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Constitutive model for fibre reinforced concrete based on the Barcelona test

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ABSTRACT

Several constitutive models for fibre reinforced concrete (FRC) have been reported in the past years based on the flexural performance obtained in a bending test. The Barcelona test was presented as an alternative to characterise the tensile properties of FRC; however, no constitutive model was derived from it. In this article, a formulation to predict the tensile behaviour of FRC is developed based on the results of the Barcelona test. The constitutive model proposed is validated by simulating the results of an experimental program involving different types of fibres and fibre contents by means of finite element software. Moreover, the simplified formulation proposed is compared with constitutive models from European codes and guidelines.

1. Introduction

The design codes and guidelines for fibre reinforced concrete (FRC) propose different constitutive models that share a common approach: the parameters that determine the tensile behaviour are retrieved from the results of flexural tests on beams [1]. The setup and load configuration adopted produce a gradual evolution of energy release during the loading procedure, which simplifies the control and the assessment of the response of the material depending of the level of damage. Moreover, an isostatic configuration is used, meaning that the internal forces may be easily derived. As an indirect consequence, the beam test has become the reference for the systematic quality control of FRC.

Nevertheless, despite these advantages, the method also shows drawbacks. On one hand, some authors suggest that the shape and size of the specimen and its production process favours a preferential alignment of the fibres along the axis of the beam [2]. This tends to increases the mechanical efficiency and the overall tensile response of the FRC, which might not occur in the case of full-scale structures without a marked preferential orientation [3–6]. On the other hand, the small area of the beam subjected to cracking reduces the total amount of non-elastic energy mobilised and contributes to increase the scatter in the results [7,8]. In addition to that, the weight of the specimen and the type of equipment required complicate the test procedure and limit the number of elements characterised per batch. This leads to a serious contradiction in terms of the quality control of FRC since it is essential to characterise a minimum number of elements in order to obtain reliable tensile strength values, especially in a materials affected by a high scatter.

Alternative tests have been proposed with the aim of reducing this favourable orientation and the scatter. This is the case of the round panel and the EFNARC panel tests. Although both of them seem to overcome the issues mentioned, the size of the specimen required increases the setup complexity, thus limiting even more the number of results obtained per batch. In this context, the Barcelona test [8,9] according to UNE 83515:2010 [10] has been proposed as an intermediate alternative between the beam and the panel tests. Even though it might show some disadvantages regarding the control of crack initiation and the estimation of the internal stress distribution, it is simpler to perform, less-time demanding and more sustainable than other methods in terms of volume of concrete consumed [8,11,12]. Furthermore, since a bigger cracked surface is mobilised, it yields values of the residual tensile strength and toughness with an average coefficient of variation that are usually below those of the beam test [8]. Such evidences suggest that the Barcelona test might be an adequate option for the systematic quality control of FRC. However, its acceptance in practice is still hindered by the absence of simplified formulation to derive the tensile constitutive models from the test results.

The objective of this paper is to propose an analytical formulation for the estimation of the tensile constitutive curve of the FRC directly from the results of the Barcelona test. For that, an

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analytical deduction is performed considering the changes in the resistant mechanism experienced by the specimen during the test procedure. Then, the formulation obtained is validated through a FEM back analysis using results of tests conducted in laboratory with concrete reinforced with steel and plastic fibres. Finally, the constitutive equations derived from the Barcelona test and from the beam test for the same concrete are compared. The results obtained confirm the validity of the formulation proposed in this paper, thus representing a contribution towards the reliable and simple characterisation of the material.

2. Description of the Barcelona test

The Barcelona test is a double punch test (DPT) performed on a cylindrical FRC specimen with a diameter and a height of 150 mm, according to the specifications in the Spanish standard UNE 83515 [10]. Cylindrical steel punches with a height of 24 mm and a diameter of 37.5 mm are placed at the centre of the top and the bottom surfaces of the specimen. As shown in Fig. 1a, an extensometer chain is placed at half-height of the specimen to measure the Total Circumferential Opening Displacement (TCOD) experienced. A constant relative displacement rate of 0.5 ± 0.05 mm is applied by the piston of the press. The force and the TCOD are also measured.

Recent studies have shown that it is possible to estimate the TCOD without the need of using the extensometer chain. Carmona et al. [12] proposed an experimental correlation between the axial displacement and the TCOD. Subsequently, Pujadas et al. [13] presented an analytical correlation that is valid for the whole extent of the curve and for any type of FRC. The same authors have also demonstrated that the test may be conducted with cubic specimens with 150 m of side without the extensometer chain [14].

During the test, the applied load produces a tensile stress field inside the specimen. In this first stage, the concrete matrix is responsible for bearing the stresses. When the tensile strength of concrete is reached, a transition stage occurs: between 2 and 4 radial cracks are abruptly formed perpendicular to the stress field (see Fig. 1b) and two wedges are formed under the cylindrical punches where the load is applied. These wedges may be idealised as cones with the same diameter of the punches [9,10,12,15,16]. In this moment, part of the elastic energy is released and a change in the resistant mechanism is observed since the fibres become active; being responsible for bearing the tensile stresses at a sectional level (see Fig. 1c). Once the cracks have appeared, the specimen enters a kinematic stage, in which the conical wedges slide into the specimen with a certain displacement (δ_p) causing the lateral displacement (δ_L) of the concrete segments and the corresponding crack opening (see Fig. 1c and d). Further detail on the failure mechanism may be found in [13].

Differences in the fracture of the specimens help to explain the particularities in the results from the Barcelona test and the flexural test. Notice that the total cracked surface in the former is up to 2.2 times that of the latter. Consequently, the total non-elastic energy mobilised in the Barcelona test will be higher, favouring smaller scatter in the post-cracking results.

In the Barcelona test, the biggest part of the elastic energy is released abruptly at the moment of cracking and a remaining small part is released during the post cracking stage. On the contrary, in the flexural test, the release occurs at a much slower rate during almost the whole post cracking stage since the crack depth increases gradually. On one hand, this may be an advantage for the Barcelona test given that the results obtained at a sectional level will reflect better the contribution of the fibres. On the other hand, this means that it is more likely to present instabilities in the precise moment that cracking occurs. It is important to remark, however, that the authors have not experienced any problem in the control of the test due to the higher dissipation of elastic energy in the moment of cracking.

3. Analytical expressions for the tensile strength

Several analytical expressions were reported in the literature for determining the direct tensile strength (f_{ct}) derived from the DPT [9,11,15–19]. In Table 1, a summary of the closed-form expressions is presented. The main parameters are the maximum load (P), the diameter and the height of the specimen (d and h, respectively) and the diameter of the plate (d'). These expressions allow

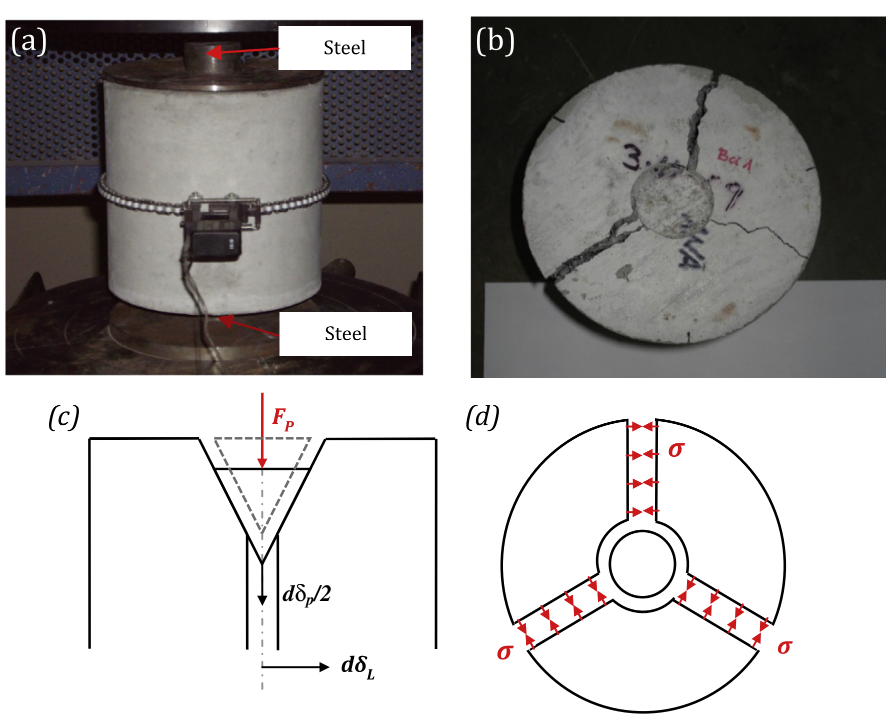

Fig. 1. (a) Barcelona test setup, (b) top view of the specimen after the test, (c) frontal view of the specimen after cracking and (d) top view of the specimen after cracking.