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EXPERIMENTAL INVESTIGATION ON TORSIONAL STRENGTHENING OF BOX RC STRUCTURES USING NSM FRP

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ABSTRACT

The near surface mounted (NSM) technique is a strengthening method that provides additional reinforcement by means of strips or bars embedded into grooves made in the concrete cover of reinforced concrete (RC) elements. The effectiveness of using NSM fibre reinforced polymer (FRP) bars or strips to enhance the shear and flexural capacity of RC elements has been demonstrated over the past decade. However, the idea of using NSM FRP reinforcement to address issues related to deficient torsional performance is yet to be explored. Torsional strengthening of RC elements (e.g. bridge girders, transfer beams) may be necessary due to degradation of materials, changes in the design codes, deficiencies in the initial design, changes in building usage etc. This paper investigates the torsional strengthening of thin walled tubular RC beams using NSM CFRP laminates.

The experimental program involved testing of six box sectioned RC beams, including two reference beams (with and without shear reinforcement) and four beams strengthened with different arrangements of NSM CFRP reinforcement, providing varying longitudinal and transverse reinforcement ratios. All the strengthening proposals resulted in significant increase in torsional moment capacity, ductility, stiffness in the elasto-plastic range and were very efficient in arresting crack propagation, proving the effectiveness of NSM strengthening technique for torsional strengthening. The proposed experimental program is described in detail and the main results are presented and discussed.

KEYWORDS

Strengthening and repair, near surface mounted (NSM) technique, torsional strengthening, box structures, test setup.

INTRODUCTION

The need for strengthening arises when a structure, or part of it, can no longer fulfil its intended purpose. According to the European Construction Industry Federation (2014), about 320bn euros were invested on rehabilitation and maintenance in 2013, thus showing the importance of this sector and demonstrating the large potential impact of the proposed research project. Although advanced composites (or FRP) have been used successfully as externally bonded reinforcement to strengthen RC structures in the past 30 years, only limited information is available on strengthening of thin walled structures in torsion, which is a critical action in bridges and larger infrastructure.

The use of externally bonded FRP reinforcement (EBR-FRP) for torsional strengthening of RC elements, whereby the FRP material is bonded directly on the surface of the structural element, has been discussed in various studies like Al-Mahaidi & Hii, (2007), Alkhrdaji & Thomas, (2002), Barros et al. (2013), Barros and Fortes (2005), Chalioris (2007), Chalioris (2008), Deifalla et al. (2013), Deifalla, Awad, and Elgarhy (2013), Deifalla and Ghobarah (2005) and Deifalla and Ghobarah (2010). These studies examined the effect of different parameters, including: FRP reinforcement ratio, 4 and 3-side strengthening, full and strip strengthening, interaction between flexural and shear strengthening. The performance of EBR FRP, however, is limited by various factors, namely linked to the quality of bond between FRP and substrate. As a result, a new technique, whereby FRP laminates/bars are installed into thin grooves made in the concrete cover of the element to be strengthened (near surface mounted – NSM-FRP), has been developed to improve the efficiency of strengthening applications. A few general applications of the NSM technique in flexure and shear are described in Panchacharam and Belarbi (2002), El-Hacha and Rizkalla (2004), Lorenzis and Nanni (2001) and Jing, Raongjant, and Li (2007) and only one research project on torsional strengthening can be found in the literature viz., Al-Bayati, Al-Mahaidi, and Kalfat (2016), but exclusively applied to solid beams.

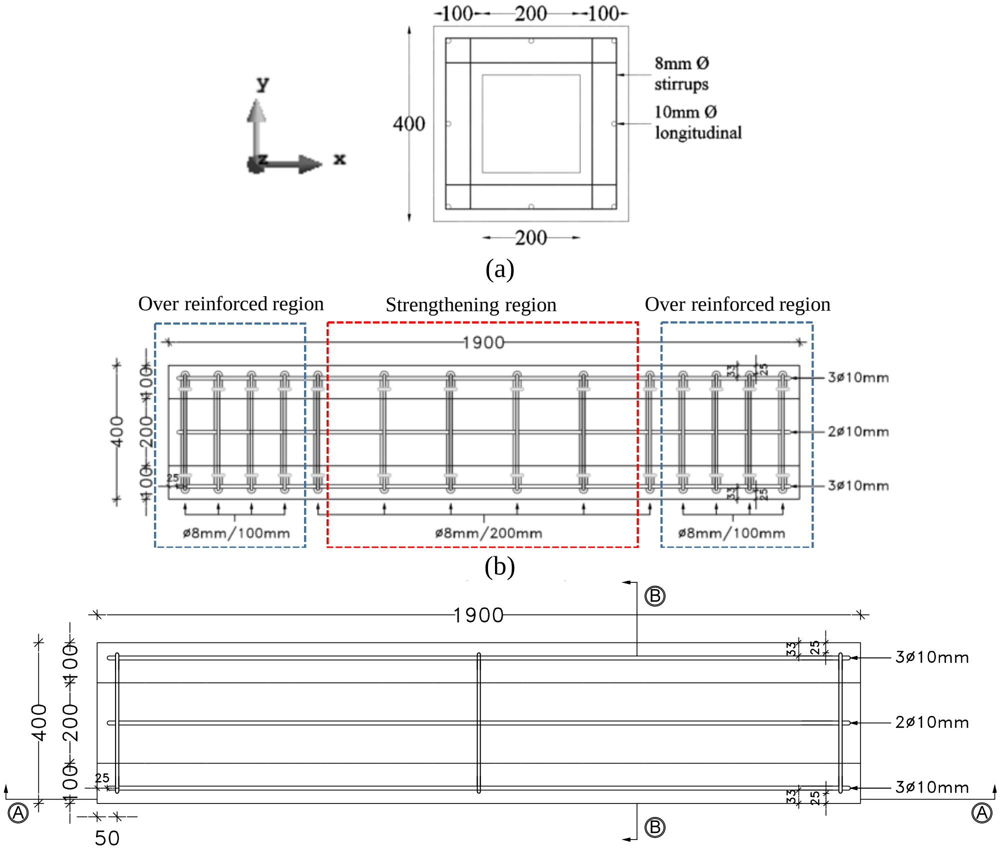
Comparing the EBR and NSM techniques, in EBR there is stress concentration in the corners and premature detachment of the FRP along with the concrete cover which is observed in Al-Mahaidi & Hii, (2007). This happens in NSM only in later stages i.e., when FRP are subjected to higher strain rate as the material in placed inside the concrete cover, resulting in lesser FRP material and making the technique cheaper than EBR. The strengthening effectiveness of FRP laminates is as large as deeper they are installed into the groove (Dias and Barros (2017)), but the depth of the grooves is in general limited by the concrete cover thickness since cutting the existing steel stirrups can only be executed if additional measures are taken to avoid shear failure (Costa and Barros (2010)). NSM technique involves lesser surface preparation as only grooves are executed, however in EBR the whole surface needs to be prepared consuming more time and work. Failure mode in EBR is abrupt due to sudden rupture of FRP (debonding, stress concentration and concrete spalling) and in NSM it is less prone to happen, changing the failure mode to concrete compressive failure.

Considering all of the issues above, NSM FRP promises excellent advantages for strengthening of thin walled tubular structures. The current lack of refined design guidelines, however, often results in conservative applications and inefficient use of material. For example, a conservatively high amount of FRP (about 42 km of ‘thick and thin’ laminates) was used for the strengthening of Westgate bridge (2.58 km), in Australia, where lower FRP strain was considered for torsional design, resulting in higher cost of rehabilitation. More advanced design guidelines and efficient application strategies are needed for the successful rehabilitation of torsionally-critical elements. The proposed work developed an innovative torsional strengthening solution using CFRP laminates.

EXPERIMENTAL WORK

The experimental activity of the current research involves testing of 6 hollow sectioned beams. It consists of 2 reference beams with one and four stirrups in the central area of study (1000 mm), and four NSM-CFRP strengthened beams (with 4 stirrups in central region).

Geometry and casting



(a)

(b)

(c)

Figure 1: Geometric details (a) Cross section R_C35/45_4S (b) Longitudinal section R_C35/45_4S & (c) Longitudinal section R_C35/45_1S (dimensions in mm)

The geometric details of the beam (transverse and longitudinal sections) is shown in Figure 1. The external section is 400 mm x 400 mm and the internal hollow section is 200 mm x 200 mm, with wall thickness of 100 mm satisfying the EuroCode 2 (2004) condition for effective wall thickness. Each beam has a length of 1900 mm, and is longitudinally reinforced with 8 steel bars of 10 mm diameter and transversally with steel stirrups of 8 mm diameter spaced at 100 mm in the extremities (for limiting the damage due to the loading and fixing conditions) and at 200 mm in the testing region. One of the reference beam, R_C35/45_1S consists of only three stirrups of 8 mm placed at the two ends and in the centre of the beam Figure 1(c). The reinforcement cages were prepared according to the details shown in Figure 1. Four strain gauges were attached to the reinforcements, two in longitudinal reinforcement and two in transverse reinforcement closer to the central section of the beam.

Material characterisation

The mechanical properties of concrete, steel and FRP were determined before performing the torsional tests (Table 1). Compression tests were performed on five concrete cylinders of 150 mm diameter at 28 days according to BS EN 12390-3 (2009), to determine the average compressive strength (f_c) and the results on three cylinders were used to obtain the average modulus of elasticity (E_c). Tensile tests according to EN_10002-1 (1990) and ISO 6892-1 (2009) were carried out on 5 samples of each 10 mm diameter and 8 mm diameter bars to evaluate the average tensile strength (f_t) and modulus of elasticity of steel (E_s) reinforcement. The strengthening was performed with S&P CFRP laminates of 10 mm x 1.4 mm and epoxy resin 220 from the same manufacturer. The tensile tests on FRP were performed according to BS EN ISO 527-5:2009 (2009) for three specimens of each batch. The first three strengthened beams S1_L2S5, S2_L2S10 and S3_L4S5 are reinforced with batch 1 FRP and the last beam S4_L4S10 is strengthened with batch 2 FRP.

Table 1 Mechanical properties of concrete, steel reinforcement and FRP

Material	Compressive or tensile strength (MPa)	Coefficient of variation	Modulus of elasticity (GPa)	Coefficient of variation
Concrete	31.80	3.00%	34.54	4.00%
Steel (8 mm bar)	566.70	7.50%	195.98	0.40%
Steel (10 mm bar)	449.49	2.69%	205.73	2.69%
FRP (batch 1)	2346.43	6.00%	205.04	1.00%
FRP (batch 2)	1982.38	3.00%	199.83	1.00%

Strengthening

Eight strengthening combinations were examined over three series of tests. However, only the first series is described in this paper. The different strengthening schemes were proposed on the basis of an in depth preliminary finite element (FE) analysis, which involved variation of FRP longitudinal and transverse reinforcement ratios, three and four strengthening faces, straight and L-shaped CFRP laminates, and application of 25% and 50% of pre-stress in FRP laminates. More details of the research can be found in Gowda and Barros (2016). Based on the results of the numerical analysis four strengthening configurations (Figure 2) were explored in series one, details of which are presented in Table 2.

Table 2 Strengthening details with reinforcement ratios and spacing of the FRP laminates

Sl. No.	Beam	ρ_{sl}	ρ_{fl}	$\rho_{l,eq}$	ρ_{sw}	ρ_{fw}	$\rho_{w.eq}$	s_{fl}	s_{fw}
1	S1_L2S5 (Figure 2a)	0.218	0.014	0.232	0.980	0.056	1.036	134	65
2	S2_L2S10 (Figure 2b)	0.218	0.014	0.232	0.980	0.112	1.092	134	40
3	S3_L4S5 (Figure 2c)	0.218	0.028	0.246	0.980	0.056	1.036	80	65
4	S4_L4S10 (Figure 2d)	0.218	0.028	0.246	0.980	0.112	1.092	80	40

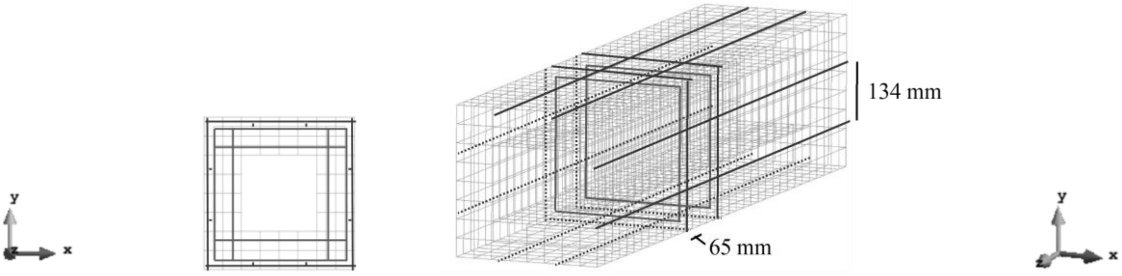
(ρ_{sl}= steel longitudinal reinforcement ratio, ρ_{fl}= FRP longitudinal reinforcement ratio, $\rho_{l,eq}$= longitudinal equivalent reinforcement ratio, ρ_{sw}= steel transverse reinforcement ratio, ρ_{fw}= FRP transverse reinforcement ratio , $\rho_{w,eq}$= equivalent transverse reinforcement, s_{fl}= spacing of the longitudinal FRP and s_{fw}= spacing of the transverse FRP).

The equivalent reinforcement ratios for the FRP are calculated according to the following equations for longitudinal reinforcement (Equation 1a) and transverse reinforcement (Equation 1b).

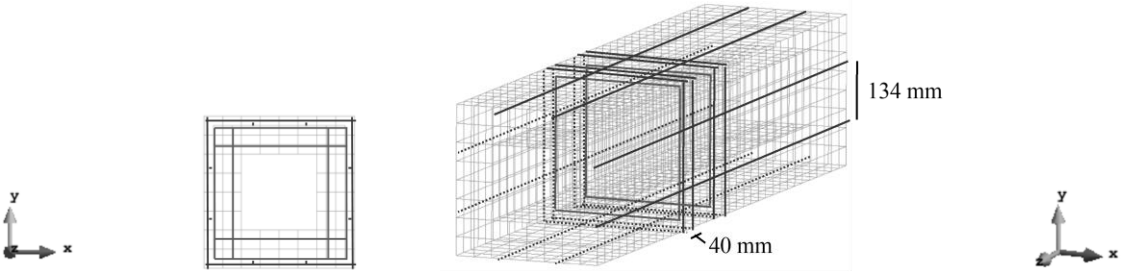
$$\rho_{l,eq} = \rho_{sl} + \rho_{fl} = \frac{A_{sl}}{(b_w d)} + \left(\frac{A_f E_f}{E_s}\frac{1}{bd_f}\right) \qquad \textit{1a}$$

$$\rho_{w,eq} = \rho_{sw} + \rho_{fw} = \frac{A_{sw}}{(b_w s_w)} + \left(\frac{A_f E_f}{E_s}\frac{1}{bs_f}\right) \qquad \textit{1b}$$

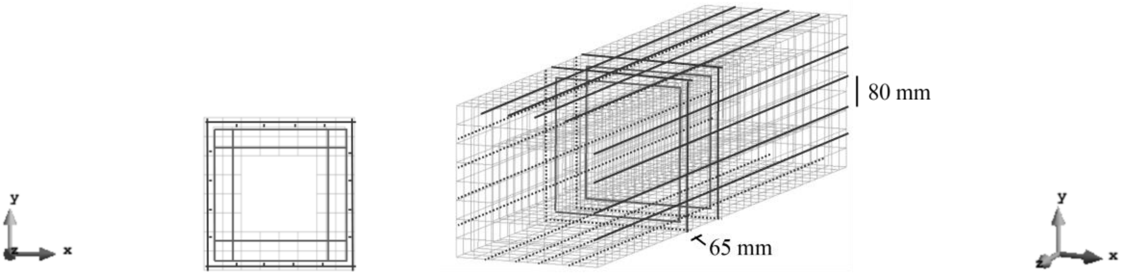
(A_{sl}= longitudinal reinforcement area, b_w= width of web, d= effective depth, A_f= area of FRP, E_f= mod of elasticity of FRP, E_s= mod of elasticity of steel, d_f= depth of FRP, A_{sw}= trasverse reinforcement area, s_w= transverse reinforcement spacing)



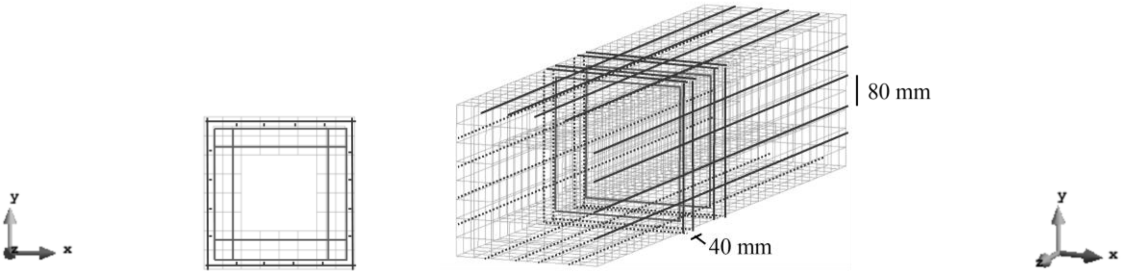
(a) S1_L2S5: Transverse bars at 65 mm between the stirrups & Longitudinal bars at 134 mm



(b) S2_L2S10: Transverse bars at 40 mm between the stirrups & Longitudinal bars at 134 mm



(c) S3_L4S5: Transverse bars at 65 mm between the stirrups & Longitudinal bars at 80 mm



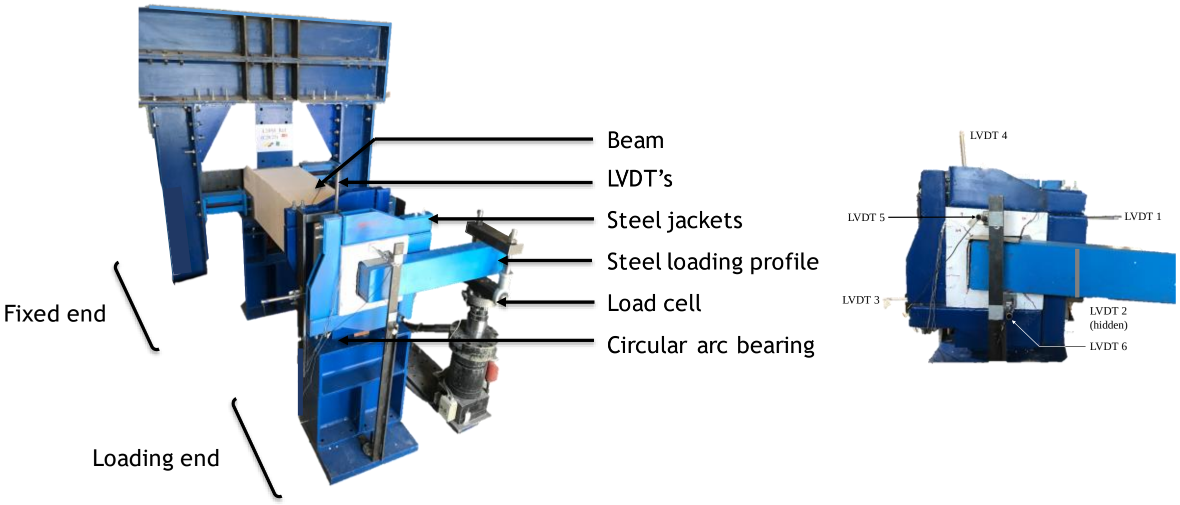
(d) S4_L4S10: Transverse bars at 40 mm between the stirrups & Longitudinal bars at 80 mm

Figure 2 Strengthening configurations (a) S1_L2S5 (b) S2_L2S10 (c) S3_L4S5 (d) S4_L4S10

Test setup

Figure 3 shows the experimental test setup for testing the beams in torsion. One of the extremities of the RC beam (herein considered the fixed end) is attached to a very stiff frame of I shape steel profiles with additional mechanisms for avoiding all possible displacements except the longitudinal deformation of the beam.

At the loading end, the beam is rested on steel sections and circular arc bearing with pinned support. The circular arc bearing (CAB) is a solid steel section cut with an arc radius of 350 mm from the centre of the beam so as to maintain the same radius during testing, without resulting in any additional forces or moments. The circular arc bearing includes graphite grease between two sheets of Teflon placed on the two contact faces of the CAB for minimizing friction in this device. The torsional moment was applied to the beam through steel loading profile, specifically designed for the purpose. It is connected to the load cell through steel elements and hinges for avoiding the introduction of parasitic forces in the piston of the actuator. To minimize damage in the concrete specimens in the loading region, and to improve the transmission of the applied moment to the central study region of the specimen, two braces of steel jackets were fastened in the specimen's loading end. Each bracing is composed of four steel sections of 52 mm interconnected through bolts. The two bracings are placed at a distance of 400 mm.



(a) (b)

Figure 3 Experimental test setup

The adopted monitoring system, consisting of LVDTs and an inclinometer, is shown in Figure 3(b). The LVDT's were placed at a distance of 200 mm from the front face on the external section on each face of the beam, and the inclinometer was placed at 550 mm from the loading end (internal, not seen in figure), on top of a thick steel section to avoid noise in the data recorded during testing. Two LVDT's were placed on the front face of the beam to measure the beam's axial deformation. An LVDT was also placed at the back face (fixed end) and two dial gauges on the left and right face at the fixed end to measure the displacements of this region. The test was performed under displacement control at a rate of 20 micro meter per second.

RESULTS AND DISCUSSIONS

Figure 4 presents the torsional moment *vs.* torsional angle of rotation of the tested beams discussed in the present work, and the relevant results are included in Table *3*. When compared with the R_C35/45_4S reference beam, the increase in the torsional capacity provided by the adopted strengthening configuration varied between 38 and 46%, with the maximum been observed for the beam with the largest longitudinal and transversal strengthening ratio. The strengthening systems started being active mainly after concrete crack initiation, and provided an increase of the torsional stiffness in the elasto-plastic stage of the response of the specimens, being notable the increment of the ultimate torsional angle (an indicator of ductility). However, the results seem to indicate that the level of torsional strengthening effectiveness is not proportional to the strengthening ratio, and a maximum would exist above which the cost competitiveness of this strengthening strategy is not justifiable from an economic point of view.

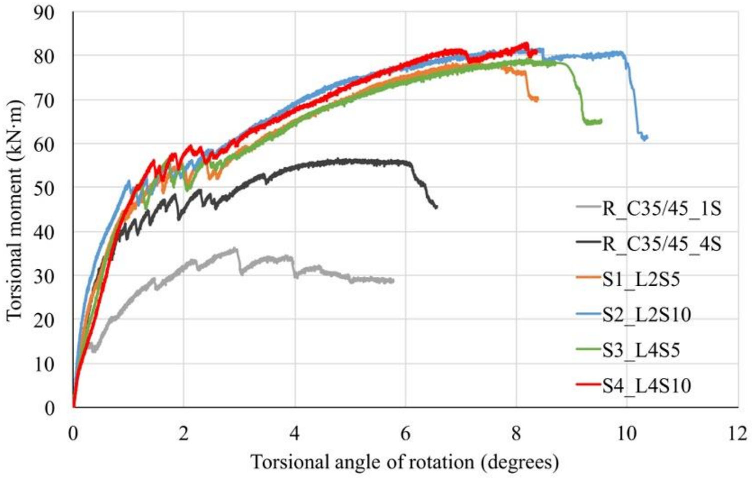
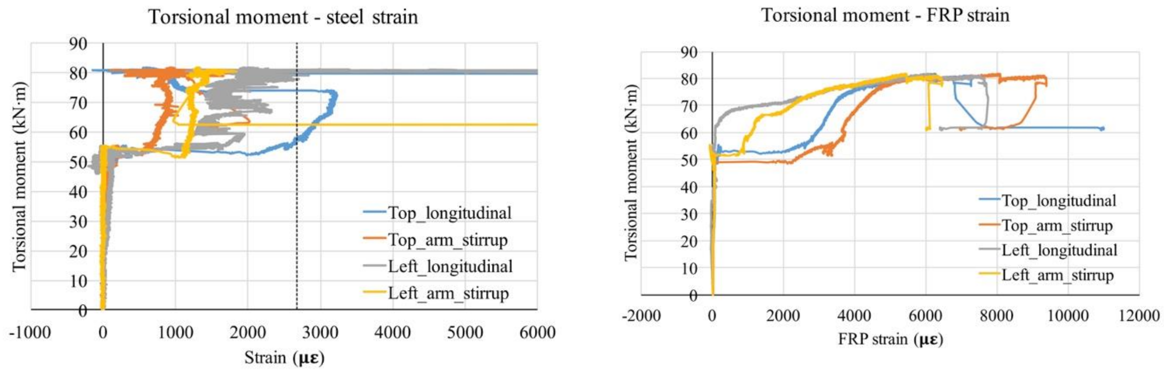


Figure 4 Torsional moment – torsional angle of rotation

Table 3 Experimental results of the tested beams

Sl. No.	Beam description	Max torsional moment (kN·m)	Percentage increase wrt. R_C35/45_4S	Percentage increase wrt. R_C35/45_1S	Angle at max torsion (degrees)	Max Strain in steel $(\mu\varepsilon)$	Max strain in CFRP $(\mu\varepsilon)$	Average crack spacing (mm)
1	R_C35/45_1S	36.4	-	-	2.90	20999	-	400
2	R_C35/45_4S	56.7	-	55.9	4.78	19285	-	200
3	S1_L2S5	78.3	38.1	115.4	7.31	5121	6901	100
4	S2_L2S10	81.7	44.1	124.7	8.40	20327	10986	75
5	S3_L4S5	79.4	40.0	118.3	8.23	-	11364	100
6	S4_L4S10	83.0	46.4	128.3	8.19	8942	3952	75

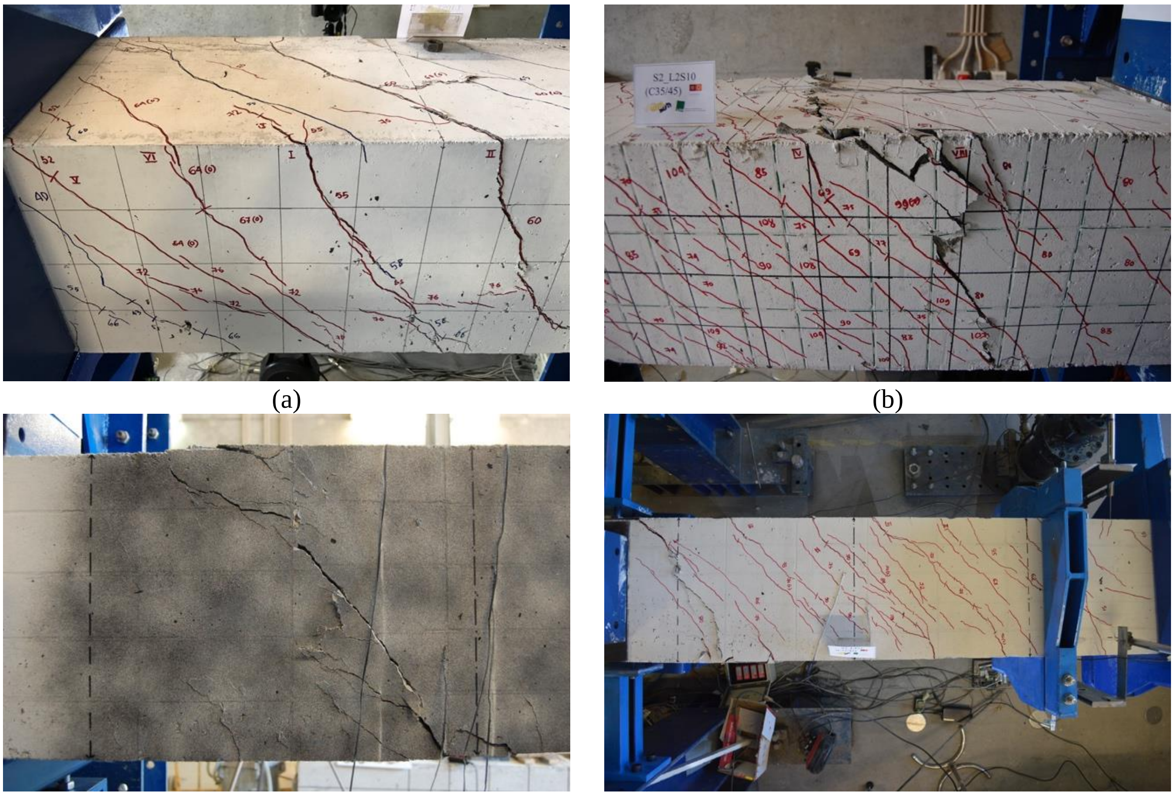
Figure 5 presents the evolution of torsional moment versus the strains in (a) steel and (b) CFRP of strengthened beam S2_L2S10. The yielding strain of longitudinal (3.38‰) and transverse (2.68%) steel bars is presented in vertical dashed lines, being visible that at failure these reinforcements have yielded. Figure 5b shows that the CFRP laminates have reached a maximum strain of 11‰, which is 85% of its tensile rupture. Both the reinforcements are activated closer to 27 kN·m (torsional cracking moment), and a sudden increase at 55 kN·m is observed where they fully start contributing until the CFRP is ruptured causing the failure.



(a) (b)

Figure 5 S2_L4S10 (a) Torsional moment – steel strain (b) Torsional moment – FRP strain

In order to verify if the test setup had any translations, an LVDT was placed at the base of loading end where the maximum recorded displacement was 0.3 mm, proving the setup to be very stable. Two types of failure were observed, concrete crushing in the reference beams (R_C35/45_1S and R_C35/45_4S) and CFRP rupture followed by concrete crushing in all the strengthened beams. Images of few beams after failure are presented in Figure 6 viz., (a) reference beam R_C35/45_4S, (b) S2_L2S10 (c) S3_L4S5 and (d) S3_L4S5.



(a) (b)

(c) (d)

Figure 6 Failure images (a) R_C35/45_4S (right face) (b) S2_L2S10 (right face) (c) S3_L4S5 (left face) (d) S3_L4S5 (Top face)

As seen in the above figure, the cracks were widely spaced in the reference beam (200 mm average crack spacing), whereas in all the strengthened beams a more diffused crack pattern was observed. Also the reference beam had lesser cracks with respect to strengthened beams, due to the presence of CFRP laminates arresting the propagation of cracks.

CONCLUSIONS

According to the results obtained in the experimental work, the following conclusions can be drawn:

- The conceived test setup is suitable for assessing the torsional performance of strengthening systems of thin walled tubular RC elements;
- The adopted NSM-CFRP strengthening configurations have provided an increase of the torsional capacity varying between 38 and 46% with respect to reference beams, and an increase of ultimate torsional angle between 27 and 57%, an indicator of the favourable effect in terms of ductility;
- When considering the average crack space of the reference beam, the decrease ensured by the adopted strengthening configuration was 38%, therefore these systems were very effective in arresting the crack propagation, limiting the maximum crack width, which has also beneficial effect in the durability of the strengthened RC structures.
- Premature delamination of FRP in corners as in the case of EBR strengthening is not observed in this technique;
- Beams failed by CFRP rupture followed by concrete crushing, after yielding of the internal steel reinforcement.

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