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# Experimental and numerical investigation of the effect of steel fiber on fiber reinforced concrete under multiaxial compression

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**ABSTRACT:** Concrete is one of the most widely used building materials in the world and the use of fiber-reinforced concrete (FRC) in structures to increase its tensile strength and improve its behavior has been extensively developed in recent decades. It is necessary to determine the constitutive equations of FRCs when the numerical investigation of their behavior is running. These equations should be including relations to handle the effect of steel fibers on the behavior of FRC. In this study, the behavior of FRCs with a different percent of steel fiber under triaxial compression, with different values of confining pressure, is experimentally and numerically investigated. Hoek cell is used in triaxial tests. In the numerical simulation, five-parametric constitutive equations with Willam-Warnke (W-W) failure criterion, isotropic hardening/softening function and non-associated plasticity were used and substepping integration method was carried out for integration of constitutive equations. For applying the effect of steel fibers on the failure surface, Kt coefficient was determined from the results of biaxial experimental tests on SFRCs. The constitutive equations are implemented with UMAT subroutine in ABAQUS and specimens are simulated in ABAQUS. By the comparison of the experimental (maximum strength) results and the numerical (stress-strain curve) results, an acceptable agreement was seen between them. Finally, based on the consistency between experimental and numerical results, it was concluded that the numerical model could be used, with enough confidence, to predict the behavior of SFRCs specimens.

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## 1- Introduction

As hardened concrete is brittle and has low tensile strength, many studies have been conducted on the production of fiber reinforced concrete (FRC) [1, 2]. Different types of fibers such as steel, polypropylene, and a hybrid form of them were considered in the Studies. In recent decades, many tests have been conducted to research the behavior of FRCs under triaxial stresses and to propose appropriate constitutive models for FRCs [3-6]. The constitutive equations include different material parameters that are determined from the experimental data.

In this study, a constitutive model is extracted to numerically study the steel fiber reinforced concrete (SFRC) under triaxial compression. This model involves the Willam-Warnke failure criterion for the plastic behavior of SFRC as introduced in [5, 7, 8], isotropic hardening\softening rule and the non-associated flow rule of Grassl et al. [9] for determining the plastic deformations. Also, in this study, kt coefficient is proposed to conduct the effect of fibers on the triaxial strength of FRCs. In this paper, we used three batches of material parameters in the numerical simulations. Which the first set is from the experiments that we conducted in this study on SFRC specimens with different contents of steel fibers; the other two batches are from the experiments reported in the literature.

## 2- Experimental program

Four mix designs, with 0%, 0.5%, 1% and 2% steel fibers, were used to make 16 standard cylindrical specimens with diameter and height of 150×300 mm2 and 40 cylindrical specimens with diameter and height of 54×108 mm2. The corrugated steel fibers with a tensile strength >1100 MPa and l_f/d_f≅25mm/0.75mm=33.3 were used.

Triaxial tests were performed on the SFRC cylindrical specimens in accordance with ASTM C801 [10] (see Figure 1). These experiments were conducted under four confining pressure: 5, 10, 15 and 20 MPa. A typical load protocol for the triaxial compression test is depicted in Figure 2. we can realize that after applying 5 MPa lateral pressure, the axial and confining stresses were increased until a specified confining pressure is achieved. While keeping the confining pressure constant, the additional axial stress is increased at a constant stress rate of 0.2 MPa s-1 through the platens located at the ends of Hoek cell.

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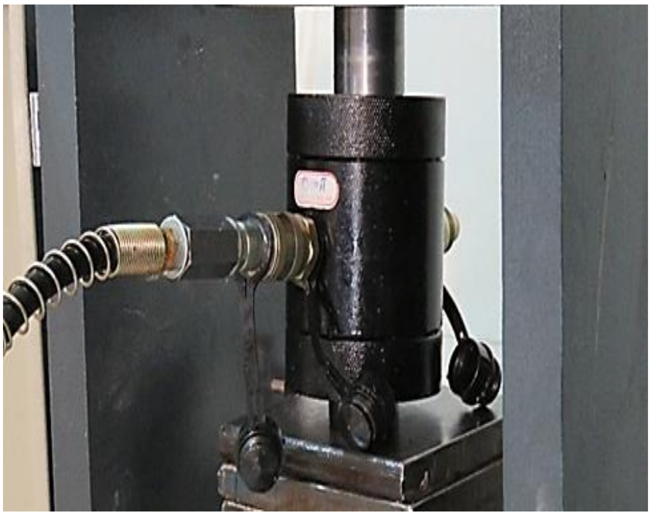

Fig. 1. A Hoek cell for triaxial test.

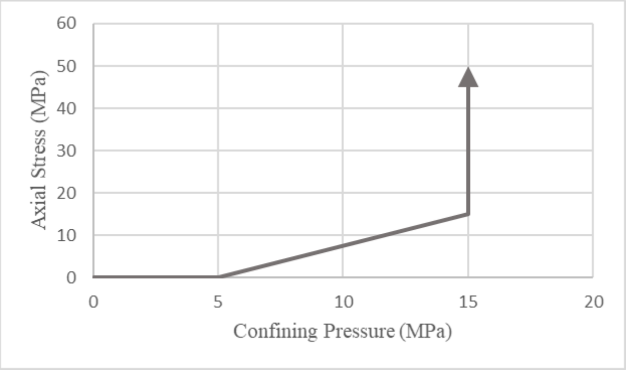

Fig. 2. A typical load protocol in the triaxial test.

Table 1. Results of triaxial tests on SFRCs.

| Triaxial peak stresses (MPa) for confining pressures | | | |
|---|---|---|---|
| 5MPa | 10MPa | 15MPa | 20MPa |
| 64.6 | 83.1 | 95.2 | 113 |
| 61.3 | 78.7 | 90.2 | 110 |
| 68.5 | 87.3 | 99.5 | 117 |
| 57.6 | 73.8 | 89.1 | 108 |

The constitutive model for SFRCs is proposed based on the plasticity model adopted in this study and involves the loading criterion, the hardening/softening function and the non-associated flow rule.

For the simulation of SFRCs under triaxial stresses, the W-W five-parameter loading surface has been used in the literature. Using Haigh-Westergard coordinates, the W-W [7] failure surface for SFRC is expressed via

$$F(\xi,\rho,\theta)=\rho-K(\bar{\varepsilon}_p)\rho^f(\xi,\theta)=0 \tag{1}$$

the effect of steel fibers is specifically included in the yield surface (1) via parameters $k_t$ and $k_c$ as follows

$$\begin{aligned} k_c &= 1+0.056\lambda_f \\ k_t &= 1+0.33\lambda_f \end{aligned} \tag{2}$$

## 3- Results and discussions

The results of triaxial compressive tests are summarized in Table 1 for the SFRC specimens. The so-called strength enhancement coefficient due to the confining pressure is calculated in the range 3.9 to 6.3 for these SFRCs indicating a high scatter in this coefficient in accordance with the literature

with the use of triaxial test results, the failure envelope of SFRC specimens can be depicted according to ASTM C801. Figure 3 shows failure envelop in terms of $\sigma_n-\tau$ . It is clear that for the range of stress values considered here the effect of steel fibers on the failure envelope is mild

In order to verify our numerical results, experimental stress-strain data for plain concrete from literature are used. Figure 4 shows comparisons between the numerical results and the experimental data of SFRCs under multiaxial compression reported in Pantazopoulou and Zanganeh [11]. The numerical stress-strain curves are in very good agreement with the experimental curves.

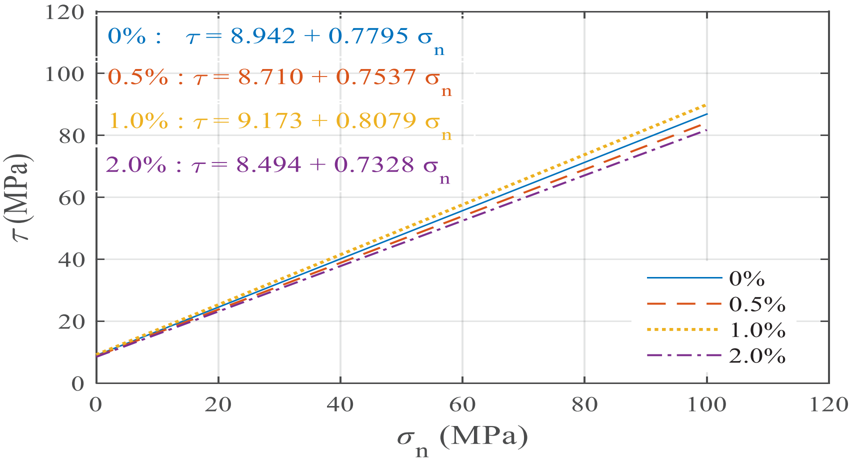

**Fig. 3.** $\sigma_n - \tau$ **failure envelope of SFRC specimens.**

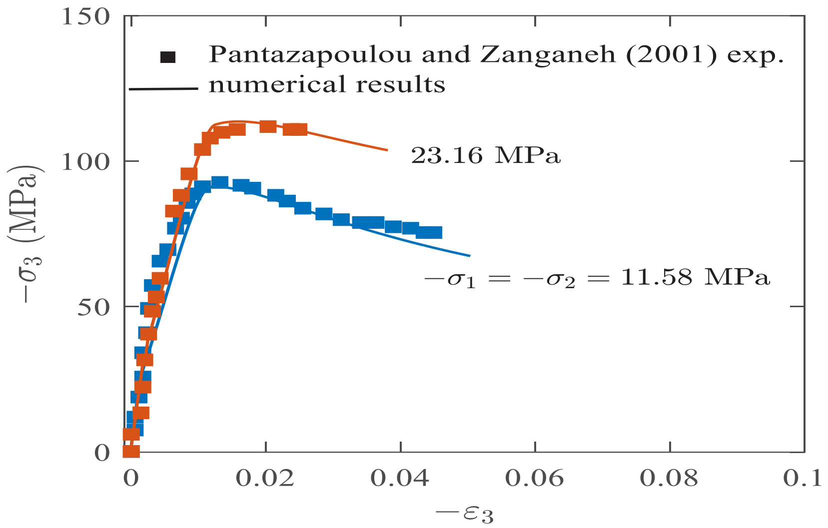

**Fig. 4. fStress-strain curves for SFRCs under triaxial loadings.**

## 4- Conclusion

In this study, constitutive equations are proposed based on non-associated flow rule with w-w failure criterion, isotropic hardening\softening function, and Grassl plastic potential function. Triaxial tests conducted on SFRC specimens and experimental data have been employed to determine the various material parameters of the plasticity model of SFRCs. The good agreement between numerical results and the experimental data indicates that not only the adopted constitutive equations represent the behavior of SFRCs very well, but also the implemented integration scheme can be employed in practical applications of SFRCs.

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