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Exploitation of FRP Fabric Reinforcement

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Abstract
This paper presents findings from a combined experimental and numerical investigation into novel use of Carbon Fibre Reinforced Polymer (CFRP) fabric as reinforcement in concrete beams. The paper presents the development of a MATLAB-based computer code that incorporates the complex mechanical and geometric behaviour of 3D CFRP geometries, effects of concrete cracking, concrete–CFRP bond, equilibrium, compatibility and boundary conditions for analysing CFRP fabric reinforced concrete beams. The model predictions were compared against experimental results, including strain data and load-deflection relationships.

Keywords: Beams; Computer; Concrete; FRP; Fabric; Models; Reinforcement

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Introduction

Despite Fibre Reinforced Polymer (FRP) has been used as reinforcement in concrete structures for decades, the full-potential of FRPs has not exploited largely due to the current wisdom of using them as direct replacement for steel bars. Due to the brittle material behaviour of FRPs, some design principles which work well for steel reinforcement can lead to structurally inefficient designs and/or brittle failure of FRP-reinforced concrete structures. For example, concrete beams under-reinforced with steel bars ensure safe ductile behaviours, but the beams similarly reinforced with FRP bars can fail in brittle manner due to the rupture of the FRP. FRP stirrups are also ineffective in shear. A team led by the second author of this paper has previously shown [1] the potential of channel-shaped CFRP reinforcement (Figure 1) fabricated using multi-direction fabrics for eliminating brittle failure in FRP-reinforced concrete beams – a major limitation associated with contemporary FRP reinforcement designs. Unlike the widening of a single major crack that causes brittle failure of the beams with FRP bars, the beams reinforced with CFRP channels showed distributed small cracks, and an ability resits a part of the load during post-cracked regime (Figure 1).

Given the different mechanical and geometric characteristics of the channel-shaped FRP reinforcement, the existing design codes for concrete beams reinforced with steel/FRP bars cannot be used for design. This paper presents how a numerical design too using was developed for designing CFRP channel reinforced concrete beams.

Experiments

Experimental results of concrete beams reinforced with CFRP channels and tested in a previous study [1] were used to validate the proposed design methodology. The CFRP reinforcement channels were fabricated using a wet lay-up method where a number of dry fabrics with fibres orientated in multiple directions were impregnated using an epoxy resin. The required channel shaped geometry was obtained by folding the wet, resin-impregnated laminate around a mould. The details of the fabrication process of the CFRP channels and the concrete beams can be found in elsewhere [1]. The beams with dimensions 1000 mm (long) x 120 mm (wide) x 120 mm (deep) were tested in four-point bending (see Figure 2) at a slower load rate 2 mm/min, a rate representative of a quasi-static load. The experimental results of the applied load–midspan deflection and the measured strain at the top concrete surface (i.e. compression surface) at midspan were used to validate the proposed design methodology.

Design methodology

Since no simplified design rules are available to design the beams with FRP channel reinforcement, detailed strain/stress analysis was carried by considering force and moment equilibrium of the beam. This was done by first dividing the beam into a finite number of segments along the beam span and then the equilibrium of each beam segment was sought numerically using a computer code written using MATLAB. As a starting point, it was assumed a linear strain distribution through the thickness of each beam section (i.e. plane sections remain plane) and local strain compatibility between concrete and CFRP. Stress distributions and resultant forces of concrete in compression, concrete in tension and tension in the CFRP were determined by combining the knowledge of assumed linear strain distribution and the stress–strain relationship of each material. The centroid location of each resultant force component was determined by using the knowledge of first moment of area. At a given externally applied load, the equilibrium equations were first written for each beam segment based on two independent variables of an assumed linear strain distribution (in the present model, strain at the top of the beam section and the neutral axis depth were considered as the two variables). The variables were then determined by iteratively solving the force and moment equilibrium equations. The applied moment on each beam segment which was required for the equilibrium analysis was determined by using the knowledge of bending moment distribution of the beam. The deflection profile of the beam was then calculated by numerically integrating the known curvatures of the beam segments along the beam span. The analysis was then repeated for a range of externally applied load values. The step-by-step procedure used in the present study is shown in Figure 3.

Material mechanical models

CFRP. The mechanical properties of the CFRP laminate were determined experimentally and these results are published elsewhere [2]. The results showed the stress–strain (σ-ε) relationship is largely linear within the strain range the CFRP channel experienced during the actual beam test. Therefore, in the analysis the CFRP was assumed to be linearly-elastic with Young's modulus of 23.6 GPa along the longitudinal direction of the beam. This value was determined using initial linear portion of the experimentally determined σ-ε curve.

Concrete in compression. Hognestad's parabolic stress-strain curve was assumed for concrete in compression on loading [3]. Using standard cylinder tests, the compressive strength of concrete was determined to be 38 MPa.

Concrete in tension. Using the knowledge of concrete compressive strength, the tensile strength of concrete (f_t) was assumed to be 3.8 MPa**.** A linear-elastic behaviour was assumed for concrete in tension with the same initial modulus as in compression.

Tension-softening. Due to the presence of a fracture process zone (FPZ) the tensile stress in concrete may not drop to zero immediately after the attainment of f_t. Owing to different geometry and mechanical characteristics of the CFRP channels, the tension-softening models those used for concrete reinforced with steel bars may not be accurate for the beams investigated in the present study. As a starting point, the equilibrium analyses of the beam segments were performed with two assumed softening models (Figure 4). The first model assumed no tension-softening (i.e. tensile stress drops to zero after f_t) and the second model was a simplified model developed for FRP fabric textile-reinforced concrete [4].

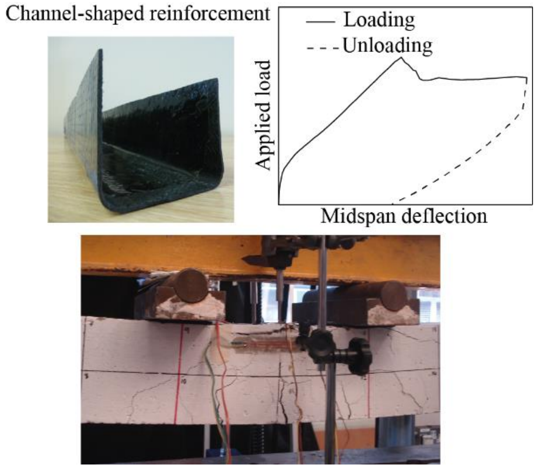

Figure 1: Load-deflection and failure behaviour of CFRP channel reinforced concrete beam

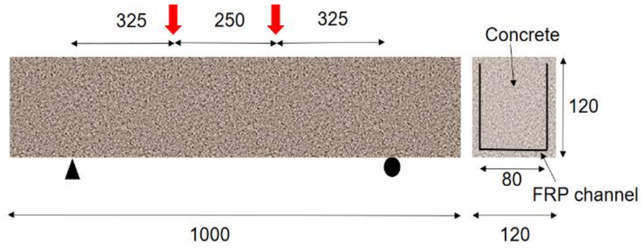

Figure 2: Four-point bending test arrangement and cross section geometry of the beam

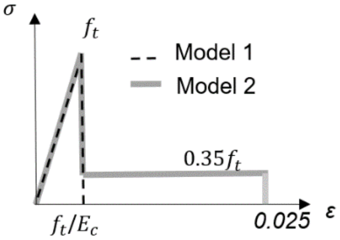

Figure 4: Tension-softening models for concrete

Results

The results of the numerical model were compared against experimental results. For brevity, the results of one test beam are shown in this paper. Figures 5a compares the predictions from the model with the experimentally-determined load–midspan deflection relationship.

Modelling of the beam's behaviour after the peak load (i.e. post-failure regime) was beyond the scope of the present paper. Figures 5b compares the predictions from the model with the experimentally-determined load–strain at compression surface (i.e. top surface) at midspan. The results suggest the negligence of tension-softening of concrete overestimated the strain, and hence deflection predictions from the model. The tension-softening model of FRP textile-reinforced concrete appears to represent the load response of the concrete beams.

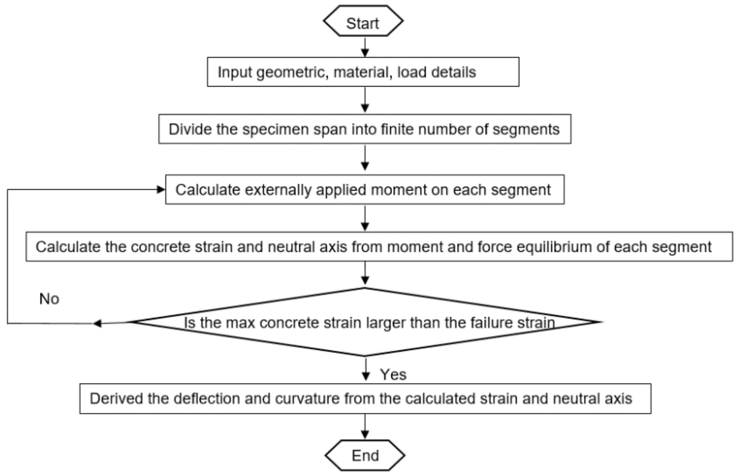

Figure 3: Step-by-step MATLAB procedure

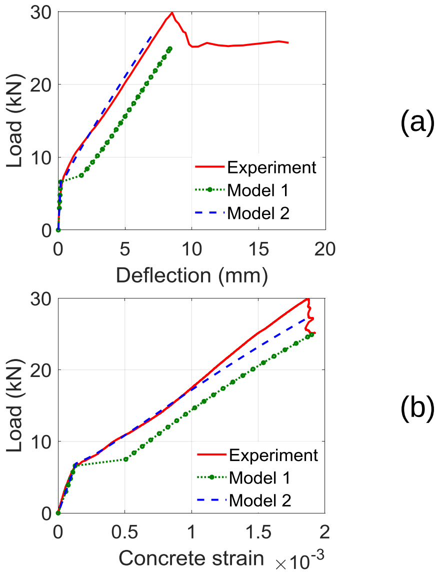

Figure 5: (a) Load-midspan deflection (b) Load-strain at top of concrete relationships

Conclusions

The results suggest design of concrete beams reinforced with channel shape FRP reinforcement can be carried out by using numerical codes that solves equilibrium analysis of the beam. However, the determination of an appropriate tension-softening model is required for accurate analysis. Future research involves the extension of the numerical codes for the failure prediction and post-failure regime of the beams. Detailed investigation of the concrete–FRP bond, load response, failure behaviour and optimal design of non-conventional reinforced geometries will also be considered.

Acknowledgments

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