Engineering Failure Analysis 52 (2015) 45–60

Contents lists available at ScienceDirect

Engineering Failure Analysis

journal homepage: www.elsevier.com/locate/engfailanal

Seismic cracking and instability of concrete dams: Smeared crack approach

M.A. Hariri-Ardebili [a,*], S.M. Seyed-Kolbadi [b]

[a] Department of Civil Environmental and Architectural Engineering, University of Colorado, Boulder, USA
[b] Iranian Commission of Large Dams (IRCOLD), Tehran, Iran

ARTICLE INFO

Article history:
Received 31 December 2014
Received in revised form 22 February 2015
Accepted 28 February 2015
Available online 11 March 2015

Keywords:
Concrete dam
Earthquake
Shear transfer coefficient
Smeared crack

ABSTRACT

Modeling the material behavior and estimation of the cracking capacity of concrete dams under the dynamic loading is important for safety operation purposes. In the present paper, an improved 3D co-axial rotating smeared crack model is used with the ability of updating the variable shear transfer coefficient. The model is implemented in the finite element code to assess the seismic cracking of three types of concrete dams, i.e. gravity, buttress, and arch dams.

Results of the crack profiles confirm importance of the shear transfer coefficient in dynamic analysis of large concrete structures. It is found that the proposed model lead to less diffused cracks in concrete dams and can reasonably matches with the results obtained from experimental tests.

1. Introduction

An integrative constitutive model is required to capture the mass concrete behavior from linear elastic to softening, and final cracking. Different models have been proposed to simulate the concrete under static and dynamic loading. The models based on *continuum* and *discrete* crack approaches are samples of the most favorable ones.

Discrete crack appears in different forms based on the field of study and its application, e.g. "interface", "crack", "joint", or "fault". Numerous joint and interface models have been proposed for concrete structures. Of particular interest to concrete dam engineering are the models of Ayari and Saouma [1], Fenves et al. [2], Divoux et al. [3], Hall [4], Ahmadi et al. [5], Puntel et al. [6], Arabshahi and Lotfi [7], Shi et al. [8]. Discrete crack model explicitly represents the crack as a separation of nodes, which is a realistic representation of the opening crack. This model is also useful when the location and direction of cracks are recognizable before loading the structure.

On the other hand, the models based on continuum crack are divided into two major groups, i.e. the *damage mechanics* and the *smeared crack* approach. In the smeared crack approach, cracks (joints or interfaces broadly speaking) are modeled in an average sense by appropriately modifying the material properties at integration points in the regular finite elements meshes. Smeared cracks are convenient when the crack intensity and orientation are not known beforehand, because formation of a crack involves no re-meshing or new degrees of freedom.

The smeared crack model itself can be classified into three main categories, i.e. *fixed single*, *fixed multi-directional*, and *rotating crack* approaches. The distinction lies on the orientation of the crack, which is either kept constant, updated in a

* Corresponding author. Tel.: +1 303 990 2451.
E-mail address: mohammad.haririardebili@colorado.edu (M.A. Hariri-Ardebili).

http://dx.doi.org/10.1016/j.engfailanal.2015.02.020
1350-6307/

step-wise manner or updated continuously [9]. The basic theory and application of the smeared crack model studied by Willam et al. [10], Malvar and Fourney [11], Guzina et al. [12], Weihe et al. [13], Moslera and Meschke [14], Cervera and Chiumenti [15], Suryanto et al. [16], Broujerdian and Kazemi [17]. In these searches, the constitutive model, numerical (mainly finite element) implementation, boundary value problems, and error analysis were investigated and the results were compared with the experimental tests.

It is noteworthy that the damage and failure process of the concrete dams can be modeled using different numerical techniques, e.g. discrete element method [18], finite difference method [19], mesh-free method [20], and extended finite element method [21]. However, finite element method is the fundamental technique in most cases [22–24].

In addition to the aforementioned fundamental studies, some researchers used the smeared crack model for seismic analysis of concrete dams. Following is the summary of the researches, their applications, advantageous and shortcomings in full seismic nonlinear analysis of concrete dams:

- Bhattacharjee and Leger [25] investigated the cracking of a 2D gravity dam under static loading using smeared crack model. Both the fixed crack and coaxial rotating crack models were used. The ultimate resistance and post failure behavior was predicted by an indirect displacement control analysis technique. No seismic load was used in the analyses.
- Ghaemian and Ghobarah [26] used the smeared crack model developed by Bhattacharjee and Leger [25] for seismic analysis of 2D gravity dam models. The fluid–structure interaction was considered; however, the foundation was assumed to be rigid.
- Espandar and Lotfi [27] developed a non-orthogonal fixed smeared crack model with ordinary and high fracture energy values and used for 3D analysis of arch dams. They reported that the comparison between the ordinary form of smeared crack and elasto-plastic models reveals major differences in the results. However, comparison between the fictitious form of smeared crack and elasto-plastic models shows very similar results.
- Mirzabozorg and Ghaemian [28] used a rotating smeared crack model for analysis of 2D gravity and 3D arch dams. They used the uni-axial strain energy as a simple softening initiation criterion. Foundation interaction was ignored in their analyses.
- Calayir and Karaton [29] used a similar co-axial rotating smeared crack model to Mirzabozorg and Ghaemian [28] for 2D seismic analysis of gravity dams; however, their model follows the exponential strain softening rule.
- Hariri-Ardebili et al. [30] used the rotating smeared crack model in conjunction with three-parameter Menetrey and Willam [31] failure criterion for crack analysis of 2D gravity dams. Both the reservoir and foundation dynamic interaction effect were taken into account. They reported that the model is capable of tracing crack propagation within mass concrete under cyclic loading.

The contribution of the authors, in the present paper, is developing an integrative co-axial rotating smeared crack model for concrete structures. An advanced five-parameter failure criterion is adapted for crack initiation and propagation. The model is capable of handling the monotonic and cyclic behavior with acceptable accuracy. It is used then for seismic analysis of all three major types of concrete dams, i.e. gravity, buttress, and arch dams. The results of the numerical models are compared with the experimental ones previously tested by the other researchers.

2. Constitutive model for smeared crack

The proposed model is capable of simulating the behavior of the (concrete) element in various states of, pre-softening behavior; fracture energy conservation; nonlinear behavior during the softening phase; and finally, crack closing/reopening behavior. In the pre-softening phase a linear elastic relationship is assumed between the stress and strain vectors. The elastic modulus matrix, $[D]_{el}$, may be defined for isotropic, orthotropic and an-isotropic materials.

2.1. Co-axial rotating crack concept

During the softening phase, the elastic stress–strain relationship is substituted with an an-isotropic modulus matrix corresponding to the stiffness degradation level in the three principal directions. In this study, secant modulus stiffness approach is used for the stiffness formulation in which the constitutive relation is defined in terms of total stresses and strains. The stiffness modulus matrix based on the smeared crack propagation model is given in Eq. (1). It is noteworthy that the extracted modulus matrix is co-axial with the principal strains in the considered location within the cracked element [28].

Table 1
Constant shear transfer coefficients in terms of open and close ones.

Type and status of cracks	β_{12}	β_{23}	β_{13}
Crack in one direction (crack is open)	β_O	1	β_O
Crack in one direction (crack is close)	β_C	1	β_C
Crack in two or three directions (cracks are open)	β_O	β_O	β_O
Crack in two or three directions (cracks are close)	β_C	β_C	β_C