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Experimental study on the steel-fibre contribution to concrete shear behaviour

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HIGHLIGHTS

- Average strains have been measured by photogrammetry with good accuracy.
- SFRC specimens exhibited greater shear stiffness compared to RC.
- Shear effectiveness of fibres depends on reinforcement crossing the shear plane.
- Numerical modelling of RC and SFRC push-off specimens show good global behaviour.

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ABSTRACT

This paper aims at studying the shear contribution of steel fibres in concrete. Ten reinforced concrete (RC) and steel-fibre reinforced concrete (SFRC) initially uncracked push-off specimens were tested. Average normal and transverse strains at the vicinity of the shear plane were measured by photogrammetry with good accuracy. Experimental results reveal that constant shear stress flow assumption is adequate. SFRC specimens exhibited greater shear stiffness compared to RC. Moreover, shear effectiveness of fibres after diagonal cracking seems significantly dependent on reinforcement crossing the shear plane. Numerical modelling of RC and SFRC push-off specimens shows good global behaviour.

1. Introduction

The study of the shear behaviour of structural concrete members has always been a difficult task to tackle, since many factors must be taken into account simultaneously. For instance, in the vast majority of structural members shear loads act together with other forces such as axial force, bending moment or torsion. Moreover, there are many other factors that can affect the shear response of a reinforced concrete (RC) specimen [1–11], such as diameter and amount of transverse reinforcement, bond conditions of steel bars in the concrete matrix, aggregate interlock, dowel action, or type of cement, among others. Now focusing on steel-fibre reinforced concrete (SFRC) elements, other factors have also to be added to the previous ones [12–17]: length and diameter of the steel fibres, fibre tensile strength, steel-fibre content, orientation, or the bond conditions of the steel fibres into the concrete matrix.

The problem concerning all the mechanisms of shear transfer in concrete elements has been addressed from different points of view, but despite this, the topic has been revisited in order to better understand this complex phenomenon. The mechanisms of shear transfer have been studied by many researchers based on the so-called push-off test [1–4,9,11,12,17–22], mainly in pre-cracked specimens.

The behaviour of a push-off specimen under shear loads is very different if the specimen has been pre-cracked or not. Mattock [2] stated that the shear-transfer strength of initially uncracked specimens is developed by a truss action after diagonal cracking occurs, while in cracked specimens the behaviour depends on the shear-transfer mechanisms that take place at the location of the crack: aggregate interlock, dowel action, or the axial restraint of the reinforcement crossing the shear plane. Thus, pre-cracked specimens reduce the ultimate shear stress and increase slip displacements, compared to uncracked ones.

When the location of the crack is not imposed, diagonal shear cracks at a certain orientation with respect to the shear plane occur [11]. The final failure in the element is usually governed by the

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failure of the concrete compression struts that are generated between the cracks. The compression that occurs between the compression struts and the reinforcement, both crossing the shear plane and those parallel to this one, originate a truss mechanism. It is often assumed that the distribution of normal and shear stresses in the area of the shear plane is constant [10]. In the push-off test it remains unclear whether the assumption of a constant distribution of shear stress in the shear plane is really accurate, not only at failure but also at any load level applied after diagonal cracking occurs. Moreover, even though a constant shear stress distribution is assumed, it is hard to extrapolate relevant information as a basis for validation of theoretical 2D material models. On the one hand, the relation between the shear stresses with the shear strains produced has not been studied thoroughly in the push-off test in initially uncracked specimens. On the other hand, other more technically complex tests have been carried out in order to achieve this objective [6]. Moreover, the extent to which initially uncracked specimens really behave like a truss action remains unclear to these authors.

Finally, it is important to outline that new measurement tools such as the photogrammetric technique are appearing as complimentary ways to study cracking behaviour in concrete elements. This method can overcome certain problems of traditional methods, which can be time-consuming or are possibly subjected to human errors. Among others, it is worth noting the work by Valença et al. [23–25] who have developed a methodology to map and measure cracks, so making it possible to easily monitor the evolution of cracking with time.

Therefore, the main objective proposed in this paper is to measure experimentally the displacement and the strain fields in uncracked push-off specimens. It is intended to validate the photogrammetric technique as an alternative valid measurement tool able to provide a nearly continuous measurement of the displacement and strain fields in the vicinity of the shear plane.

Moreover, it is intended to study different shear behaviours in push-off specimens made of reinforced concrete (RC) and reinforced concrete with steel fibres (SFRC).

Finally, a numerical modelling of the RC and SFRC push-off specimens tested is carried out, in order to study to what extent it is possible to predict the response of push-off specimens, since they are subjected to very dominant shearing stresses.

Thus, this paper is organized as follows. In this first section, an introduction relating the purposes of this paper is presented. In Section 2, the experimental programme is described in detail. In Section 3, the results of the experimental programme are presented, and then analysed in Section 4. In Section 5, the numerical modelling and validation of the RC and SFRC specimens is carried out. Finally, in Section 6, the most relevant conclusions are drawn.

2. Experimental programme

To carry out the experimental programme, ten push-off specimens have been prepared. This set of specimens will be tested under push-off action without precracking. The geometric details of all the specimens are the same as shown in Fig. 1.

The parameters analysed are: (a) amount of reinforcement crossing the shear plane; and (b) type of concrete with or without steel fibres.

In the experimental programme each parameter range is as follows:

- The longitudinal reinforcement crossing the shear plane can be 0, 2, or 3 stirrups of 8 mm diameter. The location of this reinforcement is done according to Fig. 1. It is important to mention that secondary reinforcement is required in the two blocks in order to prevent the push-off specimen of premature failure outside the vicinity of the shear plane. Details of the secondary reinforcement are also included in Fig. 1.
- Steel-fibre content: 0 and 50 kg/m^3 corresponding to volumetric steel-fibre ratios of 0% and 0.63%.

Table 1 shows the details of the ten specimens included in the experimental programme. Designation of the specimens is carried out using *Z-Hx-nFI8-NF-i*, where: '*Z*' refers to the characteristic Z-shape of the *push-off* specimen; '*Hx*' refers to the type of concrete (reinforced concrete 'HA' or concrete with steel fibres 'HF'); '*nFI8*': refers to the number of 8 mm stirrups crossing the shear plane (0, 2 or 3 stirrups); '*NF*': refers to initially uncracked specimens; and '*i*' refers to the specimen repetition (1 or 2). Specimens were cast horizontally, vibrated and stripped after 24 h. Furthermore, they were kept horizontal in a humid environment to minimize the effects of shrinkage.

2.1. Material properties

Concrete: Five mixtures were made with 300 kg/m^3 of Portland Cement type CEM II/B-V 42.5 N (UNE-EN 197-1:2000 [27]), and additives were included in four of them (see Table 2). Aggregates used were crushed limestone gravel with sizes ranging from 7 to 20 mm. Maximum aggregate size was 12 with exception of Mix1, which was 20 mm. This change was because of difficulties observed when concrete casting. Water-cement ratio considered was 0.63. Table 2 lists the dosages taken into account for each mixture. In order to obtain the concrete compressive strength, an average number of four 100 × 100 mm cubes per mixture were prepared. Concrete compression strength was expressed in terms of 150 × 300 mm cylinder specimens, using the conversion expression included in Section 3.1.2 of EC-2 (2004) [26]. Values of average concrete compressive strength for each specimen and each mixture are expressed in Table 1.

Steel: C class (EC-2 (2004) [26]) was used. Fig. 2 shows the results of the characterization tests (UNE EN-10002-1 [28]).

Steel fibres: fibres used were low carbon steel hooked-end steel: 35 mm length, 0.55 mm diameter, nominal aspect ratio (length/diameter) equal to 63.63, and minimum tensile strength equal to 1100 MPa. Two 550 × 150 × 150 mm prismatic specimen were made for fibrous mixtures (3, 4, and 5), and 3-point bending tests were performed according to UNE-EN 14651:2007 [29], in order to determine the corresponding limit of proportionality ($f_{fct,L}$), and the residual flexural tensile strengths (f_{Rj}) (see Table 3). The results for the bending tests, as well as the average values, are shown in Fig. 3.

2.2. Test set-up

A steel-loading frame was designed to perform the tests as shown in Fig. 4. The frame includes a servo-hydraulic actuator which has a bearing capacity of 500 kN.

Between the push-off specimen and the actuator a 500 kN load cell is attached to measure the total load transmitted by the jack (Fig. 4). Moreover, a sliding base plate is also attached on the push-off side of the frame to center the specimen, reducing any eccentricities in the load application.

2.3. Instrumentation

To measure displacements three types of measurements are made using: linear variable displacement transformers (potentiometric transducers); a 100 mm Demec strain gauge; and 2D photogrammetry by means of a Canon EOS 5D Mark II of 21.1 MPx camera with sensor of 36 × 24 mm and 85 mm focal length (Fig. 5). Two 400 W halogen lights have been used at both sides of the camera to avoid hot spots in the pictures.

To measure the relative displacements in order to obtain slip and crack opening values the dorsal side of each specimen is set out with three potentiometric transducers (Fig. 5a): two for measuring horizontal crack opening (H_1 and H_2); and the last one for measuring slip displacement (V_1) between the two blocks. Moreover, to measure relative displacements between two points in the front side of the specimen the photogrammetric technique is carried out (Fig. 5c). On the same side, five pre-drilled stainless-steel discs are attached to the concrete surface using a suitable adhesive, to compare the Demec measurements with the photogrammetric ones (Fig. 5b). The instrumentation also includes the aforementioned load cell (Fig. 4), and an encoder to control the load application rate.

2.4. Test procedure

The load is applied to the specimen with the servo-hydraulic jack at a constant piston rate of 0.015 mm/s, which is controlled by the encoder device. From the beginning of the test a series of photographs are taken at intervals between one and two seconds so there is a continuous register of photo measurements. The push-off test is not carried out in a single step up to failure, because it was also necessary to obtain measurement of Demec points. Thus, the load was applied in several steps (between 5 and 10). It is important to mention that when reaching failure displacements could be poorly controlled, and therefore softening behaviour could not be reported. In the meantime the camera stopped taking pictures to ease further image post-processing.

3. Test results and observations

There are three different methods in which the information about displacements and strains can be obtained: from the