Construction and Building Materials 46 (2013) 211–223

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A model for the prediction of the punching resistance of steel fibre reinforced concrete slabs centrically loaded

Bernardo N. Moraes Neto [a,c], Joaquim A.O. Barros [b,*], Guilherme S.S.A. Melo [c]

[a] University of Minho, Dept. Civil Eng., School of Eng., Guimarães, Portugal
[b] University of Minho, ISISE, Dept. Civil Eng., School of Eng., Campus de Azurém, Guimarães, Portugal
[c] University of Brasília – UnB, Dept. Civil Eng., Campus of Darcy Ribeiro, Brasília, Brazil

HIGHLIGHTS

- An analytical model is developed for the prediction of the punching load of SFRC slabs.
- A new approach is proposed to simulate the fibre reinforcement contribution.
- A data base of 154 punching tests was built to assess the predictive performance of the model.
- By predicting the experimental results of the DB the accuracy of the model was evidenced.
- The predictive performance was also demonstrated by comparison to the previsions of other models.

ARTICLE INFO

Article history:
Received 23 February 2013
Received in revised form 27 April 2013
Accepted 29 April 2013
Available online 26 May 2013

Keywords:
Reinforced concrete
Flat concrete slab
Punching
Steel fibre reinforced concrete
Analytical models

ABSTRACT

With the aim of contributing for the development of design guidelines capable of predicting with high accuracy the punching resistance of steel fibre reinforced concrete (SFRC) flat slabs, a proposal is presented in the present paper and its predictive performance is assessed by using a database that collects the experimental results from 154 punching tests. The theoretical fundaments of this proposal are based on the critical shear crack theory proposed by Muttoni and his co-authors. The proposal is capable of predicting the load versus rotation of the slab, and attends to the punching failure criterion of the slab. The proposal takes into account the recommendations of the most recent CEB-FIP Model Code for modelling the post-cracking behaviour of SFRC. By simulating the tests composing the collected database, the good predictive performance of the developed proposal is demonstrated.

1. Introduction

In recent years the use of steel fibres to increase of the punching resistance, and mainly, to convert brittle punching failure mode into ductile flexural failure mode of reinforced concrete (RC) flat slabs has been explored. In fact, available research [1–3] showed that, if proper mix compositions of steel fibre reinforced concrete (SFRC) are used, steel fibres can be suitable shear reinforcement for RC flat slabs, by improving the load carrying capacity and the energy absorption performance of the column–slab connection. These benefits are derived from the fibre reinforcement mechanisms provided by fibres bridging the micro-cracks that arrest the crack propagation, favouring the occurrence of large number of cracks of small width.

The resisting tensile stresses supported by the steel fibres in a cracked concrete have also the favourable effect of delaying the yield initiation of longitudinal and transversal conventional steel reinforcement, which contributes to increase the ultimate load carrying capacity of RC structures or to a partial suppression of conventional reinforcements.

By testing prototypes of real [4,5] or smaller scale [6], the use of steel fibres has been investigated as, practically, the unique reinforcement of the flat slabs for residential and commercial buildings. This type of slabs, generally designated by Elevated Steel Fibre Reinforced Concrete (ESFRC) slabs, is reinforced with a steel fibre volume percentage, V_f, of about 1%, and it includes a minimum continuity bars, also referred as anti-progressive collapse bars, placed in the bottom of the slab in the alignment of the columns [7]. In spite of the promising results obtained in these tests, reliable design models capable of predicting, with high accuracy, the load carrying capacity, the deformational response and the failure modes possible to occur in ESFRC slabs are not yet available, which is a considerable resistance for a comprehensive acceptation

---

* Corresponding author.

E-mail addresses: bnmn@hotmail.com (B.N. Moraes Neto), barros@civil.uminho.pt (J.A.O. Barros), melog@unb.br (G.S.S.A. Melo).

0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.04.034

Nomenclature

A'_s	area of compression reinforcement
A_s	area of tension reinforcement
b	width of a isolated slab element
b_0	critical perimeter for punching shear
$b_{q,c}$	loaded line for square slabs in circular edge conditions
$b_{q,q}$	loaded line for square slabs in rectangular edge conditions
c'	distance of the flexural reinforcement to the concrete tensile surface
d	internal arm of the slab
d_0	diameter of the aggregates
d_f	diameter of fibre
d_g	maximum diameter of the
d_{g0}	reference diameter of the aggregates
e	edge of the column's cross section
E	modulus of elasticity of concrete
E_s	modulus of elasticity of reinforcement
F'_s	internal compressive force of compressive reinforcement
f_c	average compressive strength of concrete in cylinder specimens
F_{cr}	internal compressive force of concrete in radial direction
F_{ct}	internal compressive force of concrete in tangential direction
f_{ct}	average tensile strength of concrete (Brazilian test)
f_{Fts}	post-cracking strength for serviceability crack opening
f_{Ftu}	post-cracking strength for ultimate crack opening
f_{Ri}	residual flexural tensile strength of fibre reinforced concrete corresponding to CMOD_i
F_s	internal compressive force of tensile reinforcement
F_{sr}	internal tensile force of reinforcement in radial direction
F_{st}	internal tensile force of reinforcement in tangential direction
f_{sy}	yield strength of reinforcement
h	slab thickness
I_0	second moment of area of uncracked concrete cross-section
I_1	second moment of area of cracked concrete cross-section
L	span of slab
l_f	length of fibre
m_{cr}	bending moment at crack initiation
m_r	radial moment per unit width
m_R	resisting bending moment (plastic bending moment)
m_t	tangential moment per unit width
r	radial orientation
r_0	radius of the critical shear crack
r_1	radius of the zone in which cracking is stabilized
r_c	radius of a circular column
$r_{c,eq}$	radius of a circular column in an equivalent slab of circular geometry
r_{cr}	radius of cracked zone
r_q	radius of the load introduction at the perimeter
$r_{q,eq}$	radius of the load introduction at the perimeter in an equivalent slab of circular geometry
r_s	radius of circular isolated slab element
$r_{s,eq}$	radius of circular isolated slab element in an equivalent slab of circular geometry
r_y	radius of yielded zone
t	tangential orientation
V	shear force
V_{exp}	experimental punching shear strength
V_f	fibre volume percentage
V_{flex}	shear force associated with flexural capacity of the slab
V_R	nominal punching shear strength
$V_{R,cd}$	design concrete contribution to punching shear strength
$V_{R,d}$	design punching shear strength
$V_{R,fd}$	design fibre contribution to punching shear strength
$V_{R,sd}$	design shear reinforcement contribution to punching shear strength
V_{the}	theoretical punching shear strength
V_u	punching failure load
w	shear crack opening
w_u	maximum acceptable crack width imposed by design conditions
x	neutral axis of slab
z	axis orthogonal to the slab with origin at the bottom surface of the slab
β	efficiency factor of the bending reinforcement for stiffness calculation
$\Delta\varphi$	angle of a cracked radial segment of slab
ε'_s	compressive steel reinforcement strain
ε_c	concrete strain
ε_{cu}	ultimate strain of concrete in compression zone
ε_{fu}	ultimate strain of fibre in tensile zone
ε_s	strain of steel reinforcement in tensile zone
ε_{su}	ultimate strain of steel reinforcement in tensile zone
$\varepsilon_{t,bot}$	concrete tensile strain at the bottom surface of the slab
$\nu_{R,}$	nominal shear stress
ν_c	concrete nominal shear strength
ρ	tensile reinforcement ratio
ρ'	compressive reinforcement ratio
$\sigma_{f,r}$	post-cracking tensile strength of SFRC in radial direction
$\sigma_{f,t}$	post-cracking tensile strength of SFRC in tangential direction
τ_b	average interracial bond strength of fibre matrix
χ_1	curvature in stabilized cracking
χ_{cr}	curvature at cracking
χ_{ts}	tension stiffening parameter
χ_y	yielding curvature
ψ	rotation of slab

of this structural concept that apparently has several technical and economic advantages. Due to the brittle character of punching failure mode, the existence of a design model capable of predicting correctly the punching resistance and the deformation capacity of SFRC flat slabs is of paramount importance in this context. Some analytical models were proposed for the evaluation of the punching resistance of SFRC slabs, some of them with an eminent empirical nature, but the predictive performance of these models was, in general, limited to the simulation of a relatively small number of tests carried out by the authors [8–11]. In the present work a database collecting 154 punching tests with SFRC slabs was developed to appraise the predictive performance of these models and the one proposed by the authors of the present work. This model is based on the Critical Shear Crack Theory (CSCT) proposed by Muttoni [12], being possible to determine the punching resistance of SFRC slab by intersecting a curve corresponding to the load versus rotation (V–ψ) of the column–slab connection, with a curve that defines the failure criterion. This model integrates the contribution of fibre reinforcement mechanisms using the recommendations of the most recent CEB-FIP Model Code 2010 [13]. The present paper