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Shear strengthening of reinforced concrete beams strengthened using embedded through section steel bars

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ABSTRACT

A new shear strengthening technique, designated as embedded through section (ETS), has been developed to retrofit existing reinforced concrete (RC) elements. This technique calls for holes to be drilled through the beam section; then bars of steel or FRP materials are introduced into these holes and bonded with adhesives to the surrounding concrete. When concrete cover has not the bond and strength requisites to guarantee a strengthening effectiveness for the Externally Bonded and Near Surface Mounted techniques, ETS strategy can be a competitive alternative since it mobilizes the beam's concrete core which is, generally, free of damage. To explore the potentialities of the ETS technique for the shear strengthening of RC beams, an experimental program was carried out, composed of RC T-cross section beams shear strengthened by using steel bars. The influence on the shear strengthening efficiency of the inclination and shear strengthening ratio of ETS configurations was evaluated; the study also examined the interaction of ETS bars and existing steel stirrups. An increase of shear capacity up to 109% and 136% in the beams with and without internal stirrups, respectively, was obtained. Inclined ETS bars provided higher increase of shear resistance than vertical ones.

1. Introduction

Reinforced concrete beams need to be strengthened when they are insufficiently reinforced in shear and become subjected to higher loads, or when their shear capacities fall below their flexural capacity after flexural strengthening. Shear failure should be avoided because of its brittle and unpredictable nature. The relatively recent approaches for shear strengthening of RC beams made use of composites materials [1]. Competitive strengthening solutions using materials like carbon or glass fiber reinforced polymers (CFRP or GFRP) can be developed due to the high strength-to weight ratio, high durability (not corrodible), electromagnetic neutrality, ease of handling, rapid execution with low labor costs and low impact on architectural and aesthetic appearance. The most popular techniques based on the use of FRP reinforcements are the Externally Bonded Reinforcement (EBR) and the Near Surface Mounted (NSM). According to the EBR technique, sheets or laminates of carbon fiber reinforced polymers (CFRP) are bonded on the faces of the elements to be strengthened. In case of the NSM technique, CFRP laminates or bars are installed into slit/grooves sawed into the beams' concrete cover and bonded to the concrete substrate by polymer adhesive. Due to the confinement provided by the surrounding concrete and the higher laminate-concrete bond surface [2–5], the available experimental research showed that NSM is more effective than EBR for both the flexural [3,6–9] and shear strengthening [10–15]. Other concerns regarding the use of EBR, apart from the relatively high cost of the FRP systems, are the susceptibility to fire and acts of vandalism, as well as the longer time needed to prepare the beam zones for the FRP bond. Maximum efficiency using composites material is obtained when the strengthening system is able to exploit its full tensional strain. Both EBR and NSM techniques rely on the stress transfer capacity between FRP and the concrete substrate. However, the latter is usually the most damaged part of the RC elements. Most of the experimental tests showed that the strengthened elements fail by debonding in EBR shear strengthening configurations. When using NSM technique the current failure modes are concrete fracture, followed by debond of the FRP systems. When the percentage of strengthening NSM-reinforcement is relatively high, the concrete cover including the FRP reinforcement has the tendency to detach due to the reasons explained elsewhere [16]. By applying the NSM technique, the full tensile capacity of the CFRP reinforcements can only be attained when these reinforcements are surrounded by relatively high strength concrete and bond transference length is assured [13].

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A new strengthening technique, designated as Embedded Through-Section (ETS), has recently been investigated for the shear strengthening of RC beams [17,18]. According to this technique, steel or FRP bars are inserted into holes bored through the cross section and bonded with an epoxy adhesive. This technique can be more effective for the shear strengthening due to the higher confinement provided by the concrete surrounding the bars, and the larger concrete fracture surface that is mobilized during the pullout process applied to the ETS bars crossing the shear crack. The ETS technique can also be extended for the punching shear strengthening of concrete slabs [19,20]. Significant increase of shear capacity has been pointed out by Valerio et al. [17,21] who investigated the use of the ETS technique for the shear strengthening of RC existing bridges, performed pullout tests for assessing the strengthening effectiveness of adhesive materials, and different embedment lengths for the ETS bars. The shear stress transfer mechanisms developed in an ETS bar were studied by Barros et al. [22] using similar specimens to the ones tested by Mattock and Hawkins [23] for traditional embedded steel bars. In this context, direct shear tests were executed with the purpose of capturing the main features of FRP/steel ETS bars as they contribute to the shear resistance, and to providing data for a rational decision about the most effective bars and adhesives for this type of application [22]. From the results, a significant increase in shear strength was obtained with a relatively low shear reinforcement ratio, and it was verified that steel bars were very effective for this purpose. Chaallal et al. [18] carried out tests to assess the effectiveness of the ETS technique using vertical CFRP bars by comparing the performance of the ETS, EBR and NSM techniques on beams with different percentages of internal steel stirrups. It was demonstrated that the ETS technique provided the highest efficiency and was able to convert shear failure into a flexural failure. In the continuation of a comprehensive research project initiated by Barros et al. [22] on the ETS shear strengthening effectiveness, an experimental program was carried out by Barros and Dalfré [24] with RC beams shear 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 existing steel stirrups and their interaction with the strengthening bars. A significant increase of load carrying capacity was obtained (between 14% and 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 failed in bending, despite the very high percentage of flexural reinforcement used. The present work aims to contribute to a deeper understanding of the shear mechanisms of ETS technique, and provide useful data for the establishment of design guidelines on the shear strengthening of RC beams using this technique. For this purpose a comprehensive experimental program with almost real size scale RC beams, designed to fail in shear, was conducted; the results describe deflection, strains in the relevant shear reinforcement and strengthening systems, as well as an analysis of failure modes. Furthermore, the applicability of existing guidelines for the prediction of the contribution of FRP systems for the shear strengthening of RC beams is also assessed. This experimental and analytical research is a step forward on the already existing information on the use of ETS technique for the shear strengthening of RC elements [17,18,24].

2. Experimental program

2.1. Test series

The geometry and the reinforcement arrangements of the ten T cross-section beams are shown in Fig. 1. The reinforcement systems were designed according to Eurocode 2 [25], considering the flange contribution, and using an high percentage of longitudinal reinforcement (ρ_{sl} = 2.79%). A high percentage of steel stirrups (ϕ8@90 mm) in the L_2 beam's span was applied for promoting the occurrence of shear failure in the shorter span (L_1), the one shear strengthened with the adopted ETS configurations, see Fig. 1. The monitored beam span (L_1 = 0.9 m) is 2.5 times the effective depth of the beam's cross section (L_1/d = 2.5). According to Collins and Mitchell [26], beyond this limit the arch effect is negligible. The differences between the tested beams are restricted to the shear reinforcement systems applied in the L_1 beam's span. The experimental program consisted of the following two series of beams: 0S-Series that did not have conventional steel stirrups; 2S-Series that has steel stirrups ϕ6@300 mm, corresponding to a shear reinforcing ratio ρ_{sw} = 0.10%. Each series has a reference beam without any applied strengthening (Figs. 1 and 2) and four beams with different ETS strengthening solutions (Fig. 3). The investigated parameters are the strengthening ratio (ρ_{fw}) and inclination (90°,45°) of the ETS steel bars, as well as the influence of the percentage of existing steel stirrups. A 10 mm diameter (d_{ETS}) bar was adopted as ETS strengthening. Table 1 reports the strengthening configurations, indicating the number of applied ETS bars, inclination (θ_{fw}), spacing (s_{fw}), shear strengthening ratio (ρ_{fw}), the percentage of steel stirrups (ρ_{sw}) and total shear reinforcement ($\rho_{sw} + \rho_{fw}$). Fig. 3 shows the strengthening configurations of the two tested series. In the design of the ETS configuration it was assumed that the ETS bars work like steel stirrups with the capacity of mobilizing the yield stress of the steel, and a perfect bond for the bars/adhesive/concrete was considered. As previously demonstrated by Barros and Dalfré [24], the effectiveness of the ETS bars is higher if they are placed in between existing stirrups. Following this approach, the arrangements indicated in Table 1 and Fig. 3 were adopted, leading to four different ρ_{fw} values. The ETS strengthening ratio varied between 0.15% (ETS vertical bars spaced at 300 mm) and 0.34% (ETS bars at 45° and spaced at 180 mm).

2.2. Material properties

The concrete average compressive strength (f_{cm}) of the beams was evaluated at 28 days and at the age of the beams' tests (approximately 225 days) by executing compression tests with cylinder specimens of 150 mm diameter and 300 mm height

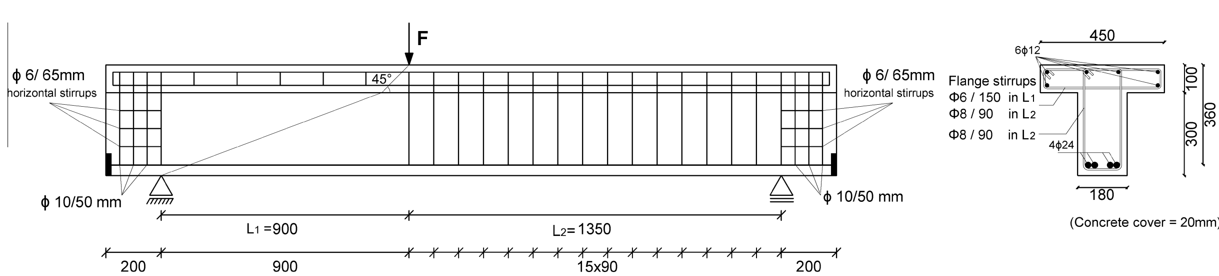

Fig. 1. Tested beams: geometry, steel reinforcements applied in all beams (dimensions in mm).