Tensile behaviour of glass fibre reinforced concrete

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ABSTRACT: From the results of the research carried out in the last years on fibre reinforced cement based materials, it can be pointed out that, for the fibre contents usually employed in practice, the post-peak tensile behaviour is the most improved material characteristic. However, difficulties in carrying out valid direct tensile tests have limited the research in this field. The scarcity of investigation on the tensile behaviour of glass fibre reinforced concrete (GFRC) is also probably due to the ageing problems of GFRC systems. In order to contribute to a better knowledge of the uniaxial tensile behaviour of GFRC, deformation-controlled uniaxial tensile tests were carried out at Stevin Laboratory (NL). Polymer-modified glass fibre reinforced cement (PGFRC) specimens manufactured by spray up and premix techniques, and GFRC specimens are tested at the age of 28 days. The experimental response of the tested specimens is illustrated and the results are used to validate a computational code developed for the analysis of fibre reinforced concrete (FRC) structures, wherein the most recent concepts of fracture mechanics of brittle materials are included.

1 - BACKGROUND INFORMATION

1.1 - *Glass fibre reinforced concrete*

Glass fibre reinforced concrete manufactured by spray or premix process has proven to be an attractive material for a wide range of applications (PCI 1981, Majumdar 1991). Several factors have contributed for this, namely: manufacture facilities in terms of shape, size and finishing; economy in transport and handling equipment; decrease of superimposed loads on structural components due to the relative low weight of GFRC systems; satisfactory mechanical properties and good physical performances. However, soon it was recognized the long-term decline of the properties of these composites (Majumdar 1974). The chemical attack on glass by the alkaline cement environment and the growth of hydration products, mainly calcium hidroxides, in between the filaments in the strand have been pointed out as the responsible by the durability of the GFRC mechanical properties (Bijen 1983, Leonard 1984, Bentur 1986, Shah 1988, Li 1991). The ways of improving the retention of the GFRC properties with age have been directed to the following main procedures: reduce the chemical aggressiveness of the cementitious matrix by employing low alkali cements (Akihama 1987); protect the fibres from the corrosive environment through a polymer or admixtures mix addition, which has the capacity to envelop the fibres by a protective film (Bijen 1990); interfer in the fibre chemical composition and fibre surface treatment (Fyles 1986).

The submicron particles of the acrylic polymer applied in the Forton-PGFRC surround the strand filaments, obstructing the fibre engulfment by the cement hydration products and protecting the fibres against a chemical attack. A significative improvement in the durability of these composites under weathering conditions has been claimed (Bijen 1990).

1.2 - *Tensile behaviour*

The deformation-controlled uniaxial tensile test is probably the most suitable procedure to study the brittle behaviour of cement-based materials (Gopalaratnam 1985, Wang 1990, Hordijk 1991). The tensile load-deformation curve schematically represented in Fig. 1 can be regarded as a typical curve of a bar of PGFRC under deformation controlled uniaxial tensile test, as long as the fracture behaviour is governed by the fibre pull-out mechanism. Comparatively to plain concrete (PC), fibre reinforced concrete (FRC) has a less steep softening branch (branch III), a larger ultimate deformation and a more enlarged nonlinear branch before peak load (branch II). The initial part of the pre-peak curve (branch I) appears to be a straight line, indicating that FRC behaves linearly in this region. In this first branch, load does not create new microcracks until the stress level represented by the bending over point (BOP) is reached. Between BOP and peak load, the response is usually described by a nonlinear branch (branch II). This branch is more enlarged when a high percentage of fibres is employed. In this stage a substantial amount of energy is required to propagate the microcracks (process zone). The localization of the process zone is usually associated to a stress concentration which is due to a material heterogeneity or to a structural descontinuity (such as a notch). If the process zone is developed within the measuring length, whose deformation is used as test control parameter, a load-deformation relationship, as indicated by branch III in Fig. 1, can be obtained and used to get the stress-crack opening relationship (Hillerborg 1976). The load that can be transferred decreases with an increasing deformation of the process zone. As a result of this load reduction, the composite material outside the process zone unloads (branch IV). The pull-out mechanism of fibres bridging the fracture surfaces in the process zone is responsible for the energy increase of the FRC as compared with PC.

2 - EXPERIMENTS

2.1 - *Mix composition*

Comparatively to conventional concrete, GFRC mixes are generally characterized by greater cement factors, higher contents of fine aggregates and smaller sized coarse aggregates.

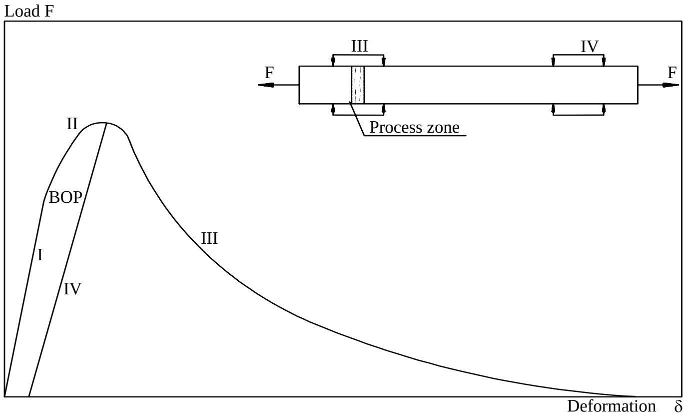


Figure 1 - Load-deformation relation for a (fibrous) concrete bar under uniaxial tensile loading.

Two different mixes were used in the experimental program. The method of mixing the PGFRC compositions determined the mix procedure. In the premix method, it is recomended to mix in the first stage the aggregates, cement, water and admixtures until the mix gets the adequate workability. In a second stage the fibres are added to the mix during the strictly time needed to soak the fibres in the slurry. In the spray-up method, chopped glass fibres and cement slurry are simultaneously sprayed onto a form, usually from separated nozzles, and in fact they are mixed at the moment of placement. The mortar was previously prepared and introduced in a deposit of the spray equipment. The ratio between the amount of glass fibre and cement slurry is controlled by the spray gun operator.

Typical mix compositions of commercial PGFRC systems are given in Table 1.

Table 1 - Mix composition of the PGFRC composites (FORTON 1992)

Constituent (Kg)	Spray-up 5/5	Premix 3/7
Cement PcB	50	50
Sand LG 56	50	50
Forton Compound VF 774	7	10
Water	13	12
AR Glass fibres	6.3	3.75
Characteristics:		
Cement-sand ratio (Weight)	1	1
Water-cement ratio (Weigth)	0.33	0.34
AR-glass fibres (Weight)	5	3
Polymer solids (Volume)	5	7.2
AR glass fibres	Cem-FIL 205/5B roving cut into 31 mm strands during spray-up production	Cem-FIL 60/2 chopped strands 12 mm long

2.2 - *Preparation of the specimens*

The PGFRC tensile specimens were sawed from two 605×755x50 mm panels made by FORTON BV Company. One panel was manufactured by the premix process and the second panel by the spray technique. Until demoulding, the panels were covered with a polyethylene sheet. After demoulding the panels were stored in a climatic room at 20ºC and 65% RH. The panels were transferred to the Stevin Lab. at an age of 7 days and stored in a natural environment of the laboratory until testing. Additionally, some GFRC tensile specimens were manufactured in the Stevin Lab. and obtained from sawing cubes of 150 mm side length, in a direction orthogonal to the casting direction.

The dimensions of all tensile specimens were 150x60x50 mm. Two saw cuts reducing the middle cross-sectional area to 50x50 mm were initially used. However, difficulties in glueing the specimens to the machine loading platens forced the reduction of the net area of the specimens to 30x50 mm.

2.3 - *Experimental setup*

Tests were carried out on a closed-loop electro-hydraulic loading machine which has the capacity of 300 kN in tension, see Fig. 2.

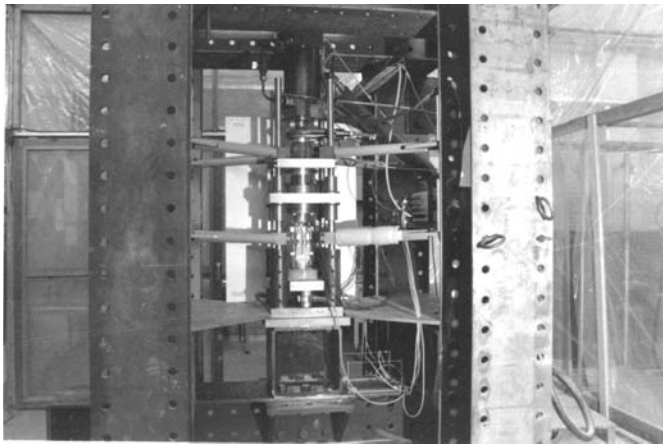


Fig 2 - Photo of the testing rig used in a deformation--controlled uniaxial tensile test (Stevin Laboratory).

The averaged signal used for the deformation-controlled tests was given by four LVDT's with a base length of 35 mm (lmeas=35 mm) mounted on the corners of the specimen, see Fig 3.

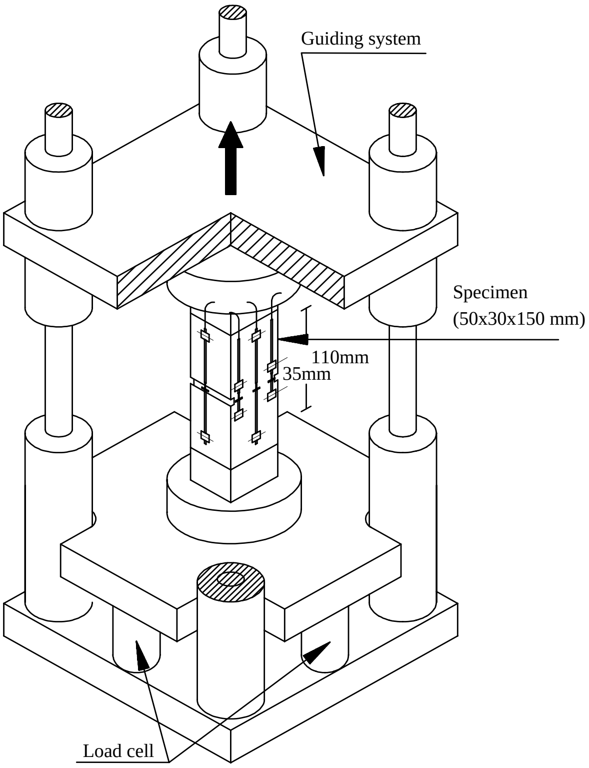


Figure 3 - Schematic representation of the test equipment and the measuring devices.

The deformation rate for GFRC and PC specimens was 0.16 μm/s and 0.08 μm/s respectively. The highest deformation rate was necessary in order to perform a tensile test up to 2 mm of deformation within a working day. Furthermore, doubling the speed of the deformation did not seem to significantly influence the results (Hordijk 1991). The averaged deformation measurements of the four LVDT's with a base length of 110 mm (lmeas=110 mm) was used to calculate the Young's modulus. The specimens were glued to steel platens fixed to the load equipment. More detailed information is given in Barros (1992).

2.4 - *Experimental results*

2.4.1 - PGFRC specimens

Per each Forton' panel three tensile specimens were tested. A typical stress-deformation (σ-δ) curve corresponding to the specimen manufactured by spray up technique is shown in Fig 4. The stress is defined as the load (average result of the four load cells) divided by the net cross-sectional area, while the deformation is the average result of the four corresponding LVDT´s (35 and 110 mm base length).

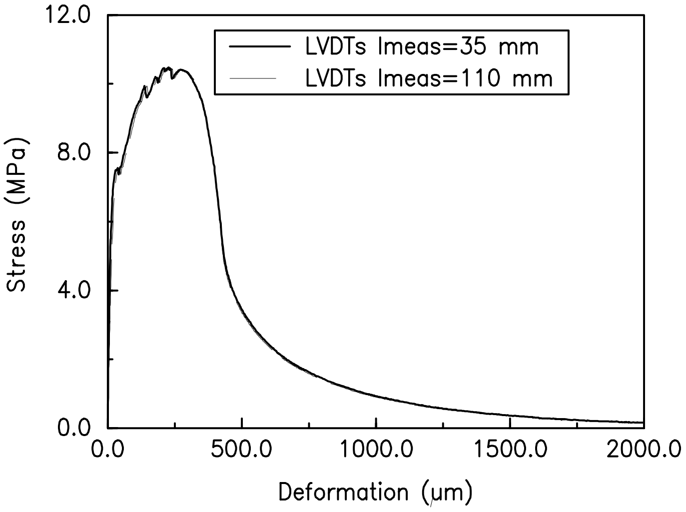


Figure 4 - Stress-deformation curve for a PGFRC spray up specimen.

Before peak load, the σ-δ curve is characterized by a relative large nonlinear branch. The high percentage of fibres (5%) employed in the spray up specimen originates the diffusion of microcracks, which in combination with the fibre debonding mechanism is responsible for this behaviour. At 2 mm of deformation, the specimen had still capacity to transfer some load via crack due to the frictional rigidity mobilized by the fibre pull-out mechanism. After the complete separation of the specimen in two halfs, it was observed that the fibres were distributed in parallel layers to the front and rear specimen's face, revealing the process of manufacturing. As in each layer the fibres were 2D randomly distributed, the most part of these fibres offer an effective reinforcement.

The stress-deformation relationship corresponding to a typical premix PGFRC specimen is plotted in Fig. 5.

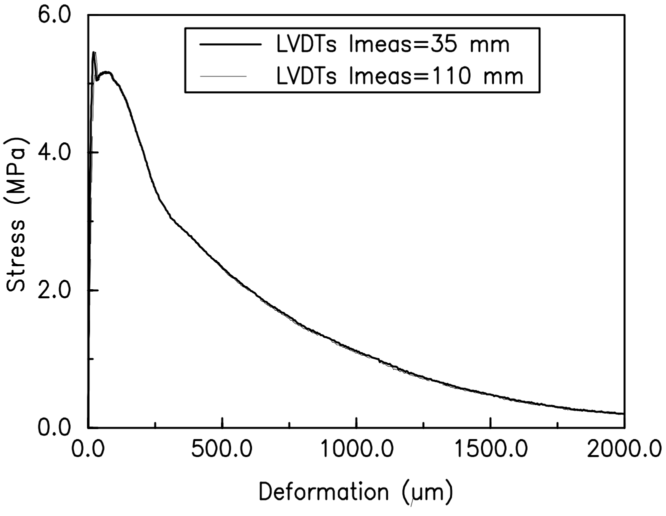
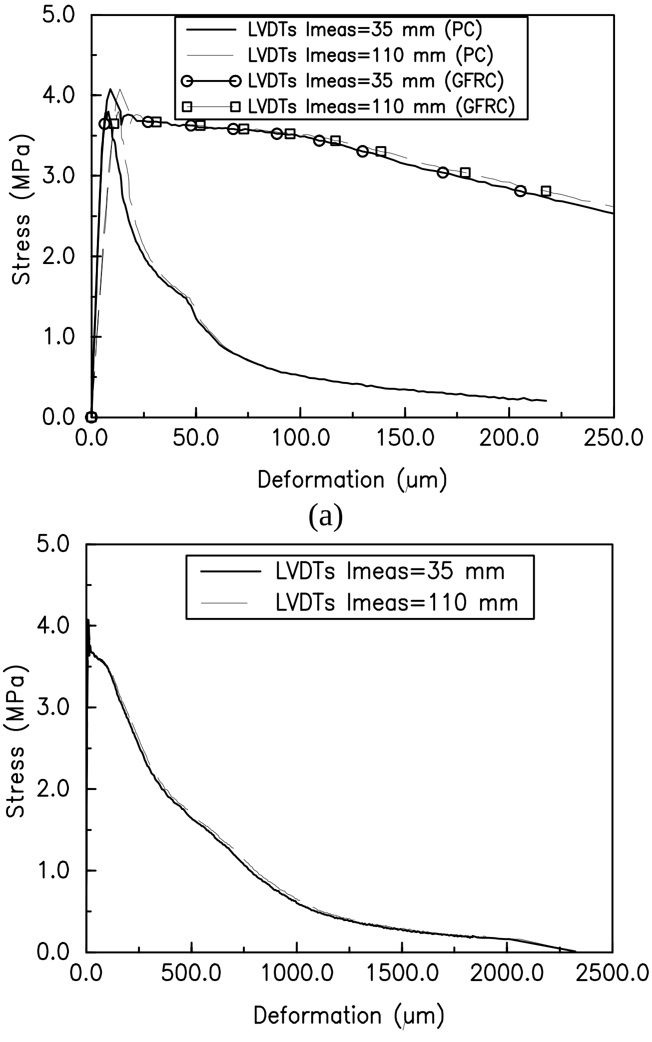


Figure 5 - Stress-deformation curve for a PGFRC premix specimen.

From comparison between the stress-deformation curves of the spray up and the premix specimens, it can be observed that the strength of the premix specimen is considerably lower, and the nonlinear branch before peak loading is less pronounced. This behaviour can be justified by the lower percentage of fibres (3%) and by the 3D randomly fibre distribution. Since the specimen is loaded in the uniaxial direction, this fibre orientation is not effective as it is in the 2D fibre distribution of the spray up specimens.

2.4.2 - Results of the plain mortar and the GFRC specimens

Additionally, some experiments were performed on plain mortar and GFRC specimens both manufactured at the Stevin Laboratory. Two GFRC and two PC specimens were tested. Typical results of the stress-deformation relationship are shown in Fig. 6.



(a)

(b)

Figure 6 - Stress-deformation curves for: (a) plain mortar and GFRC specimens, (b) GFRC specimens.

Figure 6(a) clearly illustrates that the glass fibres modify the post-peak behaviour increasing the energy absorption capacity, improving the deformation capacity and increasing the tensile strength marginally as well. A scatter in the deformation at peak load was observed either on the GFRC specimens manufactured in Stevin Lab. as well as on the PGFRC specimens produced with the premix technique. Consequently, it appears that the premix technique tends to scatter the FRC properties, probably due to the difficulty in obtaining a uniform fibre distribution in the mix.

2.4.3 - Comparison of the results

The average values of the most significant properties obtained in the deformation controlled uniaxial tensile tests are summerized in Table 2.

Table 2 - Overview of the main tensile properties

	mortars			
	plain	premix GFRC	premix PGFRC	spray PGFRC
Fracture energy G_f (J/m^2)	230	1912	3017	4286
σ^{peak} (MPa)	3.8	4.4	5.5	10.8
δ^{peak} (μm)	11	55	78	250
δ^{ult} (μm)	≅300	≅2350	≅2550	≅2200
(1) w_0 (μm)	≅300	≅2300	≅2500	≅2000
(2) w_c (μm)	311	2234	2820	2040

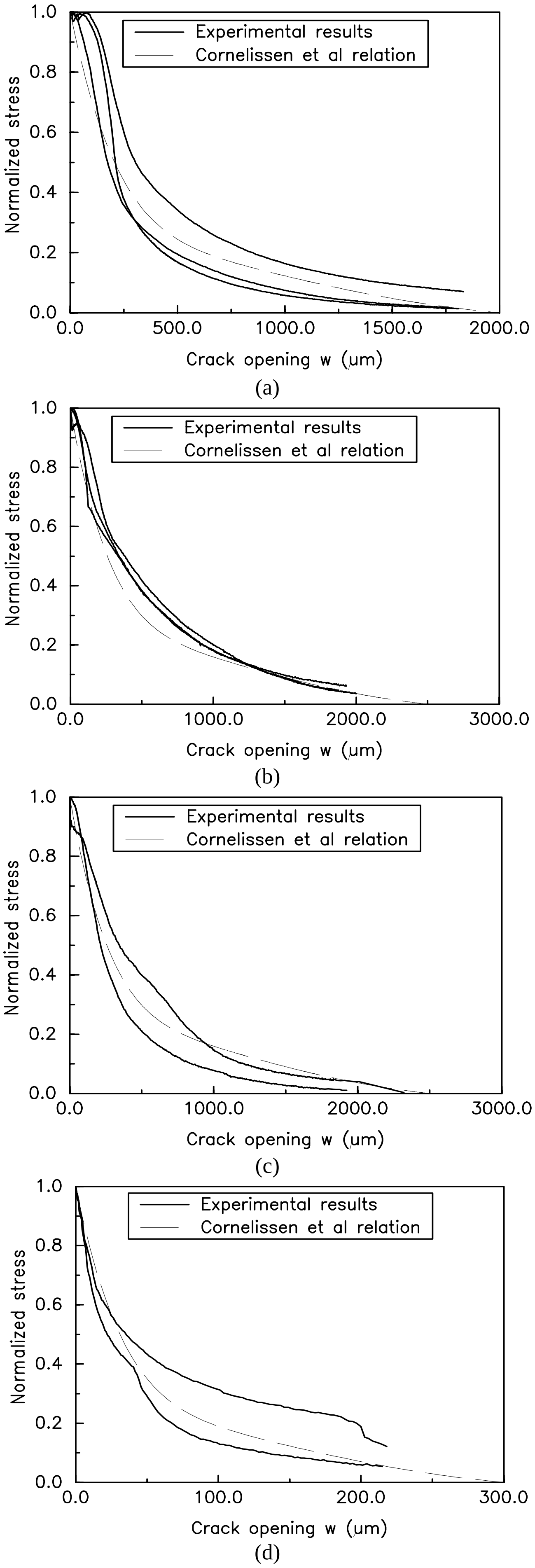
(1) estimated ultimate crack opening

(2) critical crack opening, $w_c=5.14G_f/f_{ct}$ (Hordijk 1991)

The increase in fracture energy when adding glass fibres in the mix is evident. However, the tensile strength is markedly increased for the PGFRC made with the spray up technique only. Consequently, there is a significative difference between the results of the tensile strength of the premix (P)GFRC and the spray up PGFRC. This property is largely determined by the fibre orientation.

The relations between the normalized stress (stress divided by the tensile strength) and crack opening displacement (σ/f_{ct}-w) are plotted in Fig. 7 for the specimens tested. The relationship proposed by Cornelissen (1986) is also represented in Fig. 7,

$$\frac{\sigma}{f_{ct}} = \left\{1+\left(c_1\frac{w}{w_c}\right)^3\right\}\exp\left(-c_2\frac{w}{w_c}\right) - \frac{w}{w_c}\left(1+c_1^3\right)\exp\left(-c_2\right) \quad (1)$$



(a)

(b)

(c)

(d)

Figure 7 - Normalized stress-crack opening curves: (a) spray PGFRC; (b) premix PGFRC; (c) GFRC; (d) PC.

wherein values of 3 and 6.93 were assumed for c_1 and c_2 respectively. The critical crack opening w_c is material dependent and takes the values 2500, 2000, 2500, 300 μm for the spray PGFRC, premix PGFRC, GFRC and PC specimens respectively, which are close to the results prescribed in Table 2. It can be concluded that expression (1) can approximate fairly well the tensile softening behaviour of the GFRC specimens.

3 - NUMERICAL ANALYSIS

3.1 - *Comparison of experimental and numerical results*

The specimens experimentally tested were analysed by a finite element computational code developed for the analysis of FRC structures. The finite element mesh with the applied boundary conditions is presented in Fig. 8.

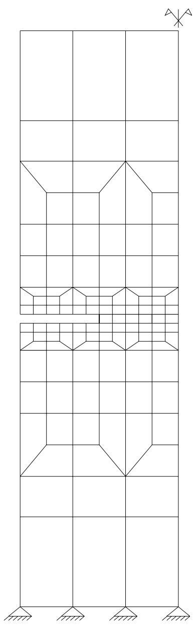
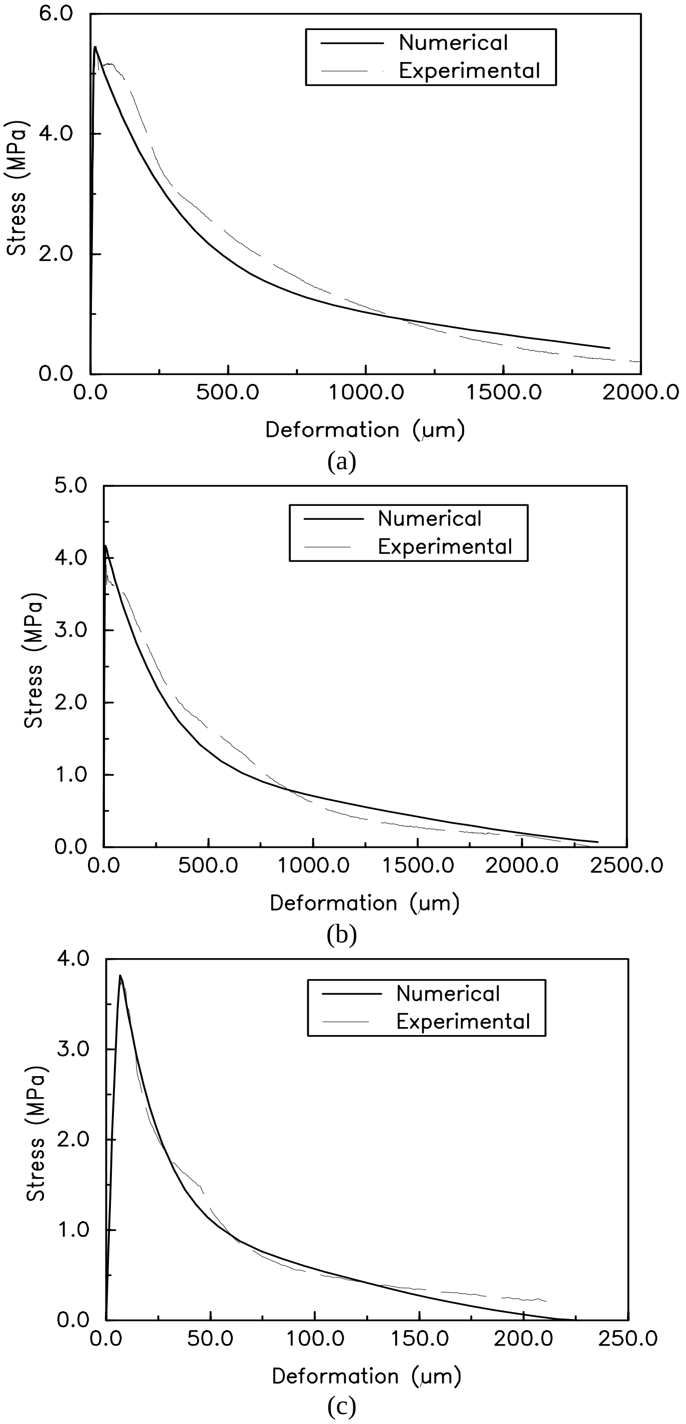


Figure 8 - Finite element mesh used in the analysis of the tensile specimens.

A four-node elements were integrated using four-point Gaussian quadracture. The lower boundary was assumed to be fixed and the present analysis had been carried out under direct displacement control at the top of the speciment. For the plain mortar and premix GFRC specimens it was taken a Young's modulus of 25 GPa, while for the premix PGFRC it was assumed a value of 17.5 GPa. These values match fairly well the linear branch of the experimental response. For Poisson's ratio it was taken a 0.2 value. A linear elastic behaviour was assumed for the material between cracks. The stress-crack opening displacement relationship (expression (1)) was transformed into a crack stress-strain relation, which was used to simulate the softening behaviour (crack constitutive law).

The experimental and numerical response (average stress and deformation as defined in section 2.4.1) are compared in Fig. 9.



(a)

(b)

(c)

Figure 9 - Numerical and experimental average stress-deformation (lmeas=35mm) relation for: (a) premix PGFRC; (b) GFRC; (c) PC, specimens.

It can be concluded that the present numerical model catch with enough accuracy the experimental tensile behaviour of the specimens analised. In the case of spray PGFRC specimens (this analysis is not included in the present work), the microcracking spreads throughout a large zone of the specimen and the fibre debonding mechanism (interfacial fibre-matrix stress transfer) is improved which can be responsible for the considerable extent of the nonlinear branch before peak load. Therefore, a nonlinear pre-peak tensile constitutive law should be used to simulate this behaviour. In the PC and fibrous specimens reinforced with relative low percentage of fibres, a pre-peak linear elastic tensile behaviour is accurate enough. The nonlinear softening diagram represented by expression (1) is a good relation to model the post-peak behaviour of the cement brittle material.

4 - CONCLUSIONS

The present work is concerned with the tensile behaviour of GFRC specimens with 28 days of age. The following conclusions can be summarised:

- Fracture energy of cement based materials is significantly increased by adding glass fibre to the mix composition.
- The tensile strength is largely determined by the fibre orientation which depends on the mixing method. A tensile strength of about 11 MPa is found when a spray up technique is used for the PGFRC. A tensile strength between 4.5 and 5.5 MPa is found for (P)GFRC mixes made with the premix method.
- Smeared crack models based on finite element techniques wherein softening laws and fracture mechanics concepts are included can capture the experimental response. The softening behaviour of the cement based materials can be adequately represented by expression (1).

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