SHAKING TABLE STUDY TO INVESTIGATE FAILURE MODES OF ARCH DAMS

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Abstract: Stability of concrete dams using linear elastic finite element analyses can be very subjective when the results indicate nonlinear response. To reduce uncertainty associated with failure of concrete arch dams during an earthquake, large laboratory shake table tests of a representative arch dam and reservoir have been performed at the U.S. Bureau of Reclamation’s Materials Engineering and Research Laboratory. These models were analyzed using the ABAQUS finite element computer code to determine how accurately the response could be modeled and the failure predicted. A good correspondence was found between respective laboratory tests and computer analyses in terms of predicted failure modes.

Introduction

Large laboratory shake table tests were performed on scale models of a representative arch dam and reservoir, ramping the loading up to failure of the model. Model parameters, such as dimensions and material properties were adjusted to approximate similitude. A reservoir was modeled behind the scaled structure, but it should be noted that the fluid used was pure water with no adjustment for viscosity similitude. Input motions and structural response were measured, and high quality video was used to capture the failure modes. Five variations of joint configuration were tested. A matching series of finite element models were created and analyzed using the ABAQUS finite element code to determine how accurately the response can be modeled and the failure predicted. These analyses were nonlinear both in terms of geometric behavior associated with opening, closing, and sliding along joint surfaces, and in some cases, rocking of independent concrete blocks, and in terms of material behavior associated with the tensile cracking response of concrete.

PHYSICAL MODELS

The shake table tests were completed in the U.S. Bureau of Reclamation, Materials Engineering and Research Laboratory on a one dimensional shake table (horizontal acceleration only). A typical arch dam scaled to 1:50 was tested. A sealed chamber on the upstream side of the dam was filled with water to simulate a reservoir loading. For practical reasons associated with the table, and for simplicity in numerical model calibration, a 14 Hz sinusoidal input motion was used rather than a similitude consistent earthquake ground motion. The models were constructed within a concrete block foundation on the table. Similitude was applied to the “concrete” material that made up the dam but not to the concrete foundation block. Models incorporating five different joint configurations were created and tested on the shake table. At least two tests were completed for each joint configuration to establish repeatability of the resulting failure mode. The five joint configurations tested in the laboratory are shown in figure 1.

FINITE ELEMENT MODELS

Finite element models were generated to conform to the same dimensions and joint configurations as the models tested in the laboratory. All the mesh definitions used six elements through the dam thickness. In models other than the monolithic model discrete joints were added using contact surfaces. A foundation model was not included in these analyses because the ratio of foundation to dam modulus for the laboratory tests approximates a fixed boundary condition for the dam. Furthermore, eliminating the foundation from the computer model reduced the required computation time by two-thirds.

LOADING CONDITIONS

Gravity and static reservoir loads were applied in each analysis. The reservoir water surface was 2.54 centimeters (1 inch) below the dam crest and was applied using pressure loads on the upstream face of the dam. Hydrodynamic interaction was modeled using Westergaard’s added mass approach. In the laboratory tests, a sinusoidal acceleration record with a frequency of 14 Hz was applied to the base of the model in the upstream/downstream direction. The amplitude of the input acceleration was increased in increments of 0.25 g for durations of 30 seconds until failure of the model occurred. In the computer analyses using such long time periods was not feasible. Therefore, sinusoidal acceleration records of 14 Hz frequency were created with 0.25 g amplitude increments of 10 cycle duration.

NONLINEAR MATERIAL PROPERTY CALIBRATION

The nonlinear brittle cracking material model was calibrated based on comparisons with laboratory results of the monolithic models in terms of 1) the input acceleration amplitude at which cracking was initiated; 2) the input acceleration amplitude at failure; and 3) the corresponding crack patterns. Sensitivity studies were completed in which material parameters affecting crack initiation, tension stiffening (which refers to the post cracking stress reduction rate), and shear retention were varied. These sensitivity studies were completed using the monolithic model, since the results from this model are not affected by additional geometric
nonlinearities associated with the vertical and/or horizontal joints. Results of the sensitivity studies were then used to select material property parameters for all five models.

**Crack Initiation**

The key material parameter associated with crack initiation in ABAQUS analyses is the tensile strength of the material. The direct static tensile strength has often been assumed to be 10 percent of the compressive strength. Research completed at Reclamation suggests that the static tensile strength should be increased by a factor of 1.44 for dynamic loading rates, which would result in a dynamic tensile strength of 27.6 Kpa (4 lb/in$^2$) for the monolithic laboratory models. Research by Raphael $^i$ suggests that a range of dynamic tensile strength between 145 Kpa (21 lb/in$^2$) and 214 Kpa (31 lb/in$^2$) would be appropriate for the nonlinear dynamic analysis of the monolithic model. A sensitivity study was completed in which the monolithic model was analyzed for a range of tensile strength values. Comparison of the nonlinear analysis results with the shake table test results indicated that a range of tensile strength between 55 Kpa (8 lb/in$^2$) and 110 Kpa (16 lb/in$^2$) produces the most accurate results. This tensile strength range appears to be reasonable compared to previous research. This series of analyses all resulted in the same final crack pattern indicating that variation of the tensile strength affects the cracking threshold but not the failure mode.

**Tension Stiffening**

In ABAQUS, the stress at a material point does not drop to zero instantaneously when a crack forms. When there is no reinforcement in significant regions of the model, as in this study, the post failure stress in the crack normal direction is specified as either a tabular function of stress versus displacement across the crack, or as a tabular function of the tensile stress versus associated Mode I fracture energy. The Mode I fracture energy was calculated as the area under the a linear stress-displacement curve. In this sensitivity study the monolithic dam model was analyzed using three different stress-displacement curve definitions and one stress-fracture energy curve as shown in figure 2.

It was determined that the cracking threshold was not sensitive to these changes in the tension stiffness definition. The resulting final cracking patterns were also all very similar, although some unreasonable crack orientations resulted when the rate of stress reduction with crack opening displacement was increased.

**Shear Retention**

Three monolithic dam analyses were used to investigate the effect of varying the rate of shear modulus reduction with crack opening strain. It was determined that the cracking threshold was not sensitive to changes in the rate of shear modulus reduction. The resulting final cracking patterns were also all very similar, although in this case unreasonable crack orientations resulted when the rate of shear modulus reduction with crack opening strain was decreased.

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$^i$ Raphael Jerome. Tensile Strength of Concrete. ACI Journal1984; 158-64.
FAILURE MODES

The shake table tests all resulted in similar failure modes in response to a 14 Hz sine wave input acceleration applied in the upstream downstream direction. The 14 Hz input frequency was very close to the 3rd natural frequency of the dam (14.8 Hz) so the 3rd mode shape was very evident in the deflected shape plots. Typically, the models cracked vertically at the center of the arch, diagonally downward from the arch quarter points and horizontally near the base. Independent blocks were formed and then displaced resulting in failure. Different joint configurations effected the size and number of independent blocks formed, but the shape of the cyclic deformation of the dam in response to this input motion was always the same, and therefore the crack patterns were always very similar. Cracking can not be plotted directly from the current version of ABAQUS, so a method of plotting circular crack symbols on the undeformed mesh was developed. In the resulting crack symbol plots shown in the following sections the crack circle lies in the plane of the crack, and multiple crack symbols in a single element indicate that cracking has occurred in more than one direction.

Monolithic Dam Models

The failure mode for the monolithic dam models, as shown in figure 3, initiated with a vertical crack that formed at the arch center and extended two-thirds of the dam height downward from the dam crest. This crack connected with diagonal cracks resulting in the formation of two large blocks. The ABAQUS analysis of the monolithic model resulted in a similar cracking pattern and would be expected to lead to a similar failure mode. Figure 4 shows a combination of undeformed crack symbol plots and exaggerated deformation plots from the nonlinear analysis. The analysis and laboratory test results also matched in terms of the input amplitudes associated with cracking.

Single Vertical Joint Models

During the shake table tests of the single vertical joint models, the vertical joint opened all the way to the dam base and diagonal cracking formed closer to the dam-foundation contact, as shown in figure 5. Figure 6 shows crack symbol plots and exaggerated deformation plots from the nonlinear analysis. The resulting cracking pattern for the ABAQUS analysis shows the elimination of vertical cracking at the center of the dam and the development of horizontal cracking closer to the foundation. Again the anticipated failure mode would conform to the laboratory results and the results also matched in terms of the input amplitudes associated with cracking.

Single Horizontal Joint Models

During the shake table tests of the single horizontal joint models, as shown in figure 7, the unbonded horizontal joint opened, followed by formation of diagonal cracks which terminated at the joint. Then vertical cracks formed at the center of the arch creating large independent blocks. Figure 8 shows crack symbol plots and exaggerated deformation plots from the nonlinear analysis which clearly illustrate the type of element distortions which were associated with localized cracking in these smeared crack analyses. Results of the ABAQUS analysis show the elimination of horizontal cracking near the base of the dam and the development of both a vertical joint at the center of the arch and diagonal or vertical cracking at the arch quarter points. Again the
anticipated failure mode would conform to the laboratory results and results also matched in terms of the input amplitudes associated with cracking.

**Seventeen Vertical Joint Models**

During the shake table tests of the seventeen vertical joint models, as shown in figure 9, the vertical joints opened and closed. Then horizontal cracks developed, connecting the contraction joints and causing the formation of independent blocks. Figure 10 shows crack symbol plots and exaggerated deformation plots from the nonlinear analysis. The results of the ABAQUS analysis show the elimination of vertical cracking and the development of horizontal cracking. Figure 10 also shows multiple cracks developing in some elements along the dam crest, which could correspond to some of the fragmentation of the concrete along the dam crest seen in the laboratory. The analysis and test results in terms of the input amplitude associated with cracking did not match for this joint configuration. Cracking occurred at input amplitudes of .5 to .6 g in the laboratory while cracking occurred between 1.5 and 2.0 g in the analysis.

**Seventeen Vertical And Two Horizontal Joint Models**

During the shake table tests of the seventeen vertical and two horizontal joint models, as shown in figure 11, cracks developed along the upper horizontal joint and many of the vertical joints causing the formation of a series of small blocks. Figures 12 and 13 show exaggerated deformation plots. In the nonlinear analysis this joint configuration resulted in a purely kinematic failure due to independent block movements. Both crack initiation and failure in the shake table test occurred at an input amplitude of 0.75 g which was also the input amplitude at failure of the ABAQUS model. In the ABAQUS analysis concrete blocks at the arch center fell upstream of the dam and blocks located at the quarter points fell downstream of the dam. Again the anticipated failure mode would conform reasonably well to the laboratory results.

**CONCLUSIONS**

Results of the ABAQUS smeared crack analyses corresponded well with the respective laboratory tests with respect to cracking, although interpreting the results does require some engineering judgement. The finite element analyses predicted concrete cracking in the same locations and orientations as the cracking which occurred in the laboratory models. The cracking thresholds computed from the analyses and recorded during the laboratory tests were within the same range in most cases. The analyses also indicated that the first cracks formed on the upstream face, which could not be recorded in the laboratory experiment.

A good correlation was found between the failure modes seen in the laboratory tests and those that could be extrapolated from the ABAQUS smeared crack analyses. The laboratory model failures were kinematic failure modes. Concrete cracking led to the formation of independent blocks, after which these blocks were subjected to continued shaking of significant duration (30-second time periods at each amplitude level) until a kinematic failure occurred. In the computer models, failures were associated with non-convergence of the numerical analysis. When significant cracking occurred in a localized area the resulting loss of stiffness in the cracked elements led to excessive distortion in neighboring elements. Further increases in the input amplitude resulted in non-convergence in the numerical model. The smeared cracking analysis, however, is limited in that the full kinematic failure can not be modeled without redefining the mesh to model discrete
cracks as they form to create independent blocks. Where independent blocks were built into the model, such as in the seventeen vertical and two horizontal joint model, the ABAQUS analysis did model the resulting kinematic failure well. The ABAQUS analyses were very successful at predicting the failure modes seen in the laboratory tests, although engineering judgement is required in extrapolating final crack configurations and the final failure modes from the crack patterns which exist at the point when the analysis terminates.

REFERENCES


Figures

Figure 1. Model Configurations
Figure 2

Variation Of Tension Stiffening Definition

Fracture Energy Tension Stiffening Definition

Figure 3. Monolithic Dam Failure
Figure 4

Figure 5. Single Vertical joint Model Failure
**Figure 6**

**Figure 7. Single Horizontal Joint Model Failure**
Figure 8

Figure 9. Seventeen Vertical Joint Model Failure
**Figure 10**

**Figure 11. Seventeen Vertical & Two Horizontal Joint Model Failure**