IOP Conf. Series: Earth and Environmental Science 233 (2019) 032019 doi:10.1088/1755-1315/233/3/032019

A Damage Model of Ultra High Performance Concrete and its Application in Seismic Design of Gravity Dam

Tianxiao Ma[1], Liaojun Zhang[1*], Wei Xie[1], Weiqiang Wang[2]

[1]College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210098, China

[2]Centre for Built Infrastructure Research, School of Civil Environmental Engineering, University of Technology Sydney, NSW 2007, Australia

[*]Corresponding author's e-mail: ljzhang@hhu.edu.cn

Abstract. The ultra high performance concrete is currently the most innovative cement-based engineering material, which has shown a much better performance in strength and durability than the conventional concrete and has received increasing attention worldwide as its application emerges in the engineering field. Based on the theory of damage mechanics, a plastic damage model of the ultra high performance concrete material is established and studied on in this paper. Through the finite element numerical calculation, the rationality of the parameter setting and the applicability of the damage model are verified by comparing its results with those of the cubic compression test and the simply supported beam bending test and then the ultra high performance concrete is introduced to the hydraulic engineering design in this paper. Taking the Koyna gravity dam as an example, a scheme for seismic reinforcement using ultra high performance concrete in the weak part of the gravity dam, which is vulnerable to damage, is proposed. The results show that the scheme can significantly reduce the damage degree of the dam under earthquake action, limit the development of the crack to the upstream and avoid the occurrence of penetrating cracks, as a result of which the seismic performance of the dam is greatly improved. The research results of this paper provide a new idea for high dam design in strong earthquake areas.

1. Introduction

Concrete is a common building material in civil and hydraulic engineering. As to the engineering building structures, the relatively high stress usually occurs in local areas, with a limited impact range. However, the concrete of some specific local areas may well crack or be crushed bearing unallowable stress due to large loads, with the common range of its tensile strength 1.0~2.0MPa and its compressive strength 10~20MPa in hydraulic engineering. The conventional solution to this problem is to enlarge the section size to enhance the integral strength of the structure or to proceed the reinforcement process in a localized area, whereas the former one increases the design difficulty and cost, while the other can't help prevent cracks occurrence though the cracking is limited. In addition, when the concrete cracking occurs, the steel corrosion process will be accelerated, reducing structural strength and inducing potential dangers to the engineering safety.

The ultra high performance concrete with ultra high strength, durability and strain strength is considered to be the most innovative cement-based engineering material. Its tensile strength reaches 10~30MPa and the compressive strength 100~300MPa. Therefore, the utilization of the ultra high performance concrete in some key or high stress parts of the structure can probably improve the overall strength and mechanical properties of the structure, in which the ultra high performance concrete of high practical value is a promising material to replace the traditional concrete[1,2].

Finite element numerical analysis is one of the effective methods for studying ultra high performance concrete. It is essential to research on the constitutive relationship of the ultra high performance concrete and to correctly reflect its damage and failure behavior. Plastic damage mechanics is an effective approach to study on such materials, which can reflect the sequential formation-propagation-destruction process of material cracks[3]. At present, the application of ultra high performance concrete emerges in the fields of building structures and bridges. Some scholars have studied its antiknock and impact resistance properties[4-6]. But it has not been applied to hydraulic projects so far. Gravity dam is one of the classic dam types in hydraulic engineering. When confronted with strong earthquakes, the dam heel may well crack when subjected to large tensile stress and the dam toe may be partially crushed when subjected to high compressive stress. Meanwhile, at the variable cross-section of the dam head, the upstream and downstream faces may have cracks or even penetrating cracks, which affects the safe operation of the gravity dam. This paper originally introduces the ultra high performance concrete to the design of hydraulic engineering. Taking the Koyna gravity dam as an example, the ultra high performance concrete damage model is established in the ABAQUS software, with the ultra high performance concrete utilized in the vulnerable part of the dam to analyze the damage and failure law under earthquake action. The results show that the ultra high performance concrete can effectively improve the seismic performance of the dam and the research in this paper provides a new idea for the seismic design of gravity dams.

2. The damage model of ultra high performance concrete

2.1. Concrete uniaxial tension and compression damage model and parameters

The concrete plastic damage model proposed by Lubliner, Lee and Fenves[7] considers the differences of tensile and compressive properties of materials and can reflect different damage states of concrete structures, respectively breaking, crushing and stiffness degradation, under the conditions of cyclic and dynamic loading. The stress-strain relationship curves are shown in Fig. 1 and Fig. 2 [8]. In the case of uniaxial compression, the linear elastic relationship is obtained when the initial yield stress is less than σ_{c0} and the stiffness of elasticity is E_0. When the initial yield stress reaches σ_{c0} and proceeds to increase, the typical material is characterized by stress hardening within a certain range under the plastic law. After exceeding the ultimate stress σ_{cu}, it enters the softening stage, which is mainly manifested by the continuous decrease of the elastic modulus of the material.

As shown in Fig. 1 and Fig. 2, assuming that the initial value of the elastic stiffness is E_0, the stress-strain relations under uniaxial tension and compression loading are respectively as follows:

$$\sigma_t = (1-d_t)E_0(\xi_t - \tilde{\xi}_t^{pl}) \tag{1}$$

$$\sigma_c = (1-d_c)E_0(\xi_c - \tilde{\xi}_c^{pl}) \tag{2}$$

Drawn from the curve in Fig. 1, the equations can be obtained as follows:

$$\tilde{\varepsilon}_{\text{in}} = \varepsilon_c - \varepsilon_{0c}^{el} \tag{3}$$

$$\varepsilon_{0c}^{el} = \frac{\sigma_c}{E_0} \tag{4}$$

$$\tilde{\varepsilon}_{c}^{pl} = \tilde{\varepsilon}_{\text{in}} - \frac{d_c}{(1-d_c)}\frac{\sigma_c}{E_0} \tag{5}$$

Where: $\tilde{\varepsilon}_{\text{in}}$ is inelastic strain, ε_c is total strain, ε_{0c}^{el} is elastic strain, d_c is compressive damage variable, $\tilde{\varepsilon}_{c}^{pl}$ is plastic strain.

The stress-strain curve of concrete under uniaxial tension is shown in Fig. 2. Similar to the uniaxial compression, the mechanical behavior of concrete after cracking is expressed as follows:

$$\tilde{\varepsilon}_t^{ck} = \varepsilon_t - \varepsilon_{0t}^{el} \tag{6}$$

Where ε_t is the total strain, ε_{0t}^{el} is the elastic strain when the material is not damaged.

The relationship of cracking strain $\tilde{\varepsilon}_t^{ck}$ and plastic strain $\tilde{\varepsilon}_t^{pl}$ is as follows:

$$\tilde{\varepsilon}_t^{pl} = \tilde{\varepsilon}_t^{ck} - \frac{d_t}{(1-d_t)}\frac{\sigma_t}{E_0} \tag{7}$$

Under cyclic loading conditions, the damage variable d is a function of stress state and uniaxial damage variable and there is the following assumption:

$$(1-d_t) = (1-s_t d_c)(1-s_c d_t) \tag{8}$$

where s_t and s_c are functions of the stress state that are introduced to represent stiffness recovery effects associated with stress reversals.

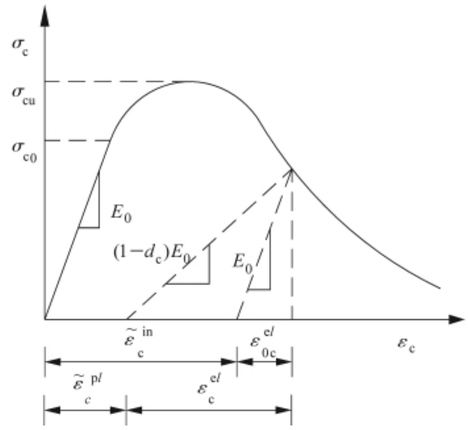


Fig.1 Uniaxial compressive stress-strain curve

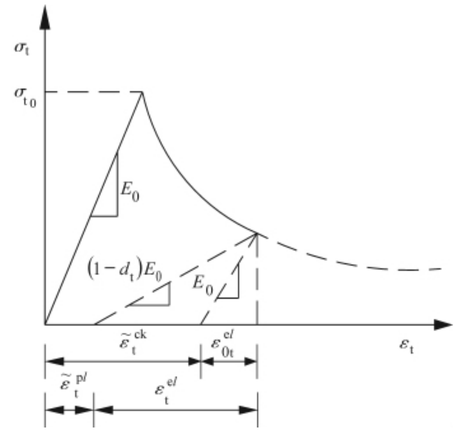


Fig.2 Uniaxial tensile stress-strain curve

2.2. Damage model and parameters of ultra high performance concrete

For ultra-high performance concrete, some scholars have studied its basic mechanical parameters and damage constitutive models. Based on the experimental and theoretical analysis of 200MPa-level ultra high performance concrete, the literature [9,10] put forward the assumption that the damage variable and inelastic strain of ultra high performance concrete have first-order exponential decay relationship:

$$d_k = A_0 e^{\frac{-\tilde{\varepsilon}_{norm}^{in}}{t_0}} + B_0 \tag{9}$$

$$A_0 = \frac{1}{e^{\frac{-1}{t_0}} - 1} \qquad B_0 = -\frac{1}{e^{\frac{-1}{t_0}} - 1} \tag{10}$$

Where d_k is the tensile or compressive damage factor, $k = t$ or $k = c$ represents stretching and compression, respectively; $\tilde{\varepsilon}_{norm}^{in}$ is normalized inelastic strain; t_0 reflects the evolution rate of damage factor with inelastic strain, and is suitable to be set 0.65 for ultra high performance concrete.

The method above is easy to operate and the results are in good agreement with the experimental curve. Thus a damage model of the ultra high performance concrete is established in this paper based on the assumptions above.

In the plastic damage constitutive model of concrete, the plastic potential energy flow is assumed to be uncorrelated potential energy flow, and the flow potential function G is in the form of Drucker-Prager hyperbolic function, which can be described as follows:

$$G = \sqrt{(f_c - m \bullet f_t \bullet \tan\beta)^2 + \bar{q}^2} - \bar{p} \bullet \tan\beta - \sigma \tag{11}$$

where f_t and f_c are uniaxial tensile and compressive strength, respectively; β is the expansion angle and m is the plastic surface eccentricity. The description of the flow surface is controlled by two parameters, β and m. The yield surface is defined by two parameters, f and γ, on the basis of the concrete triaxial test analysis and the yield surface criterion proposed by Lubliner. In this paper, according to the recommendation in the literature [9], β is set 38°, m is 1, f is 1.14 and γ is 0.6667.

3. Verification of the plastic damage model

3.1. Cube uniaxial compression test

In this paper, the numerical simulation analysis is carried out, in comparison with the cubic compression test in literature [5], through applying the damage model elucidated in chapter 2 to verify the rationality of the parameter setting in this paper. The parameters of ultra high performance concrete in literature [5] are shown in Table 1.

Table 1. Key parameters for concrete model.

Model parameter	Value
f_c	170 MPa
f_t	18 MPa
Poisson's ratio	0.19
B1	0.8
w_{lz}	6.00mm
ω	0.10

f_t is the uniaxial tensile strength; B1 governs the compressive damage and softening behaviour; w_{lz} governs the fracture energy of each element; ω governs the volume expansion.

As shown in Fig. 3, the finite element model is established. Both ends of the model, respectively the loading end and the support end, are simulated by large stiffness elements. And the material of the middle cube test block (100mm×100mm×100mm) is the ultra high performance concrete, which is simulated by solid elements with the plastic damage constitutive relation applied. In order to avoid the influence of friction, the coefficient of friction is set to zero. And it is solved by the displacement loading method based on the implicit dynamic algorithm. As shown in Fig. 4, the cube stress and strain data are extracted and compared with the test curve in literature [5] .

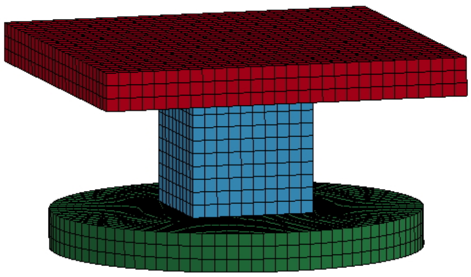


Fig.3 Cube compression test model

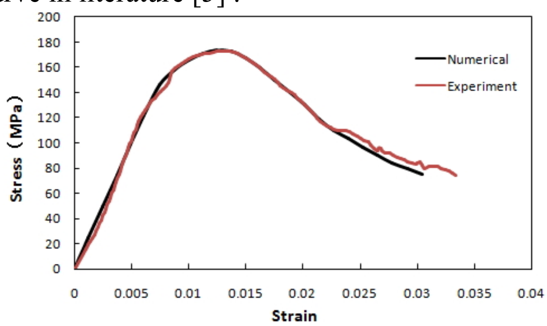


Fig.4 Comparison between numerical simulation results and literature [5]

As shown in Fig. 4, the UHPC material has a linear elastic relationship at the initial loading stage. When the stress reaches 140MPa, the material enters the strengthening stage. When the yield stress reaches 170MPa, the material begins to soften, as the elasticity modulus continues to decrease until it breaks. The model established by the concrete plastic damage theory can better simulate the compression of ultra high performance concrete and also proves the rationality and feasibility of the parameter setting method of the previous section.

3.2. Simply supported beam bending test

A finite element model of the simply supported beam bending test (Fig. 5) is established and the test in the literature [5] is simulated. Both the loading end and the supporting end are simulated by a large stiffness elements and the rectangular specimen (400 mm × 100 mm × 100 mm) is simulated by ultra high performance concrete, the material parameters are the same as those of the cube test. The displacement loading method is used and solution is solved by implicit dynamic algorithm.

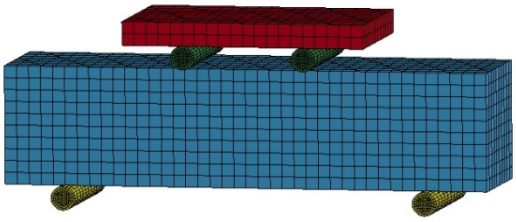


Fig.5 Simply supported beam bending test model

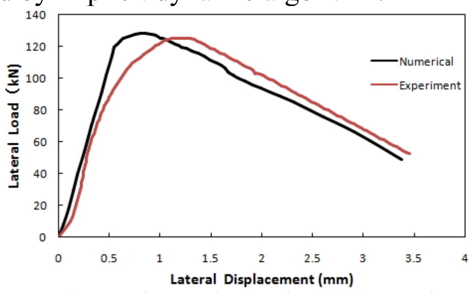


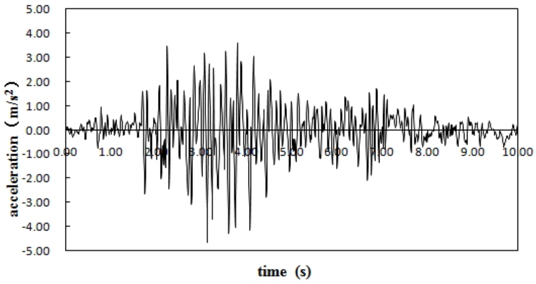
Fig.6 Results comparison between numerical simulation and literature [5]

It can be drawn that the setting of the tensile parameters is feasible and is capable of reflecting the true characteristics of the material. The UHPC material cracking damage area through numerical calculation is shown in Fig. 7, and the damage range and failure mode are relatively close to the experimental results. It can be seen that the numerical calculation can not only accurately simulate the loading-displacement curve, but also the failure mode of the material.

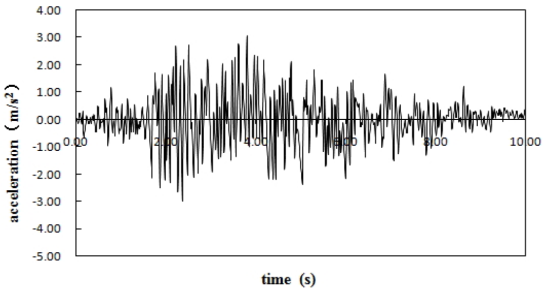
Fig.7 Numerical simulation results of UHPC cracking damage and comparison with literature [5]

4. Verification of plastic damage model of ultra high performance concrete

Under the action of strong earthquakes, local high tensile stress is likely to occur at the downstream slope of the gravity dam head, which leads to the damage and cracking of the concrete structure and may well proceed to develop towards the upstream as the ground motion continues. In severe cases, penetrating cracks may occur, posing a threat to the dam safety. Taking the Koyna gravity dam as an example, it is a block concrete gravity dam with a height of 103m, its head slope19.25m wide and lies on the Goina River in India. The water level at the time of the earthquake was 91.75m then. The planar four nodes elements are used to discretize the dam to establish a finite element model, regardless of the foundation impact. The concrete plastic damage model is adopted in regard to the dam material. The specific material parameters are: concrete elastic modulus 30GPa, Poisson's ratio $\mu = 0.2$, density $\rho = 2630\ \text{kg/m}^3$, tensile strength 2.9MPa, compressive strength -24.1MPa. Besides, the Rayleigh damping is used and the damping ratio is 5%. The Koyna seismic waves are input respectively and the time history curves are shown in Fig. 8. The calculation time step is set to 0.01s for a total of 10s.



（a） Horizontal direction



（b） Vertical direction

Fig.8 Koyna seismic wave

During the earthquake action, the initial damage occurs in the heel and the downstream slope of the dam. As the ground motion continues, the damage gradually develops towards the upstream as the damage of the neck of the dam proceeds and the damage close to penetration eventually forms.

Drawn from the idea of “wrapping silver in gold”, the utilization of the ultra high performance concrete in some specific parts of the dam, which are prone to damage, is proposed in this paper. The reinforcement range is shown in orange in Fig. 11. The upstream width of the neck of the dam is 2m and the downstream 3m, the thickness of the dam heel is 3m. The parameters of the ultra high performance concrete material are consistent with the previous section with other conditions unchanged, and the damage distribution of the dam body is shown in Fig. 12.

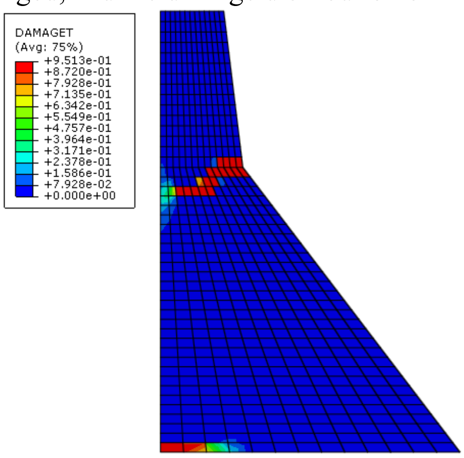


Fig.9 Numerical calculation results of dam body damage distribution

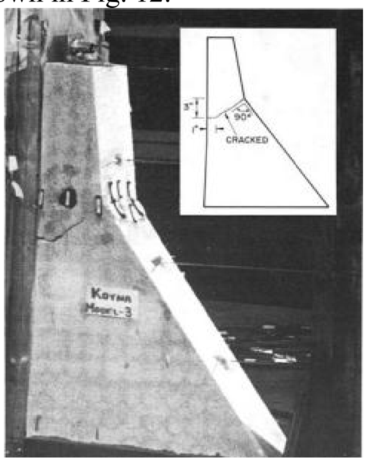


Fig.10 Model test result [11]

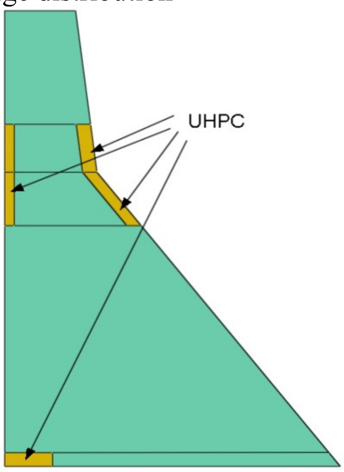


Fig.11 UHPC reinforcement area

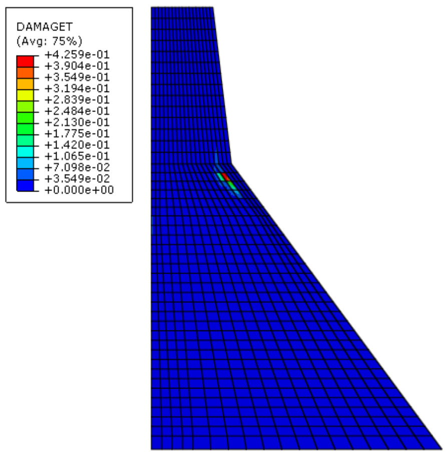


Fig.12 Damage area after UHPC reinforcement

As shown in Fig. 9 and Fig. 12, without the ultra high performance concrete utilized, the largest damage value of the dam is about 0.95 and a penetrating crack develops from the downstream to the upstream. While using the ultra high performance concrete at some specific parts of the dam prone to damage, the largest damage value is reduced to about 0.426 with a smaller damage area. There is no damage signs of the dam heel and no penetrating crack in the neck of the dam as well. It can be concluded that the ultra high performance concrete can not only help reduce the damage degree significantly of the vulnerable parts of the dam, but is also capable of preventing the potential penetrating crack from developing towards the upstream, as a result of which the seismic safety of the dam is eventually ensured effectively with rather modest engineering cost.

5. Conclusion

(1) Through the finite element numerical analysis, a plastic damage model of the ultra high performance concrete is established and studied on in this paper. And the rationality of the parameter setting and the applicability of the model are verified through comparison with the experimental results of the cubic compression test and the simply supported beam bending test.

(2) The ultra high performance concrete is originally introduced to the design of hydraulic projects in this paper. By taking the gravity dam as an example, a scheme for improving seismic performance, utilizing the ultra high performance concrete in the high stress and vulnerable parts of the dam, is discussed. The results show that the design scheme can effectively reduce the damage degree and prevent the penetrating cracks of the dam body, with the seismic performance of the dam significantly improved. The research in this paper helps provide a new idea for the seismic design of gravity dams.

Acknowledgments

This research was financially supported by National key Research and Development Plan of Ministry of science and technology of the People's Republic of China (2017YFC0404903) and National Natural Science Foundation of China (20175033311).

References

[1] Brühwiler, E. and Denarié, E. [2008] "Rehabilitation of concrete structures using ultra-high performance fiber-reinforced concrete," Proc. of the Second International Symposium on Ultra-High Performance Concrete, Kassel, Germany.
[2] Graybeal, B. A. [2005] " Characterization of the behavior of ultra-high performance concrete, " Ph.D.Dissertation, Dept. of Civil and Environmental Engineering, University of Maryland, CollegePark, Maryland.
[3] Shen X P, Mroz Z, Xu B. Constitutive theory of plasticity coupled with orthotropic damage for geomaterials[J]. Applied Mathematics and Mechanics: English Edition, 2001, 22(9):1028-1034.
[4] Rong Z, Sun W, Zhang Y. Dynamic compression behavior of ultra-high performance cement based composites[J]. International Journal of Impact Engineering, 2010, 37(5):515-520.
[5] Zhang F, Wu C, Zhao X L, et al. Experimental and numerical study of blast resistance of square CFDST columns with steel-fibre reinforced concrete[J]. Engineering Structures, 2016.
[6] Zingaila T, Augonis M, Arruda M R T, et al. Experimental and numerical analysis of flexural concrete-UHPFRC/RC composite members[J]. Mechanika, 2017, 23(2).
[7] Lee J, Fenves G L. Plastic-Damage Model for Cyclic Loading of Concrete Structures[J]. Journal of Engineering Mechanics, 1998, 124(8): 892-900.
[8] ABAQUS 6.14 Analysis User's Guide Volume III: Materials.
[9] Y.H.LiParametric Identification for Reactive Powder Concrete DamagePlasticity Constitutive Model and FEM Verification [D]. Beijing Jiaotong University, 2009.
[10] Y.Wang, M.Z.An, Z.R.Yu,. Research on the mechanical properties of reactive powder concrete:a review [J]. Concret, 2013, (12):21-26.
[11] Dams N R C U, Earthquake engineering for concrete dams: design, performance, and research needs: National Academies Press, 1990.