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Research Article

Study on Tensile Damage Constitutive Model for Multiscale Polypropylene Fiber Concrete

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Polypropylene fibers perform well in roughness enhancement and corrosion resistance. They can dissipate energy when cracks occur in concrete. Furthermore, they can improve the concrete tensile properties by synergistic work with it. To study the tensile properties of the multiscale polypropylene concrete, uniaxial tensile strength of 18 fiber reinforced and 3 plain concrete specimens was experimentally tested using the paste steel method. The test results indicate that both the strength and the peak strain can be substantially improved. Based on the results, a tensile damage constitutive model was proposed and implemented into FLAC3D for numerical experimentation. The numerical results are consistent with the experimental observations in general and some discrepancies are discussed.

1. Introduction

Polypropylene fibers perform well in roughness enhancement and corrosion resistance. They can dissipate energy when cracks occur in concrete. Furthermore, they are capable of improving the concrete tensile properties by synergistic work with it. The experiments on how polypropylene fibers improve tensile strength and ductility of the concrete have been conducted by many scholars from different countries.

Ramakrishnan [1–3] examined the properties of the bundle polypropylene fiber concrete by experiment, and the results showed that, with the increase of the amount of fiber added, the energy absorption capacity in later stage improves, and the toughness index increases as well. Experiment was conducted to compare ordinary concrete specimens with fiber concrete specimens by Choi and Yuan [4], and the results showed that adding polypropylene fiber into concrete can enhance the tensile splitting strength of the concrete and also significantly improve the toughness.

Deng et al. [5] investigated the mechanical properties of polypropylene fiber concrete under uniaxial tension and acquired the complete stress-strain curve. They proposed a theoretical solution of uniaxial tensile stress versus crack width curves and concluded that this concrete is of good ductility and energy absorbability. The bending and splitting tensile tests were carried out on 15 specimens of two groups by Huang et al. [6] in order to study the influence of the mixing amount and length of the polypropylene on the mechanical properties of concrete. The results indicated that the tensile strength and splitting toughness of concrete could be remarkably improved through adding the polypropylene fiber. Liu et al. [7] studied 5 different amounts of fiber concrete added, derived variable curves of flexural strength, compression strength, and tension splitting strength, and then proposed the optimal fiber added amount as 1,200~1,500 g/m^3.

The studies on the tensile property of polypropylene fiber concrete have gotten many findings [8–13]. However, there are few studies about multiscale effect through numerical analysis and more close attention should be paid to the tensile constitutive model. In this paper, the uniaxial tensile strength test on 7 groups of concrete prism specimens with

Table 1: Physical and mechanical properties of polypropylene fiber.

Fiber number	Diameter (mm)	Length (mm)	Tensile strength (MPa)	Modulus of elasticity (Gpa)	Elongation (%)	Density (g/cm^3)
FF1	0.026	12	641	4.5	40	0.91
FF2	0.1	19	322	4.9	15	0.91
CF1	0.8	50	706	7.4	10	0.95

Note: FF: fine polypropylene fiber; CF: course polypropylene fiber.

Table 2: The amount of polypropylene fiber (kg/m^3) for different specimens.

Specimen number	Fiber table	Mix amount (kg/m^3)
A0	None	0
A1	FF1	0.9
A2	FF2	0.9
A3	CF1	6.0
A4	(CF1 + FF1)$^{\blacktriangle}$	6.0
A5	(CF1 + FF2)$^{\blacktriangle}$	6.0
A6	(CF1 + FF1 + FF2)$^{\bullet}$	6.0

Note: ▲ represents amount CF1 that is 5.1 kg/m^3 and amount of FF1 or FF2 that is 0.9 kg/m^3; • denotes the added amount of CF1 that is 5.1 kg/m^3 and amount of FF1 or FF2 that is 0.45 kg/m^3.

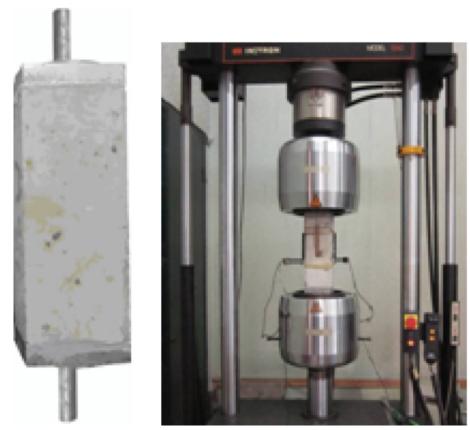

Figure 1: The test device and a typical test specimen.

different-scale polypropylene fiber added were carried out. Based on the results, the stress-strain relationships of the specimens were obtained and influences of fiber category and amount added on the tensile strength were investigated. A tensile damage constitutive model is proposed. Validation on this model is carried out through numerical experimentation by FLAC3D. The performance of the proposed model is assessed through comparison between the numerical results and the experimental values based on the stress level. In addition, the discrepancy is also discussed.

2. The Uniaxial Tensile Test

2.1. Experiment Description. Raw materials of the polypropylene fiber concrete include the ordinary Portland cement of 42.4R, fine sand, crushed stones with 5~20 mm particles, and the polypropylene fiber from Ningbo Dacheng New Material Co., Ltd. The physical and mechanical properties of the three different fibers are listed in Table 1. The strength grade of concrete is C30 and the mixing ratio of cement, sand, crushed stone, and water is 1 : 1.23 : 3.24 : 0.51 [14]. The types and the amount of polypropylene fiber that are mixed into the concrete are listed in Table 2.

The dimensions of the specimens are 100 mm × 100 mm × 300 mm. 7 groups of concrete were made and each group contains three specimens made of the same kind of concrete. Using structural adhesive to glue two head faces of the specimens to the steel plate of 20 mm thickness, the tension tests were carried out through 1342 INSTRON electrohydraulic servo material testing machine, as shown in Figure 1.

Table 3: The axis-tensile test results for multiscale polypropylene fiber concrete.

Specimen	f_t/MPa	$f_{t/\text{ratio}}$	$\varepsilon_p/\mu\varepsilon$	$\varepsilon_{p/\text{ratio}}$	E_t/GPa	E_t
A0	1.362	1	119.3	1	18.30	1
A1	1.498	1.11	120.1	1.01	17.25	0.94
A2	1.602	1.18	124.4	1.04	18.40	1.0
A3	1.690	1.24	178.1	1.49	18.45	1.01
A4	1.530	1.12	133.8	1.12	18.24	1
A5	1.485	1.09	141.7	1.18	19.80	1.08
A6	1.728	1.27	145.2	1.22	18.89	1.03

2.2. Test Results and Analysis of the Experiment. Table 3 summarizes the uniaxial tensile test results. f_t is the tensile strength, ε_p represents the peak strain, and E_t denotes the deformation modulus (the secant modulus when the stress is 50% of the peak value is used [15]). Figure 2 shows the tensile stress-strain curve. It can be seen from Table 3 that, compared to the ordinary specimens, tensile strength of the specimens with polypropylene fiber added is improved to varying degrees. The tensile strength of A6 is the most significantly increased, up to 27%, with three kinds of fiber used, and it increases by 27%. The increase of tensile strength of A5 is less significant, only by 9%, with one crude fiber and one fine fiber added. It is obvious that the tensile strength can be considerably increased through adding proper fiber with reasonable mixing proportion of crude and fine fibers. For A1 and A2, there is no increase of deformation modulus due to adding of fiber. For the other specimens, there is

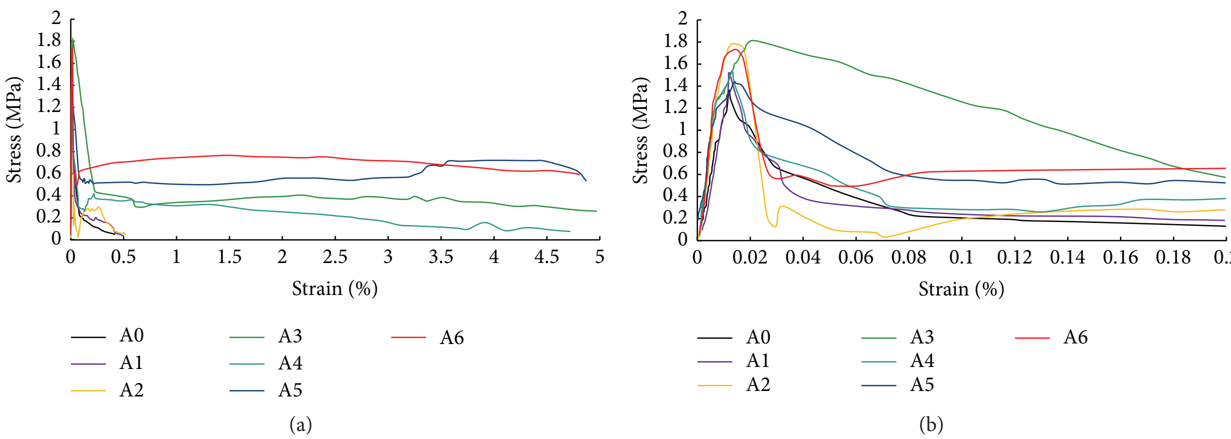

Figure 2: The axial tensile stress-strain curve of multiscale polypropylene fiber concrete.

only marginal increase. Thus, the adding of fiber does not obviously increase the deformation modulus of specimens.

As shown in Figure 2, compared with the plain concrete, the peak strain of all the specimens of polypropylene fiber concrete is improved to varying degrees. The peak strain of A3 with the crudest fiber added is improved the most by 49% while peak strain of A1 is marginally improved by 1%. It is obvious that crude fiber can considerably improve the peak strain of concrete while the effect of the fine fiber is less obvious.

It can be observed from Figure 2 that the area surrounded by the stress-strain curves during the descending segment is larger than that of the ordinary concrete. The area of A5 and A6 in which the crude fiber mixed with fine fiber added is the largest. Furthermore, the area of A3 is larger than that of A1 and A2. It indicates that adding the polypropylene fiber to concrete can transform the fragility of concrete and improve the toughness. In addition, the crude fiber works more effectively than the fine fiber. Nonetheless, the roughness of the concrete can be the mostly improved through mixing the crude fiber and the fine fiber.

For the concrete added to crude polypropylene fiber, strain hardening of low stress occurs during the descending segment of stress-strain curve. That is, the strain increases rapidly while the attenuation of stress is not obvious. It indicates that the crude fibers can act through bridging function when the concrete cracks, so the fibers can improve the toughness of concrete under tension. However, this was not observed in A0, A1, and A2 since the fine fiber has poor tensile capacity. It cannot sustain sufficient elongation to produce the strain hardening of low stress when the concrete cracks appear.

3. Mechanism Analysis

In the process of concrete pouring, cracks or voids in concrete may be introduced due to the temperature effect or the uneven vibration. When the concrete is subjected to the external load, stress concentration occurs on the cracks, and it makes the crack expand, resulting in the damage of the structure finally. Adding polypropylene fiber to concrete can reduce the amount and scale of cracks through cementation between concrete and fiber. Thus, it substantially reduces the stress concentration in the microcracks under external load and effectively improves the peak stress of the concrete. When the macroscopic cracks occur in the concrete under tension, the polypropylene fibers can withstand the load due to the good toughness. The added fibers slow down the expansion of crack and improve the peak strain of concrete.

The crude polypropylene fiber is of higher bearing capacity than the fine type. Cracks appear in the concrete mixed with crude fiber only when the peak stress is reached. After that, the stress decreases rapidly. In addition, as the crude fibers can sustain part of the load, the low stress-strain hardening phenomenon can be observed when the stress decreases to a certain level. The fine polypropylene fiber's bearing capacity is low. The stress decreases rapidly when the specimens are damaged, and there is no stress-strain hardening observed at low stress level.

4. Tensile Damage Constitutive Model and Numerical Validation

4.1. Tensile Damage Constitutive Model. Combining the standard tensile constitutive model [14] with the experimental results, the following stress-strain relationship can be obtained:

$$\sigma_t = \begin{cases} E_c \varepsilon_{t,r} x & (\varepsilon \le \varepsilon_{t,r}) \\ \left(\dfrac{\rho_t}{\alpha_t (x-1)^{1.7} + x} \right) E_c \varepsilon_{t,r} x & (\varepsilon > \varepsilon_{t,r}) \end{cases} \tag{1}$$

in which $x = \varepsilon/\varepsilon_{t,r}$, $\rho_t = f_{t,r}/E_c\varepsilon_{t,r}$, $\varepsilon_{t,r} = f_{t,r}^{0.54} \times 65 \times 10^{-6}$, and $\alpha_t = 0.312 f_{t,r}^2$. Parameter α_t controls the descending segment of stress-strain curve of the concrete under uniaxial tension. Table 4 lists the α_t values for the different specimens; $f_{t,r}$ is the representative value of the uniaxial tensile strength, which is the experimental value in this paper. $\varepsilon_{t,r}$ is the peak strain corresponding to $f_{t,r}$.

TABLE 4: Values of control parameter α_t for different specimens.

Specimen	α_t
A0	1.748
A1	1.695
A2	1.706
A3	0.387
A4	1.049
A5	0.51
A6	0.945

When $\varepsilon > \varepsilon_{t,r}$, the following equation can be derived from (1):

$$\sigma_t = \frac{f_{t,r} x}{\alpha_t (x-1)^{1.7} + x}. \tag{2}$$

For the decreasing piece of stress-strain curve, (2) can be written in the incremental form, by derivation:

$$\frac{\Delta\sigma_t}{\Delta x} = \frac{-\alpha_t (x-1)^{0.7} (0.7x+1) f_{t,r}}{\left(\alpha_t (x-1)^{1.7} + x\right)^2}. \tag{3}$$

Implement (3) into FLAC3D software for numerical experimentations, in which the strength parameters are systematically reduced [16].

4.2. Numerical Validations. In order to verify the proposed method, the dimensions of the FLAC3D model are selected as 100 mm × 100 mm × 300 mm, the same as the test specimens. This numerical model is partitioned into 24,000 elements and 26,901 nodes, as shown in Figure 3. We applied the constraints in normal direction at the bottom of the specimen and apply an even load in a vertical direction at the top.

Figures 4–10 show the comparison between the numerical results and the experimental stress-strain relationship for each specimen.

Comparisons show that the numerical simulation results fit the experimental tests well for specimens A0, A1, and A2. Furthermore, the numerical results match well the test results before the stress reaches the peak value. After that, there are some certain discrepancies. In addition, the numerical experimentations cannot capture the stress-strain behavior that is observed in experimental results. Generally for the same strain value, the stress value is smaller than the test result. The reason lies in the bridging effect, through which the fibers act on the concrete test specimens. However, this effect is not considered in the numerical model.

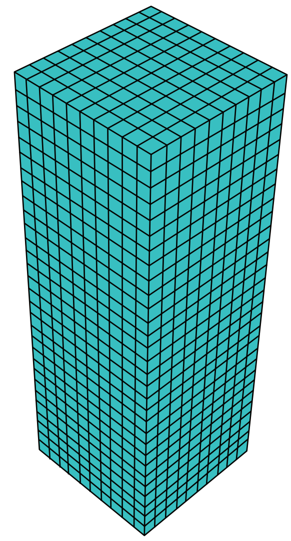

FIGURE 3: Specimen model.

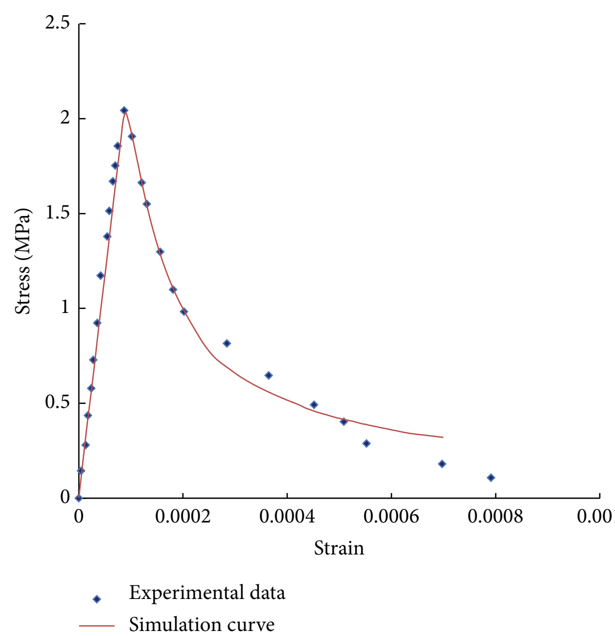

FIGURE 4: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A0.

5. Conclusions

Based on the uniaxial tensile test results, this paper proposes a tensile damage constitutive model for multiscale polypropylene concrete. Numerical experimentations through FLAC3D demonstrating the reliability of the proposed model are given for a series of specimens. The main work and findings include the following:

(1) The tensile strength of multiscale polypropylene fiber concrete is higher than that of the ordinary concrete and the strength ratio ranges from 1.09 to 1.27. The strength increase of A6 is the most significant, up to 27% with three types of fiber added.

(2) The peak strain can be improved by 1%~49%. In addition, adding fiber to concrete can substantially improve the toughness of concrete.

(3) A tensile damage constitutive model is proposed. The numerical validation on this model through FLAC3D shows a good agreement with the experimental data

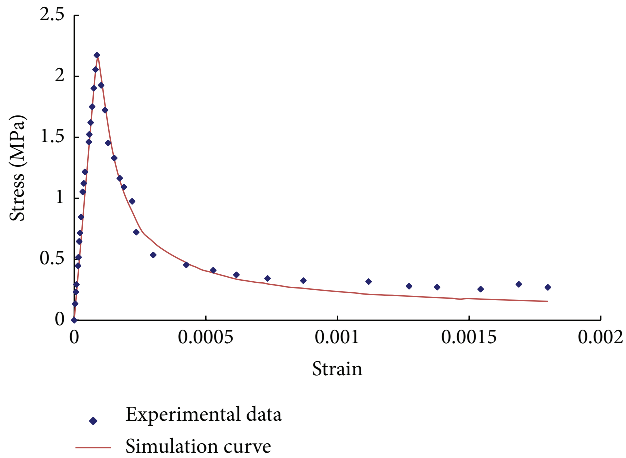

FIGURE 5: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A1.

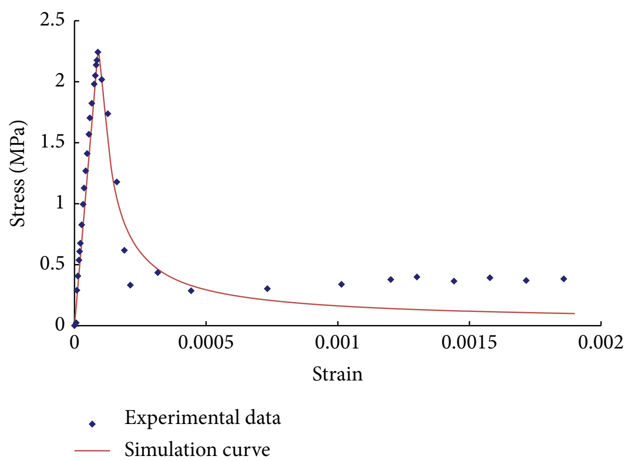

FIGURE 6: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A2.

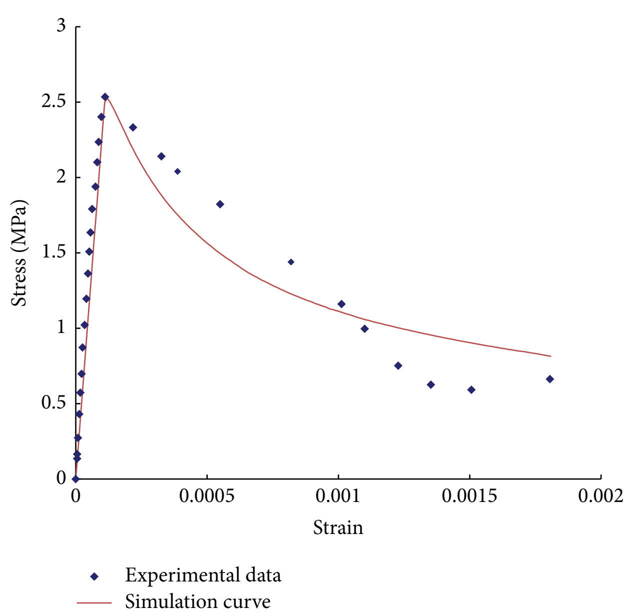

FIGURE 7: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A3.

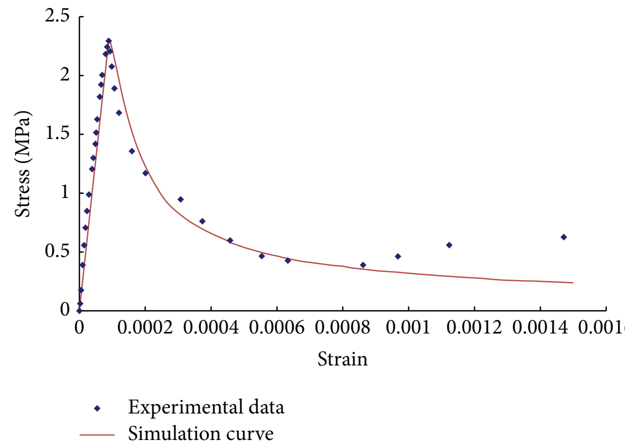

FIGURE 8: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A4.

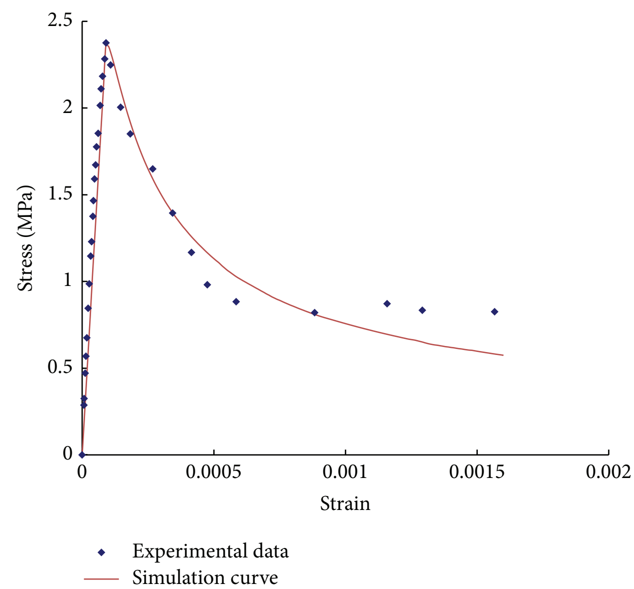

FIGURE 9: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A5.

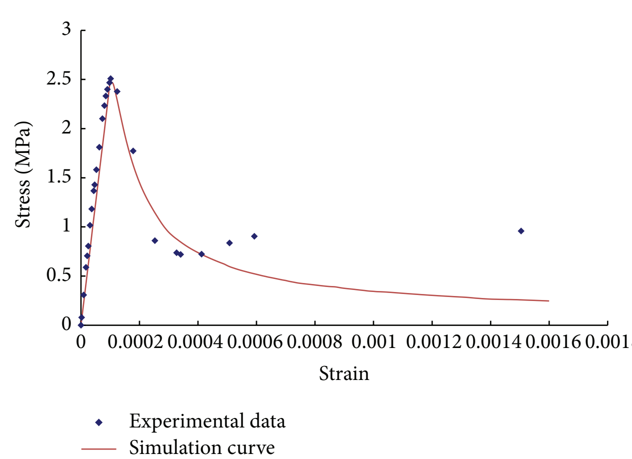

FIGURE 10: Comparison of stress-strain relationship between numerical simulation and experimental tests for specimen A6.

before the strain hardening of low stress of the concrete and after that the differences between the numerical and experimental results are considerable. Therefore, this discrepancy should be further investigated in the following research.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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