DAMAGE EVOLUTION INVESTIGATION IN STEEL AND POLYPROPYLENE FIBER REINFORCED CONCRETE

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Abstract. *In fiber-reinforced concrete cement-based materials, the random dispersion of discrete fibers in the cementitious matrix causes deviations in the global structural behavior. Bending tests are crucial to analyze the mechanical performance of the composite for project and design at a structural level. Different numerical approaches have been employed in the literature in order to analyze fracture propagation and damage evolution in fiber reinforced concrete beams under bending. Traditionally, the association of probabilistic and numerical approaches reproduces the variability regarding the fiber dispersion in the cement matrix and its influence in the material mechanical behavior with less computational effort. In this sense, this paper proposes a damage evolution investigation to perform a numerical fracture analysis using the Extended Finite Element Method (XFEM). Mixed-mode fracture behavior is considered. Probability density functions are used to generate random values of tensile strength, which are assigned to each finite element in the model. These numerical methodologies are based on a constitutive damage model, adjusted to experimental results of failure mechanisms in fiber-reinforced concrete. The numerical analyses reproduce experimental tests reported in the literature by Monteiro et al. (2018), as the three-point bending tests, for steel and polypropylene fibers. The results show that the probabilistic techniques can efficiently predict the load-displacement behavior at the macroscale since the load capacity ranges present a good agreement with the experimental reference. Moreover, it is possible to study and predict the fracture behavior of the beam in mixed mode based on numerical models and Computational Damage Mechanics.*

Keywords: *Fracture; Fibers; Damage; Composite Materials; Finite Element Analysis.*

1 Introduction

In recent decades, due to its excellent mechanical properties, fiber reinforced concrete (FRC) has been widely studied in Civil Engineering. The addition of fibers in the cement matrix can reduce the brittleness of the composite material (Congro *et al*. [1]; Figueiredo [2]; Silva *et al.* [3]). Naaman [4] points out that up to 1960s, these investigations had almost no applications, once the scientific knowledge was not developed to the point to identify the most significant benefit of fiber reinforcement: the energy absorption capacity. Since then, the modern developments of FRC verified that fibers are capable of significantly increasing the cracking tensile strength of concrete. Many fiber materials were introduced in the civil engineering industry and new applications have been discovered.

Figueiredo [2] points out that the increment in the composite fracture energy is due to the fiber bridging mechanism, where fibers work transferring the stresses from matrix to the reinforcement during crack propagation. This bridging process significantly decreases the crack opening velocity in the cement matrix and provides a bigger post cracking carrying capacity to the composite. The studies of the application of discrete fiber reinforcement in concrete are not limited to experimental procedures. Numerical methods are also capable of predicting the composite mechanical behavior. According to Congro *et al.* [1], one typical mathematical model carried out for macroscale analysis considers homogeneous equivalent properties taken from experimental curves of the material. An example is Zhan *et al.* [5] work, which validates FRC beam numerical models at the macroscale using an embedded crack approach.

The anisotropic behavior of the composite due to fiber random dispersion in the cement matrix is described through a probabilistic approach coupled to finite element simulations (Naaman *et al*. [6] apud Congro *et al.* [1]). Congro *et al.* [7] reported that the composite tensile strength is the most sensitive material parameter. Thus, the probabilistic functions were used to generate random tensile strength values that were included in the elements of the finite element model.

This methodology was also used in the study reported by Congro *et al*. [1] to represent steel FRC behavior in uniaxial tensile tests. Here, the methodology is applied to model both the steel and polypropylene FRC macroscale bending behavior.

This paper proposes the application of probability density functions to model the random dispersion of fibers in the cement matrix for steel and polypropylene fiber reinforced concrete in three-point bending tests. This methodology adopts equivalent properties for the composite, calibrating the numerical parameters considering the experimental results reported in the literature by Monteiro *et al.* [8]. Moreover, the Extended Finite Element Method (XFEM) is selected to model crack propagation in the matrix.

2 Experimental Procedure

The finite element analyses were carried out using the commercial software Abaqus ®. These simulations were based in the three-point bending experimental study reported by Monteiro *et al.* [8] with steel and polypropylene fiber reinforced concrete (SFRC and PFRC, respectively). The steel and polypropylene fiber aspect ratio are 80 and 74, respectively; the fiber volume fractions used are 2.00% and 0.66%, respectively; the specimen dimensions are 550 x 150 x 150 mm. The finite element simulations were carried out using linear quadrangular elements (Q4) with full integration and displacement control. Table 1 presents the input parameters reported by the experimental tests, where E refers to the composite Young modulus, Sd refers to the standard deviation of the property; Ft is the composite tensile strength and Delta is the displacement at failure.

Table 1. Input parameters for the composite model considering Monteiro *et al*. [8]

Composite	E (MPa)	Sd	Ft (MPa)	Sd	Delta (mm)
SFRC	32800	1000	5.47	0.54	11.00
PFRC	20450	500	1.92	0.14	0.63

According to Congro *et al*. [7], the random dispersion of fibers in the cement matrix leads to deviations in the global mechanical behavior of fiber reinforced concrete at the macroscale. The fiber random dispersion effect was incorporated in the models through a subroutine written in MATLAB ® , which generates different tensile strength values for each element of the central region of the model. The fibers were incorporated only at the central section of the model to reduce computational cost. Additionally, it is a well-known fact that the critical fracture will be located in the central region of the specimen. The tensile strength parameter is generated considering the standard deviation value provided by the experimental test. For the current investigation, the tensile strength values generation was based on the normal and the logistic probability density functions. In this sense, the variation of tensile strength in each central element of the numerical model with probability density functions can include the effects generated by the random fiber dispersion during the concrete mix procedure.

The main idea of the probabilistic study of this paper is to reproduce the three-point bending test through a finite element analysis. Figure 1 summarizes the workflow for the numerical and probabilistic analyses developed in this paper. Firstly, a three-point bending finite element model is built (Figure 2). Secondly, using a sub-routine developed in MATLAB, random values of tensile strength are generated, according to the probability function that governs the random distribution of this parameter. These values will be assigned to each element in the central region of the model, given the expectation of fracture in this region. Then, the computational analyses are carried out in the finite element software Abaqus ®. Finally, load-displacement curves present the global structure response.

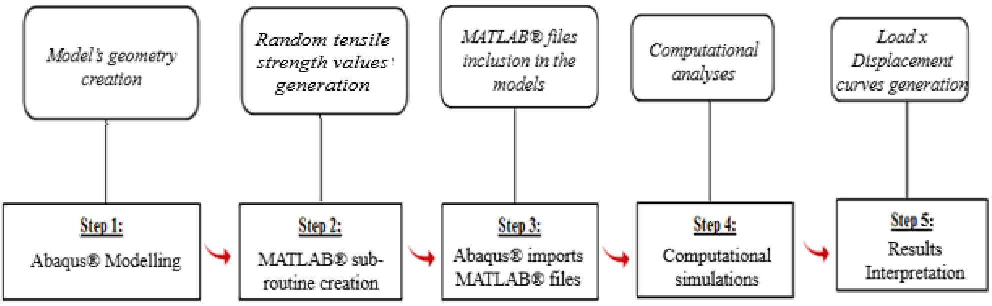


Figure 1. Workflow for the numerical analyses.

Several runs for each probability function are carried out in order to analyze the global behavior of the composite. Figure 2 shows the FE mesh considered for the numerical simulations for both fiber types and the boundary conditions for the 3-point bending test model.

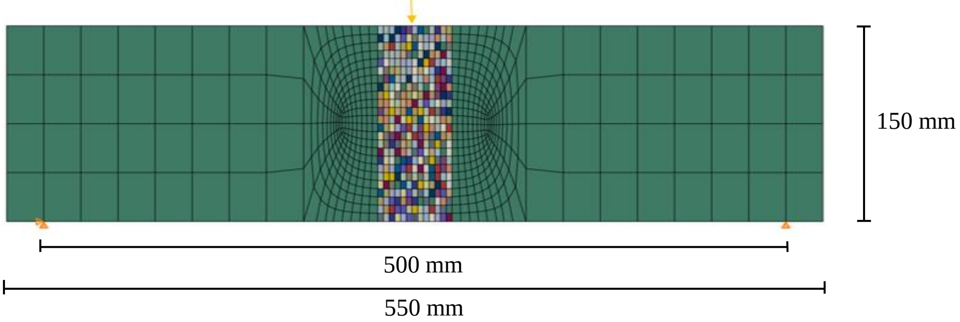


Figure 2. Finite element model and boundary conditions for the three-point bending test.

3 Results and Discussion

3.1 Steel Fibers

Figure 3 compares the experimental curves obtained by Monteiro *et al.* [8] for the steel fiber-reinforced concrete (SFRC) and the finite element analyses, considering probability functions to simulate the random reinforcement dispersion in the cement matrix.

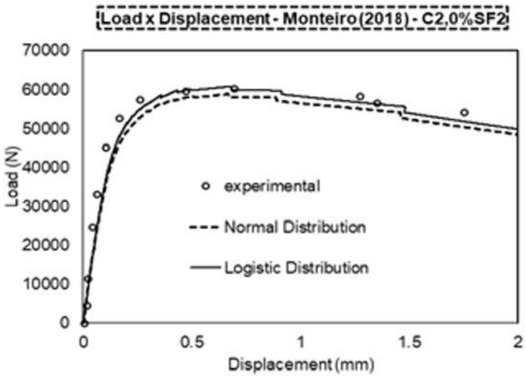
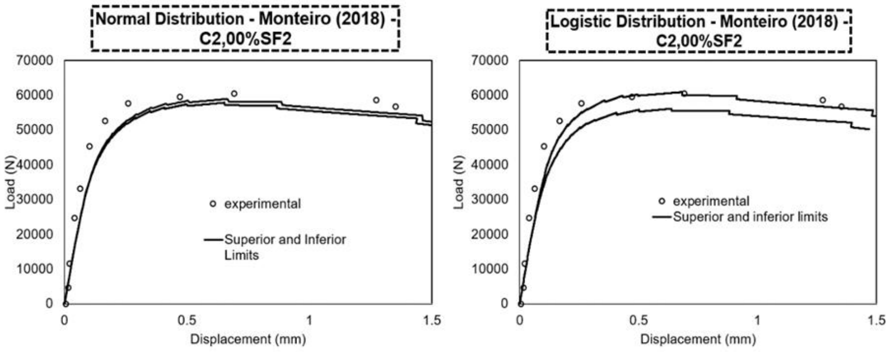


Figure 3. Load-displacement curves for SFRC: experimental results and finite element analyses considering normal and logistic probability distributions.

According to Figueiredo's [2] tensile and bending experimental results, the addition of fibers to the matrix can significantly increase the material fracture energy and, consequently, its post cracking carrying capacity. Monteiro *et al.* [8] reached similar results through experimental tests. The curves in Figure 4 show that the numerical analyses can simulate the mechanical behavior of fiber reinforced concrete at the macroscale successfully. Moreover, the logistic probability distribution curve was fitted better the experimental reference results because the random generation of tensile strength values represents more accurately the fiber dispersion effect in the cement matrix.

Several analysis sets were carried out for each probability function in order to assess the random tensile strength parameters considering normal and logistic probability functions. Figures 4 (a) and (b) indicate the lower and upper limits for the load-displacement curve of the steel fiber reinforced concrete considering the random values for tensile strength. These multiple runs are performed in order to evaluate the deviations in the mechanical behavior of the composite due to the random dispersion of fibers.



(a) (b)

Figure 4. Load-displacement curves for SFRC considering the random dispersion of fibers: (a) normal distribution; (b) logistic distribution.

3.2 Polypropylene Fibers

Figure 5 compares the load-displacement experimental curves obtained by Monteiro *et al*. [8] for the polypropylene fiber-reinforced concrete (PFRC) and the finite element analyses considering probability functions to simulate the reinforcement random dispersion in the cement matrix.

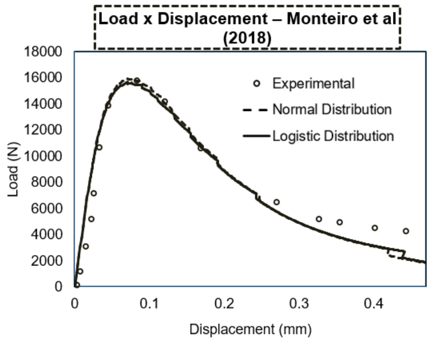
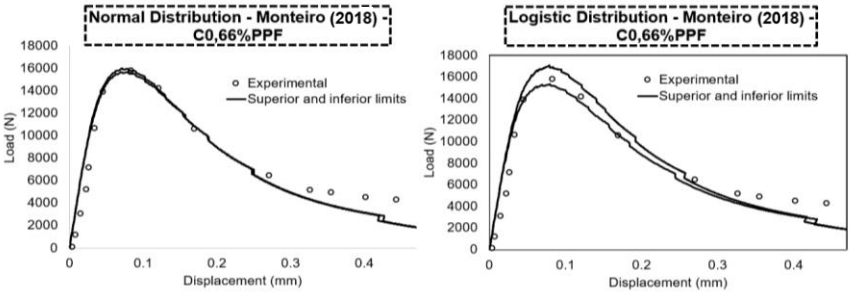


Figure 5. Load-displacement curves for PFRC: experimental results and finite element analyses considering normal and logistic probability distributions.

Figures 6 (a) and (b) indicate the lower and upper limits for the load-displacement curve of the polypropylene fiber reinforced concrete considering the random values for tensile strength. These multiple rounds are performed in order to evaluate the deviations in the mechanical behavior of the composite due to the random dispersion of fibers.



(a) (b)

Figure 6. Load-displacement curves for PFRC considering the random dispersion of fibers: (a) normal distribution; (b) logistic distribution.

According to the sets in Figure 6, the normal probability distribution was able to better simulate the experimental curve for PFRC. In this sense, the FEM analyses with homogenous properties allied to probability methodologies can successfully represent the mechanical behavior of the polypropylene fiber reinforced concrete at the macroscale.

4 Conclusions

This paper proposes the methodology for the numerical simulation of the behavior of fiber reinforced concrete at the macroscale under bending conditions. The adoption of probability distribution functions to generate random mechanical properties to the numerical models was capable of simulating the influence of the fibers in the reinforced concrete. For the same specimen and the same probability distribution function, the load-displacement curves are sensitive to the random generation set. Then, it was possible to analyze each probability function sensitivity in this application. Also, the FE simulations considering the logistic distribution for the parameters presented a higher sensitivity for three-point bending test models. However, it was not possible to confirm which probability function is more accurate for the current application. A more definite conclusion would require thousands of simulations. In the polypropylene fiber concrete analysis, the normal distribution provided results, which were closer to the experimental curve, while in the three-point bending test applied to steel fiber concrete, the logistic distribution seemed better. In this sense, this study was able to make a probabilistic sampling with accurate results. Finally, this technique is verified for bending tests and demonstrates that it can adequately simulate the composite global behavior at the macroscale.

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Authorship statement.

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