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PHASE-FIELD MODELING OF CONCRETE: NUMERICAL SIMULATION AND EXPERIMENTAL VERIFICATION

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Abstract:

Simulation of concrete structures behavior is very popular in engineering design, as the concrete is the most used the material in the world. The possibilities are related to the development of Finite Element Method (FEM) based software and the possibility to implement advanced constitutive models or computational mechanics methods which can provide satisfying results. The most popular concrete constitutive model available in many FEM software is Concrete Damage Plasticity (CDP) model which takes into account both tension and compression response, as well as damage field which can be considered as the level of stiffness decrease in the material. Another approach is a Phase-Field Damage Model (PFDM) which found application in recent years in modeling response of various materials exposed to extreme loading conditions. In this paper, the Drucker-Prager constitutive model is enhanced to compute a strain energy which produces damage in material under the certain conditions. The damage is considered as the additional degree of freedom in 3D solid element, where the threshold value of a critical total strain energy is declared as the limit quantity. The functionality of the proposed approach is considered by comparison of experimental and simulation results for uniaxial compression test.

Keywords: phase-field damage model, Drucker-Prager, concrete, uniaxial compression experiment

1. Introduction

Concrete structures are highly favored in civil engineering structural design due to the respectable strength and reliability. A modeling of the concrete structures behavior can offer the essential information necessary in a design procedure. The available EC standards as well as national standards offer the relations and limits based on concrete characteristics and mechanics laws, but complex structures often need specific loading and boundary conditions which are not covered by the standards. As a complementary solution, various software tools, usually based on Finite Element Method, are developed by researchers and engineers which can solve such problems. The specific behavior of concrete structures can be taken into account by implementing the appropriate constitutive model such as Concrete Damage Plasticity (CDP) model [1, 2]. This model includes both, tension and compression response, as well as a damage computation as local internal variable related to the plastic strain field. However, this model has some disadvantages such as mesh and step size sensitivity, large number of material parameters, and problems with local damage jump which can cause losing of convergence stability.

One alternative which can be considered is a Phase-Field Damage Model (PFDM) [3, 4], which is cutting-edge technique implemented in various FEM software, but it is still under the investigation and the improvements are constant in recent years. The most popular application of PFDM is for brittle and ductile modeling of fracture in metals [5-7], especially steel and aluminum, but also it is used for modeling of high and low cyclic fatigue in other materials such as Shape Memory Alloys [8]. Also, it is successfully used for application to the concrete structures by implementation into the Drucker-Prager (DP) constitutive model [9].

In this paper, the theory and implementation of PFDM into the Drucker-Prager model is given as it is done in the PAK-DAM software. The standard degradation function for brittle fracture is used, along with linear hardening of yield function in DP model. The standard cube specimens are experimentally investigated and the obtained force-displacement response is compared to the simulation results for the uniaxial compression test and the identified material parameters.

2. Phase-field damage model for Drucker-Prager model

2.1 Phase-field damage model based on critical total strain

In concrete, after the initial yield stress is achieved, a plastic strain can be observed as well as decrease of strength which is described by damage variable. The stress-strain response change the trend and nonlinear relationship can be observed. The PFDM considers the damage as additional degree of freedom, where the damage variable range is defined as $d \in [0,1]$. If $d=0$, the material can be considered as intact, while opposite limit when $d=1$ means totally destroyed material without any stiffness. This theory is based on a Griffith's theory [10]. Francfort and Marigo [11] proposed a regularized approach which minimize energy functional based on equilibrium of the surface and the bulk strain energy. For this purpose, a regularized crack functional valid for multi-dimensional problems is [12]:

$$G_l(d) = \int_V \gamma_l(d, \nabla d)\, dV \quad . \tag{1}$$

The crack surface density function per unit volume is defined as:

$$\gamma_l = \frac{1}{2l_c}\left(d^2 + l_c^2 |\nabla d|^2\right) \quad , \tag{2}$$

where l_c is the characteristic length and ∇ is the gradient operator. A total strain energy consists of the elastic-plastic part and a fracture contribution [12, 13]:

$$\psi_{\mathrm{int}} = \psi_{\mathrm{ep}} + \psi_{\mathrm{f}} \quad . \tag{3}$$

The elastic-plastic strain energy is defined in relationship to the constitutive relations of the material, while the fracture part comes from the phase-field. The elastic-plastic strain is:

$$\psi_{\mathrm{ep}} = g(d)\left(\frac{1}{2}\boldsymbol{\sigma} : \boldsymbol{\varepsilon}_e + \sigma_0 \bar{\varepsilon}_p + \frac{1}{2} H \bar{\varepsilon}_p^2\right) \quad , \tag{4}$$

where $g(d)=1-d^2$ is the degradation function, $\boldsymbol{\sigma}$ is the stress tensor, $\boldsymbol{\varepsilon}_e$ is the elastic strain tensor, σ_0 is the initial yield stress, $\bar{\varepsilon}_p$ is the equivalent plastic strain, and H is the linear hardening parameter. In the concrete structures, the damage does not occur immediately after the loading starts, so a threshold should be determined. This is straightforward from the work-density criterion defined by Miehe et al. [13], if the fracture surface energy density is:

$$\psi_f = G_v\left[d+\frac{l_c^2}{2}|\nabla d|^2\right]. \tag{5}$$

In the previous equation, a specific fracture energy per unit volume is defined as $G_v = G_c / l_c$ [6]. After the appropriate derivation of previous equations, the final term for the fracture strain energy density is:

$$\psi_f = \frac{G_v}{2}\left(1-g(d)\right)+G_v l_c \gamma_l. \tag{6}$$

Finally, the total internal potential energy can be calculated as:

$$P=\int_V \psi_{\text{int}} dV = \int_V \left(\psi_{\text{ep}}+\psi_{\text{f}}\right) dV. \tag{7}$$

Equilibrium of variation of the total internal potential energy δP and the external potential energy:

$$W_{\text{ext}} = \int_V \mathbf{b}\cdot\delta\mathbf{u} dV + \int_A \mathbf{h}\cdot\delta\mathbf{u} dA, \tag{8}$$

where $\mathbf{b}$ is a body force per unit volume V, $\mathbf{h}$ is a boundary traction per unit area A, and $\mathbf{u}$ is a displacement vector. Applying the appropriate math transformation, the equilibrium equation and the phase-field damage evolution law are [3, 6, 14]:

$$\begin{aligned} &Div[\boldsymbol{\sigma}]+\mathbf{b}=0 \\ &G_v\left[d-l_c^2\nabla^2 d\right]+g'(d)\psi_{\max}=0, \end{aligned} \tag{9}$$

where $\psi_{\max}=\psi_{\text{ep}}/g(d)-G_v/2$.

2.2 Drucker-Prager constitutive model

The concrete behavior can be described by Drucker-Prager constitutive model with non-associative yield criterion. It can take into account both tensile and compression loading conditions. The yield condition is defined as [9]:

$$f=\alpha_p I_1+\sqrt{J_{2D}}-k_p \tag{10}$$

where the hardening is described by linear rule: $k_p=\sigma_0+H\bar{\varepsilon}_p$, α_p is the material parameter, I_1 is the first invariant and J_{2D} is the second invariant of deviatoric stress. The plastic potential is described by function:

$$g = \alpha_n I_1 + \sqrt{J_{2D}} - k_p \quad . \tag{11}$$

where α_n is the additional material parameter. The plastic strain increment is then:

$$\Delta\boldsymbol{\varepsilon}_p = \lambda_p \mathbf{n}_{DP} = \lambda_p \frac{\partial g}{\partial \boldsymbol{\sigma}} \quad , \tag{12}$$

where λ_p is the plastic multiplier and the equivalent plastic strain increment is:

$$\Delta\bar{\varepsilon}_p = -\lambda_p \frac{\partial g}{\partial k_p} = \lambda_p \quad . \tag{13}$$

3. Comparison of experimental and numerical uniaxial compression test

The experimental investigation of concrete specimens is realized by compression testing machine – MATEST ServoPlus Research + ServoStrain 2000kN. The standard [15] 150 mm cube specimens are tested. The loading is controlled by the displacement rate of 1mm/min. The maximum recorded compression strength is 49.975 MPa. The stress-strain response is recorded by the piston stroke and the force measured by the compression testing machine. The compression testing machine and the specimen are shown in Fig. 1.

Fig. 1. Experimental investigation of concrete specimen in compression testing machine

The simulation of the uniaxial compression test is modelled by one element example. One 3D element of size 150 x 150 x 150 mm, is constrained at one side, while the opposite side is loaded by prescribed displacements. The material parameters are fitted to achieve the stress-strain response of the experimental investigation. Only material parameters for the compression loading conditions are given in Table 1.

Yield stress σ_0[MPa]	Young modulus E [MPa]	Poisson's ratio [-]	Mat. parameter $\alpha_{p,n}$
49.975	9258	0.192	0.0

Table 1. Material parameters necessary for the simulation in PAK-DAM

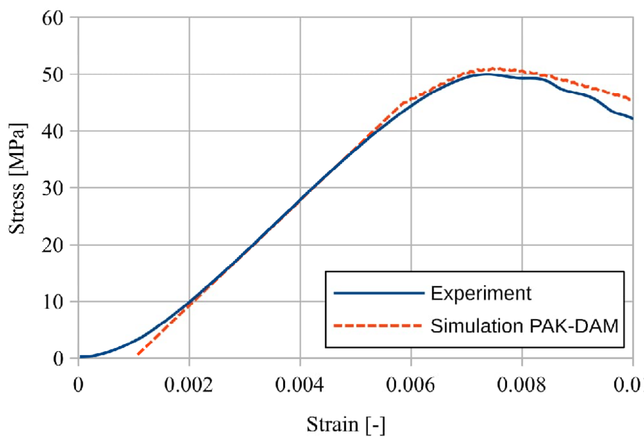

Fig. 2. Stress-strain response for the uniaxial compression test of standard cube specimen: experiment vs. simulation results

As it can be noticed from Fig. 2, the experimental stress-strain curve exhibits a non-linear behavior due to the several reasons, but the most important is the measurement of the strain by the piston displacement recorded by the compression machine. Such measurement of the strain includes the deformation of the entire testing machine, the elastic deflection of the compression plates, and the specimen slipping between the compression plates. Other reasons could be heterogeneous strain distribution in the specimen and effect of friction between the compression plates and the specimen. Also, this can cause reduced value of the Young modulus in comparison to the expected values. However, this paper does not tend to precisely capture the characteristics of the specific specimen, but the idea is to show the possibility to reproduce the behavior by the proposed simulation technique.

In this scope, the comparison of the experimental and the simulation results is given in Fig. 2. It can be observed that the experimental and the simulation curve are parallel in the elastic stage of loading, and when the plastic strain occurs, the linear hardening explained in Drucker-Prager constitutive model captured the response. The maximal strength of the specimen is achieved at the same strain level. After that point, the damage of the material occurs and the stress decreases according to the chosen degradation function.

4. Conclusions

The simulation of the concrete structures behavior is one of the most popular topics among the FEM software developers but also engineers and researchers. Specially, prediction of damage evolution in civil engineering concrete structures is essential for safety what increase the interest in this field at the highest level. Beside the classical concrete constitutive models which considers the damage as internal variable, the PFDM offers the possibility to predict the damage evolution as additional degree of freedom in various materials. The Drucker-Prager constitutive model can be modified and enhanced by PFDM to capture the response of the concrete structures in both tension and compression state of stress. For this purpose, DP model is implemented into the PAK-DAM software and the simulation response for the uniaxial compression loading is compared to the experimental investigation of standard specimen. The recorded results show very good functionality of the proposed implementation what is very promising for the further application in real engineering problems.

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