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Behaviour of FRC Beams with Different Combination of Fibers

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Abstract: The use of fibers in reinforced concrete (RC) beams mainly improves both the bearing capacity and the cracking control. In this way, positive effects on the service life of RC structures can be expected. In this paper, the fiber influence on the flexural behaviour of RC beams with different longitudinal reinforcement ratios (0.5% ≤ρs≤ 1.2%) is analyzed by testing small-scale RC beams. Concretes incorporating 0, 25 and 50 kg/m^3 of steel, 6 and 12 kg/m^3 of glass macro fibers, and 5 and 10 kg/m^3 of polymer macro fibers were studied. Crack and deflection control, as well as bearing capacity and crack localization were evaluated for a broad range of fiber-reinforced concrete (FRC) toughness. It is verified that fibers, in the longitudinal reinforcement ratio considered, improve the bending behaviour at serviceability limit state (SLS) and ultimate limit state (ULS) of RC beams, without limiting the structure ductility. It was also confirmed the philosophy of the fib Model Code 2010, such that FRC can be considered as a composite material where performance parameters govern its mechanical behaviour. Finally, the several data available allowed to deeply analyze fib Model Code 2010 formulations (mean crack spacing and flexural bearing capacity) and to propose modifications where needed.
Keywords: Crack spacing, cracking control, fiber-reinforced concrete, flexure, longitudinal reinforcement ratio

INTRODUCTION

The use of fiber-reinforced concrete (FRC) in beams with longitudinal conventional reinforcement (RC) improved reflection control,1–3 crack control4–9 shear resistance,10–13and in some cases flexural bearing capacity.3 To the contrary, FRC can provoke a crack localization (one flexural crack widen more than the other cracks do) after RC beam yielding that could reduce the element ductility.14–16Fibers transfer stresses across a crack leading to a more diffused crack pattern characterized by narrower and more closely spaced cracks,5,17 while in shear they also enhance the aggregate interlock mechanism. Thanks to this improved crack control, positive effects on the service life of RC structures are expected. Apart shear, the fiber influence is related to the weighted ratio between FRC post cracking performances and longitudinal reinforcement ratio (ρs = As/(bwd). The latter generally varies between 0.6 and 1.2% for RC beam ductility reasons, while a very broad range of FRC toughness is now available in the market. However, the majority of studies present in the literature about the flexural behaviour of RC beams deals with post cracking mechanical performances typical of steel fibers,1,3,7,9 since very few studies consider other fiber types.14,18 This underlines the need of studying FRC with different post cracking response as compared to steel fibers, in order to prove their effectiveness and evaluate code formulation accuracy. The fib Model Code 201019 introduced FRC as structural material, providing design rules to take into account fiber effects properly; this represented a great contribution for further applications of fibers combined with conventional bars. Although most studies from which the Code formulations were developed were mainly related to steel fibers, this Code assume FRC as a composite material where performance parameters govern its mechanical behaviour. In this way, as the effect of fibers is related to FRC toughness, regardless of fiber type and amount, different fibers can be considered (steel, polymer, glass, or others).A recent paper presents the results of the first part of this research where different contents of steel, glass, or polymer macro fibres were incorporated in RC beams with a typical value of longitudinal reinforcement ratio equal to 0.9%.14 In addition to the analysis of crack pattern and bearing capacity, the results were compared with the predictions of fib Model Code 2010.19

This study concluded that for the used testing conditions the effect of fibers on the flexural behaviour of RC beams is mainly related to FRC toughness (measured from the residual parametersfR1 and fR3), regardless of fiber type and amount. A significant reduction in crack spacing was mainly observed for high values of fR1, while the fiber contribution on the reduction of the post cracking deflection resulted note worthy for fR1 ≥ 3 MPa. For the used longitudinal reinforcementration and for the wide range of FRC toughness considered no reduction of RC beam ductility were seen, even if crack localization occurred after rebar yielding in the majority of FRC samples. When considering the fibModel Code 2010 approach, the mean crack spacing predictions seemed to be characterized by a progressive increasing underestimation for FRC toughness increase. Based on these encouragement conclusions and considering that further tests varying other principle variables should be necessary in order to improve the current fib Model Code 2010 prediction models, a second part of the research was performed. The influence of steel, glass, or polymer macrofibres on the crack pattern, the bearing capacity and the failure type of RC beams with longitudinal reinforcement ratios between 0.5% (value close to the lower bound adopted in practice) and 1.2% (upper bound generally adopted in practice) is discussed in this paper. The experimental results are compared with the mean crack spacing and the strength capacity predictions of fibModel Code 2010. The flexural bearing capacity formulation resulted reliable, while some modification are proposed for the mean crack spacing one, since it was observed that the model adopted by fib Model Code 2010to describe the post cracking strength in tension at serviceability limit state (SLS, fFts) seems not to be representative for mean crack spacing estimations.

RESEARCH SIGNIFICANCE

The present experimental program aims of clarifying the influence of a broad range of FRC toughness (considering steel, polymer and glass fibers in different amounts) on the flexural behaviour (especially cracking control, deflection control, and possible limitation of ductility due to crack localization) of RC beams characterized by values of longitudinal reinforcement ratio typically adopted in practice and of evaluating fib Model Code 2010 formulations. The influence of fibers different than steel ones is still not well-studied and it was not directly considered in the development of most fib Model Code 2010 equations. Results underlines that the effects of fibers is mainly related to their post cracking strengths (with linear relations between main parameters) and that the ductility reduction is not an issue. In addition, fib Model Code 2010formulation for mean crack spacing prediction was improved by proposing to use a residual tensile strength at crack opening equal to 0.15 mm (σ0.15) instead of fFts. This will allow designers to estimate with higher accuracy both mean crack spacing and crack width of FRC elements.

EXPERIMENTAL PROGRAM

The study was performed on seven types of concrete mixtures, a reference plain concrete (CONTROL) and six FRC, two incorporating 25 or 50 kg/m3 of hooked-end steel fibers 50 mm long and 1 mm diameter (S-25 andS-50), two adding 6 or 12 kg/m3 of 36mm long and0.54mm diameter crimped glass macro fibers (G-6and G-12) and two with 5 or 10 kg/m3 of 58mm long and0.67mm diameter embossed polymer macro fibers (P-5and P-10). Fiber type and amount were chosen in order to obtain a broad range of FRC toughness and to be coherent with the first part of this research.14 More details on fibers properties and post cracking performances can be found in Conforti et al.14All concretes were prepared from the same base concrete using Portland cement, natural siliceous sand,12 mm maximum size granitic crushed stone, and 0.41water/cement ratio. A high-range polycarboxilate-based super plasticizer was added in each concrete in order to obtain a slump of 60 ± 10 mm. Three RC beams (more details in Section 3.1), three standard beams (according to EN 1465120), and six100 × 200 mm cylinders were produced for each concrete (for a total of 42 RC beams). All specimens were cured in moist room for 28 days and then remain in laboratory in door up to testing. Testing ages were between 60 and 90 days in order to minimize the variation of concrete mechanical properties during the testing period (both standard beams and cylinders were tested at the same age of RC beams).

TABLE 1 Compressive and bending (EN14651) properties of concretes (CV in brackets)

Series	f_c (MPa)	f_L (MPa)	$f_{R,1}$ (MPa)	$f_{R,2}$ (MPa)	$f_{R,3}$ (MPa)	$f_{R,4}$ (MPa)
CONTROL	46.2 (0.04)	4.54 (0.07)	—	—	—	—
S-25	45.2 (0.02)	5.13 (0.03)	3.86 (0.21)	3.89 (0.26)	3.52 (0.27)	3.33 (0.29)
S-50	46.8 (0.01)	5.10 (0.08)	5.43 (0.16)	5.29 (0.08)	4.94 (0.06)	4.58 (0.05)
G-6	48.6 (0.01)	4.84 (0.03)	1.99 (0.19)	1.60 (0.17)	1.05 (0.16)	0.68 (0.20)
G-12	48.9 (0.02)	4.92 (0.05)	3.12 (0.14)	2.71 (0.15)	1.73 (0.12)	1.13 (0.10)
P-5	54.6 (0.02)	5.10 (0.07)	1.79 (0.07)	1.89 (0.13)	2.14 (0.09)	2.25 (0.08)
P-10	45.8 (0.04)	4.59 (0.04)	2.58 (0.07)	3.11 (0.17)	3.57 (0.16)	3.74 (0.17)

Table 1 presents the mechanical properties of each concrete: the mean values of the compressive strength(fc) from cylinders, and the nominal stress at limit of proportionality(fL) and the residual strengths at crack mouth opening displacement (CMOD) of 0.5, 1.5, 2.5,and 3.5 mm (fR,1, fR,2, fR,3 and fR,4) from standard beams.

20It can be observed that the compressive strength (48 MPa on average) and the post cracking residual strengths($1.8 \le f_{R,1} \le 5.4$ MPa and $1.0 \le f_{R,3} \le 4.9$ MPa) of different concretes are similar to the one adopted by Confortiet al..14 Therefore, the post cracking response of the different FRC in terms of nominal stress versus CMOD curves is analogous to the one previously showed. This allows in the following to directly compare the results of this research to those obtained in the former experience.

RESULTS AND DISCUSSION

All RC beams belong to series 0.5 and 1.2% showed a flexural failure characterized by steel yielding before the concrete in the compression zone reaches its maximum useable strain (under reinforced beams). As shown in Figure 2, where the load versus net mid-span deflection mean curves of series 0.5% (Figure 2a) and 1.2%(Figure 2b) are reported, the failure was reached after the three typical stage: an initial un cracked stage (up to the flexural cracking load, Pcr), a cracked stage (which includes crack formation and stabilized crack stage), and steel yielding stage. For both longitudinal reinforcementratios, the fiber influence was not observed neither on Pcrnor on the onset of stabilized crack stage. A clear fiber influence, which magnitude varies as a function of rebar amount and FRC toughness, was instead observed on crack width, crack spacing, deflection, maximum load and crack localization. Table 2 and Table 3 summarize the mean values (coefficient of variation CV in brackets)of the main experimental results in terms of:

- Flexural cracking load (Pcr)
- Net mid-span deflection at steel stress of 340 MPa, which corresponds to a load of 26 kN (δP26) and 55 kN(δP55) for series 0.5 and 1.2%, respectively;
- Maximum flexural crack width at steel stress of480 MPa, which corresponds to a load of 37 kN(wmax,P37) and 78 kN (wmax,P78) for series 0.5 and 1.2%,respectively;

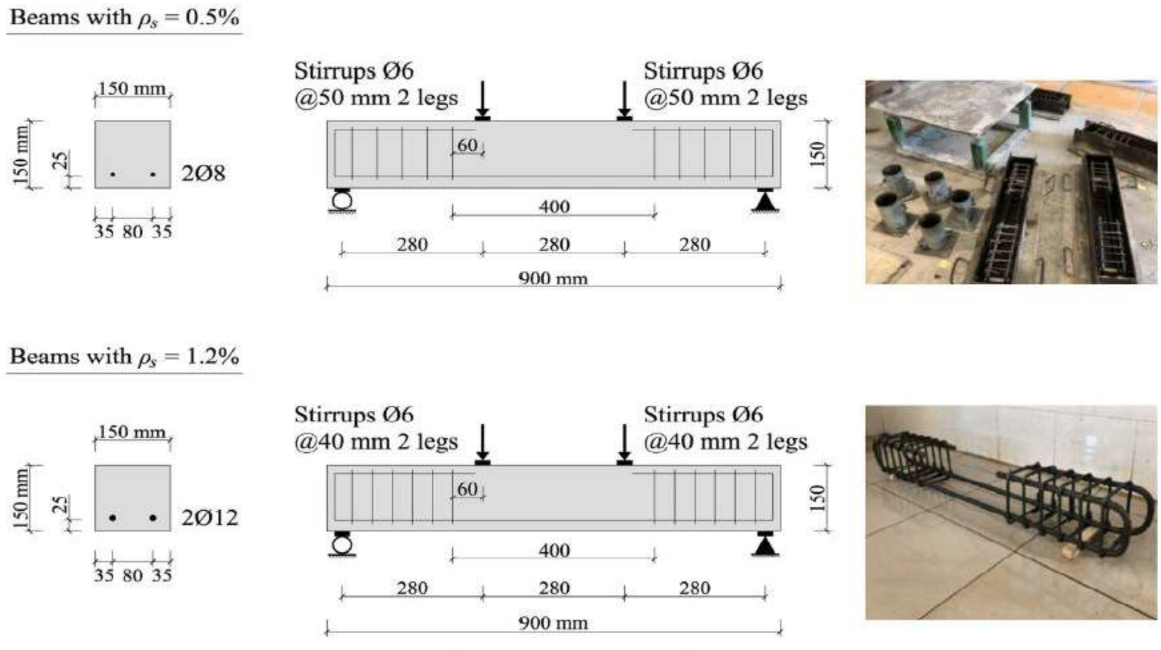

FIGURE 1 Geometry, reinforcement details and loading scheme of reinforced concrete beams with $\rho_s = 0.5\%$ and $\rho_s = 1.2\%$

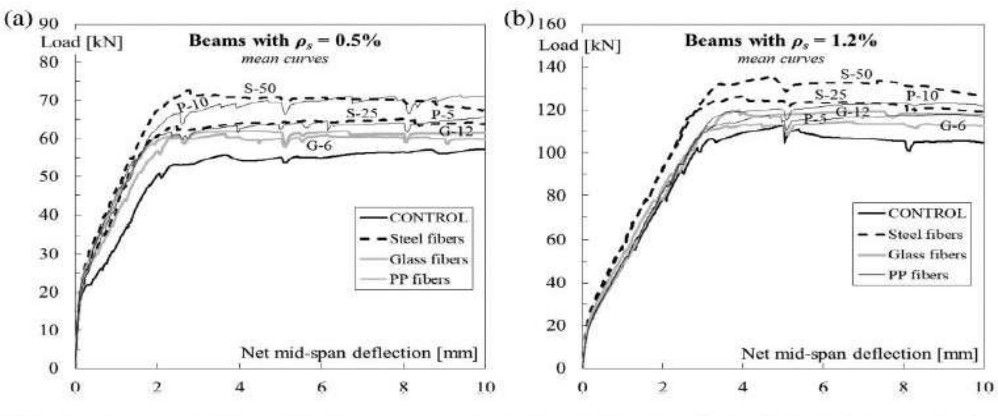

FIGURE 2 Load versus net mid-span deflection mean curves (up to 10 mm) of samples with longitudinal reinforcement ratios of 0.5% (a) and 1.2% (b)

TABLE 2 Experimental results of flexural tests on reinforced concrete beams with ρs = 0.5%

	P_{cr} (kN)	δ_{P26} (mm)	$w_{max,P37}$ (mm)	s_r (mm)	δ_{CL} (mm)	P_{max} (kN)	δ_u (mm)
CONTROL	16.9 (0.04)	0.61 (0.09)	0.20 (0.00)	118 (0.20)	— — —	58.2 (0.01)	20.6 (0.04)
S-25	16.7 (0.11)	0.33 (0.11)	0.15 (0.00)	85 (0.09)	2.0 2.5 —	65.5 (0.02)	21.2 (0.05)
S-50	16.5 (0.06)	0.24 (0.27)	0.10 (0.71)	76 (0.08)	2.8 3.0 3.1	74.6 (0.01)	19.8 (0.04)
G-6	15.9 (0.05)	0.38 (0.24)	0.18 (0.16)	104 (0.06)	— — 2.0	62.5 (0.03)	23.1 (0.10)
G-12	15.6 (0.03)	0.30 (0.11)	0.16 (0.09)	90 (0.11)	2.5 2.5 2.0	62.7 (0.01)	18.8 (0.11)
P-5	16.4 (0.03)	0.33 (0.04)	0.18 (0.20)	109 (0.02)	— — —	67.0 (0.01)	20.2 (0.02)
P-10	14.0 (0.16)	0.35 (0.17)	0.15 (0.00)	90 (0.15)	2.5 2.5 —	73.5 (0.04)	20.6 (0.02)

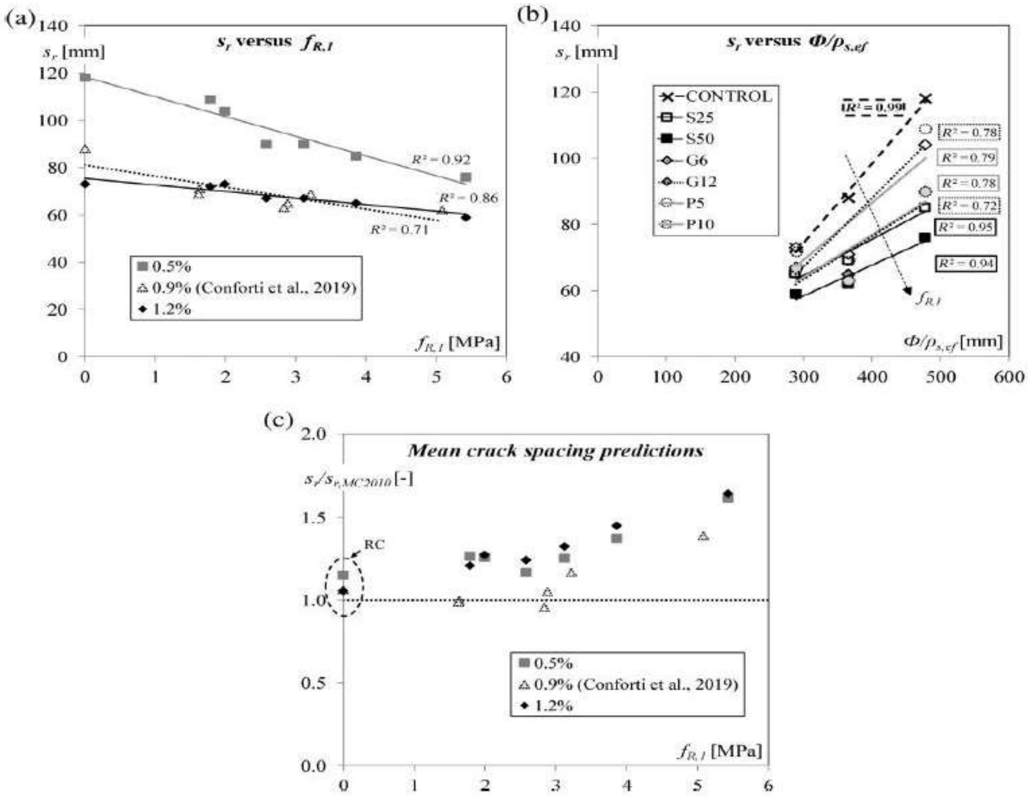

FIGURE 3 Influence of fiber reinforced concrete on mean crack spacing of reinforced concrete beams as a function of $f_{R,1}$ (a) and $\Phi/\rho_{s,ef}$ (b); crack spacing predictions of *fib* Model Code 2010 (c)

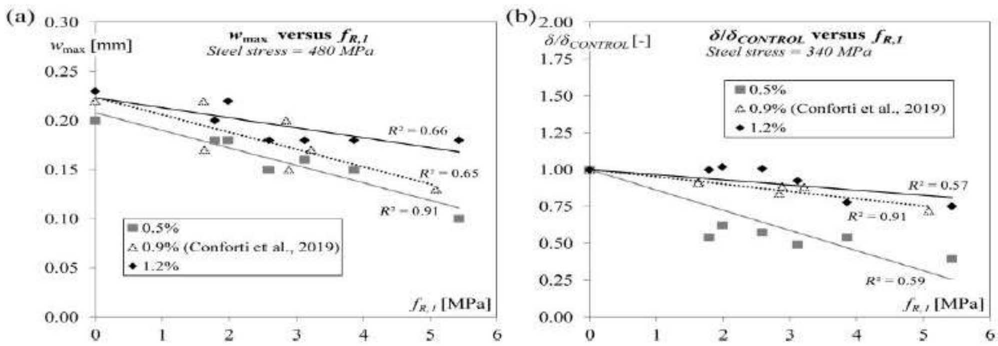

FIGURE 4 Influence of the residual strength $f_{R,1}$ on the maximum crack width (a) and postcracking deflection (b)

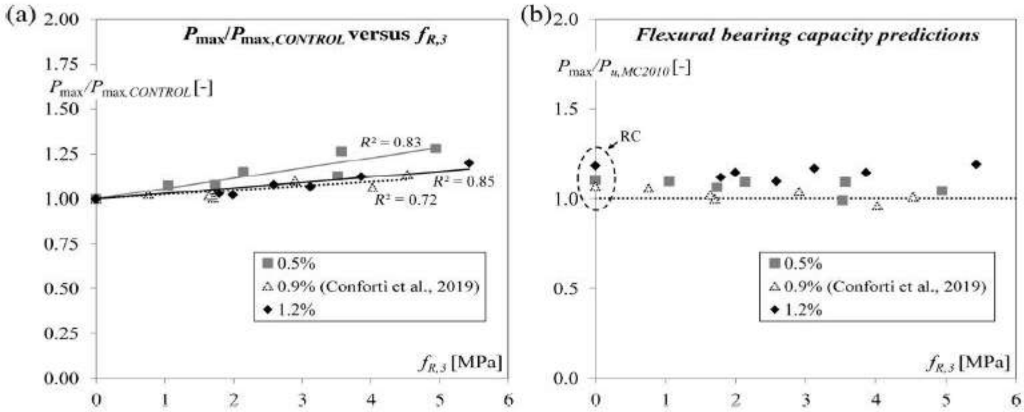

FIGURE 5 Influence of fiber reinforced concrete on the maximum bearing capacity of reinforced concrete beams (a) and flexural strength predictions of *fib* Model Code 2010 (b)

To better understand the different crack development in RC beams with and without fibers, Figure 6 shows the final crack pattern and crack width versus deflection curves of a CONTROL and a S-50 sample for ρs = 0.5% and ρs = 1.2%. The main aspects already underlined can be once again observed: clear reduction of crack spacing using steel fibers, especially in the case of ρs = 0.5%;reduction of crack spacing passing from ρs = 0.5% toρs = 1.2% (as already acknowledged in the literature,23);flexural collapse characterized by compression zone failure after rebar yielding and crack localization when fibers are present.

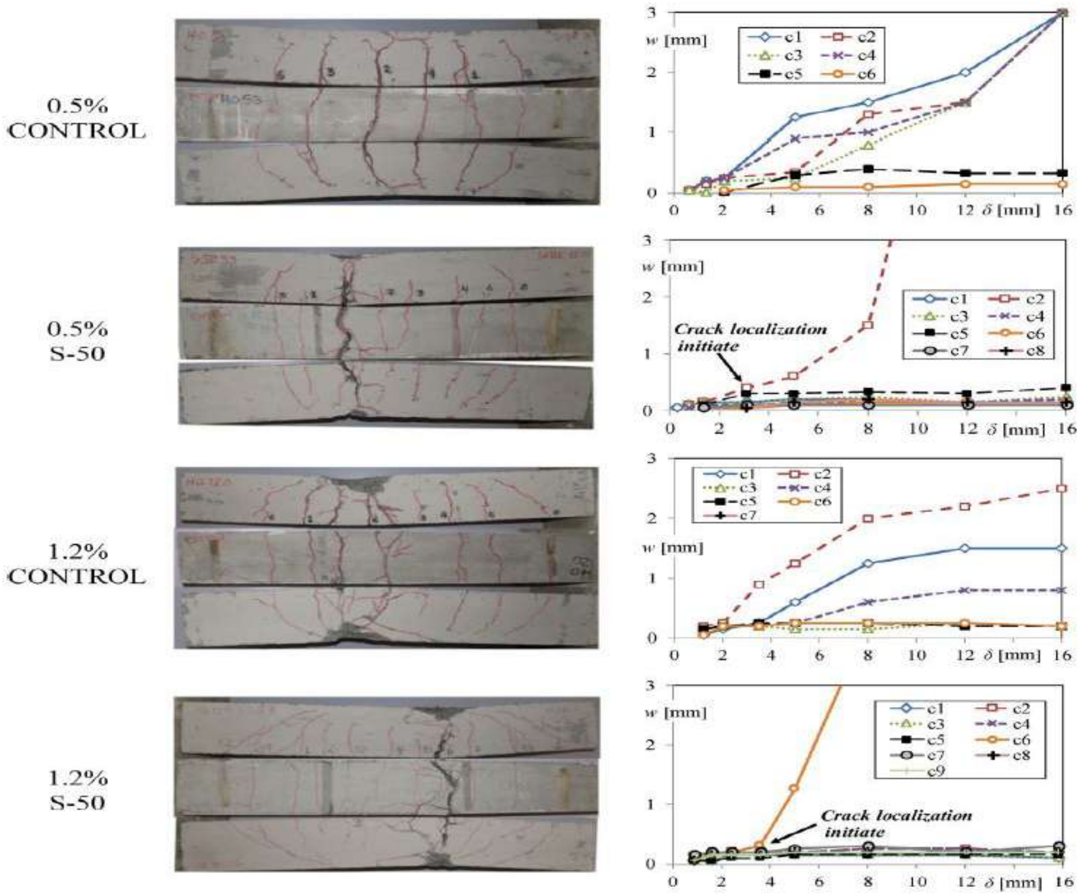

FIGURE 6 Crack development and final crack pattern of CONTROL and S-50 samples with ρ_s equal to 0.5 and 1.2%

The probability of occurrence of crack localization is summarized in Figure 7 as a function of longitudinal reinforcement ratio for each FRC; a clear relation between crack localization and FRC toughness cannot be established. It can be underlined that crack localization probability increases as FRC toughness increases and as longitudinal reinforcement ratio decreases. The probability of having crack localization is very high using high amount of steel or glass fibers. In addition, this figure shows that the crack localization probability is generally high using fibers, since it is greater than 50% in most of cases. Since the flexural behaviour of RC beams at ULS is not related only to the bearing capacity, it is important also to discuss the fiber influence on RC beam ductility, which could be affected by this crack localization. Defining the ductility in terms of displacement as the ratio between δu and the deflection at rebar yielding (δy) and given that δy is similar for any series, can be carried out. The ductility of RC beams isnot compromised for the typical values of longitudinal reinforcement adopted in practice (in particular for0.5% ≤ρs≤ 1.2% and FRC toughness characterized by fR3varying between 1 MPa and 4.9 MPa). However, crack localization leads to a maximum crack opening after rebar yielding greater in RC beams incorporating fibers than in the case of CONTROL beams, as shown in Figure 6.

CONCLUSION

The influence of FRC post cracking performances (1.8 ≤ fR,1 ≤ 5.4 MPa and 1.0 ≤ fR,3 ≤ 4.9 MPa) and longitudinal reinforcement ratio (0.5% ≤ρs≤ 1.2%) on the flexural behaviour of RC beams was evaluated by means of an experimental program on small-scale beams. Steel, polymer, and glass macrofibers in different amounts were studied. Based on these experimental results, the following conclusions can be drawn:

1. The relations between sr, wmax, δ and fR1 at SLS and between Pmax and fR3 at ULS remain mainly linear even varying the longitudinal reinforcement ratio, confirming the independence of these relations from fiber type.
2. The relation between sr and Ø/ρs,ef is still linear adding fibers. However, an increase of fR1 leads to a decrease of line slope. An increase of Ø/ρs,ef results in a higher crack spacing reduction due to fibers as well.
3. A reduction of maximum crack width is remarkable for values of fR1 greater than 2 MPa (up to 50, 40, and22% for ρs equal to 0.5, 0.9, and 1.2%, respectively).For fR1 < 2 MPa this reduction is lower than 10%.
4. For a longitudinal reinforcement ratio ranging between 0.9 to 1.2%, the deflection reduction at SLSis noteworthy only in the case of fR1 > 3–3.5 MPa (that is the case of steel fibers), while for ρs = 0.5%even lower values of fR1 are able to lead to a non negligible deflection reduction. Concerning ULS, the increase of flexural bearing capacity due to fiber is significant only for low longitudinal reinforcementratios (ρs around 0.5%).
5. Even if the probability of having crack localization increases as FRC residual strength increases and longitudinal reinforcement ratio decreases, a strong relation between crack localization and FRC toughness cannot be established. The probability of crack localization resulted very high in concretes incorporating50 kg/m3 of steel fibers and 12 kg/m3 of glass ones.
6. In the typical range of longitudinal reinforcement ratio adopted in practice for RC beams, fibers do not compromise the beam ductility due to crack localization. However, for a given longitudinal reinforcement ratio, a relation between crack localization and FRC toughness cannot be established. It can be only stated that crack localization probability increases as FRC toughness increases and as longitudinal reinforcement ratio decreases.
7. The fib Model Code 2010 formulation for bending moment resistance is reliable, while the one regarding mean crack spacing predictions is characterized by a progressive loss of accuracy by increasing fR1 (regardless longitudinal reinforcement ratio). This loss of accuracy is mainly due to parameter chosen by fibModel Code 2010 for describing fiber effect, that is, fFts. In fact, for a typical value of crack width at stabilized crack stage, fFts overestimates the residual tensile stress transfer across cracks by fibers. Based on this experimental program, a residual tensile strength at crack opening equal to 0.15 mm (σ0.15) was proposed to be used. However, further tests should be carried out in order to prove the reliability of this parameter by a broad and comprehensive experimental programand if needed, improve it again.

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