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ANALYTICAL PREDICTION OF THE SEISMIC RESPONSE OF A REINFORCED CONCRETE CONTAINMENT VESSEL

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ABSTRACT

Under the sponsorship of the Ministry of International Trade and Industry (MITI) of Japan, the Nuclear Power Engineering Corporation (NUPEC) is investigating the seismic behavior of a Reinforced Concrete Containment Vessel (RCCV) through scale-model testing using the high-performance shaking table at the Tadotsu Engineering Laboratory. A series of tests representing design-level seismic ground motions was initially conducted to gather valuable experimental measurements for use in design verification. Additional tests will be conducted with increasing amplifications of the seismic input until a structural failure of the test model occurs. In a cooperative program with NUPEC, the United States Nuclear Regulatory Commission (USNRC), through Sandia National Laboratories (SNL), is conducting analytical research on the seismic behavior of RCCV structures. As part of this program, pretest analytical predictions of the model tests are being performed. The dynamic time-history analysis utilizes a highly detailed concrete constitutive model applied to a three-dimensional finite element representation of the test structure. This paper describes the details of the analysis model and provides analysis results.

ACKNOWLEDGMENT

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INTRODUCTION AND BACKGROUND

In some nuclear power plants, the concrete containment structure is connected to the reactor building through intermediate floors that support auxiliary equipment needed to operate the plant. The RCCV test model is a substructure consisting of the RCCV and surrounding intermediate floors isolated from the reactor building. The scale of the model was small enough that the shaking table could deliver the desired loads, yet large enough to include structural details so that the model adequately simulated an actual plant. Artificial earthquake acceleration time histories, scaled to excite a response in the test model similar to that of an actual RCCV, were developed based on the Second Modified Standardization Survey for power plants in Japan. The excitations that caused the most significant response of the RCCV model were selected from among the survey results and used in the test series. It is often difficult to meet similitude requirements for all components of the structure, and to resolve such issues extensive research on specimen tests has been conducted for several years [1]. Based on this research, it is expected that the dominant mode of failure for the RCCV under extreme seismic loading is the loss of shear capacity in the lower wall near the basemat juncture.

To match the model's response to the full-scale prototype, the spectral accelerations have to be matched. Therefore, in the scaled model test, both the mass and the input time history

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were adjusted consistent with scaling laws. The 1:8 scale model was thus developed so as to simplify the structural configuration while simulating the proper shear behavior in the lower walls. The top slab of an actual containment was replaced with a thick flat cap at the top of the cylindrical section of the model, and weights were attached to the top in order to obtain shear strains in the lower walls that were similar to a full scale prototype. The acceleration time histories for the tests are based on the response spectra for realistic earthquake records. These acceleration records are adjusted in frequency and amplitude consistent with scaling laws.

The primary objective of the USNRC sponsored analysis is to evaluate the predictive capability of available software for computing the complex seismic behavior of RCCV structures and to verify their capacities under extreme load conditions. With respect to the experimental program, the analysis is used to demonstrate that the simplifying design features and assumptions adopted in the design of the RCCV 1:8 scale model provide an appropriate simulation of the behavior of RCCV structures.

ANALYTICAL MODELING BASIS

The calculations are performed with the ANACAP-U concrete material behavior model [2], which interfaces with the ABAQUS [3] general-purpose finite element program. The material behavior model accounts for the time history dependence of cracking and cumulative stiffness degradation that may occur in the series of tests planned for the RCCV test model. Time-marching nonlinear dynamic analyses are performed in series so that damage is accumulated from one test to the next. This required the storage and processing of large volumes of data. In a previous seismic analyses of a scaled model Prestressed Concrete Containment Vessel (PCCV), a mesh optimization study was conducted to minimize the number of degrees of freedom in the finite element model, while still accurately predicting the structural response [4]. The RCCV finite element mesh was selected to have a similar amount of detail as the PCCV mesh from the previous study. Figure 1 illustrates the three-dimensional finite element grid used in the dynamic calculations. This 180° model assumes a plane of symmetry, with the symmetry plane parallel to the direction of horizontal shaking and the access tunnel penetration located 90 degrees from the symmetry plane. This symmetry assumption will prevent twisting motion and any rocking perpendicular to the horizontal shaking direction. The attached weights are explicitly modeled with lead encased in steel shells as constructed.

The steel liner is also shown in Figure 1. Liner anchorage connection details are not included in this global model because of grid size constraints. The model is not intended to capture local tearing at stiffener discontinuities or anchorage failure. However, plastic straining that is calculated in the liner will give a reasonable estimate of the average response of the liner. Material plasticity in the liner and reinforcement bars is considered. The liner and all steel plates are modeled with membrane-type elements, which include the shear contributions but ignore the bending characteristics of the liner. All reinforcing bars, shown in Figure 2, are explicitly modeled as bar subelements embedded in the concrete continuum elements. The bar stiffness and forces are superimposed on the concrete element, and thus the effect is smeared over the concrete element through the element shape functions. This modeling is consistent with the smeared cracking basis of the concrete material model and can capture load redistribution and ultimate capacities fairly accurately. There is no diagonal reinforcement in the test specimen. Stirrups across the wall thickness and basemat reinforcement are also included. All bolted connections are assumed to be constructed such that no slippage occurs.

The concrete static compressive strength is increased by 15%, based on discussions with NUPEC, to account for strain rate effects. The material model used for the concrete in the RCCV wall and basemat is a modern version of the classical smeared cracking model [5] and is contained in a computer subprogram called ANACAP-U [2]. This model describes the constitutive material behavior at an element integration point and is accessed by ABAQUS through a user material interface. Thus, the coupled ANACAP-U/ABAQUS system provided the concrete structural analysis capability required for capturing the complex dynamic behavior of the RCCV model.

The concrete material model allows cracks to form in three mutually orthogonal directions at each integration point, with directions dictated by the principal stress and strain states. Crack initiation is based on an interaction criterion between the principal strain and principal stress, thereby permitting the development of direct and split cracking under multiaxial stress states. Once a crack forms, it can never heal, but it can close and reopen under the cyclic conditions of a seismic motion. The model accounts for shear transfer due to aggregate interlock, with reduced shear stiffness across a crack as a function of crack opening strain. In compression, the model uses a modified Drucker-Prager yield surface with strain softening behavior in the compression regime after the material has exceeded the ultimate compressive strength. Hysteretic unloading and reloading behavior in this regime is also included to account for the stiffness and strength degradation under cyclic loading.

ANALYSIS RESULTS

Preliminary analyses were performed to learn about the basic characteristics of the RCCV model. Initially, mode shapes and resonant frequencies were predicted for the RCCV structure. The first three mode shapes are shown in Figure 3. The first mode, at 15.1 Hz, is dominated by the sliding shear type deformations, although there appears to be some rocking of the top mass, which causes some bending deformations in the walls. The second and third modes are greater than 40 Hz, and will have a smaller impact on the structural response than the first mode. Subsequently, a static pushover analysis was performed to determine the capacity of the model under a quasi-static, monotonically increasing load. For this calculation, a monotonically increasing horizontal force is applied to the weights at the top of the model. From previous experience, the static pushover analysis will have a higher capacity than a dynamically tested model. As a quick estimate of the dynamic capacity of the model, a knockdown factor was applied to the static pushover results. The predicted results of the static pushover analysis, the quick estimate of the dynamic capacity, and the peak response from seismic calculations are shown in Figure 4.

The test plan for the RCCV model includes several low-level sinusoidal and random wave inputs for establishing the dynamic characteristics of the test model. Then separate applications of the horizontal and vertical components of the S1 level (larger than an operating basis earthquake) input will be followed by the combined horizontal and vertical S1 accelerations. The S1 earthquake has a peak ground acceleration in the horizontal direction of about 0.22 g's and a peak acceleration in the vertical direction of about 0.14 g's. The calculated peak horizontal displacement of the top section relative to the base is 0.11 cm (0.043 in.). Comparison of similar plots for the relative vertical displacement at points around the top section indicates that some rocking of the top section will occur.

The S2 earthquake has a peak ground acceleration in the horizontal direction of about 0.41 g's and a peak acceleration in the vertical direction of about 0.22 g's. The response spectral acceleration for the S2 earthquake is shown in Figure 5. For the sliding shear mode, Figure 5 indicates that the dynamic amplification causes the load for this mode to be near 1.3 g's, assuming a 5% damping factor. The second and third frequencies could expect an amplified loading of between 0.4 and 0.8 g's, and therefore these frequencies are less important than the first, but not negligible. The predicted peak relative horizontal displacement from the S2 analysis is 0.22 cm (0.086 in.). The analysis predicts considerable cracking in the model. The initial cracks are because of shear oriented at angles to the radial and vertical directions and are in the lower wall regions. The cracking is of a progressive nature; thus, continued loading causes greater shear deformation and spreading of the cracks. Damage accumulates during the testing, and many sequential tests are planned. It is not practical to analyze all the events that are tested. Therefore, the model will be expected to accumulate more damage (because it is exposed to considerably more cycles of excitation) than the analytical predictions.

Following the S1 and S2 design level seismic tests, design-margin tests will be performed to determine the ultimate capacity of the RCCV. The tests planned consist of earthquakes that are 2, 3, 4, 5, and 6 times larger than the S2. The 2S2 will be tested first, followed by a 3S2, and so forth until the model fails. Analyses were performed for a 2S2 test and a 4S2 test. Although considerable damage to the concrete and reinforcing bars is predicted during the 2S2 test, the structure is not expected to exhibit a structural failure. Predicted cracking for the 2S2 is shown in Figure 6. Crack directions are expected to be predominately at 45 degree angles, especially in wall sections that are almost parallel to the direction of shaking, and are caused by the large shear stresses in the concrete. Near the symmetry plane, where the wall sections are perpendicular to the direction of shaking, horizontal cracking is expected due to large vertical rocking motion. Cracks are predicted to cover virtually the entire surface of the concrete cylinder wall. The analyses predict a peak relative horizontal displacement of 0.85 cm (0.33 in.) for the 2S2 test and 1.9 cm (0.75 in.) for the 4S2 test. The predicted relative horizontal displacement of the top mass is shown in Figure 7 for the 4S2 test. Analytical predictions show large shear strains in the cylinder walls near the basemat during the 4S2 test. These shear strains are large enough to indicate a likely shear failure of the RCCV during the 4S2 test.

CONCLUSIONS

This effort couples advanced analytical simulations with large-scale model testing to advance the understanding of seismic capacities of RCCV structures. The analytical predictions described in this paper were reported to NUPEC and the USNRC before the start of the test. These blind predictions will be compared to experimental test data. Posttest analytical evaluations are also planned. Similar past (and ongoing) programs [6, 7] have validated this computational methodology for static capacities of reinforced and prestressed containments under internal pressure. Safety concerns, which continue to increase the anticipated levels of seismic events, require validated analytical methods. Once the analytical methodology is validated for seismic loads using scaled models, verification of capacities of actual RCCV structures can be extrapolated from the scale-model test results through numerical simulation.

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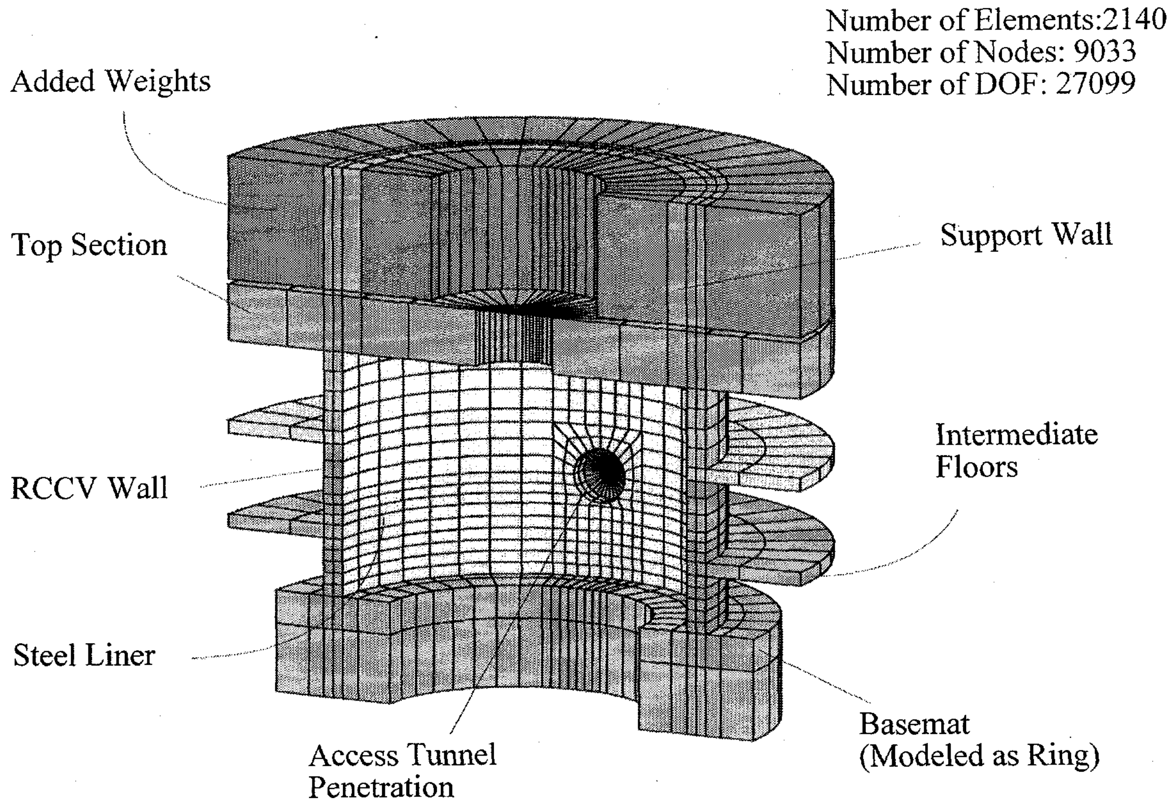


Figure 1. 3D Finite Element Model for Seismic Calculations

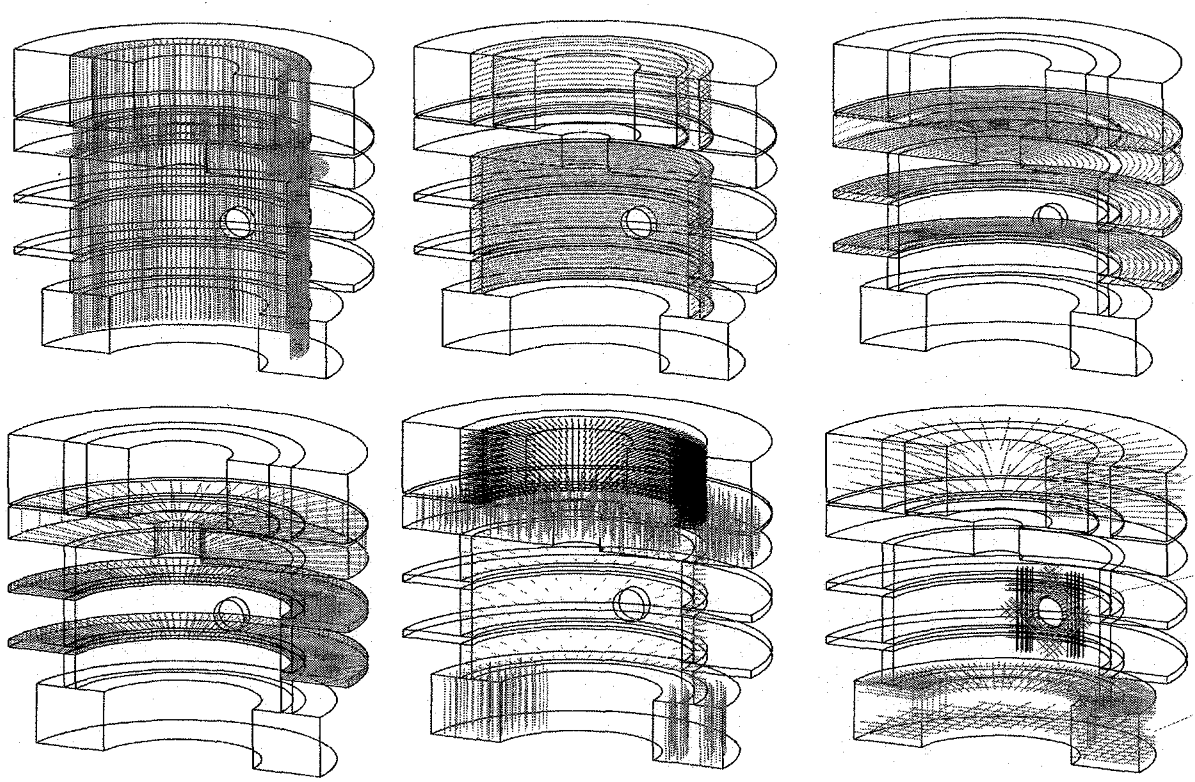


Figure 2. Modeling of Reinforcing Bars

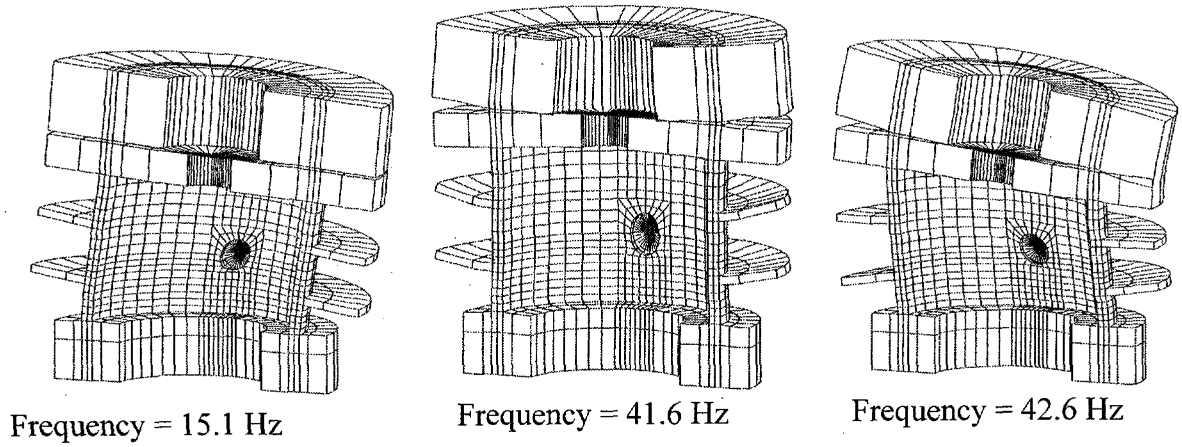


Figure 3. Resonant Frequencies and Mode Shapes

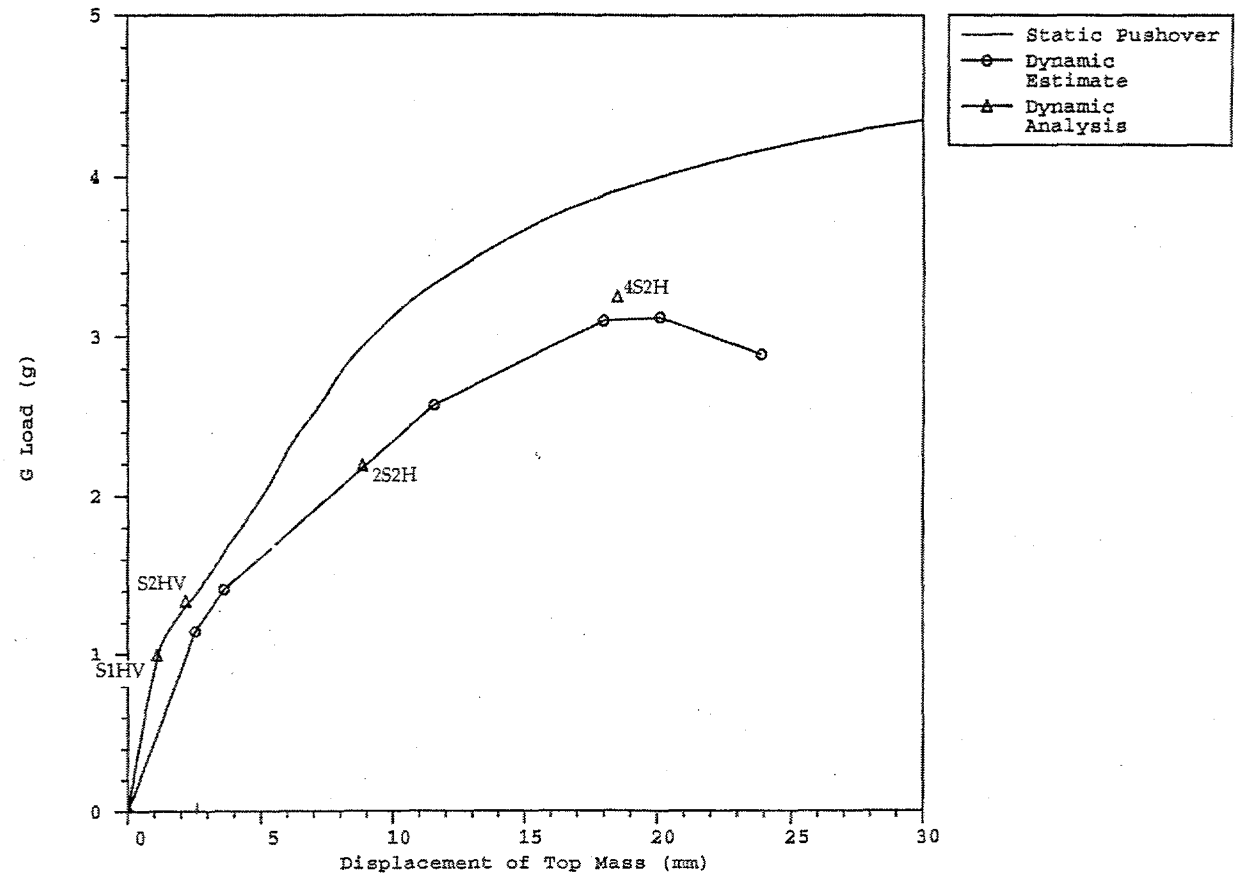
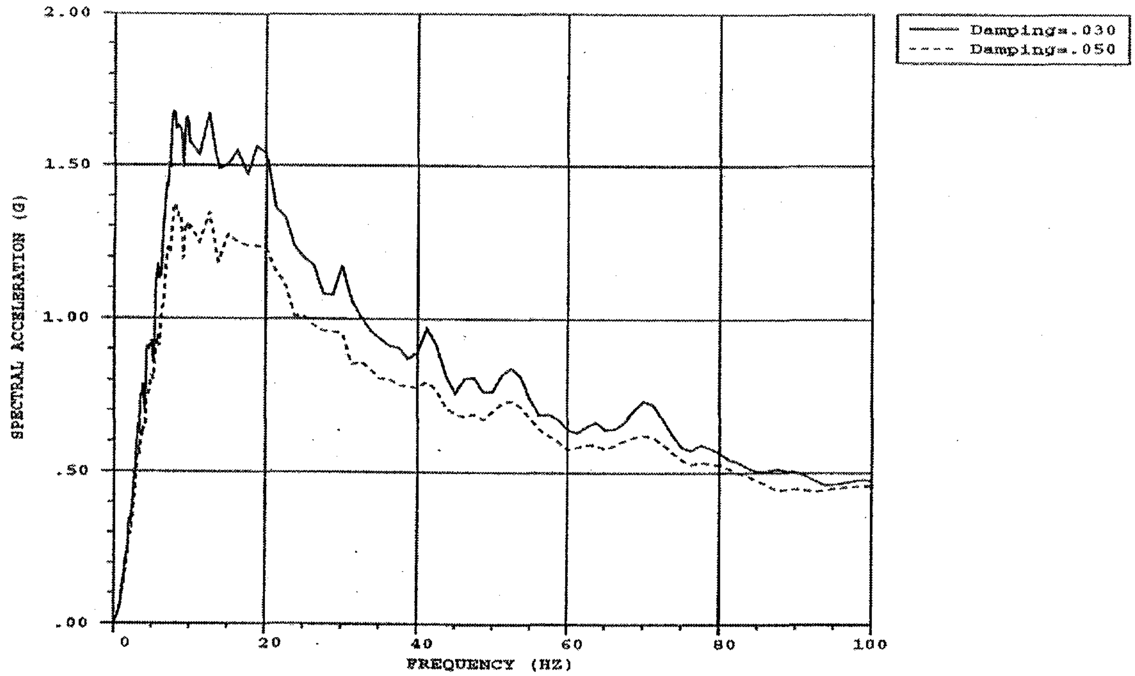
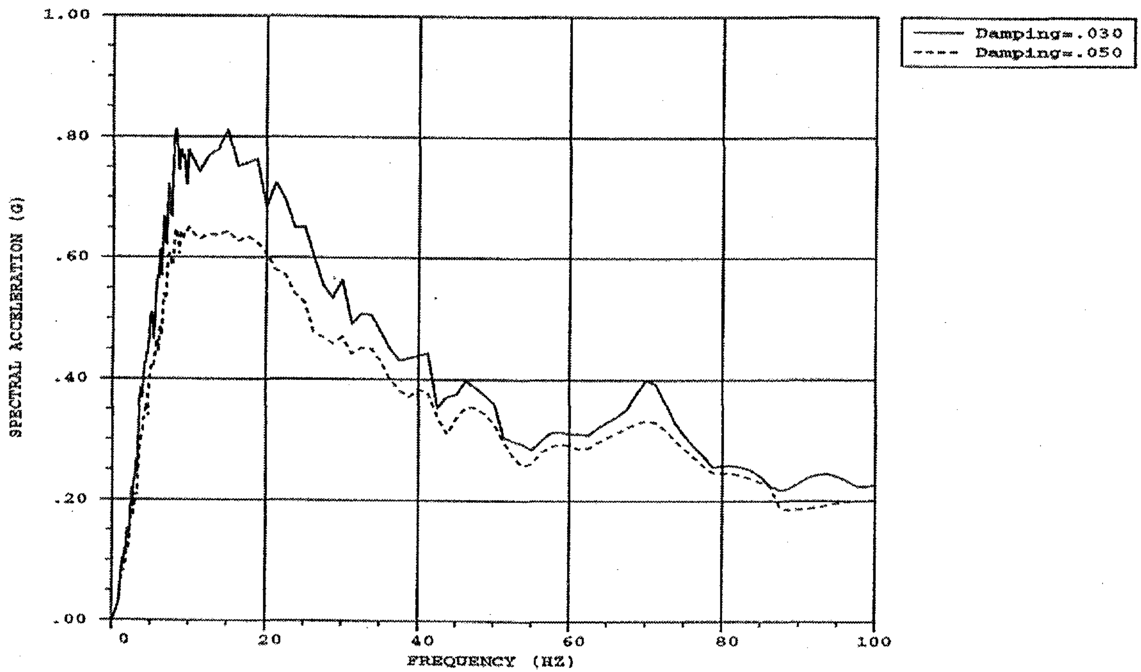


Figure 4. Static Pushover Capacity



Spectral Acceleration of Horizontal Record



Spectral Acceleration of Vertical Record

Figure 5. Response Spectra of S2 Earthquake Record

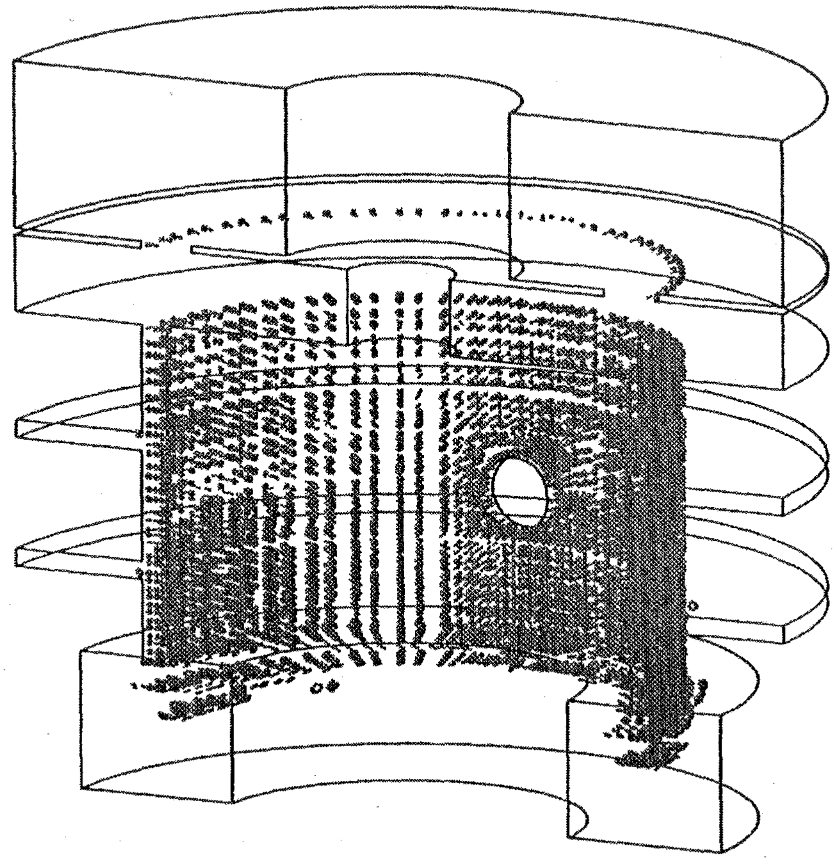


Figure 6. Open Cracks After 2S2 Test

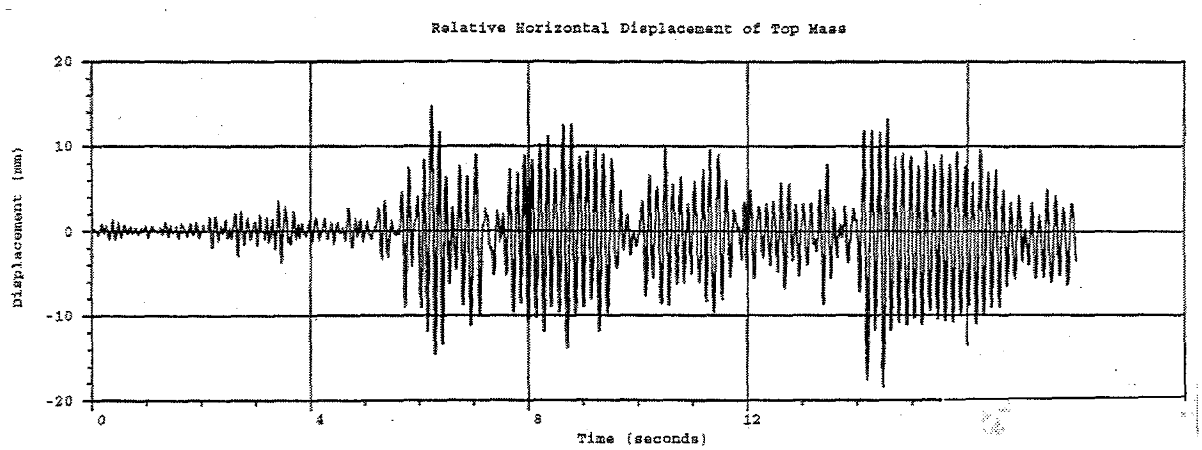


Figure 7. Relative Horizontal Displacement of Top Mass During 4S2 Test