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# Investigation of Concrete Damaged Plasticity for steel fiber reinforced concrete through numerical analysis

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**Abstract.** The use of reinforced concrete with steel fibers (SFRC) in conventional structures has grown in civil construction due to its mechanical characteristics, which have advantages when compared to conventional concrete as better responses to tensile stresses and post-fissuring behavior. These factors lead researchers to deepen their studies on properties and computational models in order to obtain better predictions for the structures built with this composite. This work then has the main objective compare the Concrete Damaged Plasticity (CDP) parameters suggested by Chi et al. [1] to the default used for plain concrete, simulating the SFRC as homogeneous material. The presented analysis is performed using the finite element method (FEM), using the ABAQUS software as a processing environment. Uniaxial tensile and compressive test parameters are used as input to calculate the CDP parameters for SFRC. Beam models are tested according to the proposed test parameters EN-14651 using the parameters suggested by Chi et al. [1] and default values for concrete. The model showed resistance, within the acceptable margins, consistent with the experimental ones. However, these changes in CDP parameters showed a little impact on mechanical response and curve shape. This process of obtaining the constitutive behavior for SFRC proved to be acceptable from the practical point of view since it uses the results of tests of easy execution as input parameters, but a few adjustments need to be done in order to obtain reliable results.

**Keywords:** steel fibers, steel fiber reinforced concrete, SFRC, concrete damaged plasticity, ABAQUS.

## 1 Introduction

Concrete, agglomerate resulting from the mixture of cement, water, small and large aggregates, and, eventually, additives and/or additions, is the most widely used construction material [2]. This composite has been the most used structural material in the world due to its low cost of production and application, in addition to the ability to adapt to the most varied forms and construction processes. It also has the advantages of easy handling and application, and high resistance to compressive stresses.

Despite its advantages, concrete has a characteristically fragile behavior and relatively low tensile strength, reaching only 10 % of its compressive strength.

The addition of fibers to the cementitious matrix appeared with the same intention of applying steel reinforcement. This component proved to be a great alternative for improving tensile performance. The fibers act as tensile reinforcement, improving its performance as a whole, due to a reduction of the characteristic fragile behavior of this material. The fibers, in addition to being more efficient in the control of the concrete cracking process, contribute to improve several mechanical properties such as shear, torsion and fatigue resistance when compared to those of conventional concrete [3].

Among the different types of fibers, steel fibers are the most used for structural applications and are taken into account in many non-structural applications [2]. Steel fiber reinforced concrete (SFRC) is characterized as a heterogeneous mixture, combining the characteristics of its components generating a composite with better mechanical aspects. Steel fibers are manufactured in the most diverse formats, aiming at the production of a resistant SFRC by providing a better adhesion and anchoring of these elements to the concrete matrix.

With the above mentioned, studying the constitutive behavior of such material has a important hole in constructing or reformulating tools and design standards that guarantee greater safety in structures with SFRC, in addition to exploring their performance more efficiently and economically.

Therefore, this work has a main objective present a study through finite element analysis in order to validate the Concrete Damaged Plasticity as model to simulate SFRC behaviour using as input tensile and compressive constitutive models and formulations for CDP parameters found in literature.

## 2 Concrete Damaged Plasticity

It was decided to adopt the Concrete Damaged Plasticity (CDP) damage model to represent the non-linearity intrinsic to the behavior of the SFRC. The CDP is a model of continuous damage with plasticity that applies the concept of elastic damage along with isotropic traction and compression plasticity to simulate the behavior of concrete.

The model takes into account parameters related to the biaxial state of tension in the concrete and the constitutive data under monolithic tension for uniaxial compressive and tensile stresses. For uniaxial stresses, in both compression and traction, the material is loaded till it reaches the maximum resistance, then, it begins to suffer from a stiffness degradation represented by the minoring factors $d_t$ e $d_c$ for tensile and compressive stresses respectively, as showed in figure 1. The damage factors range from 0 (undamaged composite) to 1 (totally damaged composite).

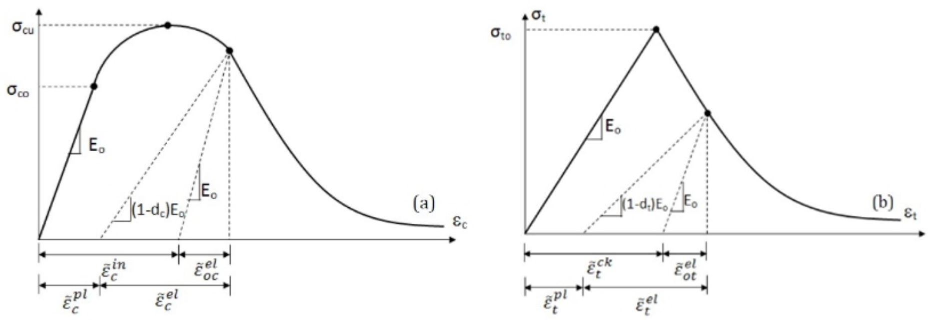


Figure 1. Constitutive behavior under uniaxial (a) compression and (b) tensile stress.[4]

In the Haigh-Westergaard space, the stress state of any infinitesimal element is characterized by the principal stresses $\sigma_1$, $\sigma_2$, and $\sigma_3$. If the main stresses represent an internal point on the failure surface, there is an elastic behavior, or that is, there is no yield of material. If the point is exactly on the failure surface, the infinitesimal solid flow starts and if the yielding tension is exceeded, the point will be outside the failure surface, in which case two situations are possible: a material failure or an increasing deformation with no changes in tension (ideal plasticity). [5]

The value of $K$ determines the shape of the yield surface for the material. This variable is defined as the ratio between the distance of the hydrostatic axis to the compressive and tensile meridians in the deviatoric plane. For general cases involving concrete, the module for this relation is 2/3 (figure 2).

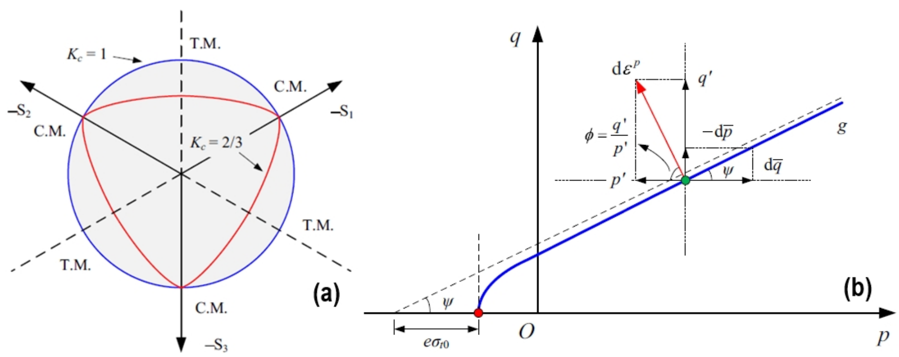


Figure 2. (a) Failure surface in the deviatoric plane; (b) Potential flow in the meridional plane.[4]

The failure surface is a geometric combination of two different Drucker-Prager functions, then a hyperbolic potential flow function is used to define the flow rule. The dilation angle is the slope of the linear Drucker-Prager function in the meridional plane p-q that gets closer to the hyperbolic potential flow function for the material. The distance between these two functions in the p-axis is the eccentricity, as shown in figure 2 [4].

Physically, the dilation angle is represented as the internal friction angle of concrete, which ranges between $31°$ to $40°$. The eccentricity is represented as the ratio between the tensile and the compressive strengths of the material, which usually is 0.1 for concrete [4].

The viscosity is related to the convergence of the model simulated, acording to Manual [4] this value should be very small and preferably no greater than 0.1. Then, the last CDP parameter is the ratio between the biaxial compressive and the uniaxial compressive strengths of concrete in a plane state of tension. For concrete, this relation usually is 1.16.

In the work presented by Chi et al. [1] relations were developed and validated capable of determining the input parameters of the CDP model for concrete reinforced with steel and polypropylene fibers, taking as a parameter geometric factors of the fibers and their proportions of addition to the cementitious matrix. The authors state that the presence of fibers will affect directly the biaxial strength and failure surface of SFRC. The relations found are presented below.

$$\lambda_{pf} = V_{pf} SF_{pf} \tag{1}$$

$$\lambda_{sf} = V_{sf} SF_{sf} \tag{2}$$

$$k_c = 1 + 0.056\lambda_{sf} \tag{3}$$

$$k_t = 1 + 0.08\lambda_{sf} + 0.132\lambda_{pf} \tag{4}$$

$$K^{hf} = K\frac{k_t}{k_c} \tag{5}$$

$$\frac{\sigma_{b0}^{hf}}{\sigma_{c0}^{hf}} = \frac{k_t^2}{0.132k_c} \times ((0.728 - \frac{0.749}{k_t}) + \sqrt{(0.728 - \frac{0.749}{k_t})^2 + \frac{0.03}{k_t^2}}) \tag{6}$$

$$\psi = 36° + 1°(\frac{\sigma_{cm0}}{3.5\sigma_{c0}}) \tag{7}$$

$$\psi^{hf} = \psi \times (1 - a_\psi\lambda_{sf} - b_\psi\lambda_{pf}) \tag{8}$$

Where $\lambda$ represents the the characteristic value for the fiber that relates the volume and shape factor which $sf$ and $pf$ stands for steel fiber and polypropylene fiber respectively, $k$ is the recalculated value for the meridian distance that the subscritptions $c$ and $t$ stands for the compressive and tensile meridians respectively, $K^{hf}$ is the failure surface shape factor for FRC, $\sigma_{c0}^{hf}/\sigma_{b0}^{hf}$ is the ration between biaxial and uniaxial compressive strengths for FRC, $\sigma_{cm0}$ is the compressive strength of FRC, $\sigma_{c0}$ is a equivalency factor equal to 10 $MPa$, $\psi$ is the dilation angle for plain concrete and $\psi^{hf}$ is the dilation angle for FRC.

# 3 Constitutive Models

## 3.1 Uniaxial compressive behavior

A significant improvement in post-peak behavior in uniaxial compression tests is reported in the literature by several authors in research with the SFRC, however, no significant gains in total resistance are observed [6–9].

Having the statement above, Nematzadeh and Hasan-Nattaj [10] performed an experimental evaluation of SFRC specimens under uniaxial compression, giving as results models capable of properly predict experimental curves based on fiber type and compressive strength.

This model was the one chosen due to its large range of experimental data presented and a variety of compressive models proposed by other authors used to compose the present model. Furthermore, it has also exhibited an easy implementation because uses only three input parameters, showing versatility for its application in a great range of different SFRC classes. The curve can be obtained using the following equations:

$$f_c = f_{cf}^{'} \frac{\alpha(\frac{\epsilon}{\epsilon_0})}{(\alpha-1)(\frac{\epsilon}{\epsilon_0}) + e^{\frac{(\frac{\epsilon}{\epsilon_0})^{n}-1}{n}}} \tag{9}$$

$$\alpha = 0.01, \quad n = 0.0071RI^{-1.142} \tag{10}$$

$$\epsilon_0 = (0.00051 + 0.000172RI)f_{cf}^{'0.33} \tag{11}$$

Where, $RI$ is the reinforcement index, the product between the fiber volume and the shape factor of the fiber (the ratio between the fiber length and its diameter), $\epsilon_0$ is the limit strain for the linear elastic behavior, $\epsilon$ is the total strain, $f_cf^{'}$ is the compressive strength, $f_c$ is the compressive tension, and $\alpha$ and $n$ are fitting factors found experimentally.

### 3.2 Uniaxial tensile behavior

It is known that fibers provide an increase in the tensile strength of concrete as they inhibit the formation and propagation of cracks in the matrix. There are several factors that influence this increase, such as the percentage of fibers, the adhesion between fiber-matrix, fiber resistance, and shape factor.

The $fib$ - Model Code for Concrete Structures[11] does not recommend direct tensile tests for SFRC due to its complexity of assembly and interpretation of results. For this reason, it is suggested to determine tensile strength by flexural or splitting tensile tests. So, it is difficult to find direct tensile test data for SFRC in the literature and even harder to find uniaxial tensile stress models that use as input parameters the type of fiber and tensile resistance.

In order to create a more versatile tensile model for the SFRC, Tlemat et al. [12] presented a model generated from combinations of experimental studies and inverse finite element analysis for validation. The model assumes that the behavior of the SFRC is similar to that of simple concrete, but with improved values for tension stiffening and tensile strength [13]. Tlemat et al. [12] after a series of tests with a percentage of fibers ranging from 0 % and 6 % in volume and five different types of fibers, a relationship to determine the stress-strain diagram of the CRFA was reached, assume as parameters fiber factors and tensile strength. The relations and formulations for the model are presented in the figure 3.

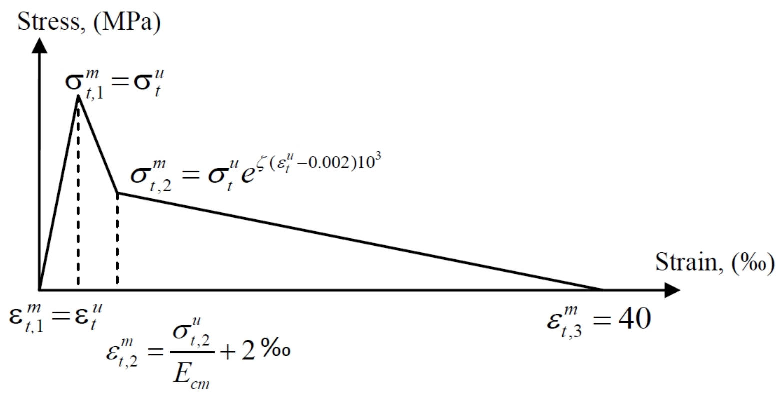


Figure 3. Stress-strain curve for SFRC under tensile uniaxial stress.[12]

# 4 Analyzed model

For this study, the experimental data report from Barboza [14] is used to validate the model results. Were tested six cylindrical specimens, three for uniaxial compression, and three for splitting tensile. The results were a mean compressive strength of 31.202 $MPa$ and tensile strength of (diametral compression) 3.14 $MPa$. Hooked-end DRAMIX steel fibers with 60 $mm$ length and 0.75 $mm$ diameter in the volume of 1.1% were applied to the concrete mixture. Five notched beams were tested under three-point bending tests, following the recommendations of EN-14651:2005 [15], which gave the results presented in the figure 4.

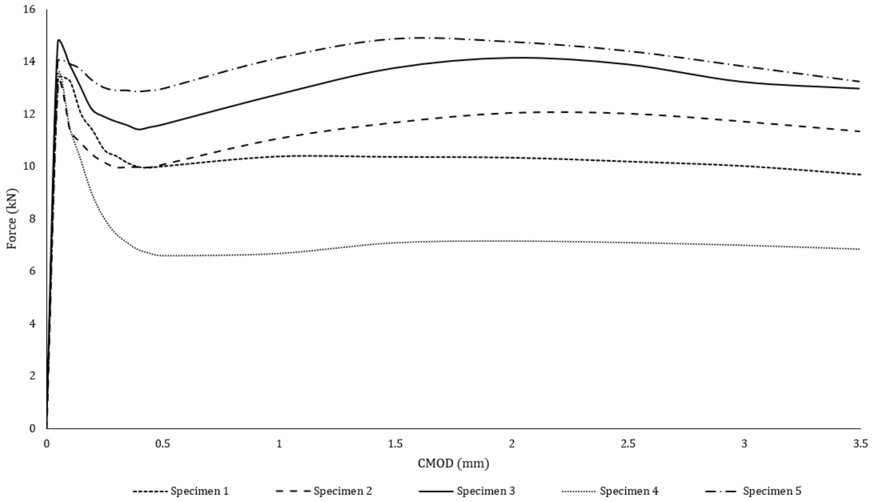


Figure 4. Experimental results envelope.[14]

Also using the data from the technical report, the CDP input parameters for the SFRC where calculated. The formulation developed by Chi et al. [1] takes into account steel and polypropylene fibers, however, in the results showed in the table 1 the volume of polypropylene fibers was considered zero. The values for Young's modulus was detrmined by the relation in the equation 12 and the Poisson coefficient was assumed to be the mean value of a range between 0.18-0.22, both parameters determined in Oliveira [16].

$$E_c = 3874\sqrt{f_c m} \tag{12}$$

Table 1. Input parameters for the CDP.

| Parameter | Chi et al. [1] | Default |
|---|---|---|
| $K^{hf}$ | 0.68 | 0.6667 |
| Dilation angle ($\psi^{hf}$) | 9.48° | 34° |
| Eccentricity ($e$) | 0.1 | 0.1 |
| Viscosity ($\mu$) | 0.00001 | 0.00001 |
| Poisson Coefficient ($\nu$) | 0.2 | 0.2 |
| Biaxial and uniaxial strengths ratio ($\sigma_{cbm}^{hf}/\sigma_{cm}^{hf}$) | 1.59 | 1.16 |

In the construction of the beam model, the symmetry of the situation was used to lower processing time. The boundary conditions were applied to the beam following the recommendations for the test set up. Two types of finite elements were used for the problem. The C3D4 elements (4 node tetrahedron) were used in the notched area and its surroundings to prevent distortion of values due to the discontinuity caused by the notch, and C3D8 elements (8 node brick) were applied to the other areas (figure 5).

The beams were tested following the procedures from EN-14651:2005 [15]. The simulations were executed in two parts, the first one was performed using the parameters obtained by Chi et al. [1] equations, and the second was submitted using the default parameters for concrete available in Abaqus User's Manual [4].

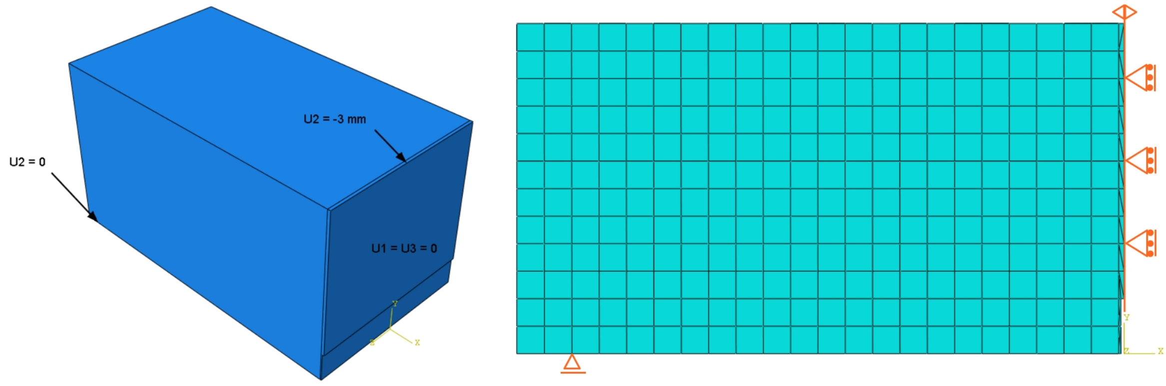


Figure 5. Boundary conditions and mesh for the beam model.

# 5 Results and discussion

From the comparison between experimental and numerical data, the following discussions arose:

- The numerical results showed a good agreement with the experimental results, especially at the first steps of the test. However, after the model reaches its peak resistance, the drop is steeper than the experimental for both cases.
- Also, the simulated beams showed a slightly more fragile than the experimental data and deformed a bit more than the experimental to reach its peak strength. This may be caused by the finite element applied in the notched region and its surroundings.
- Due to fiber orientation, the residual stresses in the tested beams vary in a gap of approximately 4 $kN$ for more or less than the mean, on the other hand, the simulated beams showed a nearly constant residual stress rate after reach the peak resistance. Furthermore, the behavior of the simulated beams was closer to the least resistant experimented beam.
- Regarding the CDP parameters, the model mechanical response was nearly affected by the modifications in the parameters.

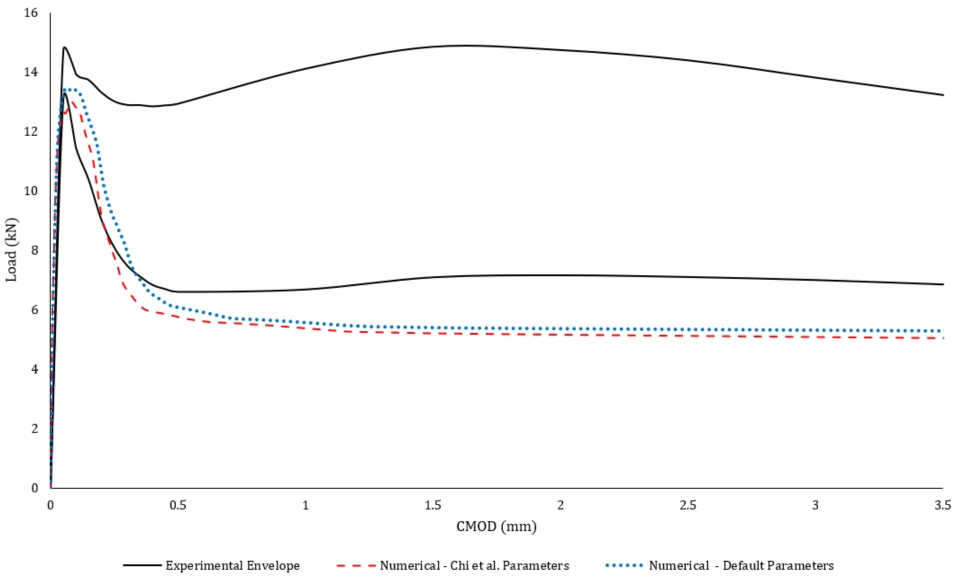


Figure 6. Numerical results and experimental results.

## 6 Conclusions

Although the damage model presented give good predictions for SFRC resistance, it is necessary for some adjustments in input parameters in order to reach reliable results. Furthermore, the presented study showed that the adjustments in the input data for the model with a higher impact on results for concrete would be changes in constitutive material models rather than failure surface modifications.

Regarding the post-peak behavior of the SFRC on simulated specimens, it is supposed that the bridge effect of the steel fibers accounted for by the Tlemat et al. [12] model is too general for the composite. After it reaches a peak resistance, the drop is too steep and a very small residual resistance is reached which continues nearly constant till a total failure.

In addition, the Concrete Damaged Plasticity has shown a great tool for failure and mechanical analysis in concrete structures, especially the ones cast with non-conventional concretes due to its capability of fitting the behavior using as input parameters the constitutive models of such composites.

**Authorship statement.** The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

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