Micro-macroscopic statistical description on damage evolution of concrete

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Abstract

In this paper, we present two types of damage model, coupled pressure-shear damage model and tensile damage model, according to the different stress state and different damage mechanism in concrete. Combining microscopic and macroscopic mechanics, we derive the damage evolution equation and obtain relevant material parameters by fitting the test data of one-dimensional compression and tension test. In order to verify the proposed damage model, we carry out numerical simulation on wave propagation problems caused by the explosive charge in concrete columns. The simulation results are consistent with experimental results, which show successfully the evolution of damage in explosion process.

Keywords: concrete, coupled pressure-shear damage, tensile damage, damage evolution

1 Introduction

It is well known that in brittle materials such as concrete, there are two kinds of damage forms, one is the tensile damage caused by tensile stress, and another is the coupled pressure-shear damage related to plastic volume dilatation phenomena caused by coupling effect of pressure and shear. From this point of view, in [1-4], damage is defined as a function of strain or stress to describe the material damage softening. And in [5], the damage is defined as a function of the hydrostatic pressure, equivalent plastic stain and accumulated plastic volumetric strain, which has been widely used in engineering and adopted by the commercial software LS-dyna. In reference [6], the damage evolution was related to the average tensile stress, crack density and volume strain, which can better reflect the cratering and caving in the penetration problem. Although many scholars have carried out a lot of work about the damage evolution of concrete and they have obtained some important achievements, there are still some shortages. First, most of the researches [7-11] are based on the macroscopic or microscopic damage theory, however, the macroscopic description has not combined together well with microscopic mechanism and hence the damage model lacks microscopic physics background; and in the microscopic model, it is difficult to combine macroscopic mechanical quantity with a variety of microscopic material parameters measured by precision instruments. Secondly, the different damage mechanism in different stress state has not been specifically considered.

Many studies such as Li Yongchi et al. [12] have demonstrated that there are mainly two different types of damage form for concrete-like materials: one type of damage behaves as growth and connection of micro-voids (supplemented by extension and connection of micro-crack), which is microscopically caused by the falling off and rupture of molecular bonds, and macroscopically shows the so-called "plastic volume dilatation phenomenon" related to pressure-shear coupling yield properties, that is the "coupled pressure-shear" damage. The other type of damage is the tensile damage which behaves as extension and connection of micro-crack (supplemented by expansion and connection of micro-void) caused by tensile stress in concrete. However, for current research on the damage of concrete, some damage models [13-15] are only suitable for simple stress state (tensile, compressive or shear). Others can be only applied to the case that the effects of pressure and shear stress in material is decoupling [16-18], which can also not well describe the actual damage evolution process or reflect "plastic volume dilatation phenomenon" for the material.

In this paper, the damage in concrete is divided into the coupled pressure-shear damage and tensile damage according to the different stress states and different evolution mechanism. Combining microscopic and macroscopic mechanics, we derived the damage evolution equation and obtained relevant material parameters by fitting the test data of one-dimensional compression and tension test. To verify the proposed damage model, we carried out numerical simulation on wave propagation

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problems caused by the explosive charge in concrete columns. The simulation results show that the distribution and evolution about the coupled pressure-shear damage and the tensile damage are in good agreement with experimental results.

2 The coupled pressure-shear damage

From the perspective of the material microstructure, there are large amounts of micro-voids and micro-cracks with different shapes, sizes, and spatial orientation, which are the micro-damage in concrete material. the "coupled pressure-shear" damage behaves as growth and connection of micro-voids, which is microscopically caused by the falling off and rupture of molecular bonds, and macroscopically shows the so-called "plastic volume dilatation phenomenon" related to pressure-shear coupling yield properties, The growth of these micro-voids results in damage evolution. Macroscopically we define the damage *D* as follows:

$$D = \frac{V_d}{V}, \quad V_d = DV, \tag{1}$$

where V is the bulk volume of the representative element, V_d is the total volume of micro-voids. Differentiating Equation (1) with time *t*, we have:

$$\dot{V}_d = \dot{D}V + \dot{V}D. \tag{2}$$

For the coupled pressure-shear damage, if the damage mainly occurs at the plastic stage and to evolve with plastic volume dilatation caused by coupling effects of hydrostatic pressure and deviatory stress, it can be assumed that the relative growth rate of each micro-void is proportional to the plastic formation work rate; and if the damage is believed to occur in both elastic stage and plastic stage, it can be assumed that the relative growth rate of each micro-void is proportional to the total work rate. As an example for simplicity, the latter has been chosen. Then we have:

$$\dot{v}_d(i)/v_d(i) = a_1\dot{W}/W_B, \tag{3}$$

where $v_d(i)$ is the volume of the *i-th* micro-void, W is the formation work, a_1 is a material constant, and W_B may be taken as the formation work at the peak of stress-strain curves. By summing Equation (3) for all micro-voids, and according to component, we have:

$$a_1\dot{W}/W_B = \frac{\dot{v}_d(i)}{v_d(i)} = \frac{\Sigma\dot{v}_d(i)}{\Sigma v_d(i)} = \frac{\dot{V}_d}{V_d},$$

i.e.:

$$\dot{V}_d/V_d = a_1\dot{W}/W_B. \tag{4}$$

From Equations (1), (2) and (4), the following damage evolution equation is obtained:

$$\dot{D} = (a_1D\dot{W} - D\frac{\dot{V}}{V})/W_B = (a_1D\dot{W} - D\frac{\dot{v}}{v})/W_B, \tag{5}$$

where *v* is specific volume. Equation (5) is the general form of the coupled pressure-shear damage evolution equation. If it is further assumed that the volume of the solid part $V_s = V - V_d$ is incompressible, i.e. $\dot{V}_s = 0$, by Equation (1) we will have

$$\dot{D} = (1-D)\frac{\dot{V}}{V}, \quad D\frac{\dot{V}}{V} = \frac{D\dot{D}}{1-D}. \tag{6}$$

Then Equation (5) can be transformed into the following damage evolution equation:

$$\dot{D} = a_1D(1-D)\dot{W}/W_B. \tag{7}$$

Our task is to optimize the material parameters a_1 and W_B by numerical fitting the MTS experimental stress-strain curve. For this paper, we assume that the material obeys the following nonlinear constitutive relation with damage:

$$\sigma = E\varepsilon(1+b\varepsilon)(1-D), \tag{8}$$

where *E* is Young modulus, *b* is a dimensionless parameter which is to be determined together with a_1 and W_B in Equation (7) by numerical fitting the MTS experimental stress-strain curve. From Equations (7) and (8), for the one-dimensional compression experiment with constant strain rate $\dot{\varepsilon}_c$, we can obtain the following system of ordinary differential equations for σ, D, ε:

$$\begin{cases} \dot{\varepsilon} = \dot{\varepsilon}_c \\ \dot{\sigma} = E(1-D)(1+2b\varepsilon)\dot{\varepsilon} - E\varepsilon(1+b\varepsilon)\dot{D} \\ \dot{D} = a_1D(1-D)\sigma\dot{\varepsilon}/W_B \end{cases}, \tag{9}$$

or

$$\begin{cases} \dot{\varepsilon} = \dot{\varepsilon}_c \\ \dot{\sigma} = E(1-D)(1+2b\varepsilon)\dot{\varepsilon}_c - E\varepsilon(1+b\varepsilon)a_1D(1-D)\sigma\dot{\varepsilon}_c/W_B \\ \dot{D} = a_1D(1-D)\sigma\dot{\varepsilon}_c/W_B \end{cases}. \tag{10}$$

The initial conditions for Equations (9) and (10) are: $\varepsilon(t=0)=0$, $\sigma(t=0)=0$, and $D(t=0)=D_0$. The terminal condition is that the stress-strain curve will reach the end point when the material completely fails, and at this point, the damage reaches the ultimate damage D_c. The initial damage D_0 and the ultimate damage D_c will be determined by numerical fitting the experimental curves together with a_1, W_B and b.

The representative stress-strain curves of C40 concrete under the three kinds of constant strain rates obtained by

MTS one-dimensional experiment are shown in Figure 1. The optimal material parameters are shown in Table 1, which are got by fitting the constant strain rate curve $\dot{\varepsilon} = \dot{\varepsilon}_c = 10^{-4} / s$. The comparison between experimental curve and simulate curve is shown in Figure 2, in which the relationship $D \sim \varepsilon$ between damage and strain is also given.

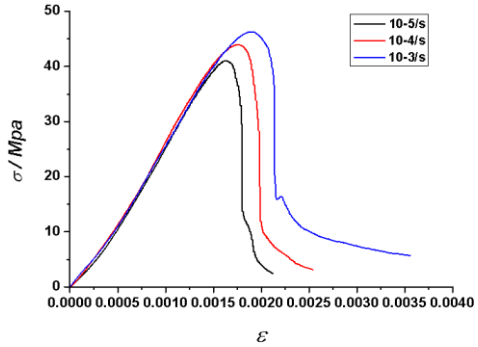

FIGURE 1 The constant strain rate stress-strain curves

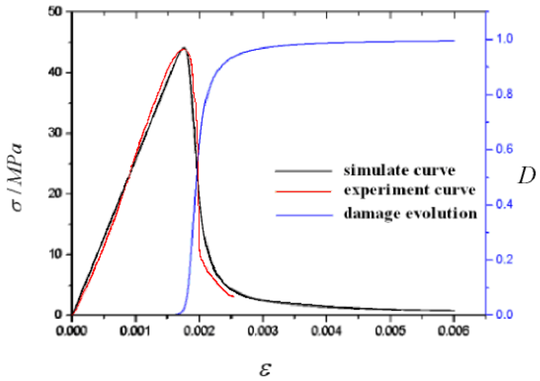

FIGURE 2 The stress-strain and damage-strain curves

TABLE 1 The material parameters of coupled pressure-shear damage evolution equation

$\dot{\varepsilon}_c$	D_0	a_1	D_c	b	W_b (MPa)
10^{-4}/s	10^{-5}	9.2	0.38	0.0001	0.04

3 The tensile damage

The main form of the tensile damage for brittle materials like concrete is the extension and connection of micro-crack caused by tensile stress in concrete. Taking mode I crack as an example, when the material is subjected to tensile stress mainly along a certain direction, the micro-cracks perpendicular to the stress will become the dominant growing crack which is the main reason for the fracture of brittle material.

Imagine there is a thin plate with a width L and unit thickness, in which there is a series of micro cracks with length of l_i perpendicular to the stress inside the material. The micro crack in representative volume element is shown in Figure 3.

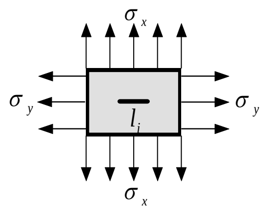

FIGURE 3 The micro crack of representative volume element

The macroscopic damage D is defined as a ratio of the total effective length of micro-crack and the total material length. The damage is assumed to be irreversible:

$$D = \frac{L_d}{L} = \frac{L - L_s}{L}, \quad \dot{D} \geq 0, \qquad (11)$$

where L_d is the total length of micro cracks, L_s the total length of no damage solid material within the total length L of material, $L_s = L - L_d$. From Equation (11) we can obtain:

$$\dot{L}_d = \dot{D}L + D\dot{L}. \qquad (12)$$

On microscopic scale, a large number of micro-cracks with the different size inside the material can be studied with the statistical methods, the growth of each crack may be assumed statistically independent, the interaction between micro-cracks is ignored; Thus the total length L_d of the crack in material can be described by the statistical sum of all the micro-cracks length in material, that is:

$$L_d = \sum l_i. \qquad (13)$$

In order to analyse the growth process of a single micro-crack, the following hypothesis similar to Fen et al. [19] for micro void is made.

1) In the process of micro cracks growing up, the surface energy due to an increase in surface area of the micro-crack is supplied by the elastic strain energy of a limited area around the medium, and the limited area is determined by the velocity of Rayleigh wave propagation along the crack surface.

2) The threshold condition of micro-cracks growing up can be determined based on Griffith fracture theory.

The threshold stress σ_c in critical state for quasi-static growth of the plane stress crack (length 2l) is:

$$\sigma_c = \sqrt{\frac{2\eta E}{\pi l}}, \qquad (14)$$

where E is the Young modulus, and η is the surface energy per unit area. The strain energy of unit volume is:

$$w=\int \sigma d\varepsilon=\int_{\sigma_c}^{\sigma}\frac{1-\nu^2}{E}\sigma d\sigma=\frac{1-\nu^2}{2E}\left(\sigma^2-\sigma_c^2\right), \quad (15)$$

where ν is Poisson ratio. In the process of micro-cracks (length $2l$) growing up, the elastic strain energy in volume element is:

$$W=\frac{1-\nu^2}{2E}\left(\sigma^2-\sigma_c^2\right)2l\cdot 2l\cdot 1=\frac{2\left(1-\nu^2\right)\left(\sigma^2-\sigma_c^2\right)}{E}l^2 . \quad (16)$$

After the crack (length $2l$) growing $2\Delta l$, the increase of surface energy ΔU in volume element is:

$$\Delta U=4\eta\Delta l . \quad (17)$$

The released strain energy ΔW of limited area around the medium can be obtained by Equation (16)

$$\Delta W=\frac{4\left(1-\nu^2\right)\left(\sigma^2-\sigma_c^2\right)}{E}lC_R\Delta t , \quad (18)$$

where C_R is the velocity of Rayleigh wave, which is equal to:

$$C_R=\frac{0.862+1.14\nu}{1+\nu}C_s=\frac{0.862+1.14\nu}{1+\nu}\sqrt{\frac{G}{\rho}}=\frac{0.862+1.14\nu}{1+\nu}\sqrt{\frac{E}{2(1+\nu)\rho}} , \quad (19)$$

where C_s is the velocity of transverse wave, G the shear modulus, ρ the density, ν the Poisson ratio.

According to the above hypothesis (1), $\Delta W=\Delta U$, we have:

$$\Delta l=\frac{\left(1-\nu^2\right)\left(\sigma^2-\sigma_c^2\right)}{\eta E}lC_R\Delta t . \quad (20)$$

So the growth rates of a single crack is:

$$\dot{l}=\frac{\left(1-\nu^2\right)\left(\sigma^2-\sigma_c^2\right)}{\eta E}lC_R . \quad (21)$$

And using Equations (13) and (21), the rate of change of the total length of the crack is:

$$\dot{L}_d=\frac{\left(1-\nu^2\right)\left(\sigma^2-\sigma_c^2\right)C_R}{\eta E}L_d . \quad (22)$$

This is the kinetic equation of crack growth. Using Equations (12) and (22) we can get:

$$\dot{D}=\frac{1-\nu^2}{\eta E}(\sigma^2-\sigma_c^2)C_R D-\frac{D}{L}\dot{L} . \quad (23)$$

Equation (23) is the general form of tensile damage evolution equation.

If the growth length of crack is assumed to equal the decrease length of the solid material, namely $\dot{L}_d\approx-\dot{L}_s$, then $\dot{L}=\dot{L}_d+\dot{L}_s=0$ and Equation (23) can be simplified as:

$$\dot{D}=\frac{\left(1-\nu^2\right)\left(\sigma^2-\sigma_c^2\right)C_R}{\eta E}D . \quad (24)$$

The condition of damage developing is $\sigma\geq\sigma_c$, the tensile stress exceeds the threshold stress σ_c.

For our concrete material C40, the tensile fracture strength by experiment is $f_t=3.48MPa$, which will be taken as the threshold stress σ_c, namely $\sigma_c=f_t=3.48MPa.$ The Young modulus is $E=29.3GPa$ and the Poisson's ratio is $\nu=0.20$. The specific experimental methods and specimen preparation have been illustrated in Li Ping et al. [20]. When the micro-crack length is taken as $130\mu m$, the surface energy η will be 0.08 J/m^2 by Equation (14). And the velocity of Rayleigh wave C_R obtained using Equation (19) is:

$$C_R=\frac{0.862+1.14\nu}{1+\nu}\sqrt{\frac{E}{2(1+\nu)\rho}}=\frac{0.862+1.14\times 0.2}{1+0.2}\sqrt{\frac{29.3GPa}{2(1+0.2)2306kg/m^3}}=2109m/s .$$

The material parameters in tensile damage evolution are shown in Table 2.

TABLE 2 The material parameters in tensile damage evolution

ν	$\eta(J/m^2)$	$E(GPa)$	$\sigma_c(MPa)$	$C_R(m/s)$
0.2	0.08	29.3	3.48	2109

4 The wave propagation problems caused by explosive load

As an example to verify and apply the damage models presented, a numerical simulation of the cylindrical concrete under the internal uncoupled explosive load has been carried out by the finite element program HVP similar to EPIC-2 [21, 22]. By the experiments on MTS with confining pressure and SHPB, we have obtained the following dynamic coupled pressure-shear viscoplastic yield criterion for damaged concrete:

$$\bar{\sigma}=f_c\Psi(p^*)\left(1+B\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)(1-D) , \quad (25)$$

where:

$$\Psi\left(p^*\right)=\sigma_m^*-\gamma f_c e^{-\beta(p+p_{3t}^*)/f_c},$$
$$p^*=\frac{p}{f_c},\quad p_{3t}^*=\frac{p_{3t}}{f_c},\quad \sigma_m^*=\frac{\sigma_m}{f_c}. \qquad (26)$$

where $\bar{\sigma}$ is Mises equivalent stress and f_c is the static uniaxial compression strength, variables with the superscript "*" are dimensionless quantities normalized by the static uniaxial compression strength f_c; the influence of hydrostatic pressure on the yield strength is described by the yield factor $\Psi(p^*)$ which is a function of hydrostatic pressure, $p^*=\frac{p}{f_c}$ is the normalized pressure p is the actual pressure, p_{3t} is the maximum hydrostatic tensile strength, σ_m, γ, β are the material parameters; $\dot{\varepsilon}$ is the strain rate, and $\dot{\varepsilon}_0$ is the reference strain rate, B is the strain rate coefficient; $D=D_1+D_2$ is the total damage which includes the coupled pressure-shear damage D_1 and the tensile damage D_2, i.e. the two kinds of damage will all decrease the material strength with a linearly weakening manner. By experiments of triaxial confining pressure, we have also obtained the relationship between the hydrostatic pressure and volume strain η:

$$p=k_0\eta+k_1\eta^2+k_2\eta^3+k_3\eta^4,\ (\eta=v/v_0-1), \qquad (27)$$

where k_0, k_1, k_2 and k_3 are material parameters. All relevant material parameters in Equations (25)-(27) are shown in Table 3

TABLE 3 The material parameters of concrete

k_0 (GPa)	k_1 (GPa)	k_2 (GPa)	k_3 GPa)
6.98	124.50	-3251.3	21330
γ	β	p_{3t}^*	σ_m^*
6.7825	0.2958	0.025	7.0

The calculation model is shown in Figure 4: the outer radius of concrete column is 30 cm, the inner radius is 5 cm, the radius of TNT explosive in the center of concrete column is 1 cm, the foam is padded between the explosive and concrete materials. The explosive column is detonated by means of centerline initiation.

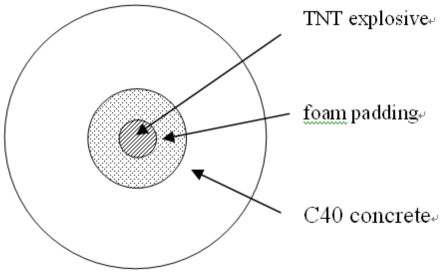

FIGURE 4 The calculation model

The calculation results are shown in Figures 5-8, in which Figures 5 and 6 are the moiré patterns of coupled pressure-shear damage at the t=45 μs and t=90 μs after the centre initiation respectively. It can be seen from the two figures that in the inner region of the concrete column, the coupled pressure-shear damage reaches the ultimate value accompanying with completely crushing destruction of material; while in the outer region of the concrete column, the coupled pressure-shear damage has not yet occurred, and in the middle region of concrete column, the damage value is between initial damage and ultimate damage. Due to the probability perturbation method adopted in the calculation, the damage manifests itself an asymmetric distribution in the circumferential direction, which is consistent with experimental results.

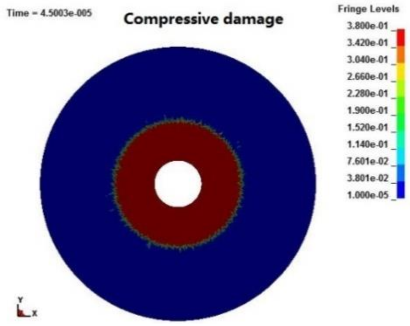

FIGURE 5 t=45μs coupled pressure-shear damage moiré pattern

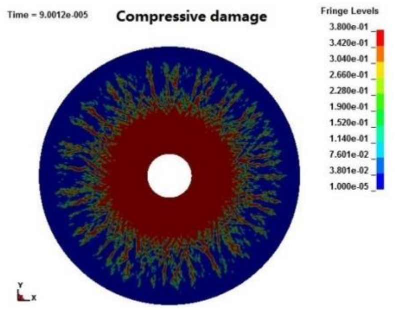

FIGURE 6 t=90μs coupled pressure-shear damage moiré pattern

Figures 7 and 8 are the moiré patterns of tensile damage at the t=45 μs and t=90 μs after the center initiation respectively. It can be seen from the two figures that in the inner region of the concrete column, there is no tensile damage occurring; while in the outer region, the tensile damage occurs because of tensile stress exceeding threshold σ_c generated due to the reflection of compression wave from the free surface of concrete column. As the case for coupled c pressure-shear damage calculation, the probability perturbation method is also adopted in the tensile damage calculation, and the tensile damage also manifests itself an asymmetric distribution in the circumferential direction.

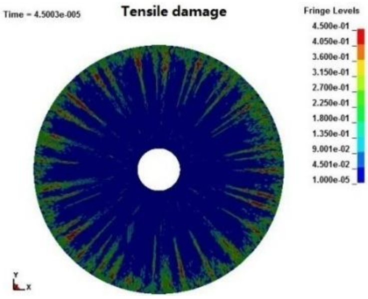

FIGURE 7 t=45μs tensile damage moiré pattern

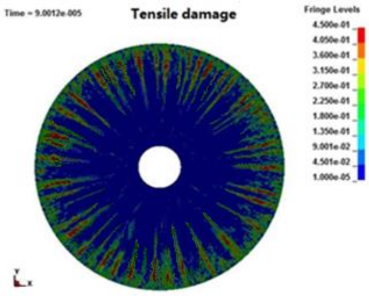

FIGURE 8 t=90μs tensile damage moiré pattern

The above calculation results are reasonable and credible by compared with experiment [23] and the theoretical analysis, and verifies the dynamic constitutive model with damage put forward in the paper is scientific and practical.

5 Conclusions

1) In this study, the damage in concrete is divided into the coupled pressure-shear damage and tensile damage according to the different stress states and different evolution mechanism;
2) Based on the idea “concrete being a system with many micro voids” and “growth of existent damage-nucleus in material”, the evolution equation of the coupled pressure-shear damage is obtained by the microscopic statistics method. The relevant material parameters in the evolution equation are determined by numerical fitting the test data of one-dimensional compression.
3) Based on the idea “concrete being a system with many micro cracks” and “the crack surface energy is supplied by the elastic strain energy around cracks”, the evolution equation of the tensile damage is obtained by the microscopic statistics method. The relevant material parameters in the evolution equation are determined from concerned theory and some test data.
4) To verify the proposed damage models, numerical simulation on wave propagation problems caused by the uncoupled explosive charge in concrete columns has been made. The simulation results show that the distribution and evolution about the coupled pressure-shear damage and the tensile damage are in good agreement with experimental results.

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