Flexural testing of concrete filled fibre reinforced polymer tubes (CFFT) with and without internal fibre reinforced polymer (FRP) reinforcement

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Abstract

FRP reinforcement has emerged as an attractive alternate of steel reinforcement due to its higher ultimate tensile strength and weight ratio, and corrosion resistant properties. This study presents the behaviour of Concrete Filled Fibre Reinforced Polymer Tubes (CFFT) with and without longitudinal FRP reinforcing bars under flexural loading. Four circular normal strength CFFT (two carbon FRP tubes and two glass FRP tubes) specimens and a steel reinforced concrete specimen (Reference) of 204 mm and 200 mm diameters respectively were cast and tested. One of the CFFT of each type of CFRP and GFRP CFFT was unreinforced while the other was reinforced. The reinforced CFRP and GFRP CFFT were reinforced with longitudinal 6Ø15 CFRP reinforcing bars and 6Ø15.875 GFRP reinforcing bars, respectively. All the CFFT were tested under increasing flexural load until the fibres at the bottom of the CFFT were ruptured. Significant increases in the ultimate flexural load and ultimate midspan deflections were observed for reinforced CFFT than unreinforced CFFT. GFRP and CFRP reinforced CFFT demonstrated identical flexural behaviour while GFRP CFFT attained even higher ultimate flexural load than the Reference specimen, although both CFFT have similar ultimate midspan deflections.

Disciplines

Engineering | Science and Technology Studies

Publication Details

Khan, Q. S., Strong, J. S., Sheikh, M. Neaz. & Hadi, M. N. S. (2015). Flexural testing of concrete filled fibre reinforced polymer tubes (CFFT) with and without internal fibre reinforced polymer (FRP) reinforcement. Proceedings of the 27th Biennial National Conference of the Concrete Institute of Australia in conjunction with the 69th RILEM Week (pp. 400-407). North Sydney, Australia: Concrete Institute of Australia.

Flexural Testing of Concrete Filled Fibre Reinforced Polymer Tubes (CFFT) with and without Internal Fibre Reinforced Polymer (FRP) Reinforcement

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Abstract: FRP reinforcement has emerged as an attractive alternate of steel reinforcement due to its higher ultimate tensile strength and weight ratio, and corrosion resistant properties. This study presents the behaviour of Concrete Filled Fibre Reinforced Polymer Tubes (CFFT) with and without longitudinal FRP reinforcing bars under flexural loading. Four circular normal strength CFFT (two carbon FRP tubes and two glass FRP tubes) specimens and a steel reinforced concrete specimen (Reference) of 204 mm and 200 mm diameters respectively were cast and tested. One of the CFFT of each type of CFRP and GFRP CFFT was unreinforced while the other was reinforced. The reinforced CFRP and GFRP CFFT were reinforced with longitudinal 6Ø15 CFRP reinforcing bars and 6Ø15.875 GFRP reinforcing bars, respectively. All the CFFT were tested under increasing flexural load until the fibres at the bottom of the CFFT were ruptured. Significant increases in the ultimate flexural load and ultimate midspan deflections were observed for reinforced CFFT than unreinforced CFFT. GFRP and CFRP reinforced CFFT demonstrated identical flexural behaviour while GFRP CFFT attained even higher ultimate flexural load than the Reference specimen, although both CFFT have similar ultimate midspan deflections.

Keywords: FRP Tube, FRP Reinforcement, CFFT

1. Introduction

Fibre Reinforced Polymers (FRP) has emerged as one of the most suited alternate option for steel reinforcement in Reinforced Concrete (RC) columns and beams. FRP reinforcement offers a number of advantages such as higher ultimate tensile strength, reduced corrosion and lower self-weight than steel reinforcement [1]. Pantelides et al. [2] concluded that larger proportion of the corrosion in steel RC specimens take place in steel helix. In the last two decades, to reduce the corrosion phenomenon in steel RC specimen, a new technique of Concrete Filled Fibre Reinforced Polymer Tube (CFFT) has been the focus of the research studies as an alternate of steel reinforcement particularly for steel helix. Ozbakkaloglu [3], Vincent and Ozbakkaloglu [4], Mirmiran et al. [5], Hong and Kim [6], Lillistone and Jolly [7], Mohamed and Masmoudi [8] investigated the effect of different geometrical aspects of FRP tubes such as tube thickness, orientation of fibres, height to diameter ratio and tube manufacturing method, unconfined concrete strength, bond between concrete and tube, and internal reinforcement ratio on the load and ductility capacity of CFFT. Nanni and Norris [9], Mirmiran et al. [10], Fam and Rizkalla [11] and Fam and Rizkalla [12] were amongst the early researchers who investigated the combined axial and flexural behaviour of CFFT. These studies showed that CFFT had significantly higher flexural strength and ductility capacity than steel (longitudinal bars and helix) reinforced specimens. Davol et al. [13] presented analytical models to characterise the flexural behaviour of circular CFFT and validated the models using a large scale 7.92 m long CFFT under flexural loading (four point loading).

Recently, FRP longitudinal reinforcing bars have also attracted significant research attention. Cole and Fam [14] investigated the flexural behaviour of longitudinal steel and FRP bars reinforced glass FRP (GFRP) CFFT. The study concluded that flexural strength and ductility attained in case of longitudinal steel bars reinforced CFFT were significantly greater than FRP reinforced CFFT; however, GFRP tubes exhibited a superior flexural behaviour than helical steel reinforcement as GFRP tubes confined the larger concrete area. Fam and Rizkalla [12] studied the flexural behaviour of circular concrete filled GFRP tubes, hollow GFRP tubes and steel tubes. They showed that the flexural behaviour of CFFT was dependent on modulus of elasticity of tube and diameter to thickness ratio of tube. Mohamed and Masmoudi [15] investigated the flexural behaviour of CFFT reinforced with longitudinal FRP and steel reinforcing bars. The study showed that confinement provided by FRP tube to the concrete core significantly increased both the flexural strength and ductility capacity. The study further showed that

CFFT exhibited smaller deflections, and higher strength and stiffness than commonly used steel reinforced beam specimens.

This experimental study investigates the flexural behaviour of unreinforced CFFT and longitudinal FRP bar reinforced CFFT under flexural loading (four point loading). In this study, the flexural behaviour of tested CFFT and steel RC (Reference) specimen is also compared.

2. Experimental Program

The experimental program reported in this study comprised four circular CFFT and a steel RC (Reference) specimen. The main objective of this study is to assess the behaviour of circular unreinforced and reinforced CFFT under four point loading. A comparison of flexural behaviour of circular unreinforced and longitudinal FRP bars reinforced CFFT, and the Reference specimen in terms of flexural load and midspan deflection has also been investigated. The key parameters studied in this experimental program were GFRP tubes, CFRP tubes, and GFRP and CFRP reinforcing bars. All the tests were conducted at the High Bay Laboratories of the School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia.

2.1. CFFT Specimens and materials

Table 1 provides details of manufacturer provided values of modulus of elasticity (E), ultimate tensile strength (f_{fu}) and ultimate tensile strain (ε_{fu}) of fibres and FRP composites used in this experimental study. Moreover, steel reinforcing bars used in this experimental study has modulus of elasticity of 200 GPa and yield strength of 500 MPa.

Table 1. FRP Tube and longitudinal FRP bars properties as reported by the manufacturer [16]

Material	Modulus of Elasticity of fibres (E), GPa	Ultimate tensile strength of fibres (f_{fu}), MPa	Ultimate tensile strain of fibres (ε_{fu}), %	Modulus of Elasticity of FRP (E), GPa	Ultimate tensile strength of FRP (f_{fu}), MPa	Ultimate tensile strain of FRP (ε_{fu}), %
CFRP Tube	230	5080	2.2	146.1	3222.6	2.2
GFRP Tube	80	2000	2.5	49.3	1224.0	2.5
CFRP Bar	140	3100	2.2	78.4	1732.0	2.2
GFRP Bar	-	-	-	62.6	1184.0	1.9

Table 2 provides details of the type of FRP tubes, internal diameter, length and thickness of FRP tubes, types of longitudinal reinforcement, and number and diameter of longitudinal reinforcing bars. All the specimens tested in this study were designed to have a length to diameter ratio (H/D) of four. The internal diameter opted for CFFT and the Reference specimen was 204 mm and 200 mm, respectively.

Table 2. Details of the specimens reported in this study

Specimen Designation	Internal Diameter (D), mm	Length (L), mm	Type of FRP Tube	Nominal FRP Tube Thickness, (t) mm	Type of Longitudinal Reinforcement	Longitudinal Reinforcement
CT	204.07	812	CFRP	0.50	-	-
GT	204.00	812	GFRP	1.50	-	-
CT-CR	204.00	812	CFRP	0.50	CFRP	6Ø15
GT-GR	203.88	812	GFRP	1.50	GFRP	6Ø15.875
Reference	200	800	-	-	Steel	4N12

2.2. Specimen Designation

The CFFT specimens reported here were designated according to the type of FRP tube and type of longitudinal FRP reinforcing bars used in reinforced CFFT. In this experimental program the influence of two types of FRP tubes i.e., CFRP tube (CT) and GFRP tube (GT), and two types of longitudinal FRP reinforcing bars i.e., CFRP reinforcing bars (CR) and GFRP reinforcing bars (GR) have been investigated. For example a Specimen CT represents a concrete specimen confined with carbon tube with no longitudinal FRP reinforcement and tested under flexural loading. The control specimen was labelled as the Reference specimen i.e., a concrete specimen confined with helical steel reinforcement with longitudinal steel reinforcing bars and tested under flexural loading.

2.3. Fibre Reinforced Polymer (FRP) Tubes

In this experimental program, CFRP tubes and GFRP tubes were used. CFRP tubes comprised 63% of carbon fibres and 37% of resin by volume, whereas GFRP tubes comprised 60% of glass fibres and 40% of resin by volume [16]**.** Both CFRP and GFRP tubes were designed to have an inner most layer of fibres oriented along the hoop direction (90° to the longitudinal direction) followed by skew layer of fibres (60° to the longitudinal direction). This stacking sequence of 90° and 60° was repeated until the required thickness of FRP tubes was achieved [16].

2.4. Fibre Reinforced Polymer (FRP) Reinforcement

In this experimental program, two types of FRP reinforcing bars i.e., CFRP reinforcing bars and GFRP reinforcing bars were used. Both CFRP and GFRP reinforcing bars comprised 55-60% of fibres and 40-45% of resin by volume [16]. In both types of bars all of the fibres were oriented along the longitudinal direction.

2.5. Unconfined Concrete Strength

A ready mix concrete was obtained from a local company in Wollongong. The target 28th day unconfined concrete strength of 32 MPa with maximum aggregate size of 10 mm and slump of 120 mm was requested. The unconfined concrete strength attained after 28 days was 37 MPa.

3. Test Methodology and Instrumentation

All specimens were tested in flexure in the Denison 5000 kN Universal Testing Machine (UTM). The testing arrangement with CFFT loaded in flexure in the UTM is shown in Figure 1. All the specimens were initially loaded to 100 kN under a load control rate of 50 kN/minute and then they were unloaded to 20 kN. This was done so that specimen could align within the loading plates of the UTM and minor eccentricities due to unparalleled plate surfaces could be adjusted. After the initial loading and unloading, the specimens were loaded at a displacement control rate of 0.3-0.5 mm/minute until failure.

Figure 1. Flexural testing arrangement used in this study

The flexural testing arrangement consists of two platen rigs i.e. bottom platen rig and top platen rig having clear spans of 705 mm and 235 mm, respectively. The bottom platen rig was placed on bottom loading platen of the UTM. The specimen was placed on the two supports of bottom platen rig with equal portion (53.5 mm) of the specimen hanging from the supports. The specimen length between the supports of the bottom platen rig was equally divided into three segments of 235 mm length each. The top platen rig was then placed on the specimen centred over the middle segment. The top loading platen of the machine was lowered until it touched the top platen rig. The specimen was loaded in the UTM until the final failure due to rupture of the bottom FRP tube fibres was reached. The desired mode of failure under flexural testing (bending) was the rupture of the bottom fibres within the middle segment of the CFFT.

All specimens were instrumented with two Linear Variable Displacement Transducers (LVDT) fixed along the diagonal corners of the loading plates of the UTM, and laser triangulation fixed in the mid on the tension side of the specimen to measure midspan deflection. The UTM also recorded the midspan deflection along with the flexural load taken up by the specimens.

4. Experimental Results and Discussions

This section deals with the failure modes observed in circular CFFT and the Reference specimen, and the flexural load-midspan deflection behaviour of reinforced and unreinforced CFFT. It also investigates the influence of FRP tube and FRP reinforcement on the flexural load and midspan deflection. The ultimate flexural load and ultimate midspan deflection for all the specimens are presented in Table-3.

Table 3. Summary of experimental results

Specimen Designation	Ultimate Flexural Load (kN)	Ultimate Midspan Deflection (mm)
CT	93.2	26.61
GT	115.6	27.26
CT-CR	223.5	44.96
GT-GR	448.4	43.13
Reference	346.9	33.16

4.1. Observed Failure Modes

The observed failure mode in all of the CFFT was due to the rupture of the bottom fibres within the middle segment of the specimen as shown in Figure 2a and 2b. The failure in CFFT was initiated with snapping sound of the bottom fibres tearing apart followed by the tearing of the fibres along the hoop direction. Afterwards, crushing of concrete occurred and eventually fibres at the top compressive side were torn apart.

(a) Specimens CT and GT

(b) Specimens CT-CR and GT-GR


(c) Specimen CT-CR

(d) Specimen GT-GR

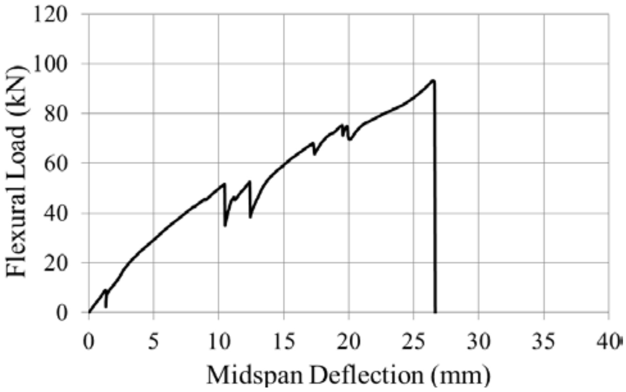

(e) Reference Specimen

Figure 2. Observed failure modes of the tested specimens

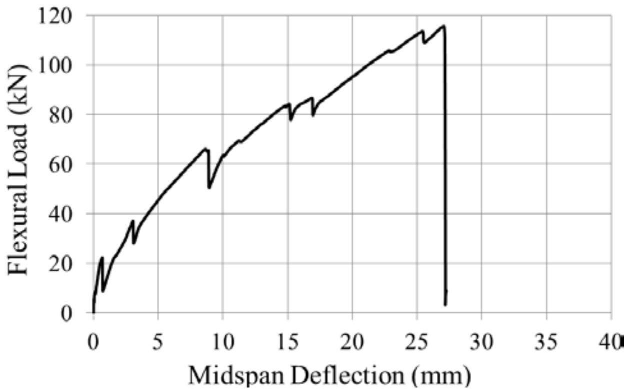
The observed failure mode in case of the FRP bars reinforced CFFT was slightly different from that in the unreinforced CFFT. In FRP reinforced CFFT, FRP bars slipped with increasing flexural load as shown in Figure 2c and 2d. The slippage observed in CFRP bar reinforced CFFT (CT-CR) was significantly more than that observed in GFRP bar reinforced CFFT (GT-GR). This was due to the fact that CFRP bars were smooth whereas GFRP bars were sand coated. Sand coating significantly increased the friction between the bars and the concrete and hence reduced the slippage of the bars and also increased the flexural strength of the CFFT.

4.2. Flexural Load-midspan Deflection behaviour

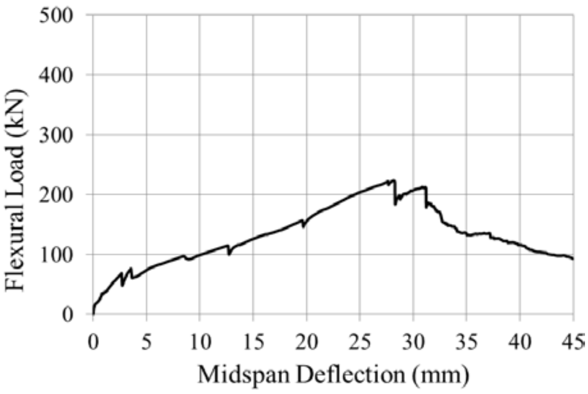
Figure 3 shows the flexural load versus midspan deflection for all the specimens. It was observed that for CFFT, the flexural load-midspan deflection curve was not as smooth as of the Reference specimen.



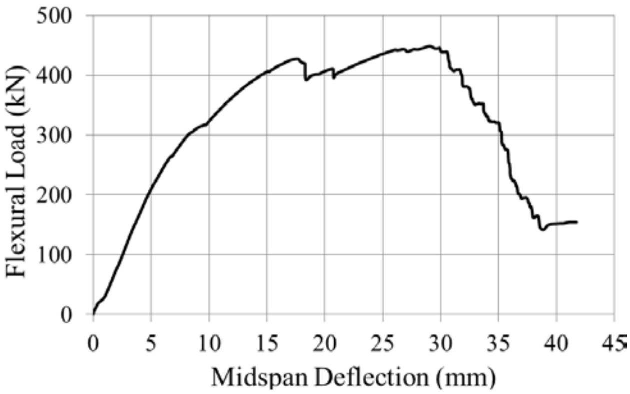
(a) Specimen CT



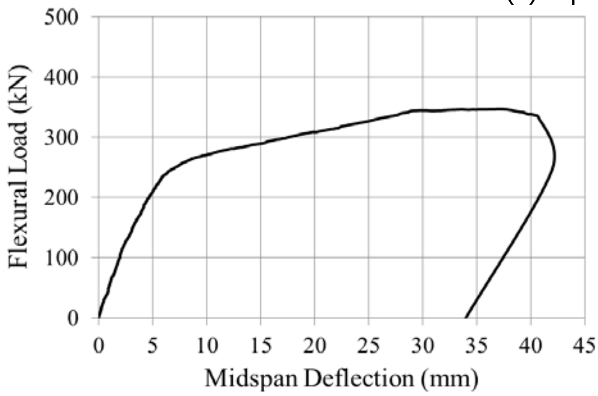
(b) Specimen GT



(c) Specimens CT-CR



(d) Specimens GT-GR



(e) Reference Specimen

Figure 3. Flexural load versus midspan deflection behaviour of the tested specimens

This difference was because in circular CFFT an increasing flexural load resulted in tearing apart of the inner layers of fibres which resulted in a sudden fall of load. However, the outer layers of fibres were still intact and resulted in again rise in load. It was noted that unreinforced CFFT failed in a highly brittle manner (Figure 3a and 3b) illustrating a sudden drop in the flexural load carrying capacity.

However, FRP bar reinforced CFFT (Figure 3c and 3d) experienced a reasonable ductile failure condition exhibiting a gradual decrease in flexural load similar to the Reference specimen (Figure 3e).

4.3. Flexural load-midspan deflection behaviour of unreinforced CFFT

Flexural load-midspan deflection behaviour of unreinforced CFFT (Figure 3a and 3b) was characterised by a mild rising curve followed by a vertical falling curve. The rising curve has several drops in load which indicated rupture of inner fibres with increasing applied flexural load. However, the curve continued to rise until the inner and outer fibres were significantly ruptured and was followed by a vertical falling curve indicating a sudden release of applied load. The final failure mode was the rupture of the fibres initiated on the bottom tension side and completed with the rupture of the top compression fibres. Both unreinforced carbon and glass tubes (CT and GT) have exhibited an identical behaviour. However, Specimen GT has manifested higher flexural load and midspan deflection than Specimen CT.

4.4. Flexural load-midspan deflection behaviour of reinforced CFFT

Flexural load-midspan deflection behaviour of FRP reinforced CFFT (Figure 3c and 3d) was characterised by a mild rising curve followed by a mild falling curve. Similar to unreinforced CFFT, mild rising curve in case of reinforced CFFT (CT-CR and GT-GR) also have several drops in load with an increasing applied load. However, drops in load were significantly smaller than those observed in unreinforced CFFT indicating the effectiveness of FRP reinforcement. Moreover, the mild rising curve continued to rise with longitudinal FRP reinforcing bars bending, and inner and outer layers of fibres rupturing with increasingly loud snapping sounds. After reaching the peak load, the load carried by the reinforced CFFT continued to decrease mildly with bending of FRP bars, and rupturing of inner and outer layers of fibres with increasingly louder snapping sounds. The test was stopped when the applied load stopped decreasing. During testing of FRP bar reinforced CFFT, a stage was noted when the flexural load almost stopped decreasing with increasing midspan deflection. Moreover, Specimen GT-GR has exhibited significantly higher flexural load than Specimen CT-CR, but identical midspan deflections in both types of tubes were observed.

4.5. Comparison of flexural load-midspan deflection behaviour of CFFT and Reference specimens

Flexural load-midspan deflection behaviour of both unreinforced (CT and GT) and FRP longitudinal bars reinforced (CT-CR and GT-GR) CFFT, and a steel RC (Reference) specimen is presented in Figure 4. Unreinforced CFFT have exhibited about 4.5 and 2 times lower flexural load and midspan deflections, respectively, than the Reference specimen. However, reinforced CFFT have depicted a significant improved flexural behaviour than unreinforced CFFT. Specimen GT-GR has exhibited higher flexural load and midspan deflection than the Reference specimen, whereas, Specimen CT-CR has exhibited lower flexural load but higher midspan deflection than the Reference specimen. Lower flexural load capacity of Specimen CT-CR than the Reference specimen was attributed to the slippage of CFRP bars.

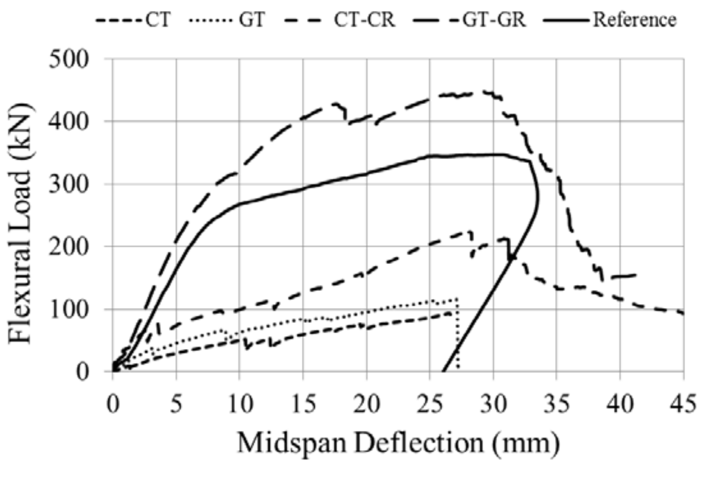


Figure 4. Comparison of flexural load-midspan deflection behaviour of the tested specimens

4.6. Influence of Fibre Reinforced Polymer (FRP) Tubes

In this study two unreinforced CFFT specimens (CT and GT) were cast and tested to study the influence of FRP tubes on flexural load-midspan deflection. The experimental results presented in

Figure 3(a) and 3(b) showed that Specimens CT and GT have almost identical ultimate midspan deflections. However, Specimen GT has exhibited almost 24% higher flexural load capacity than Specimen CT.

4.7. Influence of Fibre Reinforced Polymer (FRP) Reinforcement

In this study two FRP reinforced CFFT (CT-CR and GT-GR) were cast and tested to study the influence of FRP reinforcement on flexural load-midspan deflection. The experimental results presented in Figure 3(c) and 3(d) showed that Specimen CT-CR exhibited slightly higher midspan deflection than Specimen GT-GR. The flexural load carrying capacity of Specimen GT-GR was almost 50% greater than that of Specimen CT-CR. The lower flexural load carrying capacity observed in Specimen CT-CR was due to the fact that CFRP reinforcing bars used in this experimental study were smooth bars without sand coating. This resulted in reduced friction between the CFRP reinforcing bars and concrete and consequently, CFRP reinforcing bars slipped towards the middle portion of the specimen.

5. Conclusions

In this experimental study, four circular CFFT (two CFRP CFFTs and two GFRP CFFTs) were tested under flexural loading (four point loading). Two circular CFFT (one CFRP CFFT and one GFRP CFFT) were unreinforced and the other two CFFT (one CFRP CFFT and one GFRP CFFT) were reinforced with longitudinal FRP reinforcement. The experimental results of CFFT were compared to the steel RC specimen (Reference). The main outcomes of this study are as follows:

The observed failure mode in all CFFT was initiated by the rupture of the FRP tube fibres on the tension side followed by the crushing of concrete, and finally rupture of the fibres on the compression side. Longitudinal FRP bars reinforced CFFT failed in more progressive manner with significantly larger midspan deflections than unreinforced CFFT.

GFRP unreinforced CFFT exhibits moderately higher flexural load than unreinforced CFRP CFFT. However, GFRP longitudinal bar reinforced GFRP CFFT exhibited significantly higher flexural load carrying capacity than CFRP longitudinal bars reinforced CFRP CFFT. Moreover, midspan deflections in both types of CFFT were identical.

6. Acknowledgements

The first author thanks the University of Engineering and Technology, Lahore and the University of Wollongong, Australia for funding his PhD studies. The authors thank the University of Wollongong, Australia for providing the funding and facilities to carry out the experimental work presented in this study. They also acknowledge the technical assistance provided by Senior Technical Officer Mr. Fernando Escribano.

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