Engineering Structures 122 (2016) 226–237

Contents lists available at ScienceDirect

Engineering Structures

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

Steel fiber reinforced self-compacting concrete thin slabs – Experimental study and verification against Model Code 2010 provisions

Luca Facconi [1], Fausto Minelli *, Giovanni Plizzari [2]

DICATAM – Department of Civil Engineering, Architecture, Land, Environment and Mathematics, University of Brescia, Italy

ARTICLE INFO

Article history:
Received 7 August 2015
Revised 8 February 2016
Accepted 12 April 2016

Keywords:
Hybrid reinforced concrete
Thin slabs
Fiber reinforced concrete
Full scale experiments
High strength steel fibers

ABSTRACT

This paper reports the experimental results of 11 full scale thin plates (dim. 4200 × 2500 × 80 mm^3): 8 slabs containing three types of fiber reinforcement (2 types of high strength fibers, one added in two different contents) were tested first. Then, one slab cast with traditional reinforced concrete was tested and used as a reference slab. Finally, two slabs were produced with a typical rectangular opening, which determines a disturbed stress region: the first one was cast in classical reinforced concrete (RC) whereas the second by suitably combining fibers and rebars under a hybrid reinforced concrete (HRC) perspective. Results show that these slender plates, undergoing light loads, might be an effective structural application in which fibers could represent the unique flexural reinforcement. In presence of disturbed regions due to openings, frequent in practice, a suitably combination of rebars and fibers is proposed and discussed. Emphasis on cracking phenomena and energy absorption capacity is provided. A comparison with the requirements of the *fib* Model Code 2010 for members containing only fibers is subsequently discussed.

1. Introduction

The use of steel fibers is a well acknowledged methodology to improve the tensile performance and toughness of concrete. After several years of discussion within the research community, Fiber Reinforced Concrete (FRC) is nowadays recognized as a structural material and international [1,2] or national [3] Structural Codes are now available [4].

Many studies proved that steel fibers can be adopted as the only reinforcement in some structural elements having a high internal redundancy such as slabs on grade [5]. On the other hand, fibers may be added to concrete in order to partially substitute and optimize conventional reinforcement [6]. The combination of continuous rebars and randomly distributed chopped fibers in the matrix, generally referred to as Hybrid Reinforced Concrete (HRC), has recently gained quite high importance as a feasible way to design optimized structural elements [7–10].

Pre-cast industry represents one of the application field in which Steel Fiber Reinforced Concrete (SFRC) has been adopted first, e.g. tunnel lining applications [6] and beams [11]. In fact, the use of steel fibers, even only in partial substitution of conventional reinforcement, may allow to significantly reduce the construction time and costs that typically characterize the production process. In this context, light prefabrication structures are often built without any conventional reinforcement but fibers only, e.g. plates with small dimensions, manholes, duct elements and others.

Flat slabs have been extensively used all around the world especially for constructing floor systems in residential buildings. In addition to the typical construction advantages (e.g. simple plate–column connection and formwork geometry, reduced construction time and costs) the use of SFRC may allow for a significant reduction of conventional reinforcement. However, the limited flexural stiffness of flat slabs (due to the high slenderness) increases the possibility of early punching mechanisms [12]. In view of this, fiber reinforcement could represent an effective solution to help conventional reinforcement used to resist tensile membrane actions developed for very large deflections [13].

A number of recent experiments available in literature investigated the possibility of using fibers as the only flexural reinforcement for flat slab. Michels et al. [14,15] showed that, in several tests on flat slabs, the punching shear can be avoided (and a flexure failure is observed), for instance by adding volume fractions of fibers greater than 1.3%. However, a clear size effect associated with the thickness of slabs was seen, likely due to the 3D orientation of fibers in deeper elements, resulting in a lower bearing capacity. Authors also provided design abaci combining possible

* Corresponding author. Tel.: +39 030 371 1277; fax: +39 030 371 1312.
E-mail addresses: luca.facconi@unibs.it (L. Facconi), fausto.minelli@unibs.it (F. Minelli), giovanni.plizzari@unibs.it (G. Plizzari).
[1] Tel.: +39 030 371 5413; fax: +39 030 371 1312.
[2] Tel.: +39 030 371 1201; fax: +39 030 371 1312.

http://dx.doi.org/10.1016/j.engstruct.2016.04.030
0141-0296/© 2016 Elsevier Ltd. All rights reserved.

Table 1
Concrete mixture.

Cement type	CEM 42.5R
Cement content (kg/m^3)	370
Fine aggregate 0/4 (kg/m^3)	838
Coarse aggregate 4/12 (kg/m^3)	762
Maximum aggregate size (mm)	12
Calcium Carbonate filler (kg/m^3)	280
Water–cement ratio	0.49
Super plasticizer (% on cement content)	1.10

span and slab thicknesses for satisfactory structural behavior at Ultimate Limit States (ULS).

Pujadas et al. [16] tested a number of statically indeterminate flat slabs reinforced only with plastic polyolefin fibers (9 kg/m^3), showing a good ductility associated with a great stress redistribution capacity after cracking. However, based on an analytical approach, they suggested the need of revising some current guidelines [17] that overestimate the capacity of these slabs. Also Destrée in [18] studied free suspended elevated flat slabs with SFRC only.

When using self-compacting concrete (SCC) to construct flat slabs, the casting direction and the thin thickness of the structural elements promote the 2D orientation of fibers within the slab plane. As observed by Laranjeira et al. [19] and Ferrara et al. [20], the orientation of fibers has a prominent influence on the tensile behavior of SFRC.

This paper reports the results of a broad experimental program carried out at the University of Brescia to study the possibility of using steel fibers as an alternative reinforcement for simply supported thin slabs, made of Self-Compacting Concrete, used as floor elements in the pre-cast electrical equipment shelters.

Eleven full scale thin plates (dim. 4200 · 2500 · 80 mm^3) were tested in three different phases. Eight slabs containing three types of fiber reinforcement (2 types of high strength fibers, one added in two different contents, 20 and 25 kg/m^3) were tested first. Then, one slab cast with traditional reinforced concrete was tested and used as a reference slab. Finally, two slabs were produced with a typical rectangular opening, which determines a disturbed stress region around it: the first one was cast in classical RC whereas the second by suitably combining fibers and rebars under a HRC perspective.

Results will be critically discussed especially in terms of bearing capacity, uncracked and cracked stiffness, cracking phenomena, ductility and energy absorption.

The idea behind this research project is that thin slender plates undergoing light loads might be an effective structural application in which fibers could represent the unique flexural reinforcement, depending upon fiber performance, geometry and load. In case fibers only are not able to provide the structure with an adequate capacity to resists heavy loads, the use of HRC may allow to significantly improve the structure performance.

Unlike previous researches, a rather small thickness (80 mm) and a high slenderness (span/thickness = 32 with reference to the shortest side) characterize these elements. The slenderness/small thickness of the elements, associated with the utilization of SCC, may results in a 2D in plane orientation of fibers, promoting the plate-like behavior. This would allow the attainment of remarkable ductility, which is one of the most significant index to be checked under a design point of view in structures without classical continuous reinforcement.

2. Experimental program

2.1. Material properties

The experimental investigation presented herein was carried out by using a SCC, whose composition is summarized in Table 1. The material adopted to build the slabs was basically the same except for the type and content of steel fibers. As shown in Table 2, besides plain concrete (PC), i.e. the concrete not containing steel fibers, three types of FRC materials (FRCD25, FRCG20, FRCG25) were utilized. Table 2 highlights also the designation adopted for the materials: the acronym FRC, followed by a letter (D or G), which represents the type of steel fibers adopted, and by a number (20, 25) corresponding to a fiber dosage of 20 kg/m^3 (volume fraction 0.25%) or 25 kg/m^3 (volume fraction 0.32%) was assumed. The two types of fibers and the two dosages selected for this research were chosen after performing a series of preliminary FRC material characterization (according to MC2010 [1]). In more detail, four types of normal strength double hooked-end long steel fibers and two types of high strength long steel fibers, i.e. fibers D and G, were cast in the same concrete matrix as reported in Table 1. For each type of fiber, two different fiber contents, i.e. 20, and 25 kg/m^3 were considered. According to the preliminary results, only the high strength fibers were able to promote a strain hardening behavior of concrete under flexure. Therefore, fibers D and G with a maximum content of 25 kg/m^3 were selected for the experimental program.

The flowability and flow rate properties of SCC were assessed by the slump-flow test described by EN 12350-2 [21]. The resulting slump-flow and viscosity classes reported in Table 2 were determined according to the classification proposed by EN 206-1 (2006) [22]. As shown in Table 3, the two types of steel fibers used in this research are characterized by a considerably high tensile strength but, unlike fiber D that has a double hooked-end shape

Table 2
Properties of fresh and hardened concrete.

Concrete designation	PC	FRCD25	FRCG20	FRCG25
Slump flow class	SF3	SF3	SF3	SF3
Viscosity class	VS1	VS1	VS1	VS1
Fiber type	No Fibers	Fiber D	Fiber G	Fiber G
Fiber dosage (kg/m^3)	–	25	20	25
Fiber dosage V_f (%)	–	0.32	0.25	0.32
$f_{cm,cube}$ (MPa)	56.10	60.70	50.00	54.20
f_{cm} (MPa)	46.55	50.30	41.50	45.00
f_{ck} (MPa)	42.43	46.00	35.77	39.00
f_{ctm} (MPa)	3.65	3.85	3.26	3.45
E_{cm} (MPa)	34,900	35,700	33,700	34,600
f_L (MPa)	3.79 (c.v. 7%)	4.95 (c.v. 6%)	4.52 (c.v. 11%)	5.45 (c.v. 9%)
f_{R1} (MPa)	–	2.81 (c.v. 30%)	4.29 (c.v. 26%)	5.94 (c.v. 13%)
f_{R2} (MPa)	–	4.30 (c.v. 28%)	4.85 (c.v. 24%)	6.10 (c.v. 11%)
f_{R3} (MPa)	–	4.88 (c.v. 27%)	4.32 (c.v. 25%)	5.54 (c.v. 14%)
f_{R4} (MPa)	–	4.94 (c.v. 23%)	4.03 (c.v. 23%)	4.90 (c.v.17%)