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Continuous Unidirectional Carbon Fibre-Reinforced Concrete Beams

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Abstract

This paper reports a set of experimental results for continuous unidirectional carbon fibre-reinforced concrete beams. The fibers are embedded at different layers in the tension side of the beam below the neutral axis. All together nine concrete beams were constructed and tested, three of which contained no reinforcement. The carbon fibre-reinforced concrete beam load-deflection results are presented graphically for three beams with one-layer, one with two-layers and two with four-layers of continuous unidirectional fibres. The maximum deflections of the reinforced beams are compared with those of plain concrete beams.

Keywords: carbon fibres, FRP, continuous fibre, RC beams, concrete, carbon reinforcement, unidirectional fibres.

1 Introduction

Application of polymer composite materials was initiated in aerospace industry and then it progressed into the automotive industry and other engineering fields. During the last two decades, they have found applications in structural engineering fields, in particular for strengthening concrete structures. Fibre-reinforced plastic structures have a great advantage over their steel and concrete counterparts mainly due to their high strength to weight ratios. At the present, the main applications of fibre-reinforced plastics (FRP) in civil engineering structures are for strengthening concrete beams, columns or slabs. However, the major advantages of using FRP come when the whole structure is constructed from FRP. The structure may be constructed of carbon fibre-reinforced plastics (CFRP), glass fibre-reinforced plastics (GFRP) or more advanced composites like graphite fibre-reinforced plastics may be used. Of course, this type of material may not be economical for civil engineering structures.

The first glass fibre-reinforced plastic pultruded box beam was tested in three-point bending by the first author at the Engineering Laboratories at Lancaster University, England in the summer of 1990. However, it appears that the initial studies of the application of FRP as construction materials are due to Turvey [1]. As reported in his series of papers beginning in 1995, he and his co-researches conducted detailed experimental as well as finite element simulations of various aspects of structural members made from pultruded GFRP. The experimental investigation of a double lap single bolt tension joint made from 6.35 mm thick pultruded fibre-reinforced plastic flat sheet is reported. In this paper the effects of joint geometry and bolt torque on the structural performance of the joint is studied. The effect of load position on the lateral buckling response of pultruded GRP cantilever is experimentally investigated [2]. Similar experimental as well as finite element simulations of structural components made of GRP were conducted by Turvey [3-10]. Turvey made experimental evaluation of structural components from different aspects and tested various types of connections of FRPs. In the late 1998, New York State Department of Transportation (NYSDOT) replaced a deteriorated bridge superstructure using a fibre-reinforced slab [11]. This was the first experience for the US structural engineers to design and manufacture a fibre-reinforced composite bridge. As it was their first experience, a very careful proof test before opening it to the public and a very careful monitoring after that has been carried out [12-14]. Another investigation by Turvey et al on the performance of pultruded GRP profiles is on determining tensile tearing strengths of web-flange junctions of two sizes of pultruded glass reinforced plastics wide flange profiles [15]. As it is determinable, the applications of fibre-reinforced composites can save time and reduce the costs and public disturbances in structural engineering.

Another aspect of the application of FRPs in structural engineering is for using them as strengthening elements for concrete structures, in particular, in the repair and maintenance. FRPs can be used as strengthening elements for the tension as well as the compression sides of concrete slabs. Various experimental and numerical investigations on the applicability of FRPs in concrete structures have been carried out during the last decade. The FRP plating and steel plating of reinforced concrete (RC) beams are compared [16] for their de-bonding characteristics. De-bonding or delamination is one of the major problems in the application of FRPs as strengthening elements in concrete structures. Bolting FRP plates to RC beams or slabs is one solution as oppose to adhesive bonding, however, this method of connection has its own drawbacks [17]. The initial studies of the applications of fibre-reinforced composite plates in strengthening concrete beams are due to Saadatmanesh and Ehsani [18]. They pointed out that the epoxy-bonded glass fibre-reinforced plastic plates could provide a corrosion-free solution to increasing the load-carrying capacity of concrete bridges [19]. The other aspect of using fibre-reinforced composite strip is in extending service life of concrete and masonry structures [20]. Beams as well as columns [21-24] are externally reinforced by FRP composites and experimentally examined for their longer life cycle. Slabs are other useful concrete structures, which can benefit from being externally strengthened by FRPs. Consequently; glass fibre-reinforced plastics may be used to

externally strengthen RC slabs [25]. Here again, the de-bonding of composite strips presented a major problem, although, did not have a serious detrimental effect on the ultimate strength. This is more evident if the FRP reinforcement ratio is low. In another investigation, some criticism is made on FRP composites as having low modulus of elasticity and non-yielding characteristics, however, FRP composites can use fibres having modulus of elasticity as high as steel, i.e. graphite fibres. Obviously, for civil engineering structures, using these types of fibres will result in having very expensive structures, which, from a structural engineer's point of view, are not economical. In regard to non-yielding characteristics of FRP composites, again, polymer based resin may be used which have very high yielding properties but are not very suitable for strengthening concrete structures [26]. Instead of using steel reinforcement bars in concrete structures, FRP bars may be used for counteracting corrosion [26-34]. However, FRP bars may not match as well as steel with the concrete properties in terms of bonding. On the other hand, steel bars have very good bonding properties with concrete due to high frictional properties induced between the concrete and the steel. In order to increase the frictional properties of the surface of the rod they are sand-coated [34]. Retrofitting damaged structures with fibre-reinforced polymers is another major field of application of FRP in concrete structures [35]. Another experimental study of RC two-way slabs strengthened with CFRP strips, experienced de-bonding of the strips from the concrete [36]. It appears that the de-bonding is a major drawback in reinforcing concrete structures with FRP plates or strips. There are three types of de-bonding in adhesive bonding longitudinal plates to RC beams and slabs [37]. When de-bonding cracks initiate at the interception of a plate with an intermediate flexural or intermediate flexural/shear crack and propagate from the intercept in one or both directions, it is called intermediate crack (IC). When de-bonding cracks initiate at the plate end and propagate inwards, we have plate end (PE) de-bonding. Finally, critical diagonal crack (CDC) de-bonding from de-bonding cracks that initiate at the root of a CDC and propagate towards the PE. FRP plates can be used to improve the shear properties of concrete beams and slabs as well as their bending properties [38]. As it is evident from the literature, FRPs, due to their special properties, have a variety of applications in the form of reinforcing elements in concrete structures. CFRP in the form of grid reinforcement is used in one-way concrete slabs [39]. Another practical application of T-beam bridge repair using FRP strengthening system was carried out in 1999 in New York State [40]. After two years in service, test results indicated that the quality of bond between the laminates and concrete, and effectiveness of the system have not deteriorated after two years in service. Infrared thermography camera did not show any significant de-bonding in the system. High strength FRPs may be used to increase load carrying capacity of concrete beams in bending [41]. Aramid FRP materials are one such material that has produced higher strength than the CFRP or GFRP. The AFRP bars are used in the tension side of beams under the action of bending. More flexibility is achieved, when a beam is reinforced with AFRP in the post-cracking range than an equivalent steel-reinforced beam. Four-point loading may be used to examine shear capacity of beams. Concrete beams reinforced with FRP bars are subjected to four-point bending [42] for investigating the shear capability of the beam.

The above literature survey, if complete, shows lack of an efficient system of bonding the FRP strips to the tension face of the concrete beams or slabs. Only one case was sighted in the literature that they expressed their satisfaction of the bonding in service [40]. However, in the experimental investigations the de-bonding presented a major problem. It appears that if the structure is not loaded to its destruction the present attachment methods may work.

In the present work the problem of debonding is overcome by embedding the continuous unidirectional fibres in the concrete. However, this method can only be used for structure construction and not for rehabilitation purposes of the concrete structures.

2 Experimental Program

The experimental program consists of continuous unidirectional carbon fibre-reinforced beam construction and testing of the beams in four-point loading. Initially the type of materials used in the construction process is defined and then the type of beams constructed and tested are described.

2.1 Material Type

The fibres are continuous unidirectional carbon fibres with the following specifications:

- FIBER: CARBON
- STYLE: Unidirectional
- DENSITY: 340 gm/ m²
- WIDTH: 75 mm or 37.5 mm

The concrete mix with 10 mm aggregate size was made in the High Bay Laboratory of the Faculty of Engineering. Five cylindrical specimens were prepared from the same concrete mix as that used for the construction of the beams for strength measurement. After 28 days curing time, the cylinders were tested in compression for their strength measurement. The average of the measured strength of the five specimens was 34.5 MPa.

2.2 Beam Construction Procedure

The beam specimens' dimensions are 100*100*500 mm with squared cross-section. The first layer of the 75 mm width continuous unidirectional fibre was placed 10 mm from the beam tension surface, the second layer was placed at 20 mm from the tension surface. Consequently, the layers of fibre were positioned at approximately 10 mm from each other and the last one was placed 10 mm below the beam neutral axis. The spacing of the fibres depends on the aggregate size. The minimum spacing of the fibres in the concrete structure can not be less than the maximum aggregate size in the concrete. Figure 1 illustrates the cross section of a plain, one- and two-

layers concrete reinforced beam. The stresses furthest from the neutral axis are maximum and they reduce to zero on approaching the neutral axis. Therefore, the width of the fibre bundle may reduce accordingly. In the present investigation, a constant fibre-bundle width was used.

Figure 1: Concrete beam cross-sections (a) Plain concrete beam (b) Concrete beam with one layer of continuous unidirectional carbon fibre (c) Concrete beam with two layers of continuous unidirectional carbon fibre

3 Beam Bending Tests

All together nine beams were tested in four point bending. The aim is twofold:

1. to observe the behaviour of the fibers in the concrete in no-load status
2. to compare the fiber strengthened beams behaviour with that of plain concrete beams

Figure 2: Experimental set-up

3.1 Beam testing procedure

The INSTRON testing machine (see Figure 2) is used to apply the point loadings and measure the maximum transverse displacements (or deflections) of the beams. The data acquisition was carried out by the data acquisition system installed on the INSTRON testing machine. The speed of the loading was controllable. Initially a very low speed was used to allow the settlement of the rubber support at the point of the application of the loads, 0.1 mm/min which was then increased to a maximum of 0.5 mm/min before the failure of the beam. Beam supports and loading positions are illustrated in Figure 3.

Figure 3: Beam loading, support points and cross section

4 Tests numerical results

The loads and deflections are recorded and presented in the form of load-deflection curves in Figures 4 – 8. Due to the high number of data readings for catching the failure point, each curve is presented on a separate axis. However, it is not difficult to compare the results. The maximum load and the corresponding deflections are given for comparison purposes.

Figure 4 illustrates the results for a concrete beam with no reinforcement. As it is expected after the beam has reached its maximum load carrying capacity, a sudden fracture occurs, consequently no more load can be carried by the beam.

Figure 4: Concrete beam with no reinforcements, Maximum Load= 9093 N, Deflection = 1.17 mm

Figure 5 illustrates a similar type of results but for a beam with one layer of continuous unidirectional carbon fiber with 35 mm width and 410 mm length buried in the tension face of the beam at approximately 10 mm from the bottom of the beam. The failure load is higher than the corresponding load of the beam without reinforcement and beam can carry load even after the failure of the concrete.

Figure 5: Concrete beam with one layer of carbon fiber reinforcements with L = 410 mm, Maximum Load = 9267 N, Deflection = 1.891 mm

The next beam contains two layers of the same fiber positioned at approximately 10 and 20 mm from the bottom face of the beam respectively. After the failure of the concrete there is a sudden but minor reduction of the load, however, it carries higher load than the beam with no reinforcement and the one with one layer of fiber. The results are illustrated in Figure 6.

Figure 6: Concrete beam with two layers of carbon fiber reinforcements with $L = 410$ mm, Maximum Load = 12184 N, Deflection = 3.455 mm

Figures 7 and 8 illustrate the load-deflection results for one layer continuous unidirectional carbon fiber reinforced concrete beam, the latter having fiber length of 460 mm whereas in the former it is 410 mm.

Figure 7: Concrete beam with one layer of carbon fiber reinforcements with $L = 410$ mm, Maximum Load = 7881 N, Deflection = 1.314 mm

Figure 8: Concrete beam with one layer of carbon fiber reinforcements with $L = 460$ mm, Maximum Load = 11085 N, Deflection = 1.626 mm

For a better comparison of the experimental results illustrated above the values of the main points are tabulated and they are shown in Table 1 below.

Beam Number	B01	B02	B03	B04	B05
Beam Reinforcement Type	Plain	One Layer 410	One Layer 410	One Layer 460	Two Layers 410
Load at Concrete Failure (N)	9093	9267	7881	11085	9319
Deflection at Concrete Failure (mm)	1.17	1.89	1.31	1.63	1.64
Load at Maximum Bending Strength (N)	9093	9267	7881	11085	12246
Deflection at Maximum Bending Strength (mm)	1.17	1.89	1.31	1.63	3.359
Final Load Recorded (kN)	9093	64	1687	1218	3124
Final Deflection Recorded (mm)	1.17	19.48	17.37	11.00	33.75

Table 1: Summary of the above graphical results

5 More bending tests for beams

With the encouraging results from the initial tests, four more beams were constructed and tested. Two plain and two continuous unidirectional carbon fibre-reinforced concrete beams were constructed. The cross section of the fibre-reinforced concrete beams is illustrated in Figure 9. The cross sections of the plain concrete beams are the same as those with carbon fibres but with no fibres. Beams subjected to static loadings at two points with simply support constraints at the edges, i.e. four-point loading, similar to that illustrated in Figure 3.

Figure 9: Beam cross section

5.1 Concrete strength measurement

Similar to the first set of tests, the compressive strength of concrete is measured by testing three cylindrical specimens made of the same concrete mix as that used for the construction of the beams. The average of the three values is taken to be 43.566 MPa.

6 Numerical results for the second series of tests

The numerical results are presented in graphical form and a summary of the results are given in tabular form for convenience. The load-deflection results are illustrated

in Figures 10 to 13. The summary of the graphical results are given in Table 2. The load-deflection results for the two plain concrete beams are illustrated in Figures 10 and 11. The beams were loaded with a speed of 0.1 mm/min for the first minute and then the speed was increased to 0.2 mm/min and after three minutes it was increased to 0.3 mm/min. At the end of third minute the speed was increased to 0.4 mm/min. The failure of the beam occurred at this speed. The same sequence of loading was used for the second plain concrete beam. As expected the failure of the beam is a brittle failure with a sudden drop of the load.

Figure 10: Plain concrete beam with $L = 480$ mm, Maximum Load = 10191 N, Deflection = 2.415 mm

Figure 11: Plain concrete beam with $L = 480$ mm, Maximum Load = 9318 N, Deflection = 1.012 mm

Figures 12 and 13 illustrate the load-deflection results for the four layer continuous unidirectional carbon fibre-reinforced concrete beam. The sequence of loading was similar to that for the plain concrete beam with the exception that the speed was increased up to 0.5 mm/min and then left at this speed until the failure occurred. The interesting point to note is that the failure of both beams occurred in shear (see Figure 14). The beams resisted the bending with nearly three times the loading of the plain concrete beams. The failure of the beams occurred at opposite ends to one another.

Figure 12: Four layer carbon fibre-reinforced concrete beam with $L = 480$ mm, Maximum Load = 27481 N, Deflection = 2.248 mm

Figure 13: Four layer carbon fibre-reinforced concrete beam with $L = 480$ mm, Maximum Load = 24412 N, Deflection = 1.977 mm

Figure 14: Shear failure of four layer carbon fibre-reinforced concrete beam

Beam Number	P1	P2	FR1	FR2
Beam Reinforcement Type	Plain	Plain	Four-Layer 480	Four-Layer 480
Load at Concrete Failure (N)	10191	9318	20984	22467
Deflection at Concrete Failure (mm)	2.415	1.012	1.383	1.458
Load at Maximum Bending Strength (N)	10191	9318	27481	24412
Deflection at Maximum Bending Strength (mm)	2.415	1.012	2.248	1.977
Final Load Recorded (kN)	10191	9318	4300	8598
Final Deflection Recorded (mm)	2.415	1.012	5.353	4.108

Table 2: Summary of the above graphical results

7 Conclusions

All together nine concrete beams three without any form of reinforcement but the other six each with continuous unidirectional carbon fibre reinforcements were constructed and tested. At the present no theoretical evaluations of the beams in the form that they are constructed and tested are carried out. However, the main objective of this paper is to experimentally evaluate the influence of the carbon fibers embedded in concrete. Two different fibre widths are used, 75 and 37.5 mm. No apparent deficiencies were observed from the embedded fibres in the concrete. The fibres did not cause any separation or debonding of the fibres from the concrete. An approximately 10 mm clearance from the fibre edge was sufficient for the concrete to act as a cover. Finally four layer carbon fibre-reinforced concrete beams were constructed and tested. The outcome was excellent. The beams load carrying capacity of the carbon fibre-reinforced concrete beams was increased by approximately three times the plain concrete beam and that the beams failed in shear and not in bending. The beams were not protected against shear failure. With the successful outcome of the final tests on the four layer carbon fibre-reinforced concrete beams the final draw is that to introduce the fibers directly into the concrete and in several layers is more advantageous. Obviously, the above efforts were the very initial trials of the new method of reinforcing concrete structures. In order to reach a comprehensive conclusion, more samples with different types and sizes of fibres have to be constructed and tested. However, the initial trials are very optimistic and promising.

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