CANTILEVER TESTS ON MOMENT CONNECTION OF CONCRETE-FILLED FRP TUBES

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ABSTRACT

Extensive research has shown that concrete-filled FRP tubes (CFFTs) can be effectively used in numerous structural applications. The system provides significant improvement of confinement of concrete, leading to improved overall axial and flexural capacities over conventional reinforced concrete members. Additional advantages include physical protection of the confined concrete, providing a stay-in-place formwork and the ease and speed of construction. These advantages make the CFFT system suitable for applications such as piles, bridge columns and poles. These applications require practical and reliable moment connections of the CFFTs to concrete footings, pile caps or cap beams. One such method proposed earlier by the authors involves adhesive bonding of the hollow GFRP tubes to a short reinforced concrete (RC) stub protruded from the concrete footing, then filling the tube with concrete. This method has the advantage of eliminating the need for shoring of the hollow GFRP tube while being filled with concrete. It was also shown that an RC stub length of 1.5 times the diameter (1.5D) of the CFFT will be safe to avoid debonding of the tube. This paper extends this work by looking into the effect of varying the longitudinal steel reinforcement ratio ($\rho$%) in the RC stub on flexural performance and failure modes. Also, the performance of the connection under reversed low cyclic bending fatigue is studied with and without a sustained axial compression load. The stub total reinforcement ratio below which ductile failure occurs within the RC stub near the face of the footing was 3.4%. A higher reinforcement ratio leads to flexural tension failure of the CFFT section at the end of the short stub. A small axial compression load significantly improved cyclic bending performance of the connection.

KEYWORDS

FRP, CFFT, bond, joint, moment connection, cyclic, ductility

INTRODUCTION

The use of FRP materials in retrofitting deteriorating structures has shown great success. In new construction, the most common application of FRPs has been in the form of rebar as replacement of steel rebar. Another unique application of FRP in new construction that also showed a great promise is in the form of stay-in-place structural forms for concrete structures. An example of this is the concrete-filled FRP tubes (CFFTs) system. Prefabricated hollow FRP tubes that are already available in the market are filled with concrete, and may or may not be internally reinforced with steel or FRP rods. This technology has been successfully implemented in structural applications, including bridge columns, girders, and piles (Fam et al, 2003). The advantages of this system are: (a) FRP tubes provide confinement for the concrete, thus increasing its axial compressive strength and strain at failure, (b) FRP tubes are permanent structural formwork for concrete, which substantially eases and accelerates construction, and (c) FRP tube protects the concrete core from aggressive external environments and moisture. Structural behavior of CFFT members under various loading conditions has been thoroughly studied. One area that still lacks investigation, yet is vital to using the technology, is development and understanding of the structural behavior of moment connections of CFFT members to other structural components. One study by Zhu et al. (2006) explored different methods of connecting CFFTs to concrete foundations, including steel dowel connections and post-tensioning. All methods demonstrated behavior that was superior to that of conventional RC column connections with regard to strength and ductility. Another study carried out by Nelson et al (2008) looked into a moment connection system by direct embedment of CFFTs into footings, without using steel dowels. All these methods, however, require shoring of the tubes. Recently, a study by Lai and Fam (2009) explored a moment connection in which hollow FRP tubes are adhesively bonded to short reinforced concrete (RC) stubs protruded from concrete footings and having a diameter matching the inner
diameter of the tube. The focus of the study was on optimizing the length of the RC stubs. This paper will advance this work by studying the effects of the longitudinal steel reinforcement ratio of the stub and reversed low cycle bending fatigue with and without a small axial load, on flexural performance and failure modes.

**EXPERIMENTAL STUDY**

**Test Specimens and Parameters**

A total of five specimens were tested in this study. The test matrix is shown in Table 1 and a schematic diagram of a typical specimen is shown in Figure 1. All specimens were 1370 mm long with a GFRP tube of an outer diameter of 169 mm and a wall thickness of 3.14 mm. The tubes were fabricated using the filament-winding process. Fibers were oriented very closely to the longitudinal and circumferential direction with the approximate ratio of 1:2. The precast RC stubs were 159 mm in diameter and 253 mm in length, which represents 1.5 times the diameter of the CFFT. This length was concluded from the previous study to insure that bond failure of the tube does not occur. The RC stubs protruded out of 500 x 500 x 500 mm RC footings. Three of the four specimens (S10, C1 and C2) were reinforced with four equally spaced 10M rebar (total reinforcement ratio \( \rho \) of 2.01%), while the fourth specimen (S15) had four 15M bars (\( \rho = 4.03\% \)) and the fifth specimen (1.5D) had four 20M bars (\( \rho = 9.07\% \)). Two of the 10M specimens (C1 and C2) were tested under quasi-static cyclic loads, with one specimen (C2) having an externally applied axial load of at least 234 kN throughout the test. All remaining specimens were tested under a monotonic loading to failure.

**Table 1. Experimental program test matrix**

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>RC Stub Height (mm)</th>
<th>CFFT Diameter (mm)</th>
<th>Test Span (mm)</th>
<th>Steel Reinforcement</th>
<th>Total Steel Reinforcement Ratio (( \rho% ))</th>
<th>Applied Axial Load (kN)</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5D</td>
<td>253</td>
<td>169</td>
<td>1300</td>
<td>6 – 20M</td>
<td>9.07%</td>
<td>-</td>
<td>Static</td>
</tr>
<tr>
<td>S10</td>
<td>253</td>
<td>169</td>
<td>1300</td>
<td>4 – 10M</td>
<td>2.01%</td>
<td>-</td>
<td>Static</td>
</tr>
<tr>
<td>S15</td>
<td>253</td>
<td>169</td>
<td>1300</td>
<td>4 – 15M</td>
<td>4.03%</td>
<td>-</td>
<td>Static</td>
</tr>
<tr>
<td>C1</td>
<td>253</td>
<td>169</td>
<td>1300</td>
<td>4 – 10M</td>
<td>2.01%</td>
<td>-</td>
<td>Cyclic</td>
</tr>
<tr>
<td>C2</td>
<td>253</td>
<td>169</td>
<td>1300</td>
<td>4 – 10M</td>
<td>2.01%</td>
<td>234</td>
<td>Cyclic</td>
</tr>
</tbody>
</table>

**Fabrication of Test Specimens**

The fabrication process was in three stages. The first stage involved casting of the RC stub and footing. The next stage involved adhesively bonding the hollow GFRP tubes to the RC stubs using viscous epoxy. The last step was simply filling of the GFRP tube with concrete. All RC footings were reinforced with four longitudinal 10M rebar (at each corner). These corner bars helped to tie two layers (five layers for specimen C2) of 440 x 440 mm closed ties of 10M steel rebar. The reinforcing cages for the RC stubs were tied together using 4 mm diameter steel wire spirals. In addition to the 253 mm length protruded out of the top of the RC footing, the stub
cages were embedded down into the footing. After placement of all the reinforcing cages inside the formwork of the footing, concrete was cast and finished to a smooth surface, except for the central 170 mm diameter area, which was intentionally left with a rough surface. The concrete stub was then cast over this rough surface into SonoTubes with an inner diameter of 159 mm. This 159 mm diameter allowed for a thin 2 mm gap between the inner surface of the GFRP tube and outer surface of the RC stub. For specimen C2, 25 mm diameter longitudinal plastic tubes were placed into the entire height of the footing, to facilitate applying the axial load using prestressing tendons. After curing and removal of the SonoTubes from the stubs, a viscous epoxy layer was applied to both the inner surface of the GFRP tube and the RC stub surface. The GFRP tube was then fitted over the stub in a slow spiral motion to ensure full contact at the bond interface. After hardening of the adhesive, the GFRP tube was then filled with concrete.

External application of axial load for specimen C2

To apply an axial load on specimen C2, a specially fabricated steel system was used. This involved the use of a 152 x 152 mm hollow steel section (HSS) bearing directly on top of the CFFT section through a thin layer of plaster (Figure 2 a). Two 7-wire steel strands of 15.2 mm diameter were then passed through the HSS section and through the ducts precast into the concrete footing. The strands were then anchored at the bottom end of the footing through bearing plates with load cells integrated into the system (Figure 2 b). On the top end, a hydraulic jack was placed on top of the HSS section and loaded against another stiff steel plate. The strands were first anchored to the top of the plate. The jack was then loaded to the desired post-tension load in the strands and the tendons were locked with another set of anchors against the HSS section. The loading jack and stiff reaction plate were then removed.

Test Setup and Instrumentation

All specimens were tested in flexure using a 1000 kN Riehle machine. The specimens were placed in a horizontal position and loaded using a single point load at the end of a 1300 mm span, while the concrete footing was fixed to the base of the machine, essentially a cantilever setting. The footing was clamped to a heavy steel beam sitting on the base of the machine using two high strength steel rods and a stiff transverse steel section. For specimens C1 and C2, a swivel joint was clamped to the end of the CFFT to facilitate the push-pull regime.

The loads for all four tests were recorded using the load cell in the Riehle machine. Linear potentiometers (LPs) and machine stroke were used to measure the deflection of the CFFT at the free end. Also, additional LPs were used to monitor any slight movement of the footing to correct the free end deflection. The longitudinal strains along the extreme tension and compression sides of the outer surface of the CFFTs were measured using electrical resistance strain gauges, at various locations along and beyond the RC stub. Additional displacement type strain transducers (PI gauges) were also used to measure strains.

RESULTS

Specimens with Different Steel Reinforcement Ratios

An RC stub length of 1.5D was selected based on the results of the initial phase of this study and with the assumption that de-bonding (slippage) of the GFRP tube from the RC stub would not occur. Indeed, testing of specimens 1.5 D, S10 and S15 did not show any debonding failure of the tube. Specimen S10 failed due to excessive yielding and deflection following the development of large flexural cracks in the RC stub at the footing interface. In fact, the loading was terminated due to the excessive deflection when the load was nearly stabilized. The GFRP tube confinement effect kept the compression zone of the RC stub intact, allowing for plastic hinge to develop. Specimen S15 also developed a large flexural crack at the RC stub-footing interface,
and showed significant yielding and deflection. However, eventually the CFFT section failed due to tensile rupture of the GFRP tube at the end of the stub. The same failure mode of the CFFT occurred also in specimen 1.5D, but because it was so heavily reinforced, no evidence of yielding were observed. Also, no excessive deflection or cracking occurred.

Load-deflection responses

The load-deflection responses of all three specimens are plotted in Figure 3 a. The plots show similar initial load-deflection behaviors for all three specimens before cracking, which occurs rather early during loading. After cracking the stiffness varies according to the reinforcement ratio, with S15 showing the stiffest response. Also, the ductility of the system is directly dependent on reinforcement ratio. Specimen 1.5D showed almost linear behavior to failure, suggesting no yielding of steel, prior to rupture of the FRP tube. Specimen S15 showed moderate ductility prior to rupture of the FRP tube. Specimen S10, on the other hand, showed a quite ductile behavior with excessive deflection leading to termination of the test. The deflections at ultimate of specimens 1.5D, S15 and S10 were 111 mm, 238 mm and 271 mm, respectively.

Strains

The measured tensile strains of the GFRP tube at the end of the stub at failure were 21143 µe and 21236 µe for specimens 1.5D and S15, respectively. These values are very consistent with each other, particularly when both systems failed by rupture of the GFRP tubes at this location. The maximum GFRP tube strain reached at the same location in specimen S10 was 10072 µe. Therefore, specimen S10 was quite far from failing by tube rupture. On the compression side, the load-compressive strain behavior of all three specimens is very similar.

Critical reinforcement ratio

The base moment at the footing level, at failure is plotted versus the steel reinforcement ratios of 9.07%, 4.03% and 2.01% of specimens 1.5D, S15 and S10, respectively, in Figure 3 b. An additional point at 0% reinforcement ratio is estimated analytically based on a plain concrete section capacity. A flat plateau governed by the moment capacity of the CFFT section is established based on the average moments of specimens 1.5D and S15. By extending the line connecting the moment of specimen S10 and that at 0% reinforcement ratio, it intercepts the flat plateau at a critical point of 3.4% total reinforcement ratio. The critical point represents the minimum steel ratio required to achieve the full flexural capacity of the CFFT system. This is the optimal steel ratio for this particular GFRP tube, from a maximum strength stand point. However, this point does not provide the most ductile behavior.

Specimens Subjected to Reversed Cyclic Loading

Cyclic tests on specimens C1 and C2 did not result in tensile rupture or slippage of the GFRP tube from the RC stub. Specimen C1 was tested until significant deterioration in load capacity occurred at high displacements. In specimen C2, due to deflection of the CFFT tube, additional tension forces were built into the steel strands. As such the test was terminated at 150 mm deflection, when the load per strand about 150 kN, for safety reasons. This means that the axial load on this specimen fluctuated between 234 kN and 300 kN during the loading cycles. In any case, at the end of the tests, both specimens were severely cracked at the column-footing interface, within
the full cross-section, due to reversed loading. Moreover, the peak load of specimen C2 was generally about to stabilize, except that the increase of the axial compression load resulted in some increase of the capacity in the last few cycles.

**Load-deflection responses**

Figure 4 shows the load-deflection hysteretic curves for the two specimens. Clearly, an applied axial load ranging from 234 kN, which represents approximately 15% of the CFFT axial compressive strength, and 300 kN, has a large effect of the load-deflection cyclic behavior. The peak loads of 12.55 kN and 24.66 kN for specimens C1 and C2 respectively, represent a 96% increase in strength, which is significant. This is also consistent with the trend of a typical axial load-bending moment interaction curve, in the tension failure region below the balanced point. The stiffness of the two specimens is also clearly different, with specimen C2 exhibiting a much higher stiffness. Also, specimen C1 reaches a peak load at about ductility ratio of 2 (2Δy) and then the strength starts degrading gradually. The peak load reached is similar to that of the monotonic loading case of specimen S10, of the same reinforcement. However, while the load started degrading in C1 at relatively small deflection, it was maintained till very large deflections in S10. On the contrary, for specimen C2, a stable and more consistent hysteretic behavior is observed. In fact it appears that the load was about to stabilize but showed some incremental increases as the end due to the increase in the applied axial load with increased deflection, which occurred at a rate of approximately 1 kN per 3 mm of deflection. Therefore, the peak load may have been maintained if the applied axial load remained constant throughout the duration of the test.

Pinching of the load-deflection hysteretic response is primarily caused by the slippage of the yielded steel rebar from the surrounding concrete as the cracks open and close under cyclic loading. The lower the pinching effect the higher the amount of energy dissipated by the system. It appears though that both specimens have experienced some pinching effect in this case.

**SUMMARY AND CONCLUSIONS**

An experimental investigation was undertaken to investigate a moment connection of a CFFT system to a concrete footing. The GFRP tube of the CFFT system is adhesively bonded to a short (1.5 the tube diameter) RC stub protruding from the concrete footing, and then filled with concrete. The study investigated the effect of longitudinal steel reinforcement ratio of the stub as well as the behavior under reversed cyclic bending with and without a small axial compression load. The following preliminary conclusions can be drawn from this investigation:

1. For a given GFRP tube there is a critical total steel reinforcement ratio required in the RC stub for the CFFT to reach its full flexural strength. In this study this ratio was 3.4%. While this allows the system to reach its maximum capacity, it may not provide the most ductile behavior. In this case the GFRP tube will rupture in tension at a section near the end of the stub, provided that adequate bond length with the stub is available, which was the case in this study with a 1.5D bond length;

2. At this critical reinforcement ratio, whether the steel would yield or not, and the extent of yielding, depends on the capacity of the GFRP tube (thickness and laminate structure). In this study, some yielding has occurred at this critical point;
The specimen with the lowest reinforcement ratio of 2% showed a very ductile behavior with a plastic hinge forming at the base;

Quasi-static cyclic loading of the CFFT system results in similar peak load to that of the monotonically loaded specimen. However, while the load was sustained under monotonic loading for large deflections, it began degrading gradually with the increased drift under cyclic loading; and

The presence of a small axial load (15-20% of axial strength) significantly affects the behavior during cyclic loading, leading to a more stable hysteretic behavior, higher stiffness and higher capacity.

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REFERENCES


