Mechanical Behaviour of Concrete Beams Reinforced with CFRP U-Channels

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ABSTRACT

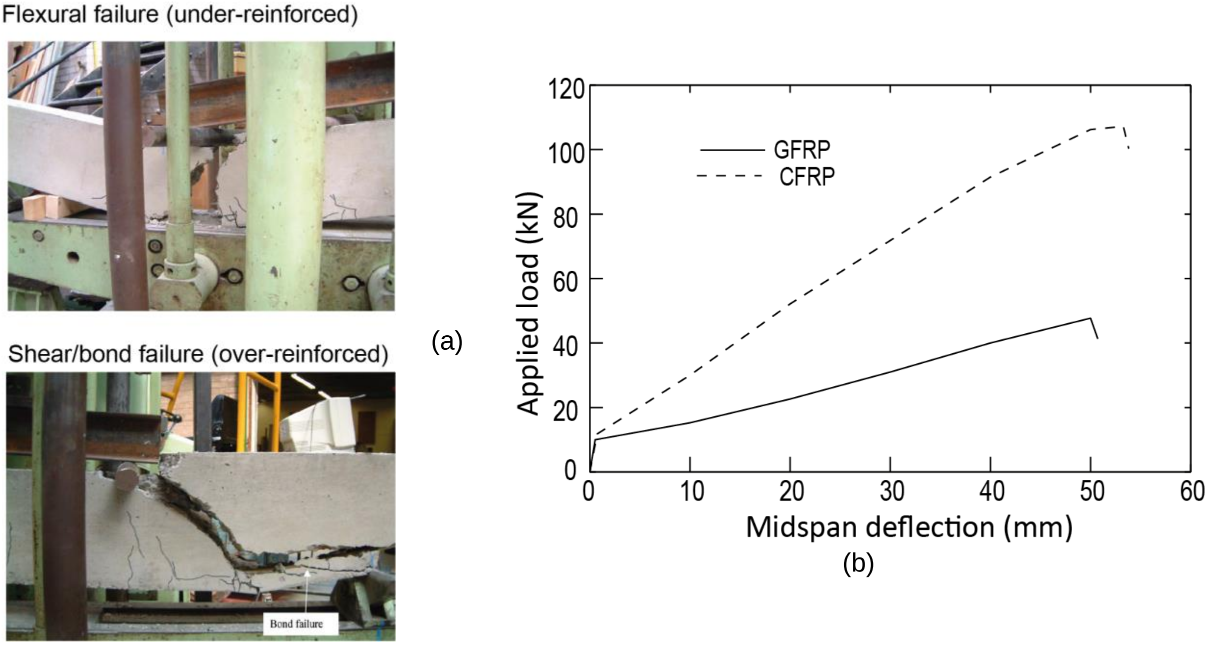
This paper presents selected findings from an experimental investigation that aimed to exploit the use of multidirectional carbon fibre reinforced polymer (CFRP) fabric as combined shear and flexural reinforcement in concrete beams. The results of the bond behaviour of rectangular prismatic concrete beams reinforced with three different CFRP fabric reinforcement configurations, a plain U-shaped channel, a U-shaped channel with aggregate coating, and a lipped U-channel section with intermittent closed loops, are presented. By considering the load response and the failure behaviour of the beams, it is shown that the use of an aggregate coating on internal and external surfaces of the CFRP channel ensured a better composite action between the CFRP reinforcement and the concrete than that between the plain CFRP channel and the concrete. On the other hand, provision of an anchorage system at the top end of the sides of the CFRP channel ensured a greater post-breakage capacity and a ductility compared to the beam with the plain CFRP channel. It is then shows that the use of U-shaped CFRP channels with aggregate coating and an anchorage system consisting of a lipped channel section with intermittent closed loops provided improved strength and ductility in concrete beams. The research output has potential to develop reinforcement systems for structurally optimised non-prismatic concrete geometries and also as permanent formwork/reinforcement in thin concrete members.

INTRODUCTION

Fibre reinforced polymer (FRP) materials are light weight and have high strengths, and their non-corrosive material behaviour has potential to provide long lifespans for civil engineering structures. Owing to these inherent characteristics, FRPs have potential applications as reinforcement in concrete structures. The nonmagnetic properties of FRP also make them useful for facilities for MRI medical equipment, airport runways, electronics laboratories, etc. Externally-bonded FRP reinforcement systems are widely used in repairing and strengthening of concrete structures where the light weight and the easy installation offer great benefits. However, the use of FRPs as internal reinforcement in concrete has not achieved a major success in the industry. The use of FRPs as a direct substitute for steel reinforcement bars and/or shear links using the same design principles as that of steel reinforced concrete means the current FRP internal reinforcement designs are largely inefficient [1]. Due to the elastic material behaviour of FRPs compared to the ductile behaviour of steel, the FRP–concrete bond and also the failure behaviour of the concrete structures with FRP internal reinforcement will be different to that of conventional steel-reinforced concrete structures.

In the studies reported in the literature, carbon (CFRP) and glass (GFRP) fibre reinforced polymer bars were mostly used as flexural and shear reinforcement in concrete beams (e.g. [2, 3]). The FRP reinforcement designs were largely done using the modified versions of the existing design guidelines (e.g. [4]) of steel reinforcement systems. The modifications usually aim to take into account the elastic material behaviour of FRPs over the ductile material behaviour of steel through the use of empirical factors. Under-reinforced beams failed catastrophically due to FRP rupture and the over-reinforced beams also mostly failed in similar catastrophic manners due to premature bond and/or shear failures. Even if the premature bond and shear failures were eliminated, the concrete crushing in the compression zone of over-reinforced beams (in over-reinforced designs the expensive FRP materials are not used efficiently) will not experience a significant ductility compared to that of conventional beams with steel reinforcement. For example, Figure 1a shows the brittle catastrophic failures noted in the under-reinforced and the over-rereinforced concrete beams reinforced with FRP bars in the study of Ashour (2006) [5]. The use of CFRP bars usually ensure higher failures loads of the concrete beams compared to the beams with GFRP bars, but the beams often failed catastrophically at the respective failure loads as can be seen from the applied load–midspan deflection relationships shown in Figure 1b for the beams tested in the study of Soric et al. (2010) [6]. Experimental investigations also suggested the poorer bond performance of the concrete–FRP reinforcement bars compared to that of steel reinforcement (e.g. [7]). Different forms of surface deformation systems of the FRP, in particular, sand-coated FRP bars have shown potential enhancement of the bond strength whilst eliminating premature debonding failure [8].

A new beam reinforcement system made from CFRP fabric was investigated in the present study. The flexible nature of CFRP fabric prior to curing with resin was used to fabricate U-channel shaped combined flexural and shear reinforcement for concrete beams. In order to eliminate potential brittle CFRP rupture failures, multidirectional fabric sheets were used to ensure adequate strain capacities for the CFRP channels. The effect of aggregate coating on the internal and external surfaces of the CFRP channel was investigated as a mean of improving the composite action between the CFRP reinforcement and the concrete. An anchorage system consisting of a lipped U-channel with intermittent closed loops was investigated in order to achieve a greater ductility compared to the reference beam with a plain CFRP reinforcement channel. The objective of the experimental programme was not to provide design data but to characterise the basic mechanics of concrete beams reinforced with CFRP fabric reinforcement. Finally, a lipped U-channel reinforcement with aggregate coating was investigated as a mean of achieving adequate strength and ductility in the concrete beams.



(a)

(b)

Figure 1. (a) Catastrophic failures noted in concrete beams reinforced with FRP bars [5] (b) Applied load–midspan deflection relationships of concrete beams reinforced with GFRP and CFRP bars [6]

CFRP U-CHANNEL REINFORCEMENT

In order to determine the effect of various CFRP channel reinforcement configurations, three concrete beams, each with dimensions 1000 mm (length) x 120 mm (width) x 120 mm (depth), reinforced with three different types of CFRP reinforcement: a plain U-channel (Beam1), a U-channel with aggregate coating (Beam2), and a lipped U-channel with intermittent closed loops (Beam3), were tested in the present study. U-shaped geometry was chosen due to its potential to provide a combined flexural and shear reinforcement system. Unlike the unidirectional FRP reinforcement systems investigated in the literature where brittle failure was inevitable, multidirectional CFRP fabric was used in the present study to fabricate the reinforcement channels. Owing to the distribution of fibres in more than one direction, multidirectional fabric has potential to eliminate brittle failures by ensuring higher strengths in transverse directions and also higher in-plane shear capacity compared to unidirectional FRPs. Despite the high material cost of CFRP compared to GFRP, the former was preferred in the study due to the poorer long-term performance of the latter in alkali environments such as in concrete. Total life cycle analyses and environmental impact assessments may be used to justify the economic viability of the proposed reinforcement system in the construction industry.

±45° dry biaxial CFRP fabric sheets (Figure 2) purchased from a commercial supplier was used in the present study. Each dry fabric sheet was 0.35 mm thick and the channels were fabricated by using a wet lay-up method. Four layers of ±45° biaxial CFRP fabric (Figure 3) were impregnated using a commercially available two-part epoxy resin. The objective of the present study was to develop a general form of an efficient CFRP fabric reinforcement system; therefore, the sophisticated manufacturing methods such as the use of autoclaves or resin infusion techniques were not considered in the present research. The chosen four-layer laminate was symmetric, since for each layer on one side of the mid-plane there was a corresponding layer at equal distance from the mid-plane on the other side with identical elastic mechanical properties and layer thickness. Since the laminate was symmetric in both geometry and mechanical properties, there will be no coupling between in-plane loading and bending deformations. The selected laminate was also balanced since it had pairs of layers with identical elastic mechanical properties and thicknesses but with +45° and -45° fibre orientations with respect to the longitudinal axis direction. Since the laminate was balanced there will be no coupling between in-plane normal loading and in-plane shear deformations.

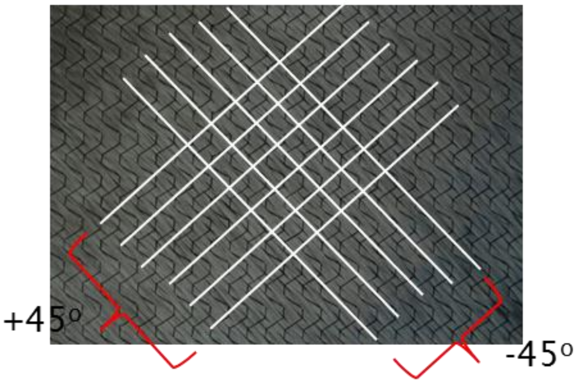


Figure 2. ±45° biaxial CFRP dry fabric

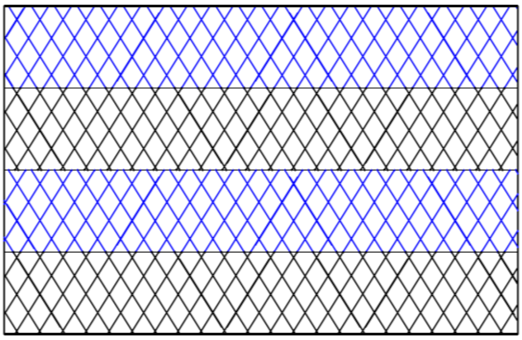


Figure 3. A schematic diagram of the four-layer ±45° biaxial CFRP fabric laminate (along the thickness direction)

FABRICATION OF CFRP REINFORCEMENT CHANNELS

Plain U-Channel

The plain U-channel of dimensions 970 mm x 80 mm x 80 mm (Figure 4a) was fabricated by folding rectangular fabric sheets. This was done by first individually impregnating each dry fabric layer with a commercially available epoxy laminating resin and then adding the subsequent layer on the top of the previous sheet. The required U-shape was obtained by wrapping the wet, rectangular CFRP laminate around a mould and cured in ambient conditions (20±2°C) for two days. The overall thickness of the hardened four-layer laminate was ~1.7 mm. The corners of the channel were rounded in order to minimise potential stress concentration effects.

U-Channel with Aggregate Coating

As a mean of improving the CFRP–concrete bond in one of the test beams, an aggregate coating was applied on all external and internal surfaces of one fully-cured CFRP U-channel (Beam2) (Figure 4b). Dried quartz gravel of size 2-5 mm purchased from a commercial supplier was used in the present study. Surface distribution density of aggregate coating was chosen to be approximately 50%. The same epoxy resin used in the wet lay-up fabrication of the CFRP channels was used to bond the aggregate on the surfaces of the fully-cured CFRP channel.

Lipped U-Channel with Intermittent Closed Loops

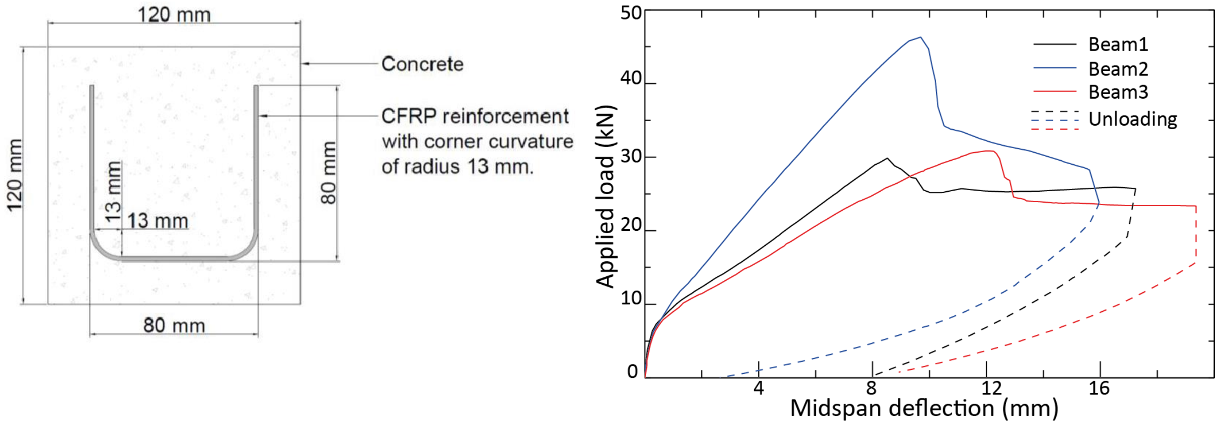
In order to investigate the effect of premature debonding that may be triggered due to the high stress concentration at the top of the sides of the CFRP channel, a lipped CFRP U-channel with intermittent closed loops (Figure 4c) was used in one the of test beams (Beam3).

(a) (b) (c)

Figure 4. Three types of CFRP U-channel reinforcements: (a) Plain U-channel, (b) U-channel with aggregate coating and (c) Lipped U-channel with intermittent closed loops

EXPERIMENTAL RESULTS

As stated previously, three concrete beams (dimensions 1000 mm x 120 mm x 120 mm) reinforced with the aforementioned three CFRP channels was tested in four-point bending (shear span=325 mm and constant moment zone=250 mm). Figure 5a shows the cross section of the beam reinforced with the plain CFRP channel (Beam1). A detailed shear analysis of the beams was beyond the scope the study, however, an approximate shear analysis ensured no premature shear failures prior to the expected flexural failure of the beams.



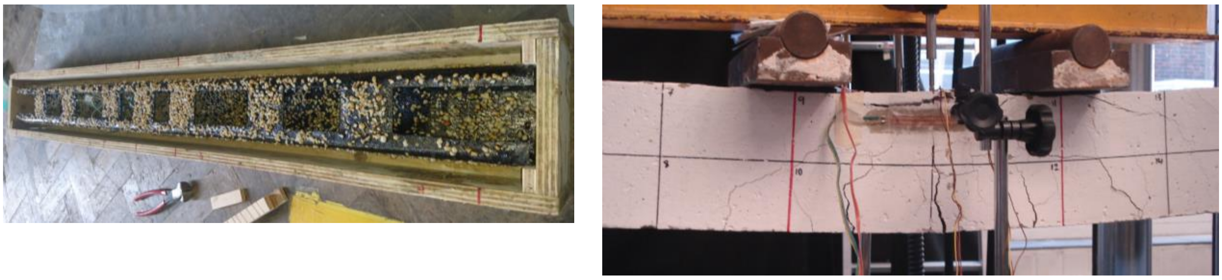
(a) (b)

Figure 5. (a) Cross sectional of the beam with plain U-channel (b) Applied load-midspan deflection relationships of the three test beam

The three beams were tested after 28 days of curing (the average compressive strength of the concrete ~38 MPa) using a servo-hydraulic test machine, displacement controlled (stroke rate 2 mm/min). Midspan deflection of each beam was measured using two digital displacement gauges, located at the front and back of the beam. The applied load–midspan deflection relationships shown in Figure 5b suggest that within the uncracked regime of concrete the behaviour of the three beams were similar. All beams failed due to the failure of the concrete compression zone in the constant moment zone. As can be seen from Figure 5b, the beam reinforced with the aggregate-coated CFRP channel (Beam2) demonstrated the highest flexural stiffness and the strength, suggesting the improved composite action between the CFRP and the in situ concrete. The peak load of ~46.65 kN of this beam is significantly higher than those of 29.88 kN and 30.86 kN of the plain and the lipped channel with intermittent close loops (Beam1 and Beam3 respectively). The results shown in Figure 5b also suggest that all beams resisted applied load beyond the peak load demonstrating a notable ductility before the final failure. The lipped U-channel with intermittent closed loops (Beam3) ensured a greater ductility and an ability to resist a significant portion of the peak load during the post-peak regime compared to other two beams.

REINFORCEMENT DESIGN FOR IMPROVED STRENGTH AND DUCTILITY

After taking into account the results of the previous three beams, a concrete beam (Beam4) reinforced with a lipped CFRP U-channel with intermittent closed loops and an aggregate coating on all internal and external surfaces was designed (Figure 6a) and tested with the aim of demonstrating improved pre-peak and post-peak strengths and ductile failure behaviour. In order to demonstrate the applicability of the research findings of the previous three beams (Beam1, 2 and 3) for beams with different design parameters, the dimensions (1370 mm x150 mm x 100 mm) of Beam4 and the concrete strength (25 MPa) were chosen to be different to those of the previous three beams. The size of the lips and the spacing of the closed loops in the CFRP channel were chosen to accommodate sufficient space for the application of aggregate coating and concrete casting. The beam was tested in four-point bending similar to the previous three beams, but with shear span 510 mm and constant moment zone of 250 mm (the clear span of the beam=1270 mm).



(a) (b)

Figure 6. (a) CFRP U-channel with intermittent closed loops and an aggregate coating on all internal and external surfaces, (b) Flexural failure of Beam4

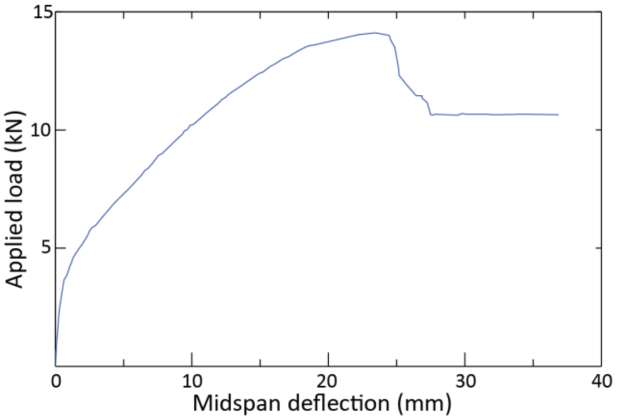


Figure 7. Applied load–midspan deflection relationship of Beam4

The beam demonstrated a distribution of flexural cracks within the constant moment zone (Figure 6b) and nominal numbers of minor cracks within the shear spans. The final failure of the beam was due to separation of a narrow concrete slit above the top edge of the CFRP channel at midspan. The applied load–midspan deflection relationship of the beam (Figure 7) demonstrates the ability of the beam to resist further applied load after the peak load and a notable ductility in the beam prior to the final failure. The results suggest unlike conventional FRP internal reinforcement designs in concrete beams where brittle failures were inevitable (e.g. Figure 1), the U-channel reinforcement system developed in the present study ensured a significant ductility and a safe failure behaviour of the concrete beam.

CONCLUSIONS

- The study has shown that U-shaped channels made from CFRP fabric have potential to ensure ductile flexural failures in concrete beams.
- The results suggests that the use of an aggregate coating on the surfaces of the CFRP channel provided an improved composite action between the CFRP channel and the concrete compared to that between the plain CFRP U-channel and the concrete.
- The provision of an anchorage mechanisms at the top edges of the CFRP channel ensured a better post-breakage resistance and a ductility compared to concrete beams with a plain CFRP U-channel.
- U-shaped CFRP channels with aggregate coating and an anchorage system consisting of a lipped channel section with intermittent closed loops provided higher strengths and better ductility in concrete beams compared concrete beams with conventional FRP bar reinforcement.

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