Engineering Structures 117 (2016) 603–616

Contents lists available at ScienceDirect

Engineering Structures

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

Composite model for predicting the punching resistance of R-UHPFRC–RC composite slabs

Malena Bastien-Masse *, Eugen Brühwiler

École Polytechnique Fédérale de Lausanne (EPFL), Station 18, 1015 Lausanne, Switzerland

A R T I C L E I N F O

Article history:
Received 27 August 2015
Revised 29 February 2016
Accepted 7 March 2016
Available online 30 March 2016

Keywords:
Composite slab
Flat slabs
Punching shear resistance
Ultra-High Performance Fiber Reinforced cement-based Composite (UHPFRC)
Strengthening
Sector model
Composite model
Near interface cracking

A B S T R A C T

Adding a thin layer of Ultra-High Performance Fiber Reinforced cement-based Composite (UHPFRC), with or without steel rebars, over a Reinforced Concrete (RC) slab is an efficient reinforcement method for existing structures. The thin layer of UHPFRC serves as a tensile reinforcement for the RC slab, creating a composite element. A recent experimental campaign showed that the layer of UHPFRC significantly increases the rigidity and the punching shear resistance of a RC slab submitted to a point force. An analytical composite model is developed herein to predict the global bending behavior of the composite slab and the punching shear resistance. A multilinear moment–curvature relation for composite sections is proposed to calculate the global force-rotation behavior of a slab which can then be used in combination with a composite failure criterion to predict the punching shear resistance. The contribution of the concrete section to the punching shear resistance is obtained with existing models from the literature. The UHPFRC layer resists to punching shear by out-of-plane bending over a limited length equal to its height. This mechanism induces tensile stresses perpendicularly to the interface with the concrete. The contribution of the UHPFRC layer to the punching shear resistance thus depends on the tensile strength of concrete. The results of this analytical composite model are in good agreement with the experimental result. A method is also proposed to consider pre-existing deformation of the RC section for a post-installed UHPFRC layer.

1. Introduction

The use of a thin layer of Ultra-High Performance Fiber Reinforced cement-based Composite (UHPFRC) as an external tensile reinforcement for Reinforced Concrete (RC) slabs is a spreading technique for strengthening existing structures [1]. UHPFRC layers reinforced (or non-reinforced) with small diameter steel rebars (R-UHPFRC) have a typical thickness of between 25 and 50 mm and are cast in place over RC slabs, creating a composite RU-RC section (Fig. 1a).

This reinforcement method was proven effective to strengthen one-way elements in bending and in shear [3,4].With its high tensile properties, the UHPFRC layer contributes to the resistance of the element by its in-plane tensile resistance and deformability as well as its out-of-plane bending resistance and rotation capacity [5,6].

In a previous paper by the authors [2], an experimental campaign on the punching shear resistance of composite RU-RC slabs submitted to a point force was presented. The tests showed that the layer of UHPFRC can increase the punching shear resistance of a RC slab by at least 69% without modifying its rotation capacity as it would be expected for a slab with added flexural reinforcement. As for one-way shear, the layer of UHPFRC resists to punching shear by out-of-plane bending (Fig. 1b), meaning that it activates a bending mechanism perpendicular to the plane of the deflected shape of the composite slab.

Over the last century, punching shear resistance of RC slabs has been the object of extensive research [7]. Various analytical models were developed to predict the punching shear resistance of RC slabs using elasticity and plasticity theories. A full review of the existing models can be found in [8].

A sector model was developed in 1960 by Kinnunen and Nylander [9]. Their model allowed simulating the behavior of an axisymmetric slab by assuming that slab sectors rotate around the edge of the column. With the assumed kinematic, the force-rotation curve of the slab is obtained and combined to a failure criterion to predict the punching shear resistance (Fig. 2). The proposed failure criterion is expressed as the ultimate tangential strain in the concrete near the column. The punching shear resistance is thus related to the state of deformation in the slab due to bending.

---

* Corresponding author. Tel.: +41 21 693 2885.
E-mail addresses: malena.bastien.masse@gmail.com (M. Bastien-Masse), eugen.bruehwiler@epfl.ch (E. Brühwiler).

http://dx.doi.org/10.1016/j.engstruct.2016.03.017

Nomenclature

List of symbols

Subscripts

R	resistance
RU	reinforced UHPFRC
RC	reinforced concrete
U	UHPFRC
Utu	UHPFRC tensile strength
c	concrete
cc	concrete in compression
cr	cracking of concrete
el	elastic state
i	steel, UHPFRC or concrete
r	radial
s	steel
sc	top steel reinforcement layer in RC section
sh	UHPFRC strain hardening
sU	steel reinforcement in the R-UHPFRC layer
sy	yielding of steel
t	tangential
x	related to the calculation of the height of the compression zone

Latin upper case

A	area
B	side length of slab specimen
E	modulus of elasticity
EI_0	elastic flexural rigidity
EI_1	flexural rigidity after concrete cracking
EI_2	flexural rigidity after tensile strength of UHPFRC is reached
F	force in cross section
F_{RU}	force in the R-UHPFRC tension chord
F_T	force in the composite R-UHPFRC–RC tension chord
M	moment
M_{lyr}	resisting moment of composite beam calculated with the layered analytical model
M_{ml}	resisting moment of composite beam calculated with the multilinear moment curvature
M_{test}	resisting moment of composite beam obtained from a bending test
S	parameter related to the calculation of the height of the compression zone
V	punching shear force
V_c	concrete contribution to punching resistance
V_{calc}	Calculated shear force
V_{exp}	Measured shear force
V_U	UHPFRC layer contribution to punching resistance

Latin lower case

b	beam width
b_0	critical perimeter for punching shear set at $d_{sc}/2$ from the column face
b_1	distance between two force introduction points in the square test slab
b_2	distance between force introduction point and nearest slab side
c	side length of column
d	flexural depth for a tensile reinforcement: distance from the bottom compression face of the slab to the centroid of the tensile reinforcement
d_g	maximum diameter of aggregate
d_{g0}	reference aggregate size set at 16 mm
f	strength of a material
f_c	concrete compressive strength
f_{ct}	concrete tensile strength
f_{sy}	yield strength of steel reinforcement
f_{Uc}	UHPFRC compressive strength
f_{Ute}	maximum tensile elastic strength of UHPFRC
f_{Utu}	tensile strength of UHPFRC
$f_{Ut,S1}$	softening tensile strength of UHPFRC
h	height
l_{ch}	UHPFRC characteristic length for the softening behavior
l_{NIC}	near interface cracking length at the UHPFRC – concrete interface
m	bending moment per unit width
r	radius measured from the center of the slab
r_0	radius of inclined crack at the level of the top reinforcement, located at d_{sc} from the column side
r_c	radius of circular column
r_q	radius of force introduction at perimeter
r_s	radius of circular slab
r_U	radius of inclined crack at the top of the slab located at h_c+h_U from the column side
w_{Ut}	crack opening in UHPFRC
x	height of the compression zone

Greek lower case

α_c	minimum angle of the inclined shear crack
β	efficiency factor to take into account the reduced torsional rigidity of orthogonal reinforcement
ε	strain
ε_{sy}	yielding strain in steel reinforcement
ε_{c1}	strain in concrete at maximum compressive strength
ε_{Uc}	strain in UHPFRC at maximum compressive strength
ε_{Ute}	strain in UHPFRC at tensile elastic limit strength
ε_{Utu}	strain in UHPFRC at maximum tensile strength
θ_U	angle of rotation in the UHPFRC hinge
κ	curvature in a cross-section
κ_1	curvature when cracking has stabilized in a RC cross-section
κ_{add}	curvature when the layer of UHPFRC is added to a RC section
κ_{TS}	reduction in the curvature due to tension stiffening
λ	remaining ratio of f_{Utu}
ρ	reinforcement ratio
ρ_{TC}	reinforcement ratio in the tension chord
σ	stress
ψ	rotation
ψ_{add}	rotation when the layer of UHPFRC is added to a RC slab

The sector model served as a basis for further model developments [10–12]. Hallgren [10] modified the failure criterion using fracture mechanics. Muttoni [12] used the sector model to develop the critical shear crack theory (CSCT) in which the failure criterion is a function of the slab rotation. The CSCT is now the basis for the punching shear resistance calculation in the *fib* Model Code 2010 [13] as well as the Swiss standards for the design of concrete structures [14].

The objective of the presented work is to develop analytical models to include the contribution of the UHPFRC layer to the punching shear resistance calculation of a composite slab. First, a multilinear moment–curvature relation is proposed to predict the