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Flexural and shear strengthening of RC beams with composite materials – The influence of cutting steel stirrups to install CFRP strips

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ABSTRACT

Experimental, numerical and analytical investigations have revealed that Carbon Fibre Reinforced Polymer (CFRP) strips with larger cross section height improve the effectiveness of the Near Surface Mounted (NSM) technique for the flexural strengthening of existing reinforced concrete (RC) beams. However, this height is limited to the concrete cover thickness of the longitudinal steel bars, since the application of strips of cross section height larger than the cover thickness requires that the bottom arm of the steel stirrups be cut. This work aims to assess the influence, in terms of shear resistance, of cutting the bottom arm of steel stirrups to install NSM strips for the flexural strengthening of RC beams. The obtained results showed that, for monotonic loading, cutting the bottom arm of steel stirrups led to a decrease of the beam's load carrying capacity of less than 10%. Due to the high effectiveness of the adopted NSM flexural strengthening systems, shear can be a predominant failure mode for these beams. To avoid this type of failure mode, strips of wet lay-up CFRP sheets with U configuration were used, resulting in effective strengthening solutions for RC beams. In the present paper the experimental program is described, and the obtained results are presented and discussed.

1. Introduction

Sustainable rehabilitation practices require the use of competitive strengthening solutions. The techniques based on the use of Carbon Fibre Reinforced Polymer (CFRP) strips and wet lay-up sheets can be very competitive, since CFRP materials have high mechanical and durability performance, are lightweight, easy to install, and do not change significantly the original geometry of the strengthened elements. The Externally Bonded Reinforcement (EBR) [1] and the Near Surface Mounted (NSM) [2,3] techniques are most commonly used for the strengthening of reinforced concrete (RC) elements.

The NSM technique consists of installing CFRP strips into thin slits opened on the concrete cover of the elements to strengthen. The strips are bonded to the surrounding concrete by using an epoxy-based adhesive. FRP bars of round or square cross section made of carbon, glass or aramid fibres have been used in the NSM technique [4,5], but available experimental [6], analytical and numerical [7] research demonstrates that strips of rectangular cross section are the most effective in terms of strengthening performance. Using the NSM technique, significant flexural strengthening effectiveness was obtained for beams [8], slabs [9], as well as in terms of the shear strengthening of RC beams [10].

Significant increments in terms of flexural and shear resistance can also be achieved with the EBR technique but, when compared to the strengthening effectiveness provided by the NSM technique, EBR is not as competitive, due to its longer execution times and susceptibilities to acts of vandalism and to the effects of environmental aggressiveness [3]. To take into account the occurrence of FRP premature debonding failure modes, the FRP design tensile strain should be limited to a certain value [1] that can be significantly lower than its ultimate tensile strain value obtained in tensile tests with FRP specimens, which is a serious concern for the competitiveness of FRP-based strengthening techniques.

Experimental [11], numerical and analytical [7] studies have also shown that the larger is the height of the CFRP strip cross section the more effective is the NSM flexural strengthening. However, this height is limited to the thickness of the concrete cover, since the use of strips with a cross section height larger than the concrete cover thickness requires that the bottom arm of the steel stirrups be cut.

The influence, in terms of the beam's load carrying capacity, of cutting the bottom arm of steel stirrups for the installation of CFRP strips is analysed in the present work. To take into account relevant aspects for this study, the experimental program is composed of beams of distinct cross section depth, since it is reasonable to assume that the deeper is the beam cross section the smaller might be the influence of cutting the bottom arm of the stirrups in terms of the NSM flexural strengthening effectiveness.

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Nomenclature

E_c	modulus of elasticity of concrete (at 28 days)	f^*_{fu}	tensile strength of the FRP
E_f	modulus of elasticity of FRP	f_{sum}	steel tensile strength
E_{sm}	modulus of elasticity of steel	f_{sym}	steel yield strength
$E_{sm,eq}$	equivalent modulus of elasticity of steel = $(\sum E_{sm,i} \times A_{si})/(\sum A_{si})$	$f_{sym,eq}$	equivalent steel yield strength = $(\sum f_{sym,i} \times A_{si})/(\sum A_{si})$
F_{max}	maximum experimental load	tf	thickness of FRP
F_{Rd}	design resistant load	ε^*_{fu}	ultimate FRP strain
F_{sy}	yield initiation load (at $\varepsilon_{sy,eq}$)	$\varepsilon_{fL,Fmax}$	strain in the strips at F_{max}
F_{VEi}	maximum experimental load obtained testing VEi	$\varepsilon_{fL,max}$	maximum strain in the strips
F_{VRi}	maximum experimental load obtained testing VRi	$\varepsilon_{fV,Fmax}$	strain in the strips of wet lay-up CFRP sheets at F_{max}
f_{ck}	characteristic value of the concrete compressive strength	$\varepsilon_{fV,max}$	maximum strain in the strips of wet lay-up CFRP sheets
		$\varepsilon_{sy,eq}$	equivalent steel yield strain $(f_{sym,eq}/E_{sm,eq})$

A relatively high strengthening ratio of CFRP strips was used in order to promote the occurrence of shear failure mode for the strengthened beams. To avoid the occurrence of this brittle and abrupt failure mode, the beams strengthened in flexure were also strengthened in shear using strips of wet lay-up CFRP sheets of U configuration that were placed between existing steel stirrups. The experimental program is described and the results are presented and discussed.

2. Characteristics of the beams and strengthening systems

The experimental program is composed of three series of beams. Each series differs in cross section height and contains four beams (Fig. 1 and Table 1). For the generic *i*th series the beams have the following designations:

- VRi – reinforced concrete reference beam.
- VEi – equivalent to the VRi beam, but with the bottom arm of the steel stirrups cut.
- VLi – equivalent to the VEi beam, and strengthened in flexure with NSM CFRP strips.
- VLMi – equivalent to the VLi beam, and strengthened in shear with strips of wet lay-up CFRP sheets of U configuration.

All beams have a cross section width (b) of 0.2 m in order to assure the same anchorage length to the bottom arm of the steel stirrups.

The percentage of NSM CFRP strips applied in the VLi and VLMi beams of the *i*th series was designed in order to have the potential of doubling the load carrying capacity of the corresponding VRi reference beam. However, this strengthening capacity can be compromised in beams without shear strengthening systems, since the VLi beams have a shear resistance lower than the flexural capacity that NSM CFRP strips can provide. This justifies the presence of VLMi beams in the tested series, with a hybrid strengthening configuration in an attempt to avoid the occurrence of shear failure modes. The EBR U shear strengthening configuration of wet lay-up CFRP sheets has also the purpose of offering extra resistance to an eventual premature detachment of the NSM strips in the tested region of the beams (smaller shear span).

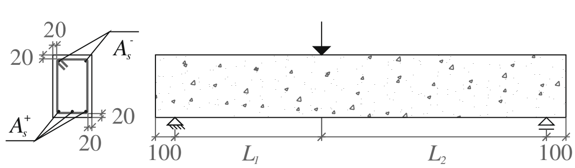

Fig. 1. Beam geometry and loading conditions – see Table 1 (dimensions in mm).

For the flexural strengthening of a beam, two CFRP strips of 1.4 mm × 20 mm cross section dimensions were used (Fig. 2). Since the *fib* bulletin 14 [12] does not have recommendations for the flexural strengthening design with NSM systems, the ACI 440 [1] recommendations were followed. However, for the design of the shear strengthening configurations the *fib* guidelines [12] were adopted, and three strips of one layer of wet lay-up CFRP sheet of 50 mm width (w_f) were obtained, which were placed according to the scheme represented in Fig. 2.

The strengthening systems were applied in order to reproduce, as much as possible, the conditions found on a job site. Therefore, the extremities of the strips remained 100 mm far from the supports of the beams, since due to the intrinsic process of opening the slits in real RC frames (see Fig. 3) they can not be opened up to the faces of the supporting RC columns.

With the same concern, a U configuration for the shear strengthening systems was adopted, since a full wrapping shear configuration, despite being the most effective shear strengthening strategy [13], rarely can be applied, due to the continuous character of the beam/slab connection.

In the three series of beams the shear span ratio (L_1/d, where d is the internal arm of the cross section) was maintained almost constant and equal to 2.5. This value favours the occurrence of shear failure mode in the beams strengthened in flexure. The three series of beams have cross section of distinct height in order to provide different bond transfer length for the stirrups and for the CFRP strips of wet lay-up sheet crossed by the shear failure crack, since this parameter is highly relevant in terms of shear strengthening effectiveness. To localize the occurrence of the shear failure crack in the L_1 span of the strengthened beams (Fig. 1), this span has a smaller length than the L_2 span in all the tested beams.

Table 1
Dimensions of the beams of the three series.

Series	L_1 (mm)	L_2 (mm)	b (mm)	h (mm)	A_s^+ (bottom face)	A_s^- (top face)
1	550	950	200	250	$2\phi10 + 1\phi6$	$2\phi10$
2	750	1150	200	320	$2\phi10 + 1\phi10$	$2\phi10$
3	900	1300	200	380	$2\phi12 + 1\phi8$	$2\phi12$