PUNCHING OF STEEL FIBRE REINFORCED CONCRETE FLAT SLABS

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Abstract

When mixed to concrete, discrete steel fibres "work" as a smeared reinforcement, being able to bridge flexural and/or shear cracks. So, steel fibres may replace part of the usual reinforcement bars, allowing to eventually decrease costs. In this work, the results of an experimental investigation regarding punching behaviour of normal strength Steel Fibre Reinforced Concrete (SFRC) flat slabs is presented. Six specimens were tested using different fibre volume contents (0, 0.5%, 0.75%, 1% and 1.25%) along with the experimental testing regarding the determination of the mechanical properties of SFRC, namely, its compressive and tensile strength, along with tensile behaviour thru an inverse analysis of flexural tests results. Results showed that both, an increase of the slab load capacity, and of its deformation, when compared with the reference slab, where SFRC was not used. Finally, the results were compared with different design proposals.

Keywords: Steel Fibre Reinforced Concrete, Mechanical Properties, Tensile Behaviour, Inverse Analysis, Punching.

1 Introduction

Some experimental research works have been performed in the last 30 years regarding the monotonic behaviour of slab-column connections using FRC (e.g. Narayanan and Darwish (1987), Harajli *et al.* (1995), Azevedo (1999), De Hanai and Holanda (2008), Cheng and Parra-Montesinos (2010), Higashiyama et al. (2011)). Results have clearly shown that the addition of steel fibres has a significant effect in increasing slab capacity and its ductility, when subjected to monotonically increased concentrated load.

In the study herein presented, the concrete used to built the slab specimens that were loaded up to failure was studied regarding its compressive and tensile resistance, along with the study of its complete tensile behaviour, thru flexural beam and slab panel tests. In previous works by the research team, it was shown that both, compressive and tensile behaviour of concrete, are high contributors for the capacity of flat slabs (Faria et al. (2011), Mamede et al. (2012)), and so, it may be concluded that FRC is prone to be used in flat slab-column connections.

SFRC tensile behaviour may be described by the tensile stress-crack opening (σ-w) relation, that may be directly obtained through uniaxial testing, or indirectly by means of bending tests (Zhang and Stang (1998), Marti et al. (1999), Voo and Foster (2003), Montaignac et al. (2012)). In this study tests were performed on notched beams according to EN 14651 (2004) and on square panels according to EN 14488-5 (2006).

2 SFRC Mechanical Properties

2.1 Concrete Composition

The concrete composition was the same for all mixes, except for the amount of fibres and plasticizer used. The steel fibres used were hooked end type Bekaert's Dramix RC 65/35 BN, with a length of 35 mm and a diameter of 0.55 mm corresponding to a slenderness of approximately 64. A total of 6 mixes was produced (M0 to M5), being mix M0 used as a reference mix with no fibres added. The remaining dosages were of 0.5% vol. (M1), 0.75% vol. (M2 and M3), 1.0% vol. (M4) and 1.25% vol. (M5). In mixes M3 to M5 a plasticizer was used in a dosage of 3.0 kg/m^3, in order to allow a correct mixing of the concrete constituents. All mixes presented a water/cement (w/c) ratio of 0.48.

2.2 Compressive and Tensile Strength

Compression tests were performed on cubes of 150x150x150 mm^3 (f_{ccm}) and the corresponding cylinder strength (f_{cm}) was computed as $0.80 \cdot f_{ccm}$. Splitting tests were performed on 150 mm diameter cylinders with 300 mm length. Using the compressive test, the following mean values of compression strength were obtained: 35.9 MPa, 33.8 MPa, 31.8 MPa, 46.2 MPa, 45.8 MPa and 44.5 MPa for the the mixes M0, M1, M2, M3, M4 and M5, respectively. Using the splitting test, the following mean values of tensile strength were obtained: 3.41 MPa, 3.43 MPa, 3.48 MPa, 4.25 MPa, 5.09 MPa and 5.44 MPa for the the mixes M0, M1, M2, M3, M4 and M5, respectively. All concrete specimens from the several mixes were tested 21 days after casting.

2.3 SFRC Post-Cracking Tensile Behaviour

In this study, this relation was determined thru an inverse analysis based in the results from two different flexural tests: notched beam and square panel tests. The beams measures were 600×150×150 mm^3 with a 25 mm deep mid span notch, and it was supported by two steel cylinders positioned 500 mm apart (EN 14651 (2004)). The square panels measures 600×600×100 mm^3, and were continuously supported along the four sides with a span of 500 mm. The centre point load was applied through a steel plate measuring 100×100×10 mm^3 (EN 14488-5 (2006)).

2.4 Inverse Analyses

In a inverse analysis, the tensile stress-crack opening (σ-w) is modified thru an iterative process, until the load-displacement curve predicted by the model coincides with the measured one. This analysis was conducted for both testing schemes, adopting the formulation proposed by Zhang and Stang (1998) for notched beam tests and using the yield line theory for square panel tests (Marti et al. (1999)), assuming a quadrilinear type σ-w relation. The results from the inverse analysis are presented in Figs. 1 and 2, for notched beam and square panel tests. It is possible to observe that after the matrix cracking, tensile stresses decrease up to the point where the behaviour inverts to a hardening one. After reaching the maximum strength, a stress reduction takes place up to relatively high crack openings.

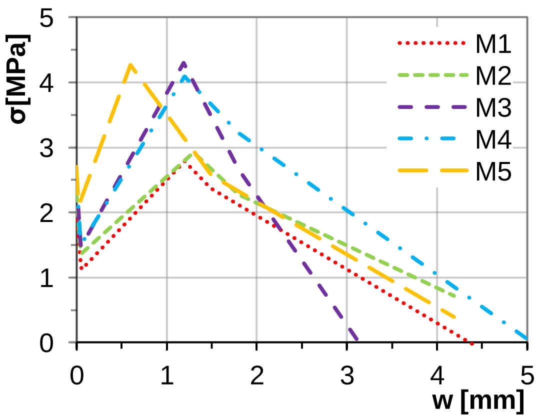

Fig. 1: σ-w relation from notched beams tests.

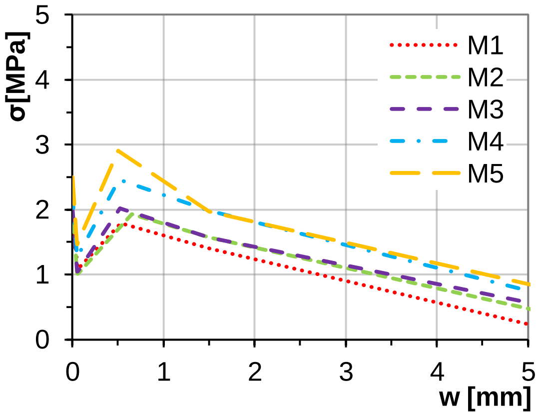

Fig. 2: σ-w relation from square panel tests.

It may be observed that σ-w relations (Figs. 1 and 2) obtained using the notched beam tests results overestimate the ones obtained from square panel tests, as expected. This may be justified due to the fact that in the notched beams there is a preferential fibre orientation along its longitudinal axis along with a predefined crack (Montaignac et al. (2012)). In square panels, the total cracks surface area is much higher than in notched beams, as also mentioned by Montaignac et al. (2012) and fibres cross cracks with different orientations, thus representing more accurately the real behaviour.

3 Punching on SFRC Slabs

3.1 Models description and test procedure

Six reduced scale flat slabs models with SFRC were tested up to failure. Specimens measured 1650x1650 mm^2 and were 125 mm thick. In all slabs, loading was applied by a hydraulic jack positioned under the slab, through a steel plate with 200x200 mm^2 placed at its centre. Eight points on the top of the slab were connected to the strong floor of the laboratory using steel tendons and spreader beams. The models simulated the area near a column of an interior slab panel up to the zero moment lines. The average effective depth of the top reinforcement was d=105 mm. The average top reinforcement ratio is of $\rho = 1\%$, for all slabs. Models were named as ND0 to ND5, cast using concrete mixes M0 to M5, respectively, and described previously. Four load cells, eleven displacement transducers and eight strain gauges, were used in order to measure applied loads, slab displacements and reinforcement bars strains, respectively. Data was measured continuously during the tests using a data acquisition system.

3.2 Experimental results: loads, displacements and failure mode

The failure loads ($V_{u,exp}$) are presented in Table 1.

Table 1
Tests results – failure loads

Model	ND0	ND1	ND2	ND3	ND4	ND5
$V_{u,exp}$ [kN]	289.2	296.0	369.3	450.7	456.0	474.7
$V_{u,exp} / V_{u,exp,0}$	1.00	1.02	1.28	1.56	1.58	1.64

From the obtained results (Table 1) it is possible to conclude that it was possible to increase the considerably the slab capacity ($V_{u,exp,0}$ is the maximum attained load in specimen ND0), thru the introduction of steel fibres in concrete, showing its beneficial effect.

3.4 Prediction of slab capacity

As mentioned before, the recent MC2010 (2010) dedicated a chapter concerning Fibre Reinforced Concrete (FRC), including provisions regarding the punching of slabs built with FRC. Those provisions are closely connected with the physical model provided in the work of Maya *et al.* (2012), that is based in the Critical Shear Crack Theory (CSCT) presented by Ruiz and Muttoni (2009), in slabs with specific reinforcement. Although EC2 (2004) does not provide any considerations regarding the use of FRC, Azevedo (1999) showed that the EC2 expression for computing the punching capacity may be adapted in order to include the beneficial effect of FRC, with satisfactory results. So, in this paper three approaches are considered: (1) MC2010 (2010), that is similar to Maya et al. (2012) simplified procedure, adopting an average fibre bridging stress; (2) Maya *et al*. (2012) complete procedure using integration; (3) Azevedo (1999). When using the MC2010 (2010), the average value expressions based in the CSCT were adopted, in order to compare with the experimental results and the level III of approximation was used according to MC2010 (2010) and to Muttoni and Ruiz (2012).

Using these previsions, the following mean value ratios $V_{u,exp}/V_{u,pred}$ and the corresponding COV were obtained, respectively: 0.88 and 0.09 [using *fib* MC2010 (2010) with law Fig. 1], 0.93 and 0.08 [using *fib* MC2010 (2010) with law Fig. 2], 0.83 and 0.14 [using Maya *et al*. (2012) with law Fig. 1], 0.91 and 0.10 [using Maya *et al*. (2012) with law Fig. 2] and 1.08 and 0.06 [using Azevedo (1999)]. When compared with the test results, the capacity provisions from MC2010 (2010) and Maya *et al*. (2012) slightly overestimate the experimental ones, while the provisions of Azevedo (1999) slightly underestimate them.

4 Conclusions

In this work, an experimental investigation on slab/column connections cast with SFRC is presented, along with a complete concrete tensile behaviour characterization using notched beams and square panels, which allowed determining the σ-w relationship thru inverse analysis. The results showed that the introduction of fibres allowed an increase in punching capacity and in the slabs ultimate deflection.

Results also showed that a slab with a fibre content of 1.25% raised the load capacity up to 64% in relation to a slab without fibres. Results are compared with MC2010 (2010) and Maya *et al*. (2012) provisions, where the concrete tensile (σ-w relationships) and compressive properties are taken into account, showing a good accuracy in the prediction of the punching capacity. Also, the prediction provided by Azevedo (1999) showed that the EC2 (2004) expression regarding the computation of the punching capacity, adapted in order to include the beneficial effect of FRC, also provides a good prediction.

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