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Numerical simulation of the punching shear behaviour of self-compacting fibre reinforced flat slabs

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HIGHLIGHTS

- In this work are presented the numerical simulations of the punching behaviour of fibre reinforced flat slabs.
- The numerical simulations were performed according to the Reissner–Mindlin theory under the FEM.
- The numerical results were able to accurately predict the experimental force–deflection relationship.
- The type of failure observed experimentally was also predicted in the numerical simulations.

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ABSTRACT

This paper presents the numerical simulations of the punching behaviour of centrally loaded steel fibre reinforced self-compacting concrete (SFRSCC) flat slabs. Eight half scaled slabs reinforced with different content of hooked-end steel fibres (0, 60, 75 and 90 kg/m^3) and concrete strengths of 50 and 70 MPa were tested and numerically modelled. Moreover, a total of 54 three-point bending tests were carried out to assess the post-cracking flexural tensile strength. All the slabs had a relatively high conventional flexural reinforcement in order to promote the occurrence of punching failure mode. Neither of the slabs had any type of specific shear reinforcement rather than the contribution of the steel fibres. The numerical simulations were performed according to the Reissner–Mindlin theory under the finite element method framework. Regarding the classic formulation of the Reissner–Mindlin theory, in order to simulate the progressive damage induced by cracking, the shell element is discretized into layers, being assumed a plane stress state in each layer. The numerical results are, then, compared with the experimental ones and it is possible to notice that they accurately predict the experimental force–deflection relationship. The type of failure observed experimentally was also predicted in the numerical simulations.

1. Introduction

The use of reinforced concrete (RC) flat slabs supported directly on RC columns is a well-accepted structural system within the building construction, since it has a quite reasonable construction flexibility allowing spans with moderate lengths between columns of about 4.5–6.0 m [1,2]. Considering their constructive and architectural advantages, flat slabs are mostly used in office, residential and parking buildings [3]. The flexural resistance of this structural system can be achieved with relatively small thicknesses for the slab's height. However, in order to avoid the brittle punching shear failure mode some specific design measures are required. The latter could be overcome with either the introduction of capitals or the inclusion of shear reinforcement. Nevertheless, these solutions are a step down on the construction efficiency. The design of these slabs is governed by both serviceability conditions and ultimate limit states under punching shear [4]. According to the available research, the punching behaviour of RC flat slabs can be improved by adopting distinct strategies such as: using a high strength class concrete [5], additional shear reinforcement [6] and discrete fibres (in particular steel fibres) [7–9]. When a hybrid reinforcement is used (i.e. rebar + discrete fibres), the steel fibres mainly confer the punching resistance, whilst the steel bars guarantee the flexural reinforcement [10].

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Fibre reinforced concrete (FRC) is mostly applied in industrial pavements, precast elements and in tunnelling. When used in large structural elements, FRC can contribute to cost reductions, since the man-labour needed for placing the conventional reinforcement is decreased (due to the fact that the reinforcement density is smaller when compared with conventional RC) [11] or even eliminated if steel fibres replace all the conventional reinforcement. Better crack resistance, ductility and toughness are among the improvements provided by fibre reinforcement. It is widely acknowledged that there are several advantages in using FRC rather than plain concrete, i.e. greater residual tensile strengths, resistance to fatigue, impact, blast loading and abrasion. Moreover, when comparing FRC with conventional mesh/bar reinforced concrete, there are also some benefits such as: increased ultimate flexural and shear strength, increased toughness fatigue and impact resistance, and better stress redistribution in the concrete composite. The application of FRC for retrofitting and seismic design purposes has also a particular interest [12–14]. For slabs on-grade, the exclusive use of steel fibre as reinforcement could be a viable and economical alternative to conventional reinforced concrete. According to [15,16] fibre contents ranging from 20 to 60 kg/m^3 should be used for this structural system. On the other hand, for suspended slabs, the exclusive use of steel fibre as reinforcement is still scarce. The outcome of FRC with enhanced mechanical strengths has been pushing the span limits upwards. Recent pilot experiences [17–19] show the feasibility of building elevated FRC slabs with 5–8 m spans (using high percentages of fibres). The results obtained so far in these pilot experiences appear promising, but they fail to address several important issues.

If fibres are properly selected in terms of type and content, they can provide effective reinforcement mechanisms to avoid the punching brittle collapse [20]. The fibre reinforcement effectiveness is not solely dependent of the type and content of fibres, the casting procedure and both rheological and mechanical properties of the concrete also influence the reinforcement effectiveness. Since steel fibres have the highest specific weight amongst the steel fibre reinforced concrete (SFRC) constituents, these fibres have a tendency to segregate towards the bottom surface, leading to a lower fibre content near the top surface [21,22]. In concrete matrices with high flowability, such is the case of self-compacting concrete (SCC), the effect of fibre segregation is mainly due to the rheological properties of the matrix in the fresh state [23]. The fibre segregation may lead to an anisotropic behaviour with different flexural capacity for positive and negative curvatures.

Several authors have proposed analytical expressions to estimate the contribution of fibres for the punching resistance based on the results obtained in experimental programs. Harajli et al. [24] have suggested a design equation to predict the increase in ultimate punching capacity of concrete slabs due to the addition of deformed steel fibres. This simple equation is based in the experimental results obtained by these authors and another ones available in the literature. A theoretical approach to model the punching resistance of interior slab-column connections using SFRC is presented by Choi et al. [25]. According to Nguyen-Minh et al. [9] this formulation does not assure a good agreement with their experimental results. More recently, Ragab [26] has simulated numerically nine steel fibre reinforced self-compacting concrete (SFRSCC) flat slabs by performing material nonlinear analysis with software based on the finite element method (FEM). Moreover, this author carried out a parametric study to analyse the influence of the ratio of flexural reinforcement (for both positive and negative bending moments) and the volume of steel fibre in the slab's behaviour. In this model, the steel fibre reinforced concrete matrix is simulated by solid elements, while the steel bars were simulated by a link element. It is possible to notice that this model has predicted with good accuracy the experimental results.

In this work, punching shear test results and numerical simulations are presented and discussed. Eight half scaled slabs reinforced with different content of hooked-end steel fibres (0, 60, 75 and 90 kg/m^3) and concrete strengths (50 and 70 MPa) were tested and numerically modelled. Moreover, a total of 54 three-point bending tests were carried out to assess the post-cracking flexural tensile strength. All SFRC slabs were heavily reinforced with conventional flexural reinforcement in order to promote the occurrence of punching failure mode. Neither of the slabs had any type of specific shear reinforcement rather than the contribution of the steel fibres. The numerical simulations were performed by adopting a FEM approach based on the Reissner–Mindlin shell theory. Regarding the classic formulation of the Reissner–Mindlin shell theory, to simulate the progressive damage induced by cracking propagation, the shell element is discretized into layers, being assumed a plane stress state in each layer. For the two out-of-plane shear components a total approach is adopted, whereas for the in-plane components it was adopted an incremental approach. The numerical results are compared to the experimental ones, and good predictions in terms of force–deflection relationship were obtained. The type of failure observed experimentally was also predicted in the numerical simulations.

2. Experimental program

2.1. Concrete properties, specimen geometry and test setup

Eight half scaled flat slabs prototypes with the dimensions of 2550 × 2550 × 150 mm^3 (Fig. 1) were centrally and vertically loaded. Two distinct ratios for the conventional reinforcement were adopted, one for the slabs' series with plain concrete and another for the steel fibre reinforced self-compacting concrete (SFRSCC) slabs' series, but the reinforcement ratio in the critical punching region was the same in both configurations (ρ = 0.88%), Fig. 2.

Eight different concrete compositions were grouped in two strength classes with compressive strengths of 50 and 70 MPa, in order to assess its influence in the punching resistance. For similar purposes, four distinct fibre contents, 0, 60, 75 and 90 kg/m^3 were adopted. The selected hooked ends steel fibres had the following mechanical and geometric characteristics: 37 mm of length (l_f), diameter of 0.55 mm (d_f), 67 of aspect ratio (l_f/d_f), and tensile strength of about 1100 MPa. Hereinafter, to easily differ the distinct slabs, the acronym C_fXf_cY will be used, where X is the theoretical content of fibres (per concrete cubic meter) and Y the target concrete compressive strength (in MPa). For example, the slab C_f60f_c70 indicates a concrete slab planned to have a fibre content of 60 kg/m^3 and a compressive strength of 70 MPa. Additionally, for each fibre reinforced slab, nine prismatic specimens with

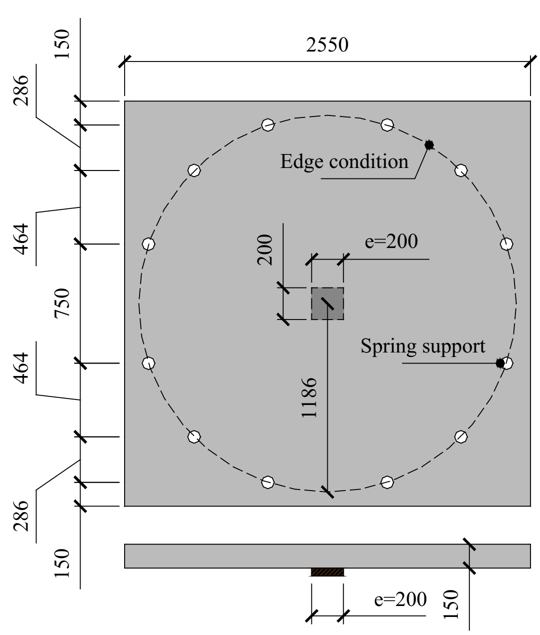

Fig. 1. Geometry of the slab prototype (dimensions in mm) [18].