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Behaviour of Steel-Fibre-Reinforced Concretes Under Biaxial Compression Loads

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Abstract

In the case of metal fibre concretes under biaxial compression, the gain of strength yielded by metal fibres can be considerable. Using a biaxial press with brush bearing platens (to avoid lateral confinement), we verified this result and studied the behaviour of metal fibre concrete subjected to biaxial loadings. Two different types of fibres were used. The results obtained demonstrate the following points: the addition of fibres makes the material much more ductile; there is an influence of the type of fibre on mode of failure, a gain of strength and an influence of the orientation of the fibres.

Keywords: Fibre concrete, biaxial loading, strength, material behaviour, anisotropy.

INTRODUCTION

Even in modern formulations, concrete, when used alone, is still a brittle material, subject to cracking, having a low tensile strength. The conventional approaches to remedy these defects consist of associating concrete with other materials, in particular steel. The best known of these approaches are called reinforced concrete and prestressed concrete. Fibre–reinforced concrete, a composite material having a cement matrix containing discontinuous fibres, is another approach.

These fibres can be of various types; here we shall consider only the case of metallic fibres.

The mechanical behaviour of metal fibre concretes (MFCs), compared to that of plain concretes, has been the object of many studies, the results of which are often contradictory.[1,2] The contradictions arise — if problems of experimental technique are excluded — from the problem of the formulation of the MFCs. It is not possible to obtain a fibre-reinforced concrete merely by adding fibres to a plain concrete, because this addition also diminishes the workability of the material. It is therefore necessary to reformulate the MFC. This makes a comparison of plain concrete and MFC somewhat illusory, since it depends on how the MFC is reformulated.

The results available in the literature deal primarily with tests in which the concrete is loaded in tension (direct tensile, splitting, bending, shear, torsion), since tensile strength is the first characteristic it is hoped to improve through the use of fibres. But concrete also cracks in compression, whether uniaxial or biaxial. Uniaxial compression again raises the problem mentioned above: 'the effect of metal fibres on compressive strength is variable'.[3] On the other hand, in the case of a biaxial compression, such as may be encountered in structures prestressed in two directions (nuclear power plant confinements, silos, etc.), recent studies[4–6] have shown that the gain of strength yielded by

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fibres can be considerable and, in particular, that the behaviour of MFCs is substantially different from that of plain concretes under this type of loading.

For example, Yin *et al.*[4] have shown that, whereas the strength of their MFC in simple compression was improved only 4% with respect to that of their reference concrete, this percentage rose to 44% in the case of biaxial strength (with a stress ratio of 1). Traina and Mansour[6] have shown that the criterion of failure of MFCs is substantially different from that of plain concretes: for a stress ratio of 1, the strength of MFCs is as much as 85% higher than the uniaxial strength of these concretes (with this percentage depending on the type and quantity of fibres). All of these authors have also noted that the mode of failure of MFCs under biaxial load is different from that observed in concrete conventional, i.e. oblique shear bands rather than fracture planes parallel to the free surface (splitting failure).

When compressed biaxially, MFC behaves like a plain concrete subjected to the same biaxial loadings together with a triaxial stress of low intensity. Van Mier[7] has shown that, in this case, this is enough to change the behaviour of the material from brittle to ductile.

Having the use of specimens of MFC formulated in accordance with the method developed at the LCPC by Rossi[8] and of the biaxial press of the ENTPE,[9] we thought it might be interesting to check the results mentioned above on these concretes.

We added to this research a study of the anisotropy of this material. In effect, MFCs almost inevitably exhibit an anisotropy due to the geometry of the fibres and to a preferential orientation of these fibres according to the mode of vibration and direction of casting (the fibres tend to lie flat). It can be anticipated that this orientation will be a significant parameter of the behaviour under biaxial loading (favourable if the fibres are oriented perpendicular to the plane of loading, unfavourable if they are parallel to it).

EXPERIMENTAL CONDITIONS

The press

Testing fibre-reinforced concretes under biaxial stresses is not easy. It requires a biaxial press large enough to take samples sufficiently representative of the material. The press of the ENTPE[9–11] uses cubic specimens of 10 cm each side. For fibres that can be as much as 60 mm long, larger dimensions would undoubtedly have been preferable. Unfortunately, no press capable of testing them exists in France (that of the INSA of Toulouse[12] can test slabs with 3 cm sides).

The press of the ENTPE has one very important characteristic: its brush bearing platens (Fig. 1). In effect, in the case of biaxial loading, the slenderness of the specimen is unity. The boundary conditions of loading may then perturb the stress field applied to the material; in particular, lateral confinement of the specimen occurs when the loading bearing interferes with the lateral strain of the specimen because of the Poisson effect. The brush bearing platen, because it allows the bearing to 'follow' the strain of the concrete, considerably reduces the lateral confinement.[13] The result, in simple compression, is cracking parallel to the direc-

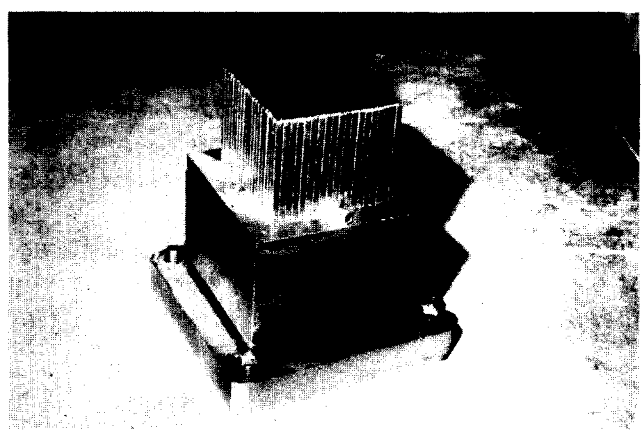

Fig. 1. The brush bearing platen.

Fig. 2. Failure of a plain concrete in biaxial compression.

tion of loading and, in biaxial compression of plain concrete, cracking planes parallel to the plane of loading (Fig. 2).

The MFCs

The ones we tested were cast at the LCPC for previous research. We have chosen these MFCs because extensive results were available such as compressive and tensile behaviour.[1] The method of composition of these concretes has already been described.[8] It should be recalled merely that it is an extended Baron–Lesage method (for a fixed water/cement ratio (w/c), the most compact fibre-reinforced concrete is also the most workable) and that, when the method is applied, the composition of the fibre-reinforced concrete is different from that of a plain concrete. The most important differences concern the quantity of cement paste and the sand–aggregate ratio.

For our study we selected two compositions, using fibres of different types:

MFC A: Amorphous iron fibres that take the form of very thin metallic ribbons. This concrete was chosen in order to study the effect of anisotropy because this effect was already noticed in the previous compression tests (on the basis of Rossi's results[1,2] it seemed to us that the effect of anisotropy would be greater on this formulation).

MFC B: Cylindrical fibres that have hooks and are delivered in plaquettes.

Table 1 gives the compositions of the MFCs tested.

The specimens

These are cubes 10 cm on a side, sawn from large blocks (102 × 92 × 56 cm) to avoid wall effects. The cubes are then surfaced and stored at 50%RH and 20°C. The concretes were 2 years old at the time of the tests.

Table 1. Compositions of the MFCs tested (1 m^3)

Constituents	*MFC A*	*MFC B*
Fibres:	Amorphous iron	Steel
Length	30 mm	60 mm
% Vol. V_f	0·5%	1%
Weight/m^3	36 kg	78 kg
Concretes:		
Aggregates		
5/20	853 kg	839 kg
0/5	896 kg	894 kg
Cement HS	420 kg	425 kg
PCA		
Water	189 litres	191 litres
Plasticizer	8·4 kg	6·5 kg

Loading paths

To explore the criterion of failure of MFCs in the stress space, we chose to subject MFC B to radial loading paths, i.e. paths for which the ratio of the stresses σ/σ_1 is constant. In our study, the following ratios were examined: $\sigma/\sigma_1=0/3$, 1/2, 2/3 (with $\sigma/\sigma_1=1$ our press was not able to reach the ultimate strength of the samples). Figure 3 shows the loading paths.

For MFC A kept for study of the influence of anisotropy, in addition to simple compressive

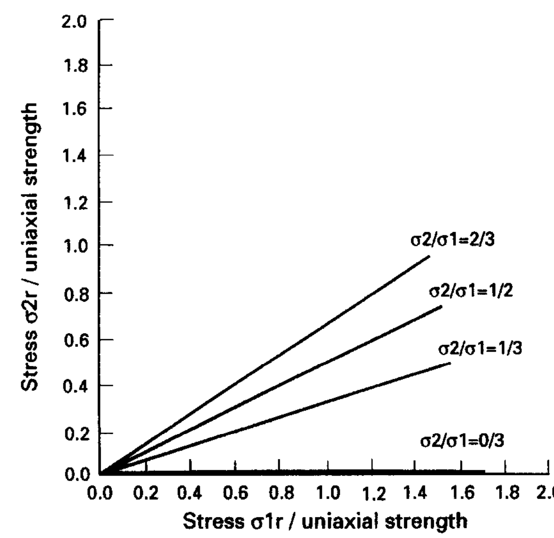

Fig. 3. The loading paths.

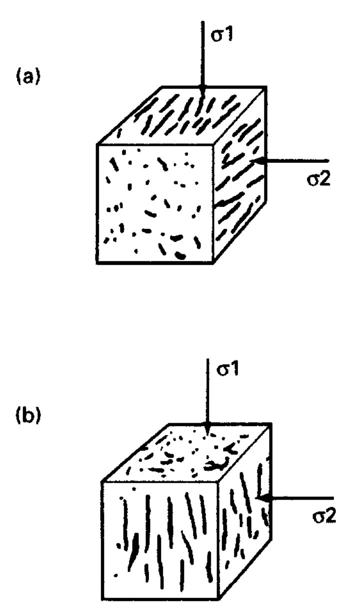

Fig. 4. Both cases tested: (a) direction of casting parallel to loading direction 1 (most loaded); (b) direction of casting orthogonal to loading direction 1.

tests, tests were carried out with a radial loading path ($\sigma/\sigma_1=1/2$). Figure 4 shows the two cases we tested to study the influence of the initial anisotropy due to casting: loading perpendicular to the direction of the fibres (or parallel to the direction of casting) and loading parallel to the direction of the fibres (or perpendicular to the direction of casting).

At least three tests were performed for each loading path.

Measurement of strains

Strains ε_1 and ε_2 were measured by gauges glued to the free surface, for both directions of loading, and ε_3 by displacement transducers for the unloaded direction.[10,11]

EXPERIMENTAL RESULTS

MFC B

Our results confirmed those available in the literature for this type of MFC, whereas in simple compression, failure is by formation of small columns parallel to the direction of loading; in biaxial compression, failure occurs by formation of a shear band inclined 20–45° with respect to the direction of greatest loading (Fig. 5). Fibres are not broken at the end of the test. The strains are also significantly greater than those commonly observed with plain concretes (Fig. 6). In terms of strength, Fig. 7 shows the results obtained in the (σ_1, σ_2) plane. Even allowing for a large dispersion (undoubtedly due to the fact that the size of our samples is a little small), a difference may be noted with respect to the results on plain concretes: the larger role of the intermediate stress. This had already been noted by Yin[4] and Traina.[12]

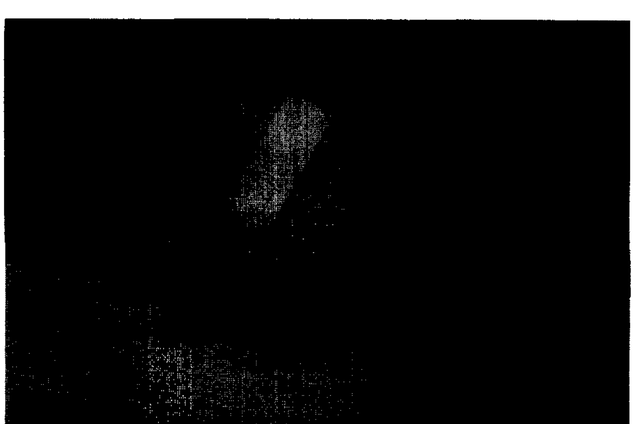

Fig. 5. Failure of MFC B in biaxial case.

In effect, when σ_1/σ_2 increases, the stress at failure $\sigma_1 r$ increases too. The gain of strength is therefore more marked than that obtained with a plain concrete (cf. Table 2).

MFC A: effect of anisotropy

Before this point is considered in more detail, it should be noted that, for MFC A, in all our tests, failures were of the same type as those observed for plain concretes. In particular, in biaxial compression, we observed no failure of the type observed in MFC B, but rather planes of cracking practically parallel to the free surface (Fig. 8), with the fibres breaking at the end

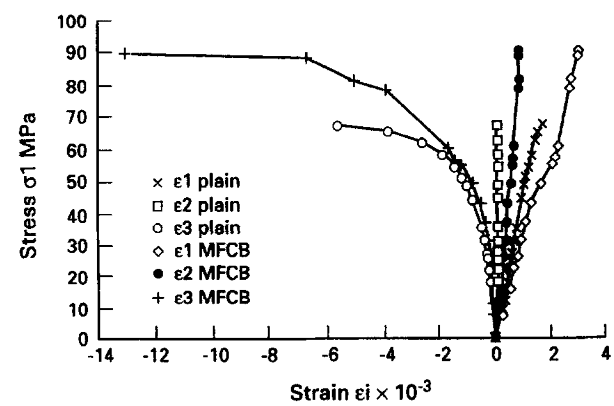

Fig. 6. Strains of MFC B compared to those of a plain concrete,[11] in the case where $\sigma_2/\sigma_1=2/3$.

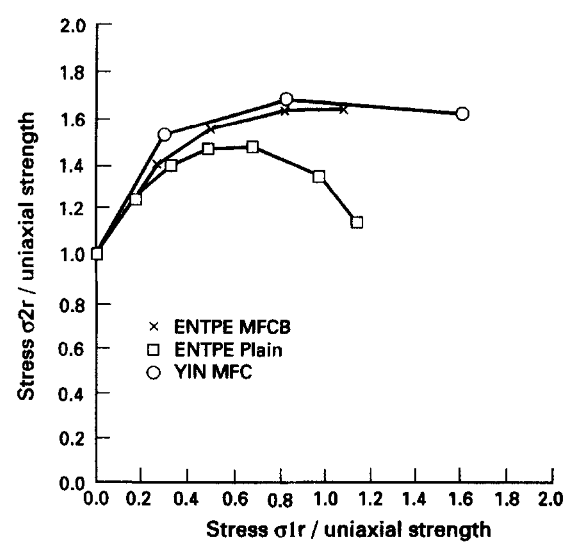

Fig. 7. Criterion of failure in biaxial case.

Table 2. Strength at failure in biaxial test

	σ_2/σ_1	1/3	1/2	2/3
Plain concrete	$\sigma_1 r$/fc	1·22	1·25	1·24
MFC B	$\sigma_1 r$/fc	1·55	1·62	1·65

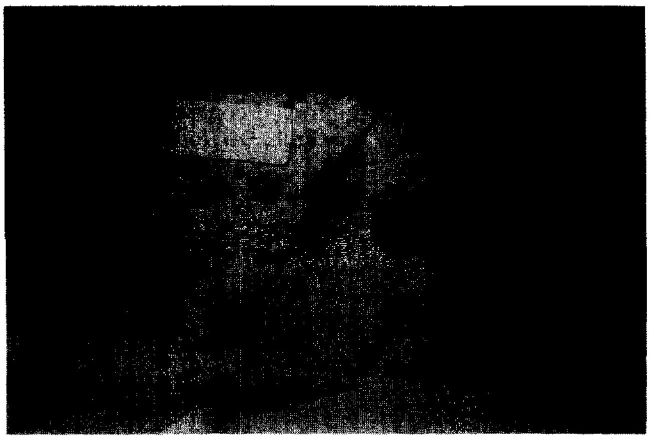

Fig. 8. Failure of MFC A in biaxial case.

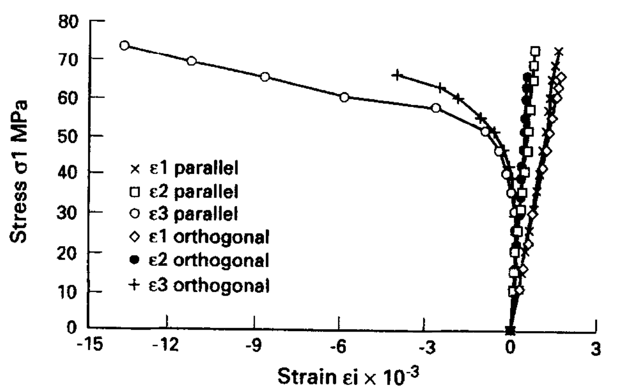

Fig. 9. Comparison of strains according to direction of loading with respect to that of casting, $\sigma_2/\sigma_1=1/2$.

of the test. The type of failure of the MFC therefore depends not only on the loading conditions but also on the type of fibres (material, geometry).

Let us now consider the problem of the anisotropy of the material. It is manifest in the strains (Fig. 9), and the material is obviously more ductile in the favourable case, when the direction of casting and the crack orientation are parallel. When the strengths are compared, the gain in the favourable case with respect to the unfavourable case is approximately 20% in simple compression and 45% in biaxial compression, with $\sigma_2/\sigma_1=1/2$ (cf. Table 3). This shows the necessity of taking this aspect of the behaviour of MFCs into account, especially in the case of biaxial loading.

CONCLUSIONS

Biaxial compressive tests on metal fibre concretes enabled us to quantify the influence of the fibres on the mode of cracking and on the deformability of the material and to study the effect of anisotropy.

Table 3. Comparison of strengths according to direction of loading with respect to that of casting, $\sigma_2/\sigma_1=1/2$

	σ_{1r}, *strength in MPa*	
Compression	*Simple*	*Biaxial 1*
Favourable case	48	86
Unfavourable case	40	60

The results obtained, which confirm those of other authors,[4,5] demonstrate the following points:

- the addition of fibres makes the material much more ductile, an effect that is quite substantial in the biaxial case. The non-linearity of the strains is very marked, especially in the unloaded direction.
- influence of type of fibres on mode of failure: failure by shear bands with steel fibres B, splitting failure (planes of cracks parallel to the plane of loading) with amorphous iron fibres A.
- gain of strength: the coupling between fibres and biaxial loading leads to a substantial strength gain. This gain is undeniable in the biaxial case.
- knowledge of the orientation of the fibres with respect to the direction of casting is necessary for full use of the strength capacity of metal fibre concretes.

These results indicate, in our opinion, that this is an economic resource that can be turned to account, in particular in horizontally and vertically prestressed structures.

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