Shear behaviour of large and shallow fiber reinforced concrete beams

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Abstract

Steel fibers are very important in beams under shear loading, as evidenced from several scientific papers reported into the last decade journals. This paper reports some recent results of an experimental campaign on FRC beams under shear loading tested at the University of Brescia, focusing on the size effect issue and the shear behavior of shallow beams. With the first regard, nine full scale beams, having a height varying from 500 to 1500 mm, were tested to analyze steel fibers influence on size effect. Concerning the shallow beams, eight beams (all having depth of 250 mm) with two different widths, fiber content were tested for evaluating the shear response of typical structural members utilized in Southern Europe in residential buildings. Results show that a relatively low volume fraction of fibers can significantly increase shear bearing capacity and ductility. The size effect issue is substantially limited and it is observed that, with a fairly tough FRC composite, it is possible to completely eliminate this detrimental effect. Shallow beams do not show the typical brittle failure also without any shear reinforcement and the effect of fibers is even more prominent than in deep beams.

Keywords: Shear, Size effect, Full Scale Experimental, Shallow beams

1 Introduction

A significant change in the shear and punching shear provisions, included in the first draft of *fib* Model Code [1,2], referred to in the following as MC2010, which was officially presented during the fib Congress in Washington D.C., can be outlined. Four different approximation levels are proposed for designing shear members, incorporating statements and models well recognized such as Modified Compression Field Theory [3] and the variable truss angle theory. The equations have been defined with a basic structure that requires two significant parameters, namely the angle of inclination of the stress field, θ, and a coefficient for a concrete contribution k_v (more often referred as β). The MC2010 first draft provides three levels of approximation to calculate these terms with the first and third based on the MCFT and the second based on a strain-modified form of plasticity. As the level of approximation increases, the quality of the predictions improves, but with more complex calculations. Several reports published over the past 25 years [4,5,6] confirm the effectiveness of steel fibers as shear reinforcement. Fibers are used to enhance the shear capacity of concrete or to partially or totally replace stirrups in RC structural members. This relieves reinforcement congestion at critical sections such as beam-column junctions in seismic applications. Fiber reinforcement may also significantly reduce construction time and costs, especially in areas with high labour costs, and possibly even labour shortages, since stirrups involve relatively high labour input to bend and fix in place. Fiber concrete can also be easily deployed in thin or irregularly shaped sections, such as architectural panels, where it may be very difficult to place stirrups. This is of paramount significance for many secondary structural elements in which a minimum conventional reinforcement is not required for equilibrium. In this respect, nine experimental tests on full-scale SFRC beams (with a height up to 1.5 m) are firstly presented in this paper, which focus on the fiber's role in delaying shear crack localization, in mitigating the size effect and in allowing a stable crack development with associated load and ductility increases. Experimental results will be evaluated in terms of strength, ductility, shear cracking, collapse mechanism and effect of fibres. Secondly, further eight experiments on full-scale shallow beams will be briefly reported, aiming at investigating the shear behaviour of a very frequent structure in the residential buildings in Southern Europe, in which architectural needs require that beams have the same thickness of the floor (i.e. secondary floor beams and main beams should have the same depth).

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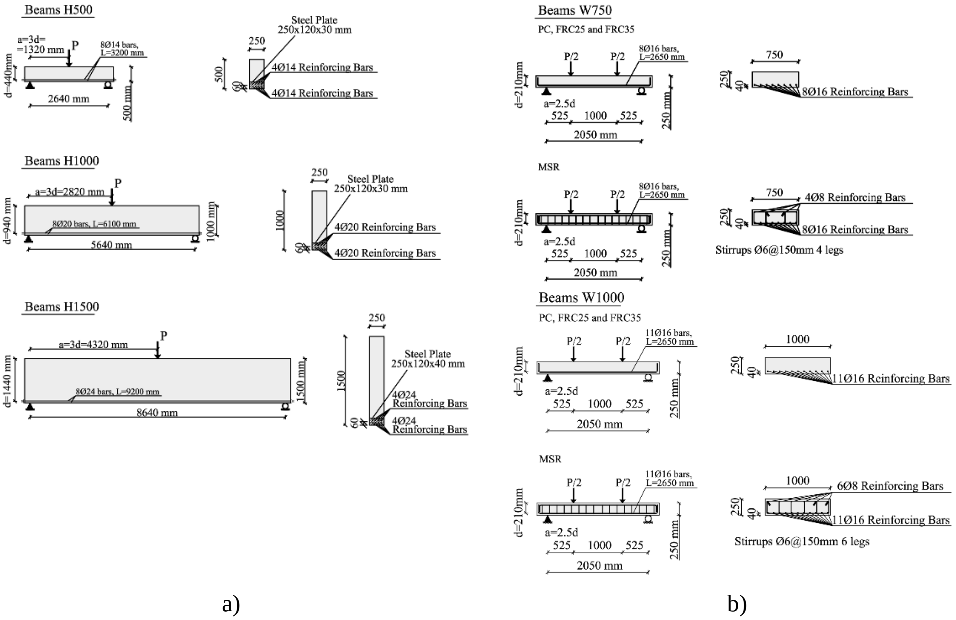
2 Experiments

All nine full-scale beams were tested under a three point loading system and a shear span-to-depth ratio a/d of 3. Beams were made with different amounts of steel fibers: 0, 50 and 75 kg/m^3 (corresponding to a volume fraction of 0, 0.64 and around 1%, respectively) and, for each fiber content, three beams with different depths were cast: 500 mm (beams H500), 1000 mm (beams H1000) and 1500 mm (beams H1500). All beams had the same width of 250 mm and gross cover (60 mm). Different effective depths were therefore obtained: 440, 940 and 1440 mm, respectively for specimens H500, H1000 and H1500.

In the case of shallow beams, all eight beams were tested under a four point loading system and a shear span-to-depth ratio a/d of 2.5. Beams were made with different amounts of steel fibers: 0, 25 (FRC25 samples) and 35 (FRC35 tests) kg/m^3 (corresponding to a volume fraction of 0, 0.32 and 0.45 respectively) and, for each fiber content, two beams with different widths were cast: 750 mm (series W750) and 1000 mm (beams W1000). Moreover, for each width, one beam with the minimum amount of transverse shear reinforcement as required by EC2 (2005) was also produced (4Ø6@150 mm stirrups for W750 MSR sample and 6Ø6@150 mm stirrups for W1000 MSR specimen). All beams had the same height of 250 mm and gross cover (40 mm), giving an effective depth of 210 mm.

Figure 1 illustrates the geometry of the specimens and the reinforcement details for all beams tested. In the case of deep beams, longitudinal reinforcement was positioned in two layers and the reinforcement ratio was approximately 1% for all test specimens. Eight longitudinal rebars having a diameter of 14, 20 and 24 mm were placed respectively in H500, H1000 and H1500 beams. For the wide shallow beams, the reinforcement ratio was again equal to 1%: 8Ø6 and 11Ø16, all disposed in one layer, were utilized respectively for series W750 and W1000.



a) b)

Fig. 1 Geometry and reinforcement details of deep (a) and shallow beams (b).

A normal strength concrete, provided by a concrete supplier, was utilized for all beams. In the case of deep beams, the mean value of the compressive strength was 38.7 MPa for PC series, 32.1 MPa for the FRC50 series and 33.1 MPa for the FRC75 set of tests. For the shallow beams, the mean value of the compressive strength was 40.5 MPa for PC and MSR series, 38.0 MPa for the FRC25 series and 36.9 MPa for the FRC35 set of tests.

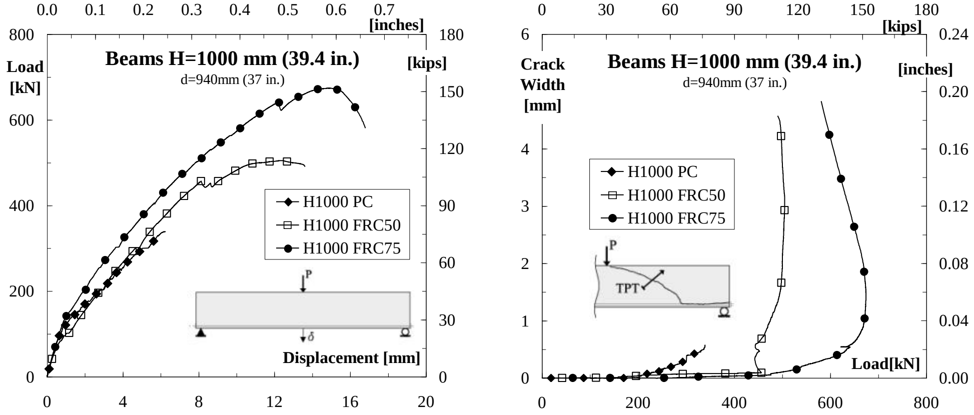
Hooked end steel fibers, having a length of 50 mm, a diameter of 0.8 mm (aspect ratio L/Ø of 62.5) and a tensile strength of 1100 MPa were adopted for all FRC samples. The yielding and ultimate tensile strength of the longitudinal rebars were: 510 MPa and 588 MPa for ϕ6 bars; 506 MPa and 599 MPa for ϕ14 bars; 537 MPa and 630 MPa for ϕ16 bars; 555 MPa and 651 MPa for ϕ20 bars and 518 MPa and 612 MPa for ϕ24 bars, typical for S500 steel according to the current EC2 (2005).

Concerning the test setup, an electro-mechanical screw jack with a loading capacity of 1500 KN for all specimens was utilized. A displacement-controlled test was therefore guaranteed, allowing for a suitable test control during critical steps such as in the case of abrupt cracking phenomena or load drops.

With regard to the instrumentation, linear Variable Differential Transformers (LVDTs) were utilized for measuring deflections at midspan (front and back side) and support displacements. Also, potentiometric transducers were employed for measuring crack widths and strut shortening.

3 Experimental results on deep beams

The experimental results, reported in Figure 2 and Figure 3, represent the midspan-displacement and the shear-crack-width development as a function of the external load for H1000 and H1500 series. A shear failure was seen for all nine elements. However, in both the FRC shallowest beams (H=500 mm), the maximum flexure load was reached, with clear yielding of longitudinal rebar and a rather significant ductility for beam H500 FRC50.

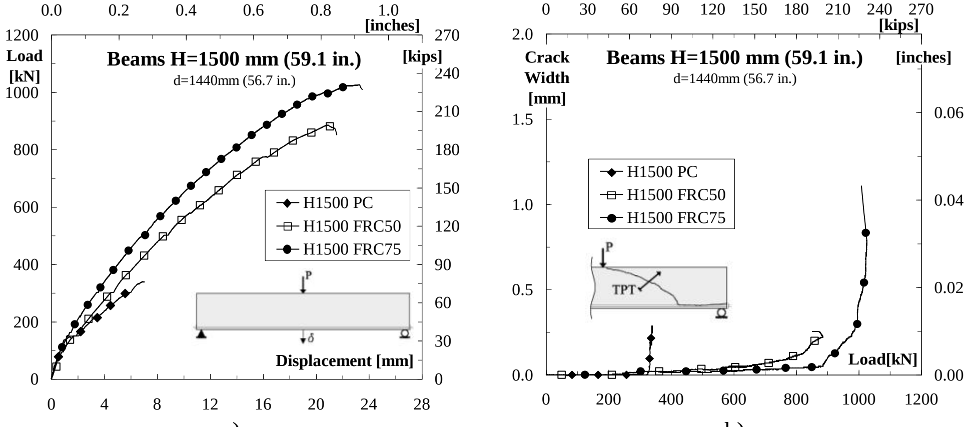


a) b)

Fig. 2 Experimental curves load vs. deformation (a) and main shear-crack-width vs. load (b) of H1000 beams.

Especially from both H1000 and H1500 test series, a significant enhanced post-cracking stiffness is observed for FRC beams, due to stiffening effect, in tension, which is due to the bridging effect of fibers (residual tensile stress at a crack) and to the smaller crack spacing, both in flexure and in shear. With increasing depth, the difference between the two fiber contents tends to become higher, i.e. the lowest content of fibers has less positive impact in diminishing the scale effect.

The addition of fibers promoted a stable propagation and progressive development of several shear cracks, which led to a more ductile behaviour with vertical deflections 2-3 times greater than those recorded in the reference plain concrete beams, as clearly evidenced by the experimental plots. Concerning shear cracking, Figure 3 b) reports the crack development vs. the load, for the H1500 series: note that the crack width evolution is better controlled in FRC: in particular, evident shear cracking begins at 320 kN for the reference sample, whereas it occurs at 570 kN and 890 kN for the FRC50 and FRC75 beams, respectively. While the plain concrete member fails at the emergence of the first shear crack, with a maximum shear crack width of 0.2-0.25 mm, multi-cracking (in shear) was seen for the FRC samples, with single shear crack wider than 1-2 mm and, even more important, still steadily propagating. The same trend can be seen for sample H1000 (Figure 2 b).



a) b)

Fig. 3 Experimental curves load vs. deformation (a) and main shear-crack-width vs. load (b) of H1500 beams.

Figure 4 depicts the final crack patterns of specimens H1000 and H1500, with the indication of the progression (see different load levels in the pictures). Note, once again, a much more distributed crack pattern for FRC samples. For the same load level, both flexure and shear crack are fairly different in the three materials: for low loads, the crack pattern is much more developed in the reference elements and the cracking phenomenon tends then to quickly stabilize. On the contrary, in FRC samples, the cracking process, after a quite postponed appearance, becomes more dynamic so that it is quite difficult to properly define a stabilized crack stage: a more distributed crack patter forms, with narrower closely spaced cracks (this aspect is quite significant under a durability point of view). Moreover, the development of new cracks continues up to the failure.

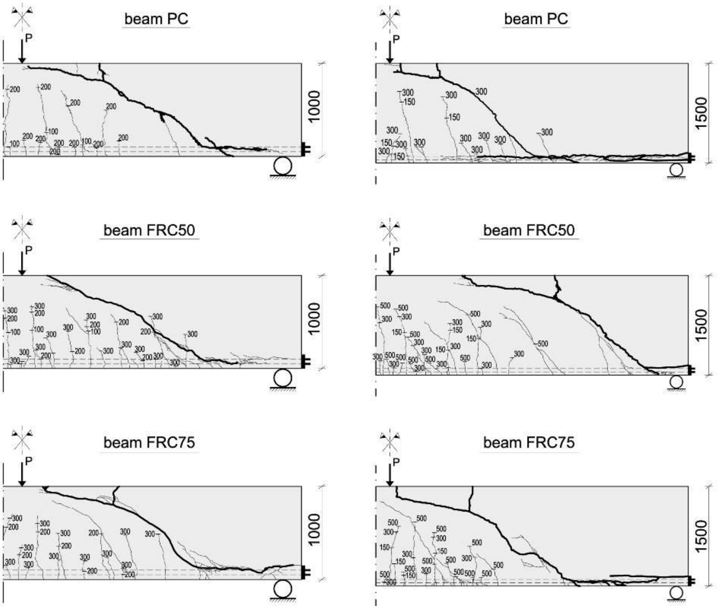
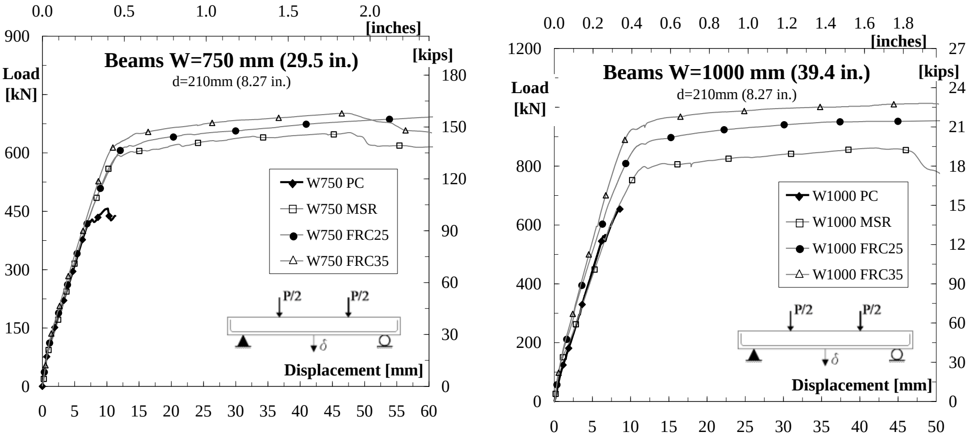


Fig. 4 Crack evolution for specimens H1000 and H1500 (loads in kN).

4 Experimental results on wide shallow beams

Figure 5 reports the load-displacement curves for all eight shallow beams: a shear failure was seen only for plain concrete members. All members containing either fibers or the minimum amount of transverse reinforcement reached the maximum flexure load, with clear yielding of longitudinal rebar and a significant ductility.



a) b)

Fig. 5 Load-displacement curves for W750 (a) and W1000 specimens (b).

Table 1 Main experimental results about deep and shallow beams.

Specimen	Type of failure	$V_{u,exp}$ [kN]	v_u [MPa]	$v_u/(f_{cm})^{1/2}$ [-]	$M_{u,fl}$ [kNm]	$M_u/M_{u,fl}$ [-]	δ_u [mm]
H500-PC	Shear	116	1.05	0.17	254	0.60	3.70
H500-FRC50	Shear*	240	2.18	0.38	285	1.11	34.95
H500-FRC75	Shear*	235	2.13	0.37	293	1.06	9.14
H1000-PC	Shear	188	0.80	0.13	1210	0.44	6.26
H1000-FRC50	Shear	272	1.16	0.20	1325	0.58	13.61
H1000-FRC75	Shear	351	1.49	0.26	1356	0.73	16.78
H1500-PC	Shear	211	0.59	0.09	2511	0.36	7.03
H1500-FRC50	Shear	484	1.34	0.24	2791	0.75	21.58
H1500-FRC75	Shear	554	1.54	0.27	2864	0.84	23.46
W750 PC	Shear	237	1.50	0.24	169	0.74	11.37
W750 MSR	Flexure	335	2.12	0.33	169	1.04	61.28
W750 FRC25	Flexure	355	2.25	0.35	186	1.00	85.39
W750 FRC35	Flexure	360	2.28	0.36	189	1.00	97.03
W1000 PC	Shear	337	1.60	0.25	232	0.76	8.62
W1000 MSR	Flexure	441	2.10	0.33	232	1.00	51.64
W1000 FRC25	Flexure	488	2.32	0.37	262	1.00	80.93
W1000 FRC35	Flexure	517	2.46	0.39	266	0.97	89.20

* Shear failure mode took place, but maximum flexure load was reached.

Fibers were also able to increase the overall ductility under flexure, thanks to the positive effect in increasing the compression softening. The post-cracking stiffness was also higher. Moreover, 25 kg/m^3 of fibers were able to completely substitute the minimum amount of transverse reinforcement in shallow beams. It results that either a minimum transverse reinforcement or a low content of fibers, in the case of shallow beams with a classical reinforcing ratio (around 1%), is able to bring the member up to a ductile flexure failure.

Looking at the cracking phenomenon, the collapse, as one would have expected, did not appear immediately after the first shear crack: two different shear cracks formed in the front and rear side and developed in a quite stable fashion, without connecting one to the other trough the width of the element. Clearly, the different behaviour at front and back side allowed for a more stable response of the member (the stress field, due to the significant width, is far to be simply 2D). Also, the height of these beams is very small, and in addition the central core of the beam results well confined by the surrounding concrete: this determines an extra resisting mechanism in shear. This is a peculiar behavior that deserves a number of thoughts for its comprehension and, eventually, for the definition of suitable design implications.

In conclusion, Table 1 reports, for all seventeen samples tested, the failure mode, the experimental shear capacity, the nominal shear stress and the ratio between the ultimate experimental moment, M_u, and the maximum flexural capacity of the member, $M_{u,fl}$ (the latter evaluated according to MC10 in the case of the FRC samples). One should note the strong size effect in plain concrete members, whereas a significant decay con be outlined in the case of FRC. Note, once again, the beneficial effects of fibers in moving the collapse mode from brittle to ductile in the case of shallow beams.

5 Concluding remark

In the present paper, the beneficial effects of providing steel fibers as spread shear reinforcement have been scrutinized. Fibers, even in relatively low amount, greatly influence the shear behaviour of beams, basically by delaying the occurrence of the shear failure mechanism and, eventually, by altering the collapse from shear to flexure, with enhanced bearing capacity and ductility. Fibers allow, if supplied in sufficient quantity, a well distributed crack pattern in the critical area under shear, delaying or even avoiding the formation of the single critical shear crack, which brings the member to a brittle failure. If this happens, it is associated with visible warning, cracking and deflections, unlike for plain concrete members. Steel fibers mitigate the size effect issue in shear, even if provided in relatively low amounts. Moreover, fibers might substitute the minimum shear reinforcement in shallow beams, typical structural typology, in Southern Europe, for residential buildings.

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References

[1] *fib* Bulletin 55, Model Code 2010 – First complete draft, Volume 1 (chapters 1-6), 318 pages, 2010, ISBN 978-2-88394-95-6

[2] *fib* Bulletin 56, Model Code 2010 – First complete draft, Volume 2 (chapters 7-10), 312 pages, 2010, ISBN 978-2-88394-096-3

[3] Vecchio, F.J. and Collins, M.P. (1986) “The Modified Compression Field Theory for Reinforced Concrete Elements Subjected to Shear,” ACI Journal, 83(2) pp. 219 231.

[4] Choi, K-K., Park, H-G., and Wight, J. (2007) “Shear Strength of Steel Fiber-Reinforced Concrete Beams without Web Reinforcement”, ACI Structural Journal, V. 104, No 1, pp. 12-22.

[5] Dinh, H. H., Parra-Montesinos, G.J., and Wight, J. (2010) “Shear Behavior of Steel Fiber-Reinforced Concrete Beams without Stirrup Reinforcement”, ACI Structural Journal, V. 107, No 5, pp. 597-606.

[6] Minelli, F. (2005) “Plain and Fiber Reinforced Concrete Beams under Shear Loading: Structural Behavior and Design Aspects”, Ph.D. Thesis, Department of Civil Engineering, University of Brescia, February 2005, pp. 422.