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Embedded Through-Section shear strengthening technique using steel and CFRP bars in RC beams of different percentage of existing stirrups

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ABSTRACT

The Embedded Through-Section (ETS) technique is a promising technique for the shear strengthening of existing (RC) elements. According to this technique, holes are drilled through the beam section, and bars of steel or FRP material are introduced into these holes and bonded to the concrete with adhesive materials. An experimental program was carried out with RC T-cross section beams strengthened in shear using the ETS steel bars and ETS CFRP rods. The research is focused on the evaluation of the ETS efficiency on beams with different percentage of existing internal transverse reinforcement ($\rho_{sw} = 0.0\%$, $\rho_{sw} = 0.1\%$ and $\rho_{sw} = 0.17\%$). The effectiveness of different ETS strengthening configurations was also investigated. The good bond between the strengthening ETS bars and the surrounding concrete allowed the yield initiation of the ETS steel bars and the attainment of high tensile strains in the ETS CFRP rods, leading to significant increase of shear capacity, whose level was strongly influenced by the inclination of the ETS bars and the percentage of internal transverse reinforcement.

1. Introduction

To avoid brittle and unpredictable failures due to lack of shear resistance in RC elements, strengthening techniques based on the use of fiber reinforced polymer (FRP) materials have been proposed and developed in the last two decades [1–4]. The efficiency of these techniques relies on the bond performance of concrete-adhesive-FRP interfaces. It has been demonstrated that the Near Surface Mounted (NSM) technique assures better bond conditions for the FRP strengthening systems than the externally bonded reinforcement (EBR) technique due to the higher confinement applied by the surrounding concrete to the FRPs [5–8]. It was also realized that as deeper is introduced a NSM FRP system into the groove opened on the concrete cover, as higher is the strengthening effectiveness of this system [9,10]. The Embedded Through-Section (ETS) technique was recently proposed for the shear strengthening or RC beams [11]. According to this technique, steel or FRP bars are inserted into holes drilled through the cross section, and are bonded to the surrounding concrete with an epoxy adhesive. In case of ETS technique, the concrete is able to provide a high confinement to the ETS bars, which increases the bond strength. Furthermore, a larger concrete fracture surface is mobilized during the pullout process of a ETS bar crossing the shear crack, when compared to the case of a NSM FRP strengthening system. When concrete cover has not the bond strength requisites to guarantee the aimed strengthening effectiveness for the EBR or NSM techniques, ETS strategy can be a technical and economic alternative since it mobilizes the beam's concrete core that is generally the less damaged zone of a beam. Significant increase of shear capacity was pointed out by Valerio et al. [11,12] who investigated the use of the ETS technique for the shear strengthening of RC existing bridges, and performed pullout tests for assessing the strengthening effectiveness of adhesive materials, and different embedment lengths for the ETS bars. The shear stress transfer mechanism developed in an ETS bar was studied by Barros et al. [13]. In this context, direct shear tests were executed with the purpose of capturing the main features of FRP/steel ETS bars as shear strengthening systems. From these tests it was verified that steel bars were notably effective for this purpose. Chaallal et al. [14] carried out experimental tests to compare the shear strengthening effectiveness of the ETS, NSM and EBR techniques based on the use of vertical CFRP bars applied on RC beams that were reinforced with different percentage of internal steel stirrups. It was verified that the ETS technique has provided the highest strengthening efficiency, and it was able to convert shear failure into a flexural failure. An experimental program was carried out by Barros and Dalfré [15] with RC beams shear

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strengthened with ETS steel bars. The variables examined in this experimental program were: the width of the beam's web, the percentage and inclination of the ETS bars, the spacing of steel stirrups and their interaction with the strengthening bars. A significant increase of load carrying capacity was obtained (up to 124%), proving that the use of ETS steel bars can be a very effective and cost-competitive shear strengthening technique. The beams with the higher percentage of ETS bars have failed in bending, despite the very high percentage of flexural reinforcement used. The ETS technique can also be extended to punching shear strengthening of concrete slabs [16,17].

Shear is a complex phenomenon due to the high number of parameters that affect shear behavior, which justifies to be not yet completely addressed. Although the parameters that influence the shear behavior of a strengthened RC element are already identified [18–20]. International guidelines on the use of FRPs [21–24] take into account only a restricted number of factors, ignoring the influence, for instance, of existing transverse reinforcement. The interaction between the strengthening system and the existing internal transverse reinforcement has been investigated for the EBR and NSM techniques, and some design approaches have been proposed in these respect [25–30].

The present work aims to contribute to a deeper understanding of the ETS shear strengthening mechanisms, and the susceptibility of these mechanisms to the interaction between ETS bars and existing steel stirrups. The ultimate purpose of this work is to provide useful data for the establishment of design guidelines on the shear strengthening of RC beams using the ETS technique. The experimental program was conceived for assessing the influence on the ETS shear strengthening effectiveness of the percentage, inclination and material type of the ETS systems. For this purpose, three series of RC T-cross section beams with different percentage of internal transverse reinforcement ($\rho_{sw} = 0.0\%$, $\rho_{sw} = 0.1\%$ and $\rho_{sw} = 0.17\%$) were tested. The experimental program is described in detail and the relevant results are presented and discussed.

2. Experimental program

2.1. Test series

Fig. 1 presents the geometry and the reinforcement arrangements of the nineteen T cross section beams of the experimental program. The reinforcement system was designed according to the Eurocode 2 [31], using an high percentage of longitudinal reinforcement ($\rho_{sl} = 2.79\%$) in order to force the occurrence of shear failure mode for all the beams of the experimental program. To localize shear failure in one of the beam's shear spans, a three point load configuration was selected, with a different length of the beam shear spans. The monitored beam span ($L_1 = 0.9$ m) was 2.5 times the effective depth of the beam's cross section ($L_1/d = 2.5$), since according to the available research [32], beyond this limit the arch effect is negligible. To avoid shear failure in the L_2 beam span, steel stirrups $\phi8@90$ mm were applied in this span. Different shear reinforcement systems were applied in the L_1 beam's span of the tested beams. In fact, the experimental program consisted of the following three series of beams: 0S-Series that did not have conventional steel stirrups; 2S-Series that had steel stirrups $\phi6@300$ mm, corresponding to a shear reinforcement ratio $\rho_{sw} = 0.10\%$, 4S-Series that had steel stirrups $\phi6@180$ mm, corresponding to a shear reinforcement ratio $\rho_{sw} = 0.17\%$, where:

$$\rho_{sw} = \frac{A_{sw}}{b_w s_{sw}} \tag{1}$$

being A_{sw} the cross sectional area of the two legs of a steel stirrup, s_{sw} the spacing of the steel stirrups, and $b_w = 180$ mm the width of the beam's web.

Each series had a reference beam without any strengthening system (Fig. 1, Fig. 2), and four beams with different ETS strengthening configurations (Fig. 3). The investigated parameters were the shear strengthening ratio (ρ_{fw}) and the inclination (90°, 45°) of the ETS bars, as well as the influence of the percentage of existing steel stirrups. In particular, the shear strengthening ratio of the ETS steel bars and ETS CFRP rods was defined as follows:

$$\rho_{fw} = \frac{A_{fw}}{b_w s_{fw} \sin \alpha_f} \tag{2}$$

where A_{fw} is the cross sectional area of ETS bar, and s_{fw} and α_f represent the spacing and inclination of this bar, respectively.

The influence of the material type of the ETS bars used for the strengthening was also investigated, by having beams strengthened with CFRP and steel bars in both 2S and 4S series of beams. The diameter of the ETS steel and CFRP bars was 10 and 8 mm, respectively. A smaller diameter for the CFRP bar was chosen in order that the estimated force at the debonding of this bar was similar to the force at yield initiation of the steel bar. Based on previous experiences [11,14,15], it was considered for the strain at debonding of this type of CFRP bars a value in the interval 0.55%–0.6%. Table 1 indicates the designation adopted for each

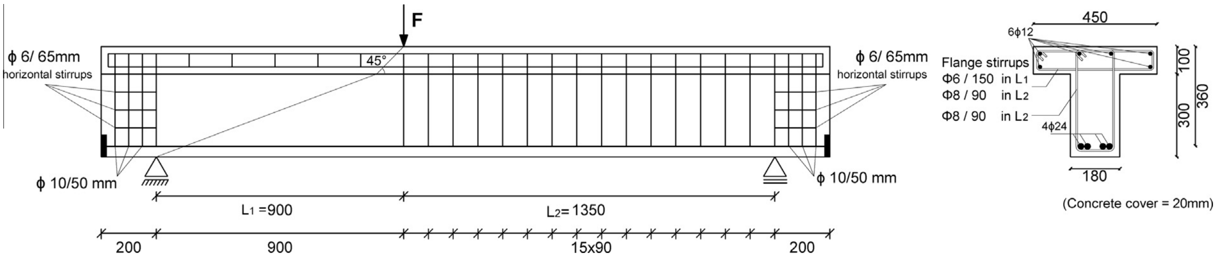
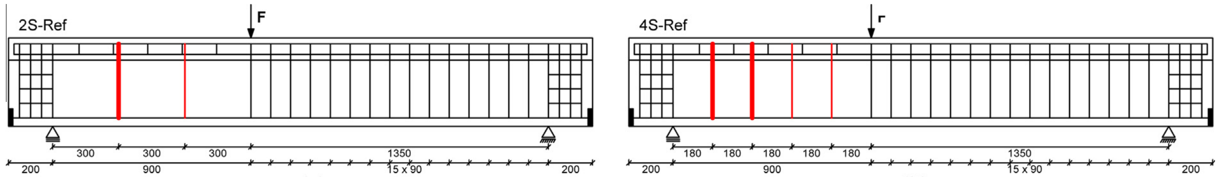


Fig. 1. Tested beams: geometry, steel reinforcements applied in all beams (dimensions in mm).



(a) (b)

Fig. 2. Reference Beams: (a) 2S-REF(stirrups $\phi6@300$), (b) 4S-REF(stirrups $\phi6@180$).