Engineering Structures 111 (2016) 411–424

Contents lists available at ScienceDirect

Engineering Structures

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

Cracking localization and reduced ductility in fiber-reinforced concrete beams with low reinforcement ratios

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ARTICLE INFO

Article history:
Received 8 March 2015
Revised 14 November 2015
Accepted 19 November 2015
Available online 7 January 2016

Keywords:
Fibrous reinforced concrete
Flexural behavior
Ductility
Cracking

ABSTRACT

The effect of adding steel fibers to concrete mixes on the flexural behavior of reinforced concrete (RC) beams was studied experimentally. Tests were conducted on conventionally reinforced beams with different reinforcement ratios, with and without fibers. Results show that the application of steel fibers leads to a pronounced reduction in flexural ductility of beams with low conventional reinforcement ratios ($\rho < \sim 0.5\%$). Ductility ratios of fibrous RC beam specimens were reduced by 50–80% compared with corresponding ratios measured on control specimens with the same reinforcement ratios but without fibers. The effects of added fibers on the flexural behavior of RC beams were examined and three aspects were reported: ductility ratio (based on deflection), distribution of curvature, and load-carrying capacity.

1. Introduction

Increased material brittleness, which is typical for high-strength concrete (HSC), is commonly overcome by adding steel fibers to the concrete mixture [1–3]. Fibers are expected to influence the cracking process, to reduce crack width and spacing [4,5] and to increase the material's ultimate strain, consequently increasing concrete toughness [6]. Hence, it is also expected that fibrous concrete mixes used in conventionally reinforced beams will improve crack control [7–9], increase the beams' structural ductility [10] and enhance their tension stiffening by bridging cracked cross-sections [11].

Indeed, cracking studies of fibrous concrete with conventional reinforcement under axial tension revealed improved crack control at service load [12–15]. However, they also reported a phenomenon of localization, manifested by distinct widening of one or two cracks, at the ultimate state, where the specimens in these studies exhibited thin, closely spaced cracks at service loads but a different cracking pattern under increased loads. Redaelli [12] and Redaelli and Muttoni [13] reported widening of a single crack at the ultimate state, compared with other cracks that developed in ultra-high performance concrete specimens at lower service loads. Deluce and Vecchio [14] reported distinct widening of one or two cracks in normal- and high-strength reinforced fibrous concrete tension specimens at the ultimate state. Localization in these studies was not related to any specific reinforcement ratios (i.e. particularly low or particularly high), yet Yang et al. [15] noted that localization in one crack is more likely to occur with increasing fiber content.

A similar phenomenon was also observed in flexural tests of HSC beams, where widening of a single crack in the concrete and local development of high strains in the tension rebars occurred under increased loads [16]. This crack localization was observed in specimens with steel fibers and low reinforcement ratios and led to a reduction, rather than an increase, in their structural ductility. Other beam specimens that were made of the same HSC but with increased reinforcement ratios exhibited increased ductility ratios that were equal to or higher than those measured in similar conventional fiber-free beams [16].

It should be noted that while there are several experimental evidences for the above-described cracking localization in axially-loaded specimens, the authors could not find experimental studies that thoroughly investigated it in flexural specimens (although this phenomenon was observed and reported, see [17] and Fig. 24 in [18]). Furthermore, as noted, this reduction in flexural ductility was observed and noticed in HSC beam specimens [16,17]. Therefore, complementary flexural tests of normal strength concrete (NSC) beams with and without fibers were carried out in the current study. The beams that were tested included various reinforcement ratios, with special attention given to specimens with lower ratios of longitudinal reinforcement. The study aimed to verify the occurrence of the above-described phenomenon in NSC, in flexure, and to explore the range of

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http://dx.doi.org/10.1016/j.engstruct.2015.11.046
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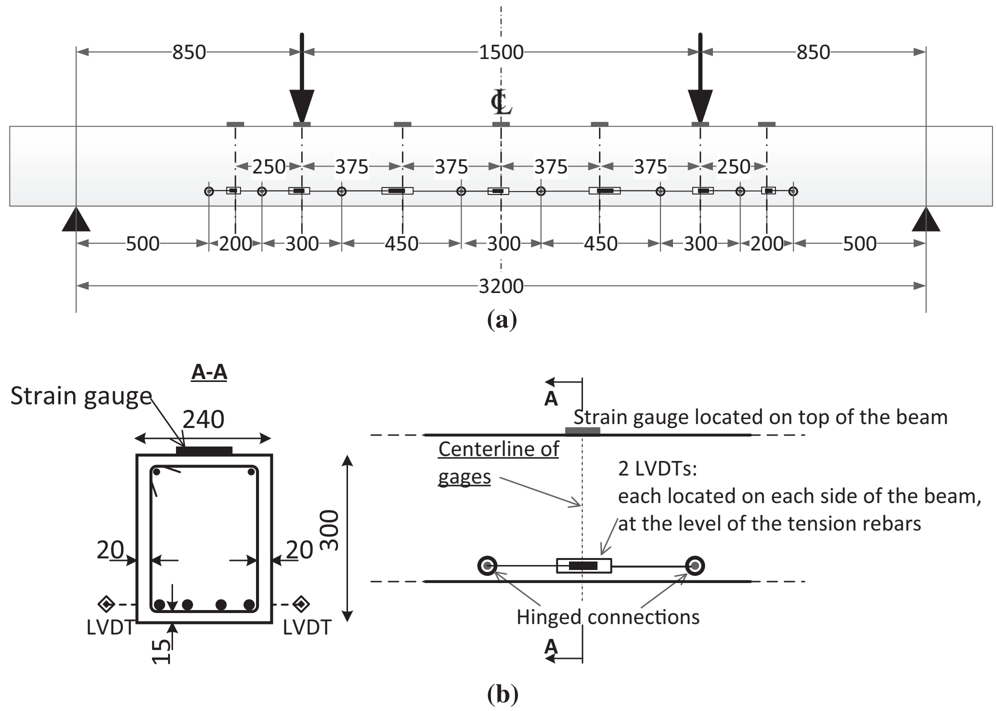

Fig. 1. Flexural test setup: (a) scheme and measurements (mid-span displacement and external load measurements are not shown in the figure) and (b) specimen cross-section and a "set of transducers" (Other details are given in Table 1. All dimensions are in mm).

reinforcement ratios within which it occurred. Thus, this research was aimed to discover whether fibrous, reinforced NSC beams behaved differently as compared with fiber-free, reinforced concrete beams and if so, at what reinforcement ratios.

2. Experimental program

The effect of adding steel fibers to concrete mixes on the flexural behavior of concrete members was studied on conventionally reinforced beams with different reinforcement ratios, with and without fibers. Two series of four-point bending tests were carried out. The first series included specimens with fibers content of $\mathbf{W_f}$ = 60 kg/m^3 (0.76% in volume) and it examined the structural behavior within a broad range of reinforcement ratios, $\boldsymbol{\rho}$ that varied from 0.15% to 3.3%. The second series focused on the behavior of specimens with reinforcement ratios ranging from 0.15% to ~1%. Some of the specimens in the second series contained less fibers, specifically $\mathbf{W_f}$ = 40 kg/m^3 (0.5% in volume). Altogether, a total number of 25 tests were carried out.

Table 1
Specimen details – fibers and steel.

			Longitudinal tension reinforcement[c]						Shear reinf.[e]	
							Max/ultimate[d]			
Specimen	**d** (effective depth; mm)	$\mathbf{W_f}$ (kg/m^3)[b]	**ρ** (%)	No. of long. rebars	diameter (mm)	Yield strength (MPa)[d]	Strength (MPa)	Strain (%)	Diameter (mm)	Spacing (mm)
NF-0-015	273	0			8	508	693/687	10.0/11.1		
40-015[a]	273	40	0.15	2	8	503	677/676	6.9/7.0	8	200
NF-1-015	273	60			8	508	693/687	10.0/11.1		
0-039[a]	270	0								
40-039[a]	270	40	0.40	2 + 2[f]	8	503	677/676	6.9/7.0	10	200
60-039[a]	270	60			10	409	579/578	8.4/9.0		
NF-0-063[a]	267	0	0.63	2	16	472	558/557	7.6/7.9	10	200
NF-1-063	267	60				412	668/667	11.0/12.1		
0-094[a]	267	0	0.94	3	16	472	558/557	7.6/7.9	10	100
60-094[a]	267	60								
NF-0-126	267	0	1.26	4	16	412	668/667	11.0/12.1	10	100
NF-1-126	267	60								
NF-0-330	242	0	3.27	5[g]	22	412	674/672	10.8/12.5	10	75
NF-1-330	242	60								

[a] Performed in the second test series.
[b] 35-mm long, hooked-end steel fibers.
[c] Top reinforcement consisted of two 12-mm rebars in specimens with 3.27% reinforcement ratio and 8-mm rebars in all other specimens.
[d] "Max" refers to the maximum stress and "Ultimate" to the stress at the rupture strain of the rebar.
[e] Within the shear span.
[f] 2ϕ8 + 2ϕ10.
[g] Arranged in two layers.