

Quantification of cracking localization in fibre-reinforced concrete beams

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Abstract. The paper presents an analysis of cracking localization in beams made of fibre-reinforced concrete with conventional reinforcement. This phenomenon has been quantified by the ratio m/n between the number of the significantly wide cracks and the total number of flexural cracks that developed within the constant moment zone of the beams. It is shown that beams with larger reinforcement ratio had larger values of m/n , that is, lower cracking localization. For the given concrete mix, when the reinforcement ratios ρ were larger than $\sim 2\%$ cracking localization was diminished. Furthermore, for low values of ρ , m/n ratios of the specimens with lower fibre contents are somewhat larger than those of the specimens with larger content. It is also shown that as the reinforcement ratio decreases below $\sim 0.5\%$ the normalized mid-span ultimate deflections decreases as well, which corresponds with the observation of the cracking localization phenomenon for low reinforcement ratios. For larger reinforcement ratio, when m/n increases above ~ 0.6 , there is no effect of cracking localization on the ultimate deflection. Moreover, in this range of r the values of d are ≥ 1.0 , as commonly expected for RFC structural elements. It is noted that the ultimate deflection of the beams corresponds to their flexural ductility.

1. Introduction

Concrete toughness may be increased by addition of fibres [1,2], which are expected to influence the cracking process and reduce crack width and spacing [3]. Hence, it is also expected that beams made of fibre-reinforced concrete with conventional reinforcement (RFC) will exhibit improved crack control, as well as increased structural ductility. However, there are studies that indicate that RFC beams showed reduced ductility when they included relatively low amounts of conventional reinforcement [4-6]. This phenomenon is caused by cracking localization, when under the ultimate load, one or only few cracks widen more than the other flexural cracks do. As a result of this widening, the part of the rebars, bridging the crack, is significantly strained and this leads to a relatively short plastic hinge in these beams.

A similar phenomenon of cracking localization was observed in experimental studies of RFC bars under axial tension for both normal [7, 8] and high [7, 9,10] strength concretes. The experiments show that the localization caused by a given amount of fibers is more pronounced for low conventional reinforcement ratios [8]. Furthermore, the results show that for a given conventional reinforcement



ratio, cracking localization is more significant for larger amounts of fiber content (and vice versa) [11, 12]. Note that the specimens in these experiments had a single, centrally-located rebar.

In order to explain this phenomenon a probabilistic model for tensile RFC bars has been introduced [13] and verified [8, 14] by the authors. Findings of these experimental and theoretical studies, which refer to axially loaded elements, can be applied in flexural elements, by considering this element as the tensile zone of a beam. However, this application cannot be done directly because of the differences between the tensile bar and tensile zone of a flexural element, such as the non-uniform strain distribution along the cross-section and the non-central location of the rebars.

This paper presents an additional analysis of the results [5], with regards to quantification of cracking localization.

2. General

The experimental program [5] included twenty five, four-point bending tests of fiber-reinforced concrete beam specimens with conventional deformed rebars. The specimens were normal strength concrete beams with cross-sections that were 240-mm width by 300-mm height and different amounts of conventional reinforcement and steel fibers. Each beam had a span of 3.2 m with 1.5 m between the two equal loads acting on it (the constant moment zone) and two 0.85-m shear spans. Figure 1 shows a scheme of the test setup. The tests were performed under manual displacement control till failure. Cracking was monitored during the test, before and after yielding of the longitudinal reinforcement.

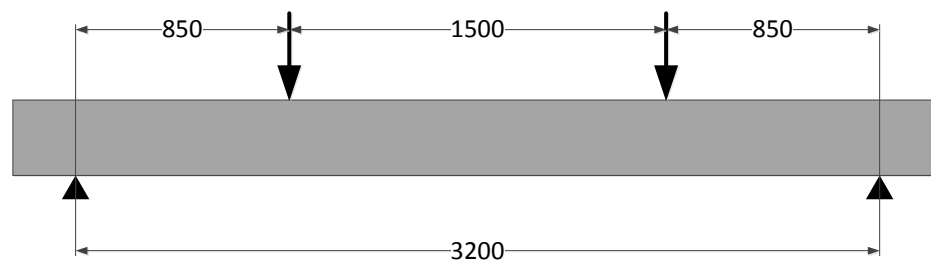


Figure 1. Scheme of the test setup (All dimensions are in mm).

Table 1. Details of the specimens.

Specimen type	No. of specimens	d_s (mm)	ρ_f (kg/m ³)	Longit. rebars	ρ (%)	$f_c^{\{1\}}$ (MPa)
NF-0-015	2	27	0	2 ϕ 8	0.15	29.8 (1.7)
40-015	2		40			30.9 (0.3)
NF-1-015	3		60			25.8 (1.0)
0-039	1	30	0	2 ϕ 8 + 2 ϕ 10	0.40	31.8 (0.6)
40-039	2		40			30.4 (0.4)
60-039	2		60			30.6 (0.2)
NF-0-063	1	33	0	2 ϕ 16	0.63	32.5 (0.4)
NF-1-063	3		60			25.4 (0.5)
0-094	1	33	0	3 ϕ 16	0.94	32.5 (0.4)
60-094	2		60			33.4 (0.5)
NF-0-126	1	33	0	4 ϕ 16	1.26	29.7 (1.0)
NF-1-126	2		60			26.7 (1.4)
NF-0-330	1	58	0	5 ϕ 22	3.27	26.5 (1.0)
NF-1-330	2		60			24.3 (0.9)

{1} Values in brackets denote standard deviations

The concrete mix was made of Portland cement type CEM I-52.5N with dolomite coarse aggregates (maximum size 19 mm), and natural quartz sand. The fibrous mixes included 35-mm long, hooked-end steel fibers with an aspect ratio of 64. The fibers content ρ_f was 40 and 60 kg/m³ (0.50 and 0.76% in volume). The longitudinal conventional reinforcement consisted of deformed rebars with different reinforcement ratios ρ , which varied from 0.15 to 3.3%. In addition, control specimens of each reinforcement ratio but without fibers, were also tested. Details of the specimen notations, their reinforcement and the effective cover d_s (distance from the bottom of the cross-section to the center of the longitudinal reinforcement) are given in Table 1. In addition, the table includes the average concrete uniaxial compressive strength f_c that were taken by 150-mm cubes (28 days wet cured).

3. Results – cracking localization

Load-deflection curves of the beams, which are presented in [5] show significant reduction of flexural ductility of RFC specimens with low amounts of conventional reinforcement. This phenomenon is more pronounced for larger amounts of fibers, as illustrated in Figure 2 for $\rho = 0.39\%$.

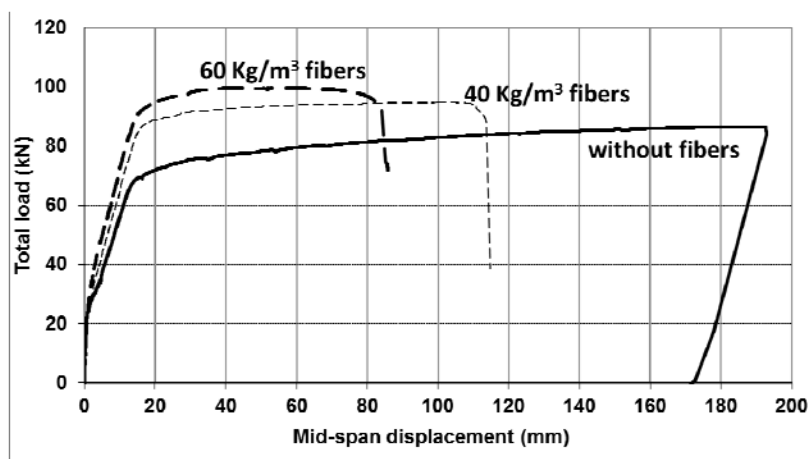


Figure 2. Reduction of flexural ductility in beam specimens with $\rho = 0.39\%$.

In order to quantify the cracking localization that leads to this phenomenon, the following further analysis of the test results has been performed.

The flexural cracks that developed within the constant moment zone (i.e., between the loading points, see Figure 1) during the tests, were counted for each of the specimens (Table 1). The average number \bar{n} for each type of specimen was taken into account in the analysis.

Post-test observation of the crack pattern shows that in the RFC beams with the lowest amount of conventional reinforcement (NF-1-015 and 40-015) only a single crack widened significantly compared with the other cracks. When ρ was increased, the number of significantly-wide cracks increased as well and for large reinforcement ratios no cracking localization was observed. Examples of cracked beams are shown in Figure 3.

For each specimen, the number of the significantly wide cracks was recorded after the test, and averaged for each type of specimen (these average numbers are denoted here as \bar{m}). The ratio $\bar{m}/\bar{n} \leq 1.0$ is a parameter that quantifies the level of cracking localization. Smaller values of \bar{m}/\bar{n} indicate more intensive cracking localization.

The results of the crack count in the RFC specimens, as well as the ratios \bar{m}/\bar{n} are listed in Table 2 and plotted versus the conventional reinforcement ratio ρ in Figure 4.



(a) Cracking localization (single wide crack) in specimen NF-1-015 ($\rho = 0.15\%$)



(b) No cracking localization in specimen NF-1-126 ($\rho = 1.26\%$)

Figure 3. Examples of post-test cracked RFC beams

Table 2. Results of the cracks count in the RFC specimens.

Specimen type	No. of specimens	n	m	m/n
40-015	2	11	1.5	0.14
NF-1-015	3	9.3	1	0.11
40-039	2	14	3.5	0.25
60-039	2	15.5	3.3	0.21
NF-1-063	3	12	7	0.58
60-094	2	12.5	8	0.64
NF-1-126	2	14.5	10	0.69
NF-1-330	2	12.8	12.5	0.98

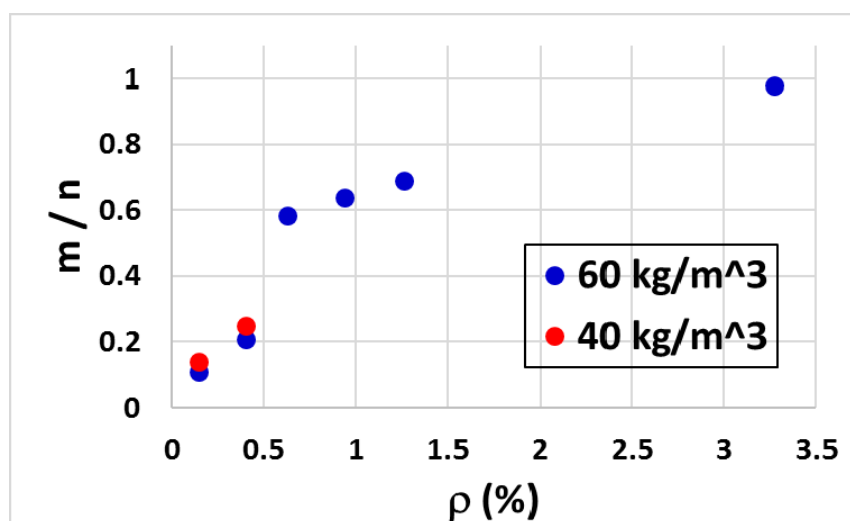


Figure 4. Cracking localization in RFC beams

It is evident from the figure that beams with larger reinforcement ratio had larger values of m/n , that is, lower cracking localization. For the concrete mix with 60 kg/m³ that was tested, when the reinforcement ratios were larger than ~2% cracking localization was diminished. Furthermore, for low values of ρ , m/n ratios of the 40-kg/m³ specimens are somewhat larger than those of the 60-kg/m³ specimens. This result conforms to the trend, according to which no cracking localization is expected in reinforced concrete beams without fibers.

Figure 5 shows the mid-span ultimate deflections δ of the RFC beams, normalized with the ultimate deflections of the corresponding beams without fibers (the values of the deflections are reported in [5]).

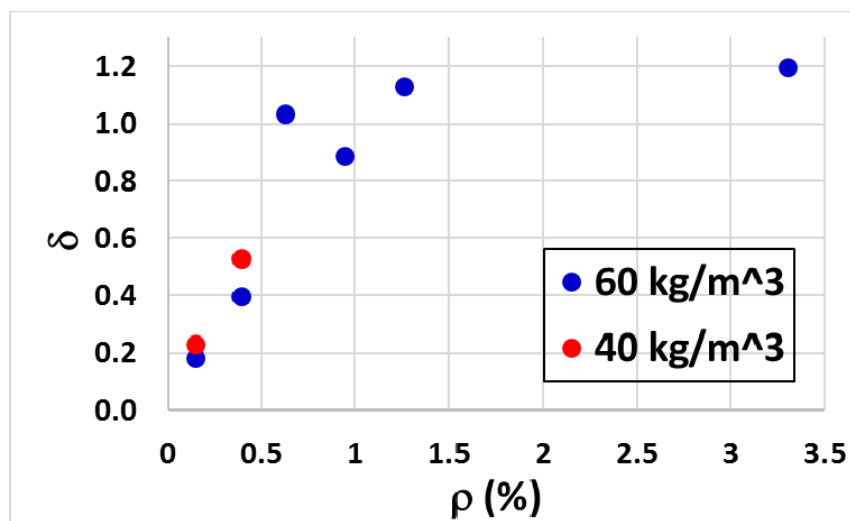


Figure 5. Normalized mid-span ultimate deflections δ of the RFC beams

It can be seen that as the reinforcement ratio decreases below ~0.5% the normalized mid-span ultimate deflections decreases as well. This result corresponds with the above observation of the cracking localization for low reinforcement ratios (see Figure 4). For larger reinforcement ratio, when m/n increases above ~0.6, there is no effect of cracking localization on the ultimate deflection. Moreover, in this range of ρ the values of δ are ≥ 1.0 , as commonly expected for RFC structural elements. It is noted that the ultimate deflection of the beams corresponds to their flexural ductility (e.g., [15]).

4. Conclusions

The paper presents an analysis of cracking localization in RFC beams, based on previously published experimental results. This experimental program included twenty five, four-point bending tests of fiber-reinforced concrete beam specimens with conventional deformed rebars. The cracking localization phenomenon has been quantified by the ratio m/n between the number of the significantly wide cracks and the total number of flexural cracks that developed within the constant moment zone of the beams.

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It is also shown that as the reinforcement ratio decreases below ~0.5% the normalized mid-span ultimate deflections decreases as well, which corresponds with the observation of the cracking localization phenomenon for low reinforcement ratios. For larger reinforcement ratio, when m/n

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