SHEAR STRENGTHENING OF CONTINUOUS REINFORCED CONCRETE T-BEAMS USING DEEP EMBEDMENT TECHNIQUE

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ABSTRACT

Despite numerous studies, shear behaviour before or after strengthening is still not fully understood, particularly in continuous concrete structures which are the norm. Upgrading shear resistance is altogether more difficult since Externally Bonded Reinforcement (EBR) or Near Surface Mounted (NSM) techniques do not allow the FRP material to be anchored into the compression zone of the T-beams and they cannot be used in cases where the sides of the beams are inaccessible. An innovative retrofit technique, named Deep Embedment (DE) or Embedded Through Section (ETS) technique involves the insertion of FRP/steel bars upwards into vertical or inclined holes which have been drilled from the soffit of concrete beams. In this way, the tension and compression chords of the beams are directly connected while the bars are bonded to the concrete core through adhesives. With this technique strengthening can be done in cases where the webs are inaccessible. Thus the main focus of this study is to significantly contribute to the current knowledge on the behaviour of Reinforced Concrete continuous T-beams strengthened in shear using the DE technique where large shear forces are combined with large negative bending moments. An experimental program consisting of ten two-span continuous T-beams designed to fail in shear was carried out in order to significantly contribute to the current knowledge on the behaviour of RC continuous T-beams strengthened in shear using this technique. Therefore, this paper reports on the test results and on their significance in being able to apply this technique on concrete structures by validating them through adequate analytical models.

KEYWORDS

Shear resistance, retrofitting, fiber-reinforced polymers, reinforce concrete T- beams, deep embedment.

INTRODUCTION

Strengthening and rehabilitation of reinforced concrete (RC) structures has become an important part of civil engineering. Gold and Martin (1999) emphasised the significant redundant building space in the UK to be strengthened, much of which was constructed in the 1960s and 1970s. Majority of the buildings from 1980s, 1990s and pre-and-post World War II need to be adapted to meet the requirements of the 21st century. Shortage of structural ductility can be the cause of the brittle and catastrophic failure of a structure. To date recent codes, require a high amount of shear reinforcement which differs from previous codes that did not obtain strict rules for [illegible] 1998; Khalifa et al. 1998, Pellegrino and Modena 2002, Chaallal et al. 2011, have shown shear capacity of RC beams can be considerably enhanced by using the Externally Bonded technique (EB). (De Lorenzis and Nanni 2001; Barros and Dias 2005; Chaallal et al. 2011, have presented results in Near Surface Mounted (NSM) technique. These techniques have been developed due to the dangerous and sudden shear failure within reinforced concrete (RC) structures. Lack of understanding concerning the shear behaviour before and after strengthening still exists within research, even though use of FRP reinforcement on the basis of experimental research on simply supported beams is defined by the International and national guidelines and codes (Concrete Society Technical Report 55, ACI, etc.). This is prominent for continuous concrete structures, which have been disregarded in the previous studies. Improvement of shear resistance is altogether more challenging by using Near Surface Mounted (NSM) and Externally Bonded Reinforcement (EBR) techniques which are broadly used for flexural strengthening. It is not realistic choice to full FRP wrapping of beams as they are frequently cast monolithically with the top slab. So, U-wrapping or side-wrapping is sometimes used. It is important to acknowledge truss action may not be mobilised due to these methods as FRP material cannot be anchored into compression zones; similarly, the impact of debonding of FRP laminates within low strains raises additional problems. In scenarios were sides of beams are unreachable the external bonding techniques cannot be used. The behaviour within FRP shear reinforcement in the negative moment region in continuous structures has not yet been fully understood; more research has been conducted on simply supported beams employing FRP shear strengthening in the positive moment regions. Large shear forces co-exist with large negative bending moments at the same location; as shown in Figure 1.

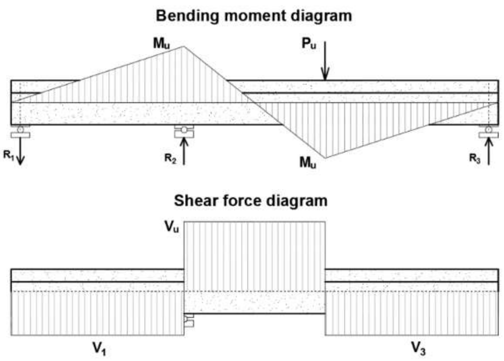

Figure 1 Bending moment and shear force diagrams in continuous beam

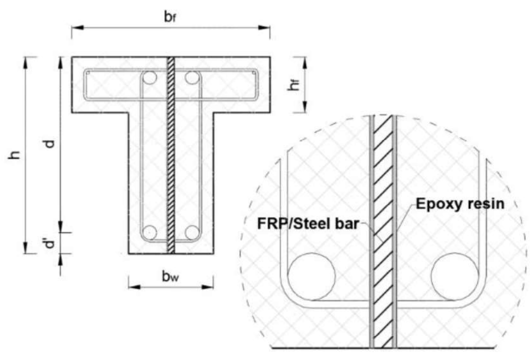

Figure 2 Deep Embedment technique

An alternative strategy for shear strengthening of reinforced concrete beams with FRP/steel bars, Deep Embedment (DE) or Embedded Through Section (ETS) has been developed (Valerio and Ibell, 2003; Valerio et al. 2009; Chaallal et al. 2011; Mofidi et al. 2012). In this technique, DE bars are epoxy bonded into previously drilled holes (vertical or inclined) through the cross section of the RC beams. In this way, tension and compression chords are directly connected and bond between FRP bars and concrete is much better, which makes this technique superior in comparison with Externally Bonded (EB) and Near Surface Mounted (NSM) methods (Valerio et al. 2009), (Figure 2). The novelty of this research is focused on how the deep embedment technique can be extended in scope by considering strengthening materials other than CFRP (GFRP and steel are being considered), angles of drilling other than vertical (angles at 45 degrees are being considered), and the effects of continuity on shear strengthening. An experimental program consisting of ten RC continuous beams has been conducted in order to provide useful data for a deeper understanding of failure mechanisms in DE strengthened continuous beams as well as the contribution of FRP/steel bars to its total shear capacity. This experimental program will be followed by the development of an analytical model for the calculation of the shear contribution of DE bars. The experimental program will be described in detail and obtained results presented.

TEST PROGRAM

The experimental program involves tests performed on ten full-scale reinforced concrete continuous T-beams. They were all designed according to the British Standards (BS 8110-1). Average geometry of typical continuous reinforced concrete beams in buildings was considered while adopting dimensions of the specimens. All test beams have the same dimensions and internal reinforcement as shown in Figure 3 and Figure 4. Their characteristics are summarised in the Table 1. Reinforcement ratios in hogging and sagging zones were kept constant at 1.31% in all beams. Stirrups were spaced at a distance, s=d/2 which corresponds to a shear reinforcement ratio ρ_{sw} =0.1%.

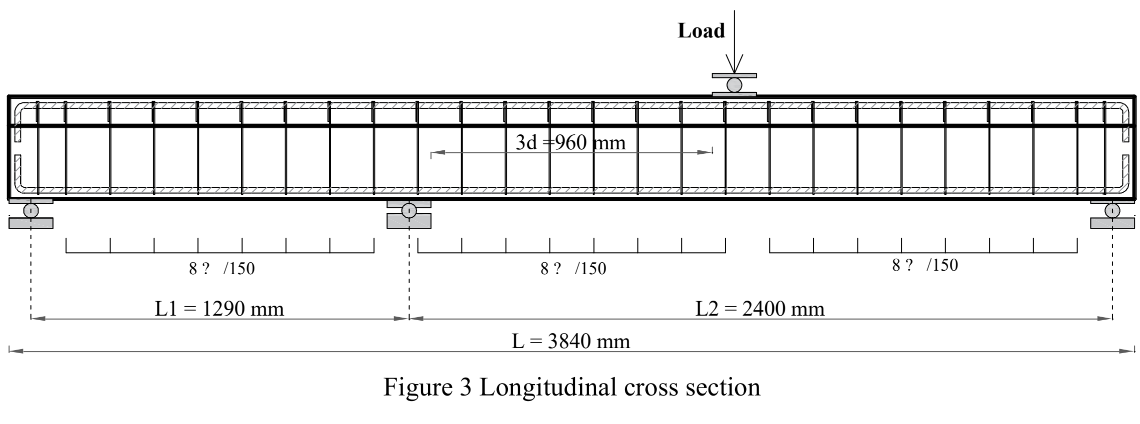

Figure 3 Longitudinal cross section

Table 1 Dimensions of the beams

Beam length	L [mm]	3840
Span 1	L_1 [mm]	1290
Span 2	L_2 [mm]	2400
Flange width	b_f [mm]	350
Beam height	h [mm]	350
Web thickness	b_w [mm]	150
Flange thickness	h_f [mm]	100
Effective depth	d [mm]	320
Shear span-to-effective depth ratio	a/d [mm]	3

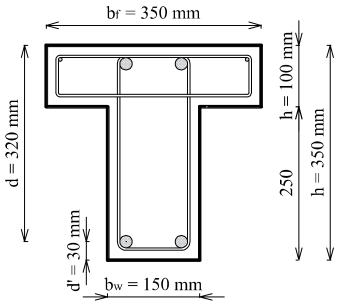

Figure 4 Vertical cross section

Materials

The concrete grade was standard C40 grade with water-to-cement ratio of 0.53 and coarse aggregate less than or equal to 20 mm. The average values from the standard cube and tensile splitting tests have shown f_{cu}= 60 MPa for the concrete compressive strength and f_{ct} = 4.86 MPa for the concrete tensile strength. Spirally wound sand-coated FRP bars and steel bars have been used for specimen strengthening together with two-component adhesive. Their properties are given in Table 2.

Table 2 Material properties

Material	Tensile strength f_{fu} [MPa]	Modulus of elasticity E_f [GPa]	Ultimate strain [%]
Aslan 200 CFRP bar	2172	124	1.81
Aslan 100 GFRP bar	827	46	1.94
Steel bar	500	210	/
Hilti HIT-RE500 Epoxy resin	43.5	1.49	2.00

Strengthening of the beams

As illustrated in the Table 3 and Figure 5, all the beams are divided into three groups (I, II and III). The control specimen, not strengthened with Deep Embedded bars, is labelled as CON. Each group consists of three beams strengthened in the shear zone using three different configurations: a) vertical bars spaced at 150 mm (C150, G150 and S150 - one bar between two shear links), b) vertical bars spaced at 75 mm (C75, G75 and S75 - two bars between two shear links) and c) inclined bars (45^0) at 150 mm (C150∠, G150∠ and S150∠ - each bar crossing two shear links).

Table 3 Description of test specimens

Group	Number of beams	Bar type	Bar diameter [mm]	Mark	Bar spacing s [mm]	Angle [^{0}]
Control	1	/	/	CON	/	/
I	3	CFRP	6	C150	150	90
				C75	75	90
				C150∠	150	45
II	3	GFRP	6	G150	150	90
				G75	75	90
				G150∠	150	45
III	3	STEEL	6	S150	150	90
				S75	75	90
				S150∠	150	45

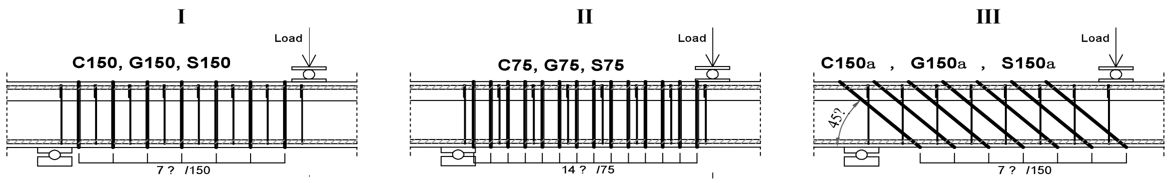

Figure 5 Strengthening configurations

PRESENTATION AND DISCUSSION OF EXPERIMENTAL RESULTS

Table 4 summarizes the experimental results obtained from the tests for all the test groups. The results are presented in terms of the loads attained at failure, experimental shear resistance, deflection at load point and the type of the failure. A simplified methodology accepted in the TR55 (Design guidance for strengthening concrete structures using fibre composite materials) was adopted in order to calculate the contributions of Deep Embedded bars to the shear resistance of the beams. ACI318 (Building Code Requirements for Structural Concrete and Commentary) and BD44 (The assessment of concrete highway bridges and structures) gave the closest predictions for the shear capacities of the beams.

Table 4 Description of test specimens

Group	Specimen	Load at failure [kN]	Shear resistance [kN]	Shear capacity increase [%]	Deflection at load point [mm]	Failure mode
Control	CON	184	135	0	7.6	Shear
I	C150	271	181	34	15.7	Shear
I	C75	315	219	62	20	Flexure
I	C150∠	320	222	64	19	Shear
II	G150	304	205	52	20	Shear
II	G75	322	222	64	25	Flexure
II	G150∠	280	191	41	14	Shear
III	S150	269	183	35	12	Shear on the right side of the load
III	S75	273	188	39	9	Shear
III	S150∠	231	160	18	7	Flexure

Table 4 shows that the shear-strengthened beams experienced significant increase in capacity with respect to the control beam. In this experimental program, the average increase in shear capacity reached around 55%. Deep Embedment strengthening system can significantly enhance the shear capacity of RC beams even in presence of a minimum amount of transverse steel reinforcement. Decreasing the DE bar spacing resulted in a higher contribution to shear resistance (specimens C75 and G75 failed in flexure). Specimens strengthened with inclined DE bars reached similar ultimate capacities as those strengthened with DE bars spaced at 75mm.

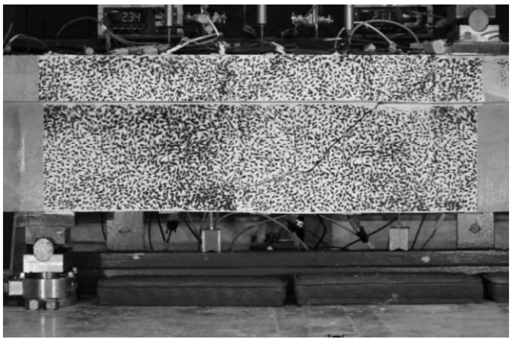

Figure 6 Shear cracks in specimen CON

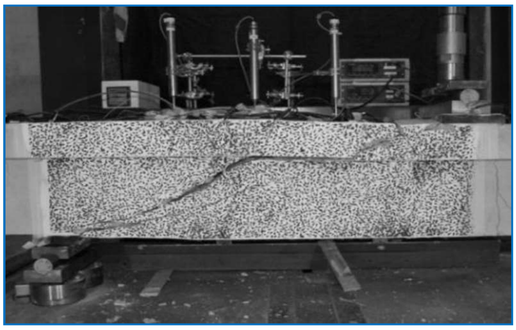

Figure 7 Shear cracks in specimen C150∠

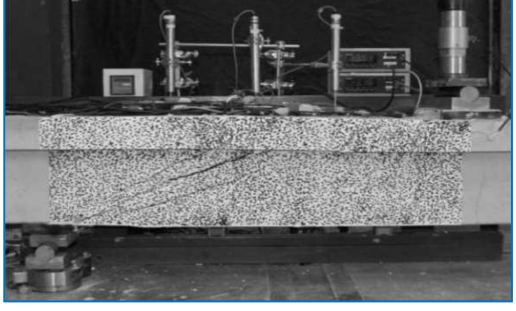

Figure 8 Shear cracks in specimen G150∠

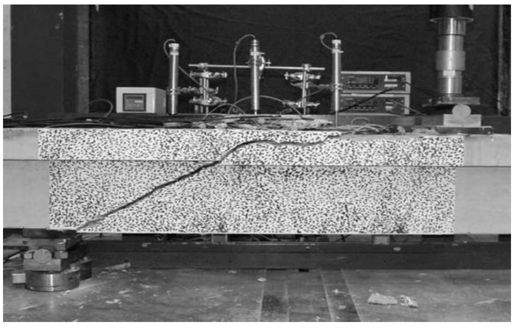

Figure 9 Shear cracks in specimen S75

Specimens CON, C150, C150∠, G150, G150∠ and S75 failed in shear whereas specimens C75 and G75 failed in flexure. The load at which the first diagonal cracks appeared was of a similar level for all beams. Diagonal cracks first started to develop on the left side of the load and then followed by parallel crack formation on the right side of the beam middle support (pin). Characteristic shear crack patterns are shown in the Figures 6, 7, 8 and 9.

Figures 10, 11 and 12 show the curves for applied load versus maximum displacement at the point load for the control and strengthened beams. They represent typical behaviour during a shear test. A loss of a beam's stiffness caused a redistribution of internal stresses and activated shear links and DE bars to increase shear resistance.

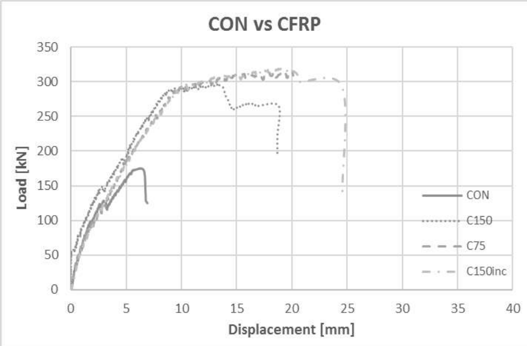

Figure 10 Load versus displacement – group I

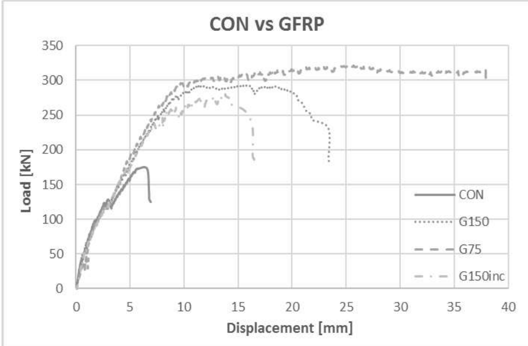

Figure 11 Load versus displacement – group II

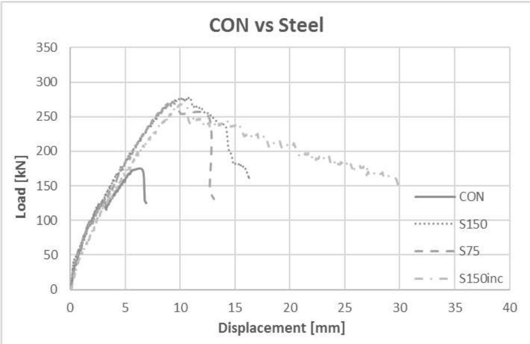

Figure 12 Load versus displacement – group III

DE technique showed to be very efficient in developing high strains in DE bars before the final failure happens, some of the DE bars experienced very high strains during the tests. Characteristic are samples G150, G150∠ and C150∠ where DE bars almost reached their ultimate tensile capacities. Fallowing figures represent some of the damaged bars (Figures 13, 14 and 15).

Figure 13 GFRP DE bar in specimen G150∠ (1.6% strain)

Figure 14 CFRP DE bar in specimen C150∠(1.5 % strain)

Figure 15 Steel DE bar in specimen S75

CONCLUSIONS

This paper presents the results of an experimental investigation involving nine tests on RC T-beams strengthened in shear using the Deep Embedment technique. On the basis of the results of the present research, the following main conclusions can be drawn:

- DE technique has been demonstrated to be effective and reliable for enhancing the shear capacity of continuous concrete beams.

- The DE technique is very promising; therefore, further data analysis is needed to address other important effects along with the development of suitable analytical models for safe use of this retrofit technique.

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