BEHAVIOR OF MASS CONCRETE USING SMEARED CRACK APPROACH IN THREE DIMENSIONAL PROBLEMS

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ABSTRACT

A smeared crack approach has been proposed to model the static and dynamic behavior of mass concrete in three-dimensional space. The proposed model simulates the tensile fracture on the mass concrete and contains pre-softening behavior, softening initiation, fracture energy conservation and strain rate effects under dynamic loads. It was found that the proposed model gives excellent results and crack profiles comparing with the available data under static loads. Morrow Point dam was analyzed including dam-reservoir interaction effects to consider its nonlinear seismic behavior. It was found that the resulted crack profiles are in good agreement with the contour of maximum principal stresses and no numerical instability occurred during the analysis.

1 INTRODUCTION

Several numerical models have been developed for seismic safety evaluation of concrete dams in two and three-dimensional space. El-Aidi and Hall [1 and 2] considered the nonlinear seismic response of concrete gravity dams using the smeared crack model. It was found that the resulted crack profiles are unrealistic due to using the size reduced strength criterion (SRS) in the proposed smeared crack model. Vargas-Loli and Fenves [3] considered the seismic response of Pine Flat dam using the smeared crack model with the brittle fracture criterion.

Bhattachrjee and Leger [4, 5 and 6] used a smeared crack model to analyze concrete gravity dams in static and dynamic loading conditions. Ghrib and Tinawi [7 and 8] used the damage mechanics theory in static and seismic analysis of concrete gravity dams.

Hall [9] proposed a special smeared crack model to simulate nonlinear behavior of the dam body and vertical construction joins simultaneously. Ghaemian and Ghobarah [10] developed a solution scheme to analyze concrete gravity dams in seismic loads. This method is called staggered method. The developed method was used in nonlinear seismic analysis of concrete dams in two-dimensional space (Ghaemian and Ghobarah [11]). Guanglun et al. [12] used the smeared crack model developed in Bhattacharjee and Leger [4] with re-meshing capability. Ahmadi et al. [13] proposed a model to simulate the static and dynamic behavior of vertical construction joints in arch dams. Gunn [14 and 15] used the damage mechanics theory to consider the effect of nonlinear behavior of the dam body under static loads in three-dimensional problems. Espandar and Lotfi [16] compared the performance of the smeared crack model and elasto-plastic model to consider the nonlinear behavior of dam body in three-dimensional space. Mirzabozorg et al. [17] extended the staggered displacement method developed in Ghaemian and Ghobarah [10] to solve the three dimensional coupled problems in time domain. Lotfi and Espandar [18] used a non-orthogonal smeared crack with a discrete crack model to simulate the nonlinear behavior of dam body and vertical construction joins in arch dams, simultaneously.

In the present article, a three-dimensional smeared crack approach is proposed to model the tensile fracture in static and dynamic conditions. The proposed model includes various aspects to simulate the nonlinear behavior of mass concrete in concrete dams.

2 CONSTITUTIVE LAW OF MASS CONCRETE

The relationship of the stress and strain vectors at the pre-softening phase is given as:

$$\{\sigma\} = [D]\{\varepsilon\} \tag{1}$$

where, $[D]$ is the elastic modulus matrix; $\{\sigma\}$ is the vector of stress components given as $\{\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{zz} \quad \sigma_{xy} \quad \sigma_{yz} \quad \sigma_{xz}\}^T$; and $\{\varepsilon\}$ is the vector of strain components including the corresponding six components of strain.

In the present study, the uni-axial strain energy has been used as softening initiation criterion. This criterion was used successfully in static and dynamic analysis of concrete gravity dams (Bhattacharjee and Leger [5] and Ghaemian and Ghobareh [11]). Based on this criterion, the area under the stress-strain curve up to the peak stress (apparent tensile stress), is used as softening initiation index. Under dynamic loads, this criterion is multiplied by the square of the dynamic magnification factor, DMF_e , which is applied on the apparent tensile strength.

In the softening phase, the secant modulus stiffness (SMS) approach has been employed for stiffness formulation in which the constitutive relation is defined in terms of total stresses and strains. Based on this formulation, the total strains on the fracture plane are decomposed into their components which are the total elastic strain and strain due to cracking. The total secant modulus matrix in local coordinate is given as:

$$[D]_{nst} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & 0 & 0 & 0 \\ D_{12} & D_{22} & D_{23} & 0 & 0 & 0 \\ D_{13} & D_{23} & D_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & D_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & D_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & D_{66} \end{bmatrix} \tag{2}$$

where,

$$D_{11} = \frac{\eta_1 E(1-\upsilon^2\eta_2\eta_3)}{1-\upsilon^2\eta_1\eta_2-\upsilon^2\eta_2\eta_3-\upsilon^2\eta_1\eta_3-2\upsilon^3\eta_1\eta_2\eta_3} \tag{3}$$

$$D_{22} = \frac{\eta_2 E(1-\upsilon^2\eta_1\eta_3)}{1-\upsilon^2\eta_1\eta_2-\upsilon^2\eta_2\eta_3-\upsilon^2\eta_1\eta_3-2\upsilon^3\eta_1\eta_2\eta_3}$$

$$D_{33} = \frac{\eta_3 E(1-\upsilon^2\eta_1\eta_2)}{1-\upsilon^2\eta_1\eta_2-\upsilon^2\eta_2\eta_3-\upsilon^2\eta_1\eta_3-2\upsilon^3\eta_1\eta_2\eta_3}$$

$$D_{12} = \frac{\upsilon\eta_1\eta_2 E(1+\upsilon\eta_3)}{1-\upsilon^2\eta_1\eta_2-\upsilon^2\eta_2\eta_3-\upsilon^2\eta_1\eta_3-2\upsilon^3\eta_1\eta_2\eta_3}$$

$$D_{23} = \frac{\upsilon\eta_2\eta_3 E(1+\upsilon\eta_1)}{1-\upsilon^2\eta_1\eta_2-\upsilon^2\eta_2\eta_3-\upsilon^2\eta_1\eta_3-2\upsilon^3\eta_1\eta_2\eta_3}$$

$$D_{13} = \frac{\upsilon\eta_1\eta_3 E(1+\upsilon\eta_2)}{1-\upsilon^2\eta_1\eta_2-\upsilon^2\eta_2\eta_3-\upsilon^2\eta_1\eta_3-2\upsilon^3\eta_1\eta_2\eta_3}$$

$$D_{44} = \beta_{12} G$$

$$D_{55} = \beta_{23} G$$

$$D_{66} = \beta_{13} G$$

where, E and υ are initial isotropic elastic modulus and Poison's ratio, respectively and η_1 , η_2 and η_3 are the ratio between the softened Yong's modulus in the three principal directions to the initial isotropic elastic modulus and β_{12} , β_{23} and β_{13} are shear re-tension factors corresponding to the principal directions. The fracture strain under static and dynamic loads is determined satisfying the fracture energy conservation principle as done in (Bhattacharjee and Ghobarah [4, 5 and 6].

The concept used in damage mechanics theory presented in (Gunn [14 and 15]) has been employed to set up shear stiffness changes due to softening phase. The shear re-tension factors in eqn (3) are determined as following:

$$\beta_{12} = \frac{1+\upsilon}{dd}\left(\frac{\eta_1\varepsilon_1 - \eta_2\varepsilon_2}{\varepsilon_1 - \varepsilon_2} + \frac{\upsilon\eta_3(\eta_1 - \eta_2)\varepsilon_3}{\varepsilon_1 - \varepsilon_2} - \upsilon\eta_1\eta_2 - 2\upsilon^2\eta_1\eta_2\eta_3\right) \tag{4}$$

$$\beta_{23} = \frac{1+\upsilon}{dd}\left(\frac{\eta_2\varepsilon_2 - \eta_3\varepsilon_3}{\varepsilon_2 - \varepsilon_3} + \frac{\upsilon\eta_1(\eta_2 - \eta_3)\varepsilon_1}{\varepsilon_2 - \varepsilon_3} - \upsilon\eta_2\eta_3 - 2\upsilon^2\eta_1\eta_2\eta_3\right)$$

$$\beta_{13} = \frac{1+\upsilon}{dd}\left(\frac{\eta_1\varepsilon_1 - \eta_3\varepsilon_3}{\varepsilon_1 - \varepsilon_3} + \frac{\upsilon\eta_2(\eta_1 - \eta_3)\varepsilon_2}{\varepsilon_1 - \varepsilon_3} - \upsilon\eta_1\eta_3 - 2\upsilon^2\eta_1\eta_2\eta_3\right)$$

$$dd = 1 - \upsilon^2\eta_1\eta_2 - \upsilon^2\eta_2\eta_3 - \upsilon^2\eta_1\eta_3 - 2\upsilon^3\eta_1\eta_2\eta_3$$

The co-axial rotating crack model has been used to simulate the behavior of the cracked element. The crack closing/reopening criterion is based on the value of principal strains in which the total strain can be decomposed into the two components of elastic and residual strain given as (Ghrib and Tinawi [7 and 8]).

3 FINITE ELEMENT IMPLEMENTATION OF THE PROPOSED MODEL

In the present article, 20-node iso-parametric element has been used in finite element implementation. The stiffness matrix and all of the other related components have been computed based on 3*3*3 Gaussian integration points. All of the related algorithms and state determination of elements are based on the average response of the element which is computed with averaging the computed strains within Gaussian points.

4 NUMERICAL RESULTS

4.1 Example I: Scaled Concrete Gravity Dam under Indirect Displacement Control

Two scaled down 1:40 of a typical concrete gravity dam subjected to equivalent hydraulic lateral loads were tested by Carpinteri et al. [19]. The modulus of elasticity, Poisson's ration, tensile strength and specific fracture energy were reported to be 35.7GPa, 0.1, 3.6MPa and 184N/m, respectively. The tested system has been show in Figure 1.

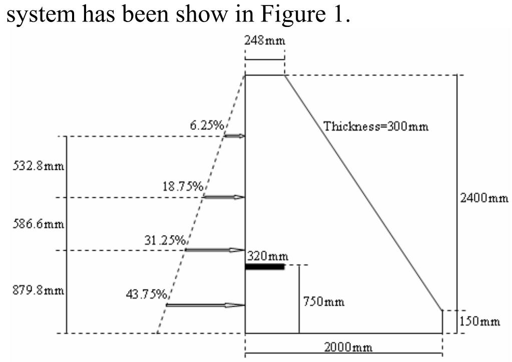

Figure 1: Scaled down 1:40 concrete gravity dam (Carpinteri et al. [19])

The crack mouth opening displacement (CMOD) was used as a control parameter adjusting the applied load. The model has 605 20-node iso-parametric elements including 4448 nodes. Figure 2 shows the response resulted from the proposed smeared crack model comparing with the experimental results. The ultimate load is in good agreement with the experimental results such that the difference is just 0.9 percent. Comparing with the results obtained using two and three-dimensional models reported in (Bhattacharjee and Leger [4] and Ghrib and Tinawi [7] and Gunn [15]), the proposed model has good performance in predicting the ultimate load and its stability is appropriate in high values of CMOD.

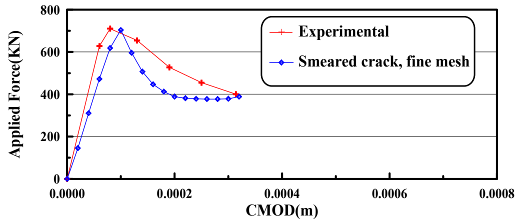

Figure 2: Comparing the theoretical response with the experimental data

Figure 3 compare the crack profiles predicted by the smeared crack model with those reported in experimental work. The crack profiles predicted in the two considered finite element models are in good agreement with the result obtained from the test.

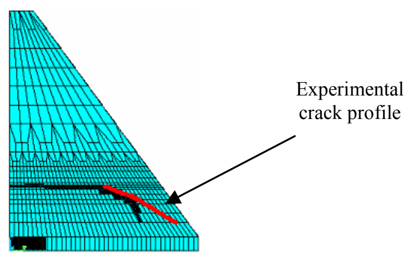

Figure 3: Crack profiles resulting in smeared crack model and experimental work

4.2 Example II: Nonlinear Seismic Analysis of Morrow Point Arch Dam

The dam body has been modeled using 40 20-node isoparametric solid elements and the reservoir model includes 1000 8-node fluid elements which have been introduced in Mirzabozorg et al. [17] (Figure 5). The modulus of elasticity, Poisson's ratio, unit weight, the true tensile strength and the ratio of the apparent to true tensile strength, specific fracture energy and the dynamic magnification factor applied on tensile strength and specific fracture energy are 27.604MPa, 0.2, 24027.15N/m^3, 2.5MPa, 1.25, 200N/m and 1.30, respectively. The pressure wave propagation speed within the reservoir and the unit weight of the reservoir are taken as 1436m/s and 9807 N/m^3, respectively. The wave reflection coefficient has been assumed a conservational value of 0.8. The system shown in Figure 5 has been excited by the three components of the Taft earthquake in 21 July 1952 recorded at the Lincol Tunnel School scaled by 1.5 in addition to applying self weight and hydrostatic pressure. The system was analyzed using the method introduced in Mirzabozorg et al. [17]. The quasi linear damping mechanism was used in dynamic analysis.

Figure 5: Finite element model of the system

It was found that the considered model is not experienced any crack due to self weight and the hydrostatic pressure. In the dynamic excitation, the first crack was appeared at 4.745s at the crest level. The position of the cracked elements, the time of cracking and the cracking order have been shown in Figure 6.

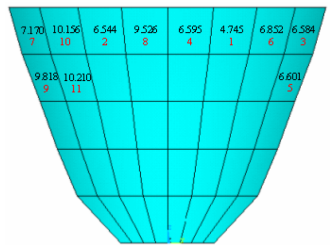

Figure 6: Crack profiles resulted within the dam body

In spite of cracking of more than 25% of the elements, the analysis is stable up to the end of the record (20 seconds) without any numerical instability. Figure 7 shows the contour of the maximum average principal stresses in which the maximum stress is 7.0005 MPa in linear analysis. Comparing Figures 6 and 7, it can be found that the predicted crack profiles in nonlinear analysis are in accordance with the contour obtained using the linear analysis.

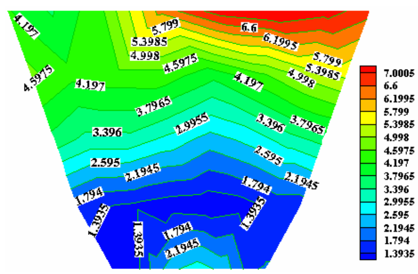

Figure 7: The contour of maximum average principal stresses using linear analysis

5 CONCLUSIONS

A local model based on the energy equivalence concept was used to develop a comprehensive smeared crack model which includes anisotropy in the three principal directions. The proposed model only requires the basic material properties such as modulus of elasticity, Poisson's ratio, tensile strength and specific fracture energy. One of the major advantages of the proposed model is its generality in anisotropic properties of the fractured element. Another advantage of the developed model is its variable shear re-tension factors which are updated based on related principal strains. The accuracy and the stability of the proposed model and the developed software were established using available experimental results. The model was checked using direct and indirect displacement control algorithms. It was found that the proposed model is accurate in predicting crack propagation path as well as the structure ultimate load and post-peak behavior under static loads and the dynamic behavior of the structure.

The developed model is suitable for the assessment of the ultimate capacity of concrete dams in three-dimensional space and also in predicting the nonlinear dynamic behavior of mass concrete on three-dimensional problems. Considering the advantages of the proposed model, it can be applied in analyzing concrete arch dams including dam-reservoir interaction effects.

6 REFERENCES

1. El-Aidi, B. and Hall, J.F. Non-linear earthquake response of concrete gravity dams, part 1: modeling, Earthquake Engineering and Structural Dynamics, 18: 837-851, 1989.
2. El-Aidi, B. and Hall, J.F. Non-linear earthquake response of concrete gravity dams, part 2: behavior, Earthquake Engineering and Structural Dynamics, 18: 853-865, 1989.
3. Vargas-Loli, L. and Fenves, G. Effects of concrete cracking on the earthquake response of gravity dams, Earthquake Engineering & Structural Dynamics, 18: 575-592, 1989.
4. Bhattacharjee, S.S. and Leger, P. Application of NLFM Models to Predict Cracking in Concrete Gravity Dams, Journal of Structural Engineering, ASCE, 120(4): 1255-1271, 1994.
5. Bhattacharjee, S.S. and Leger, P. Seismic cracking and energy dissipation in concrete gravity dams, Earthquake Engineering & Structural Dynamics, 22: 991-1007, 1993.
6. Bhattacharjee, S.S. and Leger, P. Fracture response of gravity dams due to rise of reservoir elevation, Journal of Structural Engineering, ASCE, 121(9): 1298-1305, 1995.
7. Ghrib, F. and Tinawi, R. Nonlinear behavior of concrete dams using damage mechanics, Journal of Engineering Mechanics, ASCE, 121(4): 513-526, 1995.
8. Ghrib, F. and Tinawi, R. An application of damage mechanics for seismic analysis of concrete gravity dams, Earthquake Engineering & Structural Dynamics, 24: 157-173, 1995.
9. Hall, J.F. Efficient non-linear seismic analysis of arch dams, Earthquake Engineering and Structural Dynamics, 27: 1425-1444, 1998.
10. Ghaemian, M. and Ghobarah, A. Staggered solution schemes for dam-reservoir interaction, Journal of Fluids and Structures, 12: 933-948, 1998.
11. Ghaemian, M. and Ghobarah, A. Non-linear seismic response of concrete gravity dams with dam-reservoir interaction, Journal of Engineering Structures, 21: 306-315, 1999.
12. Guanglun, W., Pekau, O.A., Chuhan, Z. and Shaomin, W. Seismic fracture analysis of concrete gravity dams based on nonlinear fracture mechanics, Engineering Fracture Mechanics, 65: 67-87, 2000.
13. Ahmadi, M.T., Izadinia, M. and Bachmann, H. A discrete crack joint model for nonlinear dynamic analysis of concrete arch dam, Computers and Structures, 79: 403-420, 2003.
14. Gunn, R.M. Non-linear design and safety analysis of arch dams using damage mechanics, part 1: formulation, Hydropowers & Dams, 2: 67-74, 2001.
15. Gunn, R.M. Non-linear design and safety analysis of arch dams using damage mechanics, part 2: applications, Hydropowers & Dams, 3: 72-80, 2001.
16. Espandar, R. and Lotfi, V. Comparison of non-orthogonal smeared crack and plasticity models for dynamic analysis of concrete arch dams, Computers and Structures, 81: 1461-1474, 2003.
17. Mirzabozorg, H., Khaloo, A.R. and Ghaemian, M. Staggered solution scheme for three dimensional analysis of dam reservoir interaction, Dam Engineering, XIV (III): 147-179, 2003.
18. Lotfi, V. and Espandar, R. Seismic analysis of concrete arch dams by combined discrete crack and non-orthogonal smeared crack technique, Engineering Structures, 26: 27-37, 2004.
19. Carpinteri, A., Valente, S.V., Ferrara, G. and Imperato, L. Experimental and numerical fracture modeling of a gravity dam, Proceedings of the First International Conference on Fracture Mechanics of Concrete Structures, Breckenridge, Colorado: 351-360, 1992.
20. Hall, J.F. The dynamic and earthquake behavior of concrete dams: Review of experimental behavior and observational evidence, Soil Dynamics and Earthquake Engineering, 7(2): 57-121, 1988.