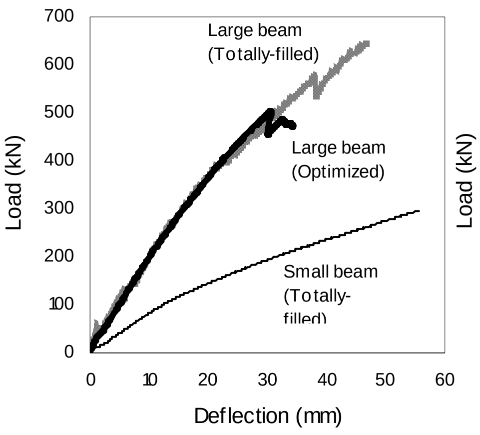


Figure 5 Load-deflection behavior of test beams

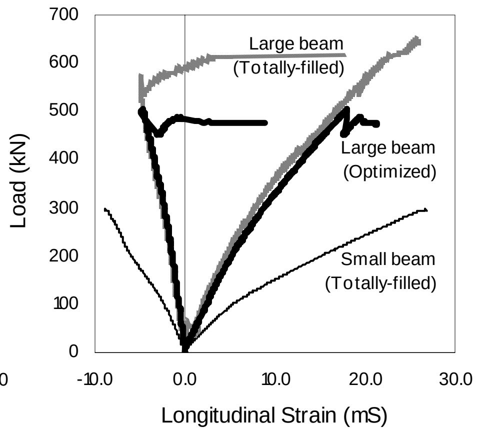


Figure 6 Load-axial strain behavior of test beams

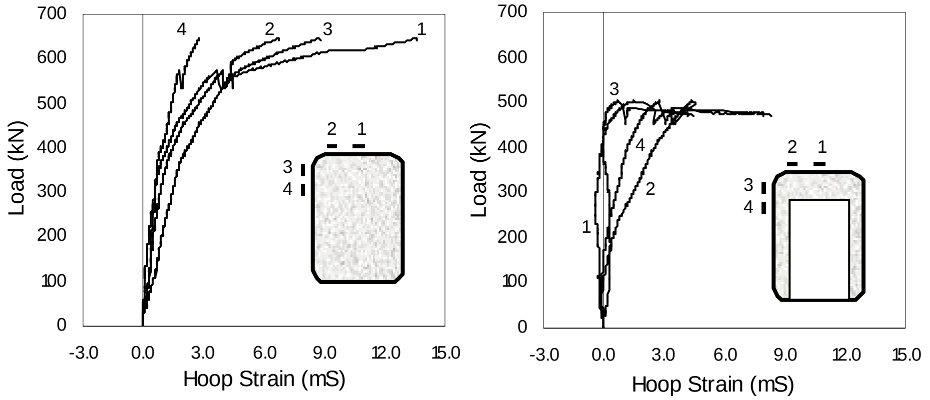


Figure 7 Load-lateral strain behavior at compression zone

Short Column Specimens

For the two tests with zero eccentricity the load versus axial and hoop strains is shown in Figure 8. The hoop strains in each case were measured at midheight on one of the shorter sides of the rectangular tube. A higher ultimate load was achieved with the complete contact of the cross-section with the loading plates, although with much less ductility than the pin ended condition. This is attributed to a localized premature failure in the pin-ended specimen. For the three compression specimens that were loaded eccentrically, the longitudinal strains at the extreme fibers were measured and shown in Figure 9. Towards the loaded side, strains were compressive. On other side of the specimen, strains were either compressive or tensile depending on the level of loading and the amount of eccentricity.

Hoop strains were measured in more details for the pin-ended concentrically loaded column. One quarter of the circumference of the specimen was instrumented with strain gauges at mid-height as shown in Figure 10. The behavior can be categorized into three phases. Very little hoop strain, less than 0.0005, is recorded until about 1200 kN. From 1250 kN to 1550 kN, the highest strains are near the middle of the longer side and at the corner. Strains are highest near the middle of the longer side due to the outward bulging of the initially straight side due to expansion of the concrete core, resulting in bending in the plate. The strain is also high at the corner due to stress concentration. In the third phase, from 1550 kN until failure the highest strains are at the center of the long and short sides due to the flexural strains induced by the internal expansion of the concrete and corresponding bulging of the sides of the rectangular tube.

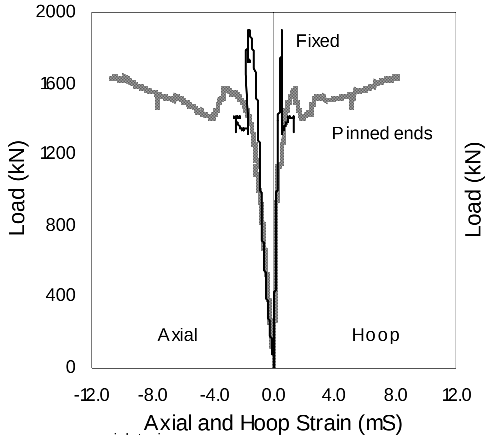


Figure 8 Load-strain behavior of columns loaded with zero eccentricity

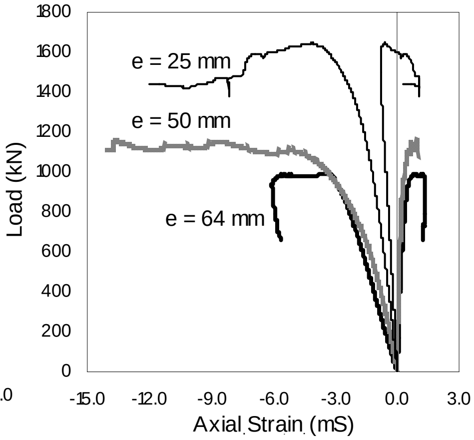


Figure 9 Load-strain behavior of columns loaded with different eccentricities

Based on the beam and column tests of the small concrete-filled tubes, a number of points on the axial load – bending moment interaction diagram have been established as shown in Figure 11.

Failure Modes

The totally-filled beams failed by rupture of the GFRP on the tension side. Rupture immediately progressed up the web as shown in Figure 12(a). The partially-filled beam failed by inward buckling of the concrete compression flange.

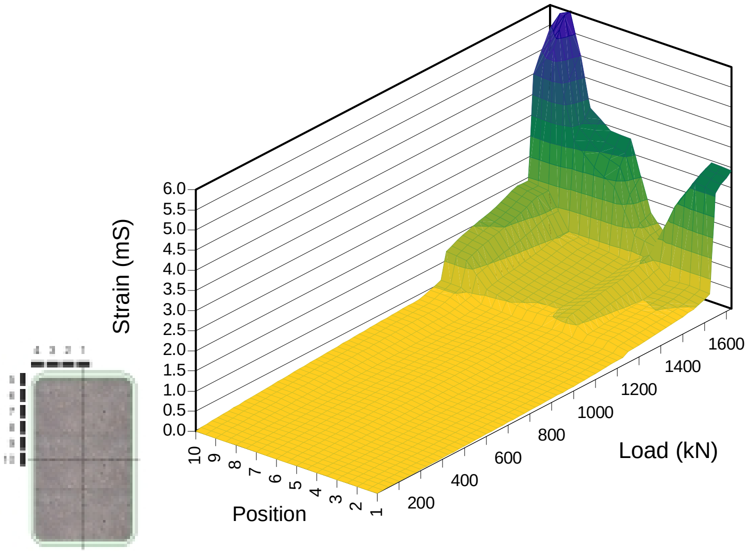


Figure 10 Variation of hoop strains on one quarter of the concentrically loaded specimen

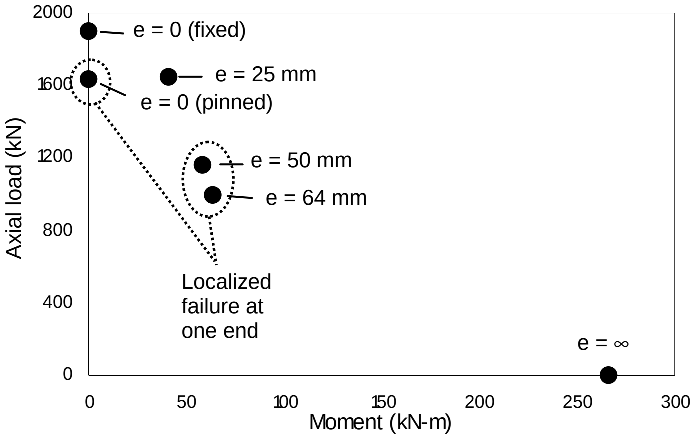


Figure 11 Axial load-bending moment interaction diagram of small specimens

The short column with complete surface contact with the loading plates and zero eccentricity as well as the one loaded with 64 mm eccentricity failed by rupture of the fibers along the corner of the tube, initiated at one end of the specimen and progressed towards the other end as shown in Figure 12(b). The pin-ended specimen with zero eccentricity and the one with 50 mm eccentricity failed by local shearing of one corner as shown in Figure 12(c). The specimen with 25 mm eccentricity failed by crushing of the tube at midheight, accompanied by fracture of the fibers in the hoop direction as shown in Figure 12(d).

(a) Large totally-filled beam (b) e = 0 (Fixed) (c) e = 0 (Pinned) (d) e = 25 mm

Figure 12 Failure modes of beam and column specimens

CONCLUSIONS

A FRP/concrete hybrid concept has been introduced. A rectangular GFRP thin tube can be totally-filled or partially-filled with concrete to optimize the concrete within the cross-section. Beams and short columns have been tested. The following conclusions are drawn:

(a) The partially-filled beam showed similar stiffness to the totally-filled beam but lower flexural strength due to the different failure mode.
(b) Totally-filled beam failed by fracture of GFRP tube in tension. Partially-filled beam failed by inward local buckling of the concrete flange.
(c) In short columns, higher hoop strains are developed in the middle of the straight sides of the rectangular tube than at the rounded corners due to local bending of the GFRP tube as a result of the bulging concrete core.

REFERENCES

1. Fam, A. Z. and Rizkalla, S. H., “Flexural Behavior of Concrete-Filled Fiber-Reinforced Polymer Circular Tubes”, *ASCE Journal of Composites for Construction*, Vol. 6, May 2002, pp.123-132.

2. Triantafillou, T. C. and Meier, U. “Innovative Design of FRP Combined with Concrete,” *Proceeding of the 1st International Conference on Advanced Composite Materials for Bridges and Structures* (ACMBS), Sherbrooke, Quebec, 1992. pp. 491-499.