Study on seismic resistance of concrete gravity dam retrofitted with UHTCC

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SUMMARY:
It is especially important to analyze seismic resistance of dam because damage failure seriously influences the safety of dam during strong earthquake. The damage failure of concrete gravity dam subjected to strong ground motion was simulated based on concrete plastic-damage model. According to the damage zone, Ultra High Toughness Cementitious Composite (UHTCC) was implemented to reinforce the main damage zone. The damage of reinforced dam and displacement action at upper portion of dam were analyzed based on the strain hardening constitutive model of UHTCC . It can be obtained that the damage zone of the dam and displacement at upper portion of dam can be apparently reduced by comparing the results of unreinforced dam and reinforced dam. The results indicates that UHTCC can effectively reduce the damage zone , control the damage extension and improve the capacity of dam to resist earthquake.

Key words: damage, seismic resistance, UHTCC

1 INTRODUCTION

Concerns about the seismic safety of concrete gravity dam have been growing around the world. Concrete is a kind of quasi-brittle material with plenty of micro-cracks. These micro-cracks penetrate to form macro-cracks which would imperil overall security of the dams under strong ground motion. So it is no time to delay to research the failure mechanism of gravity dams under earthquake and present effective strengthen measures for resisting earthquake. Some advances have been made on dynamic failure mechanism of gravity dams. Ayari and Saouma(1990)used discrete crack model combined to automatic mesh re-partitioning technique to simulate crack propagation of koyna dam. Cervera *et al.*(1995,1996) made use of smeared crack model based on blunt crack band theory to simulate the failure process of gravity dam under seismic load. Lee and Fenves(1998) analyzed the damage evolution of Koyna dam based on plastic damage model. As to the methods of resisting earthquake, it is mainly concentrated on arranging rebars at weak parts of the dam. Long *et al*.(2008)took embedded slip model(Long,2007a) and reinforcement stiffening model(Long,2007b) to simulate the dynamic response of gravity dam before and after reinforcement.

Several researchers have utilized new composite materials to strengthen dams for the past few years. Based on the mass trial work, Li(2008)developed Ultra High Toughness Cementitious Composite(UHTCC),which is reinforced with less 2.5% short fibers by composite volume fraction and can be mixed with normal procedures, while the hardened composites possesses significant strain hardening properties with the ultimate tensile strain above.

UHTCC is employed to strengthen weak parts of the gravity dam in this paper. The dynamic response of the reinforced gravity dam is gotten by utilizing concrete plastic damage constitutive model and UHTCC simple linear hardening constitutive model. The consequences show the effectiveness of taking UHTCC to reinforce gravity dams.

2 UHTCC CONSTITUTIVE MODEL

Compared to ordinary concrete, UHTCC has typical strain hardening characteristics, the ultimate tensile strain of which can reach 200 times more than that of concrete. Because of its excellent tensile properties, it is bound to be used widely in engineering. Simple linear hardening constitutive model fitted by Li(2008) based on mass trial work is used to describe UHTCC, as shown in Figure 2.1..Constitutive equation is expressed as follows:

$$\sigma = \begin{cases} E_t \bullet \varepsilon, \varepsilon \le \varepsilon_{tfc} \\ \sigma_{ftc} + E_{tu} \bullet \left(\varepsilon - \varepsilon_{tfc} \right), \varepsilon_{tfc} < \varepsilon \le \varepsilon_{tu} \end{cases} \tag{2.1}$$

where σ is tensile stress. E_t is elastic modulus. ε is strain. σ_{tfc} is initial crack strength. E_{tu} is strain hardening elastic modulus. ε_{tfc} is initial crack strain corresponding to σ_{tfc} . ε_{tu} is ultimate tensile strain.

E_{tu} can be calculated by formula as follows:

$$E_{tu} = \frac{\sigma_{tu} - \sigma_{tfc}}{\varepsilon_{tu} - \varepsilon_{tfc}} \tag{2.2}$$

where σ_{tu} is ultimate tensile strength.

According to the trial of Li(2008), E_t , σ_{tfc} , σ_{tu} ε_{tfc} ,and ε_{tu} can be obtained as 17.5Gpa,3.48Mpa,5.48Mpa,0.02% and 4.2% respectively. And then E_{tu} can be gotten as 0.48Gpa.

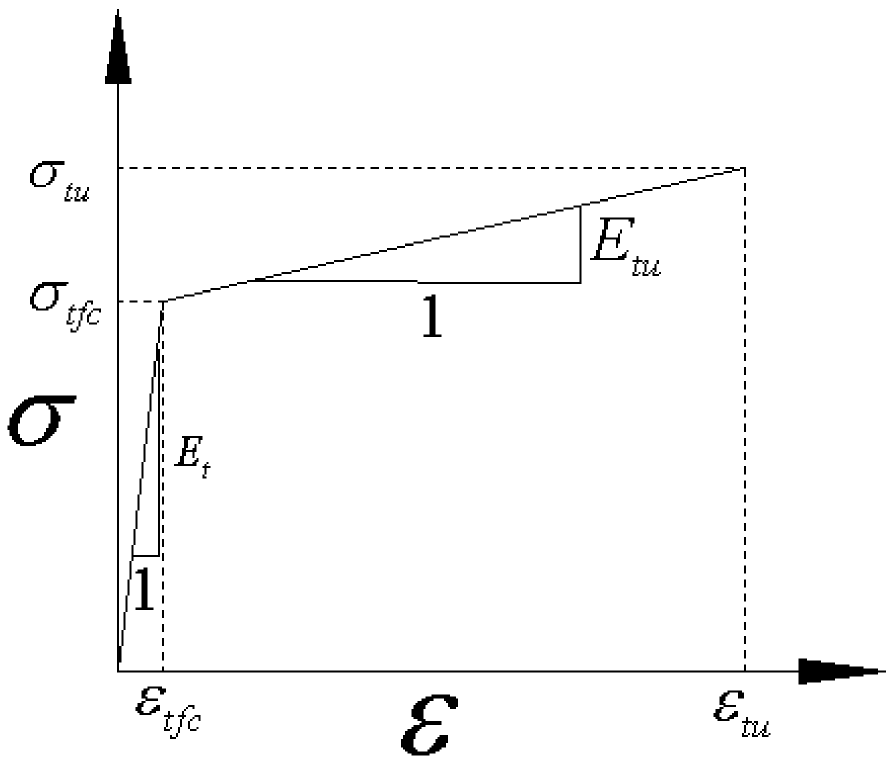


Figure 2.1. Simple linear hardening constitutive model

3 CONCRETE PLASTIC-DAMAGE CONSTITUTIVE MODEL(Lee,1998)

1) Stress-strain relationship based on damage mechanics theory

The relationship between nominal stress σ and effective stress $\bar{\sigma}$ at material point is given as follows:

$$\sigma=(1-d)\bar{\sigma} \tag{3.1}$$

where d is scalar damage factor.

The effective stress $\bar{\sigma}$ and elastic strain meet the elastic constitutive relationship, which can be expressed as follows:

$$\bar{\sigma}=D_e\varepsilon_e=D_e\left(\varepsilon-\varepsilon^{pl}\right) \tag{3.2}$$

where D_e is undamaged elastic stiffness matrix. ε and ε^{pl} denote total strain and plastic strain respectively.

2) The yield function

The yield function F is determined by effective stress $\bar{\sigma}$ and internal damage variable κ , which can be given as follows:

$$F=\left(\bar{\sigma},\kappa\right)=\frac{1}{1-\alpha}\left[\alpha\bar{I}_1+\sqrt{3\bar{J}_2}+\beta(\kappa)\left\langle\hat{\bar{\sigma}}_{\max}\right\rangle\right]-c_c(\kappa) \tag{3.3}$$

where $\bar{I}_1$ and $\bar{J}_2$ denote stress first invariant and second invariant of deviatoric stress respectively. $\hat{\bar{\sigma}}_{\max}$ denotes algebraically maximum principal stress. $c_c(\kappa)$ is compressive cohesive strength. The parameter α , determined by concrete biaxial tensile strength f_{cb} and uniaxial compressive strength f_c , and β ,determined by tensile and compressive cohesive strength $c_t(\kappa)$ and $c_c(\kappa)$ at current damage state , are given as follows:

$$\alpha=\frac{(f_{cb}/f_c)-1}{2(f_{cb}/f_c)-1},\beta=\frac{c_c(\kappa)}{c_t(\kappa)}(1-\alpha)-(1+\alpha) \tag{3.4}$$

3) The flow rule

The plastic strain rate is evaluated by the flow rule, which is defined by a scalar plastic potential function, G. For a plastic potential in the effective stress space, the plastic strain is given by

$$\dot{\varepsilon}^{pl}=\dot{\lambda}\frac{\partial G\left(\bar{\sigma}\right)}{\partial\left(\bar{\sigma}\right)} \tag{3.5}$$

where $\dot{\varepsilon}^{pl}$ is plastic strain rate. $\dot{\lambda}$ is a non-negative function referred to as the plastic consistency parameter. A non-associative flow rule is necessary to obtain proper dilatancy exhibited by frictional materials. A Drucker-Prager-type function is used as the plastic potential function:

$$G=\sqrt{\left(\in\sigma_{to}\tan\varphi\right)^2+\bar{q}^2}-\bar{p}\tan\varphi \qquad (3.6)$$

where $\in$ is a parameter. σ_{to} is uniaxial elastic ultimate stress. φ is dilatancy angle. $\bar{q}=\sqrt{\frac{1}{2}\left[\left(\bar{\sigma}_1-\bar{\sigma}_2\right)^2+\bar{\sigma}_1^2+\bar{\sigma}_2^2\right]}$ and $\bar{p}=-\frac{1}{3}\left(\bar{\sigma}_1+\bar{\sigma}_2\right)$,determined from p-q plane, are Mises effective stress index and average stress at plane stress state respectively.

4 NUMERICAL SIMULATIONS

The Koyna dam was subjected to an earthquake of magnitude 6.5 on the Richter scale on December 11, 1967.As a failure case, the analysis of resisting earthquake of Koyna dam retrofitted with UHTCC is carried out. The geometry of a typical non-overflow monolith of the Koyna dam is illustrated in Figure 4.1..The monolith is 103m high and 71m wide at its base. The upstream wall of the monolith is assumed to be straight and vertical, which is slightly different from the real configuration. The depth of the reservoir at the time of the earthquake is 91.75m.The material properties of concrete used for the simulation are given in Table 4.1.Two kinds of reinforcement schemes ,A and B, are considered. UHTCC is arranged at dam heel and surface layer of upstream and downstream of the dam in A scheme as illustrated in Figure 4.2.-(a). Compared to A scheme, UHTCC is thickened at parts where damage is more serious in B scheme as illustrated in Figure 4.2.-(b) and（c）.The dam is subjected to its self-weight and hydrostatic pressure prior to any earthquake excitation. The transverse and vertical components of the earthquake accelerations are shown in Figure 4.3.-(a) and (b) (units of g=9.81m sec^{-2}). The reservoir-dam dynamic interaction is modeled using the Westergaard(1933) added mass technique. The foundation, extension 3 times the dam height along horizontal and vertical direction, is considered massless and homogeneous linear elastic, the elastic modulus of which is 21Gpa .The finite element model consists of 1160 elements, 760 elements of which is dam body and the other is foundation.

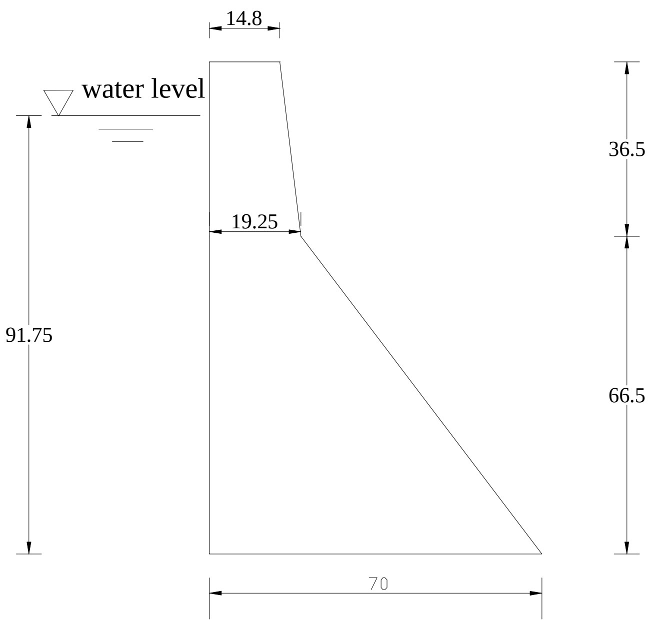


Figure 4.1.Geometry of the Koyna dam (unit:m)

Table 3.1 Material properties for the Koyna dam concrete

Young’s modulus	31027MPa
Poisson’s ratio	0.15
Density	2643kg/m^3
Dilation angle	36.31°
Compressive initial yield stress	13.0MPa
Compressive ultimate stress	24.1MPa
Tensile failure stress	2.9MPa

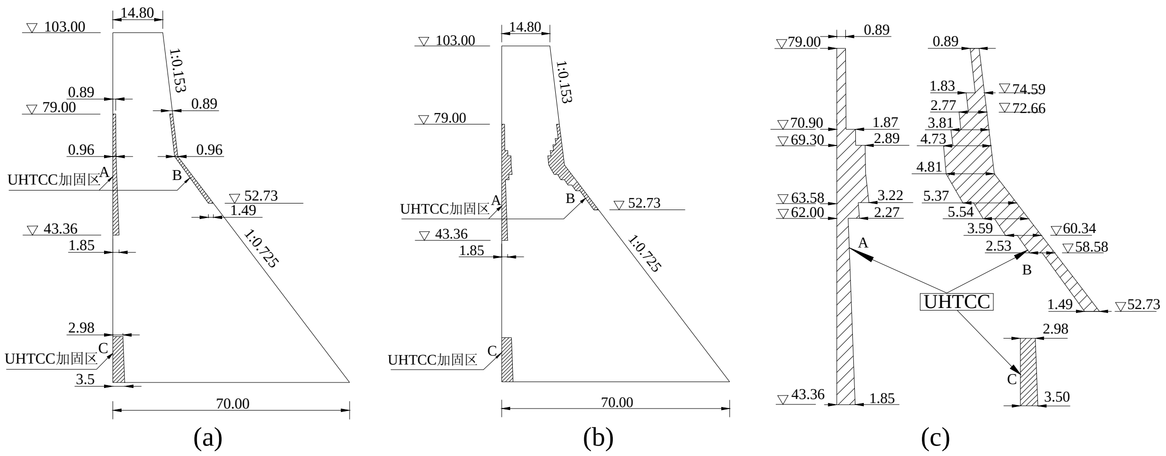


Figure 4.2. Dam section and reinforced scheme (a)A scheme and (b)、（c）B scheme

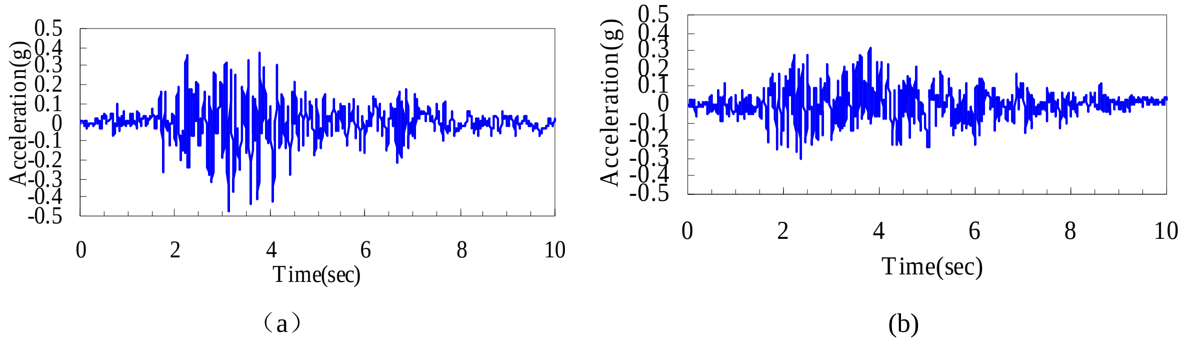


Figure 4.3. Koyna earthquake (a) transverse and (b) vertical accelerations.

4.1 Dynamic response analysis before and after reinforcement

Horizontal crest displacement time stories before and after reinforcement are illustrated in Figure 4.4..The dashed line depicts the displacement before reinforcement and the pink and azury solid line denotes the displacement of A and B reinforcement scheme respectively. From Figure 4.4., it is easily observed that the horizontal displacement is almost consistent between unreinforced and reinforced before damage initiates and the amplitude of horizontal displacement reinforced is smaller than that unreinforced from damage occurring to 6 seconds of earthquake. After 6 seconds, the horizontal displacement before reinforcement is almost negative (positive is along the downstream direction) and the amplitude of the residual displacement is 5.827mm, from which it can be obtained that the action of the earthquake on the top of the dam is slight when the macro-crack forms. In contrary to unreinforcement, the displacement reinforced overall leans to the downstream after 6s of earthquake and the residual displacement is 2.12mm,3.707mm smaller than that of unreinforcement, which illustrates the damage is minished and the integrity of the dam is improved.

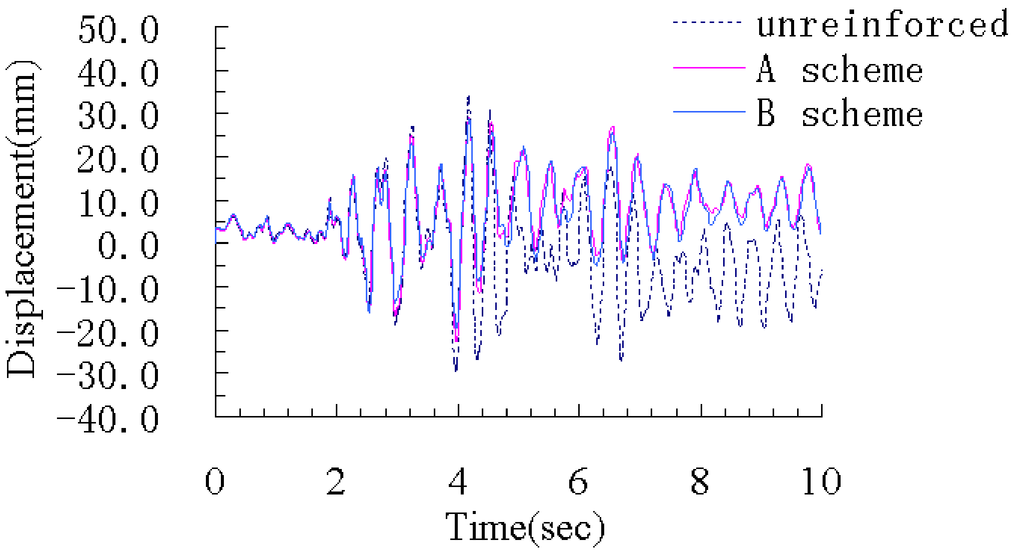
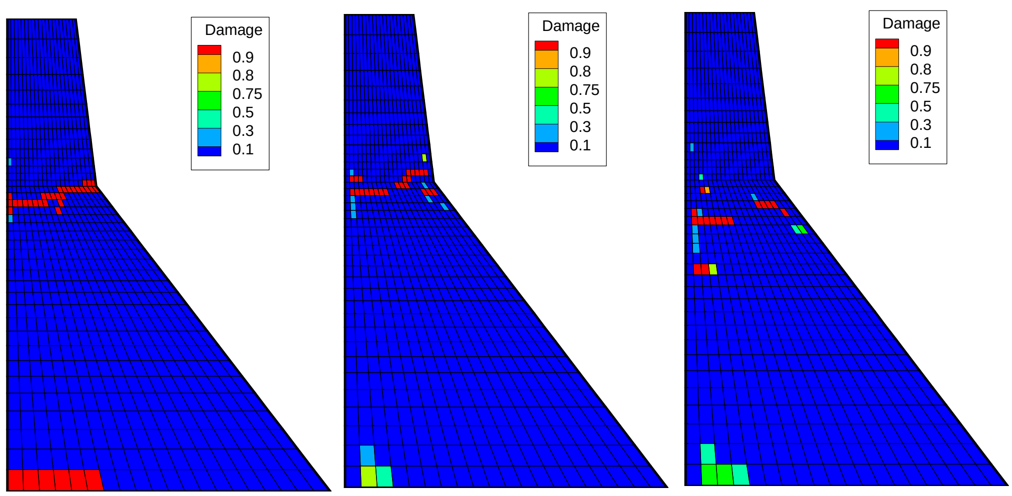


Figure 4.4. Horizontal crest displacement before and after reinforment

The damage distributions of the dam before and after reinforcement at the end of the earthquake are illustrated in Figure 4.5.-(a),(b)and(c).Before reinforcement, the damage initiates at two locations: at the base of the dam on the upstream face and in the region where the slope on the downstream face changes. The damage at the base leads to the formation of a localized crack-like band of damage element. This crack propagats into the dam along the-foundation boundary, the length of which is about 21m.The damage near the downstream change of slope forms a localized crack-like band. As this downstream crack propagates toward the upstream direction, it curves down due to the rocking motion of the top block of the dam. Comparing the results of reinforcement using A scheme with that of unreinforcement, it is obviously observed that the damage initiates at multiple regions and there is no penetration crack to form. The damage at dam heel almost disappeared. The consequence of reinforcement shows that the UHTCC is effective and practical in improving the capacity of resisting earthquake of the dam. Although the effect of A scheme is obvious, there are two longer damage band to exist. So B scheme is chosen to strengthen the weaker part. The result of B scheme, as illustrated in Figure 4.5.-(c), shows that the damage diminishes further compared to that of A scheme. The length of every damage band is obviously shorter than that of A scheme.



(a) (b) (c)

Figure 4.5. Damage distribution of the Koyna dam at the end of the earthquake: (a)unreinfored, (b) reinforced using A scheme and(c) reinforced using B scheme.

5 CONCLUSIONS

The numerical simulation of Koyna dam reinforced with UHTCC has been performed. From the consequence of the analysis , the follows conclusion can be obtained: As a new composite material, UHTCC with excellent mechanical property ,easily to be fabricated ,can reduce the crack width and length when it is used to strengthen the dam and has good application prospect in practical engineering.

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