XXXVI Ibero-Latin American Congress on Computational Methods in Engineering
CILAMCE
Rio de Janeiro, 22-25 Nov 2015

NUMERICAL MODELING OF THE MECHANICAL BEHAVIOR OF STEEL FIBER REINFORCED CONCRETE PIPES

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Abstract. *The use of steel fiber reinforced concrete (SFRC) as reinforcing material in concrete pipes used for water drainage and sewerage in partial or total substitution of steel meshes and bars may have a positive impact in product optimization inside the precast industry from a technical and economical point of view. The main effect of the fiber addition is the control of cracking processes, resulting in significant increases in composite toughness, as well also additional benefits referred to its strength. In this paper, as part of a initial stage of an on course investigation, the mechanical behavior of SFRC pipes is assessed by a simple numerical model which the SFRC is modeled as a homogeneous composite (macro scale). For numerical simulation working within continuum mechanics and a damage-plasticity model is used. The equations are solved with the Finite Elements Model and the results are compared with experimental data obtained by other authors.*

Keywords: *Numerical modeling, Steel fiber reinforced concrete, concrete pipes, non lineal model*

1 INTRODUCTION

The use of fibers as reinforcement dates since ancient times, when horsehair and thatch were used for the elaboration of mortar and bricks respectively. Further, different types of industrialized fibers appear, like carbon, aramid, glass and polymeric fibers among others. Whereas, steel fibers are the most popular fiber used as concrete reinforcement. Initially they were used in nonstructural purposes e.g. for prevention and control of shrinkage. Some researches reveal that fiber addition significantly increases flexural stiffness and energy absorption capacity of the concrete, as well reducing the cracking and resulting in a durability improvement. (Altun et al, 2006)

SFRC is a relatively emerging material in the market, which appears with the purpose of offering a technical and economically sustainable alternative to the plain concrete.Like conventional concretes, it is conformed by a hydraulic binder, portland cement in most cases, aggregates with different granulometry, water and steel fibers. These discrete fibers randomly distributed in the concrete mass replace the strengthening function provided by steel bars.

In spite of having elapsed only twenty years since its debut, the SFRC has numerous applications among which the precast products are included, being the concrete pipes part of them. However, and although several experimental campaigns has been carried out and published in the scientific literature, the generalized use of SFRC has not been put in practice yet due to several reasons. (De la Fuente et. al., 2010).In addition, the inexistence of suitable numerical models that reflects the failure mechanism of SFRC and quantifies the contribution of the fibers, represents another restriction for the consolidation of SFRC as a competent alternative in the current market.

For that reason is that in this work is exposed a non-lineal damage plasticity model capable of recreates the failure process taking into account irreversible inelastic processes associated to material instability.

2 Mechanical properties of SFRC

The most important effect in the mechanical behavior of the concrete, because the presence of fibers, occurs in the post-cracking tension resistance. This affects to many others mechanical properties at the same time as the reinforcement adherence, shear resistance, fatigue, etc. (Massicote, 2001) Emphasizing in tension, the fibers slightly stiffen the response in pre-crack stage respect to common concrete and substancially provide a residual resistance capacity in the post-crack stage. The later is due to the sewing effect that the fibers achieved between the crack lips. See Figure 1. (Mármol Salazar, 2010)

In fact, adding a 1.5% in volume of fibers to concretes or mortars, increases of between 30-40% in tensile resistance are obtained (ACI 544.1R-96, 2009). Respect to flexural resistance, the addition of steel fibers considerably increases it, even more that the one experimented in tension, because of the ductile behavior of SFRC in the cracked tensile zone, which is produced by residuals resistance. (Hannant, 1978)

In general, the addition of fibers to the concrete, does not lead to a significantly increase in compressive resistance of the concrete. (Yazici et al, 2007).

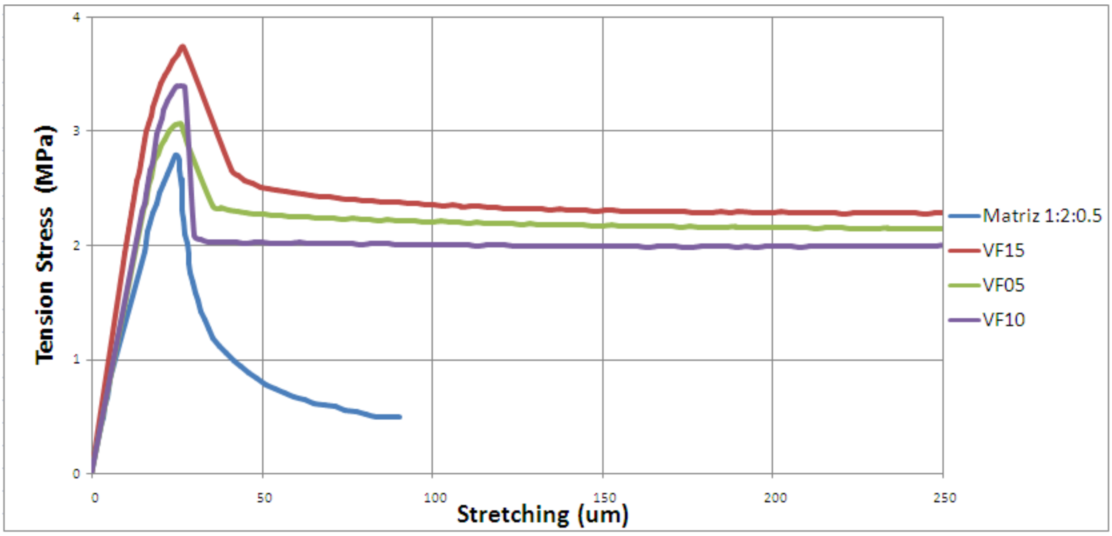

Figure 1: Tension-stretching curves in concretes in function of volume of fibers. (ACI 544.1R-96, 2009)

3 USE OF SFRC IN CONCRETE PIPES

Concrete pipes are the most efficient, economic and ecologic system for sanitary systems networks. Among its main advantages as structural element it is remarkable its good response to dynamic and impact loads, proper flexibility to eventual ground displacements through the use of expansion joints and a minimal maintenance after putting in service.

The use of concrete pipes between 400 mm and 1200 mm of diameter is the most widespread option in urban drainage. In fact, some concrete aqueducts built ,by the Romans, 2000 years ago are still in use, proof that the concrete based drainage infrastructure gather suitable durability with a good structural efficiency. (Peyvandi et al, 2013)

The use of SFRC for the manufacturing of concrete pipes implies a series of improvements related to the performance of this composite which were abovementioned, but more specifically, it should be mentioned that the fabrication of the steel reinforcement cage of the pipe requires a special bender and the use of specific machinery for its collocation which is expensive and needs time. Thus, the use of fibers as main reinforcement in place of those cages could overcome this disadvantage without endanger the overall quality of the product. (Mohamed et al, 2014)

4 MODELING COMPOSITES AND MODELING SCALES

Concretes, like others cementitious materials, are multiphase materials commonly named in the literature as “composites”. Each component of the composite has its constitutive law that conditions the behavior of the material depending on its volumetric proportion and the morphological distribution. (Molina et al, 2009)

In a macro level of observation, they can be consided as an homogeneous continuous material, meanwhile in lower levels of observation, must be considerate as multiphase materials.

There are several constitutive models referred to SFRC currently available in the literature which are classified according to the observation scale considerate:

- Macroscale models: the materials with a cementitious base can be idealized considering them as a continuum, and modelled in a theoretical frame that includes the classical formulations for the continuum e.g. localized deformations and distributed cracks.
- Mesoscale models: a better understanding of the failure mechanism of SFRC subjected to external loads can be obtained considering the mesoscalar behavior of the material. The meso scale of the concrete can be idealized considering the different phases of the composite. Thus, the interaction between those different phases (i.e. fibers, matrix, coarse aggregate and its interfaces) are explicitly considered.

  The mesoscale models take into account the phenomenon represented by the fiber-matrix bond, where each fiber is modeled as a discrete entity. These approaches provide a much more powerful description of the material behavior, modeling with special accuracy the cracking processes. The apparent macroscopic behavior observed is a direct consequence of a more complex mesoscopic phenomenon that takes place at the level of the material heterogeneity.

  The main disadvantages of these approaches are related on one hand, to the elevated computational cost and by the other hand to the big number of variables involved in the formulation of the model.
- Microscale models: they are based on a level of observation where the cementitious paste is described in terms of its chemical constituents. The typical models aim to model the microstructure of the composite where the cementitious paste is represented as a "net" of cement particles. This latter reacts together with a variety of components that leads to obtain hydrated products. The numerical modeling of this kind of hardened composites requires a wide scale of mathematical formulations and numerical methods related to hydration/dehydration concepts happened at the microstructure level. (van Breugel, 1991)

5 CONSTITUTIVE MODELS OF SFRC

Unlike that occurs in compression, the tensile behavior of SFRC is quite different from the common concrete. For that reason, one of the most important challenges is to develop a constitutive equation model that allows characterize properly the tensile behavior of this material.

SFRC should be understood as a concrete that includes in its composition discrete and short fibers, randomly distributed in its mass, which gives to the material a marked anisotropy and a non lineal behavior. Once that the concrete has cracked, the lost of adherence and fiber pull-out dissipate a great amount of energy, that leads to an important increase of the toughness. (Barros and Figueiras, 1999)

It should be considered on one hand the SFRC in the elastic range of deformations and, differentially, its behavior beyond the elastic limit. The SFRC structures should be calculated using a plastic analysis that allows to take advantage of the greater stress redistribution capacity provided by the contribution of fibers. However, it is not exists yet a constitutive model relative to the tensile behavior of the SFRC that can be considered better than others.(Álvarez, et al 2010).

5.1 Equivalent homogeneous model

As stated previously as a first step of an ongoing research, a first approach for the simulation of SFRC is consider it as a homogeneous material, that reduces the computational cost and the number of variables involved in the formulation of the model.

Basically, the equivalent homogeneous material model is a concrete model with identical elastic and no lineal compression properties that the concrete that forms the SFRC but with a hardening/softening modified curve in tension due to the contribution of the fibers. The curve that represents the tensile behavior of the SFRC can be obtained by tensile tests, indirectly by flexural tests or alternately by numerical methods. For it, we resort to a "plastic damage model" whose basics allows to simulate the multiaxial behavior of the concrete considering the phenomenon of stiffness degradation produced during plastic and elastic quasi-static load processes since the beginning of cracking process. (Oller et. al, 1988)

5.2 Damage-plasticity models

Experimentally it has been observed that the collapse mechanism in frictional materials like concrete is preceded by a non lineal dissipative process characterized by the concentration of deformations in strips with a very little thickess compared with the global dimensions of the structure. In them, irreversible processes of degradation and dissipation of energy (damage-plasticity) are concentrated while the rest of the solid experiments elastic unloading. The apparition of this strain localization mechanism implies directly or indirectly the beginning of material failure process, hence the importance of numerical models capable of simulate efficiently the phenomenon.The strips with highly localized strains can manifest under different forms which among cracking processes in structures built of mortar are found. (Sanchez, 2006)

A damage-plasticity constitutive model for the modeling of SFRC allows take the qualities of two failure mechanisms: by the side of the plasticity mechanism allows store inelastic strains (permanent) associated to a load-unload process of the material, and by the side of damage mechanism allows to generate a degradation of the elastic constants based in the evolution law of the damage variable. (Caicedo Silva, 2010)

5.3 Used model

For concrete, a modified damage-plasticity model is used (Luccioni, Rougier, 2005). By one hand, the plastic behavior is obtained as a generalization of the classic plasticity theory. As properties, the elastic properties of concrete base are used, changing only the tensile hardening curve to define the plastic threshold. The limit of the elastic behavior is defined by a yield function:

$$F^p(\sigma_{ij}; \kappa^p) = f^p(\sigma_{ij} - K^p(\sigma_{ij}; \alpha^k) \leq 0 \tag{1}$$

where $f^p(\sigma_{ij})$is the equivalent stress defined in the stresses space that could take the form of any of the yield functions of the classic plasticity (Tresca, Von Mises, Mohr Coulomb, Drucker Prager, etc.).

K$(\sigma_{ij}; \alpha_k)$ is the yield threshold and κ^p eis the plastic damage variable or isotropic hardening variable.

The following evolution rule for the plastic strains is defined:

$$\epsilon^p_{ij} = \lambda \frac{\delta G(\sigma_{mn}; \kappa^p)}{\delta \sigma_{ij}} \tag{2}$$

Where λ is the plastic consistency factor and G is the potential function.

The plastic hardening variable κ^p is obtained normalizing the dissipated energy in the plastic process to the unity and its varies between 0 for the virgin material and 1 when has been plastically dissipated all the energy that the material is capable to dissipate in this form.

The following evolution rule is used for the equivalent yield threshold:

$$K^p(\sigma_{ij}; \kappa^p) = rR^{op}\sigma_t(\kappa^p) + (1-r)\sigma_c(\kappa^p) \tag{3}$$

Where $\sigma_t(\kappa^p)$ y $\sigma_c(\kappa^p)$ represents the evolution of the yield threshold in tension and compression uniaxial tests respectively, while R^{op} is the ratio between the yield thresholds in unixaial compression and unixial tension. The load/unload conditions are derivate from the Kuhn-Tucker relationships formulated for problems with unilateral constrains.

$$d \geq 0 \quad F^p \leq 0 \quad dF^p = 0 \tag{4}$$

Considering now the damage process, and in analogous manner to the limit of plastic behavior, a limit or threshold damage is defined, which is described by a function with the following form:

$$F^d = f^d(\sigma_{ij} - K^d(\sigma_{ij}); \kappa^d) \leq 0 \tag{5}$$

Where, similarly to that seen in the plastic process $f^d(\sigma_{ij})$ is the equivalent stress defined in the stresses space, $K^d(\sigma_{ij}, \kappa^d)$ is the equivalent threshold damage and κ^d is the hardening damage variable.

The equivalent stress $f^d(\sigma_{ij})$ could be assessed using known functions of the plasticity theory as already exposed (Tresca, Von-Mises, Mohr-Coulomb or Drucker-Prager) or any other function especially developed for damage. The hardening damage variable varies between 0 for the virgin material to 1 for the material completely damaged. Is obtained normalizing the dissipated energy by damage to the unity. The following equation for the equivalent damage threshold is proposed:

$$K^d(\sigma_{ij}; \kappa^d) = r\sigma_t(\kappa^p) + (1-r)\sigma_c(\kappa^d) \tag{6}$$

where $\sigma_t(\kappa^d) y\ \sigma_c(\kappa^d)$ represents the evolution of the thresholds damage in uniaxial tension and compression respectively.

The load/unload conditions are derivate from the Kuhn-Tucker relationships and are analogous to the corresponding to the plastic process.

$$d \geq 0 \quad F^d \leq 0 \quad dF^d = 0 \tag{7}$$

The evolution of the plastic strains and damage is obtained from the simultaneous solution of the following equations named problem consistency conditions:

$$\begin{cases} F^p = 0 \\ F^d = 0 \end{cases} \tag{8}$$

These consistency equations are two lineal equations in λ and δ that can be easily solved.

6 NUMERICAL SIMULATION

The mechanical behaviour and the structural performance of the pipes were analyzed by the three edge bearing test according to standard ASTM C497. The set up of the elements for the execution of the test , according to the mentioned standard, is shown in Figure 2.

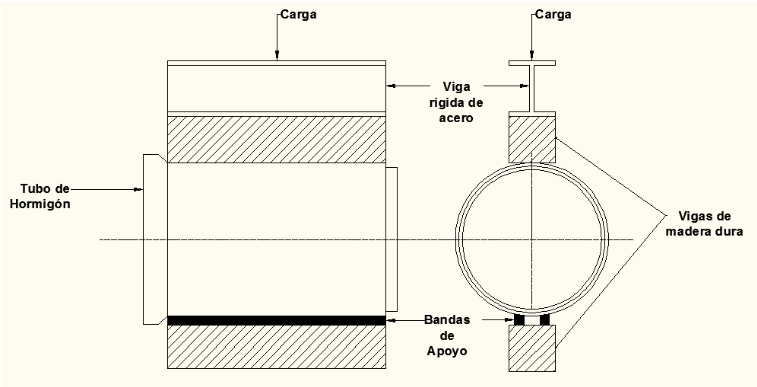

Figure 2: Set up of Three Edge Bearing Test according to ASTM C497

The adopted dimensions are the following: D_i= 300mm, wall thickness= 69mm (type C according standard ASTM C76).

A macromodel for the SFRC was used, where the material was represented as a equivalent homogeneous material. This model is implemented in a non-lineal finite elements code.

Triangular finite elements with three nodes and six degrees of freedom in plain strain state were used. In the Figure 3, the mesh adopted is depicted.

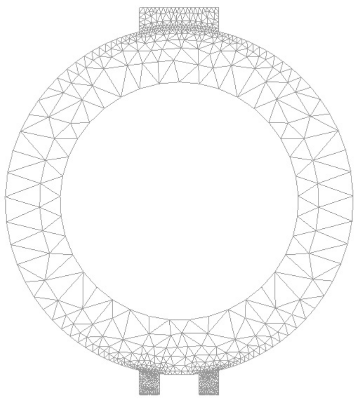

Figure 3: Finite elements mesh used

Both the pipe with the dimensions abovementioned as the lower and upper supports that are materialized with hard rubber strips, were modeled.

The obtained results show a concordance with the cracking mode of this type of pipes, where the higher tension stresses are focused in the inner sectors of the crown and the base. This stresses are those finally causes the failure. Is mentioned here that the model used is not capable to reproduce the behaviour up to the failure load. This problem could be overcome by a micro-mechanic approach that consider the fibers separately and randomly disperse in the concrete(Ruano Pascual, 2013).

In the Figure 4 a normal stresses distribution diagram coincident with the coordinates axis is shown.

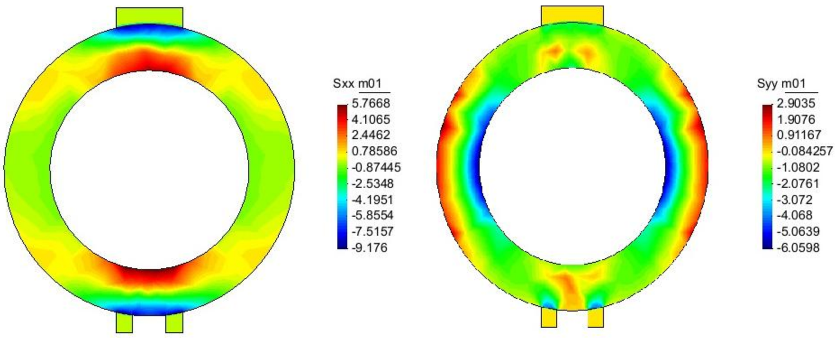

Figure 4: Normal stresses distribution diagram σ_{xx} and σ_{yy}

To verify and contrast the results obtained, they are compared with the found by other autors by experimental way (Mohamed et. al 2014). The parameters used in the simulation were taken from the Mohamed's work for the SFRC. A plain concrete mix without fibers (PC) and three SFRC mixes with different dosage of 20, 40 and 60kg/m^3 (SFRC20, SFRC40 and SFRC60) were modeled.

In the Table 1 the properties of each mix are exposed. The mechanical properties of the hard rubber are presented in Table 2.

Mix	PC	SFRC20	SFRC40	SFRC60
Young Modulus (Mpa)	35.79	34.85	37.77	34.37
Poisson's Ratio	0.5	0.5	0.5	0.5
Compression ultimate strength(MPa)	45.8	52.88	58.02	61.64
Tension ultimate strength (MPa)	5.59	6.76	7.32	7.92
Yield threshold (Mpa)	34.35	40	43.5	46.23
Initial compression/tension strength ratio	8.2	7.8	7.93	7.78
Plastic hardening variable, κ_p	0.2			
Fracture energy (N/mm)	0.1	2.58	5.4	8.55
Crushing energy (N/mm)	6.72	156.9	339.6	517.5
Fluence criterion	Lubliner - Oller			
Potential criterion	Lubliner - Oller			

Table 1: Mixes mechanical properties

Hard rubber properties	
Young Modulus (MPa)	2600
Poisson's Ratio x-x	0.15
Poisson's Ratio x-z	0.015
Poisson's Ratio z-y	0.15
Compression ultimate strength (MPa)	11
Tebsion ultimate strength (MPa)	11
Maximum elongation (%)	300
Initial compression/tension strength ratio	1
Fluence criterion	Tresca

Table 2: Hard rubber mechanical properties

The numerical values obtained as well as the experimental values for cracking loads (P_f) for different dosage together with the mix without fibers are summarized in Table 3.

Fibers dosage (kg/m^3)	P_f Experimental (N/mm)	P_f Numeric (N/mm)
No fibers	136	132
20kg/m^3	151	160
40kg/m^3	160	171
60kg/m^3	157	185

Table 3: Cracking loads according experimental tests and numerical model

As can be observed, the values numerically obtained have correlation with the experimental ones, with a difference that not exceed 10% overstimating the experimental value. As a further stage, it is suggested to include other dosages to confirm or not the trend observed in the numerical results.

7 Conclusions

The mechanical behaviour of SFRC pipes was simulated by a simple model, as a first stage of a ongoing research, where the SFRC is modeled as a homogeneous composite (macro scale). The governing equations were solved by the Finite Elements Method, and the results were compared with those obtained experimentally by others authors.

It is observed that the addition of steel fibers improves the mechanical behaviour of concrete pipes increasing the load that they can resist up to the cracking. While the numerical model used has a good correlation with the experimental results up to the moment of cracking, it seems overstimating the effects of the fibers in the pre-crack stage, because always were obtained values higher to the experimental ones.

As a further stage in the current ongoing research, is proposed the use of a micromodel that explicitly consider the fibers as discrete entities inside the cementitious mix, taking into account its interaction with the matrix, considering pull-out events and others that take place in the matrix-fiber bond. These micromodels take as data the mechanical properties of the fiber and its volumetric proportion in relation to the total of the mix achieving to reproduce the behaviour of the SFRC up to the failure.

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