

## REINFORCED CONCRETE UNDER CYCLIC LOADING

Joaquim A O BARROS<sup>1</sup>, José M S CRUZ<sup>2</sup>, Raimundo M DELGADO<sup>3</sup> And Aníbal G COSTA<sup>4</sup>

### SUMMARY

In order to contribute to the on going research effort in this field, an experimental working plan with cylinder steel fibre reinforced concrete specimens under compression cyclic loading was carried out. Sets of five specimens were reinforced with conventional transverse reinforcement of 0, 0.57, 1.71 and 4.01 volume percentage of specimen concrete core. To evaluate the fibre reinforcement effect, each of this specimens set was reinforced with 0, 30, 60 and 90 kg/m<sup>3</sup> of hooked-ends steel fibres with an aspect-ratio of 60 and a yield strength of 1250 MPa. A total of eighty tests were carried out.

The peak stress and the initial elasticity modulus were not significantly changed by fibre reinforcement. The strain at peak stress and the rigidity of the unloading/reloading branches were marginally increased with the increment of the fibre content. The slope of the softening branch was decreased with the increment of fibre content, revealing a significant increase in the energy absorption capacity. The results have pointed out that conventional transverse reinforcement can be partially replaced by appropriate fibre content, without loss of ductility and strength. This replacement could be favorable in zones densely reinforced with hoops and stirrups, like beam-column joints of structures submitted to seismic action.

### INTRODUCTION

The results obtained in the uniaxial compression tests with steel fibre reinforced concrete (SFRC) have revealed that the increment of fibre content provides a slight increase in the compression strength, stiffness and strain at peak load, and a substantial increase in the post-peak energy absorption capacity [Fanella and Naaman 1985, Otter and Naaman 1986, Ezeldin and Balaguru 1993, Mansur et al. 1997]. The magnitude of these material enhancements depends on the matrix properties, on the fibre type and content, on the type of loading (static, cyclic or dynamic) and on the strain rates used. For static monotonic loading, the aforementioned properties were already well studied [Barros 1995, Barros and Figueiras 1999]. However, the post peak behaviour of SFRC under compressible cyclic loading deserves an extra research effort, since the energy absorption capacity after peak load is the main property benefited by fibre reinforcement. This extra energy can be used to enhance the ductility of the reinforced concrete members, mainly the ductility of the columns under dynamic loading, which increases the safety of the concrete structures.

When well disposed, the conventional reinforcement of columns increases significantly the strength, the strain at peak stress and the ductility after peak load [Scott et al 1981, Mander et al. 1988, Nicolo et al. 1997]. For percentage of fibres used in practice, the confinement provided by the conventional transverse reinforcement (hoops, spirals or stirrups) and longitudinal reinforcement on column members can not be totally assured by steel fibres. However, the energy absorption capacity provided by fibre reinforcement should not be neglected, since it can increase the ductility after peak load of the column members [Masur et al. 1997, Ganesan and Murthy 1990], or replace partially the conventional transverse reinforcement.

To evaluate the effect of the fibre reinforcement on the compressible behaviour of reinforced concrete columns elements, sets of cylinder specimens reinforced with four content of fibres and four percentage of hoops were tested under cyclic loading. The influence of the fibres and transverse reinforcement on the peak stress, on the

<sup>1</sup> Assistant Professor

<sup>2</sup> Assistant

<sup>3</sup> Full Professor

<sup>4</sup> Assistant Professor

strain at peak stress, on the initial elasticity modulus, on the shape of the softening branch, on the energy absorption capacity and on the rigidity of the unloading/reloading branches is discussed in the present work.

**EXPERIMENTAL PROGRAM**

**Materials and mixtures**

The concrete mix composition is included in table 1. More details about the mix composition and the mixing procedures can be found elsewhere [Sena Cruz 1998]. Table 2 includes the main properties of the steel rods used for longitudinal and transverse reinforcement of cylinder specimens.

Table 1 – Concrete composition

Element	Content (kg/m <sup>3</sup> of concrete)
Cement	450
Sand (0-5 mm)	729
Coarse aggregates (5-15)	1000
Water	202.5
Fibres	0, 30, 60, 90

Table 2 – Main properties of the steel rods used for the longitudinal and transverse reinforcement

Steel rods	Yield strain (%)	Strain at rupture (%)	Yield stress (MPa)	Maximum stress (MPa)
φ6	0.2	12	690	740

In this work it was used hookd-ends steel fibres with the trademark Dramix ZP30/.50 [Bekaert 1991]. These fibres have a yield strength of 1250 MPa, 30 mm length and 0.5 mm diameter, with a fibre aspect ratio of  $l_f/d_f = 30 / 0.5 = 60$ . They are glued together side by side into bundles of about 30 fibres with a water solvable glue in order to perform better in fresh concrete, improving the mix workability and eliminating balling [ACI 544.1R 1996].

**Specimens**

The cylinder specimens of 150 mm diameter and 300 mm height were reinforced longitudinally with six steel rods of six mm diameter and with four different ratios of transverse reinforcement, in order to provide distinct levels of confinement (see Figure 1a). Table 3 includes the spacing between the hoops for the series of tests and the corresponding transverse reinforcement ratio,  $\rho_w$ , which is the ratio of the total volume of transverse reinforcement to volume of concrete core measured to outside of the perimeter hoop (see Figure 1a). Figure 1b shows the terminology adopted to represent each series of tests. For instance, C270\_60 is the series of specimens with hoops with 270 mm of spacing between hoops and including 60 kg/m<sup>3</sup> of fibres. Each series is composed by five specimens. Table 3 includes the series tested. The variables  $W_f$  and  $V_f$  represent the fibre percentage in weight and in volume of concrete.

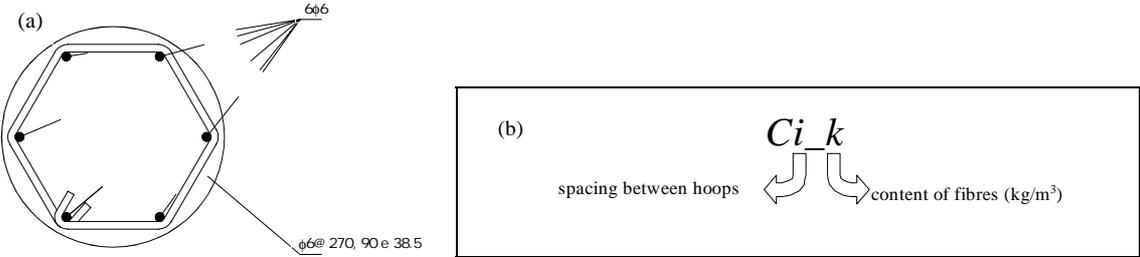


Figure 1 – cylinder specimen (a); terminology adopted to represent each series (b)

Table 3 – Series tested

Series	Spacing between hoops	$\rho_w$ (%)	Content of fibres (kg/m <sup>3</sup> )	$W_r$ (%)	$V_f$ (%)
C00_00	-	0.00	0	0.00	0.00
C00_30	-	0.00	30	1.25	0.38
C00_60	-	0.00	60	2.50	0.76
C00_90	-	0.00	90	3.75	1.15
C270_00	270.0	0.57	0	0.00	0.00
C270_30	270.0	0.57	30	1.25	0.38
C270_60	270.0	0.57	60	2.50	0.76
C270_90	270.0	0.57	90	3.75	1.15
C90_00	90.0	1.71	0	0.00	0.00
C90_30	90.0	1.71	30	1.25	0.38
C90_60	90.0	1.71	60	2.50	0.76
C90_90	90.0	1.71	90	3.75	1.15
C38_00	38.5	4.01	0	0.00	0.00
C38_30	38.5	4.01	30	1.25	0.38
C38_60	38.5	4.01	60	2.50	0.76
C38_90	38.5	4.01	90	3.75	1.15

### Equipment and test procedures

The tests were carried out with a closed-loop servo-controlled MTS testing system of series 315, with a maximum load bearing capacity of 2700 kN. The tests were performed using displacement control, with a displacement ratio of 20  $\mu\text{m/s}$  ( $6.67 \times 10^{-5}/\text{s}$ ). Each series was composed of four cyclic tests and one monotonic test.

## RESULTS

### Main aspects observed during the tests

In all tests, vertical cracks have arisen when the load was closely to the specimen load bearing capacity. This phase was followed by the failure of the concrete cover, more pronounced on specimens with high percentage of transverse reinforcement. The buckling of the longitudinal rods has occurred during the softening branch of the stress-strain relationship. The buckling length was about the spacing between the hoops. The rupture of some hoops was accompanied by the buckling of the longitudinal rods. The damaged zone, where it was occurred the failure of concrete cover, the buckling of the longitudinal rods and the failure of the hoops, was preferentially localised on the specimen top third, due to the restrain conditions imposed by the machine platens and the specimen manufacture procedure (higher compacity and percentage of fibres on the specimen bottom part). The upper load platen allows rotational movement while the lower load platen is fixed. Some of these aspects can be observed on the failure modes of series reinforced with 30 kg/m<sup>3</sup> of fibres, shown on Figures 2 to 5.



Figure 2 – Failure mode of series C00\_30



Figure 3 – Failure mode of series C270\_30



Figure 4 – Failure mode of series *C90\_30*



Figure 5 – Failure mode of series *C38\_30*

### Stress-strain diagrams

In each series of tests it was observed that the stress-strain ( $\sigma$ - $\epsilon$ ) relationship obtained in specimen submitted to monotonic loading is the enveloping diagram of the  $\sigma$ - $\epsilon$  relationship registered in the specimens under cyclic loading. The representative behaviour of each series of tests is depicted in Figures 6 to 9.

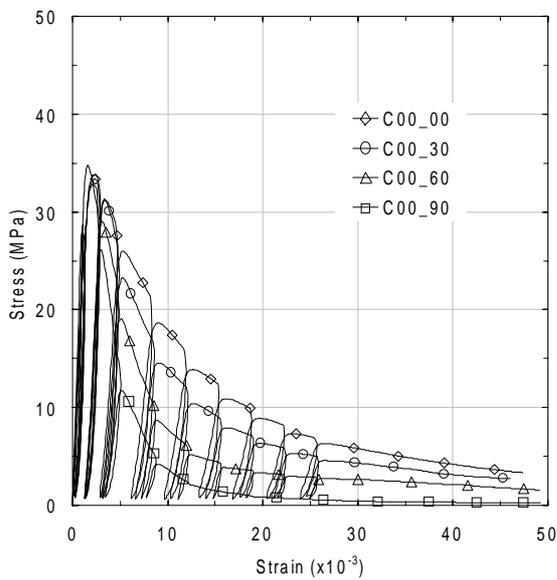


Figure 6 -  $\sigma$ - $\epsilon$  relationship for  $\rho_w = 0.00\%$

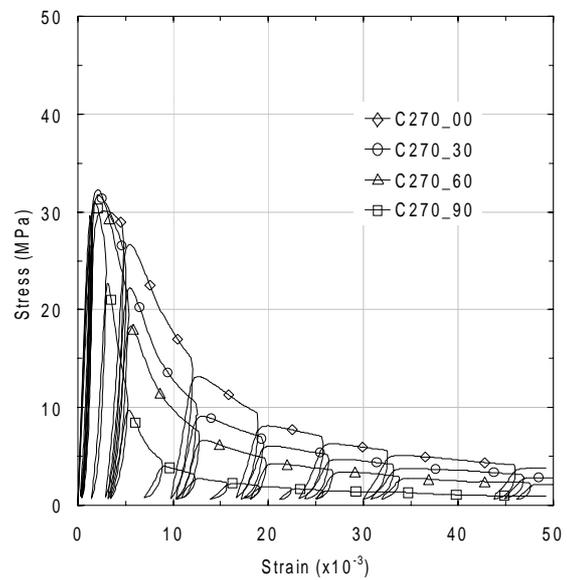


Figure 7 -  $\sigma$ - $\epsilon$  relationship for  $\rho_w = 0.57\%$

From the results it can be pointed out the following main aspects:

- The peak stress and the corresponding strain increase with the increment of the transverse reinforcement ratio;
- The increment of the peak stress and the corresponding strain with the fibre content is marginal;
- Increasing the transverse reinforcement ratio and the content of fibres,  $Q_f$ , the shape of the softening branch is smoothest;
- The energy absorption capacity increases with the increment of transverse reinforcement ratio and content of fibres.

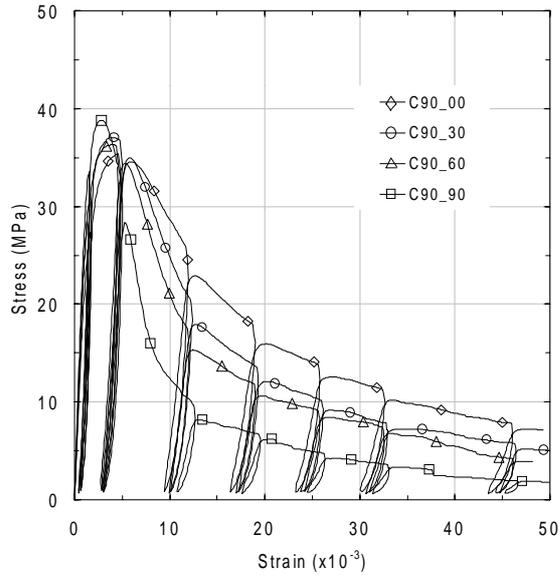


Figure 8 -  $\sigma$ - $\epsilon$  relationship for  $\rho_w = 1.71\%$

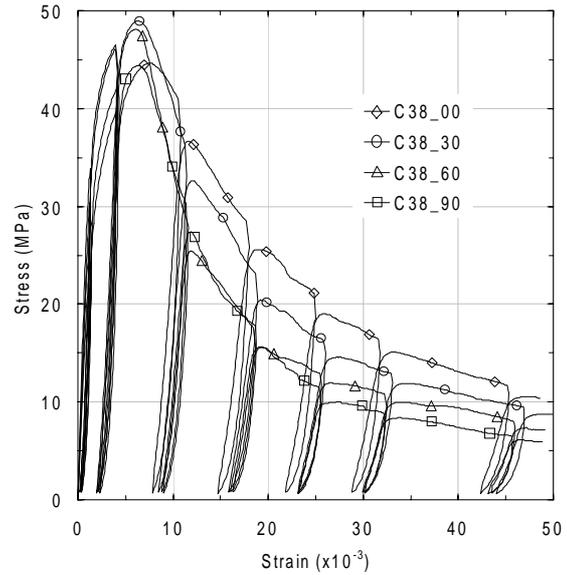


Figure 9 -  $\sigma$ - $\epsilon$  relationship for  $\rho_w = 4.01\%$

### Peak stress, strain at peak stress and elasticity modulus

From the results obtained it was verified a marginal increase in the strain at peak stress with the increment of fibre content. A much more significant increase in the strain at peak stress was observed with the increment of the transverse reinforcement ratio,  $\rho_w$ . For a constant  $\rho_w$ , the peak stress is almost the same for the content of fibres used. However, the peak stress has increased considerably with the increment of  $\rho_w$ . The initial elasticity modulus [CEB-FIP 1990] was practically insensible to  $Q_f$  and  $\rho_w$ .

### Energy absorption capacity

The property most benefited by the fibre reinforcement is the material energy absorption capacity after peak load [Barros and Figueiras 1999]. In the present work the energy dissipated in compression,  $G_c$ , was considered as the area under the  $\sigma$ - $\epsilon$  relationship of the monotonic loading tests. The influence of the content of fibres and of the transverse reinforcement ratio on the energy dissipated in compression is shown in Figures 10 and 11.

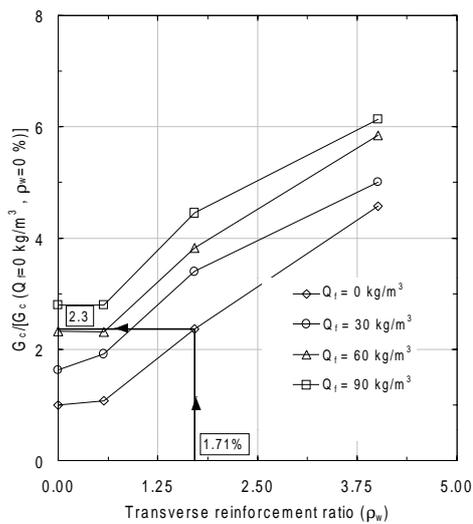


Figure 10 - Relationship between the normalized energy in compression and  $\rho_w$ , for different  $Q_f$

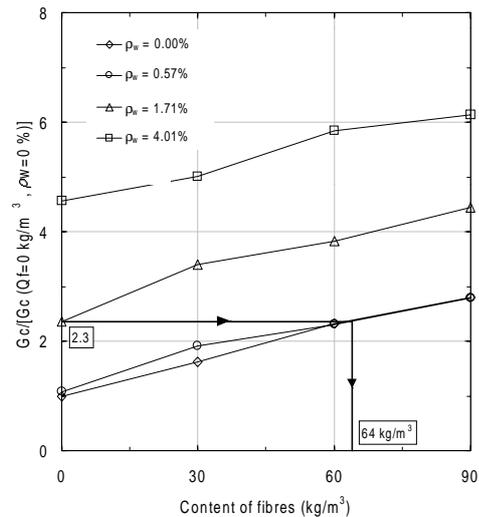


Figure 11 - Relationship between the normalized energy in compression and  $Q_f$ , for different  $\rho_w$

Analysing the diagrams of figures 10 and 11 it was observed an increase on the  $G_c$  with the increment of  $\rho_w$  and  $Q_f$ . However, this increase is more significant with the increment of  $\rho_w$ . These diagrams have a similar shape, which indicates that, for the  $G_c$  variation, the  $\rho_w$  and  $Q_f$  have an uncoupled effect. Using these diagrams, it can be evaluate the content of fibres that has a contribution for the  $G_c$  equal to a given  $\rho_w$ . In other words, it is possible to estimate the content of fibres that can replace a given  $\rho_w$ . For instance (see figures 10 and 11),  $64 \text{ kg/m}^3$  of fibres has an equal effect for the  $G_c$  as  $\rho_w = 1.71$ .

**Rigidity of the unloading/reloading branches**

To simulate the nonlinear behaviour of reinforced concrete structures submitted to dynamic loading it is also important to assess the unloading-reloading response of this composite material under compression. For design purposes it is enough to assume that a linear branch can simulate the unloading-reloading behaviour. This approach was taken in the present work and the procedure to evaluate the slope of this branch,  $E_{co}$ , is schematically represented in Figure 12. The  $E_{co}$  variation was evaluated for several strains, giving the evolution of the unloading-reloading rigidity, represented in Figures 13 to 16 for the series of tests carried.

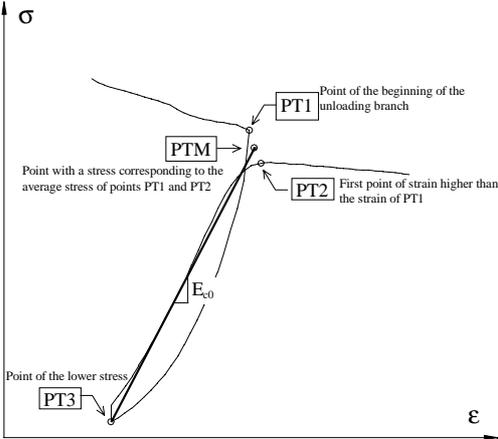


Figure 12 – Procedure to evaluate the slope of the unloading-reloading branch

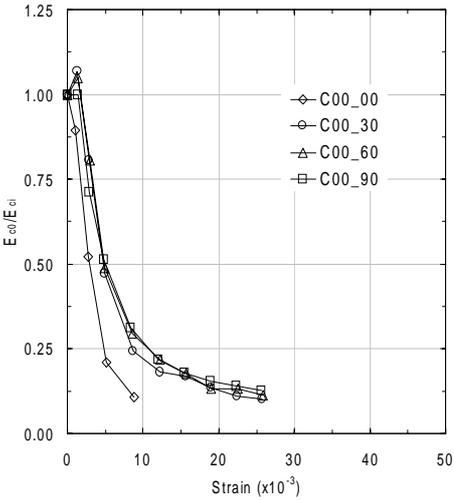


Figure 13 – Evolution of  $E_{co}$  for series reinforced with  $\rho_w = 0.0 \%$

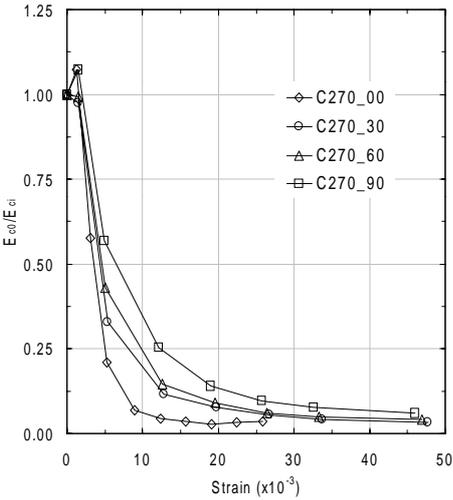


Figure 14 – Evolution of  $E_{co}$  for series reinforced with  $\rho_w = 0.57 \%$

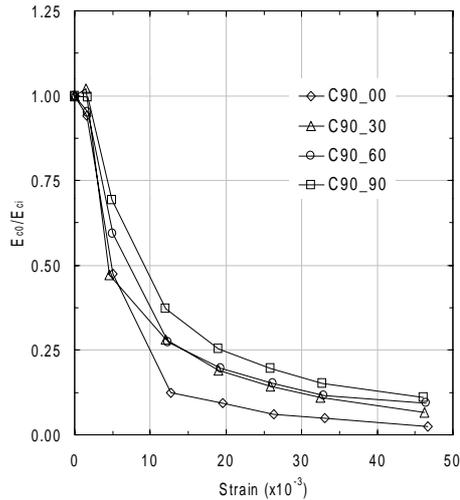


Figure 15 – Evolution of  $E_{co}$  for series reinforced with  $\rho_w = 1.71 \%$

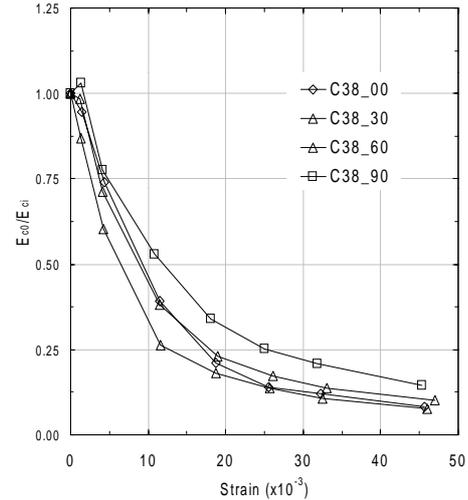


Figure 16 – Evolution of  $E_{co}$  for series reinforced with  $\rho_w = 4.01 \%$

All diagrams have a similar exponential shape. Increasing the content of fibres the rigidity degradation decreases. The rigidity degradation means less slope of the unloading-reloading branch. It is also observed that the retention of unloading-reloading rigidity is more effective using hoops than fibres. However, the fibres can replace some amount of hoops. For instance, the unloading-reloading rigidity of specimens reinforced with  $60 \text{ kg/m}^3$  of fibres and  $\rho_w = 1.71 \%$  (series C90\_60) is similar to the  $E_{co}$  of specimens without fibres and reinforced with  $\rho_w = 4.01 \%$  (series C38\_00). This means that, if it is necessary to apply a large amount of hoops, that can prejudice the concrete casting procedure and consequently the concrete quality, part of the hoops can be replaced by a given content of fibres, without loss of unloading-reloading rigidity.

## CONCLUSIONS

In the present work monotonic and cyclic compression tests were carried out with cylinder specimens reinforced with four percentage of conventional transverse reinforcement (hexagonal hoops) and four content of hooked ends steel fibres. The tests were performed using displacement control in order to evaluate the full response of this composite. From the results obtained it can be pointed out the following main conclusions:

- The stress-strain ( $\sigma$ - $\epsilon$ ) relationships of the specimens submitted to monotonic loading are the enveloping diagrams of the  $\sigma$ - $\epsilon$  relationships of the corresponding specimens under cyclic loading;
- Increasing the transverse reinforcement ratio,  $\rho_w$ , the peak stress, the strain at peak stress, the energy absorption capacity and the rigidity of the unloading-reloading branches have increased considerably. The effect of the  $\rho_w$  on the initial elastic modulus,  $E_{ci}$ , was insignificant;
- The  $E_{ci}$  is also unaffected by the presence of the steel fibres. The increase of the peak stress and of the strain at peak stress with the increment of fibre content was marginal. However, the energy absorption capacity and the rigidity of the unloading-reloading branches were increased considerably;
- The results obtained have shown that the transverse reinforcement ratio used in structural members submitted to compression loading can be partially replaced by a given content of steel fibres. The amount of this replacement should take into account the material and labour costs, the conditions of the concrete casting and the concrete quality assured in the job site;
- The ductility and the safety of the structures under seismic loading can be increased if steel fibres is also used to reinforced concrete the critical zones, like the beam-column joints.

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