# ASSESSMENT OF THE LOAD CAPACITY OF FIBER REINFORCED CONCRETE

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**Abstract**

Prediction and verification of material properties are essential to ensure the performance of most engineering structures. For those involving composite materials, as fiber reinforced concrete, the main target of probabilistic studies is not only related to the concepts of lifespan and durability, but also to how fiber distribution affects the macro material behavior. In practice, during the concrete mixing process, steel fibers are randomly distributed and dispersed under the cementitious matrix. According to fiber arrangement, orientation, and geometry, fractures can propagate along different paths. Computational simulations are employed to predict load capacity of a given structural system.

This paper presents the numerical modelling of direct tensile test for a fiber reinforced concrete. Cohesive interface elements are used to model the steel fiber behavior within the concrete matrix. These cohesive elements are placed at the edges of the solid elements, allowing fracture propagation. In order to reproduce the effect of the random distribution of steel fibers within the cementitious matrix, random values of elasticity modulus E and tensile strength $\sigma_{r}$ are assigned to each solid and cohesive element, respectively. Marangon (2011) provides the mean and standard deviation values of the experimental data. Normal, lognormal and logistic distributions are considered for each parameter. Three distinct simulation sets are analyzed: (i) structured mesh with random elasticity modulus for each solid element, (ii) structured mesh with random tensile strength for each cohesive element, and (iii) unstructured mesh with random tensile strength for each cohesive element. For each set, the predicted fracture paths and load capacity present satisfactory results when compared to those obtained experimentally by Marangon (2011). All three-distribution functions lead to results in the expected experimental range. The results also show that the fiber dispersion and orientation contribute to the structural load capacity, increasing the structure durability.

## 1. INTRODUCTION

In recent years, engineers are creating and using software that perform numerical analysis and optimization techniques with high levels of accuracy. It is important to observe that, despite the robustness of the model, the predictions, assumptions or idealized conditions may or not reflect the real phenomena. Therefore, engineering decisions are typically analyzed considering some conditions of uncertainty and their respective associated risks.

For structures involving composite materials, as fiber reinforced concrete, the main goal of probabilistic studies is to determine how fiber distribution interferes in its properties. In practice, during the concrete mixing process, steel fibers are randomly distributed and dispersed under the cementitious matrix. According to fiber arrangement, orientation, and geometry, fractures can propagate along different paths. Therefore, computational simulations are employed to predict load capacity of a given structural system. In addition, the random layout can be modeled by considering the distinct probability distributions, such as normal, lognormal and logistic functions.

Through repeated simulations, it is possible to obtain a measure of sensitivity of system response to changes in the input parameters. Finally, after these simulations, it is determined which distribution best approximates the load-displacement curve obtained when mathematical models are employed in order to represent fracture propagation.

## 2. EXPERIMENTAL AND NUMERICAL PROCEDURES

The probabilistic analysis developed in this paper is based on the direct tensile test reported in the literature by Marangon (2011). Congro et al (2017) present a numerical analysis of this test by using numerical algorithms for fracture modeling, as the Interface Element Model and the Extended Finite Element Method (XFEM). Thus, the probabilistic analysis developed in this study gives continuity to the numerical simulation of a fiber reinforced concrete structure.

A rigid system with fixed ends was introduced in order to perform the direct tensile test. The apparatus for the experimental program comes down to the use of two accessories connected together by steel plates bonded to the specimen with an epoxy resin. Figure 1 indicates the schematic representation of the experimental test (Marangon, 2011).

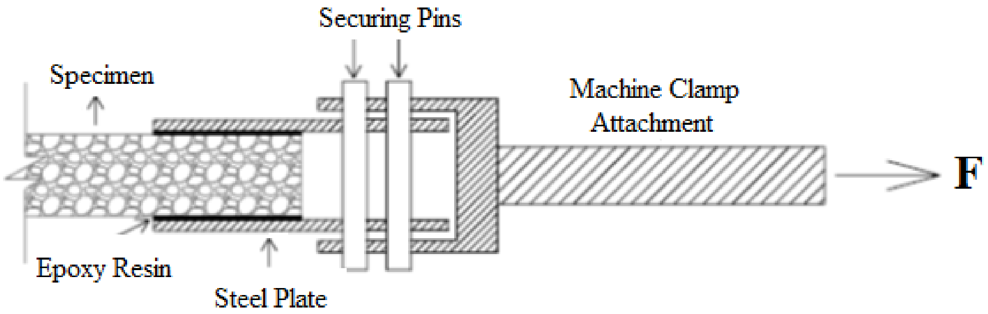
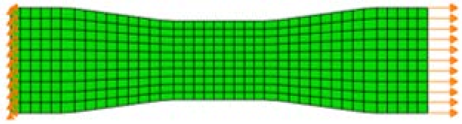



Figure 1. Schematic representation of the direct tensile test (Adapted from Marangon, 2011).

The direct tensile test reported by Marangon uses a prismatic specimen reinforced with steel fibers. This prismatic element is set at one of its edges and submitted to axial extension on the opposite side. The concrete matrix was discretized with quadrilateral elements (9.5 x 7.5 mm) under the assumption of linear elasticity. The numerical test was performed using arc-length control, with the adoption of an exponential softening model for the interface elements. Figure 2 presents the element mesh and the input parameters for the simulation.

| Fiber Reinforced Concrete | |
|---|---|
| E (GPa) | 35,77 |
| $v$ | 0,2 |



| Fracture | |
|---|---|
| $\sigma_r$ (MPa) | 4,65 |
| $\alpha$ | 1,3 |
| $\Delta\delta$ (mm) | 4,62 |

Figure 2. Element mesh and input parameters for the numerical analysis (Congro et al, 2017).

All results from the numerical simulations considering the properties above are indicated in Congro et al (2017).

## 3. FIBER ARRANGEMENT IN REINFORCED CONCRETE

In recent decades, fiber reinforced composites have been widely used in engineering structures and in high technology areas, especially due to their excellent mechanical properties. The addition of ductile fibers in the brittle matrix can significantly improve the brittleness of the matrix material. The hardening stress is determined considering the effects of the individual fibers along the structure's rupture plan, according to the crack stress-aperture curve.

The mathematical formulations employed to compute the critical fiber volume in the reinforced concrete are not checked under practical conditions, since this formulation considers that fibers are continuous and perfectly aligned to the main stress axis. In practice, fibers are discontinuous and randomly distributed in the concrete matrix. Thus, their actual behavior in concrete is different from that predicted by the formulations of Aveston, Cooper and Kelly (1971).

The variability in the cross-section of the fibers, for example, will provide deviations in their area, and consequently the force that each fiber can withstand. The variations of the fiber stiffness in the concrete matrix also influence the strength properties of the material, providing different behaviors for the composite material according to the random dispersion of the fibers (Figure 4). The elasticity modulus is variable not only for steel fibers, but also can be extended to any other fiber type, in particular to natural fibers, such as sisal and bamboo.

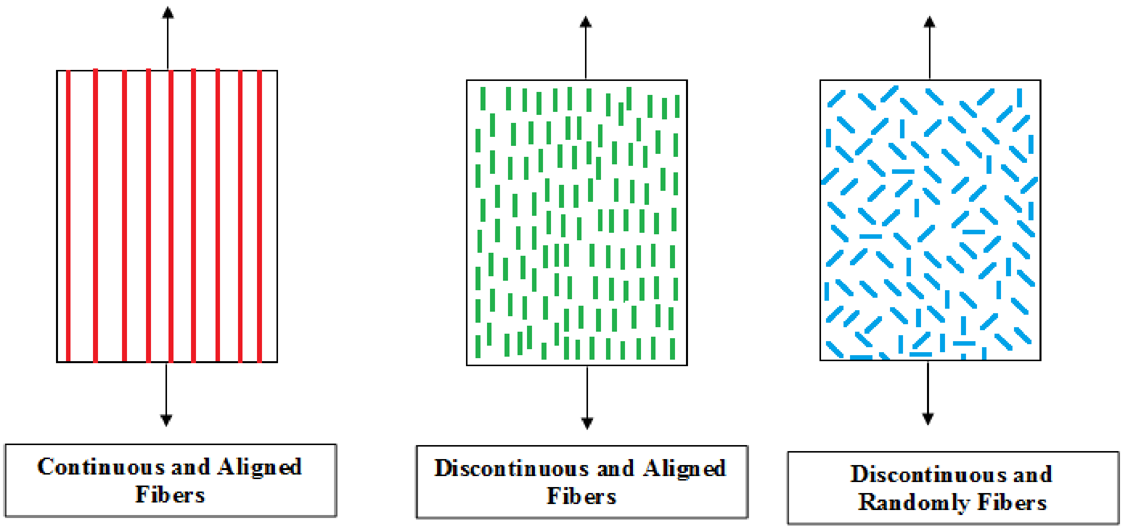



Figure 4. Representation of fibers and their respective arrangement.

In this way, the random values of stiffness and tensile strength used in the numerical simulations represent distinct values of fiber parameters in the concrete matrix. These arrangements gather random variables with known or assumed probability distributions. It is possible, in this way, to carry out repeated simulations, using in each of them a particular set of values of the random variables, originated according to the respective functions of a probability distribution. Thus, the results of the simulations are statistically variable, converting response distribution rules into response variables, allowing predictions of the structural system behavior.

## 4. PROBABILISTIC ANALYSIS

For the analysis of the load capacity of the reinforced concrete specimen with fibers, three probability density functions that best fit numerical modeling were considered: normal distribution, lognormal distribution and logistic distribution. These probability functions were chosen because Marangon (2011) explicitly provides the mean and standard deviation values of the samples tested for the direct tensile test. In this sense, the random generation of the material parameters was easier and more intuitive.

The main idea of the probabilistic study of this paper is to reproduce the direct tensile test in a finite element analysis. Secondly, using a sub-routine developed in *MATLAB*, random values of elasticity modulus 'E' and tensile strength $\sigma_r$ are generated, according to the probability function that governs the random distribution of these parameters. These values will be assigned to each of the elements in the central region of the mesh, given the expectation of fracture occurrence in this region. Figure 5 exhibits the computational model that replicates Marangon's direct tensile test.

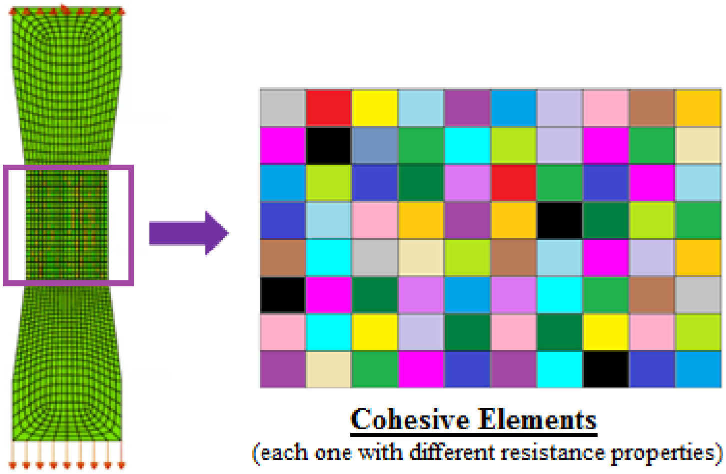



Figure 5. Computational model and detail of the central region of the specimen where the fiber properties are modified.

Two strength properties of the fiber reinforced concrete were modified: the elasticity modulus 'E' of the random fibers and, subsequently, the tensile strength $\sigma_r$. In this way, three distinct simulation sets were developed: (i) random generation of stiffness values for each element using a quadrangular structured mesh, (ii) random generation of tensile strength for each element using a quadrangular structured mesh and (iii) random generation of tensile strength for each element using unstructured mesh. The third simulation set was also included in the analyses since the fracture propagation path is better approximated through a non-structured mesh, representing accurately the structure behavior.

### 4.1. First Simulations Set

The first simulation sets used random values of elasticity modulus E, following normal, lognormal and logistic distributions. These numerical values were properly associated with the elements in the central region of the specimen. The analyses were repeated at least five times for each distribution. Table 1 summarizes the mechanical properties of the fiber reinforced concrete used throughout these simulations.

Table 1 – Fiber reinforced concrete mechanical properties for probabilistic simulations of Simulation Sets I.

| **Fiber Reinforced Concrete** | |
|---|---|
| E (GPa) | Variable |
| $\upsilon$ | 0.2 |
| $\sigma_r$ (MPa) | 4.65 |

Figure 6 presents the damage evolution variable for some simulation rounds, comparing the fracture propagation with the experimental results. This figure brings the best results for each distribution, although more rounds were performed during the analysis.

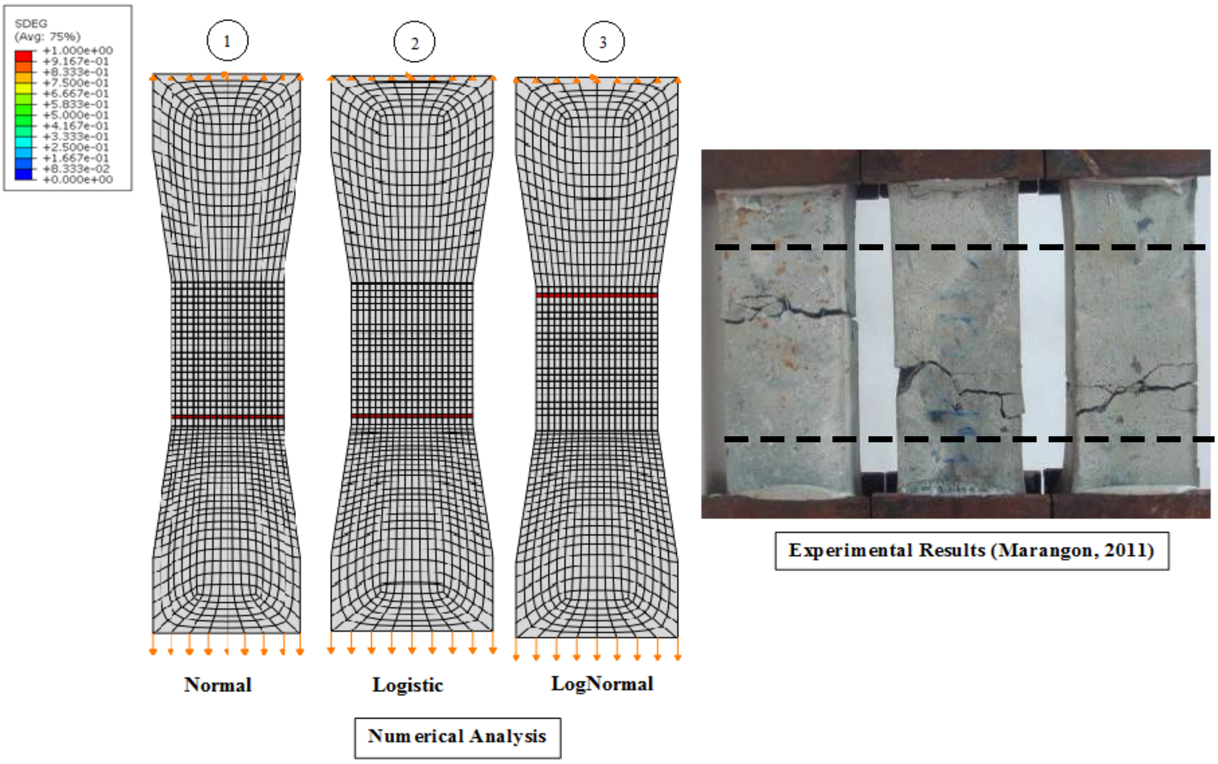



Figure 6. Comparative analysis of fracture propagation for the best simulation rounds in Simulation Sets 1.

### 4.2. Second Simulation Sets

The second simulation sets generated random values for the tensile strength $\sigma_r$, following normal, lognormal and logistic distributions. These numerical values were associated with the elements in the central region of the specimen. The analyses were repeated at least five times for each distribution. Table 2 summarizes the mechanical properties of the fiber reinforced concrete used throughout these simulations.

Table 2 – Fracture mechanical properties for probabilistic simulations of Set 2.

| **Fracture** | |
|---|---|
| $\sigma_r$ (MPa) | Variable |
| $\alpha$ | 1.3 |
| $\Delta\delta$ (mm) | 4.62 |

Figure 7 presents the damage evolution variable for some simulation rounds, comparing the fracture propagation with the results obtained experimentally. These are the best matches for each distribution, although more rounds were performed.

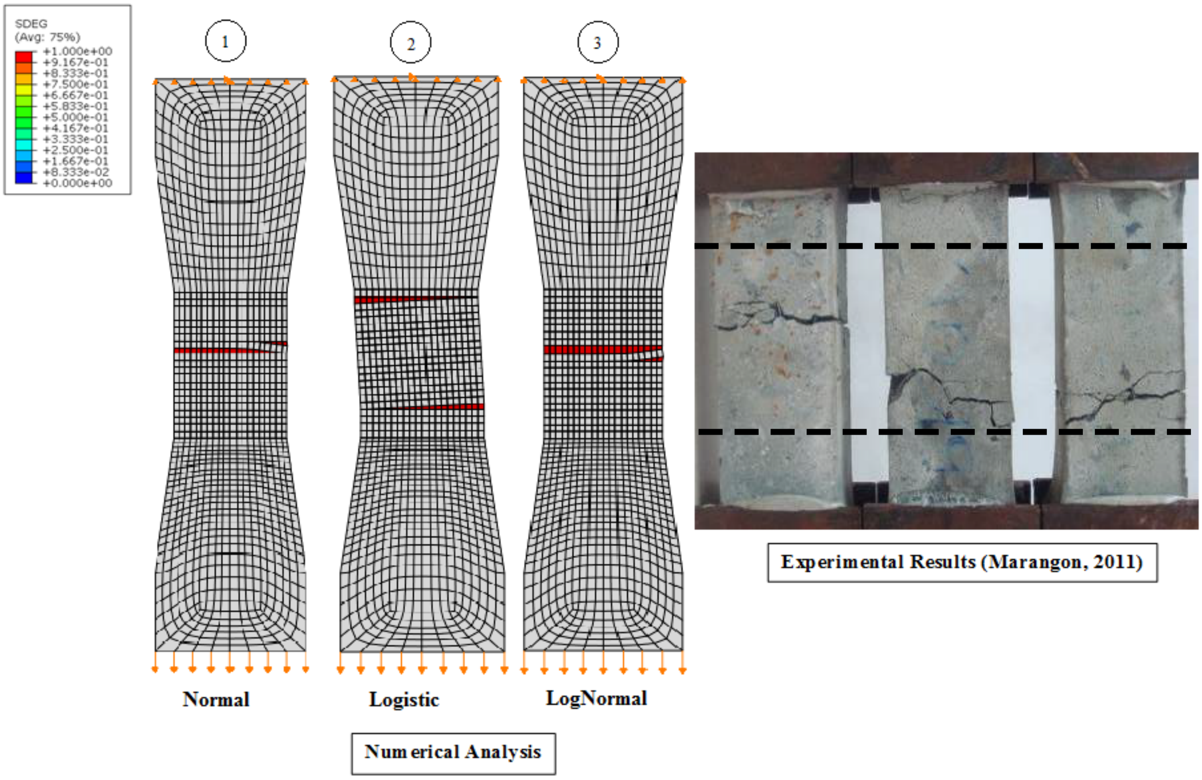



Figure 7. Comparative analysis of fracture propagation for the best matches to experimental data in Set 2.

### 4.2. Third Simulation Sets

The third simulation sets generated random values of tensile strength $\sigma_r$, following normal, lognormal and logistic distributions for a non-structured finite element mesh. These numerical values were associated with the elements in the central region of the specimen. The analyses were repeated at least five times for each distribution. The fracture mechanical properties are the same from the second simulation sets.

Figure 8 presents the damage evolution variable for some simulation rounds, comparing the fracture propagation with the results obtained experimentally in the central area. This figure shows the best results for each distribution, although more rounds were performed.

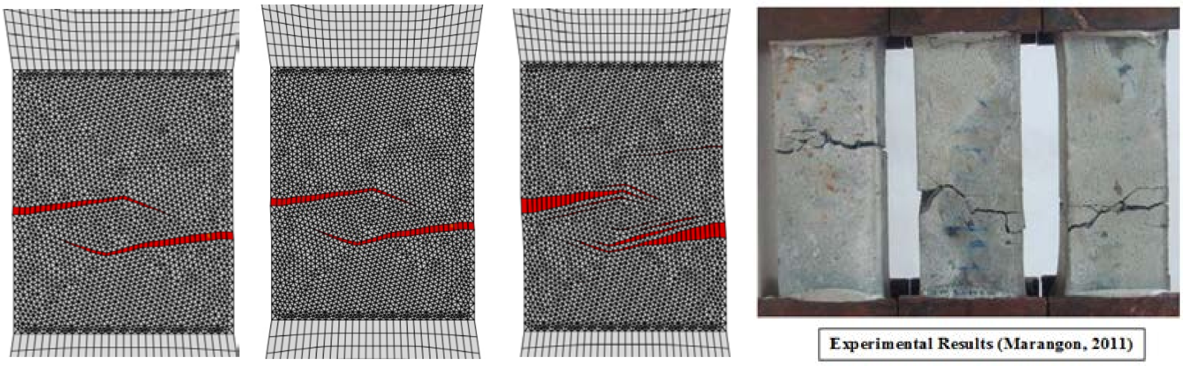



Figure 8. Fracture propagation for the best simulation rounds the third sets.

Finally, Figure 9 compares the load-displacement curves for all three-simulation sets analyzed during this paper. Each plot exhibits the probability distribution that best represents the structure behavior during the analysis.

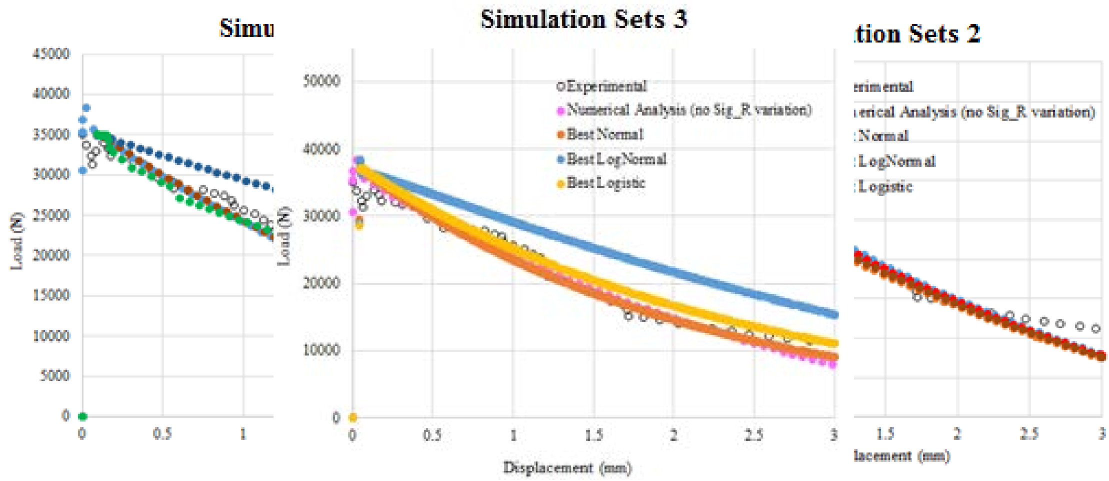



Figure 9. Load-displacement curves for each studied sets.

## 5. CONCLUSIONS

This probabilistic study was carried out in order to verify the influence of the dispersion and orientation of the steel fibers in the concrete matrix. It is important to emphasize that the addition of fibers in concrete structures reduces the effects of crack propagation in the material, due to the phenomenon of the shear stress transfer. The many possibilities of orientation of steel fibers produced some distinct behaviors in the load-displacement curves of the specimen. This effect is due to the arrangement of the fibers, which can take place in multiple directions, favorable or not to the applied load. Three distribution functions define the parameter values, randomly modifying each element of the central region of the part.

In a first simulation set, a structured mesh was used and the elasticity modulus E was modified for each of the elements of the central region of the specimen. This region has undergone a greater refinement, since it is where the fracture process occurs in this type of test. The second simulation set used a structured mesh, modifying the tensile strength $\sigma_r$ . Finally, the third set of simulations maintained the same procedure of the second set, adopting a non-structured element mesh, aiming at allowing more generally the fracture paths.

All three-distribution functions lead to results in the expected experimental range. The results also show that the fiber dispersion and orientation contribute to increase the structural load capacity. The third numerical model reached good levels of accuracy, due to the adoption of an unstructured mesh capable of reproducing the crack propagation pattern in the reinforced concrete material, as reported by the experimental procedures. In addition, fibers constitute an efficient reinforcement for the concrete, and their inclusion reduces the appearance of cracks, increasing structure durability. In this sense, the numerical simulation using cohesive elements allied to probability functions becomes an attractive approach to predict fiber reinforced concrete behavior.

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