

Shaking Table Study to Investigate Failure Modes of Arch Dams

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13. ABSTRACT (Maximum 200 words) Determining the 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 were 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. Failure modes predicted by the computer analyses corresponded well with the laboratory tests.				
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**Shaking Table Study to Investigate
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DSO-02-01

**by Terry Payne
Structural Analysis group**

March 2002

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Introduction and Scope

The failure risks associated with seismic loading of concrete dams in many cases have been estimated to be quite high. These estimates are based largely on evaluation of results from linear-elastic finite element analyses that do not account for aspects of non-linear behavior of the dam such as contraction joint opening, cracking at weak lifts, and cracking in mass concrete. No concrete dams are known to have failed during an earthquake, and cases of concrete dams subjected to large earthquake shaking with good records of the response are extremely limited. Some cracks have been reported, such as at Pacoima Dam where the dam and abutment separated during the Northridge earthquake, but the reservoir was down at the time of the event. Therefore, it is not clear exactly how a concrete dam, particularly an arch dam, might fail during an earthquake, nor is it clear how well our analytical models predict structural performance during very large levels of shaking.

In this study, 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 arch dam configuration were tested including monolithic models, models containing vertical joints to represent vertical contraction joints, models containing horizontal joints to represent weak lift lines, and models containing both vertical and horizontal joints.

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. This report will cover two preliminary studies, a series of linear elastic analyses, a series of analyses used to calibrate the non-linear material properties, and a series of five non-linear analyses used to model the dam's response using the five different joint configurations. The first preliminary study was conducted to determine the effect of removal of the foundation from the finite element model. The second preliminary study was conducted to select the most appropriate version of ABAQUS for use in the remainder of this study. Static and dynamic linear elastic analyses were completed for each of the five joint configurations tested on the shake table. Stresses, joint conditions, and displacements resulting from these five models were compared with the laboratory results in terms of acceleration and displacement time histories at times prior to cracking for each model. This series of analyses were linear elastic in terms of the material property models used, however geometric non-linearities such as opening, closing, and sliding along joint surfaces, and in some cases sliding and rocking of independent concrete blocks, were modeled. The monolithic dam model was used to calibrate the non-linear material properties. The results of the non-linear analyses were compared to laboratory results in terms of the input amplitude at which cracking was initiated, the input amplitude at which failure occurred, crack patterns, and failure modes. Each of the five joint configurations was then analyzed using non-linear material properties, and results were compared to laboratory results.

Physical Models

Tests were completed in the Bureau of Reclamation, Materials Engineering and Research Laboratory. A one dimensional shake table (horizontal acceleration only) was constructed for these experiments. The model scale chosen for these models was a 1/150 scale. The maximum height of the scaled dam was 23 11/16 inches, and the crest length was 81 13/16 inches. A sealed chamber on the upstream side of the dam was filled with water to simulate a reservoir loading. A similitude simulation of an earthquake motion was not used. Rather, for practical reasons associated with the table and for simplicity in numerical model calibration, a 14 Hz sinusoidal motion was selected. 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 modeled were: (1) monolithic (identified as tests M2 and M8), (2) a single vertical joint at the arch center (tests M6 and M11), (3) a single horizontal joint at mid height (tests M9 and M10), (4) 17 vertical joints spaced evenly along the arch (tests M12 and M13), and (5) 17 evenly spaced vertical joints combined with 2 horizontal joints (tests M14 and M15). The models were placed in a concrete block foundation on the table. A photo of a typical experiment setup is shown in figure 1.

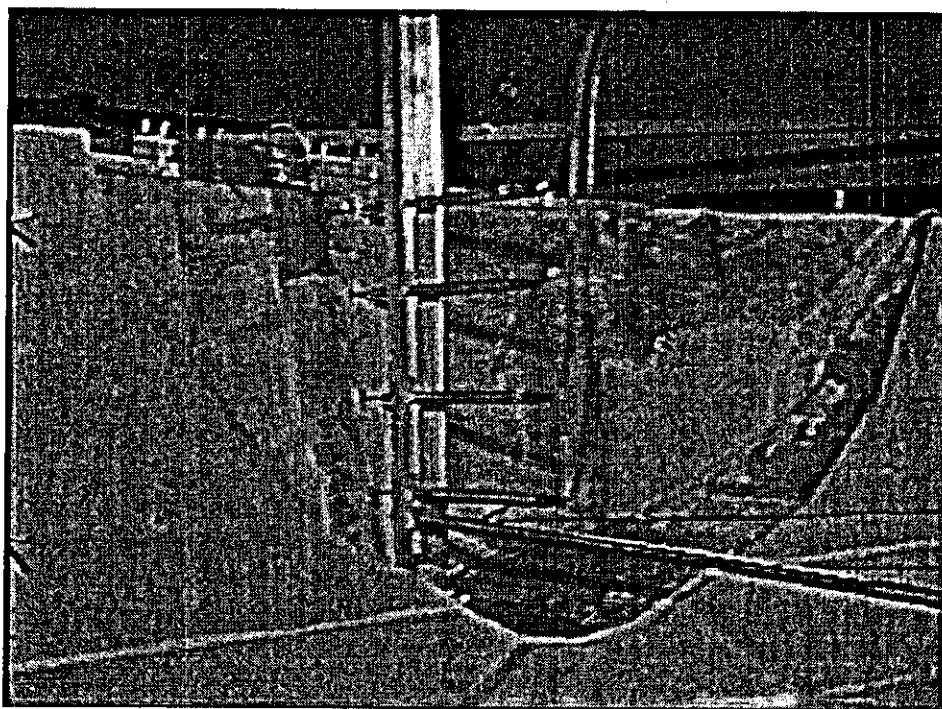


Figure 1.—Typical Experiment Setup.

The models were instrumented on the downstream face to record accelerations at six locations and displacements at two locations as shown in Appendix A, figure A.1. Figure A.2 shows the corresponding Node numbers at which acceleration time histories were recorded in the analyses.

Finite Element Models

Monolithic Models: Designated as Model M2M8

Two monolithic models were used in the preliminary analyses. The first consisted of a continuous dam and foundation mesh with 7,910 nodes and 6,556 three-dimensional, solid elements. Six first order, reduced-integration elements were used through the dam thickness. In the second monolithic model, the foundation mesh was removed, resulting a model with 1,530 elements and 1,988 nodes. No contact surfaces were used in either model. These two models, shown in figures 2 and 3, were used in a preliminary analysis, discussed in section VII.A, to evaluate the need to include the foundation in the analysis.

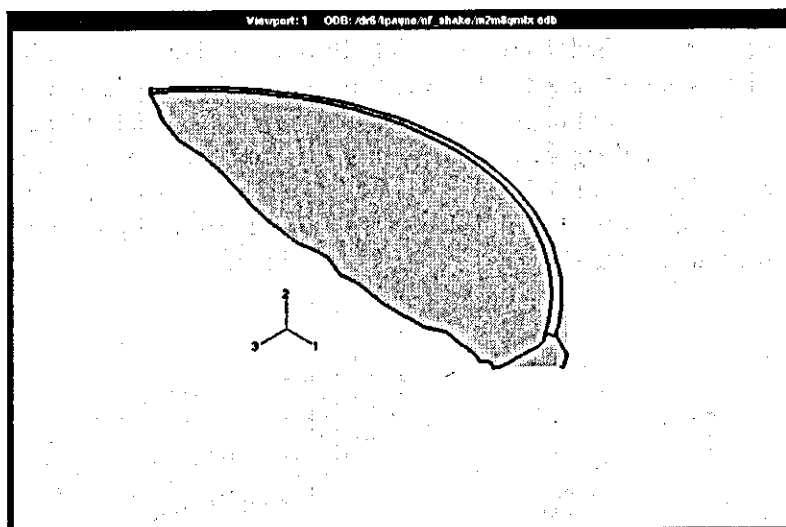


Figure 2.—Monolithic Model M2M8 without Foundation.

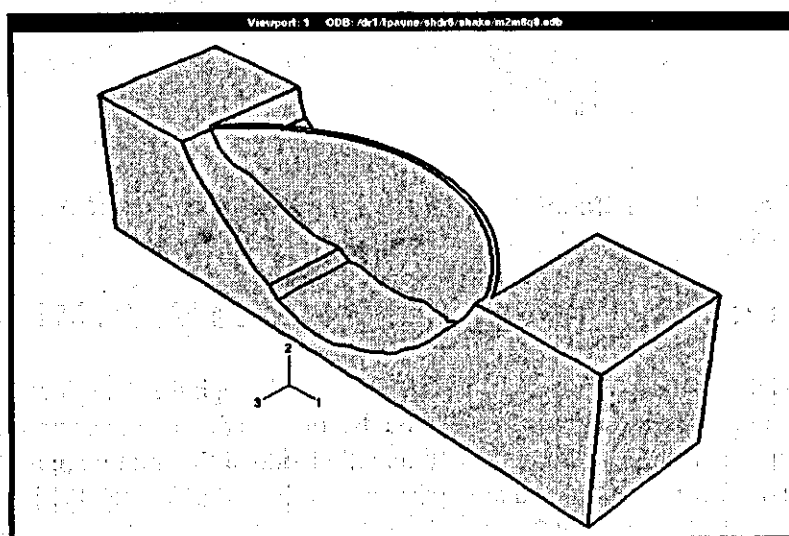


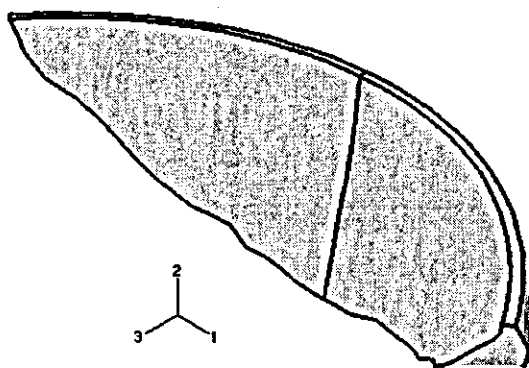
Figure 3.—Monolithic Model M2M8 with Foundation.

Single Vertical Joint Model: Designated as Model M6M11

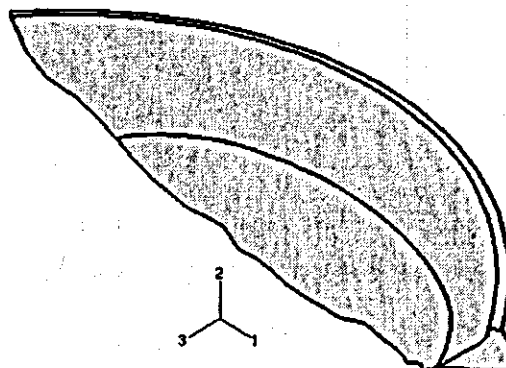
The monolithic model was modified to create Model M6M11 by adding a single vertical joint through the dam thickness at the center of the arch. This was done by creating double nodes through this section of the model so that the surfaces formed on either side of the joint were no longer connected. Contact surfaces were defined along the two surfaces that formed the joint. The joint extends down from the crest to the upper nodes of the bottom elements. The joint does not extend vertically to the base of the dam (the joint does not split the dam into two completely separate sections). This model consisted of 1,530 elements and 2,058 nodes. Figure 4 shows the single vertical joint model with features boldly outlined to show the location of the joint.

Single Horizontal Joint Model: Designated as Model M9M10

The monolithic model was modified to create Model M9M10 by adding a single horizontal joint through the dam thickness at mid height. This was done by creating double nodes through this section so that the surfaces formed on either side of the joint were no longer connected. Contact surfaces were defined along the two surfaces that formed the joint. The joint extends along the entire arch but does not include double nodes at the dam contact. This model consisted of 1,530 elements and 2,165 nodes. Figure 5 shows the single horizontal joint model with features boldly outlined in order to show the location of the joint.



**Figure 4.—Single Vertical Joint Model
Laboratory Test M6M11**



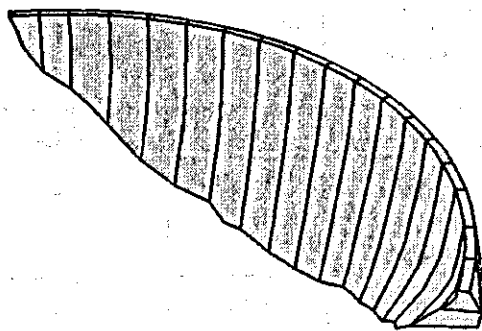
**Figure 5.—Single Horizontal Joint Model
Laboratory Test M9M10**

Seventeen Vertical Joint Model: Designated as Model M12M13

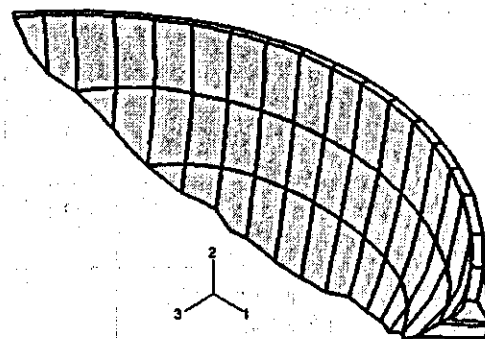
The monolithic model was modified to add 17 vertical joints through the dam thickness at nearly equal spacing along the arch. As in the previous models, this was done by creating double nodes through these sections so that the surfaces formed on either side of the joint were no longer connected. Contact surfaces were defined along the two surfaces that formed the joint. This model consisted of 1,530 elements and 2,821 nodes. Figure 6 shows the 17 vertical joints model with features boldly outlined to show the locations of the joints.

Seventeen Vertical Joints With Two Horizontal Joints Model: Designated as Model M14M15

The 17 vertical joints model was modified to add two horizontal joints through the dam thickness at locations one-third and two-thirds the dam height. As in the previous models, this was done by creating double nodes through these sections so that the surfaces formed on either side of the joint were no longer connected. Contact surfaces were defined along the two surfaces that formed the joint. This model consisted of 1,530 elements and 9,055 nodes. Figure 7 shows the 17 vertical and 2 horizontal joints model with features boldly outlined to show the locations of the joints.



**Figure 6.—Seventeen Vertical Joints Model
Laboratory Test M12M13**



**Figure 7.—Seventeen Vertical and Two
Horizontal Joints Model
Laboratory Test M14M15**

Boundary Conditions

During application of the static loads (gravity and reservoir), all the nodes located on the dam contact were fixed in all three directions, except for the preliminary analysis of the monolithic model, which included a foundation model. When a foundation model was included in the analysis, the nodes located on the base of the foundation served as the fixed boundary.

For the dynamic loading, an acceleration record was applied to these nodes in the upstream-downstream direction. The nodes remained fixed in the cross-canyon and vertical directions for the dynamic loading; accelerations were applied in the upstream-downstream direction only. Figure A.3 illustrates the boundary conditions on the monolithic dam model used for the preliminary analyses with and without a foundation model. Based on the results of the preliminary analyses, the same boundary conditions, without the foundation, were used for all five models.

Material Properties

Summary of Material Properties Obtained From Laboratory Tests

Laboratory testing was completed on the day of the shaking test. Results of the test program are summarized in Appendix B, table B.1. Complete documentation of individual material test data for all of the models is also included in Appendix B of this report. Table 1 summarizes the data available for the five model configurations included in this study.

Table 1.—Material properties provided by the Reclamation Research and Testing Laboratory

Laboratory Tests	Compressive Strength (f_c)	Splitting Tensile Strength	Modulus of Rupture (f_r)	Elastic Modulus
Monolithic Model M2 (Test Date 3/31/99)	23.25 lb/in ²	N/A	4 lb/in ²	2302.6 lb/in ²
Monolithic Model M8 (Test Date 6/21/00)	28.2 lb/in ²	N/A	N/A	N/A
Single Vertical Joint Model M6 (Test Date 8/27/99)	25.6 lb/in ²	N/A	N/A	N/A
Single Vertical Joint Model M11 (Test Date 8/22/00)	41.97 lb/in ²	4.4 lb/in ²	N/A	3758.8 lb/in ²
Single Horizontal Joint Model M9 (Test Date 7/19/00)	36 lb/in ²	N/A	N/A	N/A
Single Horizontal Joint Model M10 (Test Date 8/02/00)	52.1 lb/in ²	N/A	N/A	5172.1 lb/in ²
Seventeen Vertical Joint Model M12 (Test Date 10/3/00)	27.01 lb/in ²	N/A	N/A	2146.6 lb/in ²
Seventeen Vertical Joint Model M13 (Test Date 4/10/01)	23.2 lb/in ²	3.58 lb/in ²	N/A	3461.5 lb/in ²
Seventeen Vertical and Two Horizontal Joint Model M14 (Test Date 4/24/01)	19.63 lb/in ²	3.09 lb/in ²	N/A	3099 lb/in ²
Seventeen Vertical and Two Horizontal Joint Model M15 (Test Date 5/01/01)	21.4 lb/in ²	4.05 lb/in ²	N/A	3948 lb/in ²

Material Properties used for Linear Elastic Analyses

All ABAQUS analyses (both STANDARD and EXPLICIT versions and linear elastic and non-linear analysis types) must include linear elastic material properties. The linear elastic properties

are completely defined by Young's modulus, E , the mass density, γ , and the Poisson's ratio, ν . A density value of 125 lb/ft³ was provided for all models. Poisson's ratio values were not available, so a typical value for concrete (0.2) was used for all the models.

In the past, based on the research work of Jerome Raphael^[1] it has been assumed that both the tensile strength and the elastic modulus increase with loading speed. However, more recent research by David Harris at the Bureau of Reclamation's Material Testing and Research Laboratory indicated that increasing the instantaneous (tested) modulus of elasticity for dynamic loading is not warranted. Therefore, the elastic moduli obtained from the laboratory tests and shown in table 2 were not increased for these analyses.

Table 2.—Elastic modulus values used in the analyses

Finite Element Model Designation	Joint Configuration	Elastic Modulus (lb/in ²)
M2M8	Monolithic	2302.6
M6M11	Single Vertical Joint	3758.8
M9M10	Single Horizontal Joint	5172.1
M12M13	Seventeen Vertical Joints	3461.5
M14M15	Seventeen Vertical and Two Horizontal Joints	3948

A foundation model was used only in the preliminary analyses of the monolithic dam model. The typical concrete properties shown below were used for the foundation model for these analyses because no material property testing was completed for the concrete used to create the foundation block.

Young's Modulus	$E = 3.0 \text{ E}+6 \text{ lb/in}^2$
Poisson's Ratio	$\nu = .20$
Density	$\gamma = 0.0 \text{ lb/ft}^3$ (massless foundation used in analysis)

Rayleigh damping coefficients were used to provide some general damping. A mass proportional damping coefficient ($\alpha = 3.0$) and a stiffness proportional damping coefficient ($\beta = 0$) were used for all the analyses. These values correspond to approximately 5 percent of critical damping at frequencies between 7 and 15 Hz. Spreadsheet calculations for the Rayleigh damping factors are included in Appendix B, figure B.37.

Material Properties used for Non-Linear Material Property Calibration

All the non-linear analyses included in this study were completed using the EXPLICIT version of ABAQUS based on the conclusions of a preliminary study that is discussed in section VII.B, which compared the results from analyses completed using the two ABAQUS Solvers. The non-linear material model for concrete used in the EXPLICIT version of ABAQUS only accounts for

the tensile (brittle) behavior of concrete. In compression, linear elastic material properties apply. Therefore, ABAQUS/EXPLICIT cannot be used to model concrete hardening in compression or concrete failure due to crushing_[2].

ABAQUS/EXPLICIT uses a smeared crack model to represent the discontinuous brittle behavior in concrete. The cracking model assumes fixed (a "fixed" crack means that once a crack forms it continues to exist with its original orientation for the remainder of the analysis), orthogonal cracks. The maximum number of cracks at a material point is limited by the number of direct stress components present at the material point. In this study, three-dimensional reduced integration elements were used, so a maximum of three cracks can develop at the centroid of any given element. The direction normal to the first crack is aligned with the direction of the maximum tensile principal stress at the time of crack initiation. Subsequent cracks at any given point can form only in directions orthogonal to the first crack. Once cracks exist at a point, the component forms of all vector and tensor valued quantities are rotated so that they lie in a local system defined by the normals to the crack faces. The model ensures that these crack-face normal vectors are orthogonal so that this local system is rectangular Cartesian.

The non-linear brittle cracking material model was calibrated based on comparisons with laboratory results 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, and shear retention were varied. These sensitivity studies were completed using the monolithic model because the results from this model are not affected by additional geometric non-linearities 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.

Sensitivity to Variation in Tensile Strength (Crack Initiation)

A crack forms when the maximum principal tensile stress exceeds the tensile strength of the brittle material. Once a crack has formed it remains throughout the duration of the analysis, although closing and reopening of cracks may take place. The cracks can close completely when the normal stress across them becomes compressive.

The key material parameter associated with crack initiation is the tensile strength of the material. The direct static tensile strength has often been assumed to be 10 percent of the compressive strength; however, Jerome Raphael's paper suggests that this linear relationship between tensile and compressive strength is not justifiable_[1]. Raphael suggests the following relationships between tensile strength and compressive strength:

The Actual Static Tensile Strength	$f_t = 1.7 f_c^{2/3}$
The Apparent Static Tensile Strength	$f_t = 2.3 f_c^{2/3}$
The Actual Dynamic Tensile Strength	$f_t = 2.6 f_c^{2/3}$
The Apparent Dynamic Tensile Strength	$f_t = 3.4 f_c^{2/3}$

David Harris's research on dynamic properties of mass concrete concludes that static tensile strengths should be increased by a factor of 1.44 for dynamic loads_[3]. Table 3 lists ranges of non-linear dynamic tensile stress calculated using test data available for monolithic models M2

and M8. Using the various methods discussed above, the value of dynamic tensile strength could be as low as 3 lb/in² or as high as 32 lb/in².

Table 3.—Calculation of tensile strength ranges

Equation	Variables	Range of Tensile Strength
$.10 * f_c * 1.44$	$f_c = (23 \text{ to } 28 \text{ lb/in}^2)$	3 to 4 lb/in ²
$3/4 * f_r * 1.44$	$f_r = 4 \text{ lb/in}^2$	4 lb/in ²
$f_t = 1.7 f_c^{2/3}$ (Actual Static)	$f_c = (23 \text{ to } 28 \text{ lb/in}^2)$	14 to 16 lb/in ²
$f_t = 2.3 f_c^{2/3}$ (Apparent Static)	$f_c = (23 \text{ to } 28 \text{ lb/in}^2)$	19 to 21 lb/in ²
$f_t = 3.4 f_c^{2/3}$ (Apparent Dynamic)	$f_c = (23 \text{ to } 28 \text{ lb/in}^2)$	28 to 32 lb/in ²

Since no clear justification could be made to select a tensile strength value from the range shown in table 3, an alternative approach was taken. A series of sensitivity studies were completed in which the tensile strength was varied from 5 lb/in² to 30 lb/in² as shown in table 4. Results of the sensitivity studies were then compared with the laboratory test results to determine the most appropriate value for tensile strength.

Table 4.—Sensitivity to variation in tensile strength

Analysis ID	Tensile Limit (lb/in ²)
NLX1	5
NLX7	10
NLX9	15
NLX5	20
NLX4	30

Both tension stiffening and shear retention definitions must also be specified for the non-linear concrete material property model and were, therefore, necessary for the sensitivity studies. "Tension stiffening" refers to the post cracking rate of tensile stress reduction across the crack opening. In ABAQUS/EXPLICIT, the stress does not drop to zero instantly when a crack forms, instead the rate at which stress decreases is defined by the tension stiffening curve. For each of the five analyses used to evaluate the effect of variation in tensile strength, a tabular function of stress versus displacement across the crack was also defined to control the rate of stress reduction. In each case, the crack opening displacement at which the stress reaches zero was calculated as $u_{ck} = h * (\sigma_t / E)$. In this equation, h is the characteristic element length, σ_t is the tensile strength, and E is the elastic modulus. In these small scale models, the characteristic

length (h) ranges from 0.6 to 1.75, so a value of 1.0 was used. A value of 2302.6 lb/in² was used for the elastic modulus, and the tensile strength was varied as shown in table 4. An effort was made to keep the shape of the curves the same. Figure 8 shows the five tension stiffening curves used in this sensitivity study. The concept of "shear retention" is similar in that the shearmodulus does not drop to zero instantly when a crack forms, instead the rate of shear modulus reduction is defined by the shear retention curve. For this sensitivity study, a power law definition with an exponent of two was used to define the rate of shear modulus reduction with increasing crack opening strain. The shear retention curves corresponding to the five tensile strengths shown in table 4 are shown in figure 9.

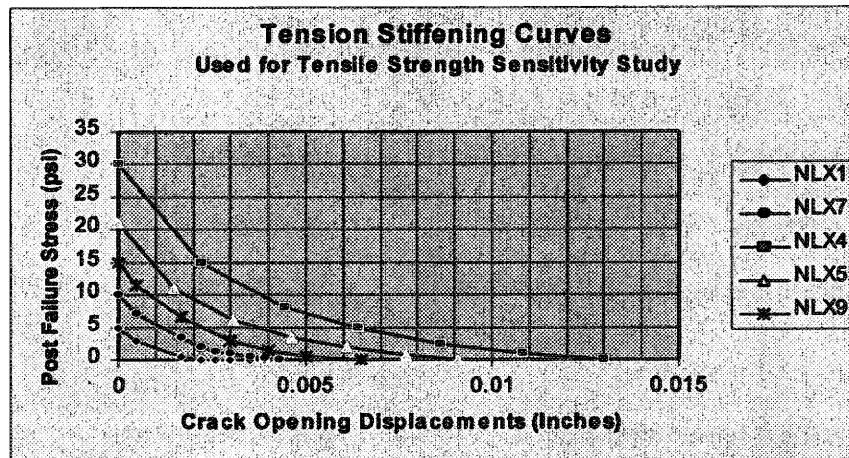


Figure 8

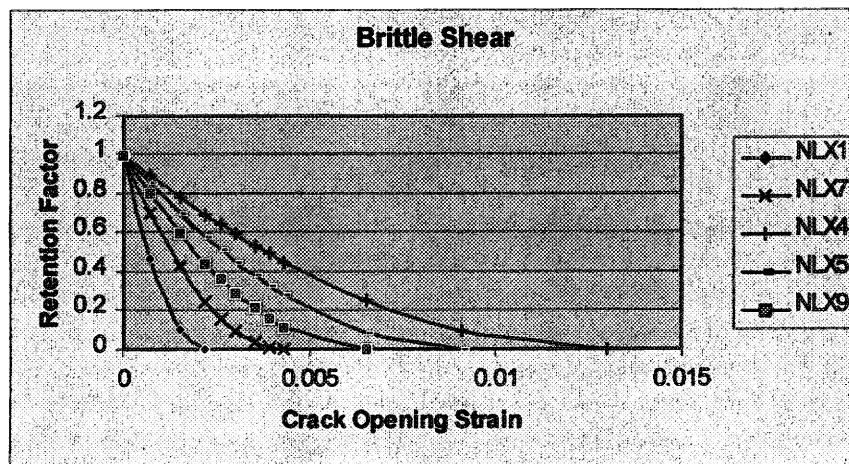


Figure 9

Sensitivity To Variation In The Tension Stiffening Definition

The tension stiffening definition controls the post cracking rate of stress reduction across the crack. When there is no reinforcement in significant regions of the model, as in this study, the post failure stress in the crack normal direction must be specified as either a tabular function of stress versus displacement across the crack or as a tabular function of the failure stress and the associated Mode I fracture energy. This approach reduces mesh sensitivity because the removal of stress is determined primarily by the opening across the crack, which does not depend on the element size.

Figure 10 illustrates the stress-displacement method of defining tension stiffening.

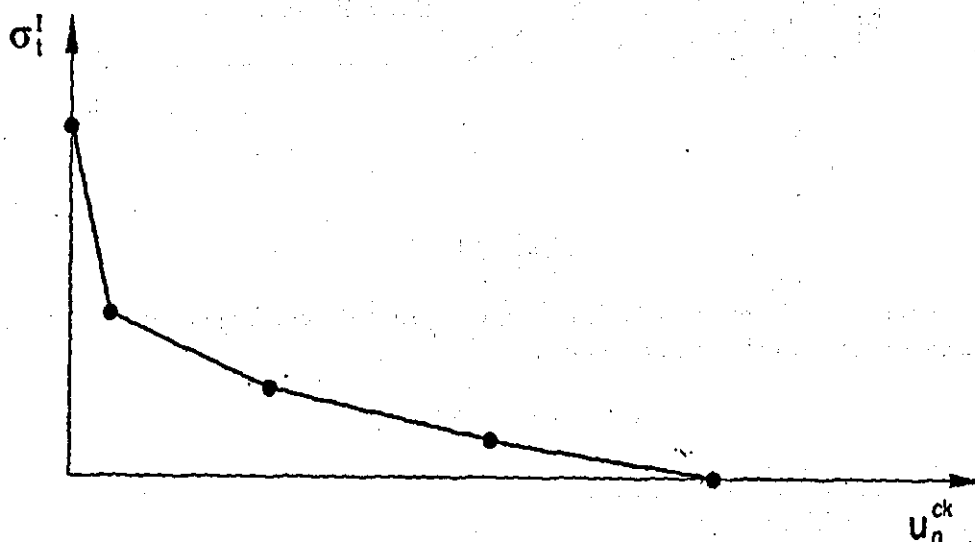


Figure 10

The displacement at which the stress across the crack opening reaches zero (u_{ck}) is defined as follows:

$$u_{ck} = h * (\sigma_t / E)$$

where: h is the characteristic crack length. For three dimensional elements, this is defined as the cubed root of the element's volume.

σ_t is the tensile stress at which Mode I brittle cracking is initiated (direct tensile stress).

E is the elastic modulus.

Figure 11 illustrates the definition of the fracture energy method of defining tension stiffening.

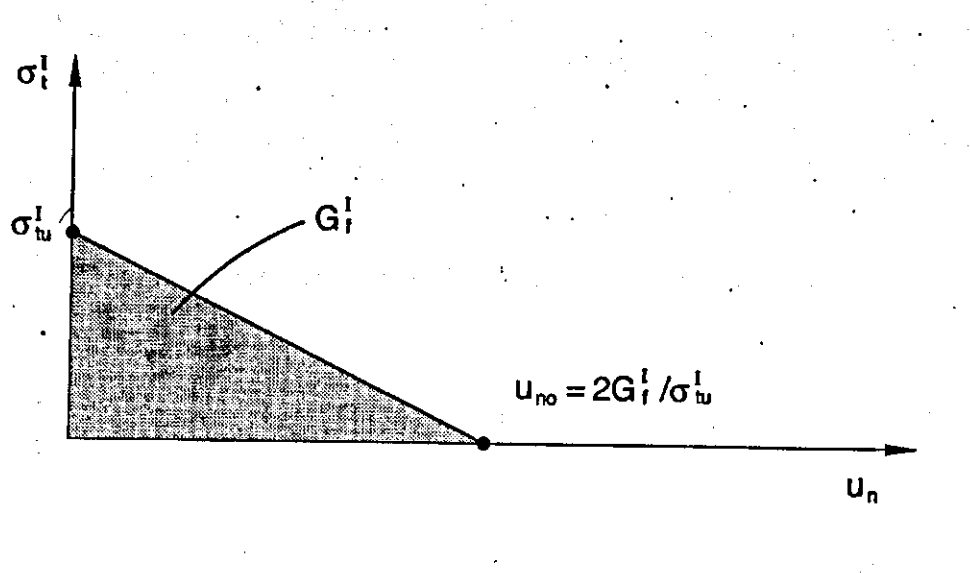


Figure 11

In this case, u_{no} is the displacement at which the stress across the crack opening reaches zero, and the fracture energy can be calculated as follows:

$$G_f^I = (\sigma_t^I * u_{no}) / 2.0$$

where: G_f^I = the Mode I fracture energy
 σ_t^I = the failure stress
 u_{no} = the crack normal displacement at which complete loss of strength takes place

In the crack detection sensitivity study, described in the previous section, the tension stiffening was defined as a stress displacement curve. The shape of this tension stiffening curve is determined by selection of the intermediate points. (See figure 10 above.) In this study, the monolithic dam model was analyzed using three different stress-displacement curve shapes to define tension stiffening in the model. The failure stress and the displacement at which the stress across the crack reaches zero were held constant and the definition of intermediate points was varied. An additional analysis was also completed in which tension stiffening was defined using the failure stress and Mode I fracture energy. For this comparison, the analysis designated NLX9 (shown in figure 9 for the crack initiation study) was modified to increase and decrease the area under the tension stiffening curve as shown in figure 12. All other material properties were held constant. One additional analysis was also completed in which the fracture energy method was used to define the tension stiffening as shown in figure 13. The Mode I fracture energy was calculated from material properties used in analysis NLX9. The tensile strength was 15 lb/in² and the Mode I fracture energy was 0.04.

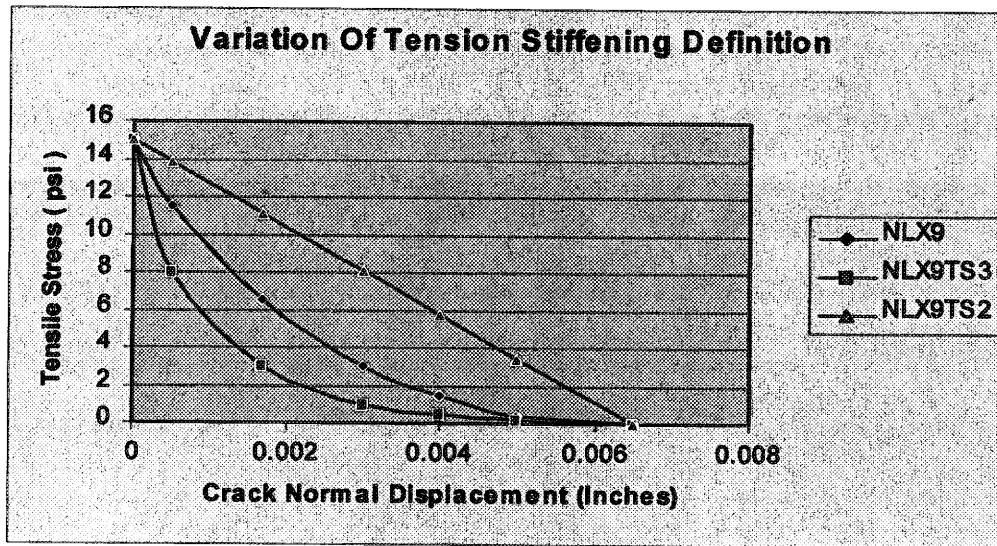


Figure 12

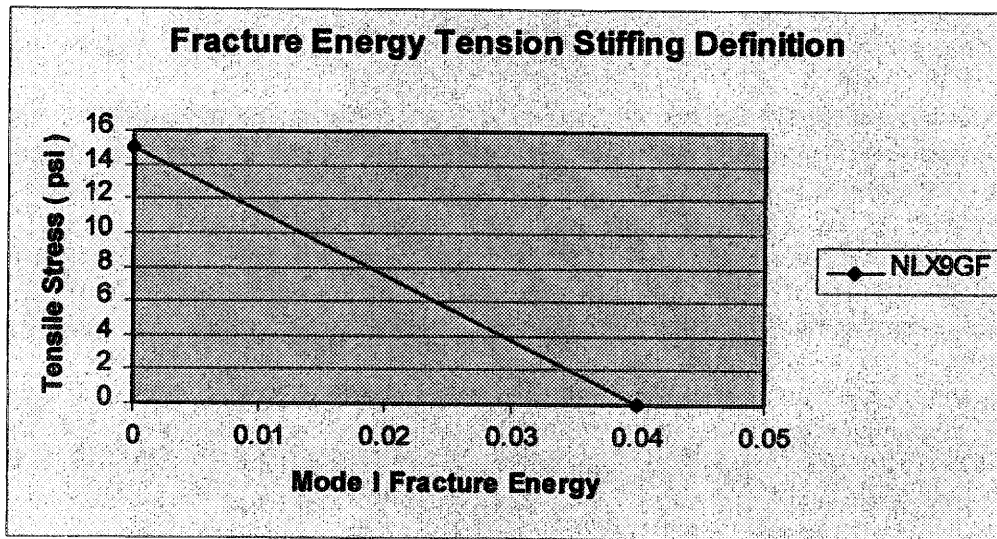


Figure 13

Shear Retention Model

Another feature of the ABAQUS/EXPLICIT concrete cracking model is the post cracked shear behavior. The mode II shear behavior is based on the fact that the shear modulus is reduced as the crack opens. The post cracked shear modulus is defined as a fraction of the uncracked shear modulus, as follows:

$$G_c = \rho(\epsilon_{m}^{ck})G$$

where: G_c = the post cracking shear modulus
 G = the uncracked shear modulus
 ρ = the shear retention factor
 ϵ_{m}^{ck} = the crack opening strain

This relationship can be specified in a piecewise linear form, as shown in figure 14, or in a power law form, as shown in figure 15.

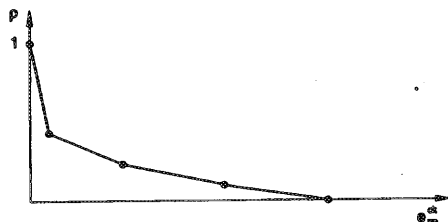


Figure 14.—Brittle Shear, Type = Retention Factor

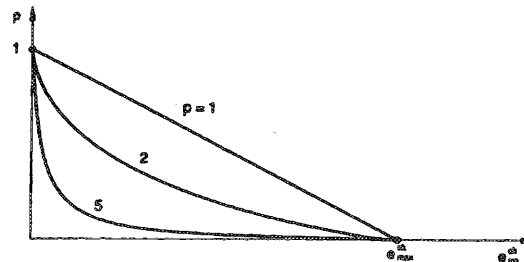


Figure 15.—Brittle Shear, Type = Power Law

In the previous sensitivity studies, the shear retention was defined using the power law method with an exponent of 2.0. In this sensitivity study, in which only the shape of the shear retention curve was varied, results from three analyses of the monolithic dam model were compared. For this comparison, the area under the brittle shear curve was increased and decreased by varying the exponent used in the power law definition, as shown in figure 16. The analysis designated NLX9 used an exponent of 2.0; the analysis designated NLX9SH1 used an exponent of 1.0; and the analysis designated NLX9SH2 used an exponent of 3.0. All other material properties were held constant.

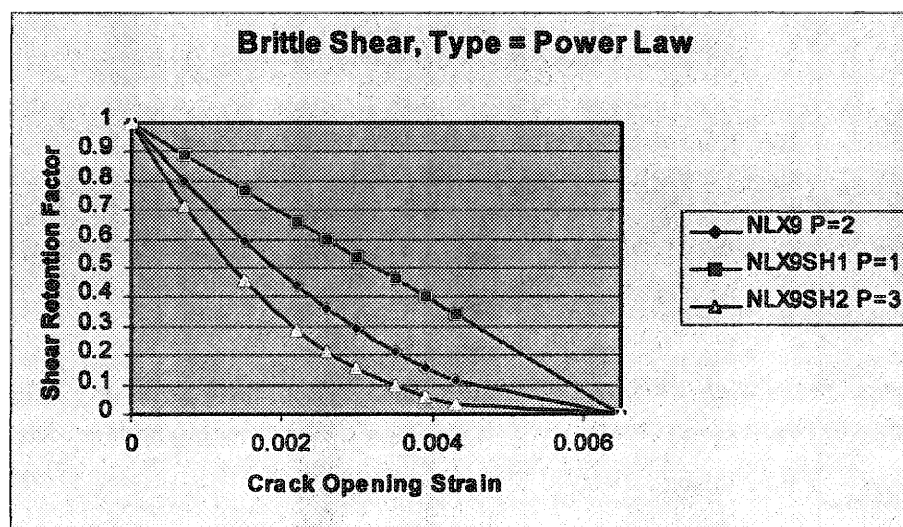


Figure 16

Material Properties used for Non-Linear Analyses of Five Joint Configurations

Based on the sensitivity study approach described in the previous sections, non-linear tensile strength parameters for each of the five analysis models were selected. Material properties applied to the various models are summarized in table 5.

Table 5.—Material properties used for analyses of five model types

Model	Elastic Modulus lb/in ²	Compressive Strength lb/in ²	Tensile Strength lb/in ²	Max. Crack Normal Strain in/in	Mode I Fracture Energy
M2M8	2302.6	25.7	15	0.0065	0.04875
M6M11	3758.8	41.97	20.5	0.0055	0.056
M9M10	5172.1	52.1	23.7	0.0046	0.055
M12M13	2804	26.2	15	0.005	0.04
M14M15	3948	21.4	13.1	0.0033	0.043

The Mode I fracture energy method was used to define the tension stiffening in each of these analyses, as shown in figure 17.

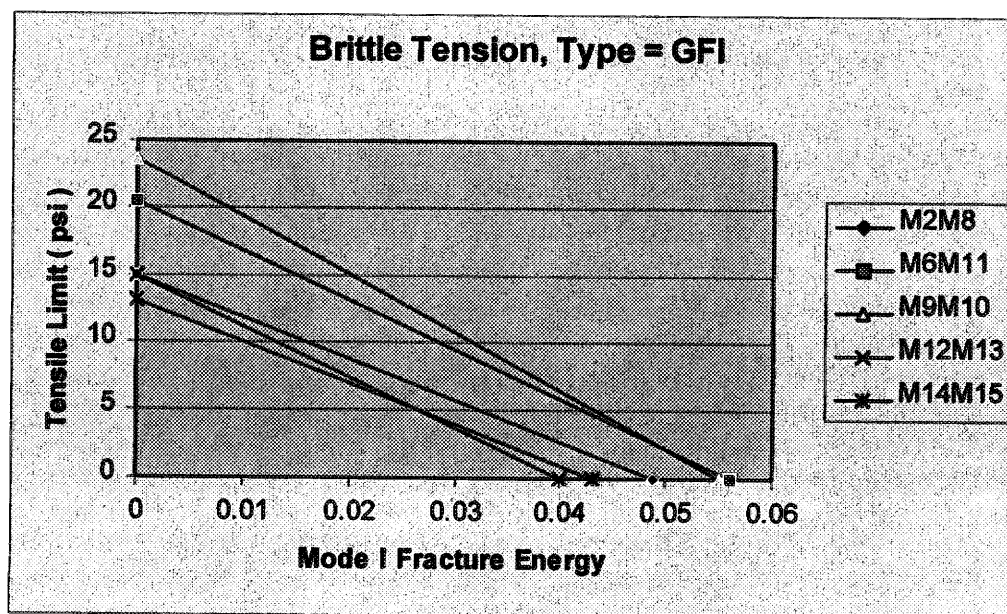


Figure 17

The post cracking shear reduction was defined using the power law method with an exponent of two for each of the five analyses as shown in figure 18.

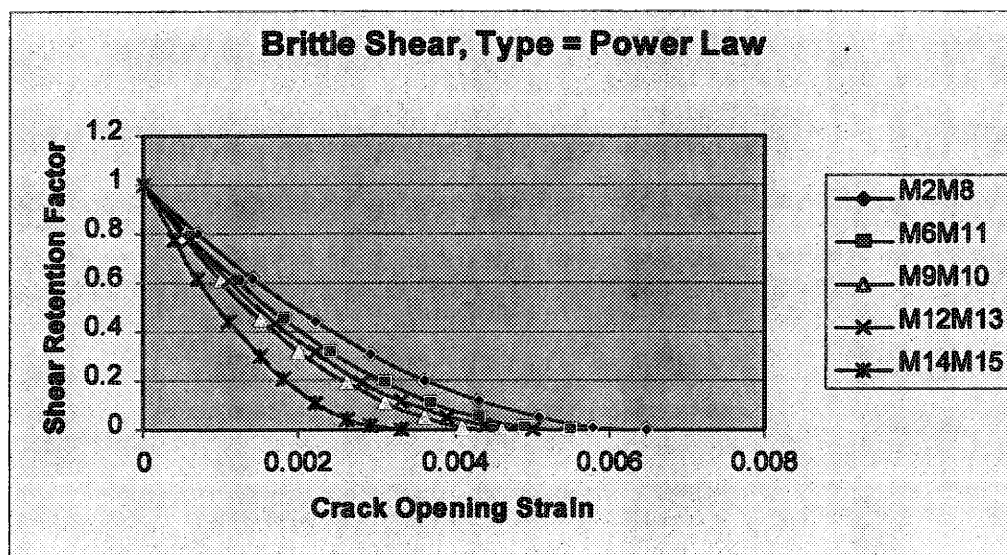


Figure 18

Loading Conditions

Static Loads

Gravity and reservoir loads were applied to each of the models in this study. The application of static loading was completed gradually over five analysis loading steps as summarized in table 6. Low viscous pressures, 5 lb/in² or less, were also added to contact surfaces to reduce "numerical chatter" on the contacts as gravity was applied. These viscous pressures were removed before the application of dynamic loads. The reservoir load was applied as stepped uniform pressures on the upstream face elements of the dam. The reservoir surface elevation was 35.48 inches (one inch below the dam crest). Equivalent uniform pressures were calculated setting the hydrostatic pressure distribution for each horizontal row of elements equal to an equivalent uniform pressure load applied over the height of the elements. The application of pressure loads is illustrated in figure A.4. Spreadsheet calculations of the pressure loads are shown on figure A.5.

Table 6.—Loading Sequence for Static Analyses

Load Step	Step Duration	Load
1	0.0 to 0.25 seconds	Contact surfaces were established
2	0.25 to 1.25 seconds	Gravity with viscous pressures
3	1.25 to 1.50 seconds	No load change
4	1.50 to 3.00 seconds	Reservoir
5	3.00 to 3.50 seconds	Removal of viscous pressures

Dynamic Loads

Hydrodynamic Interaction

Westergaard's added mass approach was used to model the hydrodynamic interaction for all the models in this study. The program, WESTMAS, was used to calculate the mass values, which were then attached to nodes on the upstream face of the dam. In ABAQUS/STANDARD analyses, three directional components of mass were applied. In ABAQUS/EXPLICIT analyses, only a scalar mass value can be used.

Acceleration Record

In the laboratory experiment, a sinusoidal acceleration record with a frequency of 14 Hz was applied to the base of the model in the upstream-downstream direction. It was intended that the amplitude of the acceleration would be increased in 0.25 g increments of 30 second duration until failure of the model occurred. In practice, the input motions applied during each shake test, as measured by an accelerometer located at the base of the foundation, varied somewhat. Figures A.6 through A.10 show the input acceleration records during the shake table tests. Two shake test were completed for each of the five model configurations. (Note that the acceleration records are not all plotted to the same scale.)

In the computer analyses, modeling such long time periods (on the order of 300 seconds) was not feasible. Therefore, sinusoidal acceleration records of 14 Hz frequency were created with 0.25 g amplitude increments of lesser duration until the analysis indicated failure. Figure A.11 shows the input motion used for the preliminary linear elastic analyses of the monolithic dam model. In this input acceleration record, each 0.25 g amplitude increment was applied for a single cycle until a 1.5 g amplitude was reached. Subsequent to the preliminary analyses, this record was modified to apply each 0.25 g amplitude increment for a duration of 10 cycles. This acceleration input record is shown in figure A.12.

Preliminary Analyses

Foundation Sensitivity Study

The first preliminary study was conducted to determine the effect of removal of the foundation from the finite element model. The models tested in the laboratory were constructed in a concrete block foundation. Originally, the finite element model also modeled the concrete block foundation. However, it was determined that analysis time could be substantially reduced through removal of the foundation. Although the material properties used for the dam "concrete" were scaled using similitude properties, the foundation block was not. This resulted in an extremely high dam to foundation modulus ratio. For example, a foundation modulus of 3,000,000 psi combined with a dam modulus of 2,303 psi results in a foundation to dam modulus ratio of 1,302:1. It was felt these laboratory conditions could be reasonably modeled using a fixed foundation dam model with significant solution time savings. Linear elastic static, modal and dynamic analyses of the monolithic model with and without discrete modeling of the foundation were compared to quantify the effect of the removal of the foundation model from the analyses. The comparison of results from these analyses, with and without a discretely modeled foundation, indicated that finite element models of the dam with fixed boundary conditions can be used to accurately simulate the conditions in the shake table tests with a two thirds reduction in the time required to complete the analyses. Therefore, the remainder of the analyses in this study were completed using dam models with fixed boundary conditions rather than using a discrete foundation model.

ABAQUS Solver Selection

The second preliminary study was conducted to select the most appropriate version of ABAQUS for use in the remainder of this study. There are two versions of the ABAQUS finite element program available: ABAQUS/EXPLICIT and ABAQUS/STANDARD. Preliminary linear elastic analyses of the monolithic dam model were completed using both versions of the ABAQUS program. Results were compared to determine if a preferred version could be identified, and to verify that both versions of the program would produce the same results linear elastically. The results of this comparison indicate that either program could be used equally well for static loads. Kinetic energy was evident during static load application in the EXPLICIT analysis; therefore, it is recommended that empty load steps be inserted after each static load application step to allow the kinetic energy level to return to zero before the next load is applied. However, the results of the dynamic analyses indicate that the EXPLICIT version of the ABAQUS program should be used for the rest of the analyses in this study. The energy levels (both kinetic and strain energy) and acceleration amplitudes appeared to be increasing exponentially as the STANDARD dynamic analysis progressed, resulting in stresses and displacements that were unreasonably high.

A detailed discussion of the results of each of these preliminary studies is included in Appendix C.

Results

Summary of Results From the Laboratory Shake Table Tests

Results of the laboratory shake table tests are summarized in table 7. Shown are the input amplitude at which cracking was first detected and the input amplitude at which failure occurred. Failure is defined as the total collapse of the structure.

Table 7.—Laboratory results

Model ID	Model Type	Input Acceleration Amplitude at Initial Cracking	Input Acceleration Amplitude at Final Failure
M2	Monolithic	0.75	5.00
M8	Monolithic	1.50	1.50
M6	Single Vertical Joint	0.70	0.85
M11	Single Vertical Joint	1.20	1.20
M9	Single Horizontal Joint	0.95	1.75
M10	Single Horizontal Joint	1.65	1.65
M12	Seventeen Vertical Joints	0.60	0.60
M13	Seventeen Vertical Joints	0.50	0.50
M14	Seventeen Vertical and Two Horizontal Joints	1.00	1.25
M15	Seventeen Vertical and Two Horizontal Joints	0.75	0.75

Figures D.1 through D.18 show photographs taken during the shake table tests for each of five model types: (1) monolithic model (figures D.1 to D.5), (2) Single vertical joint model (figures D.6 to D.8), (3) Single horizontal joint model (figures D.9 to D.12), (4) 17 vertical joints model (figures D.13 and D.14), and (5) 17 vertical and two horizontal joint model (figures D.15 to D.20).

All the test models failed in the same basic failure mode. The models cracked vertically through the center of the arch, and additional cracks formed diagonally from the arch quarter points at the dam crest curving downward to meet the lower end of the vertical crack. Cracking progressed until separate blocks formed in the upper central section of the arch, and then these blocks fell downstream.

The extent of the vertical crack varied somewhat for different model types. During shake table tests using of monolithic dam models, the vertical crack extended two thirds of the dam height downward from the dam crest, where it joined with the diagonal cracks forming two separate blocks in the central upper section of the dam. During the tests of the single vertical joint model, this crack followed the joint all the way to the dam base. In one of the single vertical joint model shake table tests, the diagonal cracks formed very near the dam foundation contact, which resulted in the formation of two large blocks, one of which swung downstream, very much as a saloon style door would swing open. During the test of the other single vertical joint model, the diagonal cracking was higher in the dam, which resulted the formation of several smaller blocks. During the testing of the single horizontal joint models, the diagonal cracks appear to form and join horizontal cracks along the horizontal joint in the center section of the dam before the development of the vertical cracking in the center section, but the final failure was essentially the same. During the test of the 17 vertical joint models, vertical cracking developed along most of the vertical joints. The vertical cracks intersected with the diagonal cracks. This resulted in the formation of more separate blocks in the upper central section of the dam, but the failure mode was still very similar. During the tests of the 17 vertical and 2 horizontal joint models, vertical cracks formed along several (but not all) of the vertical joints that intersected with cracks along the upper horizontal joint. The diagonal cracks extended down to join with cracks that formed along this upper horizontal joint. This resulted in the formation of several independent blocks in the upper central section of the dam. Then, the vertical cracks progressed downward between the two horizontal joints. As the upper level blocks were displaced downstream from the dam, new blocks appeared to be forming in the lower section of the dam.

Linear Elastic Static Analyses of Five Model Configurations

Displacements

Maximum displacements under static loads occurred at the dam crest in the center of the arch for each of the five models as shown in table 8.

Table 8.—Maximum displacements at dam crest under static loads

Finite Element Model Designation	Gravity Load Only (Inches)	Gravity Plus Reservoir Load (Inches)
M2M8	-0.01	0.056
M6M11	-0.008	0.035
M9M10	-0.004	0.025
M12M13	-0.013	0.035
M14M15	-0.013	0.039
Note: Positive displacement is in the downstream direction.		

Contour plots of the displacements in the upstream-downstream direction caused by gravity and gravity plus reservoir loads for each of the five models are shown in figures E.1 through E.5. These contours were each plotted on the deformed shape with a magnification factor of 100. Figures E.6 through E.33 show contour plots of the normal force acting on the joint surfaces at the end of the gravity and gravity plus reservoir load steps and the slip magnitude of nodes on the surfaces. A normal force of zero on a surface area indicates that the joint is open in this area at the end of the current load step. The slip magnitudes show the magnitude of the slip accumulated at nodes while the surfaces were in contact. Slip is not accumulated during times when the surfaces are not in contact.

In all cases, the dam tends to rotate upstream during the gravity loading step. The analysis of the single vertical joint model indicated that the upper half of the joint was not in contact at the end of the gravity load. There was very little radial slipping in the upper half of the joint before the joint opened. Analysis of the single horizontal joint model showed that the horizontal joint remained in contact during the gravity load step, the greatest normal forces developed near the abutments, and movement along the surface was not significant. Analysis of the 17 vertical joints model showed all 17 joints opened to some extent during the gravity loading. Joints closer to the abutment showed zero normal force over the entire surface (no arch action), and joints in the center section of the arch were in contact on the lower half of the surface and open on the upper half of the surface. Because the joints were open during most of this load step, very little slippage accumulated along surfaces. Analysis of the 17 vertical and 2 horizontal joints model also showed that most of the vertical joints were open at the end of the gravity load step, and very little slippage accumulated along the surfaces. Both horizontal joint surfaces tended to be closed, and there was very little slippage under gravity load.

In all cases, the dam tended to deflect back in the downstream direction when the reservoir load was added. The analysis of the single vertical joint model showed the joint closing and remaining in contact. Only very minor slipping (0.0001 inches) occurred at the top of the dam on the downstream face during the reservoir loading. The analysis of the single horizontal joint model showed some loss of contact near the upstream face at the abutments and near the downstream face at the center of the arch, but the joint did not lose contact all the way through the thickness at any location, and there was no slipping along the surface. Analysis of the 17 vertical joints model showed all 17 joints closing as the reservoir load was added. The largest contact forces tended to develop at mid-height on the surfaces, and very low contact forces were being transferred at the top of the joint. Very little slipping along the joint surfaces developed during static load steps. Analysis of the 17 vertical and 2 horizontal joints model also showed all 17 vertical joints closing as the reservoir load was applied. Very little slipping occurred along surfaces, and the slipping that did occur was associated with the horizontal joints. When the reservoir load was applied, the lower horizontal joint remained closed, and the downstream half of the upper horizontal joint opened in sections near the center of the arch. This joint never opened all the way through any section, and very little slipping occurred.

Maximum Principal Stresses

The maximum principal stresses determined from analyses of the monolithic model and the single vertical joint and the single horizontal joint models resulting from gravity loading were very similar in value and distribution. The analyses for these three models show that the entire downstream face is in tension, and the maximum tensile stresses develop at the dam crest, near the abutments. These tensions develop because stage construction sequencing was not modeled

in these analyses. Gravity was ramped onto the entire model uniformly during this analysis load step, and the dam contact fixed against displacement in all three directions, causing tension to develop at the abutments as the dam attempts to rotate upstream. Most of the upstream face is also in tension under gravity load. Only the lower third of the upstream face is in compression. The stress distribution changed when 17 vertical joints were modeled. Most of both faces of the dam was still in tension under gravity loading, but in this case, the regions of higher tension in the upper abutments did not develop because the evenly spaced vertical joints were free to open as the dam rotated upstream. The maximum tensions tended to develop at the arch quarter points at the dam base, on the downstream face, as the cantilevers deflected upstream. The values of maximum principal stress were also lower than those resulting from the other models. When 2 horizontal joints were added to the 17 vertical joints, both the tensions in the upper abutments and those at the quarter point along the dam base were relieved. In this case, a higher tension zone developed just below the lower horizontal joint on the upstream face. These tensions were slightly higher than those seen in the analyses of the other models.

The maximum principal stress distribution and the stress values resulting from gravity plus reservoir loading were very similar in all the models. The analyses showed most of the downstream face in compression, with the exception of some very low tensile stresses in the upper, central section of the downstream face. In the case of the 17 vertical and 2 horizontal joints model, these low tensions were more evenly distributed over the central portion of the downstream face than in the other four models. Most of the upstream face was also in compression for the combined gravity and reservoir loading, with the exception of some low tensile stresses that developed near the base of the dam on the upstream face. The magnitude of the maximum compressive stresses resulting from the analysis of the model with 17 vertical and 2 horizontal joints was a degree of magnitude higher than the values resulting from the other four models, but these appear to be stress concentrations which occur at points of intersection of vertical and horizontal joints.

Stress contour plots of the maximum principal stress resulting from static loads for each of the five models are shown in figures E.34 through E.43. Table 9 shows the maximum and minimum principal stress values resulting from each of the five analyses.

Table 9.—Maximum principal stress values caused by static loads

Finite Element Model Designation	Gravity Load Only		Gravity Plus Reservoir Load	
	Minimum	Maximum	Minimum	Maximum
M2M8	-0.02	0.42	-0.30	3.69
M6M11	-0.20	0.43	-0.33	3.74
M9M10	-0.20	0.43	-0.30	3.78
M12M13	-0.23	0.19	-0.35	3.86
M14M15	-0.31	0.52	-3.33	3.06
Notes: (1) All stresses are in lb/in ² . (2) Negative values are compressions.				

Energy Levels

Figures E.44 through E.48 plot the time histories of various energy levels resulting from the analyses of each of the five models. Each plot shows artificial strain energy, frictional energy dissipated, total strain energy, kinetic energy, energy dissipated because of viscous effects, and the total energy balance versus time for the entire model. Table 10 shows the maximum energy values for each static analysis.

Table 10.—Maximum energy level during static loading

Model	Artificial Energy	Frictional Energy	Strain Energy	Kinetic Energy	Viscous Energy	Total Energy
M2M8	0.02	0.00	2.24	0.03	0.01	0.00
M6M11	0.03	0.42	1.30	0.03	0.01	0.00
M9M10	0.01	0.86	0.99	0.01	0.00	0.00
M12M13	0.03	6.37	1.40	0.01	0.01	0.00
M14M15	0.53	135.00	2.50	0.00	0.65	0.00

The energy output can be useful in checking the accuracy of the analysis solution. The artificial strain energy is associated with constraints used by ABAQUS to remove singular modes (such as hourglass control) and should be negligible compared to the real energies such as the kinetic and strain energies. The artificial energy levels were reasonable for all five models, although the artificial energy level required when 17 vertical and 2 horizontal joints were used was substantially higher than in the other four models. The frictional energy level was also much higher in the 17 vertical and 2 horizontal joints analysis. Dissipation of frictional energy provided increased damping in this case. The strain energy was also highest when both vertical and horizontal joints were used but not significantly higher than in the monolithic dam analysis. Since these were static analyses, the kinetic energy should not exceed a small fraction of the value of the strain energy. All the analyses generated very low levels of kinetic energy, and the level of kinetic energy decreased as the complexity of the model increased. The viscous energy levels were low in all cases. The level of energy dissipated by viscous effects was highest when both vertical and horizontal joints were included, which seems reasonable because this energy dissipation is associated with the viscous pressures applied to joint surfaces. In all cases, the maximum total energy values were very low, indicating that a good energy balance was achieved.

A sudden increase in energy level appears at the beginning of the reservoir load step (1.5 seconds) in the time history plots for the first three models (M2M8, M6M11, and M9M10). This sudden increase does not appear in the plots for the last two models (M12M13 and M14M15). This is caused by a discrepancy in the load application cards used for the first three analyses. The reservoir was intended to be ramped on from zero to full hydrostatic load from 1.5 seconds to 3.0 seconds of analysis time. In the first three analysis, one-fourth of the reservoir load was actually applied at the beginning of the load step and the remainder was ramped on over the load step, so the jump in energy level is reasonable. This input error was identified and corrected in the final two analyses. In all cases where the jump in energy was recorded, the

energy levels damped back down over the load step, and good energy balance was maintained so that there was no significant effect on results at the end of the load step.

Linear Elastic Dynamic Analyses of Five Model Configurations

Deformations

Figures F.1 to F.5 show the deformed shape of the five respective models at five equally spaced intervals of a single sinusoidal acceleration load cycle with a peak amplitude of 1.0 g. These deformation plots are magnified by a factor of 10 so that the upstream-downstream oscillation of the dam crest is clearly visible.

In the case of the monolithic model (M2M8), figure F.1 shows the upstream-downstream oscillation of the dam crest. In the case of the single vertical joint model (M6M11), figure F.2 shows that the vertical joint opens as the dam crest deflects upstream and closes when the dam crest deflects downstream. In the case of the single horizontal joint model (M9M10), figure F.3 shows that as the dam crest oscillates upstream there is some sliding along the horizontal joint. In the case of the 17 vertical joints model (M12M13), figure F.4 shows all the joints in the central portion of the dam opening as the dam crest deflects upstream and closing as the dam crest deflects downstream. In the case of the 17 vertical and 2 horizontal joints model (M14M15), figure F.5 shows independent blocks forming as the dam crest deflects in the upstream direction. The vertical joints in the center portion of the dam arch opened, forming separate blocks, which tended to rock on the upper horizontal surface. The deformations in these plots are greatly exaggerated, but they show that when a 1.0 g input acceleration amplitude was applied to this model, some of the independent blocks at the center of the arch completely separated from the rest of the model. Once the upper blocks separated, the blocks formed between the upper and lower horizontal surfaces also began to rock. This analysis completed only two loading cycles of the 1.0 g input motion, which is approximately 0.14 seconds of analysis time at this amplitude level. At this point, the analysis indicated that a kinematic failure had occurred. The independent blocks in the upper central portion of the dam rocked too far in the upstream direction to recover when the dam below them deflected back in the downstream direction, and these blocks separated from the structure completely and fell upstream into the reservoir. There were two 17 vertical and 2 horizontal joints models tested on the shake table: laboratory models designated M14 and M15. Model M14 failed during the 1.00 g input acceleration loading, while model M15 failed during the 0.75 g amplitude input acceleration loading. So these results seem quite reasonable.

Figures F.6 through F.9 show additional deformation plots resulting from the analysis of the 17 vertical and 2 horizontal joints model at lower input amplitudes. Figure F.6 shows the deformations during the very first dynamic loading cycle (0.25 g). Even with a magnification factor of 10, only very slight joint openings were visible. Figure F.7 shows deformations occurring during the tenth cycle of the 0.25 g dynamic load. The three blocks located at the center of the arch on the crest rocked and tipped as a unit in the upstream-downstream direction. Each amplitude level was applied for 10 loading cycles, which was approximately 0.7 seconds of analysis time. Figure F.8 shows deformations during the last cycle of the 0.50 g loading. At this point, more blocks on the upper section were rocking and tipping in the upstream-downstream direction, and there was some separation on the lower horizontal surfaces as well. Figure F.9 shows the deformations at the end of the 0.75 g loading. These plots are very similar to those

seen at 1.00 g just prior to failure. Blocks in both the upper and mid elevations were rocking. Blocks in the upper central section of the dam actually bounced on the horizontal joint surface, alternately losing and regaining contact.

Figures F.10 through F.14 show photographs of this scale model, M15, as it failed on the shake table. Each photo is labeled with a time, in seconds, and a frame number measured from the time of the first observable cracking. The initial crack, which is very hard to see in the photos, was a vertical crack near the center of the dam that occurred at an amplitude of 0.75 g. Cracks are clearly evident 2 seconds later along the upper horizontal joint and on three of the vertical joints in the upper third of the dam. Cracks are also beginning to form on the lower horizontal joint. Independent blocks had formed in the upper and middle thirds of the dam 10 seconds after the initial cracking, and water was flowing through the cracks. Between the tenth and eleventh second after the cracks were initiated, independent blocks separated from the scale dam model, falling downstream from the dam. The final photos in figure F.14 show that 16 seconds after the initial cracking all the blocks that formed in the central section of the upper third of the dam had fallen downstream, and half of the blocks in the middle section had also been washed downstream. The dam model collapsed at an input amplitude of 0.75 g.

Displacement Time Histories

Comparisons were made of the displacements measured in the laboratory and the displacements resulting from the ABAQUS analyses for each of the five models. Two models were tested on the shake table for each of the five joint configurations. The dynamic loading for each shake table test was intended to be a 14 hertz sinusoidal acceleration record, and the amplitude was to be stepped up in 0.25 g increments of 30 second duration. It was not always possible to create this exact scenario in the laboratory. Therefore, to create the following comparisons, the input acceleration records recorded during each of the laboratory tests were examined to locate times at which the loading amplitude most nearly matched one of the amplitudes applied in the analyses before any indications of that cracking had occurred in the laboratory model. Figures F.15 through F.19 show the measured input accelerations from the laboratory tests, with the input acceleration records used for all the ABAQUS analyses, and a comparison of both at the time period selected. Figures F.20 through F.24 show time history plots of the laboratory and the analysis displacement time histories at the time period selected for the comparison. Figures F.25 through F.29 show the full displacement time histories recorded during the shake table tests in the laboratory.

Comparisons of displacements for the monolithic model were made during the 0.50 g loading using the laboratory model designated M2. Figure F.20 shows the displacement time histories at LVDT #2 (located near the crest on the crown cantilever) and LVDT #1 (located on the crown cantilever one-quarter of the way up from the base). Displacements measured and calculated at the lower elevation were similar. The ABAQUS peak displacement values were slightly lower. The comparison of the displacements near the top of the dam (LVDT #2) were not useful because the instrumentation at this location was apparently not functioning correctly during this test.

Comparisons of displacements for the single vertical joint model were made during the 0.25 g loading using the laboratory model designated M6. Figure F.21 shows the displacement time histories used for this comparison. The displacements at the lower elevation were similar. In this

case, the laboratory record was offset in the positive (downstream) direction. The entire displacement record at this instrument was offset by this amount, so this should be considered as an initial offset of the instrument. The displacements measured near the top of the dam were very small. As in the previous case, it appears the instrumentation was not functioning correctly. Comparisons of displacements for the single horizontal joint model were made during the 0.25 g loading using the laboratory model designated M10. Figure F.22 shows the displacement time histories used for this comparison. The displacements at the lower elevation were similar. In this case, the laboratory record was offset in the negative (upstream) direction. The entire displacement record at this instrument was offset by this amount, so this should be considered as an initial offset of the instrument. The displacements measured near the top of the dam were also offset in the upstream direction. The amplitude of displacement near the crest resulting from the analysis differed greatly from measured values. The differential displacement (difference between minimum and maximum peak values) resulting from the ABAQUS analyses range was 0.6 inch, while the displacement differential from the instrumentation was 0.1 inch.

Comparisons of displacements for the 17 vertical joints model were made during the 1.0 g loading using the laboratory model designated M13. Figure F.23 shows the displacement time histories used for this comparison. The displacements at the lower elevation were similar. In this case, both the laboratory record and the ABAQUS displacement curve were offset in the positive (downstream) direction. The displacements at the top of the dam resulting from the ABAQUS analysis were an order of magnitude larger than those calculated at the lower elevation; unfortunately, the instrumentation at this location was not functioning.

Comparisons of displacements for the 17 vertical and 2 horizontal joints model were made during the 0.50 g loading using the laboratory model designated M14. Figure F.24 shows the displacement time histories used for this comparison. The measured and calculated displacements at the lower elevation were similar. In this case, the laboratory record was offset in the negative (upstream) direction. The entire displacement record at this instrument was offset by this amount so this should be considered as an initial offset of the instrument. The displacements at the top of the dam resulting from the ABAQUS analysis were an order of magnitude larger than those calculated at the lower elevation; unfortunately, the instrumentation at this location was not functioning.

Acceleration Time Histories

Figures F.30 through F.35 show acceleration time history curves from the analyses of each of the five models. Acceleration measurements were taken from five corresponding shake table tests. Measurements were taken at the locations of the six accelerometers for 10 loading cycles at selected input amplitudes are shown in figures F.36 through F.45. The only models that produced somewhat similar acceleration time history records were the monolithic model (M2) and the 17 vertical joints model (M13). Analysis results from these two models tended to be higher in amplitude than laboratory measurements, but at nearly the same frequency. Where the laboratory and the analysis accelerations did not match (M6, M12, M14), acceleration amplitudes generated by the analyses tended to be higher than those measured in the laboratory. The analysis accelerations also appear to be at a higher frequency than the measured values.

Non-Linear Model Calibration Analyses

Crack Detection (Tensile Strength)

Variation in the definition of tensile strength significantly affects the results of the dynamic loading. As the analyses progressed, any failure to converge at material points was reported in the ABAQUS status file (*.sta). The analysis was continued with an increasing number of material points failing to converge until the analysis was terminated with an error message indicating that some elements had become too distorted for the analysis to continue. The current version of ABAQUS (Version 6.21) does not print cracking information directly to any of the output files generated by the program. It also does not have any crack plotting capability. Future versions are expected to have these capabilities. To obtain cracking information from the current version of ABAQUS/EXPLICIT, the *selected* results file (*.sel) must first be converted to a results file (*.fil) using the ABAQUS convert utility. The user must create a Fortran subroutine to read this results file. This code is then linked with the ABAQUS code and used to extract cracking information, such as the crack status and cracking orientation, from the ABAQUS results file. A printout of the Fortran subroutine used for post processing of cracking results in these analyses has been included in Appendix H, along with instruction for linking and executing the code. The crack information can then be plotted on the undeformed dam mesh. Cracks are represented as circles in the plane of the crack at the centroid of the element. Second and third cracks are also shown, so an element plotted with three orthogonal circles at its centroid has cracked in all three directions and no longer has any stiffness associated with it. This is a smeared cracking model; therefore, such elements are not physically removed from the mesh. A discrete crack will not form separating sections of the mesh when severe cracking has occurred; therefore, significant cracking in a group of elements can result in unrestrained deformation of surrounding elements, which causes the analysis to terminate.

The results summarized in table 11 show the effect of variation in tensile strength in terms of crack initiation, failure to converge in these analyses, and the input amplitude at failure of the two monolithic laboratory models.

Table 11.—The effect of variation in tensile strength on the input amplitude that results in cracking			
Analysis ID	Tensile Strength (psi)	Input Amplitude At Crack Initiation	Input Amplitude At Analysis Termination
NLX1	5	0.50 g	0.75 g
NLX7	10	1.00 g	1.25 g
NLX9	15	1.25 g	2.00 g
NLX5	20	1.75 g	2.75 g
NLX4	30	2.50 g	4.00 g
Model M2 (Lab)	4	0.75 g	5.00 g
Model M8 (Lab)	NA	1.5 g	1.5 g

Figures G.1 through G.5 show the initial crack patterns resulting from this sensitivity study using the monolithic model. These analyses indicated that cracking would occur on the upstream face before cracks developed on the downstream face. With only one exception, the initial cracking was oriented vertically and located at the center of the arch near the dam crest. The one exception occurred when the lowest tensile strength was used (5 lb/in²); in this case, the initial cracks were oriented horizontally and located near the base of the dam in the maximum cantilevers.

Figures G.6 through G.10 show the final crack patterns resulting from this sensitivity study. Crack results are requested at intervals within each analysis step, so these plots represent crack patterns at the last increment in which crack information was requested before failure of the analysis to converge. So, in some cases, results may be plotted at increments slightly closer to failure than in other cases and, for this reason, show more cracks. Therefore, in these plots, the general crack distribution is more significant than the number of cracks. This series of analyses resulted in the same final crack pattern. They indicate that diagonal cracks would develop on the downstream face, starting at the arch quarter points at the dam crest, and propagate in a downward curve towards the center section of the dam. These cracks would intersect with vertical cracking at the center of the arch. On the upstream face, vertical cracks would develop at the center of the arch, starting at the crest and propagating downward. Horizontal cracks would also tend to form in the center section near the dam base on the upstream face.

Tension Stiffening

Three analyses, designated NLX9, NLX9TS2, and NLX9TS3, were completed using the displacement method of tension stiffening. In each of these studies, a different relationship between stress and crack normal displacement were defined as shown in figure 12 of section V. Tension stiffening for analysis NLX9TS2 was defined as a linear curve; for analysis NLX9TS3, it was defined as a steeply dipping parabolic curve; and for analysis NLX9 (previously used in the crack detection sensitivity study), it was defined as an intermediate curve. One study, designated NLX9GF, was completed using the fracture energy method of tension stiffening. In this study, the relationship between stress and fracture energy was defined by the linear curve shown in figure 13 of section V.

Table 12.—Variation in tension stiffening definition		
Model Designation	Input Amplitude At Crack Initiation	Input Amplitude At Analysis Termination
NLX9TS2	1.25	2
NLX9	1.25	2
NLX9TS3	1.25	1.5
NLX9GF	1.25	1.5

Results of the tension stiffening definition study are shown in the final crack patterns from this series of analyses. The results were all very similar. Plots showing the crack patterns resulting from these analyses are included in figures G.11 and G.12. The linear stress-displacement tension and the stress-fracture energy tension stiffening definitions produced identical results. Analysis NLX9TS3 indicated that vertical cracks at the center of the arch near the dam crest would form parallel to the arch axis rather than radially. This orientation of these cracks does not seem reasonable.

Brittle Shear Definition

Three analyses were used to investigate the effect of varying the rate of shear modulus reduction with crack opening strain. The power law brittle shear definition was used in all three analyses with different exponents. The analysis designated NLX9SH1 used an exponent of one, analysis NLX9 used an exponent of two, and analysis NLX9SH2 used an exponent of three. These brittle shear definition curves are shown in figure 16 of section V. The results of these three analyses in terms of input amplitude of crack initiation and final failure are shown in table 13.

Table 13.—Variation In Brittle Shear Definition

Model Designation	Input Amplitude At Crack Initiation	Input Amplitude At Analysis Termination
NLX9SH1	1.25	1.75
NLX9	1.25	2
NLX9SH2	1.25	2

The cracking patterns resulting from these three analyses are shown in figures G.13 and G.14. Analysis NLX9SH1, which used a linear reduction of shear capacity with increasing crack normal strain, resulted in some cracking near the dam crest at the center of the arch that was oriented in the arch direction rather than radially. This crack orientation does not seem reasonable. Analyses NLX9 and NLX9SH2 produced nearly identical results.

Non-Linear Static Analyses of Five Joint Configurations

The results of the non-linear static analyses were identical to the results of the linear elastic analyses discussed in section VIII.B.

Non-Linear Dynamic Analyses of Five Joint Configurations

Table 14 shows results of the dynamic analyses of an identical arch dam which was modeled with each of the five different joint configurations. The table shows results in terms of the input amplitude at which cracking was initiated and the input amplitude at failure. The corresponding input amplitudes from the laboratory tests are also shown for comparison. There were two

laboratory tests for each joint configuration. In some cases, the average values from material property testing for the two laboratory models were used in the material property model for the analysis. In these cases, results from both laboratory models were listed in the table. In other cases, the material properties from one of the two models were used in the analysis and only the corresponding laboratory results were included in the table.

Table 14.—Results from five non-linear analyses

Model ID	Model Type	Input Acceleration Amplitude at Initial Cracking	Input Acceleration Amplitude at Final Failure
Analysis M2M8	Monolithic	1.25 g	2.00 g
Lab M2	Monolithic	0.75 g	5.00 g
Lab M8	Monolithic	1.50 g	1.50 g
Analysis M6M11	Single Vertical Joint	1.25 g	1.50 g
Lab M11	Single Vertical Joint	1.20 g	1.20 g
Analysis M9M10	Single Horizontal Joint	0.75 g	1.75 g
Lab M10	Single Horizontal Joint	1.65 g	1.65 g
M12M13	Seventeen Vertical Joints	1.50 g	2.00 g
Lab M12	Seventeen Vertical Joints	0.60 g	0.60 g
Lab M13	Seventeen Vertical Joints	0.50 g	0.50 g
M14M15	Seventeen Vertical and Two Horizontal Joints	No Cracking	0.75 g
Lab M15	Seventeen Vertical and Two Horizontal Joints	0.75 g	0.75 g

With only one exception, the analyses and laboratory results are in the same range. The one exception was the 17 vertical joints model, which formed cracks and failed at much higher input amplitudes in the analysis than during the laboratory test.

Figure G.15 shows the crack patterns on the undeformed mesh along side deformed shape plots for the monolithic model. It is not now possible to plot crack patterns directly on the deformed shape, but by viewing the crack pattern plots and the deformed shape plots side by side, it is

evident that the crack patterns are reasonable for this deformed shape. An additional plot from the modal analysis showing the third mode shape was also included in this figure to illustrate that the dam was responding to the higher modes. The modal analysis indicated that the third natural frequency was 14.8 Hz. The frequency of the input motion was 14.0 Hz. Figure G.16 shows a comparison of the predicted crack pattern from the analysis of the monolithic model and the crack pattern resulting from the shake table test of model M2. The analysis modeled the failure mode that actually occurred.

Figure G.17 shows the crack pattern and the deformed shape from the analysis of the single vertical joint model. The deformed shape plot of the downstream face shows a localized distortion of elements near the dam base and adjacent to the vertical joint. The vertical joint is open and horizontal cracks have propagated through the dam thickness at this location. This is a smeared cracking model, so a discrete crack can not be generated in the analysis. But the crack pattern suggests that a horizontal crack would tend to open in this area, and a horizontal crack would lead to the saloon-door type failure seen in the corresponding shake table test.

Figure G.18 shows the analysis crack pattern along side the photo of the single vertical joint model failure in the laboratory.

Figure G.19 shows the crack pattern and deformed shape from the analysis of the single horizontal joint model. In this case, the horizontal joint is open, and localized cracking at the arch quarter point has caused excessive deformation of elements in this area. The excessive deformation lead to termination of the analysis. Vertical cracking at the center of the arch is also evident. Figure G.20 shows this failure mode during a laboratory test.

Figure G.21 shows the crack pattern and deformed shape from the analysis of the 17 vertical joints model. Again, localized cracking has resulted in excessive deformation of some elements near the dam crest and the center of the arch that caused the analysis to terminate. Some horizontal cracks were also evident at lower elevations. Figure G.22 shows the failure of the 17 vertical joints model on the shake table. First, the vertical joints began opening and closing, then horizontal cracks developed connecting the contraction joints, and this caused the formation of independent blocks. The analysis does not show this failure model as clearly as the analysis of the other model types.

Figure G.23 shows the deformed shape resulting from the analysis of the 17 vertical and 2 horizontal joints model along with a photo of this model failure in the laboratory. In this case, cracking was not indicated by the analysis. A kinematic failure mode was indicated. Both horizontal and vertical joints opened and closed repeatedly forming independent blocks. These blocks underwent both sliding and rocking until the blocks in the upper center section fell upstream from the dam, and the blocks at the arch quarter points at the top of the dam fell downstream. The laboratory model did generate some diagonal cracking that connected with cracking along the upper horizontal joint. This cracking, combined with the opening and closing of the vertical joints, formed independent blocks. During the shake table test, a block near the arch quarter point fell downstream from the dam. Shortly thereafter, additional blocks fell.

Figure G.24 shows a side view of the failure of the 17 vertical and 2 horizontal joints model. This figure shows the deformation at failure of both the linear elastic and the non-linear analyses to further illustrate a purely kinematic failure mode. These deformation plots are magnified by a factor of 10 to more clearly illustrate the failure mode.

Conclusions

Static Linear Elastic Analyses

These analyses illustrated some of the benefits of including vertical joints in dams. The models with 17 vertical joints exhibited lower and more evenly distributed stresses. Increasing the number of joints used in the model increased the amount of energy absorbed in frictional effects on contact surfaces, which introduces a source of damping in the model. There were no laboratory measurements for static load application in the laboratory experiments, so no comparisons can be made with the shake table tests under static loads. The ABAQUS results for static loading seem reasonable for all five models.

Dynamic Linear Elastic Analyses

All the analyses resulted in the same general deformation sequence, which matched that seen in the laboratory shake table test. The central portion of the dam crest deflects back and forth in the upstream-downstream direction. In models with vertical joints, these joints tend to open as the dam crest deflects in the upstream direction and close as the dam crest deflects in the downstream direction. This joint opening was visible in the shake table models as a very rapid vibration along the joints followed first by the loss of the reservoir through the joints and additional cracking (in locations other than along joints), then the formation of independent blocks, and finally the loss of arch support as the displacement of large blocks increased. Comparisons of dynamic displacements at the location of LVDT#1 showed that the analysis results match the shake table measurements quite well at the lower amplitude input motions (prior to cracking in the models). It was difficult to make comparisons at the top of the dam because instrument failure at this location was a problem in most of the shake table tests. This is also the location of the maximum displacements and, in three of the models, the location of a vertical contraction joint. The dynamic accelerations resulting from the analyses did not match the laboratory test results. The analysis results tended to be higher in both amplitude and frequency.

Dynamic Non-Linear Analyses

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 that 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, which were subjected to continued shaking for 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 17 vertical and 2 horizontal joints 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 that exist at the time when the analysis terminates. The laboratory tests using arch dam models with five different joint configurations all resulted in similar failure modes in response to a 14 Hz sine wave input acceleration applied in the upstream-downstream direction. 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 downstream. Different joint configurations affected the size and number of independent blocks which formed, but the shape of the cyclic deformation of the dam in response to this input motion was always the same, so crack patterns were always very similar. The monolithic and single horizontal joint models were able to withstand higher amplitude input motions than the other joint configurations.

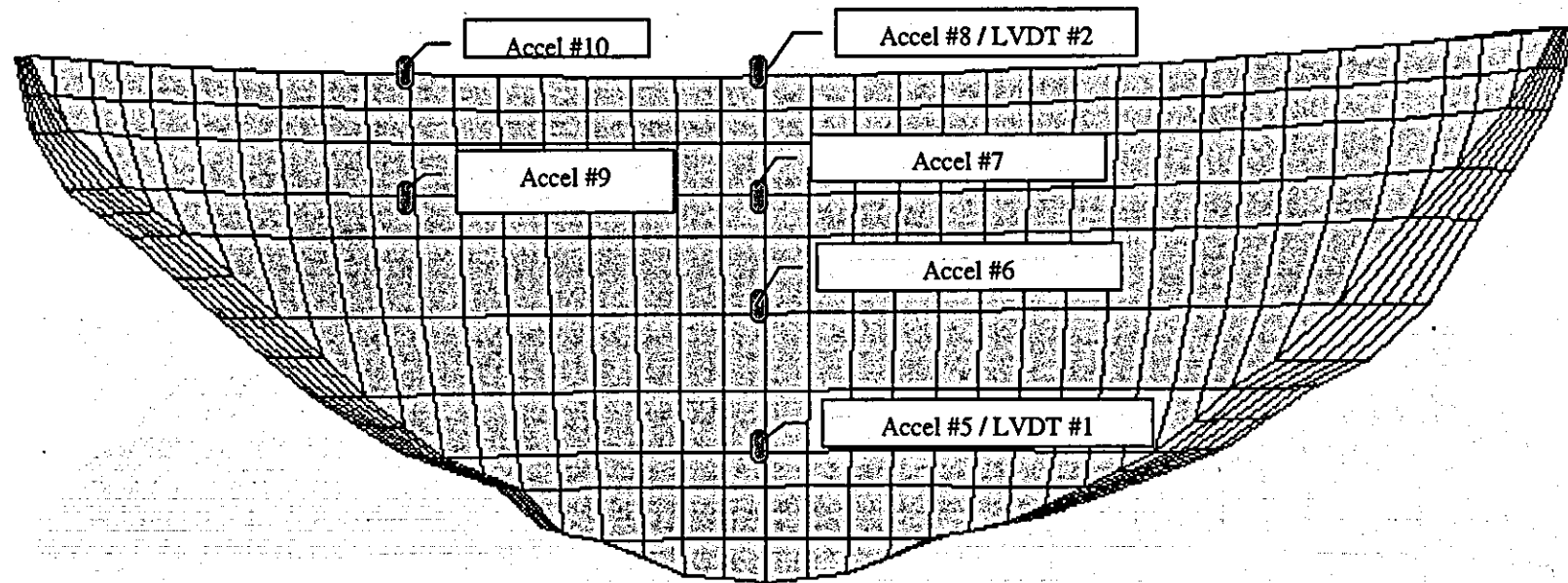
References

- [1] Raphael, Jerome M. Tensile Strength of Concrete, *ACI Journal*, Title No. 81-17, March-April 1984.
- [2] Hibbit, Karlsson and Sorensen, Inc. *ABAQUS/EXPLICIT User's Manual*, Version 6.2.
- [3] Harris, David; Mohorovic, Caroline; Dolen, Timothy. Dynamic Properties of Mass Concrete Obtained from Dam Cores Draft.

Appendix A

Boundary Conditions and Applied Loads

Viewport: 1 ODB: /dr6/tpayne/m6m11/m11grx1.odb

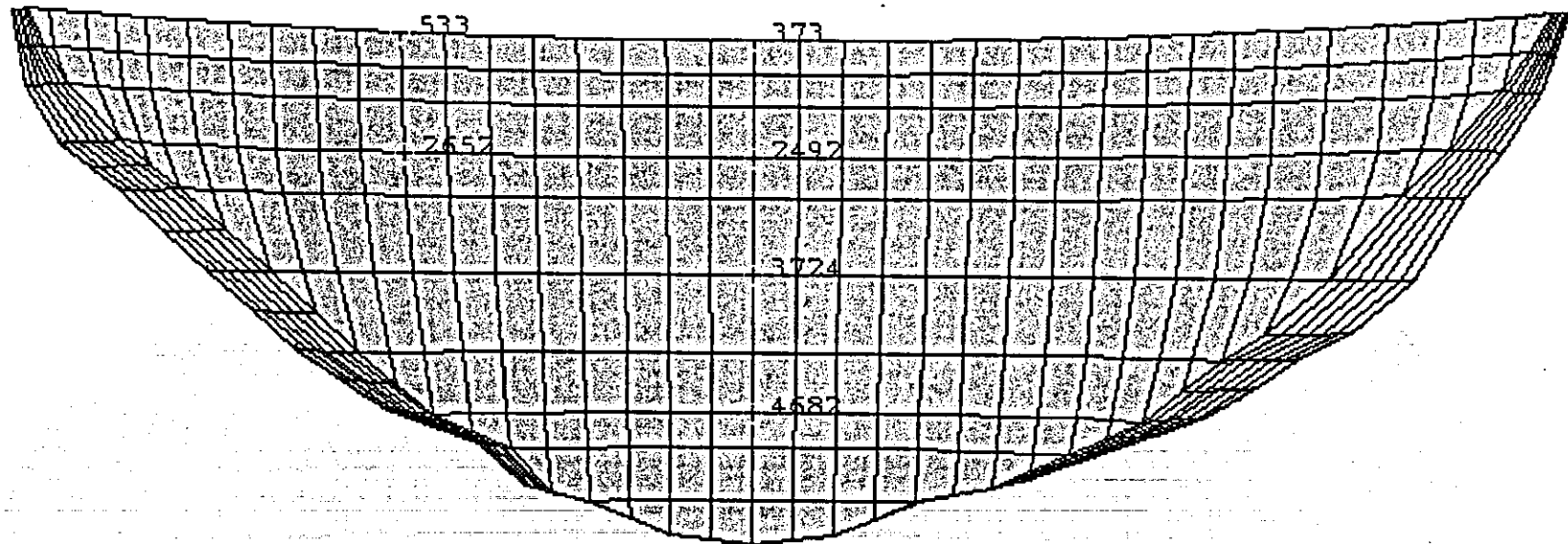


2
3 1

Locations of Output Accelerometers and LVDTs

Figure A.1

Viewport: 1 ODB: /dr5/tpayne/mf_shake/m2m8acc8x.odb



2
3—1

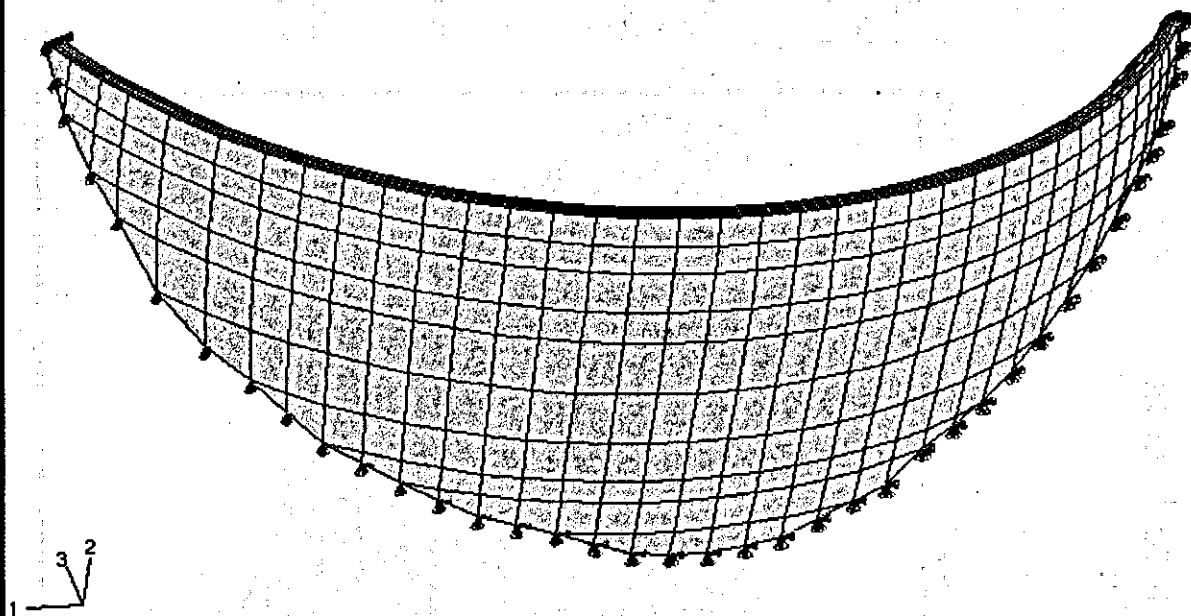
ODB: m2m8acc8x.odb ABAQUS/Explicit 6.1-1 Mon Apr 30 11:19:03 MDT 2001

Step: dynamic step Increment 20690 Step Time = 1.000

Locations of Output Nodes Used To Compare Accelerations and Displacements

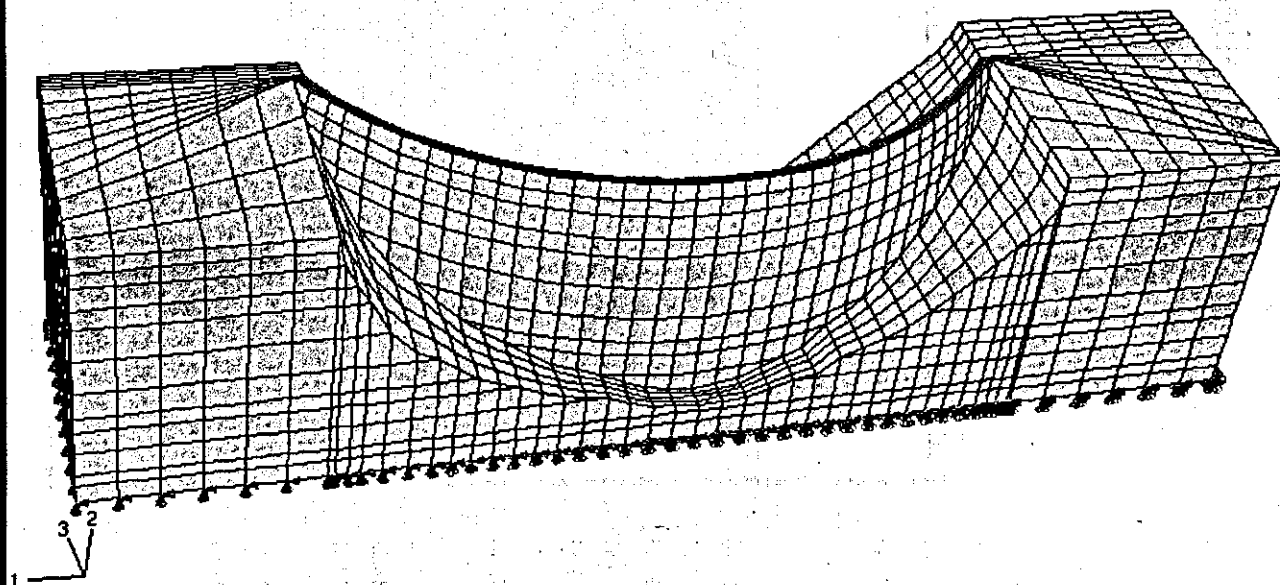
Figure A.2

Viewport: 1 ODB: /dr5/tpayne/hf_shake/m2m8gs.odb



Model and Boundary Conditions without Foundation

Viewport: 1 ODB: /dr6/tpayne/shake/m2m8gs.odb



Model and Boundary Conditions with Foundation

Figure A.3

Reservoir Load

Applied to the Upstream Face

As Stepped Uniform Pressure Loads

Water Surface Elevation = 35.48 inches

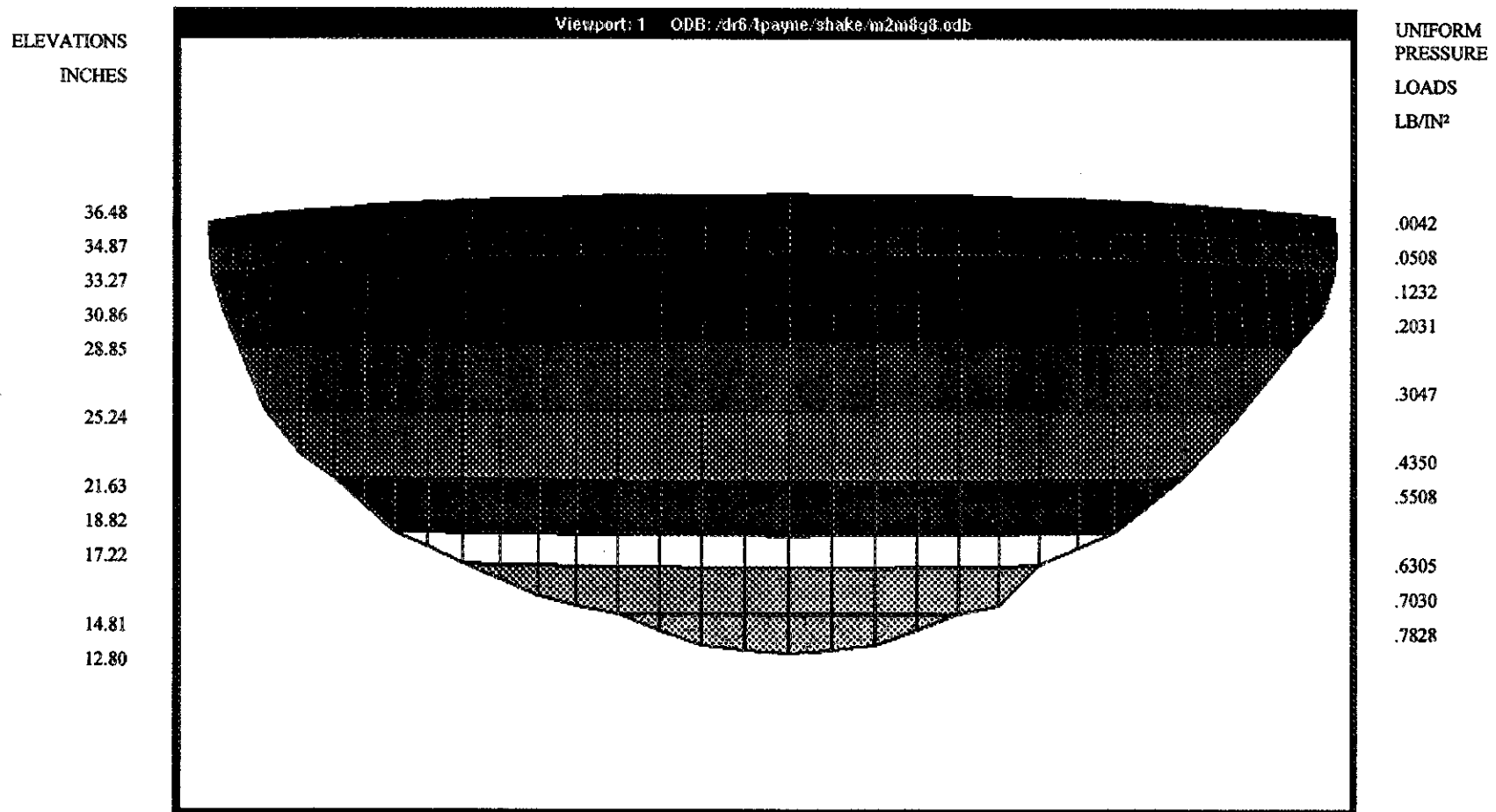


Figure A.4

Input Accelerations Used in Shake Table Tests of Monolithic Models

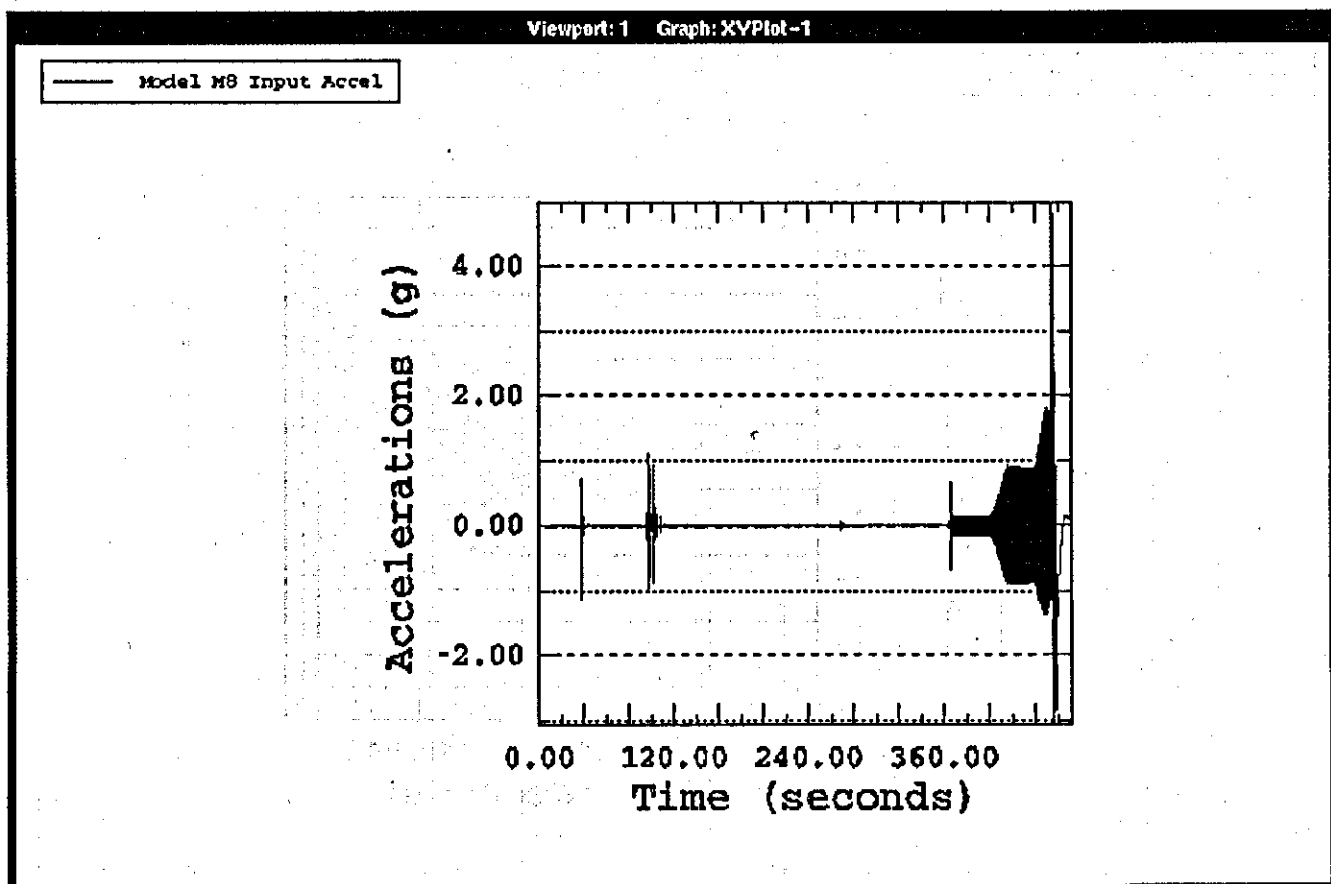
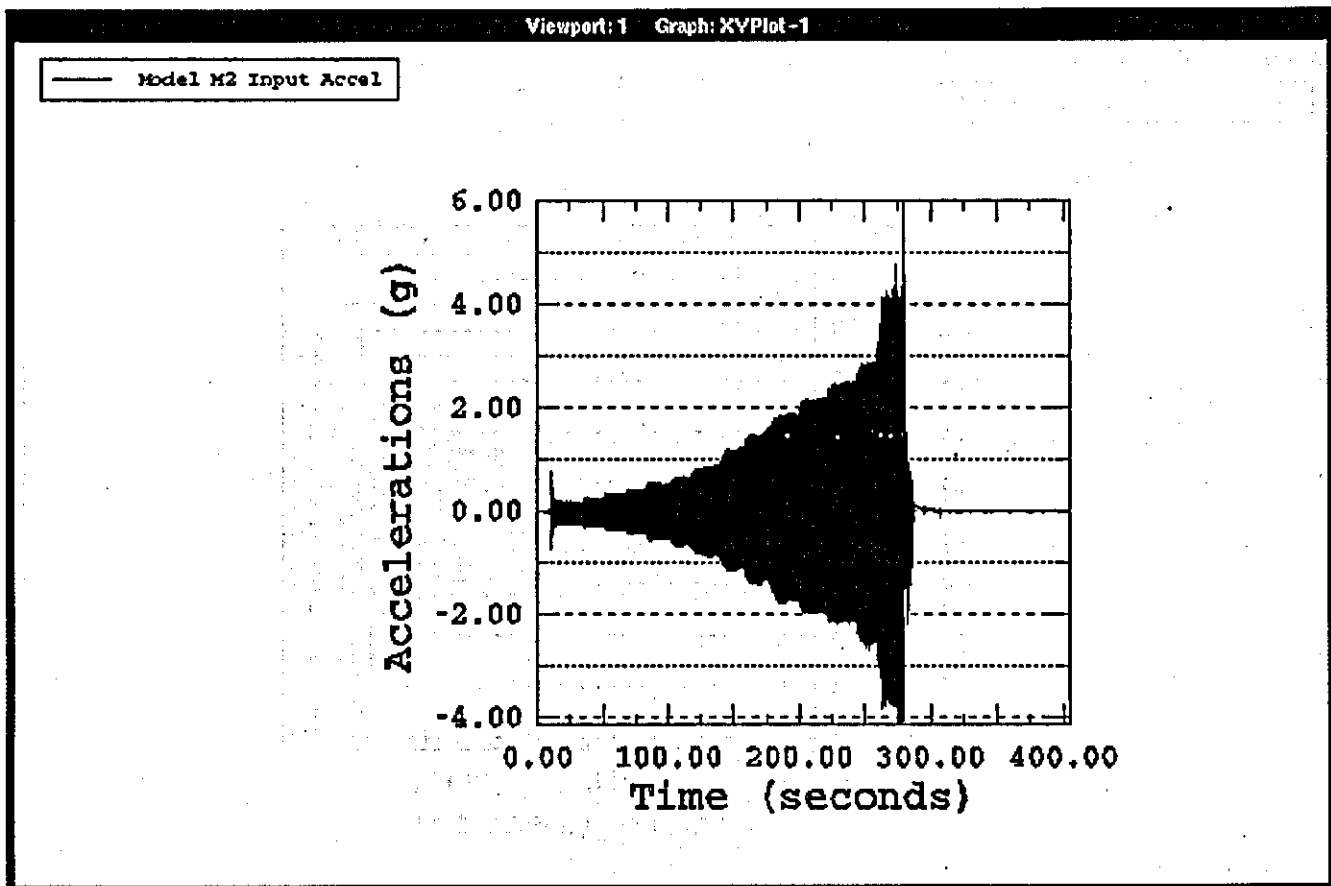


Figure A.6

Input Accelerations Used in Shake Table Tests of Single Vertical Joint Models

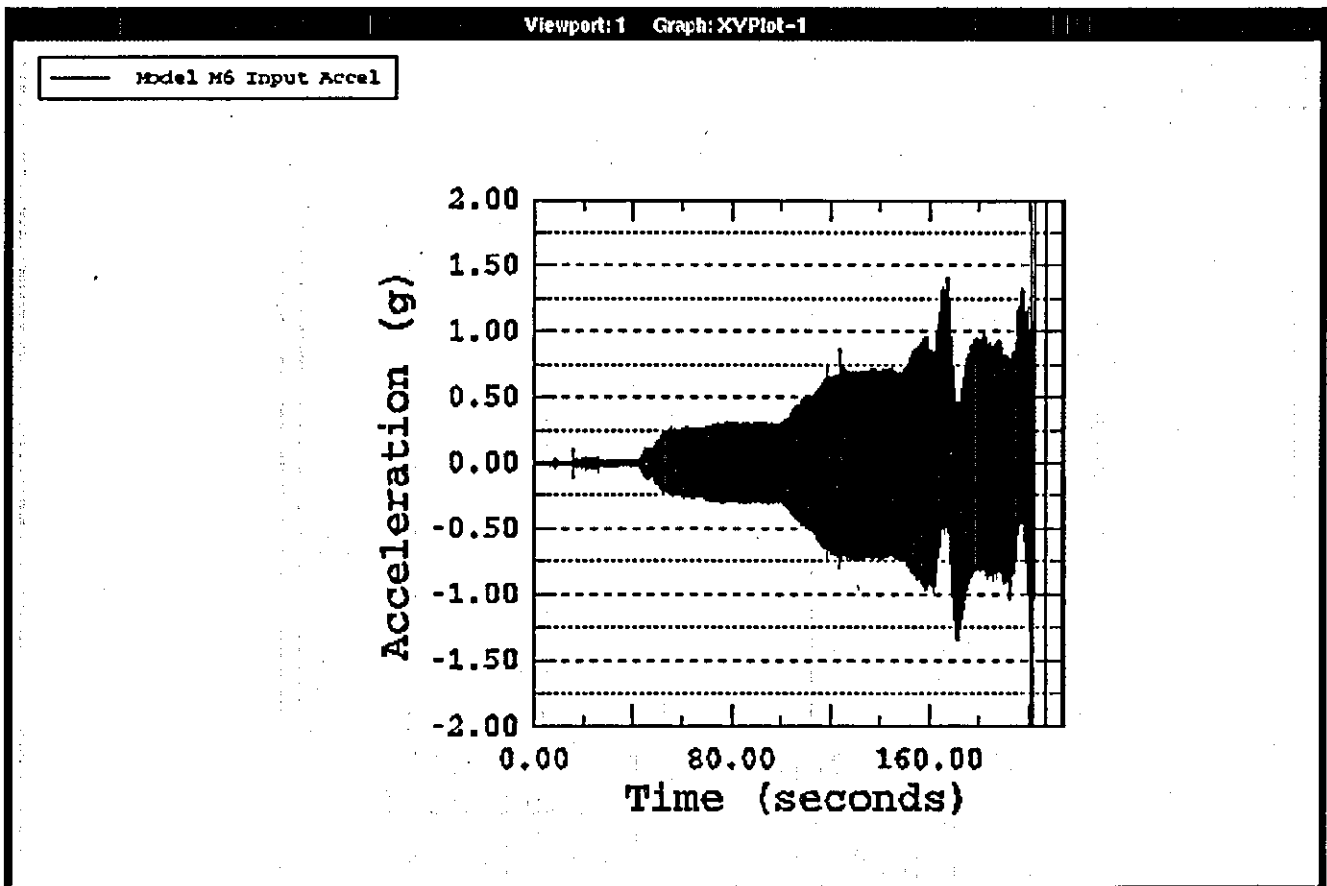
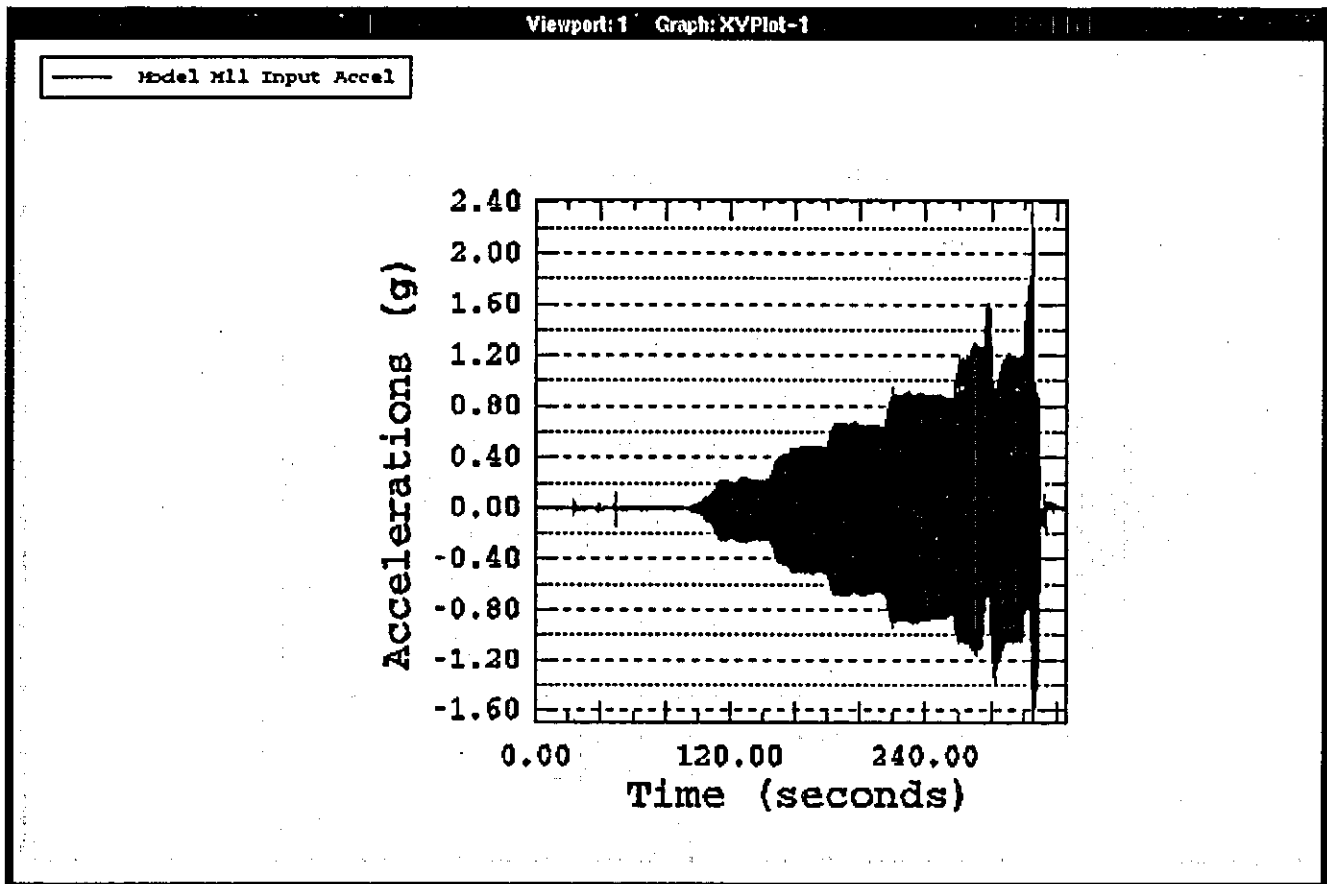


Figure A.7

Input Accelerations Used in Shake Table Tests of Single horizontal Joint Models

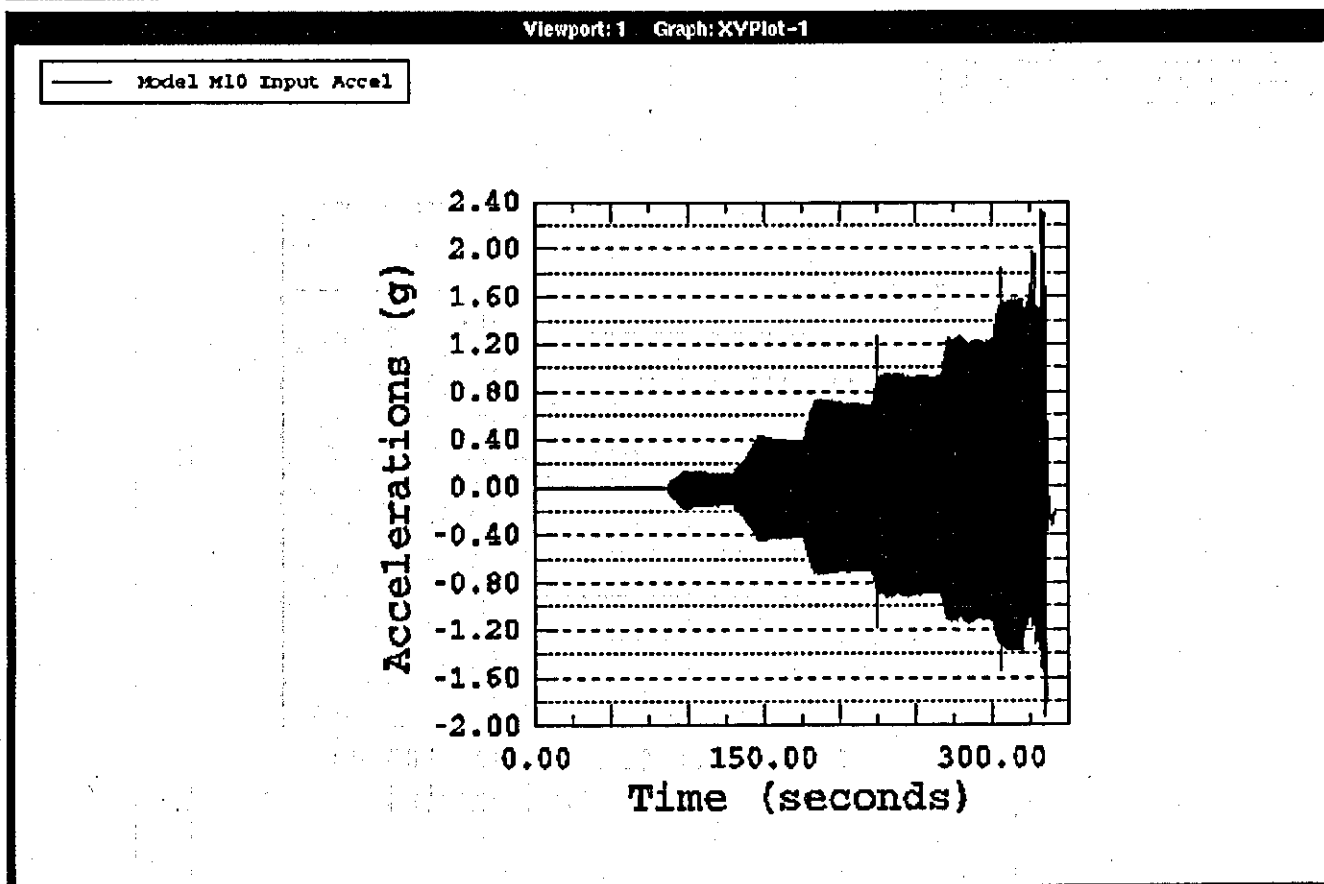
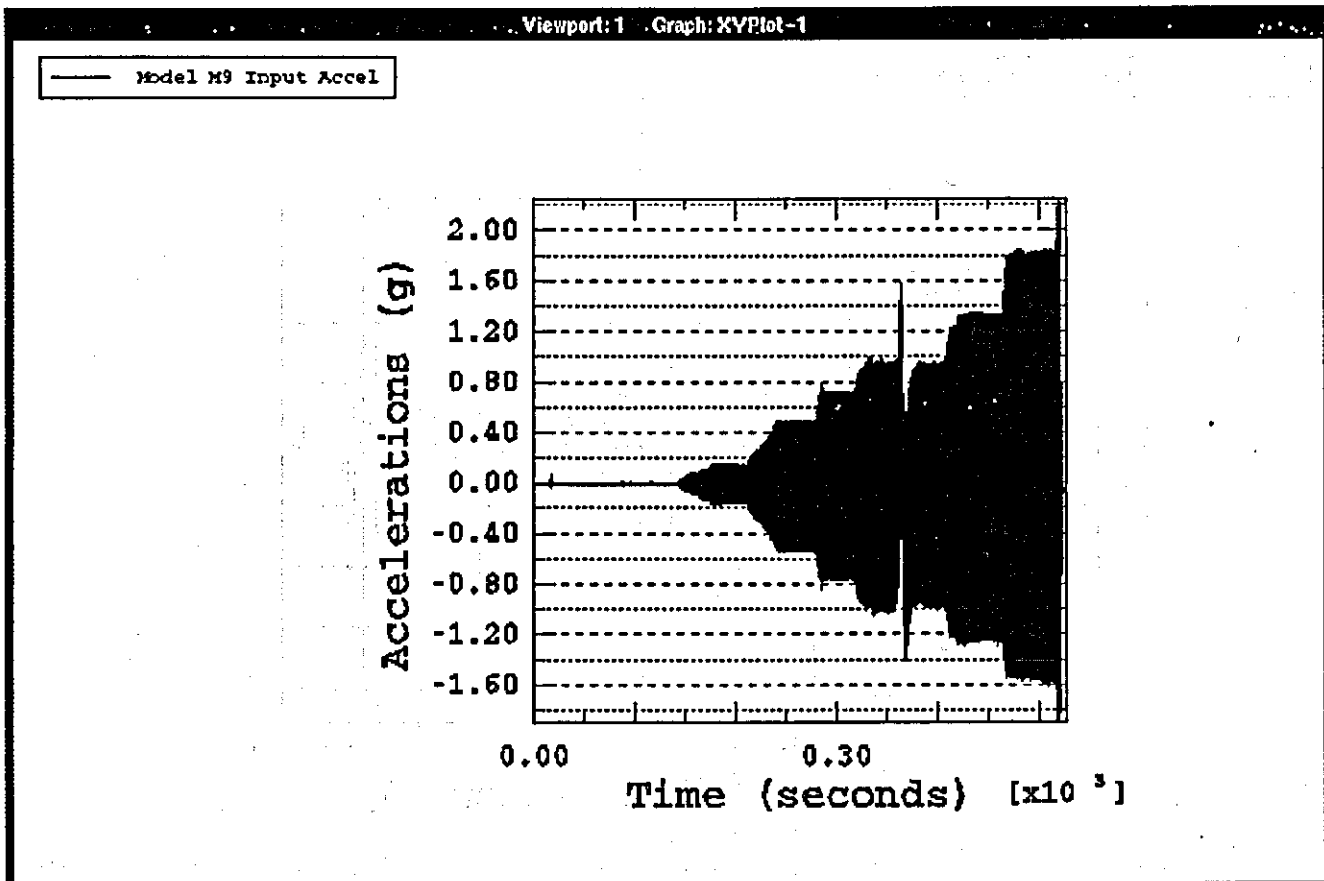


Figure A.8

Input Accelerations Used in Shake Table Tests of Seventeen Vertical Joint Models

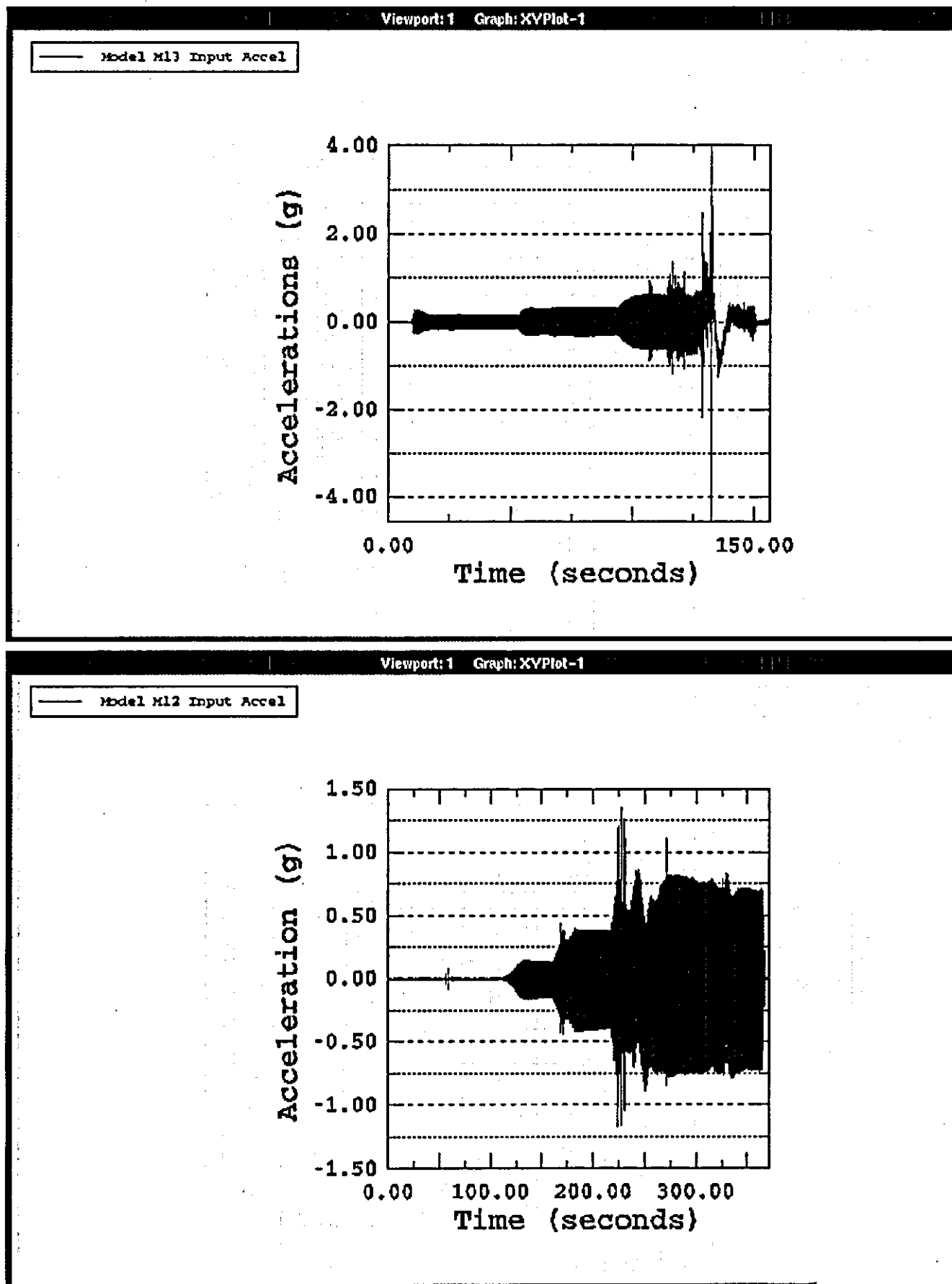


Figure A.9

Input Accelerations Used in Shake Table Tests of Seventeen Vertical & Two Horizontal Joint Models

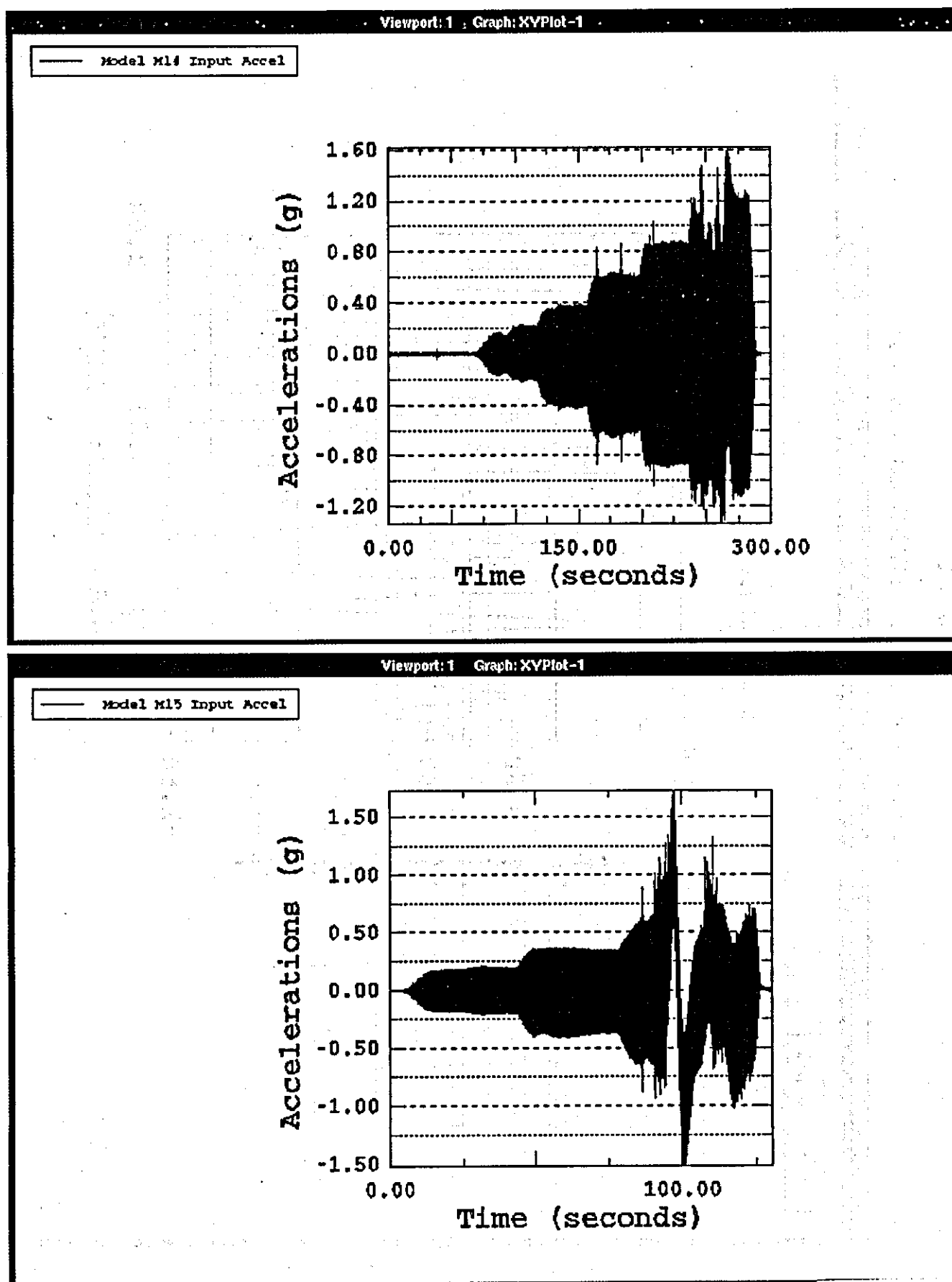


Figure A.10

Input Acceleration Record Used
For the
Linear Elastic ABAQUS STANDARD Analyses

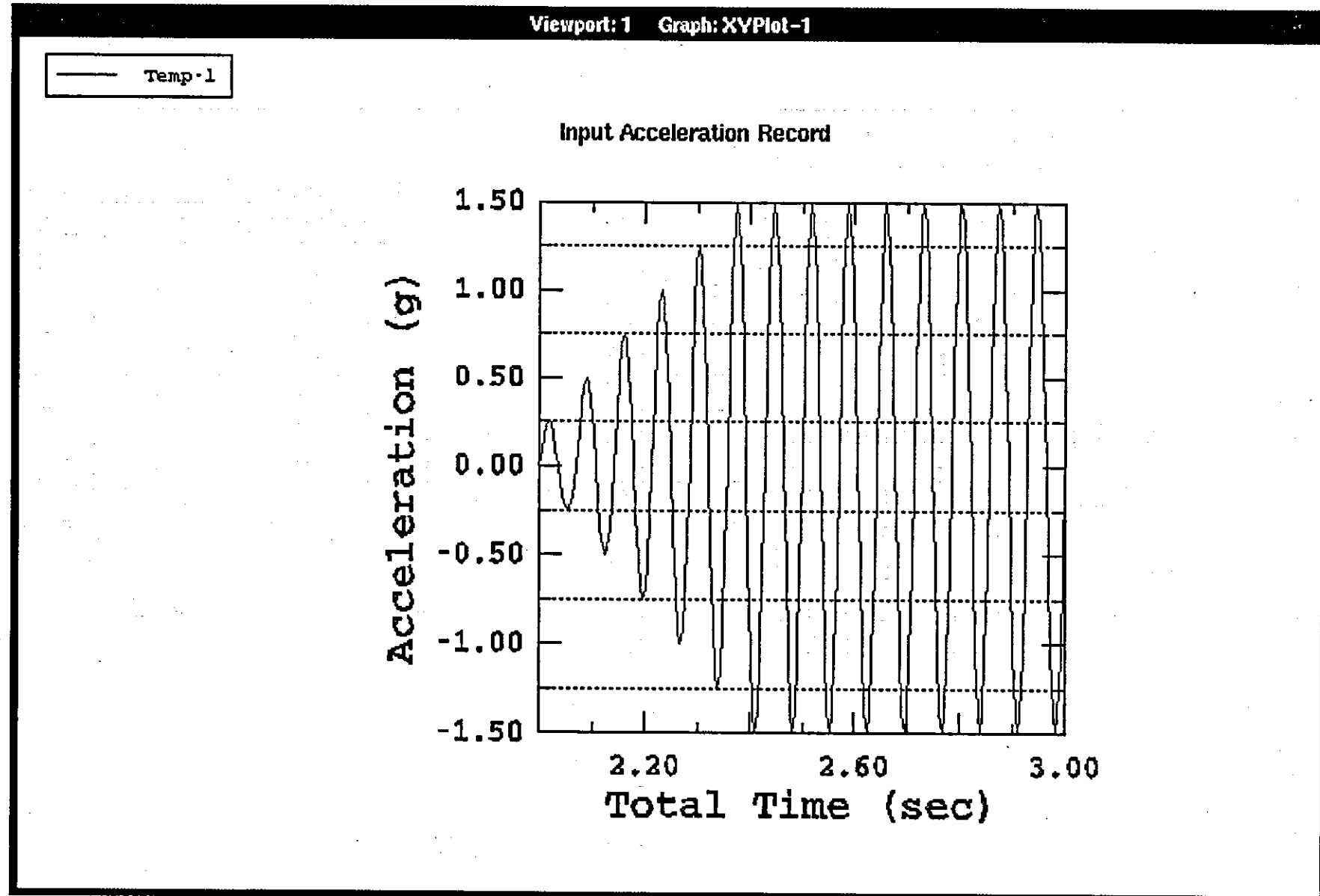


Figure A.11

Input Acceleration Record Used
For The
Nonlinear ABAQUS EXPLICIT Analysis
Model M2/M8

— Input Accelerations (g)

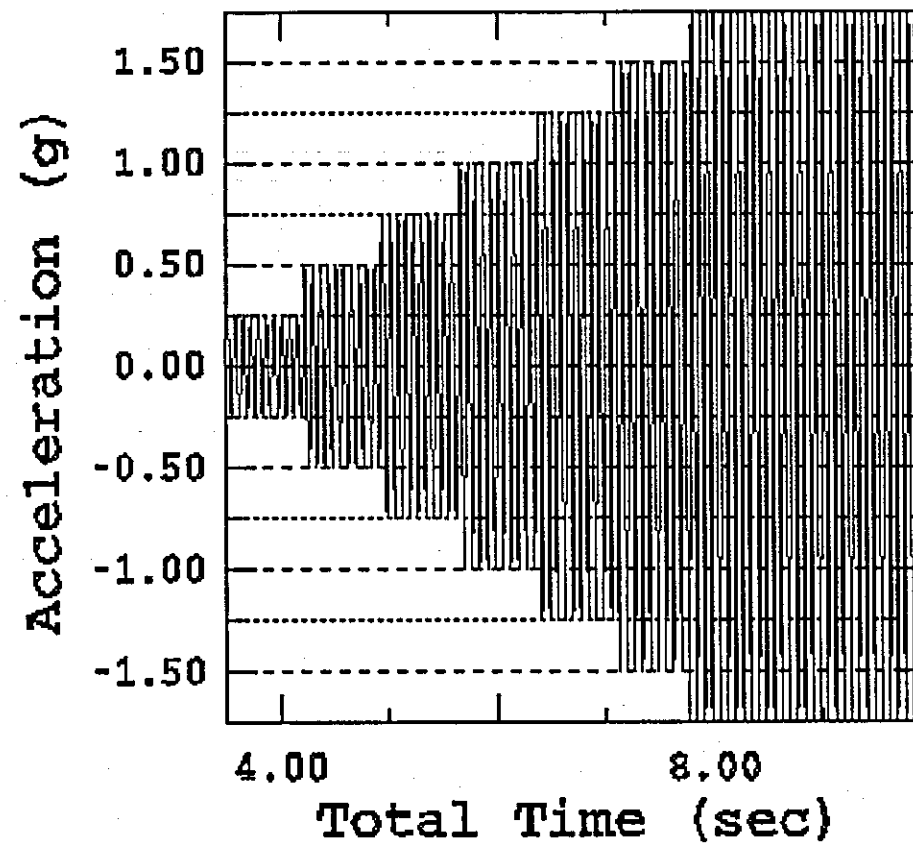


Figure A.12

Appendix B

Material Properties



Mini Dam Materials - Mix M-1 - (3/2/99)

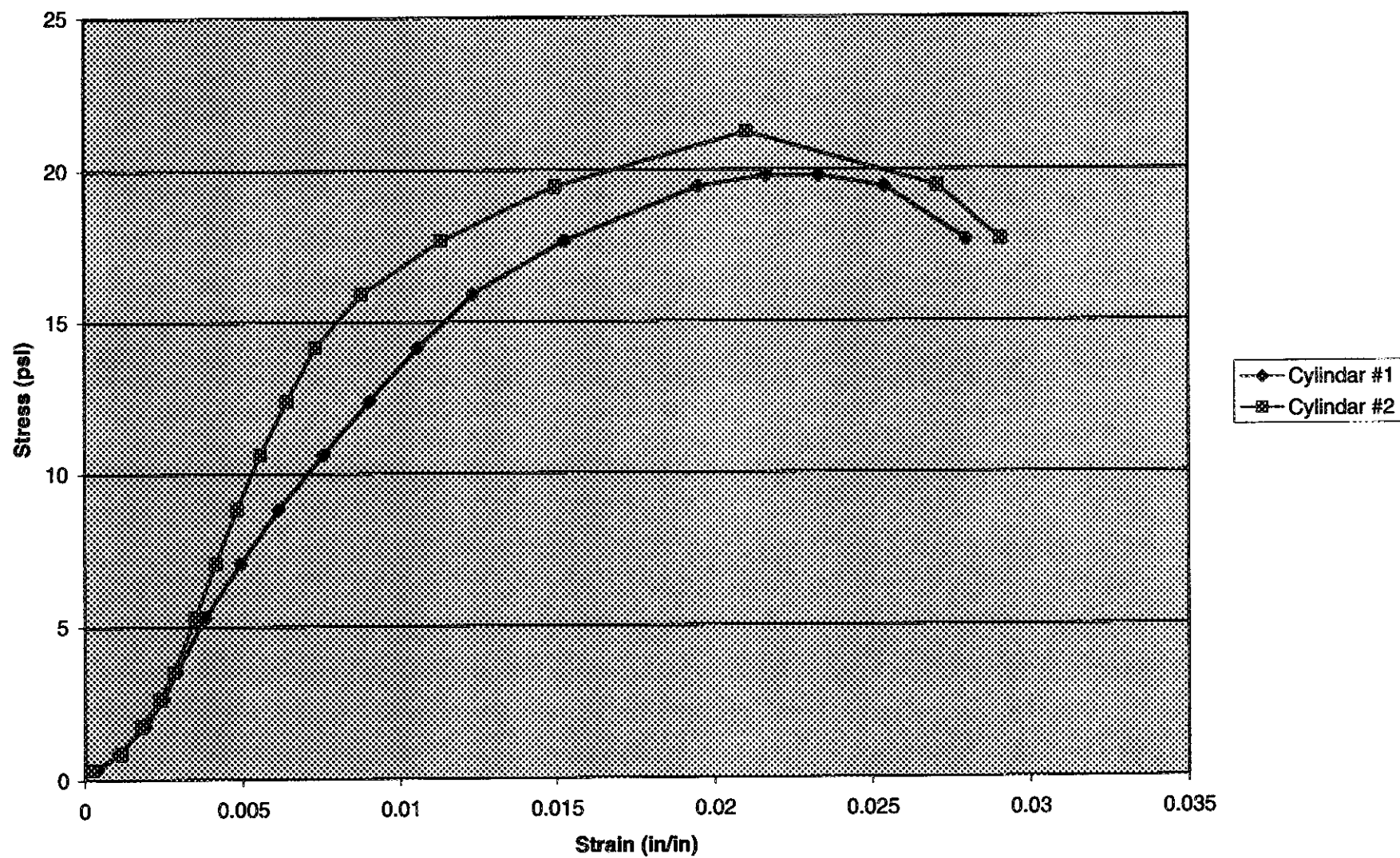


Figure B.10



Mini Dam Materials - Mix M-2 - (3/24/99)

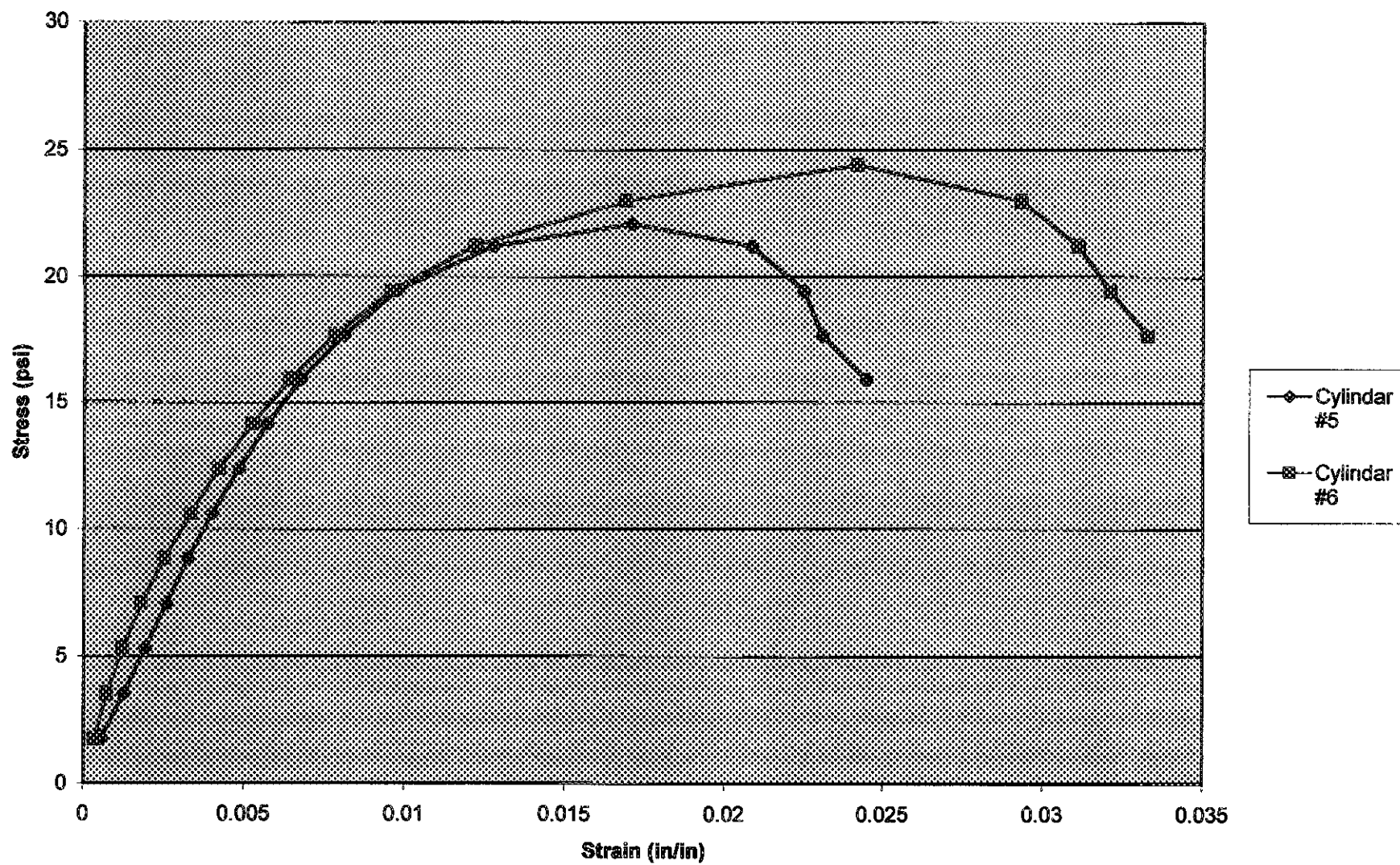


Figure B.13

Mini Dam Materials - M-4 - (7/28/99)

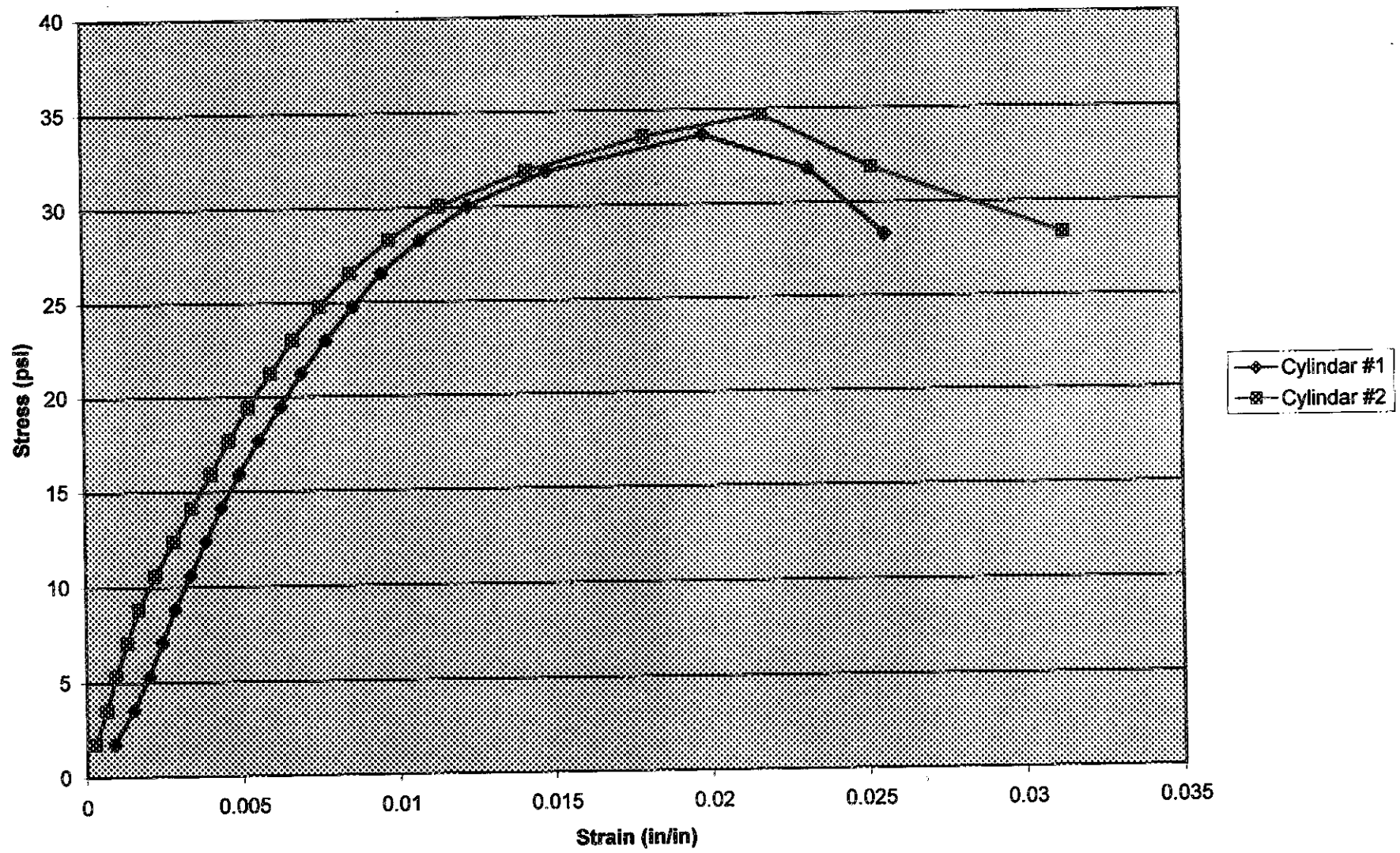


Figure B.16



Mini Dam Materials - Mix M-5 - (8/12/99)

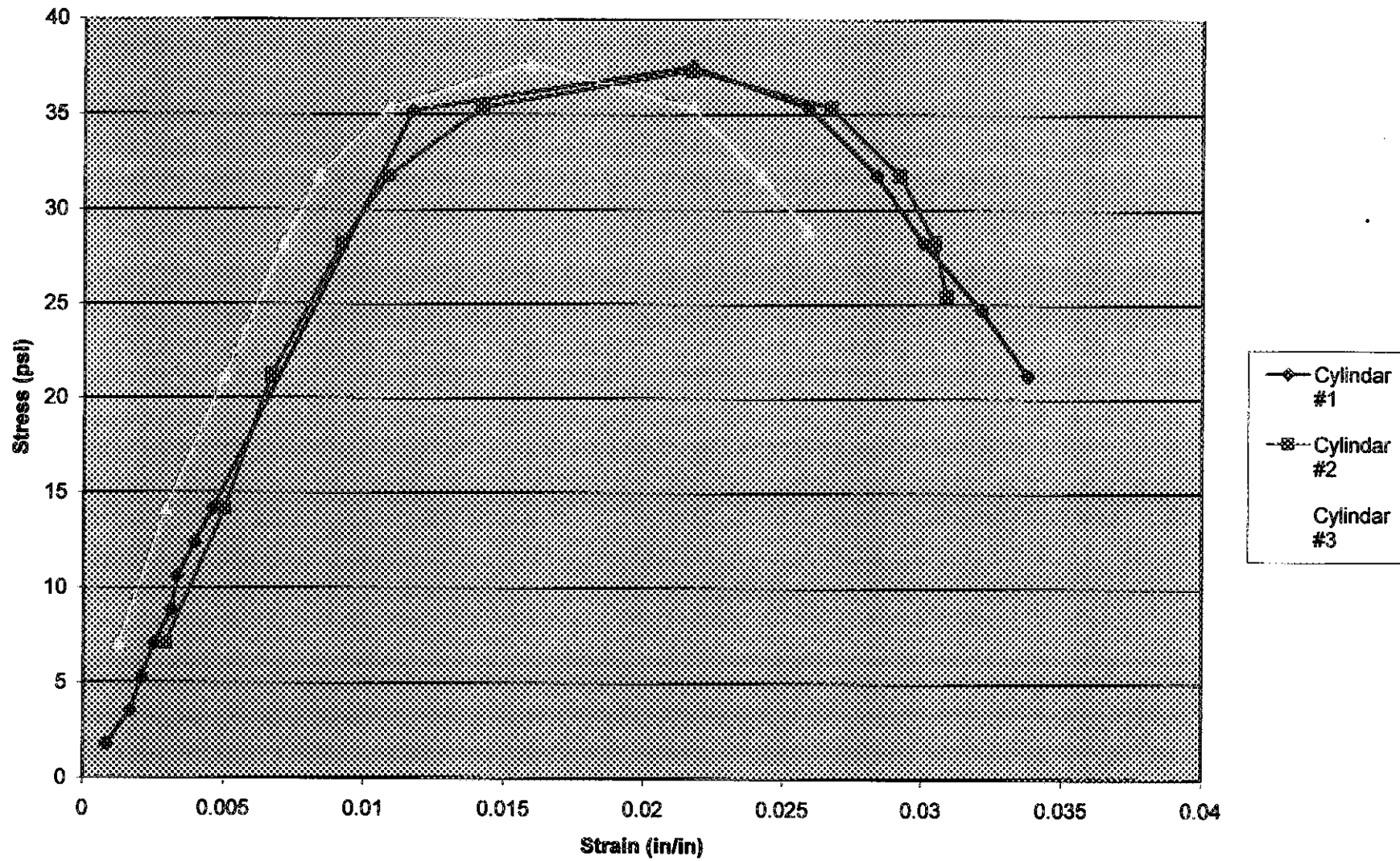


Figure B.20



Mini Dam Materials - M-10 - (7/27/00)

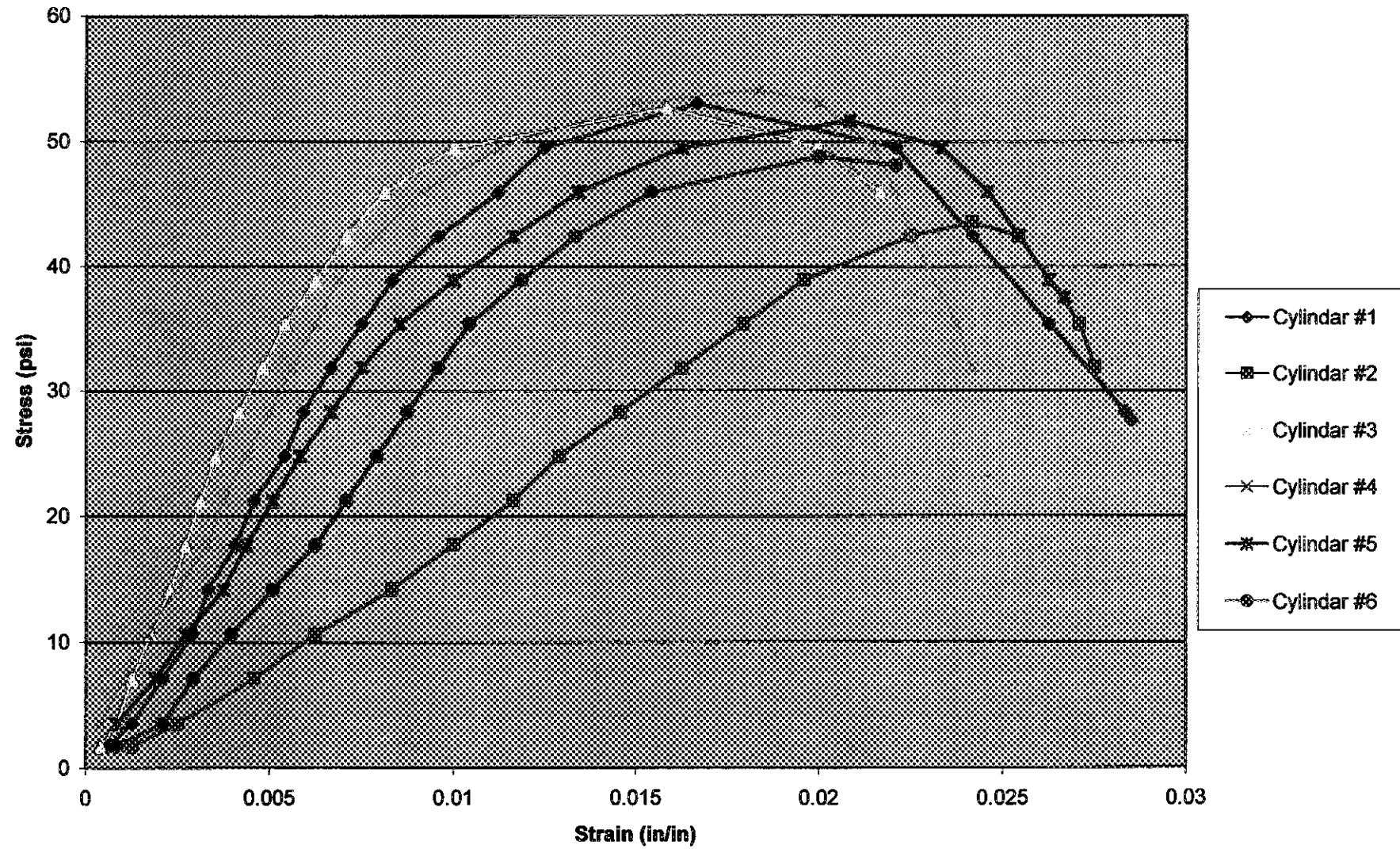


Figure B.24



Mini Dam Materials - M-11 - (8/16/00)

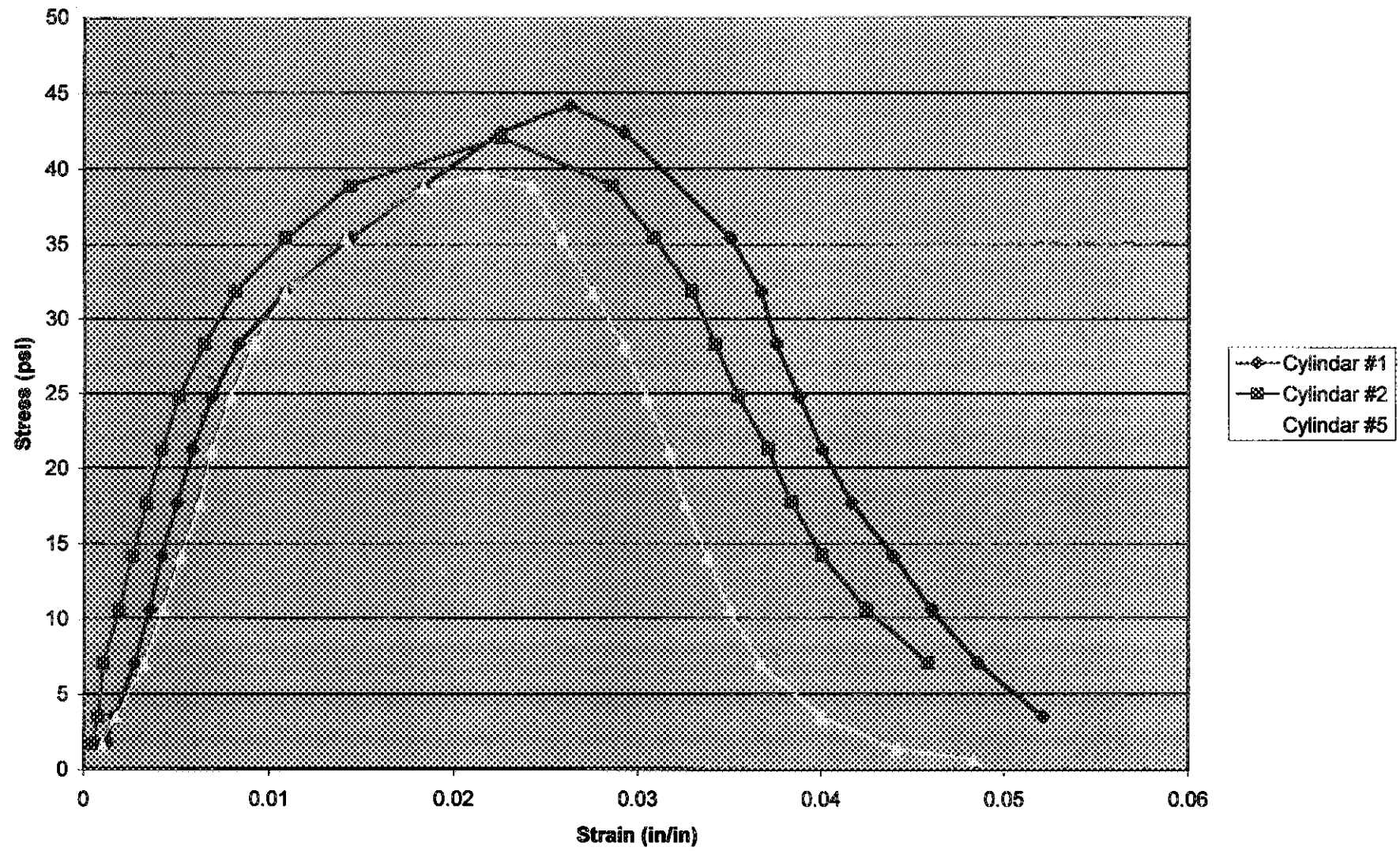


Figure B.27



Mix M-12

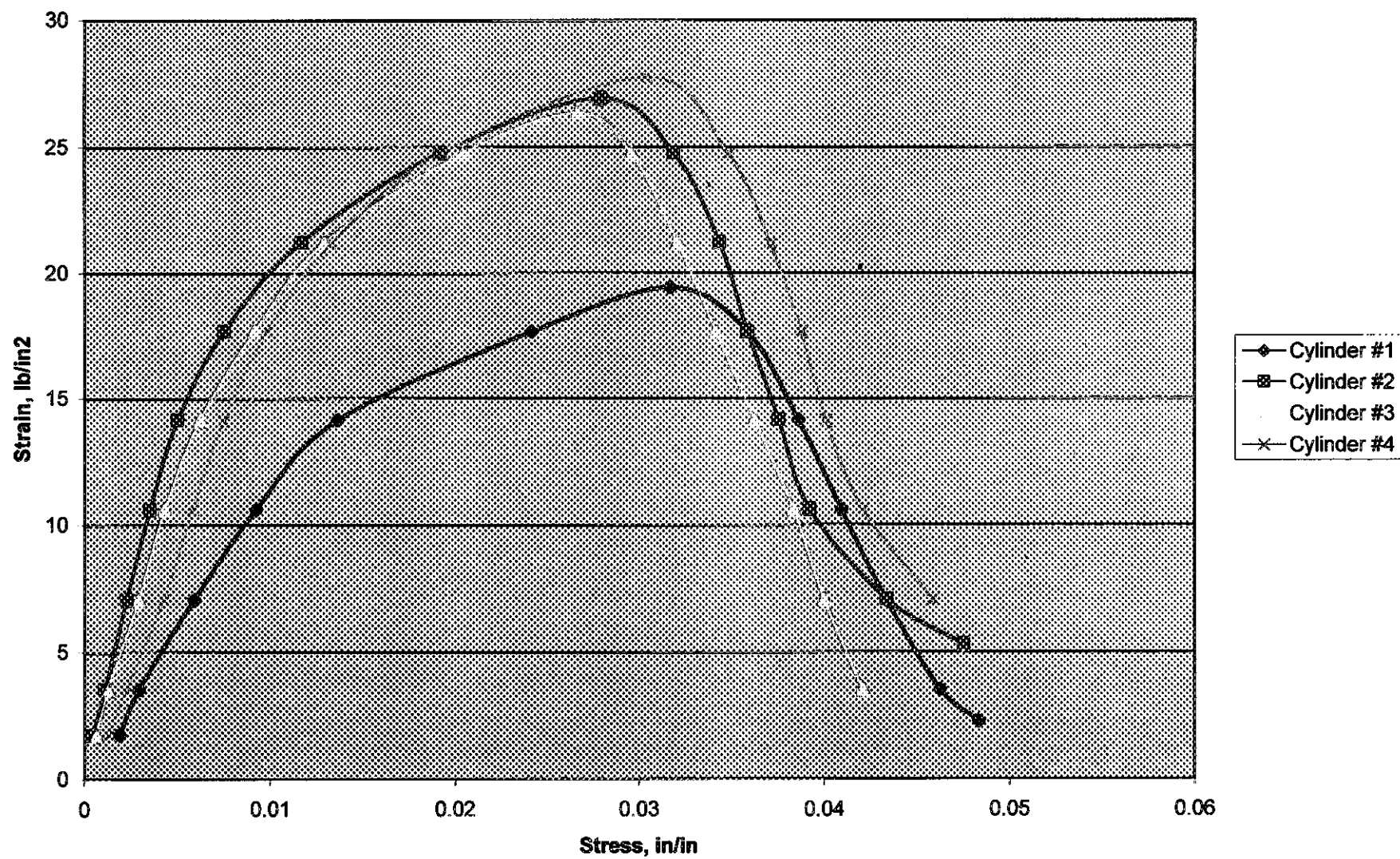


Figure B.30



M-13 6x12 Compression Tests

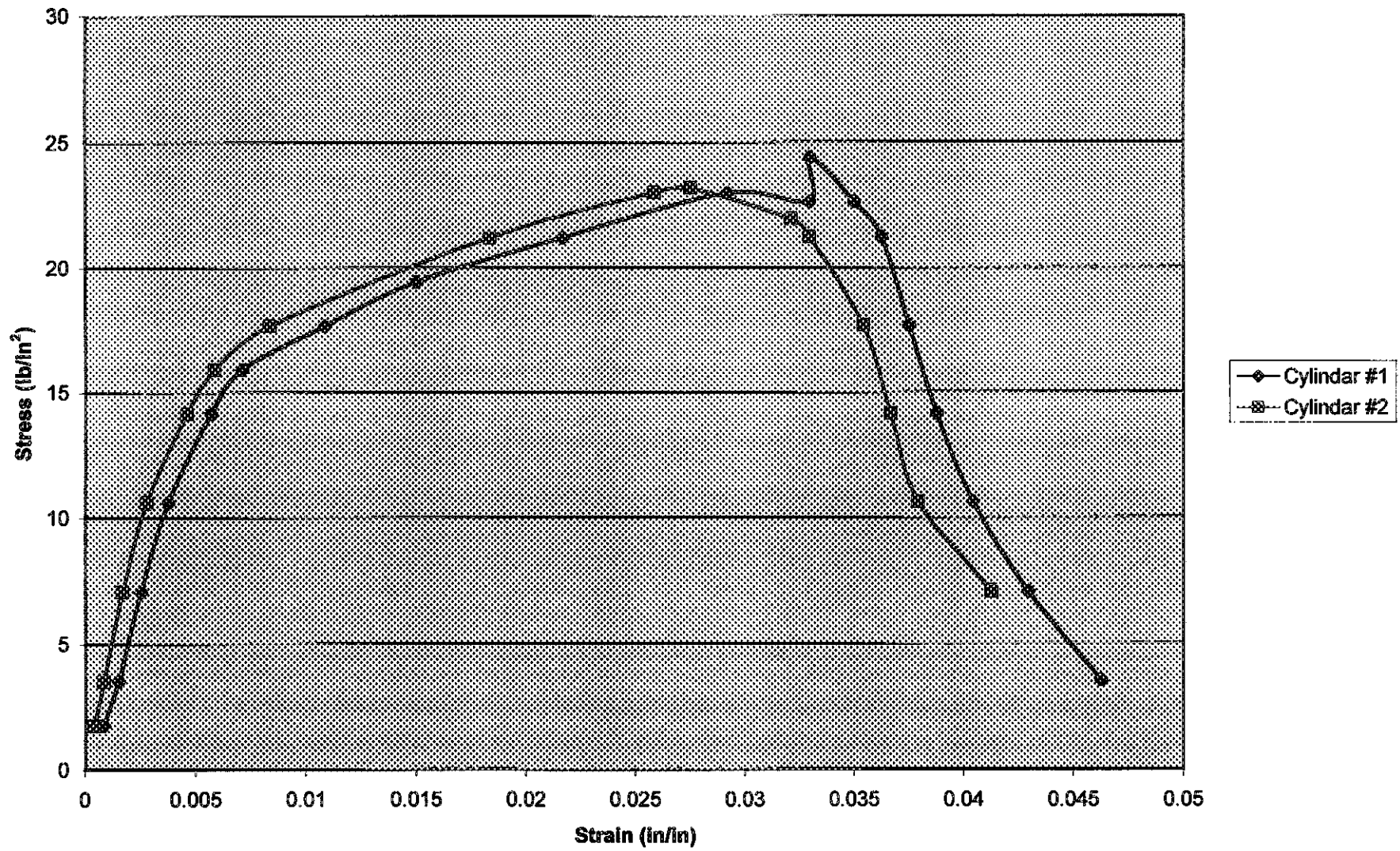


Figure B.32



Mix M-14 6x12 Compression Tests

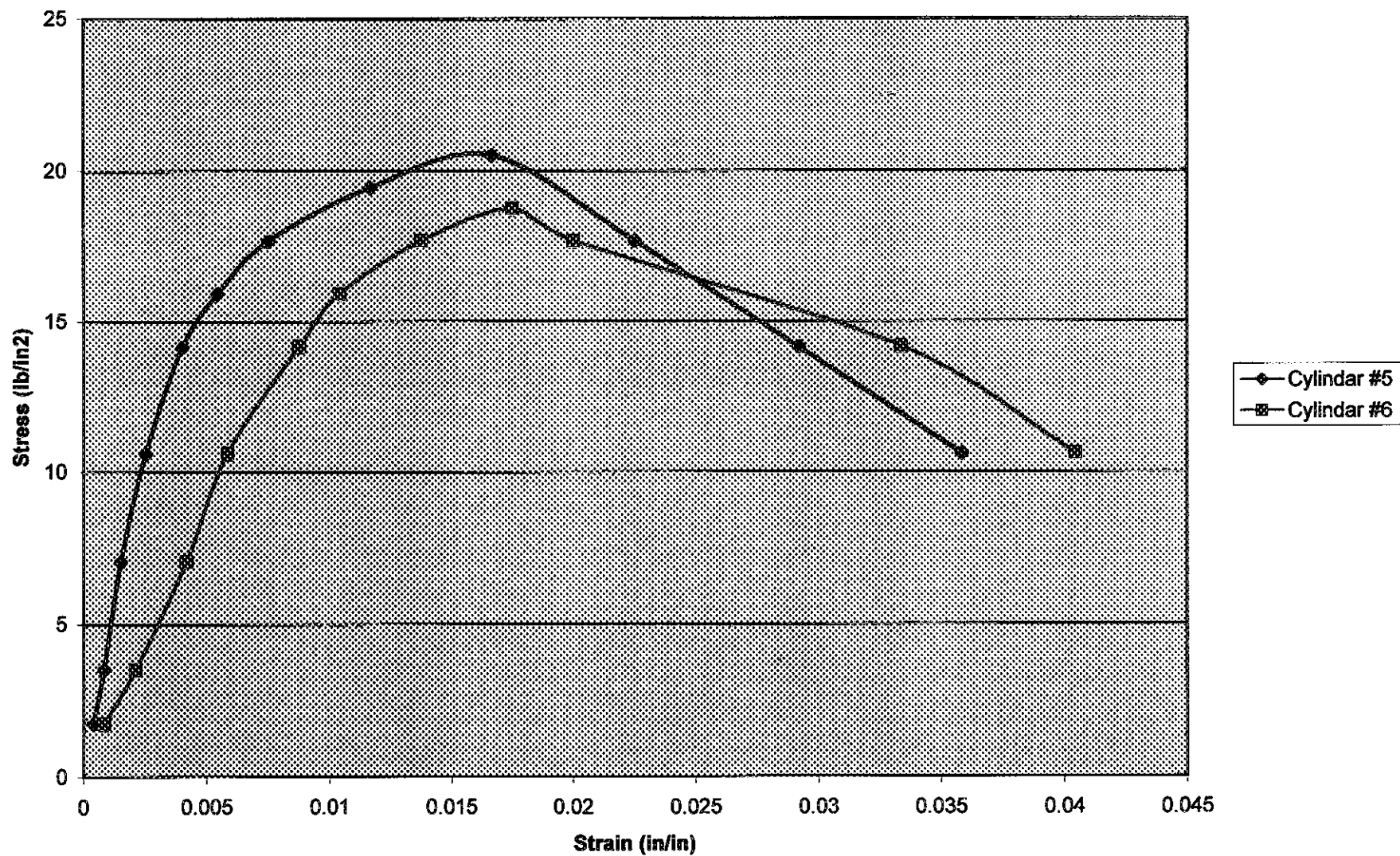


Figure B.34

M-15 6x12 Compressive Stress

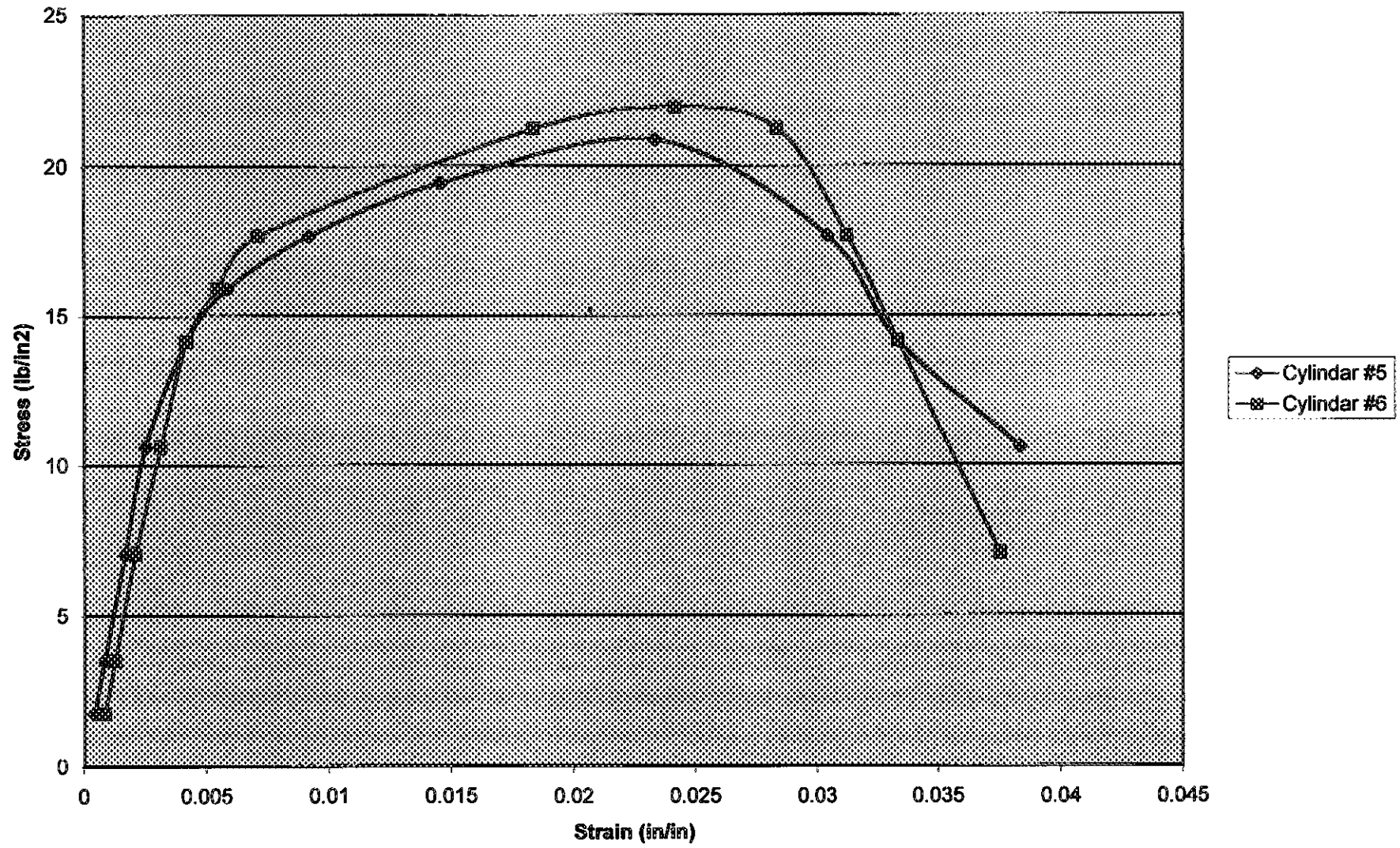


Figure B.36

Appendix C

Results of Preliminary Analyses

Background on ABAQUS/EXPLICIT and ABAQUS/STANDARD

“STANDARD” and “EXPLICIT” are separate versions of the ABAQUS finite element program. ABAQUS/STANDARD is an implicit finite element analysis finite element program. ABAQUS/EXPLICIT is an explicit dynamics finite element program. For both the explicit and the implicit time integration procedures, equilibrium is defined in terms of the external applied forces (P), the internal element forces (I), and the nodal accelerations:

$$M\ddot{v} = P - I$$

where: M is the mass matrix for the discrete model and v is displacement.

In both procedures, the calculations used to determine the internal forces (I) are the same:

- II Compute material point strain increments
- II Compute stresses and state variables from constitutive equations
- II Assemble nodal internal forces, I

However, the calculation of the nodal accelerations differs. The explicit procedure uses a diagonal element mass matrix. The equations of motion are calculated using the central difference integration rule as follows:

- Step 1: The accelerations are calculated at the beginning of the increment. The acceleration at any Node is determined by its mass and the net force acting on it.

$$\frac{d^2}{dt^2}(v) = M^{-1} \cdot (P_t - I_t)$$

- Step 2: Velocities are calculated at half the time increment

$$\frac{d}{dt}v\left(t + \frac{\Delta t}{2}\right) = \left[\frac{d}{dt}v\left(t - \frac{\Delta t}{2}\right)\right] + \left[\frac{[\Delta t(t + \Delta t) + \Delta t_t]}{2} \cdot \frac{d^2}{dt^2}v_t\right] \cdot \frac{d^2}{dt^2}v$$

- Step 3: Displacements at the end of the time increment

$$v(t + \Delta t) = v_t + \Delta t(t + \Delta t) \cdot \frac{d}{dt}v\left(t + \frac{\Delta t}{2}\right)$$

The kinematic state is “explicitly” advanced to time $(t + \Delta t)$ by satisfying equilibrium at time t and using known values of velocity and acceleration from the previous increment. The explicit method requires no tangent stiffness matrix. The explicit procedure is conditionally stable and requires a small time increment.

The implicit procedure uses Newton's method to satisfy equilibrium at the end of the increment and to compute the displacements at time $(t + \Delta t)$. Each Newton iteration in the implicit procedure solves for a correction to the incremental displacements. For each iteration, a set of simultaneous equations must be solved as follows:

$$K_j c_j = P_j - I_j - M_j * \ddot{u}_j$$

where: K is the effective stiffness matrix, (a linear combination of the tangent stiffness and mass matrices for the current iteration (j)), and c is the correction for the current iteration (j) .

The incremental displacements are updated by $\Delta u_{j+1} = \Delta u_j + c_j$. The iterations are continued until a variety of tolerance criteria are satisfied, so the implicit time integration scheme is unconditionally stable and generally uses a much larger time increment than the explicit time integration scheme_[1].

References

- [1] Hibbitt, Karlsson & Sorensen, Inc. *Introduction to ABAQUS/EXPLICIT*, 1996.

Discussion of Results from the Preliminary Studies

Comparison of Analyses with and without a foundation model

The first preliminary study was conducted to determine the effect of removal of the foundation from the finite element model. The models tested in the laboratory were constructed in a concrete block foundation. Originally, the finite element model also included the concrete block foundation. However, when dynamic loads were applied to the original linear elastic monolithic dam model with a foundation model, the analysis required 38 hours to complete 0.34 seconds of the input time history running on a J class HP Workstation. It was determined that if the foundation model were removed, 1.0 second of the input time history could be completed in approximately 8 hours using the same workstation. While the material properties assigned to the dam "concrete" were scaled using similitude properties, the foundation blocks were not scaled.. This resulted in an extremely high dam to foundation modulus ratio. For example, a foundation modulus of 3,000,000 lb/in² combined with a dam modulus of 2,303 lb/in² results in a foundation to dam modulus ratio of 1,302:1. It was felt that laboratory conditions could be modeled using a fixed foundation dam model, and significant solution time could be saved. Linear elastic static, modal, and dynamic analyses of the monolithic model with and without discrete modeling of the foundation were compared to quantify the effect of the removal of the foundation model from the analyses.

Gravity and reservoir loads were applied, followed by a 1 second acceleration input record for the two linear elastic analyses (using ABAQUS/STANDARD), one analysis with and one without a foundation model. The acceleration amplitude was stepped up in 0.25 g increments to 1.5 g. Each amplitude step was applied for one cycle until the 1.5 g amplitude was reached as shown in Appendix B, figure B.9. Displacements, maximum principal stresses, and energy levels were compared to determine the impact of removal of the foundation model.

The resulting displacements were very nearly identical for static loads. The maximum displacement occurring at the dam crest, under gravity load only, was 0.011 inches upstream with or without inclusion of a foundation model. The magnitude and distribution of the maximum principal stresses were also the same. The maximum tension was 0.43 lb/in² in the upper abutments.

Next, the reservoir load was applied, and the dam crest was displaced 0.058 inch downstream, with or without the foundation model. The magnitude and distribution of the maximum principal stresses were the same. A maximum value of 5.7 lb/in² tension occurred in a small triangular element at the base of the dam. Most of the upstream face was in compression.

Contour plots of displacement caused by static loads with and without the foundation model are shown in figures C.1 and C.3. Contour plots of the maximum principal stresses caused by static loads with and without the foundation model are shown in figures C.2 and C.4.

Figures C.5 and C.6 show energy versus time plots for the gravity and reservoir load steps resulting from both analyses. Curves shown in red are from the analysis with a foundation model, and curves shown in green are from the analysis without a foundation model. Artificial strain energy, strain energy, and total energy are shown in these plots. The measured energy levels from the two analyses were very nearly identical. The magnitude of the artificial energy level was very low, indicating that hourglassing (the development of spurious modes) in the

reduced integration linear elements was not significant in either model. Likewise, the magnitude of the total energy remained low, indicating that the equilibrium was reached successfully in each analysis.

The results of the modal analyses with and without the foundation model were nearly identical, as shown in the table C.1. The first three mode shapes for these two models are shown in figure C.7 and C.8.

Table C.1.—Modal analysis results with and without a foundation model

Mode	Natural Frequencies of Dam and Foundation System (cycles/second)	Natural Frequencies of Fixed Dam (cycles/second)
1	9.6421	9.6427
2	11.2020	11.2030
3	14.8180	14.8190

Although the same input record, output specifications, and total step times were applied to each of these dynamic analyses, the automatic increment size, determined internally by the computer program, was not the same. This resulted in very few common times at which output from the dynamic analyses could be directly compared. Results were available at 2.3227 seconds total time from the analysis without a foundation model and at 2.3228 seconds from the analysis with a foundation model, so these times were used for comparison of contour plots. Figure C.9 shows the absolute displacement contour plots at these times. The contour plot shows that the distribution of absolute displacement was very similar in the two analyses. Figure C.10 shows a time history plot of displacement at the dam crest at the center of the arch for both of these analyses. The time history plot shows that at the dam crest the displacement magnitude, relative to the dam base, is very nearly the same throughout the dynamic loading. The analysis that included a foundation model required time increments to as low as 0.0005 seconds near each of the input acceleration peaks, but the analysis that used fixed boundary conditions on the dam model never used time increments below 0.0040 seconds. The analysis without a foundation model may not have recorded the absolute peak values; therefore, the differences in the displacement from the two analysis could be less than the small differences shown in figure C.10 (less than or equal to 0.1 inch). Figure C.11 shows the maximum principal stress contour plots at 2.3227 seconds and 2.3228 seconds in the respective analyses. In both analyses (with and without a foundation model) the maximum tensions developed at the dam crest, on the downstream face, at the maximum section. When a foundation model was included in the analysis, the maximum principal stress magnitude was 23 lb/in²; when the foundation model was not included in the analysis the maximum principal stress magnitude was 18 lb/in². The stress distribution was also very similar in the two analyses.

Figure C.12 shows energy versus time plots for the dynamic load resulting from both analyses. Artificial strain energy, kinetic energy, and total energy are shown in these plots. Curves shown in red are from the analysis with a foundation model, while curves shown in green are from the analysis without a foundation model. Data available only for the first 0.34 seconds of the acceleration record from the analysis with a foundation model because of previously discussed time constraints. The analysis with a foundation model was terminated after 8 hours, after completing 0.94 seconds of the input acceleration record. The magnitude of the artificial energy was somewhat higher when the foundation was included in the analysis, but remained low in

comparison to the kinetic energy level for either analysis. The total energy curves were nearly identical within the time range where data from both analyses was available.

Kinetic energy levels increased much more rapidly when the foundation model was included in the analysis. All the energy curves show energy for the whole model, so the higher kinetic energy values for the analyses without a foundation indicate that kinetic energy was absorbed by the foundation.

Comparison of STANDARD and EXPLICIT Linear Elastic Analyses

The second preliminary study was conducted to select the most appropriate version of ABAQUS for use in the remainder of this study. There are two versions of the ABAQUS finite element program available: ABAQUS/EXPLICIT and ABAQUS/STANDARD. Preliminary linear elastic analyses of the monolithic dam model were completed using both versions of the ABAQUS program. Results were compared to determine if a preferred version could be identified and to verify that each version of the program would produce the same linear elastic results. Static and dynamic analyses were completed using each version; modal analyses can be completed only in the ABAQUS/STANDARD version.

Gravity and reservoir loads were applied, followed by a one second acceleration input record for these two linear elastic analyses. One analysis was performed using the STANDARD version of the ABAQUS finite element code, and the other analysis was completed using the EXPLICIT version of the ABAQUS finite element code. The acceleration amplitude was stepped up in .25 g increments to 01.5 g. Each amplitude step was applied for a duration of one cycle. This input record is shown in Appendix B, figure B.9. Displacements, maximum principal stresses, energy levels, and accelerations at selected nodes were compared.

The resulting displacements were very nearly the same for static loads. The maximum displacement at the dam crest, under gravity load only, was 0.011 inches upstream for both the STANDARD and the EXPLICIT analyses. The magnitude and distribution of the maximum principal stresses were also the same; the maximum value was 0.43 lb/in² tension occurring in the upper abutments. The reservoir load was applied in the next load step, was causing the dam crest to displace to a position 0.058 inches downstream from its original position. The magnitude and distribution of the maximum principal stresses varied somewhat between the two analyses. The maximum values, which occurred in small triangular elements at the base of the dam on the upstream face, were 5.7 lb/in² and 3.7 lb/in² tension from the STANDARD and EXPLICIT analyses, respectively. But most of the dam was in compression, and values were very similar for the two analyses. Contour plots of displacements and maximum principal stress resulting from static loads from STANDARD and EXPLICIT linear elastic analysis are shown in Figures C.13 through C.16.

Figures C.17 and C.18 show energy versus time plots resulting from both analyses during application of the static loads. Curves shown in red are from the EXPLICIT analysis. Artificial strain energy, strain energy, kinetic energy, and total energy are shown in these plots. The strain energy curve for the static loads from the two analyses were very nearly identical. The total energy curve from the STANDARD analysis, although still small in comparison to other energy levels, was significantly larger than the values obtained from the EXPLICIT analysis. This indicates that a more complete energy balance was obtained using the EXPLICIT version of the ABAQUS code. However, the kinetic energy should be zero or nearly zero during the static load steps. This was the case in the STANDARD analysis, but not in the EXPLICIT analysis. In the EXPLICIT analysis, the largest values 0.00006 for the gravity load and 0.002 for the reservoir load) were generated at the beginning of the respective load step. The kinetic energy appears to be damping out during the load step, but does not return to zero. If additional time were allowed following each load step, this residual kinetic energy evident in the EXPLICIT analysis would probably be damped out completely. The magnitude of the artificial energy level is also higher in the EXPLICIT analysis, and it increases during the load steps. At the end of the gravity load step, the artificial strain energy from the EXPLICIT analysis was 0.006 and from the STANDARD analysis it was 0.002. At the end of the reservoir load step, the artificial strain

energy from the EXPLICIT analysis was 0.0175 and from the STANDARD analysis it was only 0.005.

Since the automatic increment size was not the same in these two analyses, there are only a few points where output is available at the same times for comparison. Results were available at 2.88 seconds total time from both analyses, and this time was selected for comparison. Figure C.19 shows the absolute displacement contour plots at this time. When the EXPLICIT analysis code was used, the maximum displacement at the dam crest relative to the base at 2.88 seconds was 1.1 inches downstream, and the maximum relative displacement that occurred in the STANDARD analysis was 0.6 inch downstream. The distribution of displacement was very similar in the two analyses. Figure C.20 shows the maximum principal stress contour plots at these times. In both analyses, the maximum tensions developed near the dam crest on the upstream face. The maximum principal stress magnitude from the STANDARD analysis was 40 lb/in², and the maximum principal stress magnitude from the EXPLICIT analysis was only 12 lb/in². Although stress distribution was similar in the two analyses, the stress magnitudes were much higher in the STANDARD analysis.

Figures C.17 and C.18 also show energy versus time plots for the dynamic loading from both analyses. Curves shown in red are from the EXPLICIT analysis and curves shown in green are from the STANDARD analysis. The magnitude of the artificial energy was significantly higher in the EXPLICIT analysis, indicating that significantly more energy was required to control hourglassing in the EXPLICIT analysis than in the STANDARD analysis. The total energy curve was significantly higher in the STANDARD analysis, indicating that the energy balance was better maintained during the dynamic loading in the EXPLICIT analysis. Kinetic energy levels increased exponentially in the STANDARD analysis during dynamic loading, even after the input acceleration curve reached a constant 1.5 g peak amplitude. The kinetic energy curve resulting from the EXPLICIT analysis stepped up in magnitude as the input record stepped up in amplitude and then leveled off once the input acceleration amplitude reached 1.5 g. The internal strain energy also appears to be increasing exponentially during dynamic loading in the STANDARD analysis, but it levels off at a much lower level in the EXPLICIT analysis.

Figures A.1 and A.2 show the locations of six accelerometers and two LVDT's (instrumentation to measure displacements), which were placed on the downstream face of the dam during the shake table tests in the laboratory, and the corresponding Node numbers at which acceleration time histories were recorded in the analyses. Figure C.21 shows the accelerations generated at the dam crest, on the crown cantilever (Node 373), from both the STANDARD and EXPLICIT analyses, the analysis input acceleration record on the right half of the page. The corresponding laboratory acceleration records (Model M2: Accel #8 and #2) are shown on the left half of the page. Figures C.22 through C.24 show the acceleration time histories at the remaining five output location from both the STANDARD and EXPLICIT analyses, along with the corresponding Model M2 laboratory measurements.

In these plots, it is evident that, while the accelerations generated from the EXPLICIT analysis tend to reach a consistent amplitude once the input acceleration has reached 1.5 g, the accelerations generated from the STANDARD analysis continue to increase in amplitude throughout the acceleration loading history. These are linear elastic analyses, so the material properties used were identical, including the material damping coefficients. The continued amplification of the acceleration amplitudes seen in the STANDARD analysis results are not reasonable and appear to indicate some inaccuracy in the STANDARD analysis. The accelerations resulting from the EXPLICIT analysis were similar, although somewhat larger in amplitude at the higher elevations, to the measured accelerations. It is also notable that in the

analyses the acceleration amplitudes tend to be amplified with increased elevation on the dam, but the acceleration time histories measured for Model M2 in the laboratory do not show any significant amplitude magnification with elevation. For example, for points located on the crown cantilever, the acceleration amplitude generated from the EXPLICIT analysis at the dam crest (Node 373) was approximately 7.5 g, and the accelerations generated one-fourth of the way from the base of the dam (Node 4682) were approximately 2.5 g, while the input acceleration amplitude was 1.5 g. The measured acceleration amplitude at the dam crest (Accel 8) was approximately 2.5 g, the measured acceleration amplitude one fourth the way up from the dam base (Accel 5) was approximately 2.5 g, and the input acceleration amplitude was 1.5 g. It was also apparent that accelerometer #9 was not functioning during the shake test for monolithic model M2. The complete acceleration records measured during the shake table test of monolithic model M2 are shown in figure F.35.

Comparison of Displacements With & Without Foundation Model

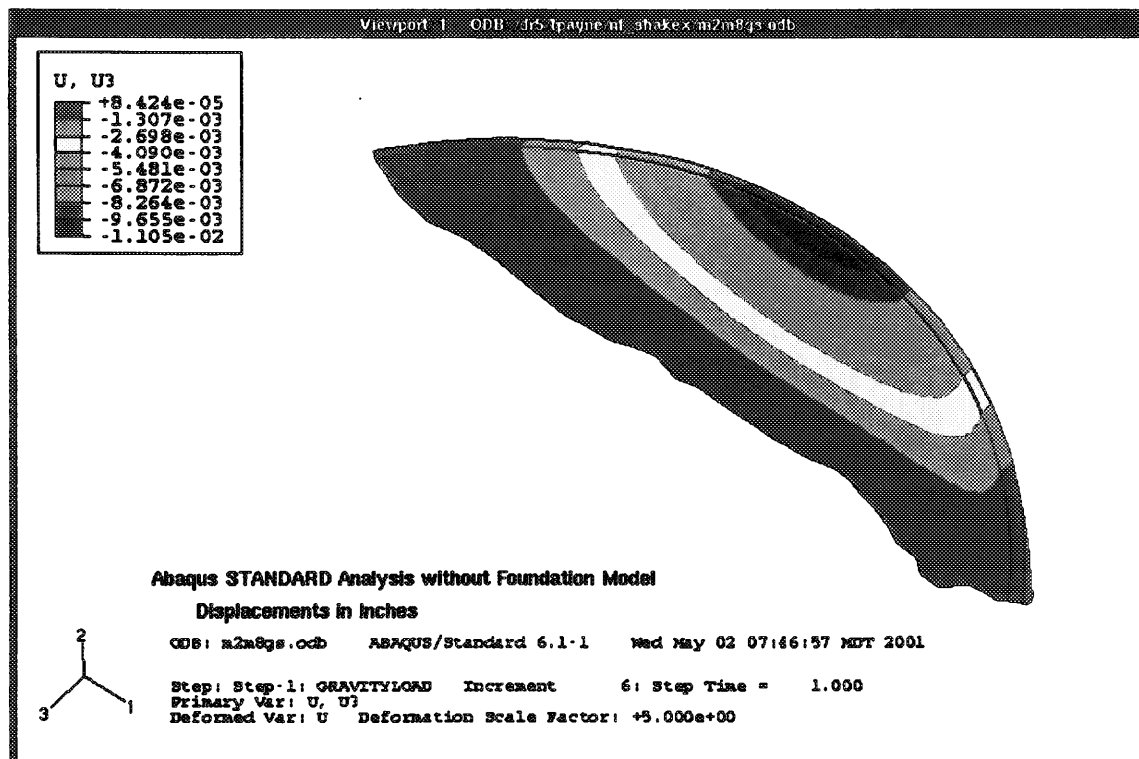
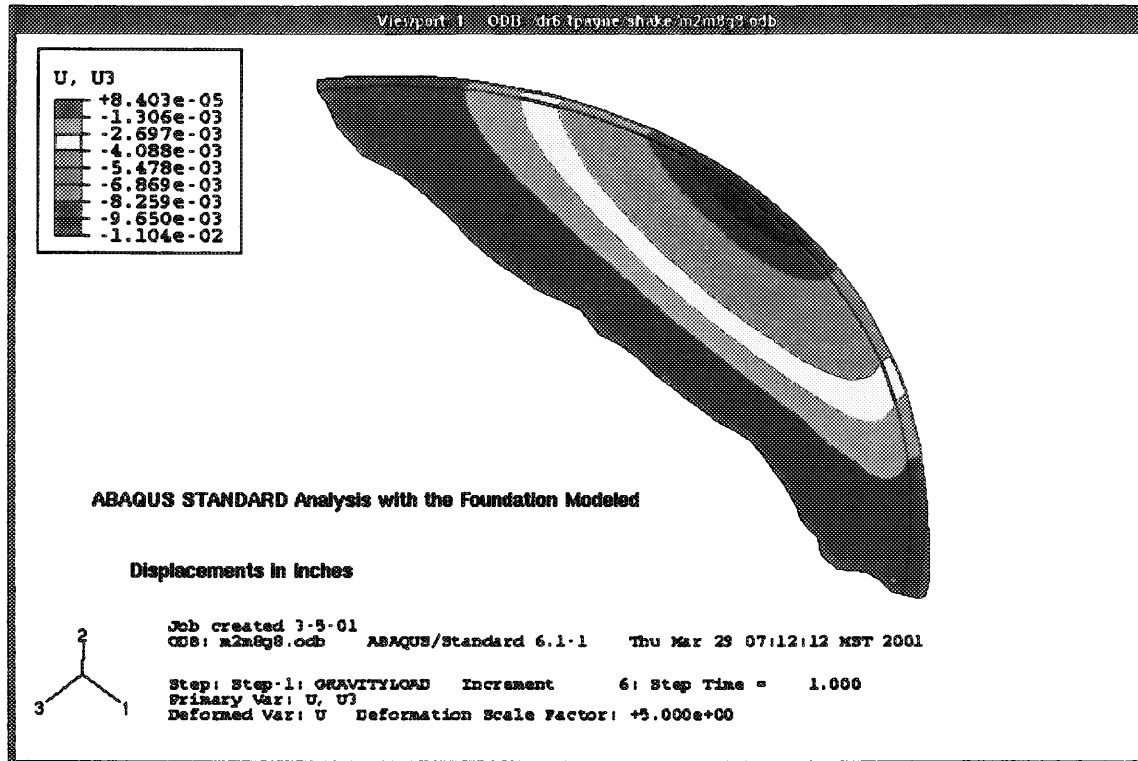


Figure C.1

Comparison of Max. Principal Stresses With & Without Foundation Model

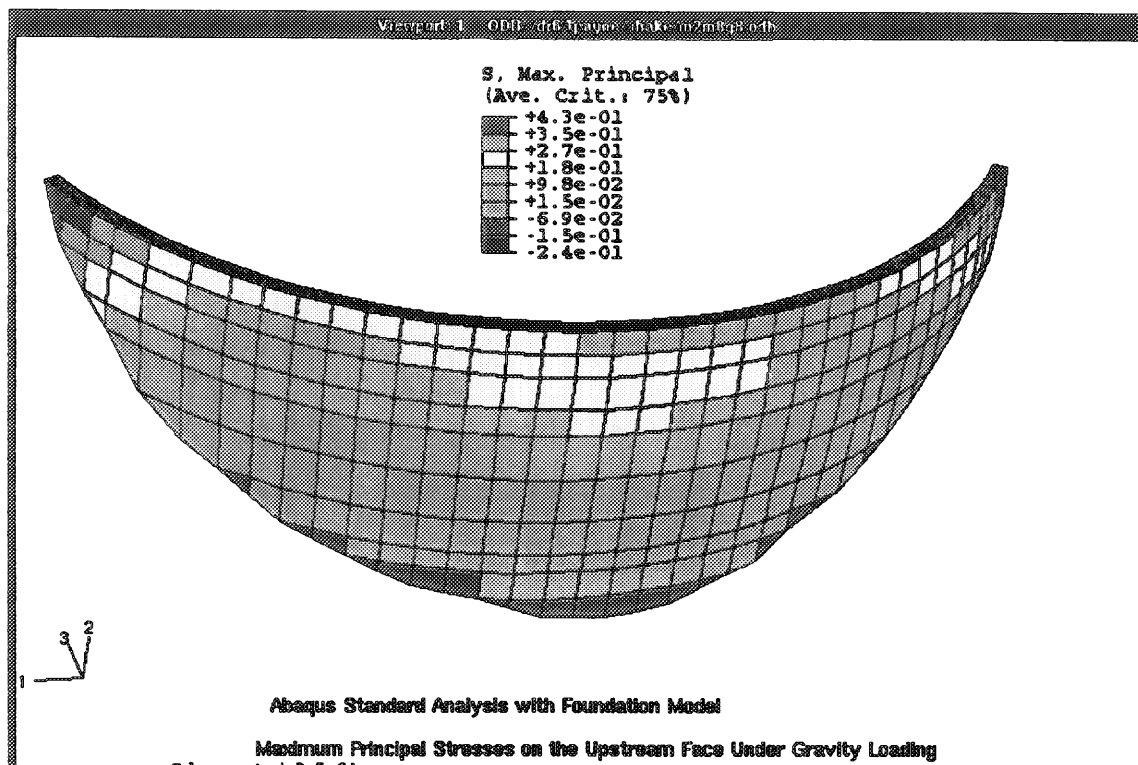
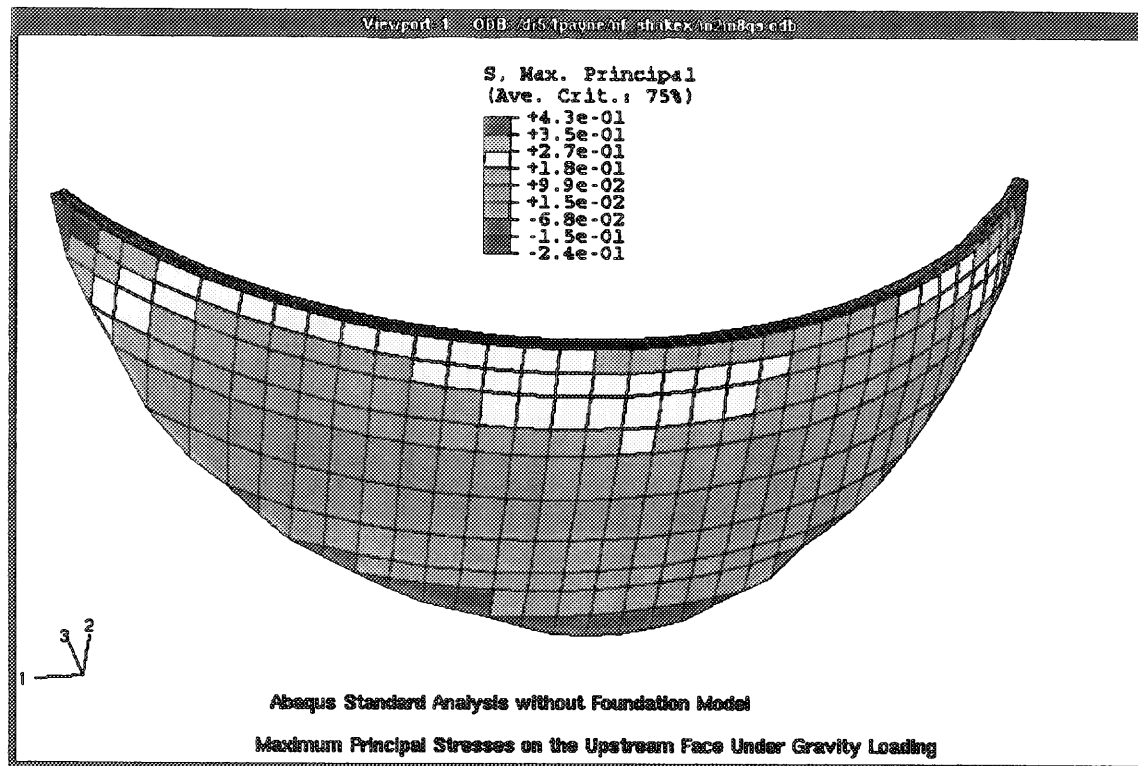


Figure C.2

Comparison of Displacements

Models With & Without Foundations

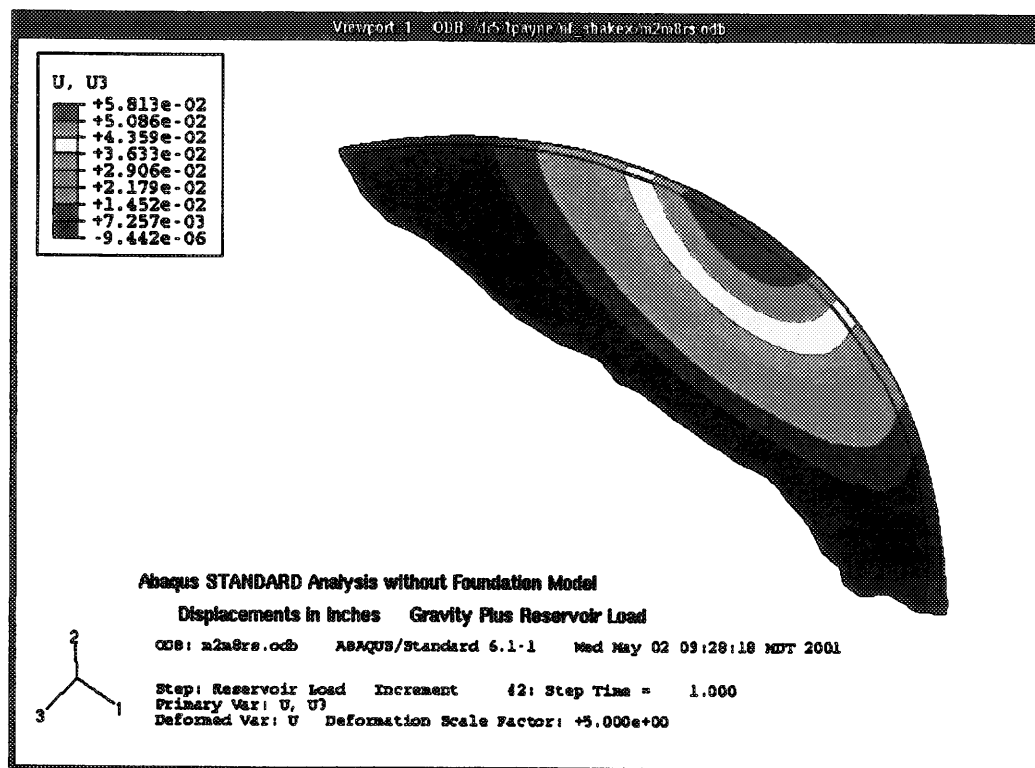
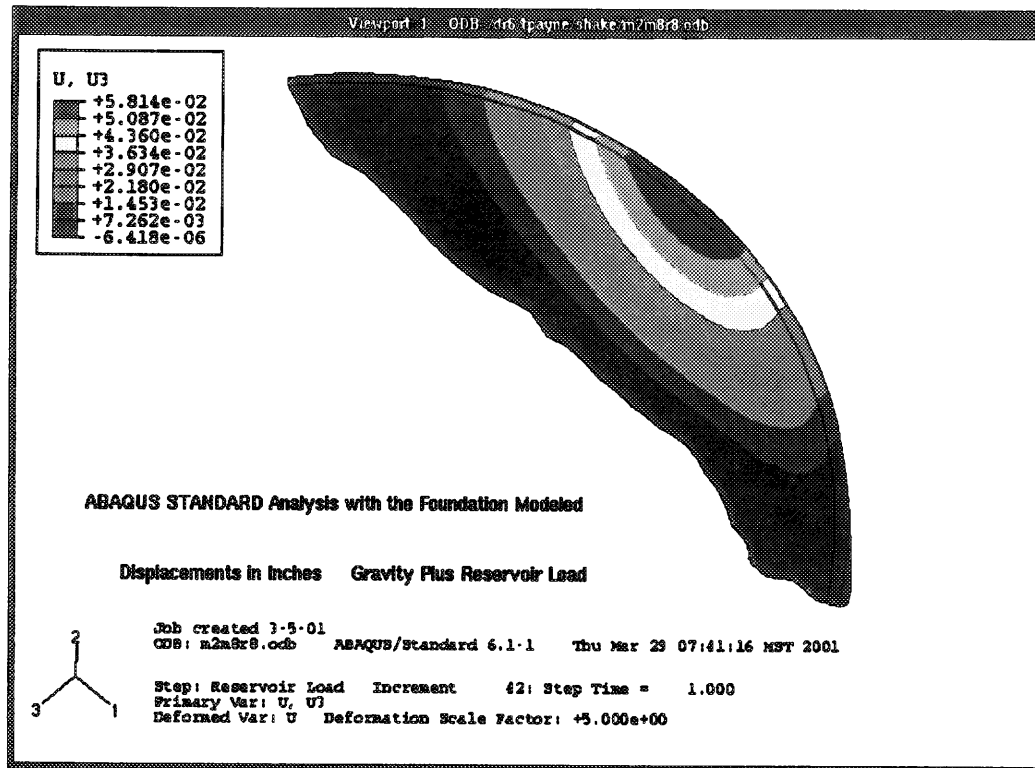


Figure C.3

Comparison of Max. Principal Stresses With & Without Foundation Model

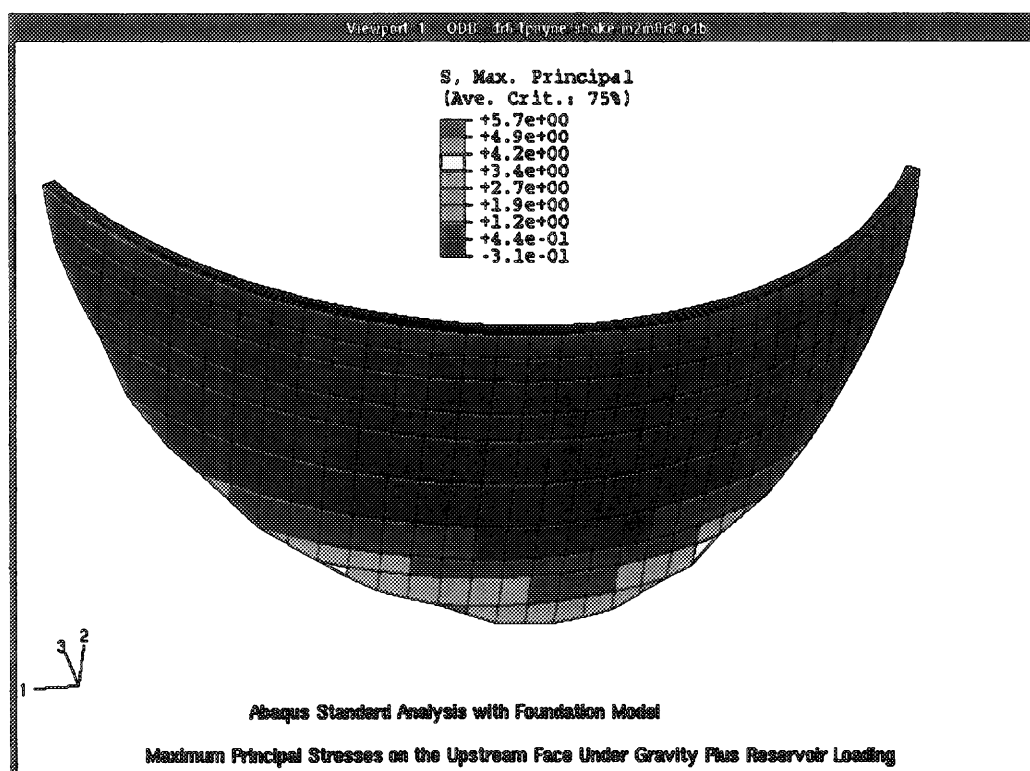
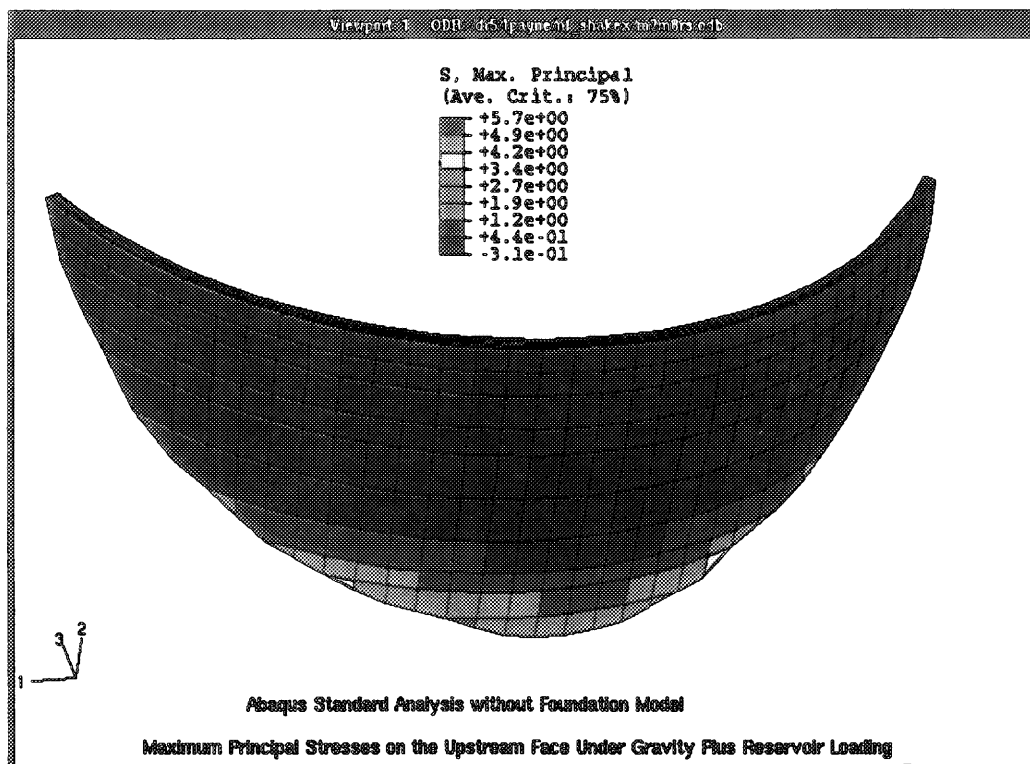
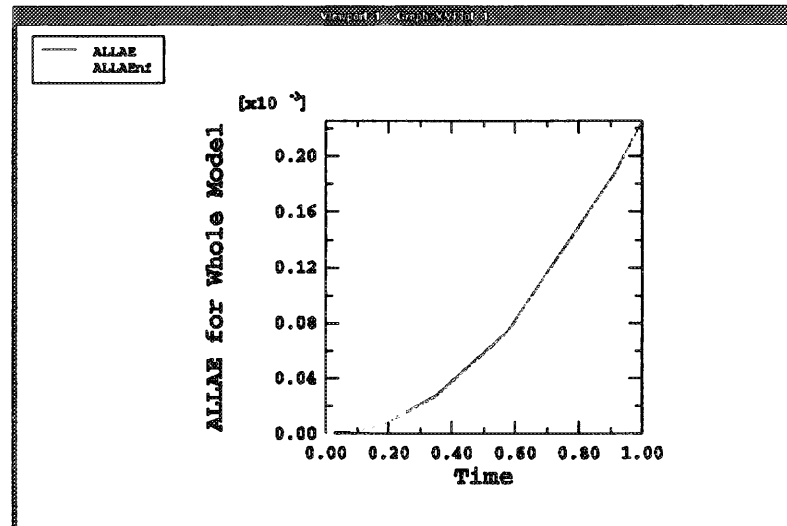


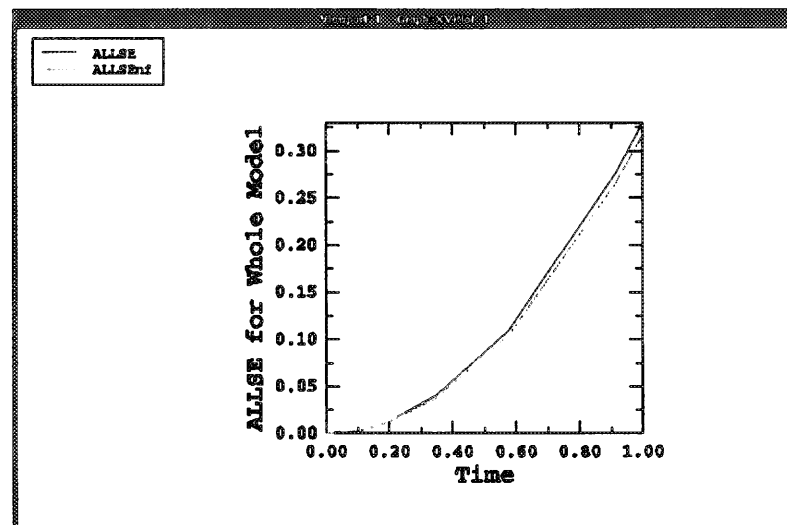
Figure C.4

Comparison of Energy Levels ABAQUS STANDARD Analyses Gravity Load With and With Foundation Models

Artificial
 Strain
 Energy



Strain
 Energy



Total
 Energy

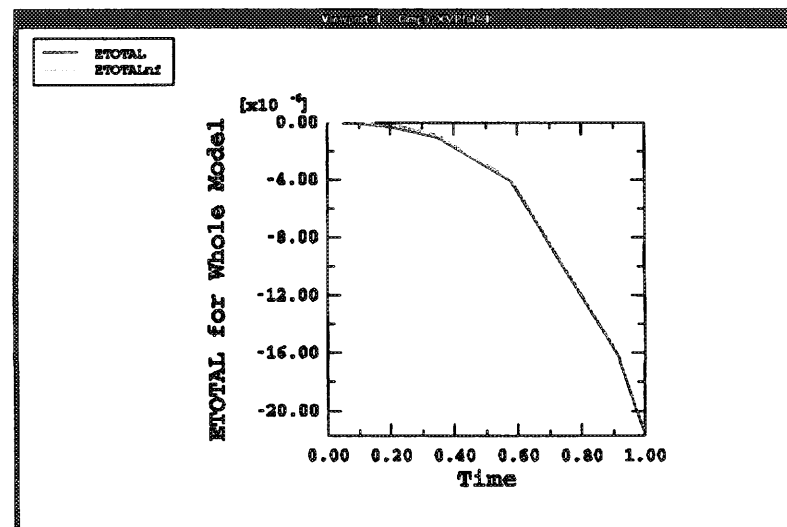
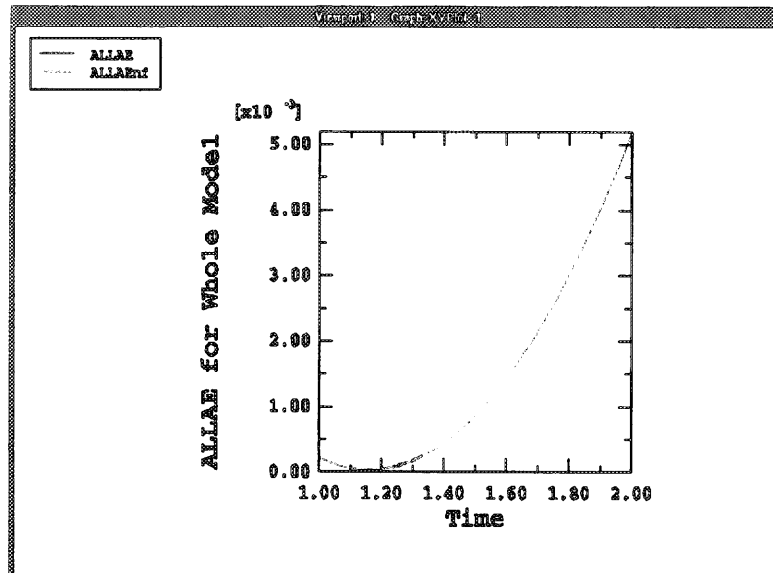


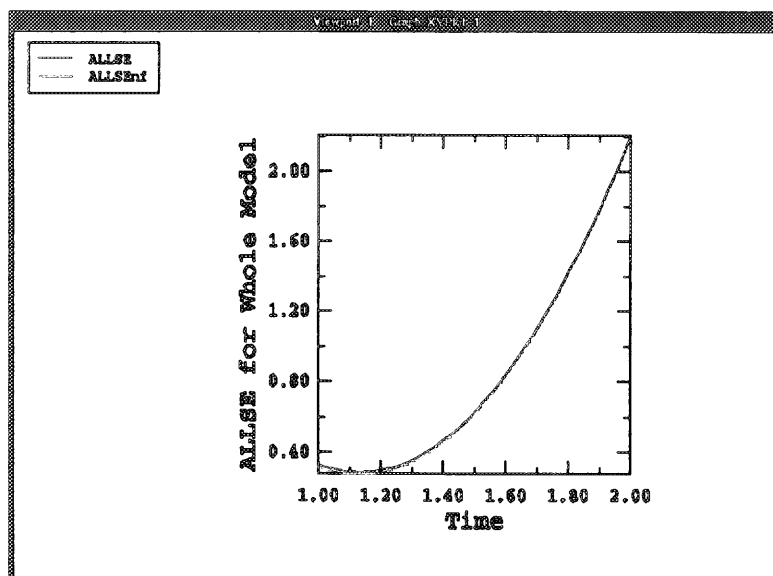
Figure C.5

Comparison of Energy Levels
 ABAQUS STANDARD Analyses
 Gravity + Reservoir loads
 With and Without A Foundation Model

Artificial
 Strain
 Energy



Strain
 Energy



Total
 Energy

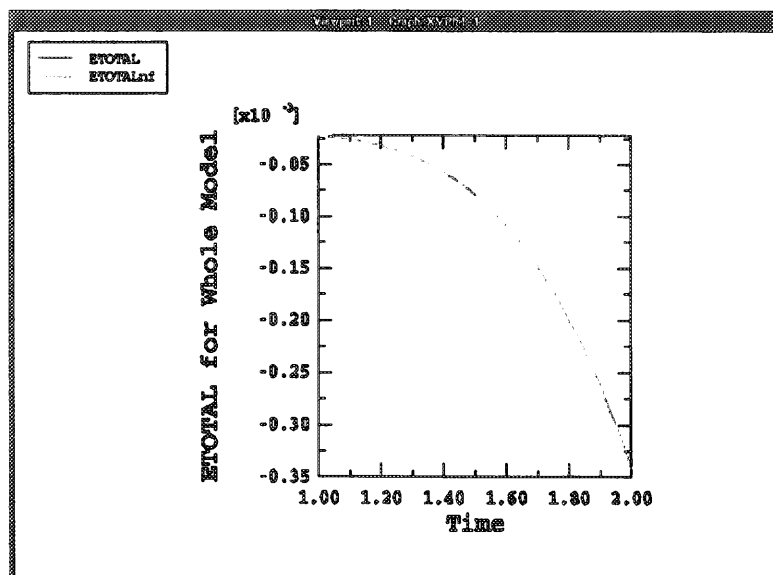


Figure C.6

Modal Analyses



Preliminary Analyses With Out Foundation Model

Modal Analyses

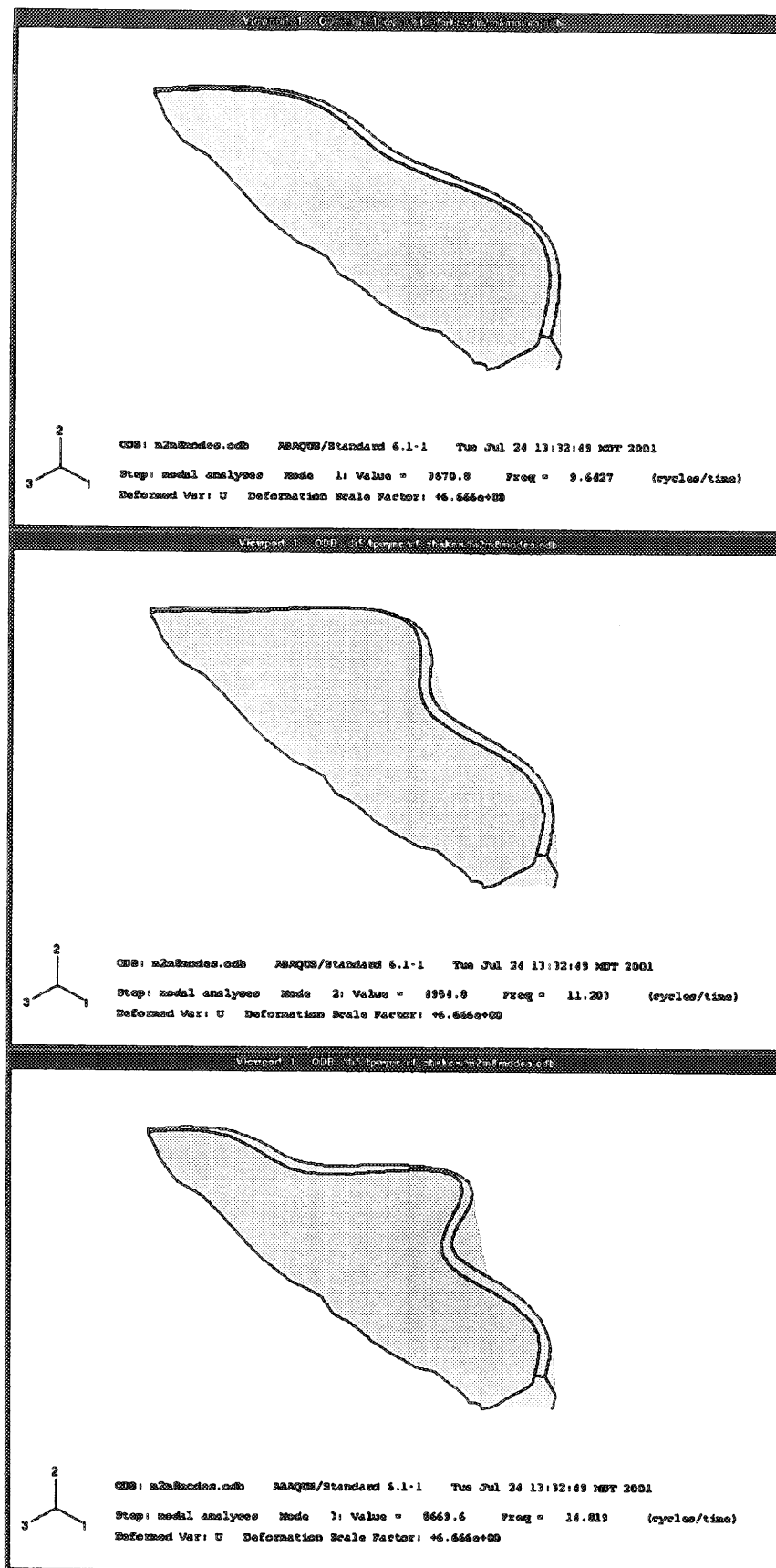


Figure C.8

Comparison of Displacements With & Without Foundation Models

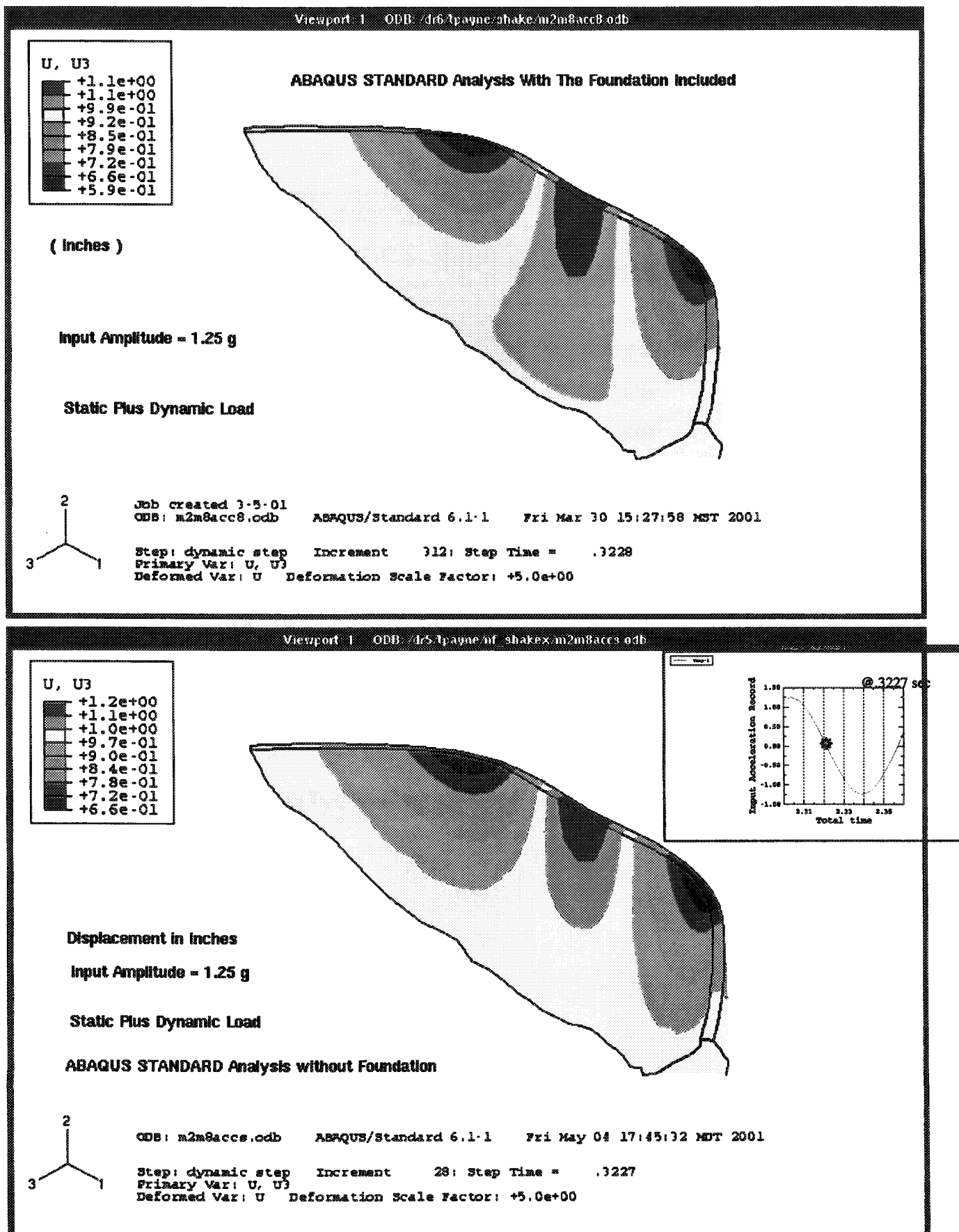


Figure C.9

Upstream/Downstream Relative Displacement Time Histories at the Dam Crest With and without a Foundation Model Included in the Dynamic analysis

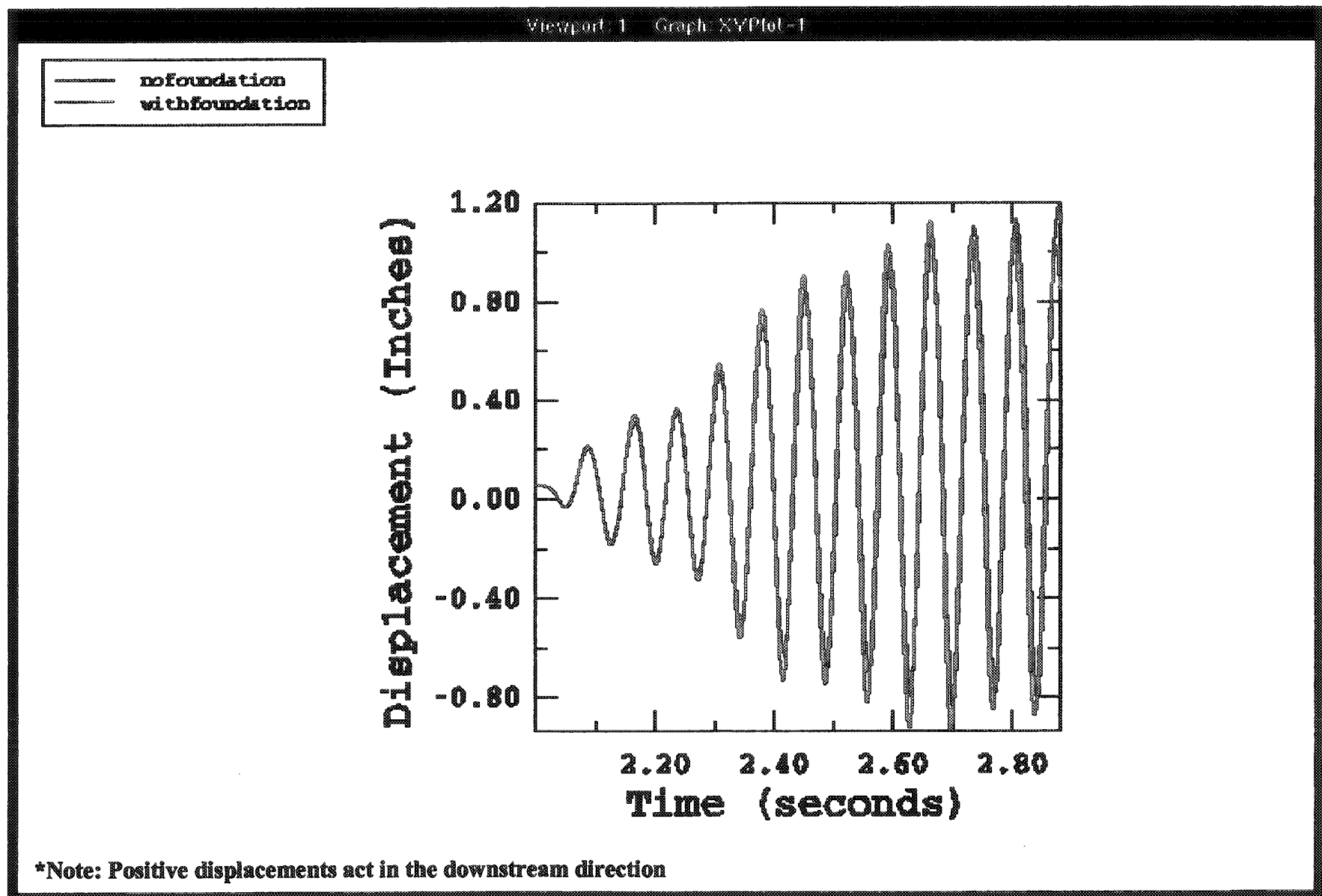


Figure C.10

Comparison of Max. Principal Stresses With & Without Foundation Models

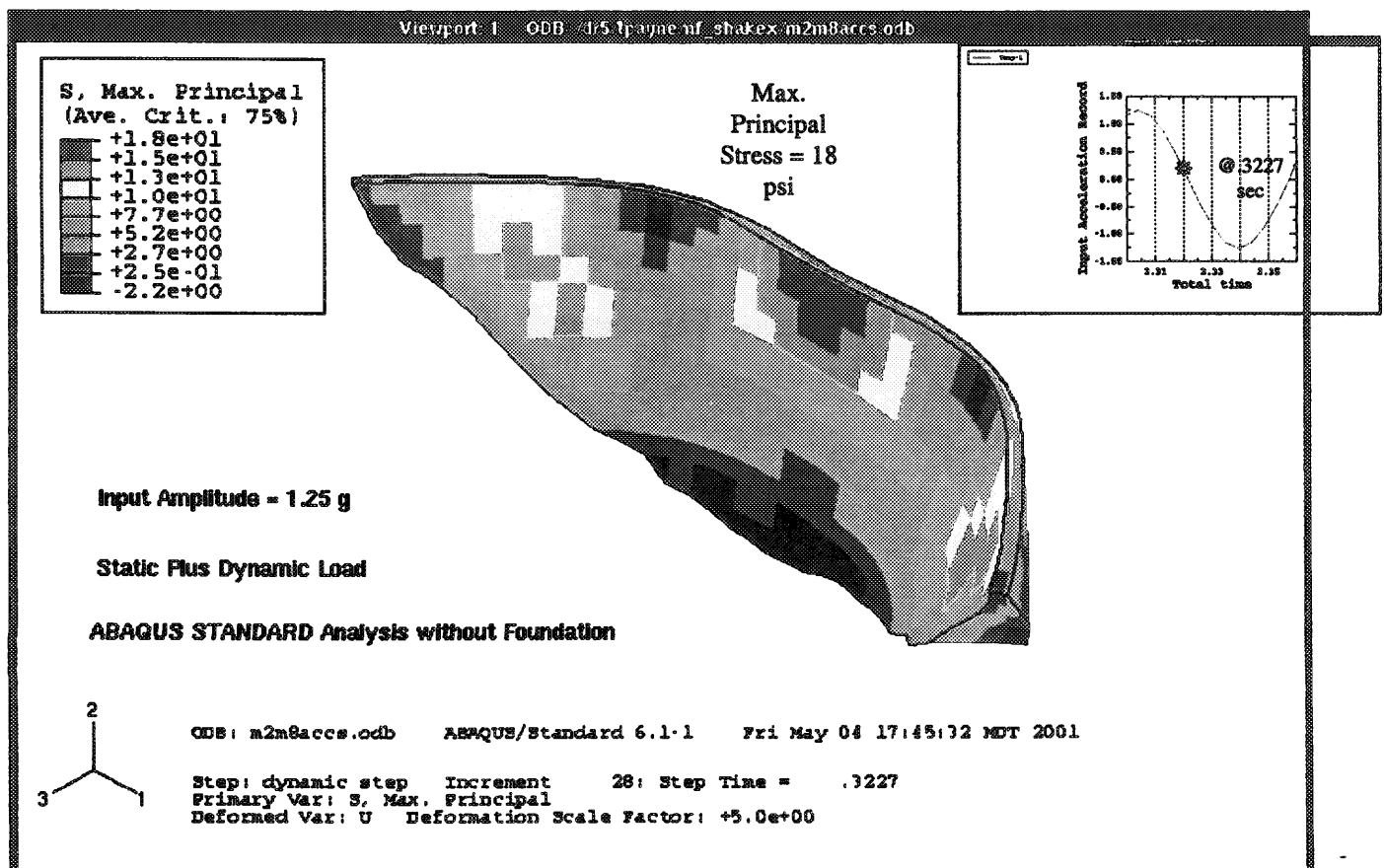
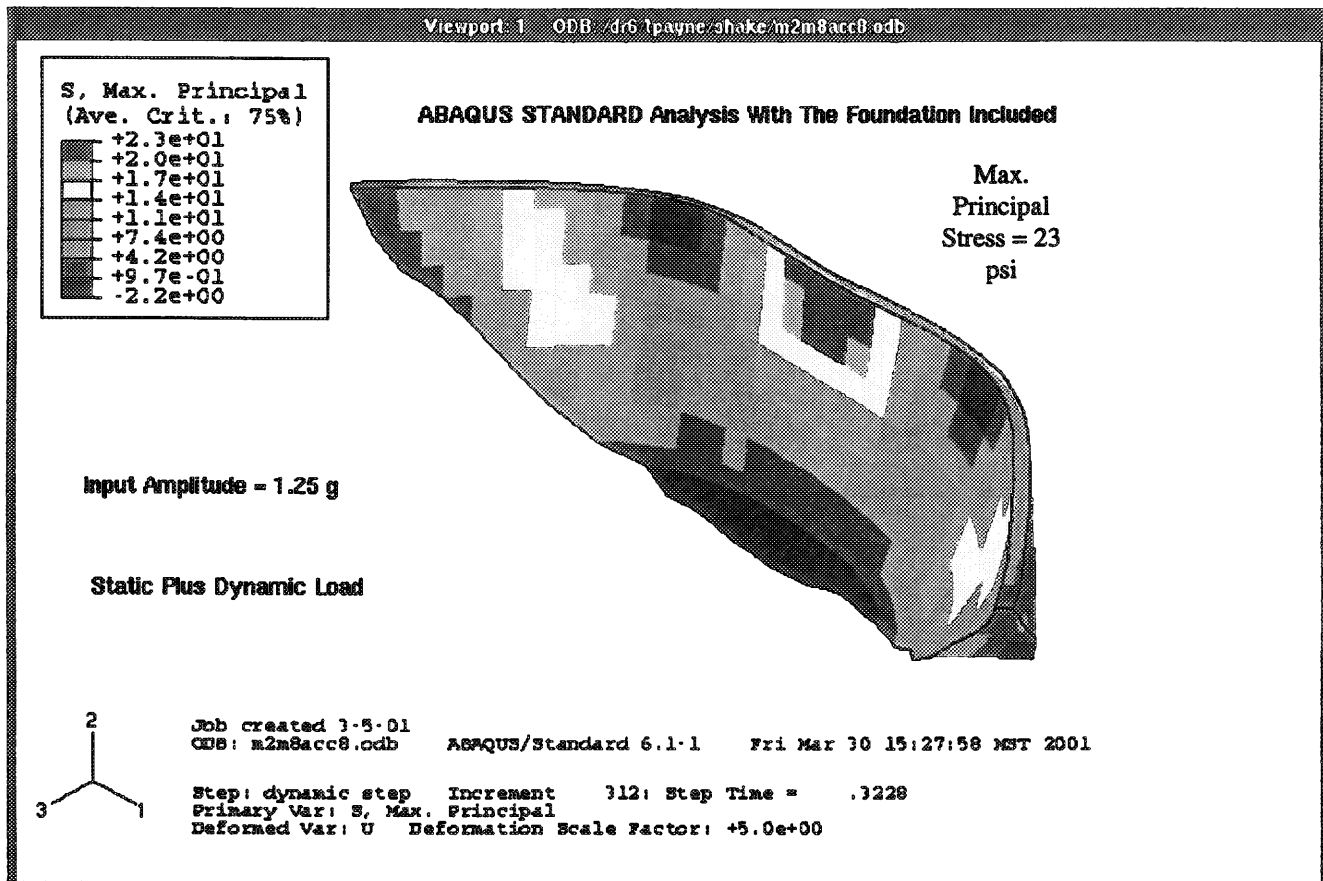
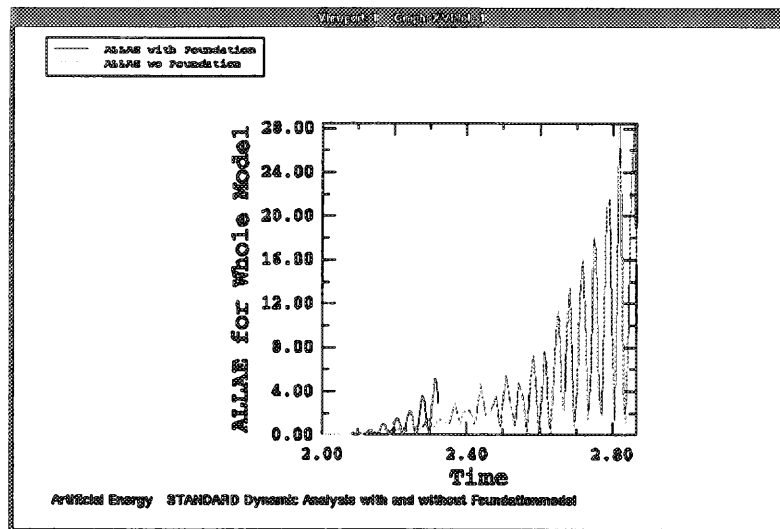


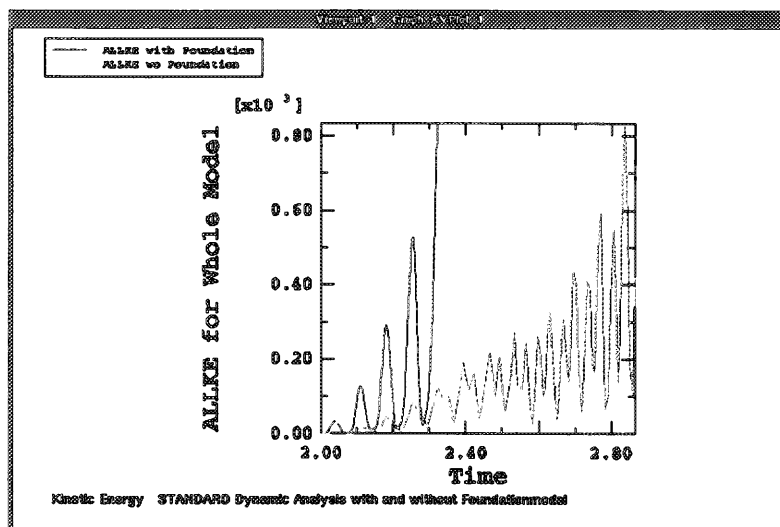
Figure C.11

Comparison of Energy Levels **ABAQUS STANDARD Analyses with/without Foundations** **Static Plus Dynamic Loading**

Artificial
Strain
Energy



Kinetic
Energy



Total
Energy

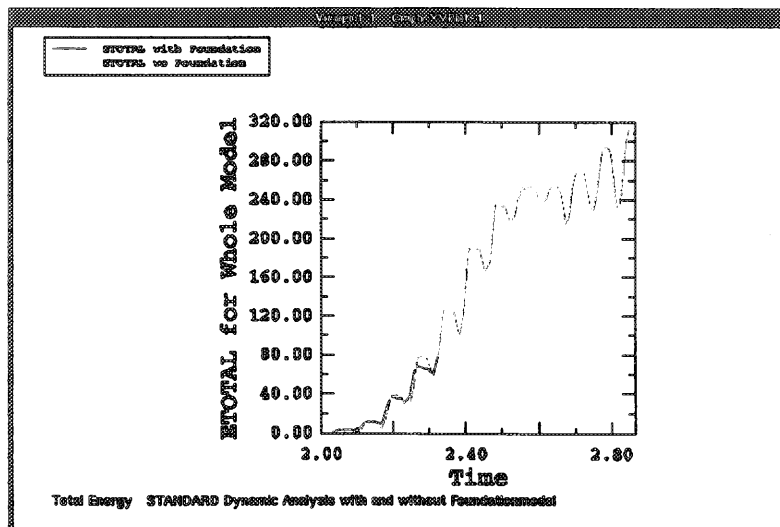


Figure C.12

Comparison of Displacement STANDARD versus EXPLICIT

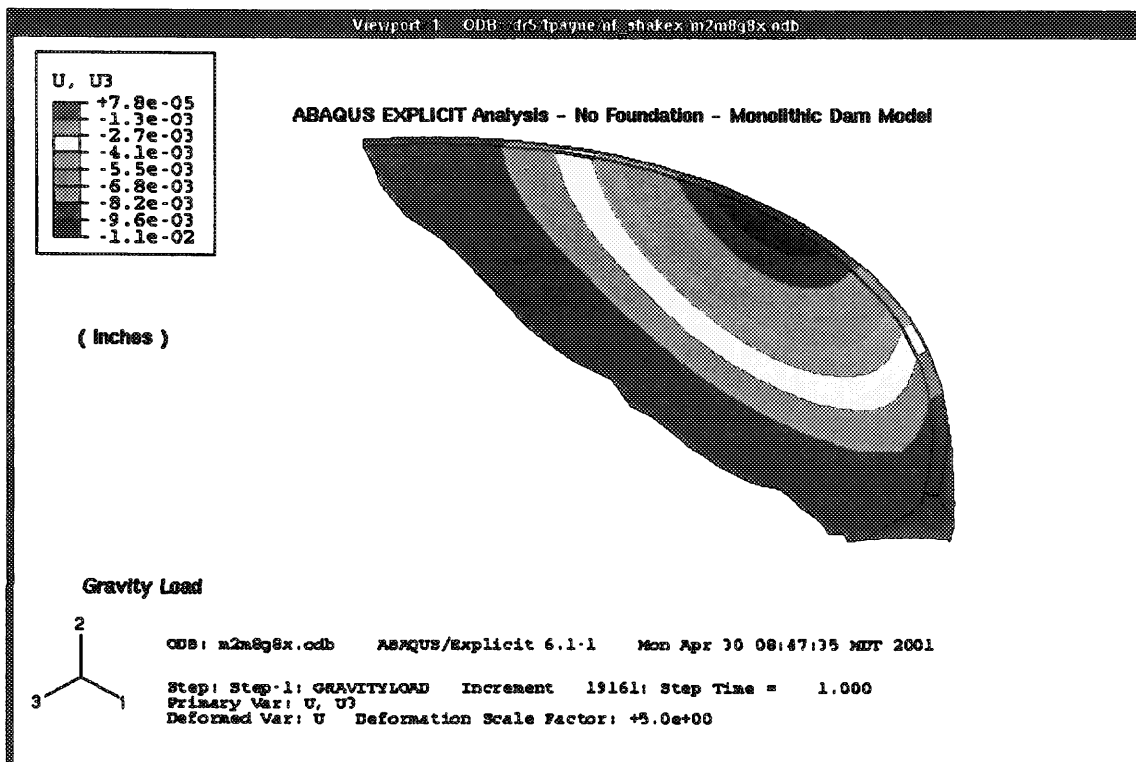
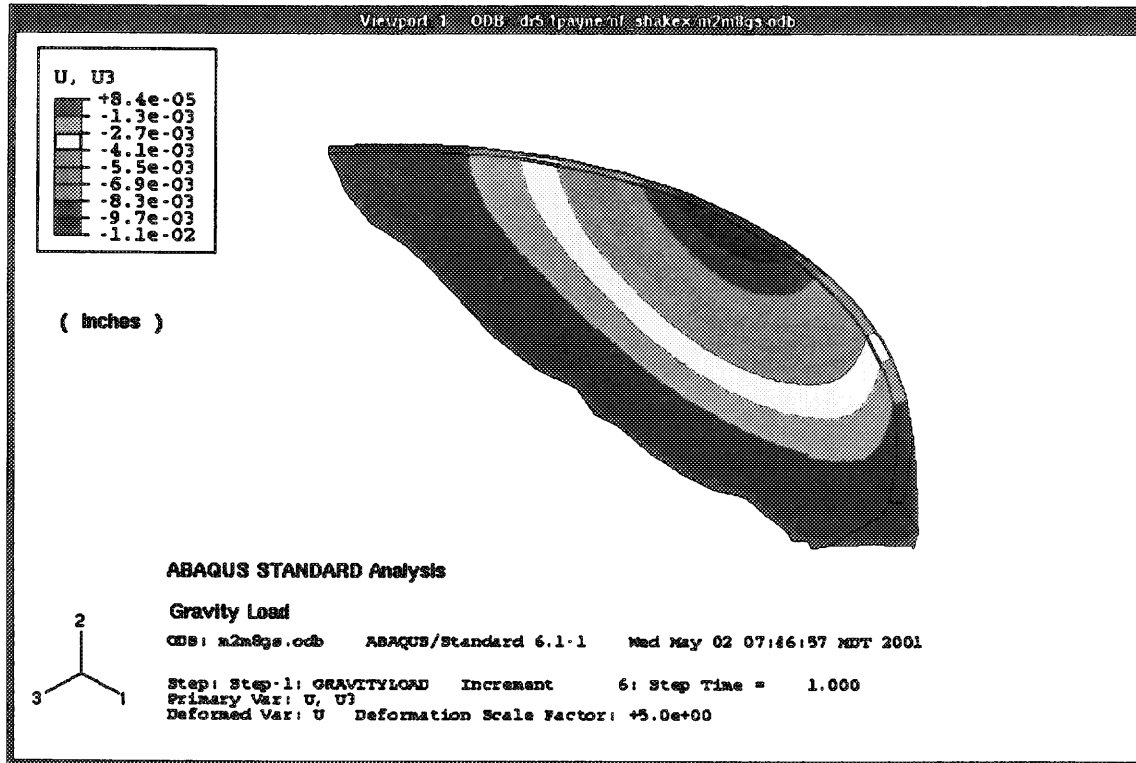


Figure C.13

Comparison of Max. Principal Stresses

STANDARD versus EXPLICIT

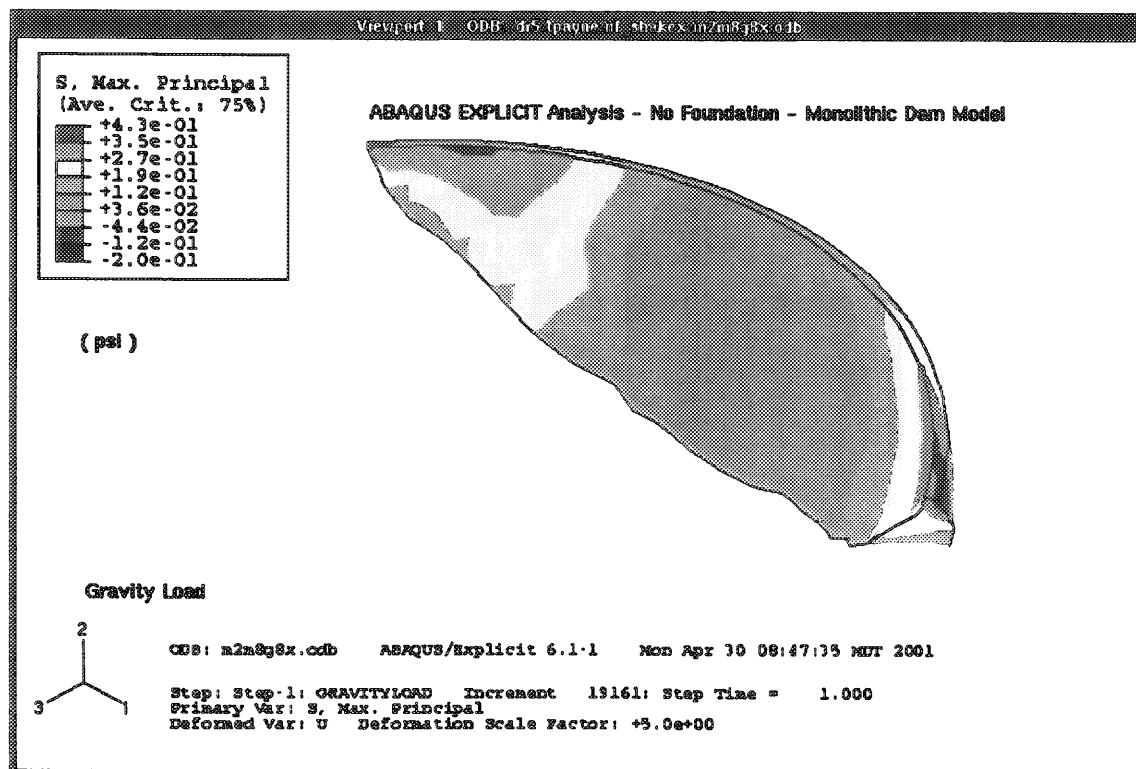
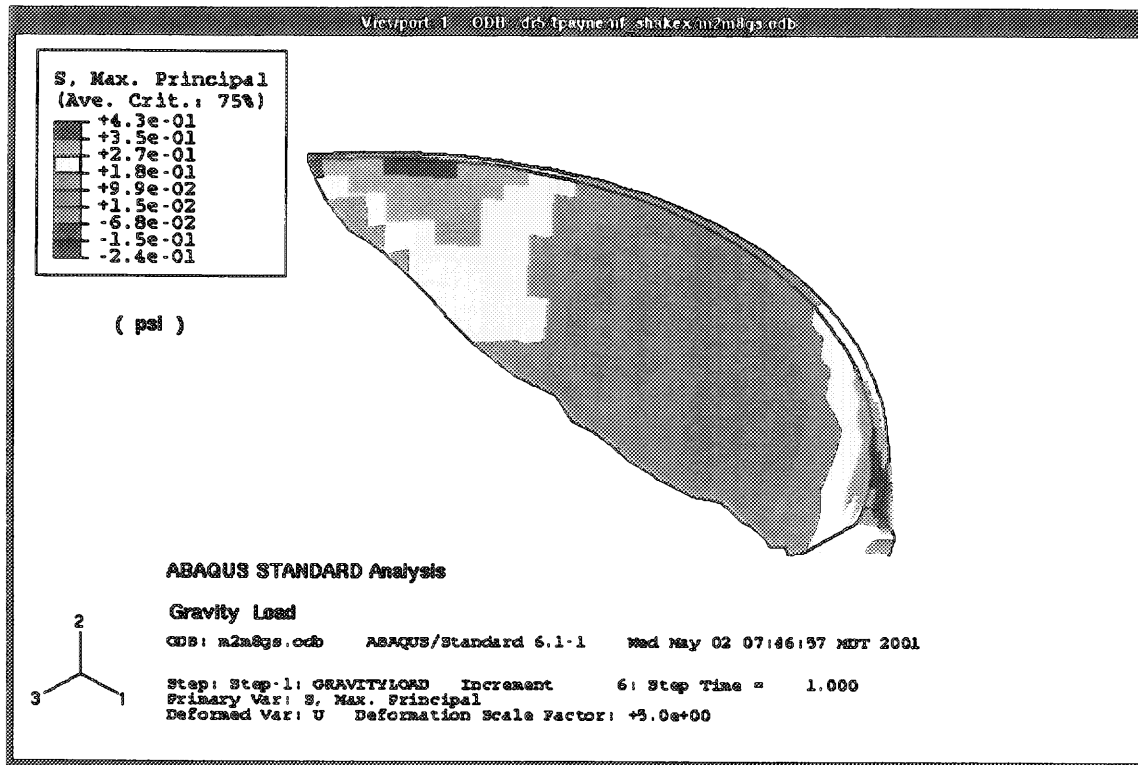


Figure C.14

Comparison of Displacements

STANDARD versus EXPLICIT

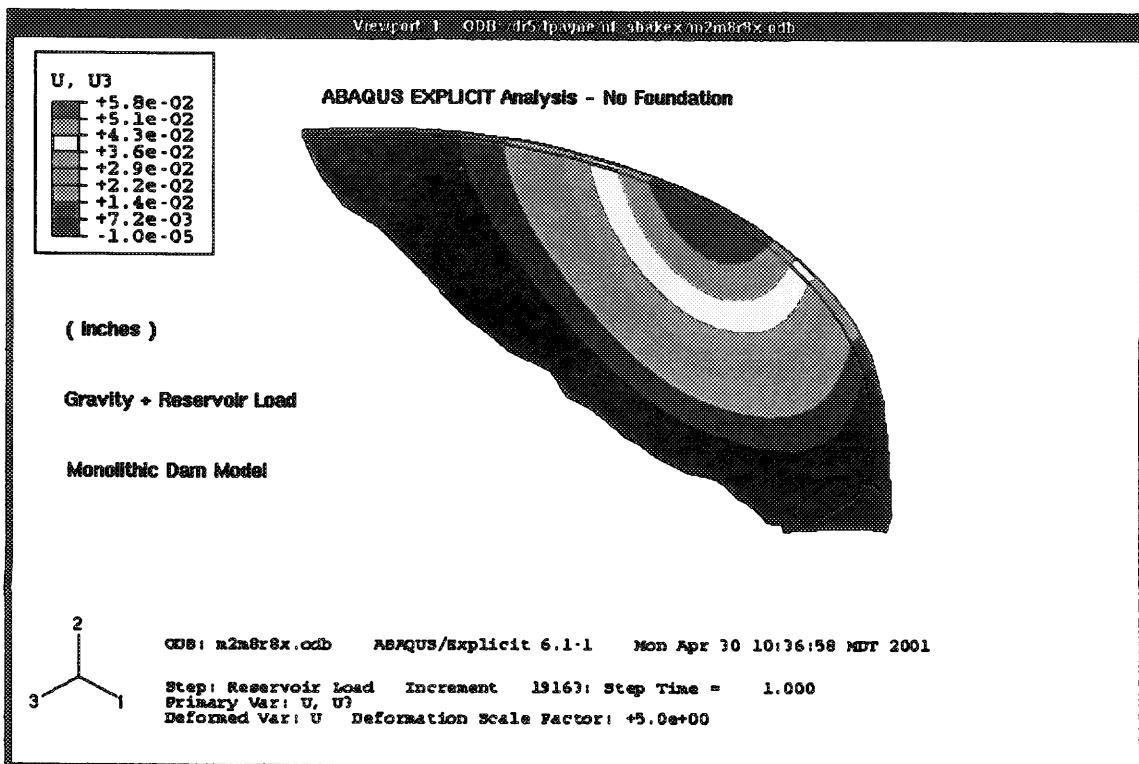
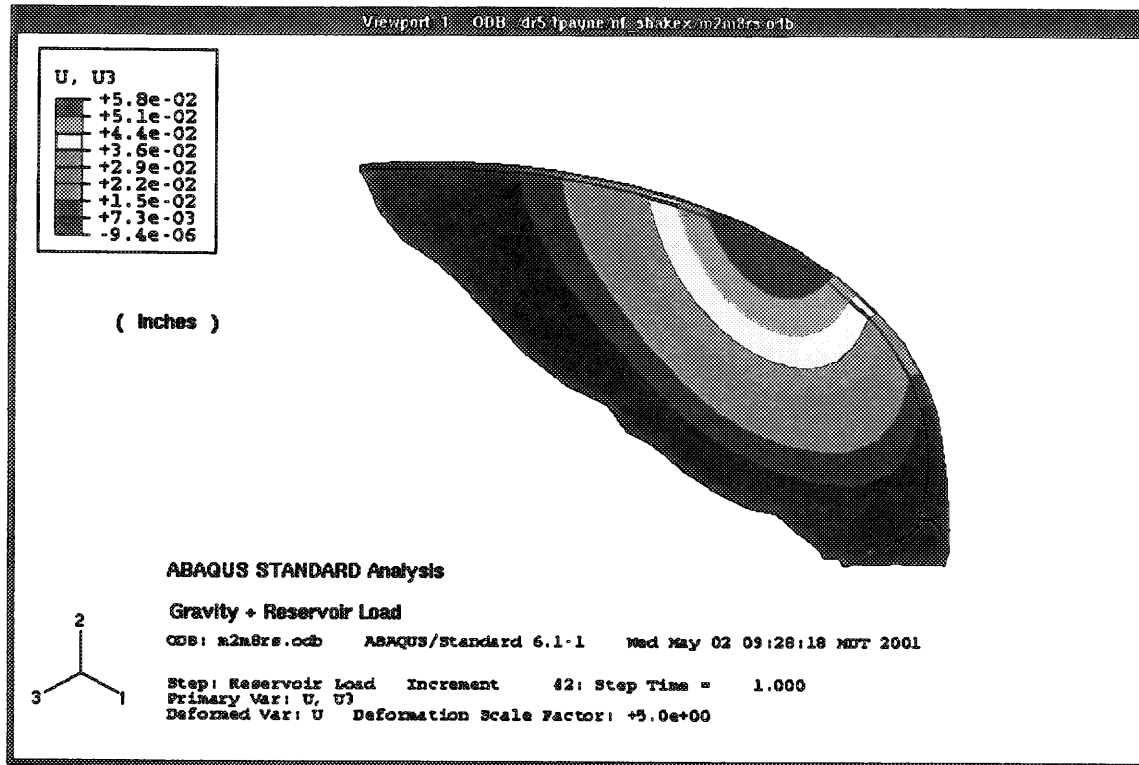


Figure C.15

Comparison of Max. Principal Stresses

STANDARD versus EXPLICIT

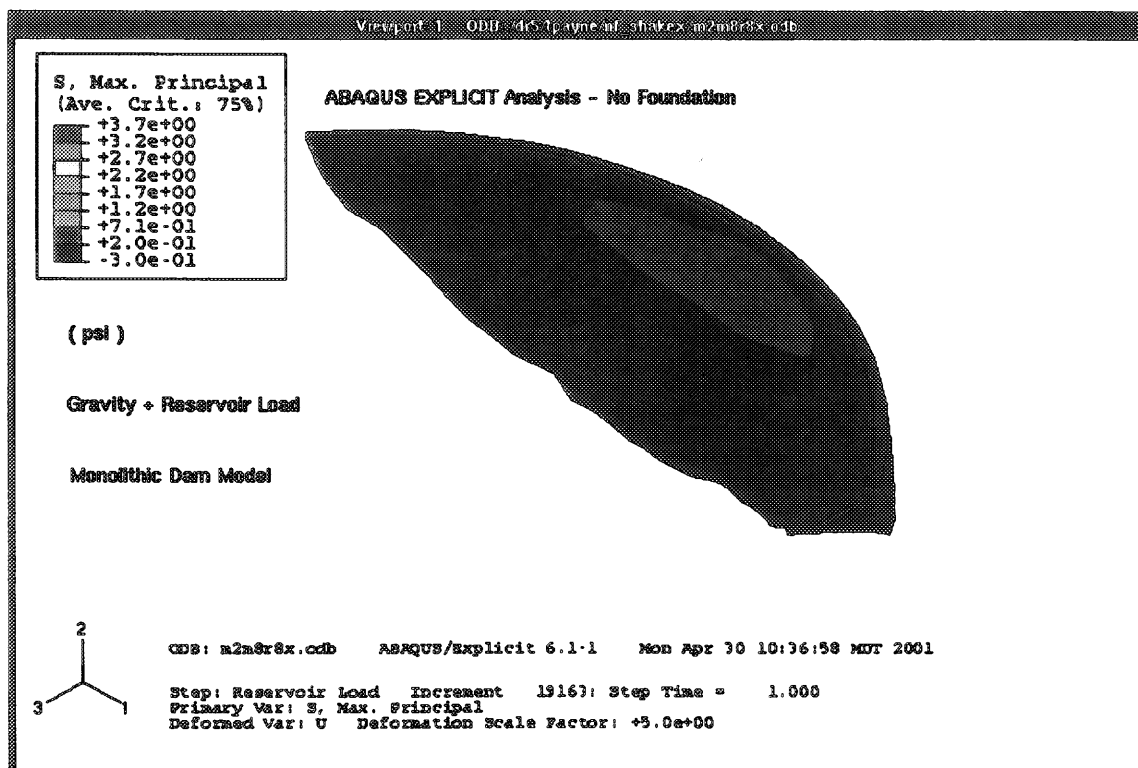
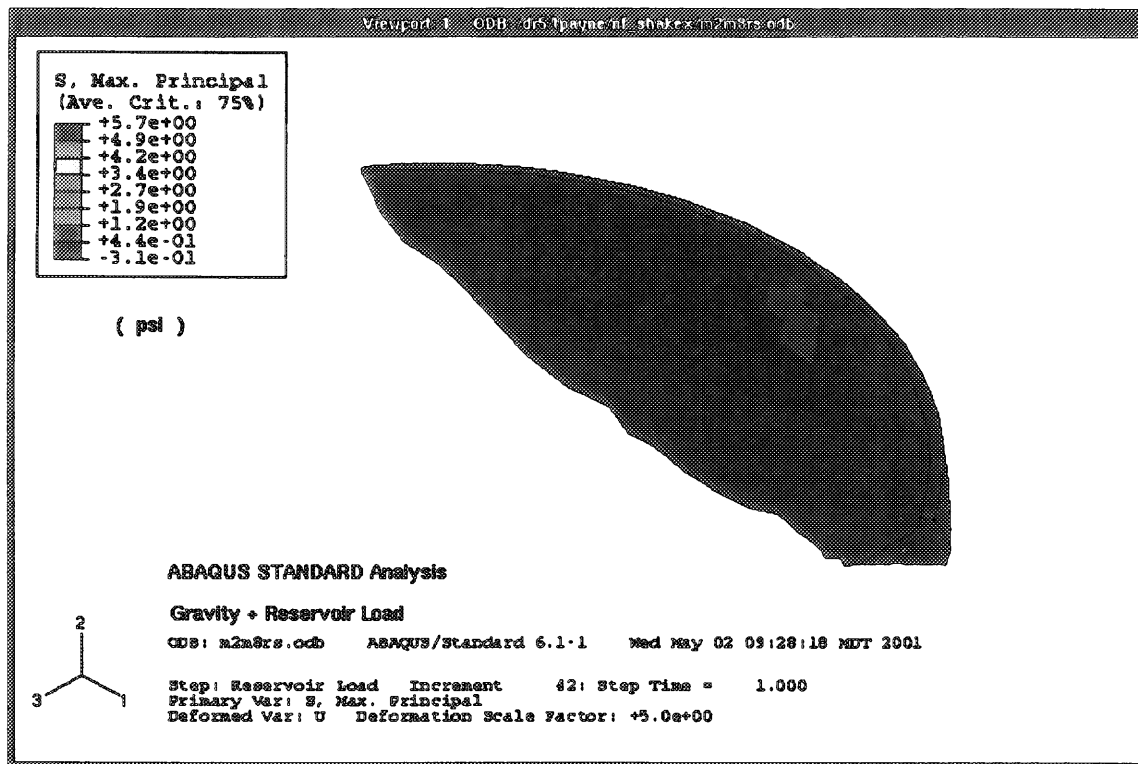
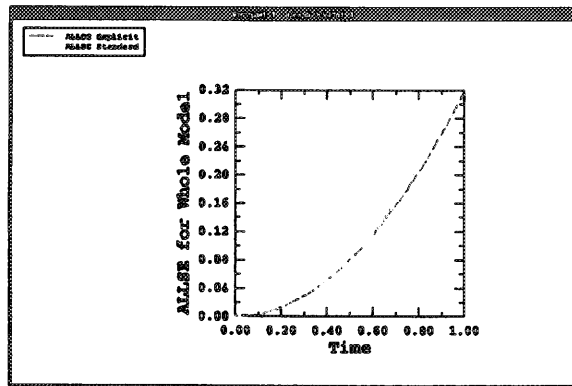


Figure C.16

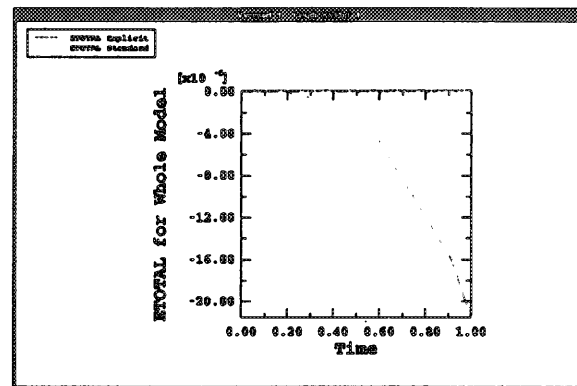
Comparison of Energy Levels

STANDARD versus EXPLICIT

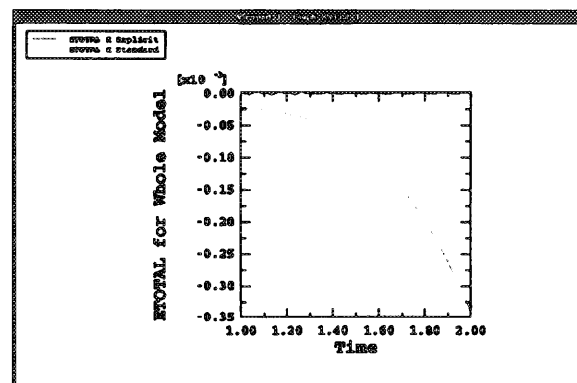
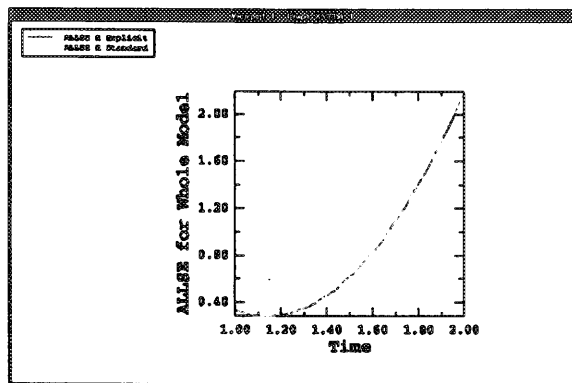
Strain Energy



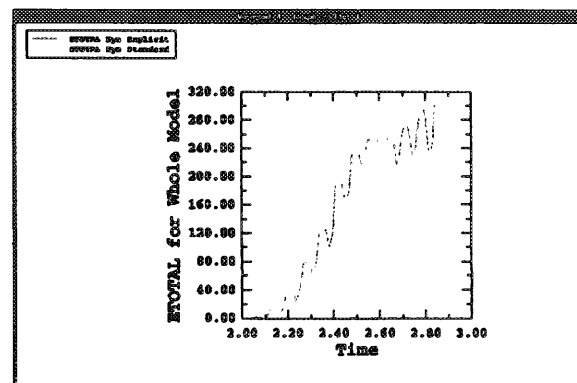
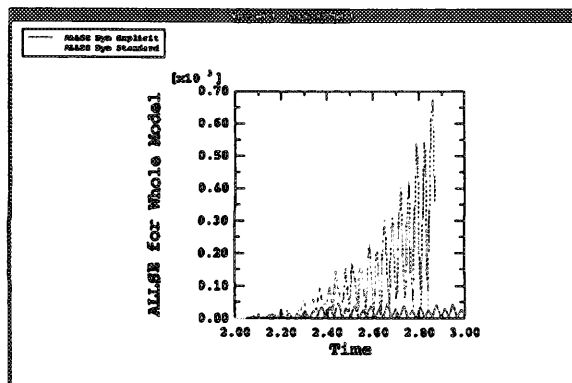
Total Energy



Gravity Load Step



Reservoir Load Step



Dynamic Load Step

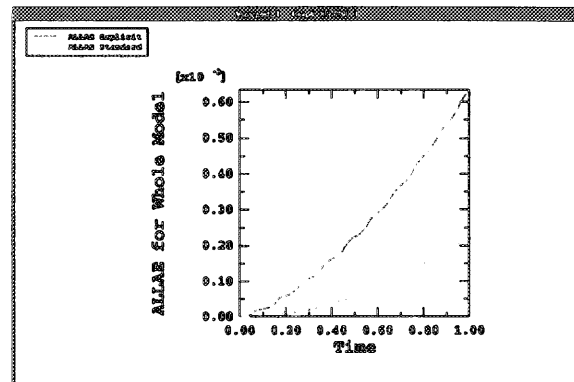
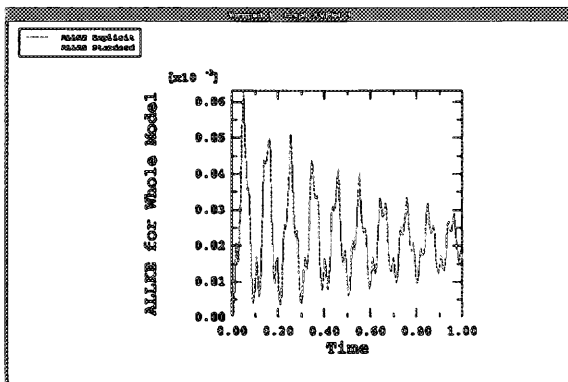
Figure C.17

Comparison of Energy levels

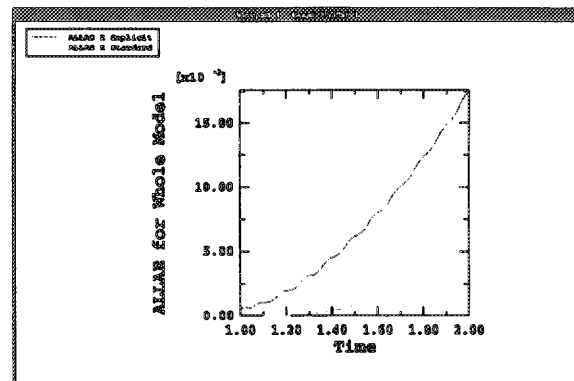
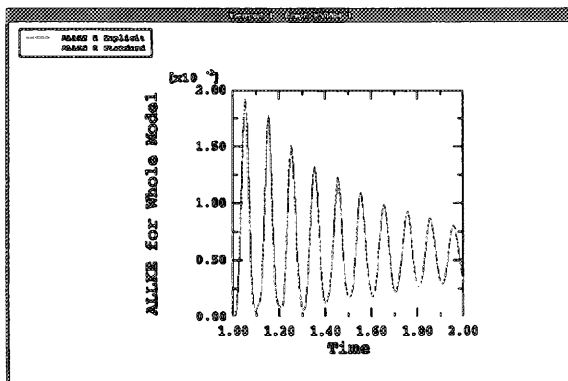
STANDARD versus EXPLICIT

Kinetic Energy

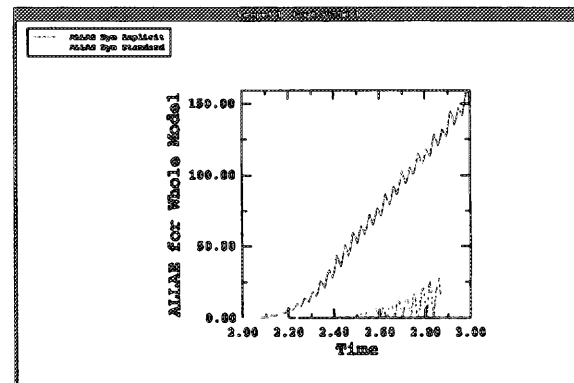
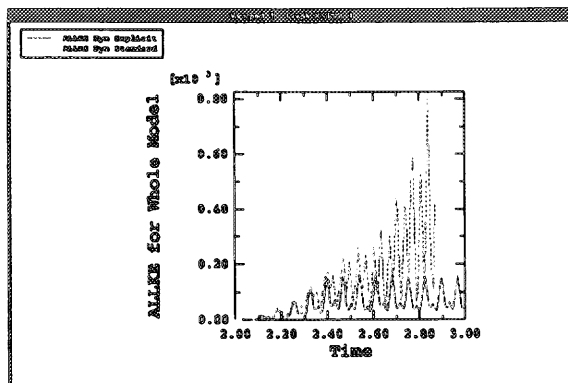
Artificial Strain Energy



Gravity Load Step



Reservoir Load Step



Dynamic Load Step

Figure C.18

Comparison of Displacements

STANDARD versus EXPLICIT

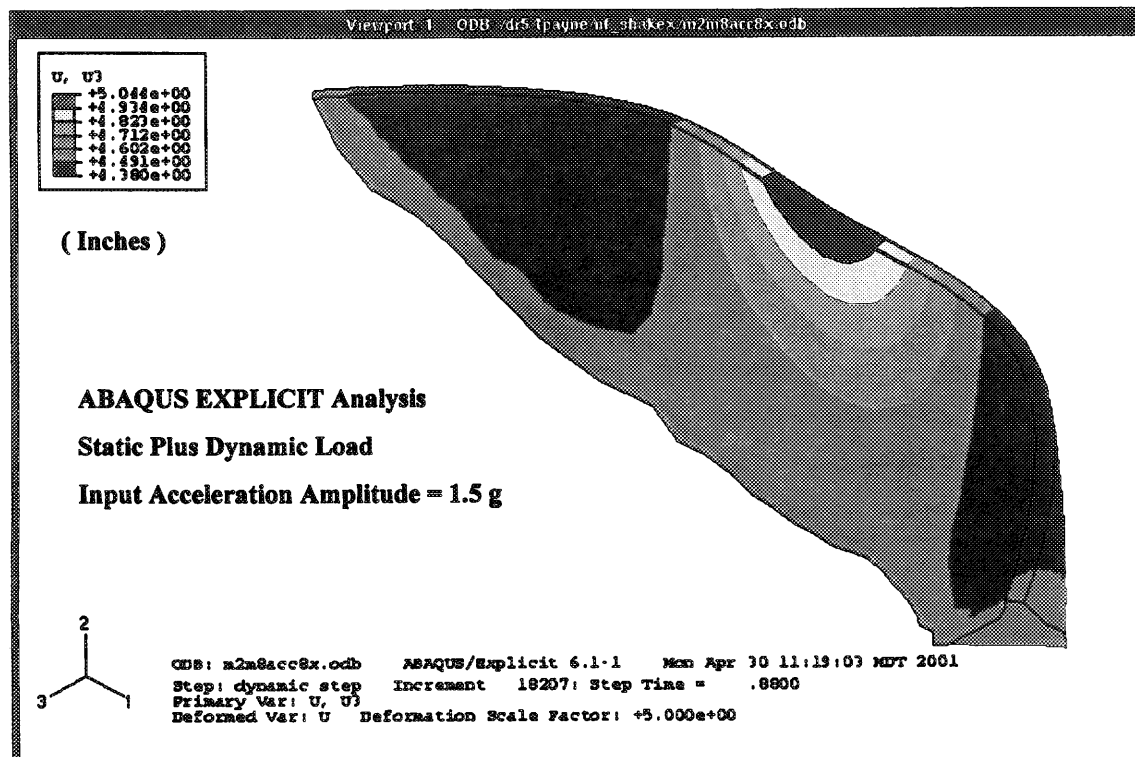
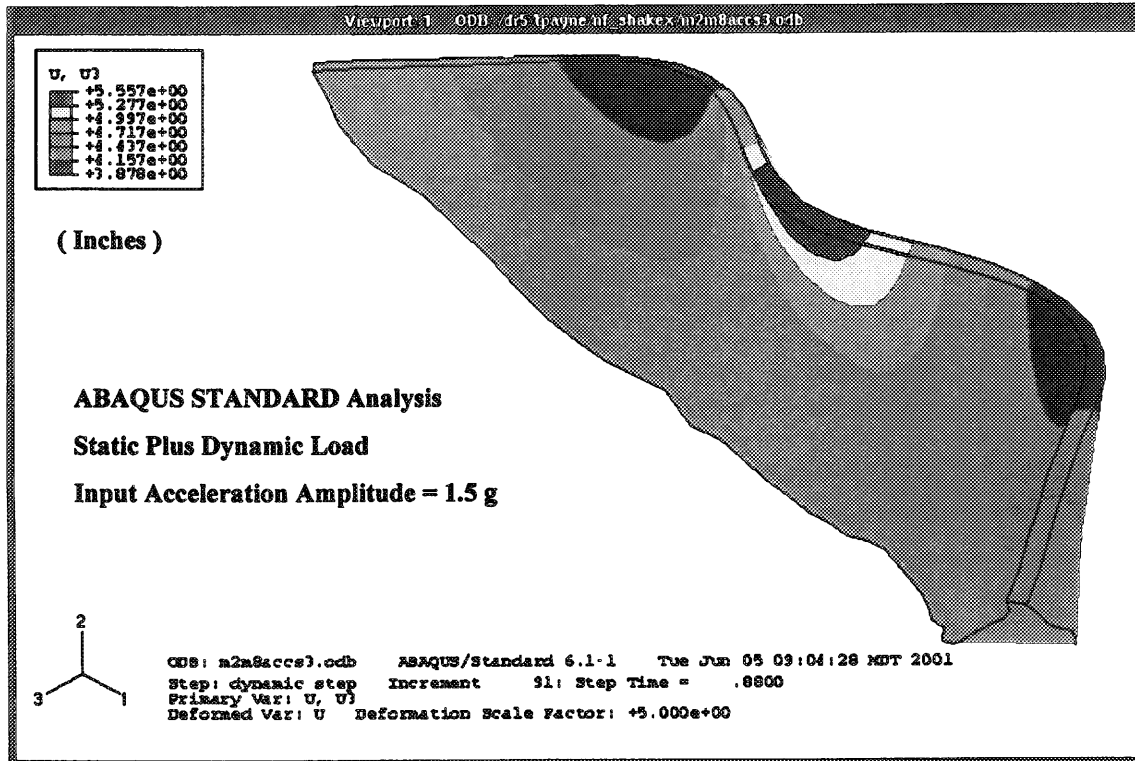


Figure C.19

Comparison of Max. Principal Stresses

STANDARD versus EXPLICIT

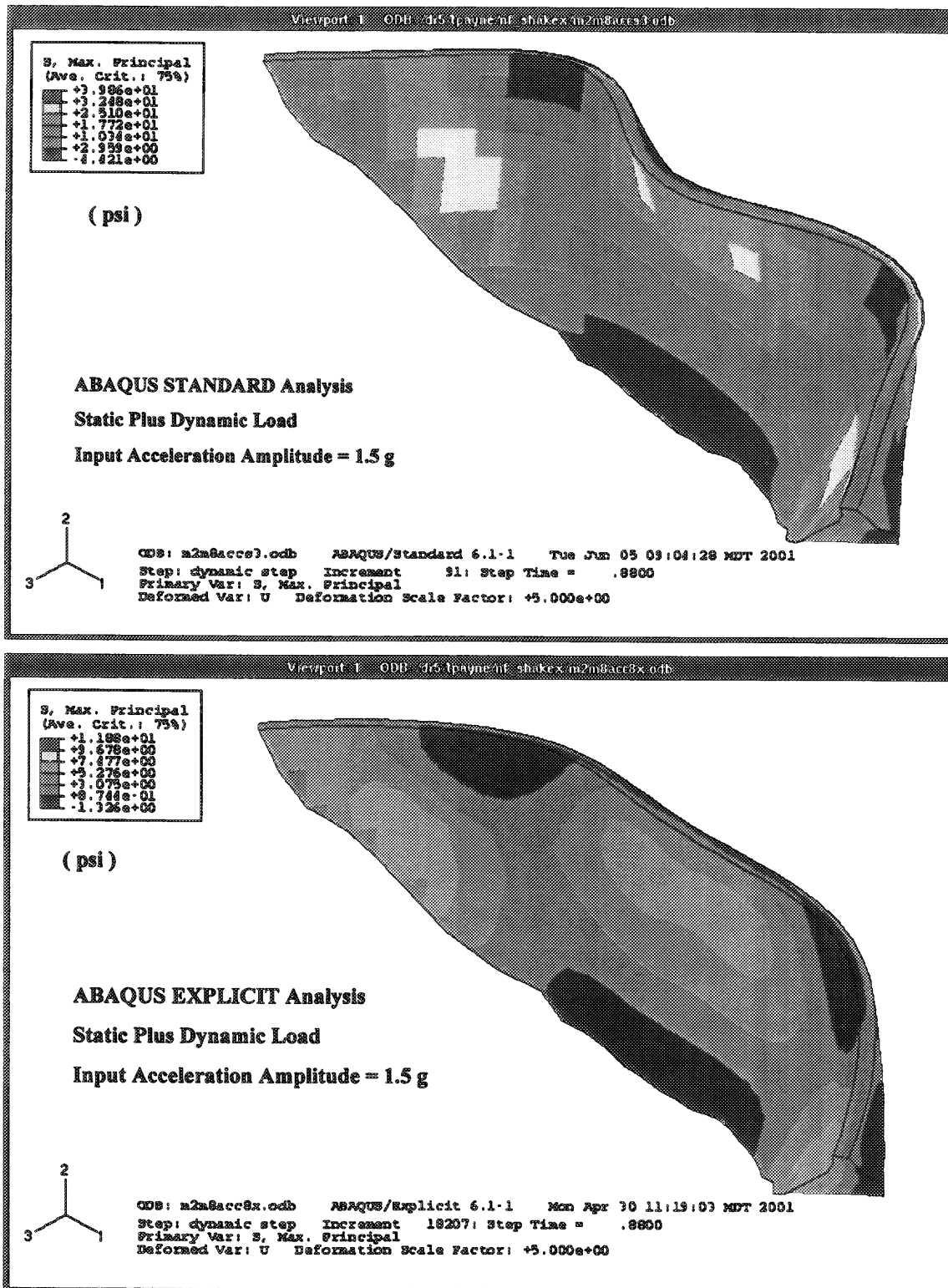
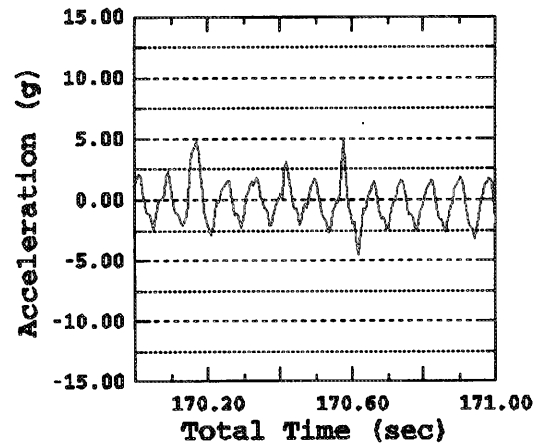


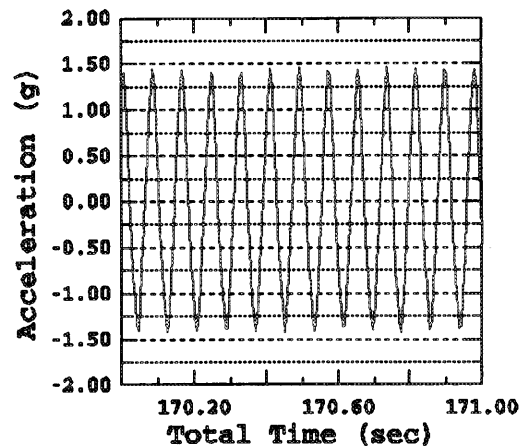
Figure C.20

Accelerations Measured in the Laboratory Experiment
Accelerometer #8 @ Dam Crest on Crown Cantilever

Temp-1

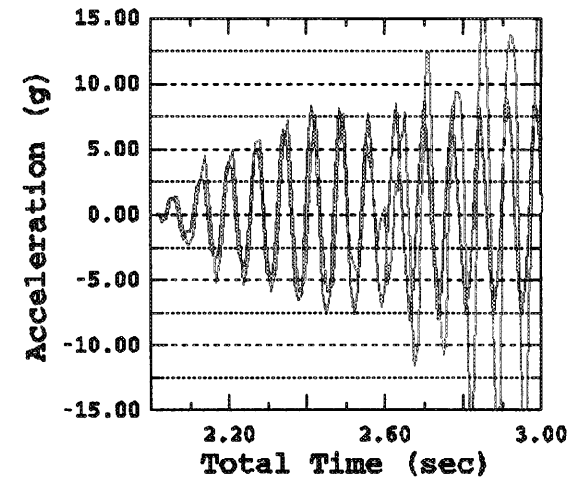


Temp-1

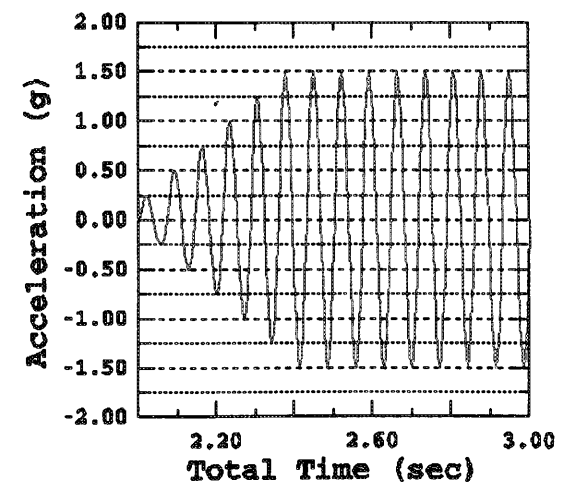


Accelerations Calculated in ABAQUS STANDARD & EXPLICIT
Node 373 @ Dam Crest on Crown Cantilever

Explicit A3 Mode 373 g
STANDARD A3 Mode 373 g



Temp-1



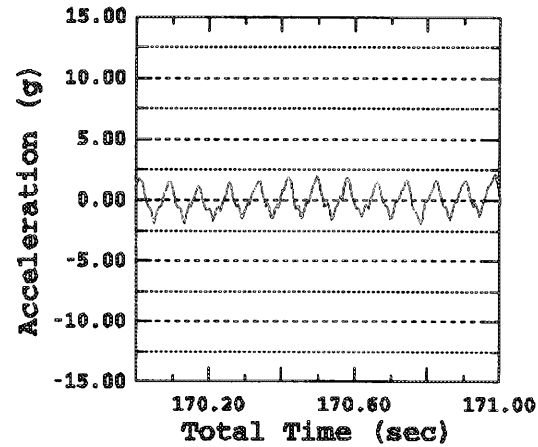
Monolithic
Model M2

Corresponding
Input Accelerations

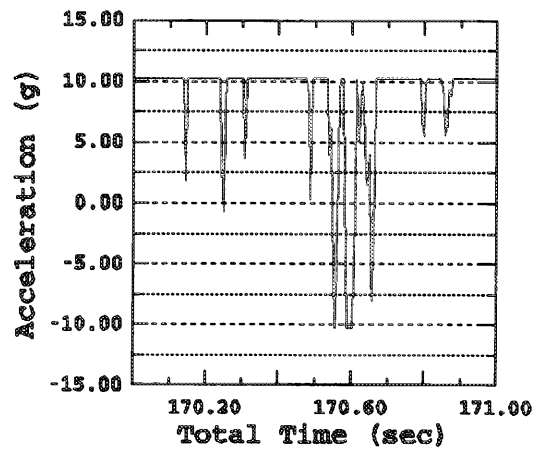
Accelerations Measured in the Laboratory Experiment

Accelerometers # 9 & 10

Temp-1



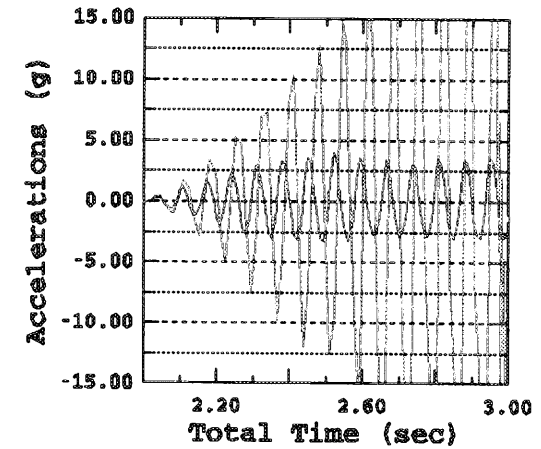
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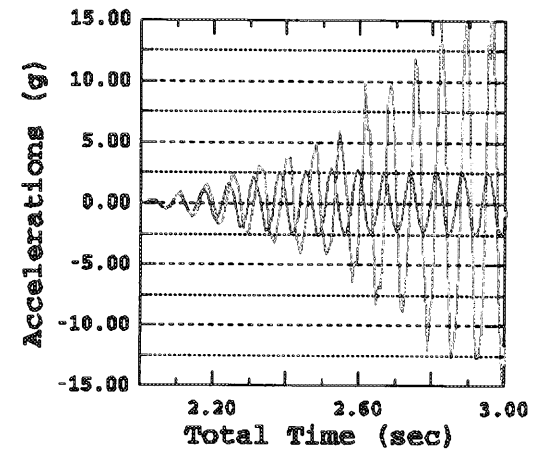
Accelerations Calculated in ABAQUS STANDARD/EXPLICIT

Nodes 533 & 2652

EXPLICIT Node 533 A3 g
STANDARD Node 533 A3 g



EXPLICIT Node 2652 A3 g
STANDARD Node 2652 A3 g

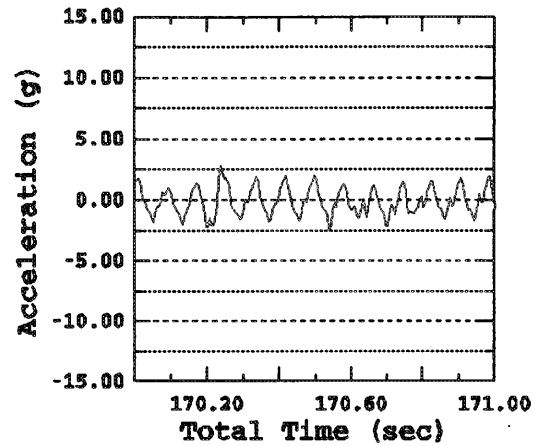


Monolithic
Model M2

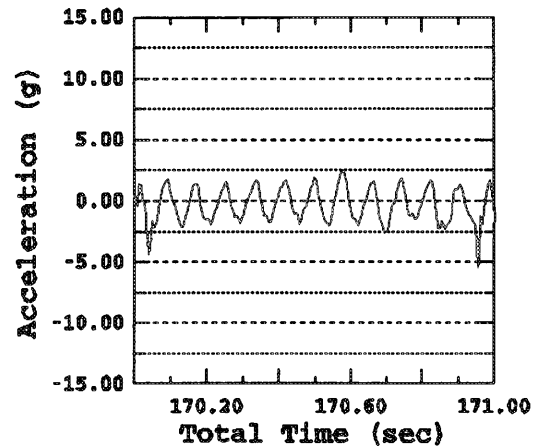
Accelerations Measured in the Laboratory Experiment

Accelerometers # 6 & 7

Temp-1



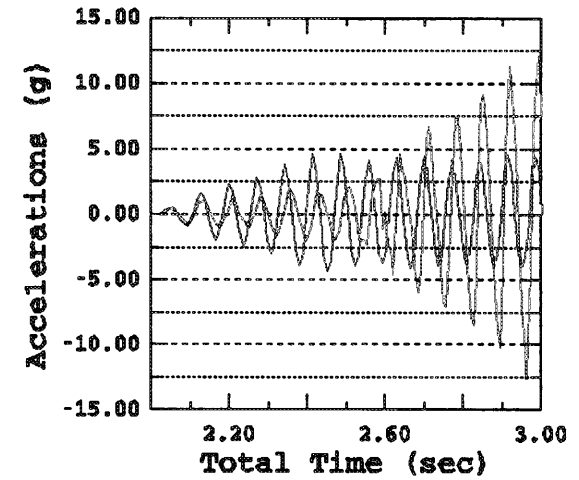
Temp-1



Accelerations Calculated in ABAQUS STANDARD/EXPLICIT

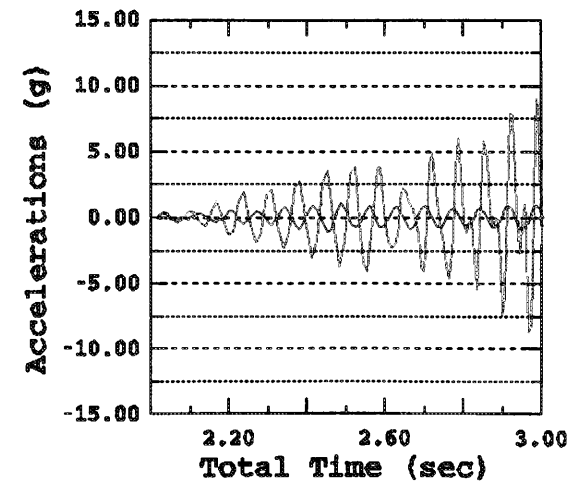
Nodes 3724 & 2492

EXPLICIT Node 2492 A3 g
STANDARD Node 2492 A3 g



Monolithic
Model M2

EXPLICIT Node 3724 A3 g
STANDARD Node 3724 A3 g

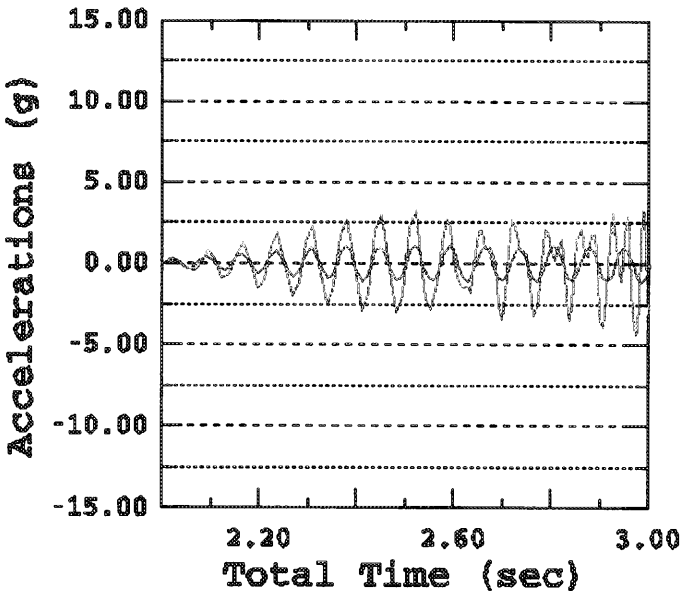
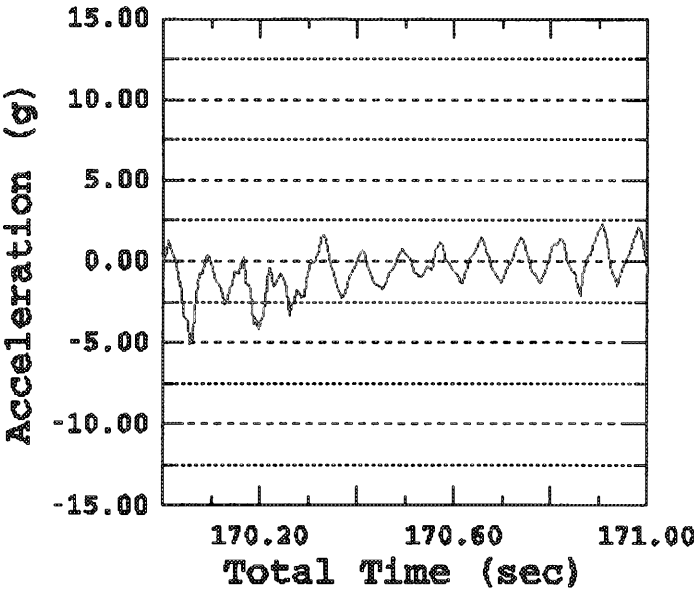


Accelerations Measured in the Laboratory Experiment
Accelerometers # 5

Accelerations Calculated in ABAQUS STANDARD/EXPLICIT
Node 4682

Temp-1

EXPLICIT Node 4682 A3 g
STANDARD Node 4682 A3 g

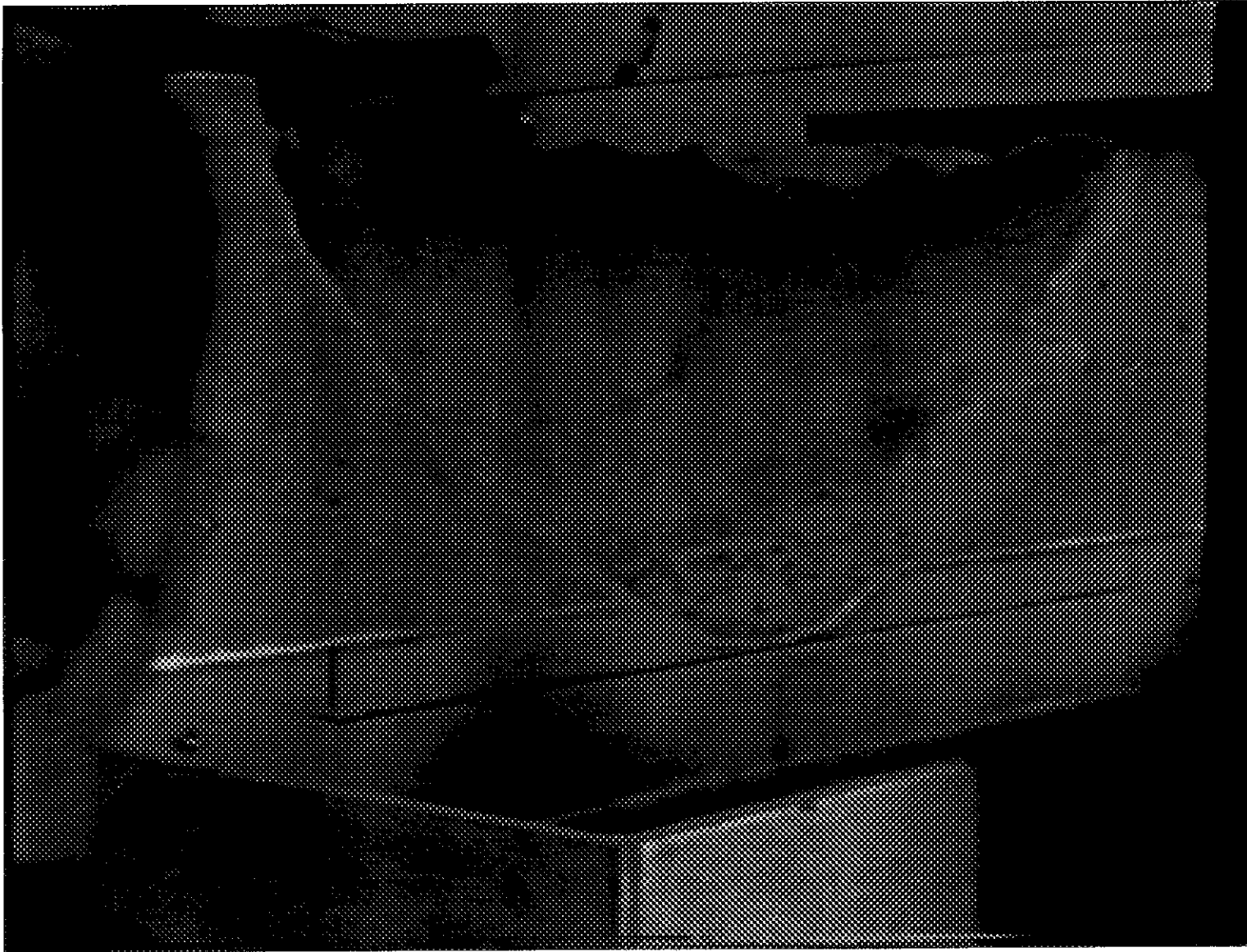


Monolithic
Model M2

Figure C.24

Appendix D

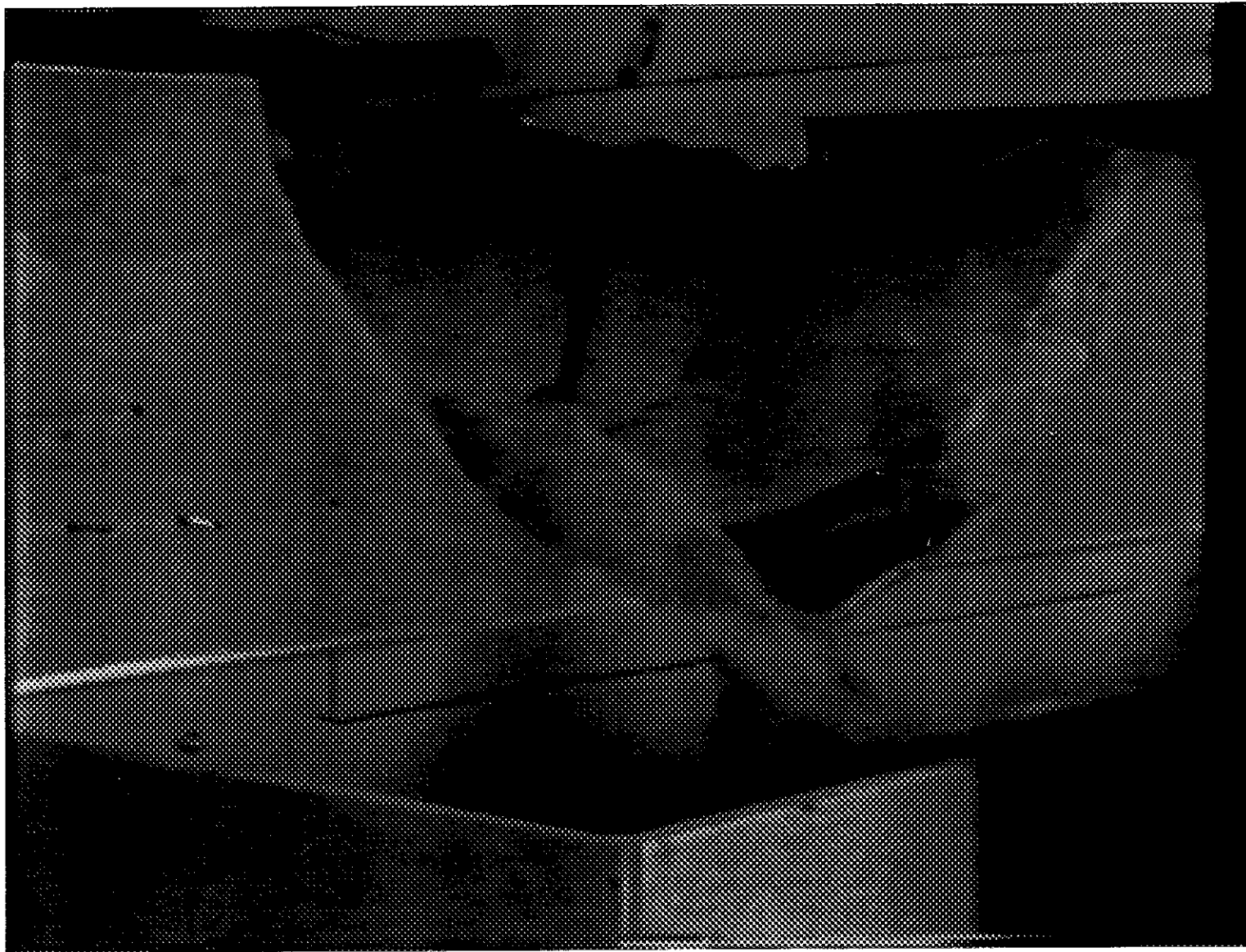
Laboratory Results for Five Different Joint Configurations



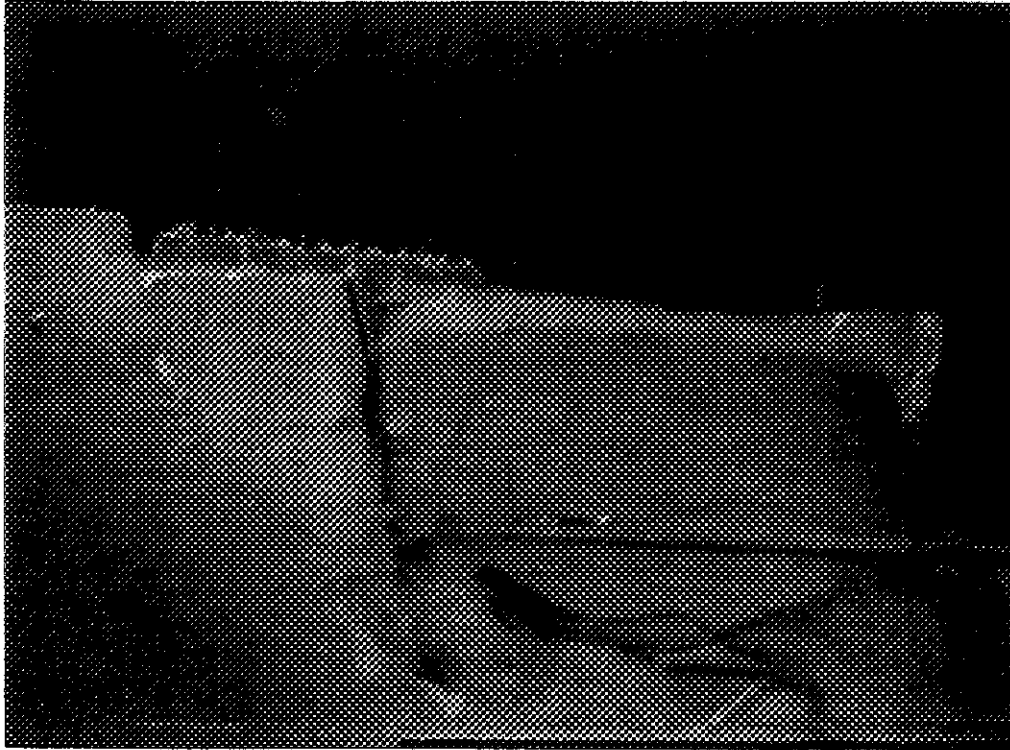
Initial Crack Pattern - Model M2 - Test Date 3/31/99



Crack Pattern - Model M2 - Test Date 3/31/99



Final Crack Pattern - Model M2 - Test Date 3/31/99



Model M8 -- 6/21/00 South view, final failure



Model M8 -- 6/21/00, South view, initial cracking



Model M8 -- 6/21/00, North view, final failure



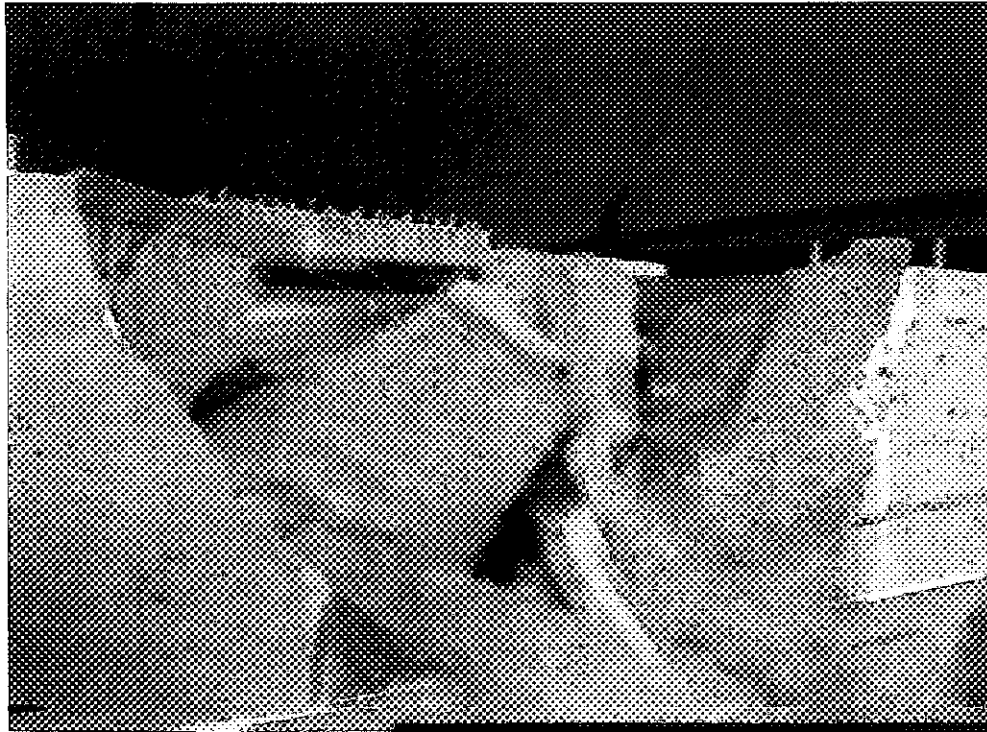
Model M8 -- 6/21/00 North view, initial cracking



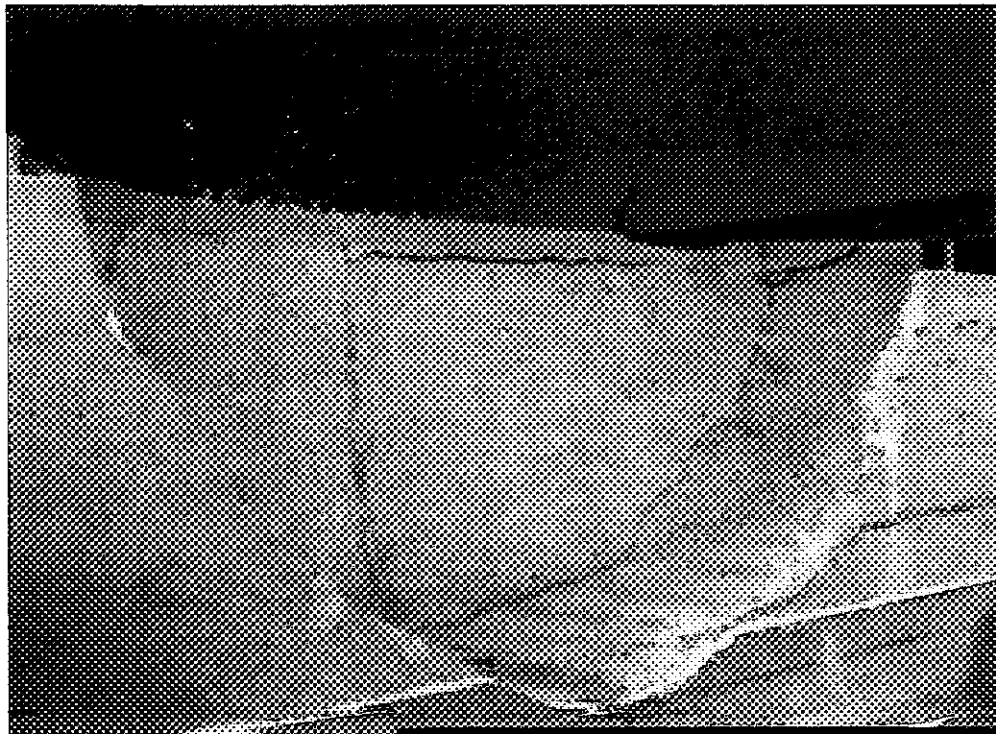
Model M6 -- August 27, 2000 -- South, initial cracking



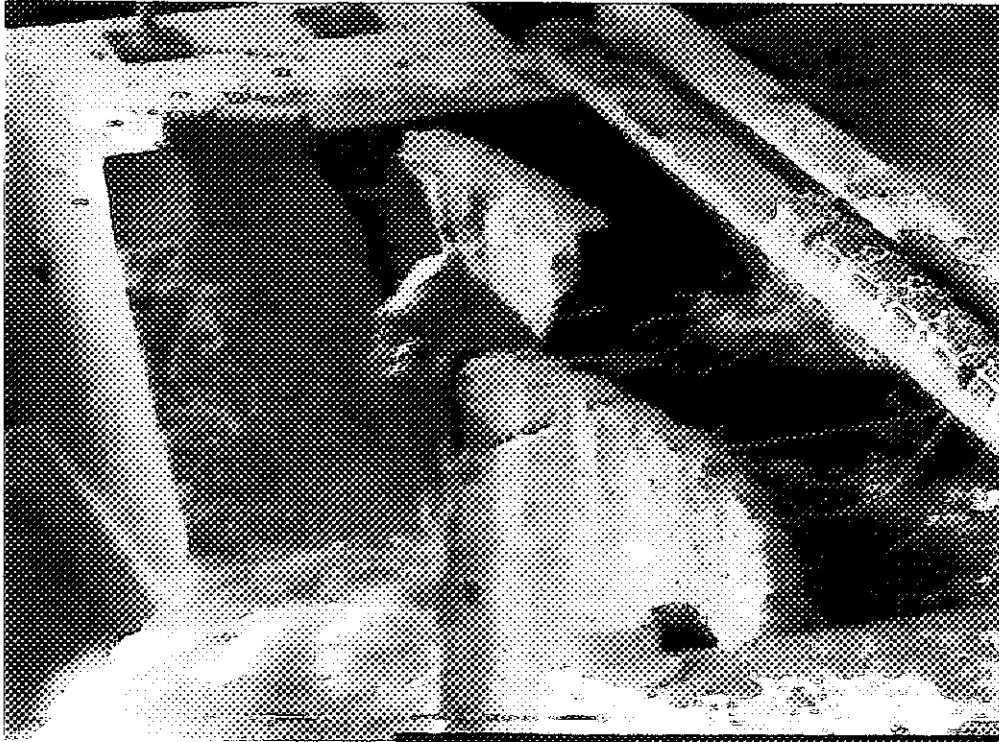
Model M6 -- August 27, 1999 -- South, final failure



Model M11 -- 8/22/00 South view, final failure



Model M11 -- 8/22/00 South view, initial cracking



Model M11 -- 8/22/00 North view, final failure



Model M11 -- 8/22/00 North view, initial cracking



Model M9 -- 7/19/00 North view, final failure

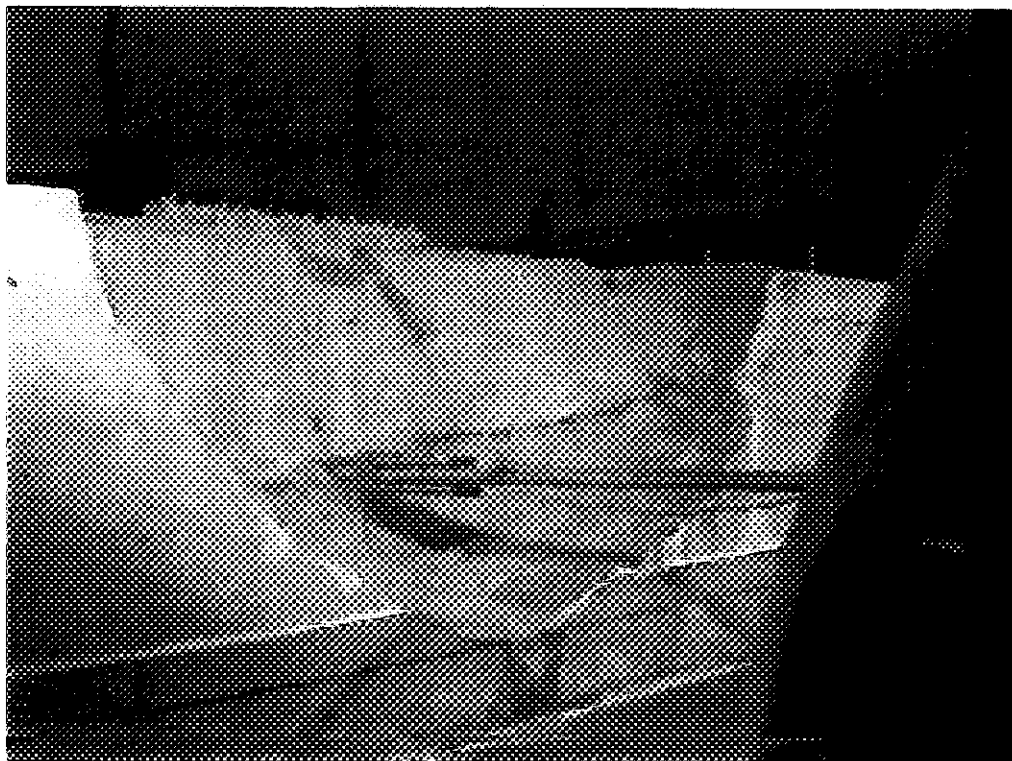


Model M9 -- 7/19/00 North view, initial cracking

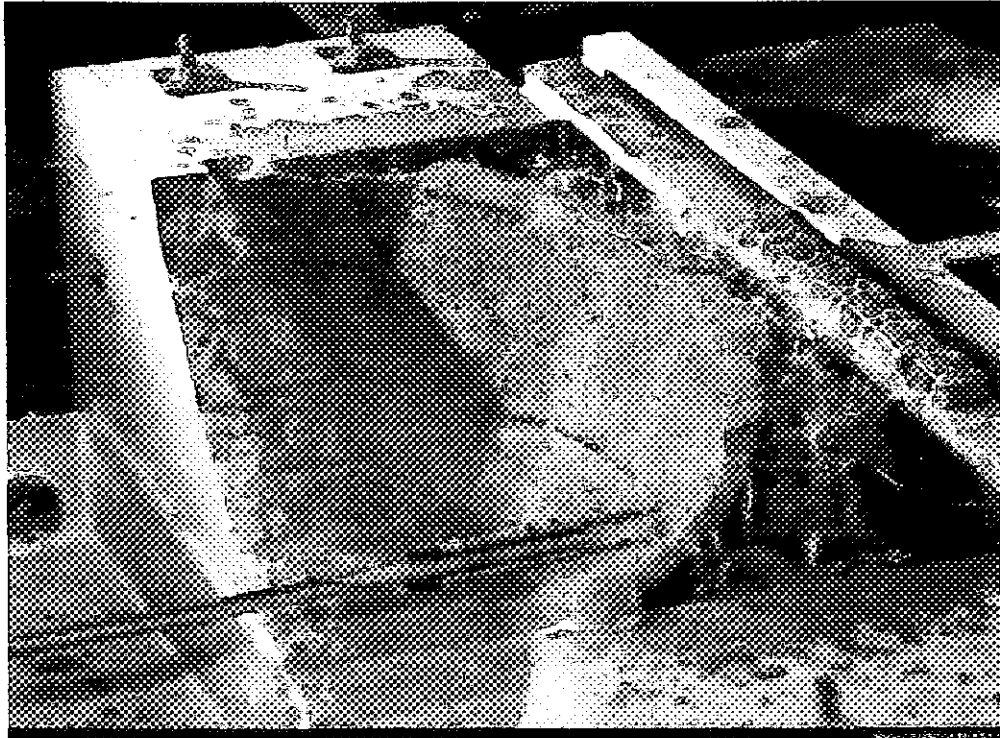
Figure D.9



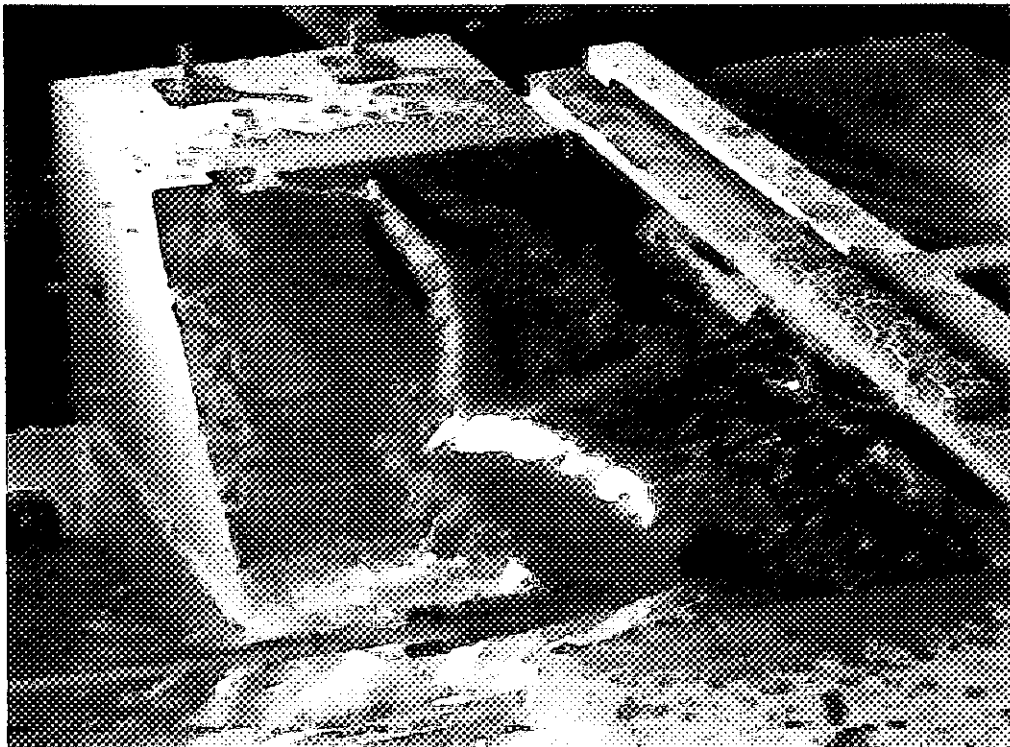
Model M9 -- 7/19/00, South view - final failure



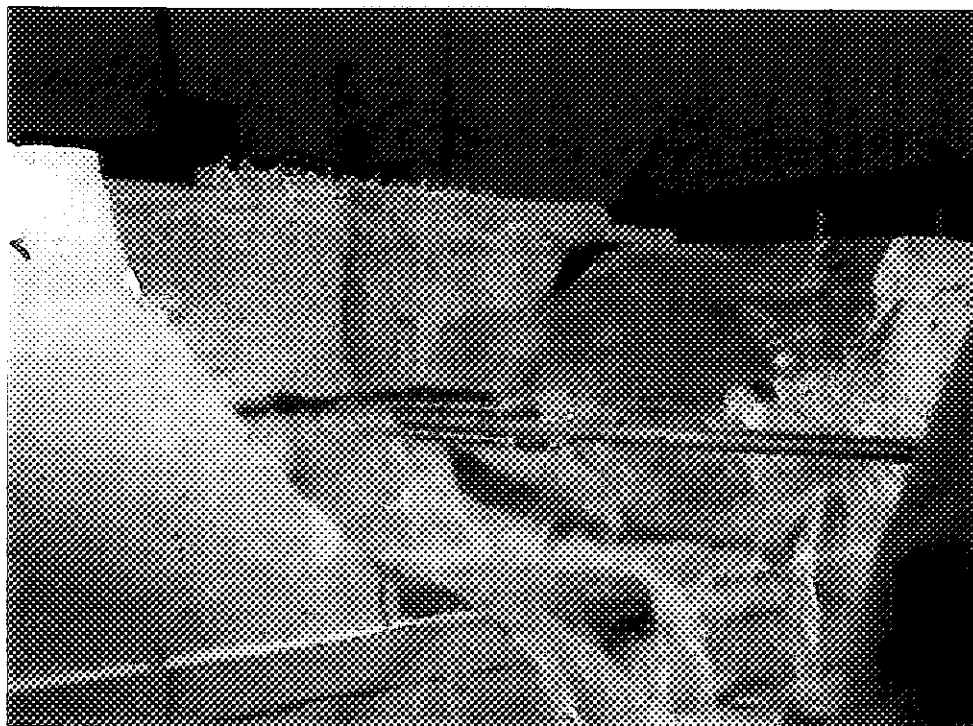
Model M9 -- 7/19/00 , South view, initial cracking



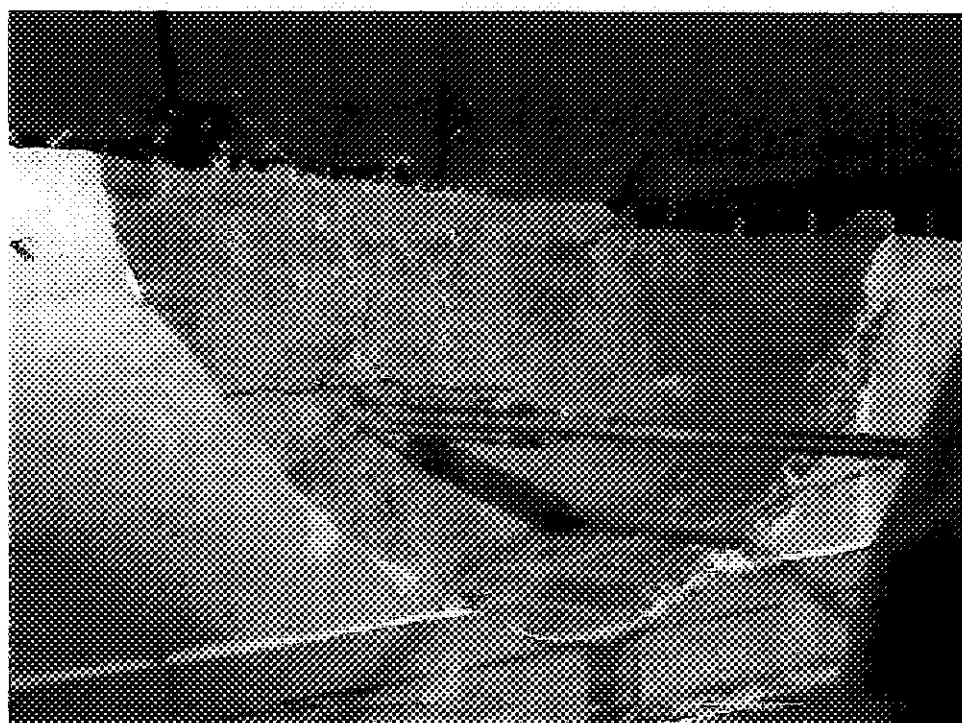
Model M10 -- 8/2/00, North view, initial cracking



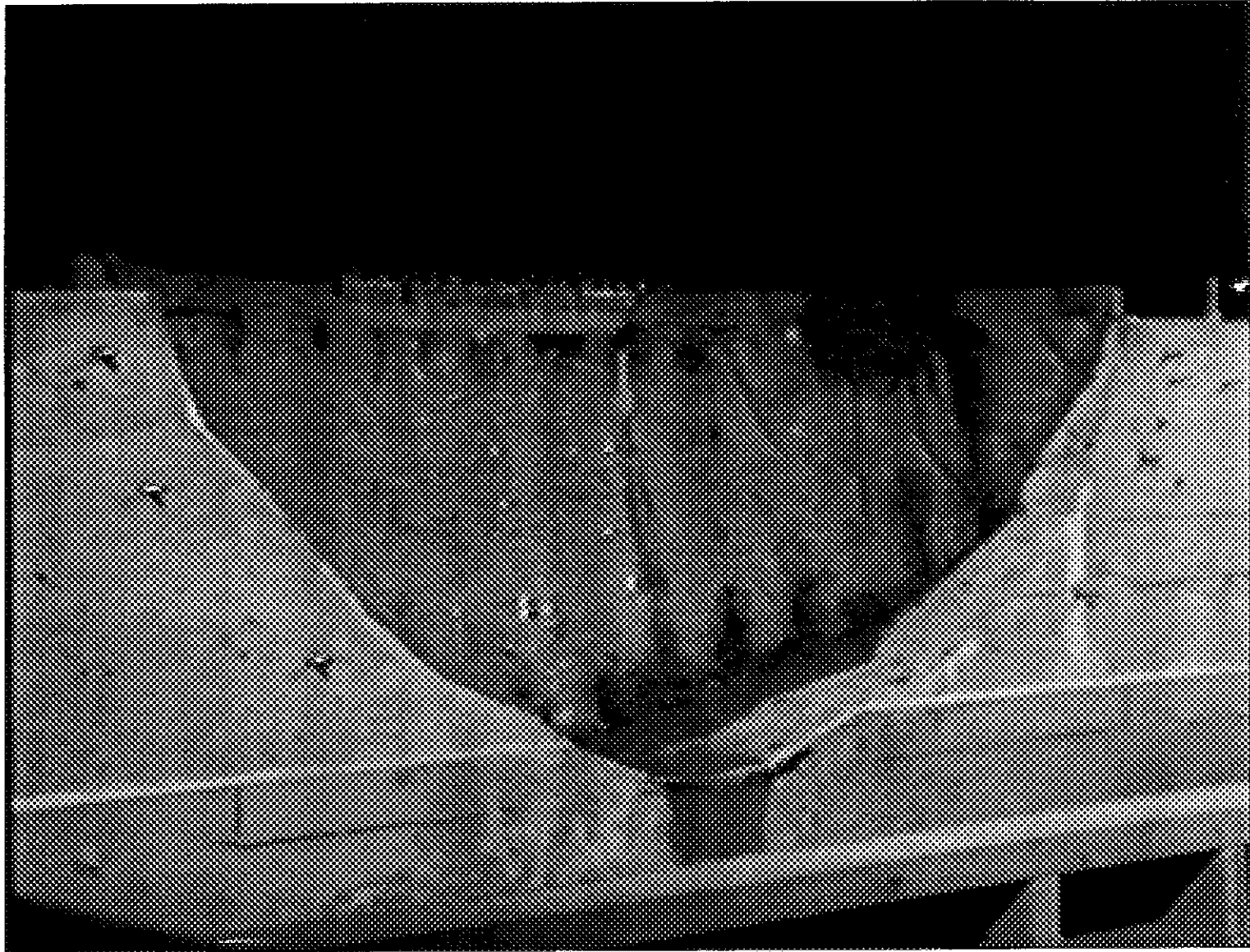
Model 10 -- 8/2/00 North view, final failure



Model M10 - 8/2/00, South view camera final failure



Model M10 - 8/2/00, South view camera initial cracking



Initial Crack Pattern – Model M13 – Test Date 4/10/01

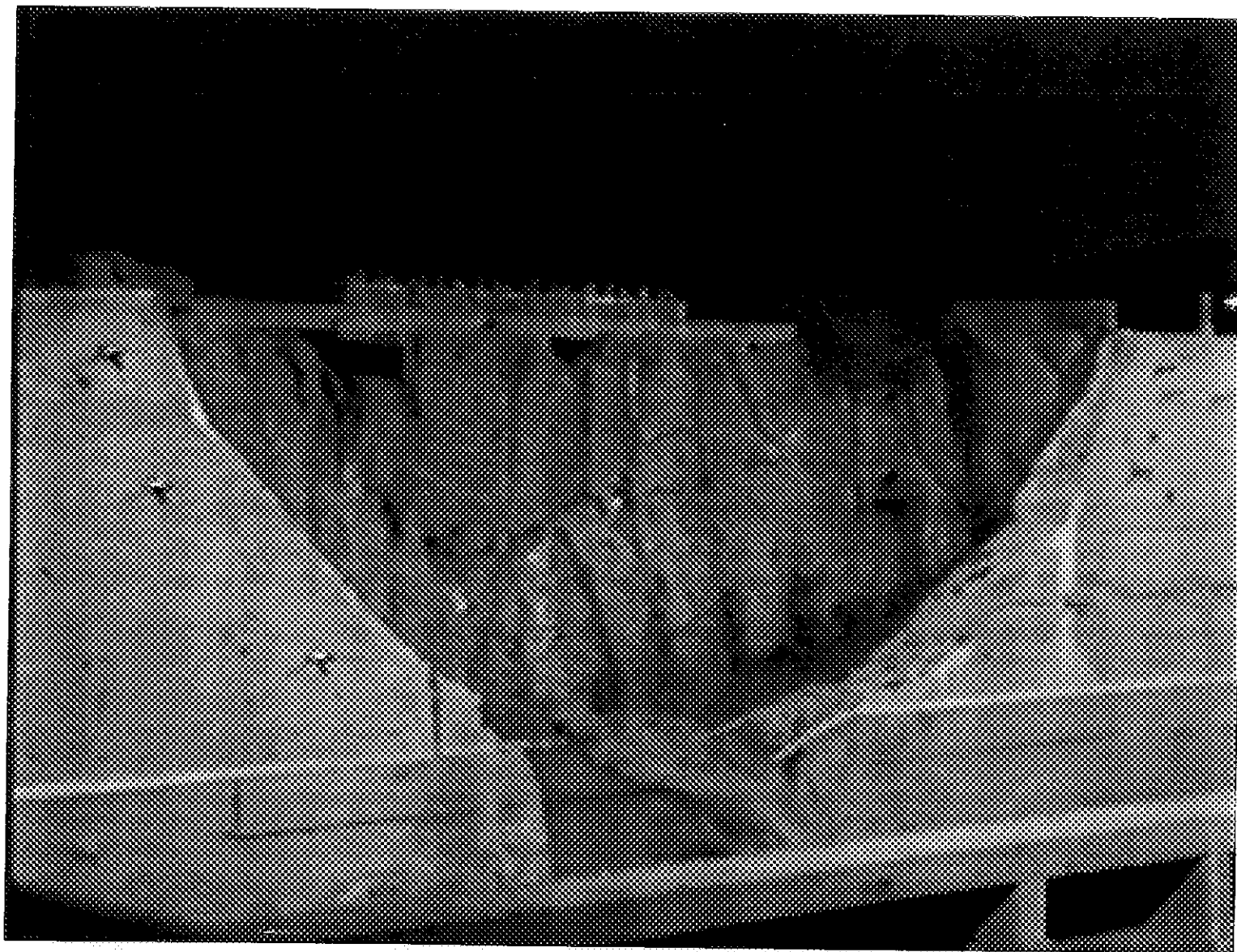


Figure D.14

Final Crack Pattern – Model M13 – Test Date 4/10/01



Figure D.15

Initial Crack Pattern – Model M15 – Test Date 5/1/01



Figure D.17

8.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

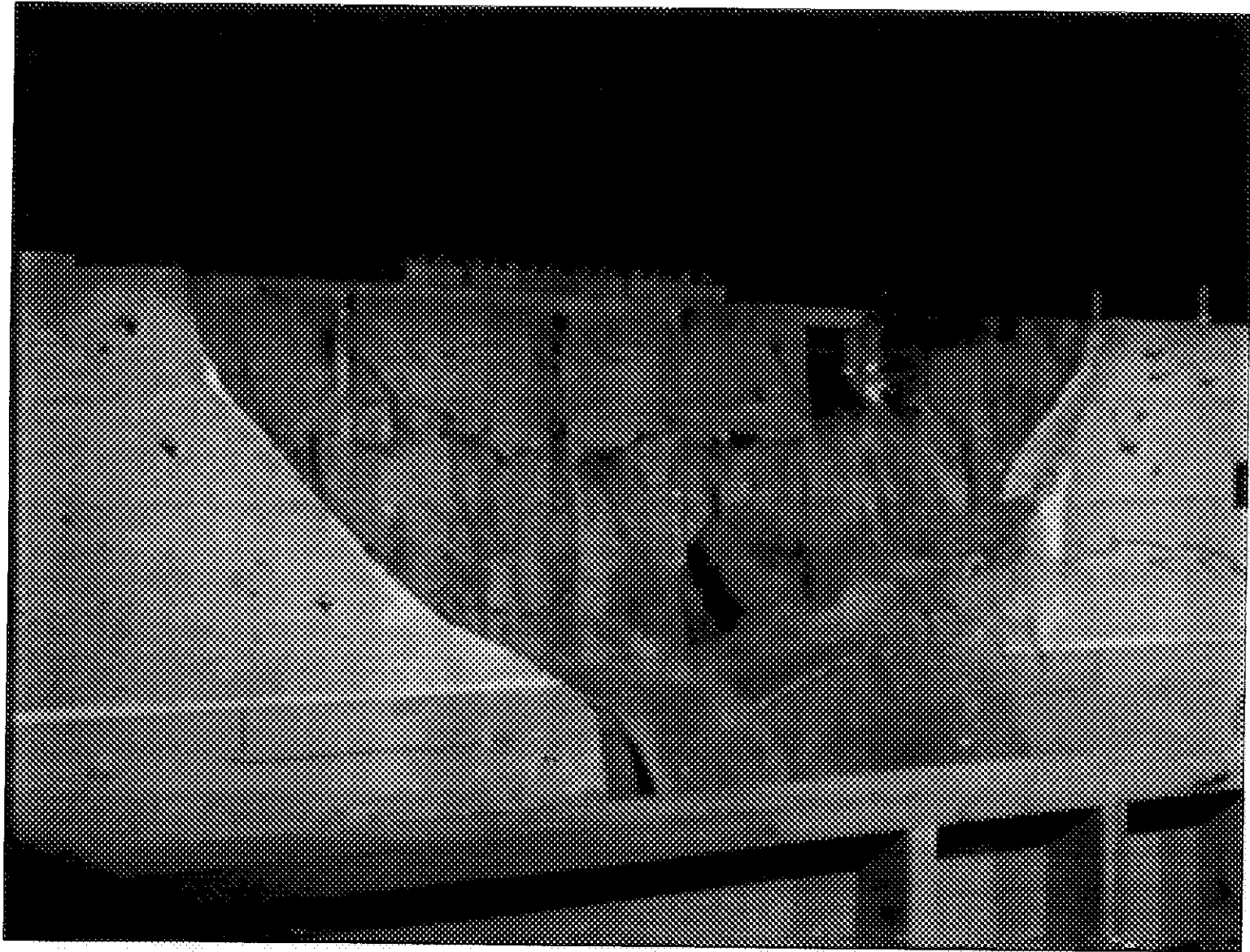


Figure D.18

11.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01



Figure D.19

12.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

Appendix E

Static Results of Linear Elastic Analyses for Five Different Joint Configurations

Monolithic Model : M2 & M8

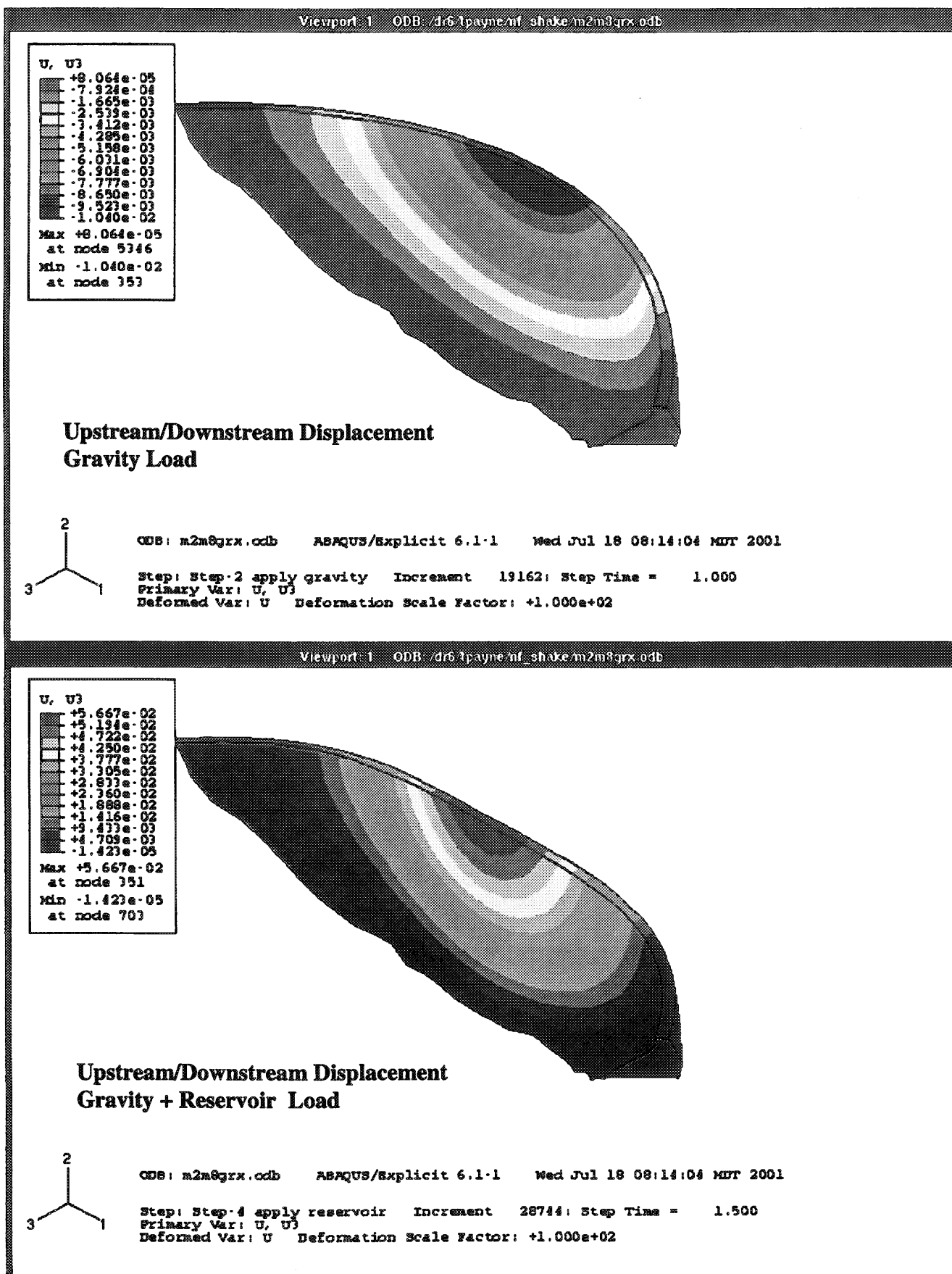
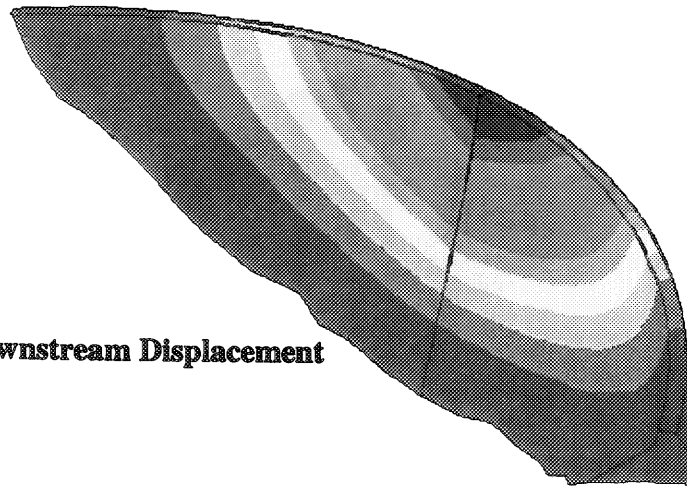
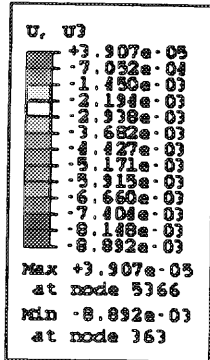


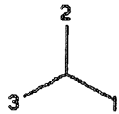
Figure E.1

Single Vertical Joint Model : M6 & M11

Viewport 1 ODB: dr61payne.m6m11.m6m11.grx1.odb



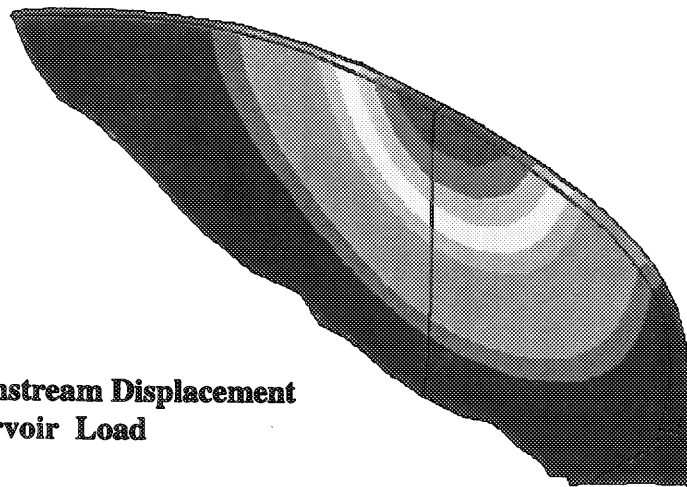
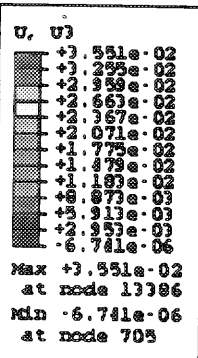
Upstream/Downstream Displacement
Gravity Load



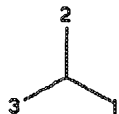
Job created 3-5-01
ODB: m6m11.grx1.odb ABAQUS/Explicit 6.1-1 Wed Aug 15 07:12:25 MDT 2001

Step: Step-2 apply gravity Increment 24482; Step Time = 1.000
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport 1 ODB: dr61payne.m6m11.m6m11.grx1.odb



Upstream/Downstream Displacement
Gravity + Reservoir Load



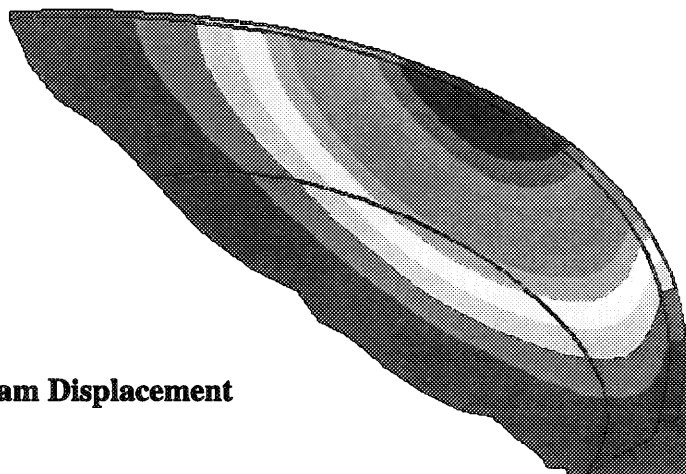
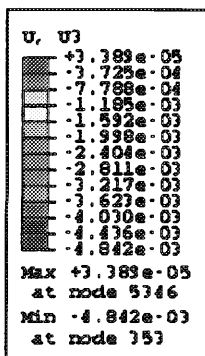
Job created 3-5-01
ODB: m6m11.grx1.odb ABAQUS/Explicit 6.1-1 Wed Aug 15 07:12:25 MDT 2001

Step: Step-4 apply reservoir Increment 36723; Step Time = 1.500
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

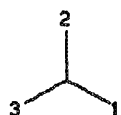
Figure E.2

Single Horizontal Joint Model : M9 & M10

Viewport 1 ODB /dr6 /payne/m9m10/m9m10grx1.odb



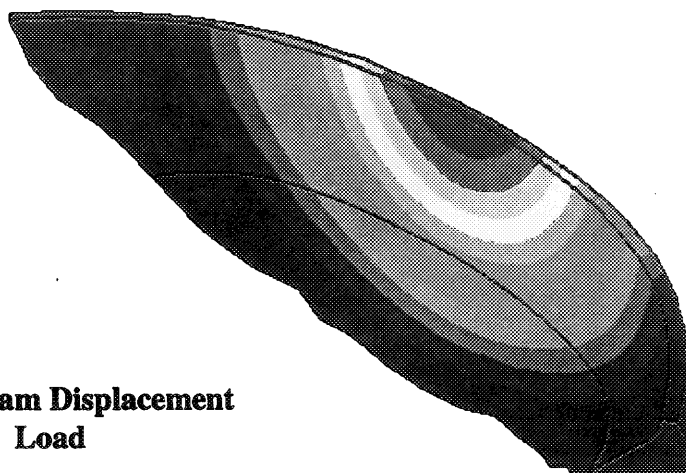
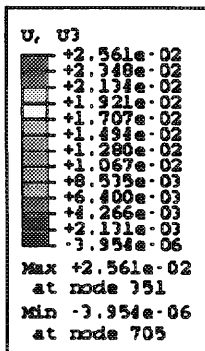
**Upstream/Downstream Displacement
Gravity Load**



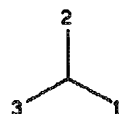
Job created 3-5-01
ODB: m9m10grx1.odb ABAQUS/Explicit 6.1-1 Tue Aug 14 14:27:20 MDT 2001

Step: Step-2 apply gravity Increment 28713 Step Time = 1.000
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport 1 ODB /dr6 /payne/m9m10/m9m10grx1.odb



**Upstream/Downstream Displacement
Gravity + Reservoir Load**



Job created 3-5-01
ODB: m9m10grx1.odb ABAQUS/Explicit 6.1-1 Tue Aug 14 14:27:20 MDT 2001

Step: Step-4 apply reservoir Increment 43070 Step Time = 1.500
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

Figure E.3

Seventeen Vertical Joint Model : M12 & M13

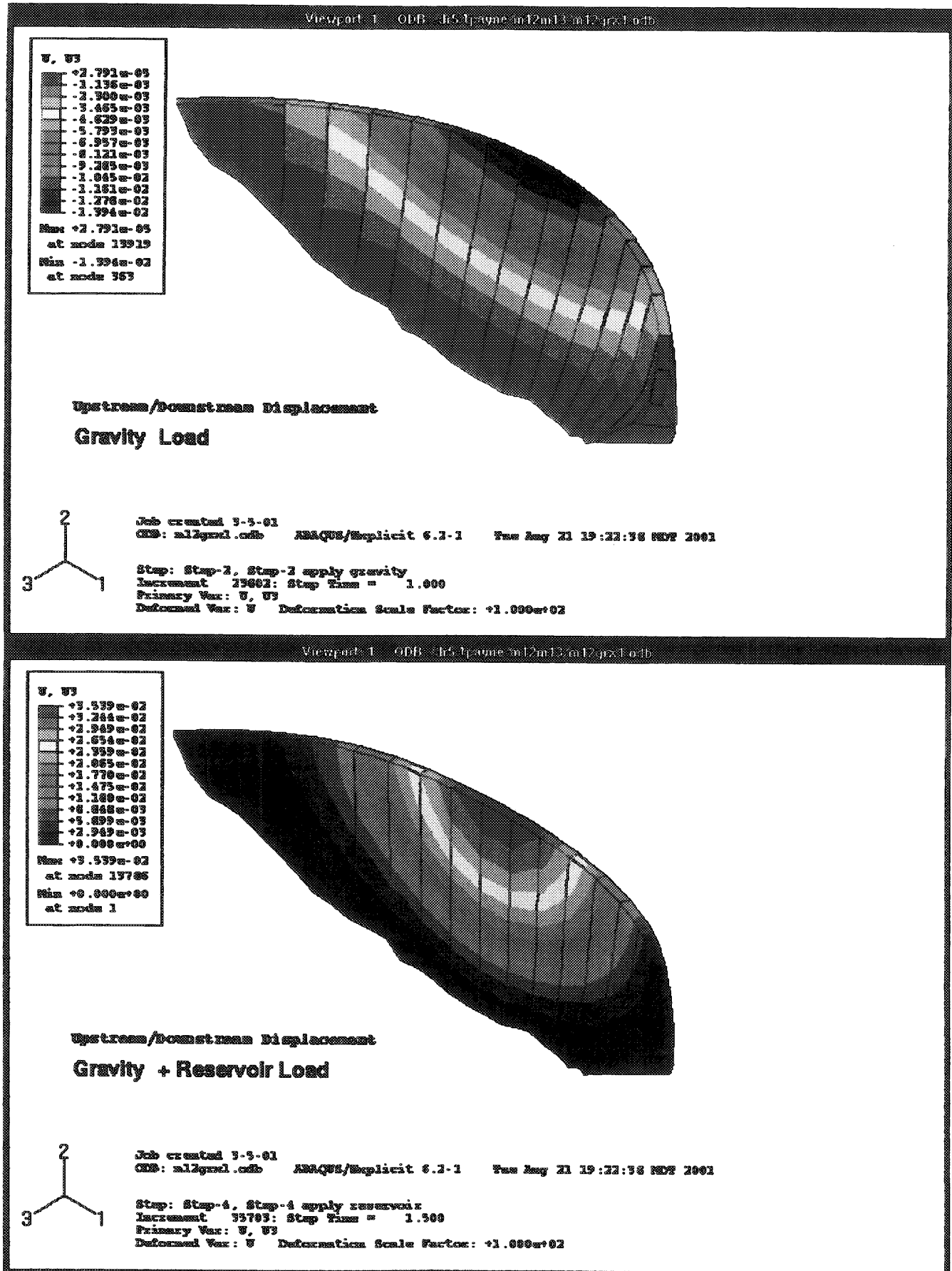


Figure E.4

Seventeen Vertical & Two Horizontal Joint Model M14 & M15

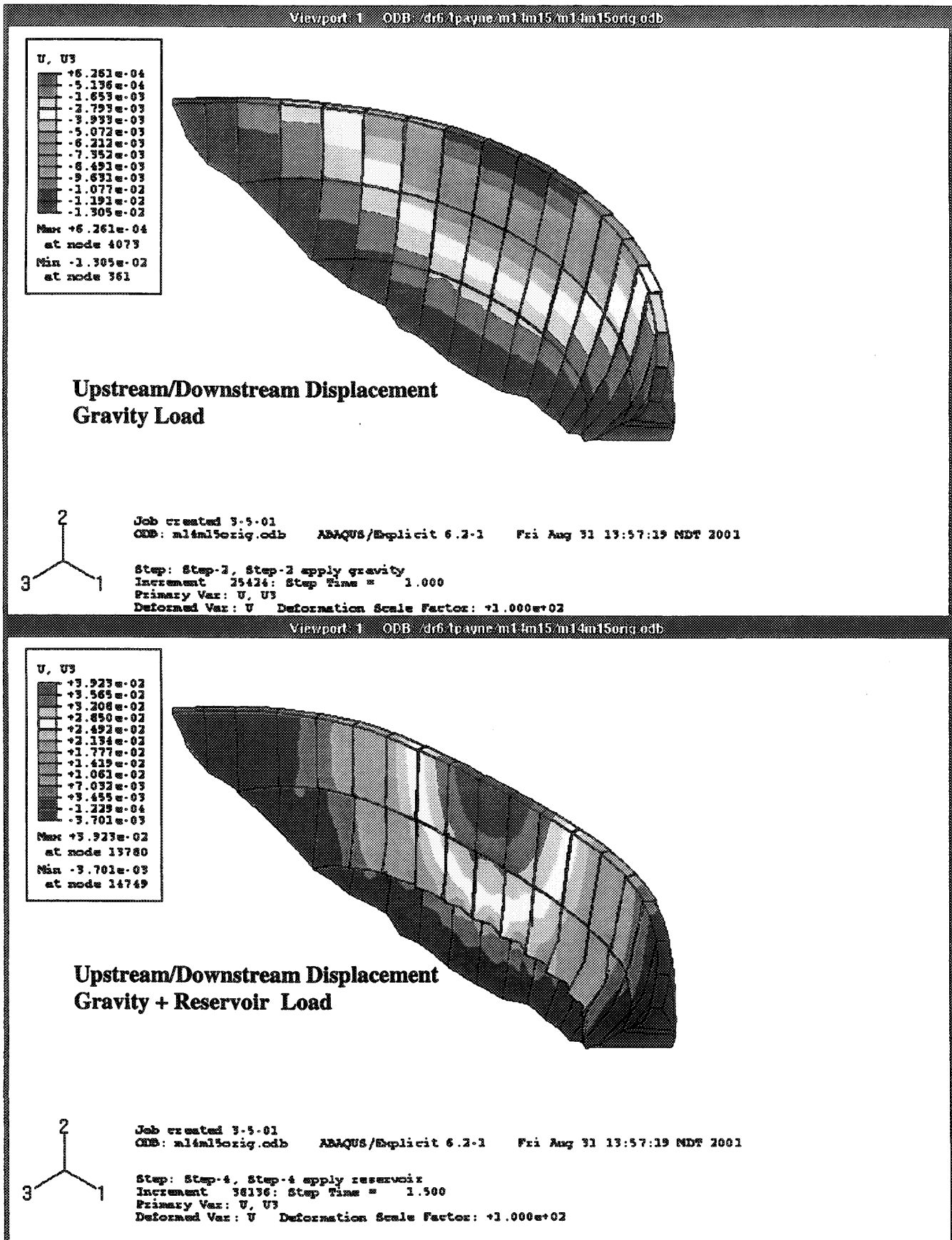
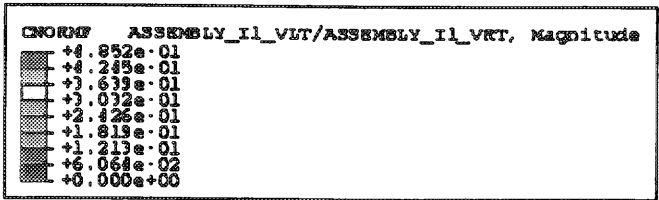


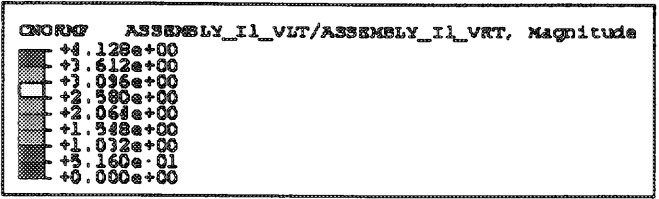
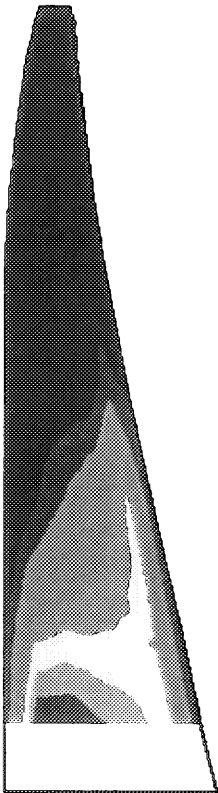
Figure E.5

Single Vertical Joint Model : M6M11

Force on Contact Surface



Gravity



Gravity Plus Reservoir

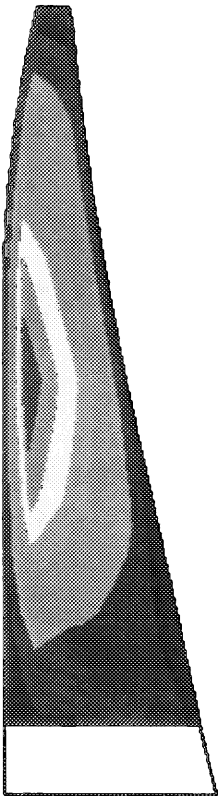
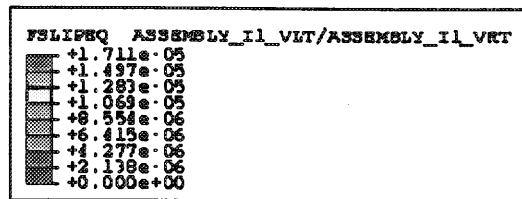


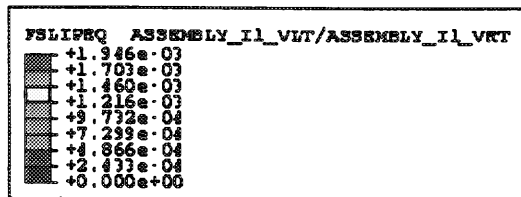
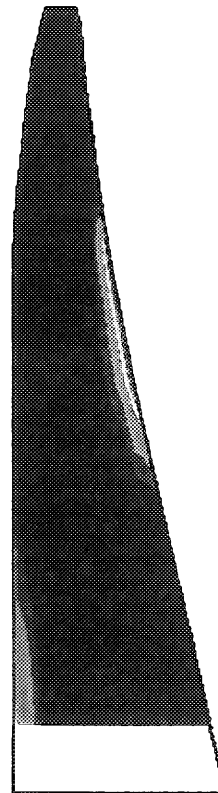
Figure E.6

Single Vertical Joint Model : M6M11

Slip Magnitude on Contact Surface



Gravity



Gravity Plus Reservoir

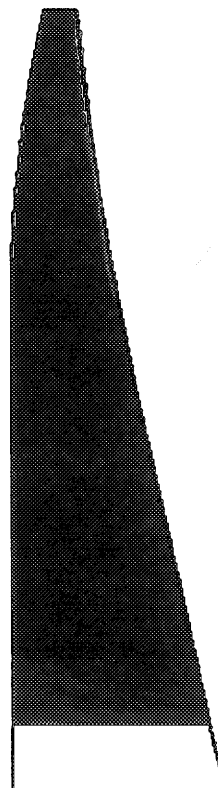
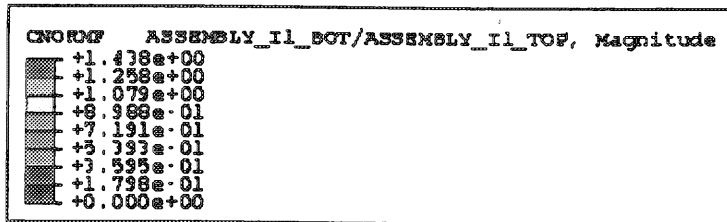


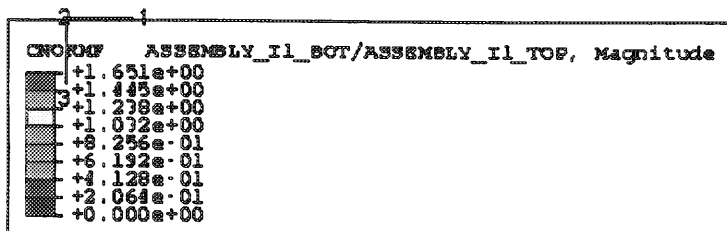
Figure E.7

Single Horizontal Joint Model : M9M10

Force on Contact Surface



Gravity



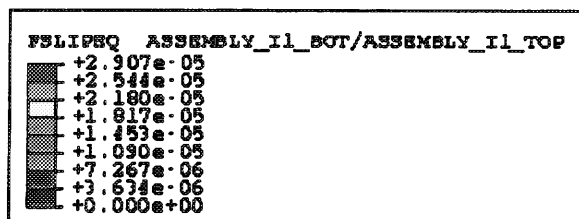
Gravity Plus Reservoir



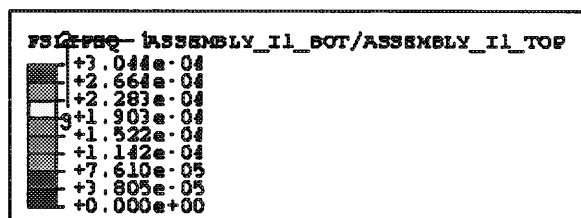
Figure E.8

Single Horizontal Joint Model : M9M10

Slip Magnitude on Contact Surface



Gravity



Gravity Plus Reservoir

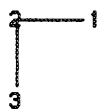
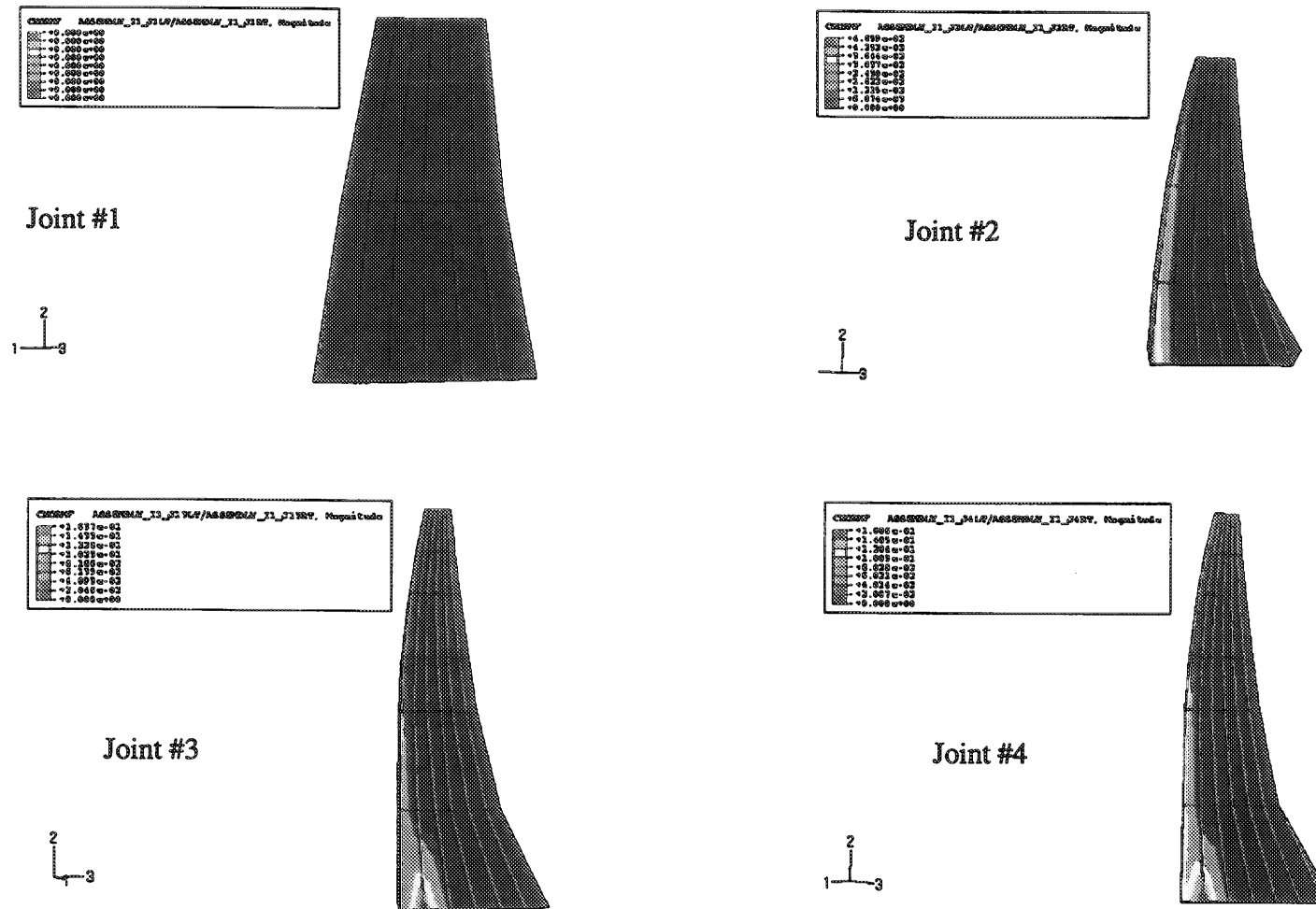


Figure E.9

Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity Load



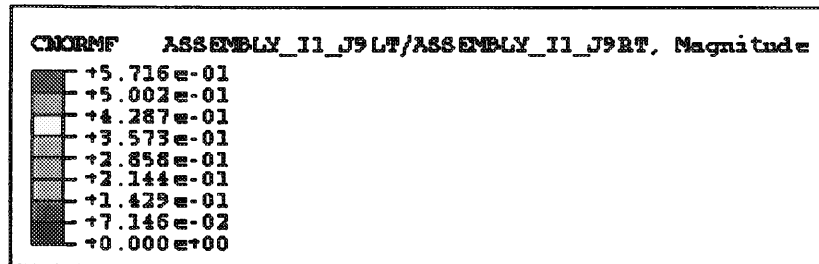
Note : A value of zero for the contact force indicates that the joint is open.

Figure E.10

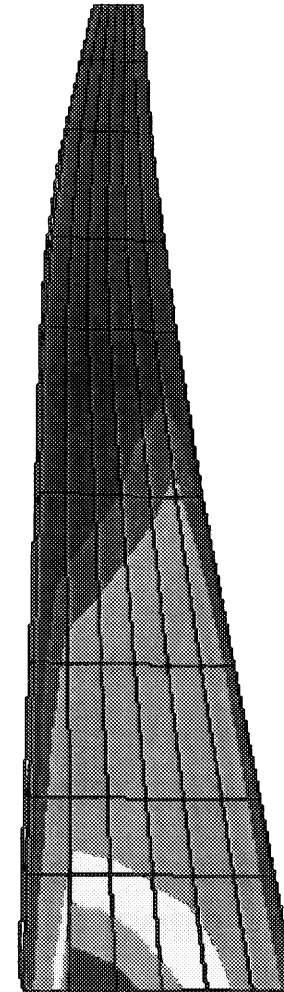
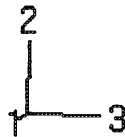
Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity Load



Joint #9
Center joint

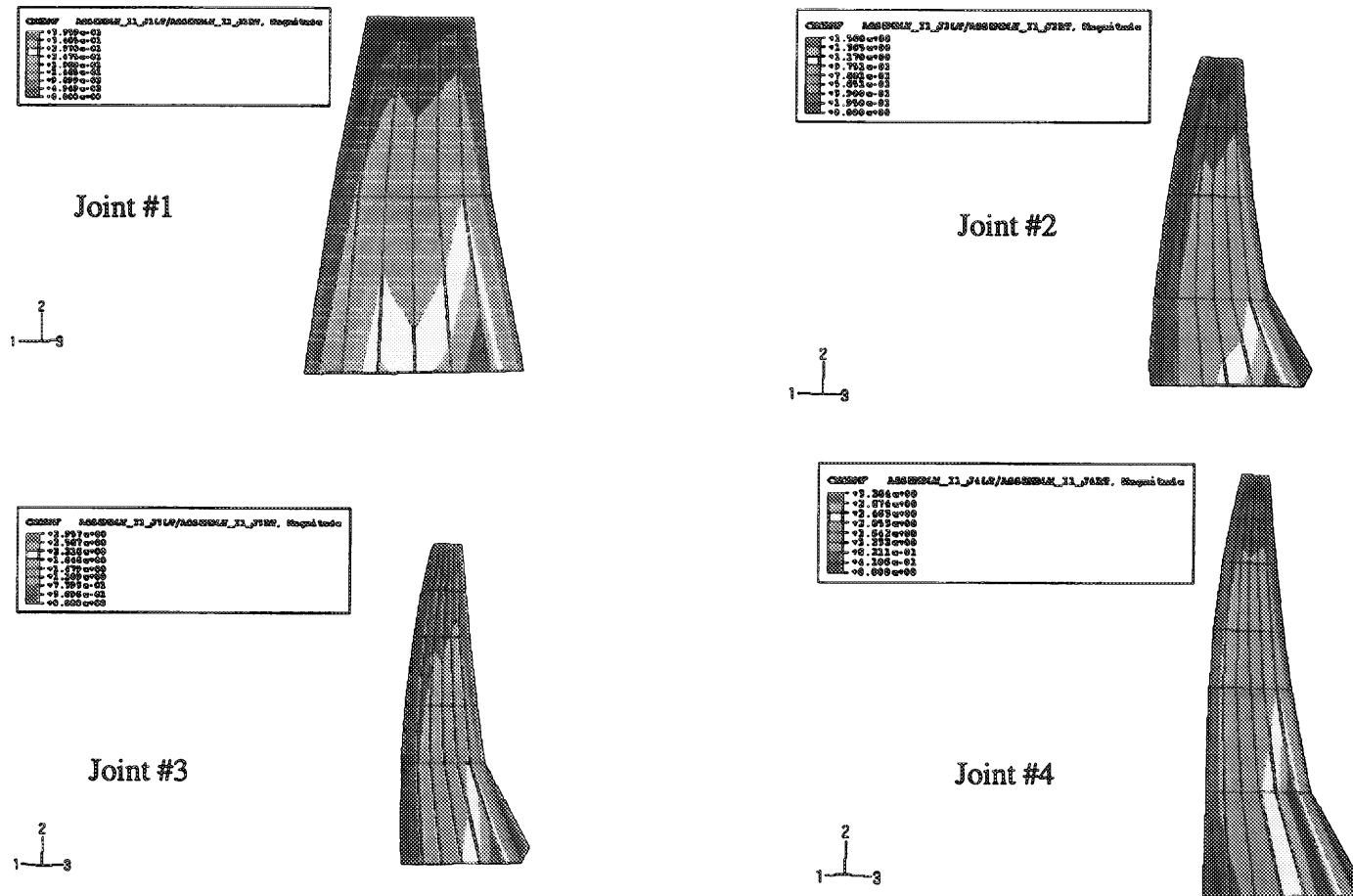


Note : A value of zero for the contact force indicates that the joint is open.

Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load



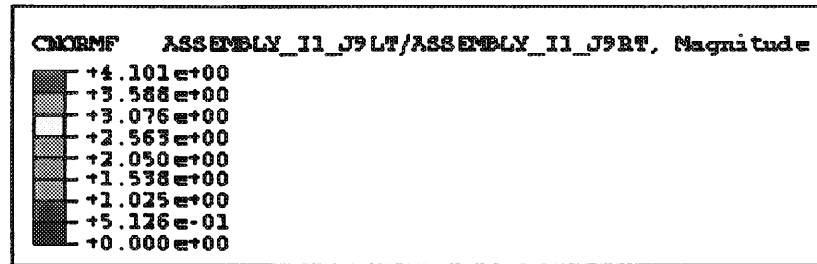
Note : A value of zero for the contact force indicates that the joint is open.

Figure E.12

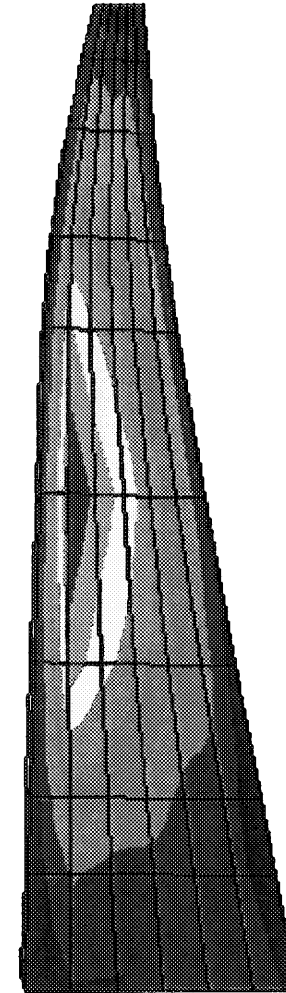
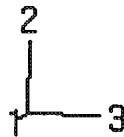
Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load



Joint #9
Center joint



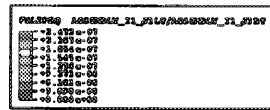
Note : A value of zero for the contact force indicates that the joint is open.

Figure E.13

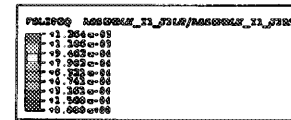
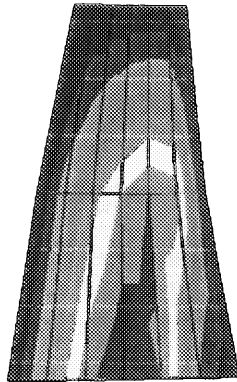
Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

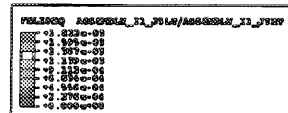
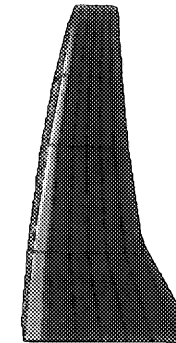
Under Gravity Load



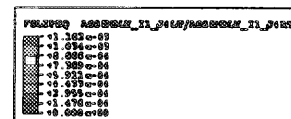
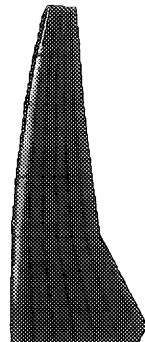
Joint #1



Joint #2



Joint #3



Joint #4

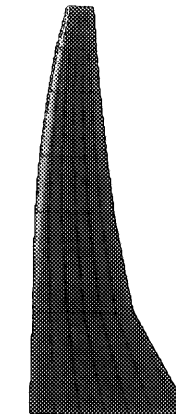
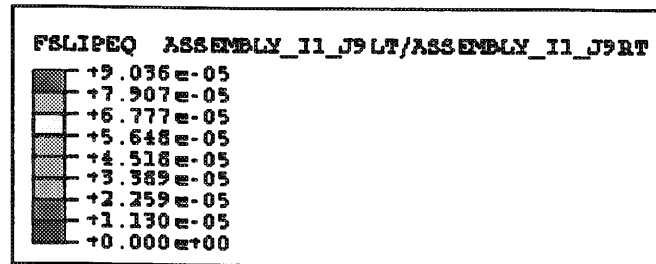


Figure E.14

Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

Under Gravity Load



Joint #9
Center joint

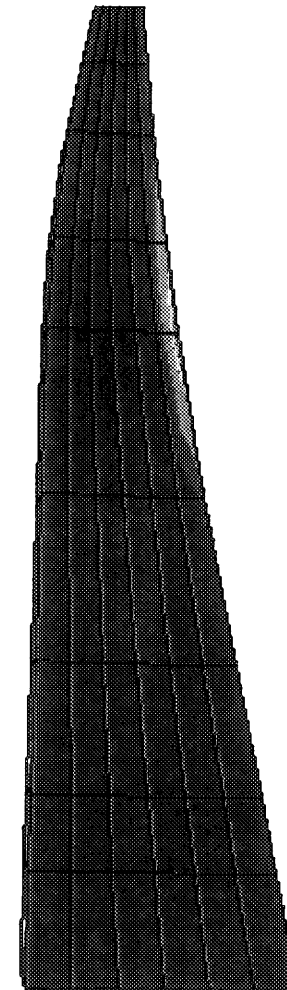
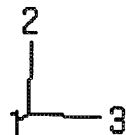
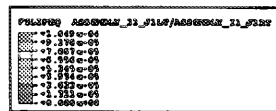


Figure E.15

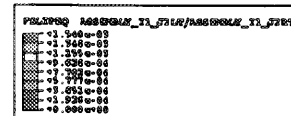
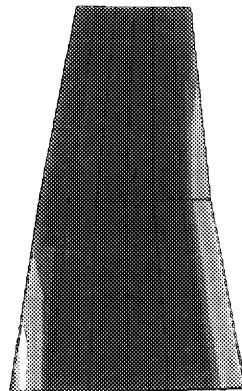
Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

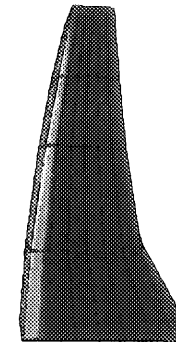
Under Gravity + Reservoir Load



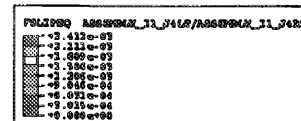
Joint #1



Joint #2



Joint #3



Joint #4

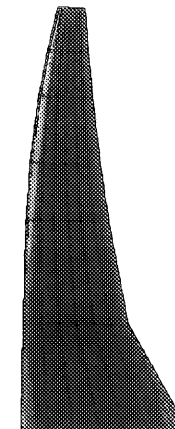
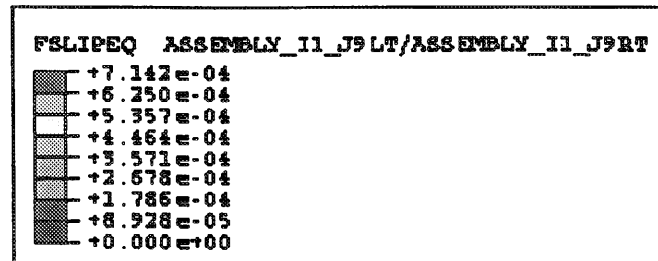


Figure F.16

Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

Under Gravity + Reservoir Load



Joint #9
Center joint

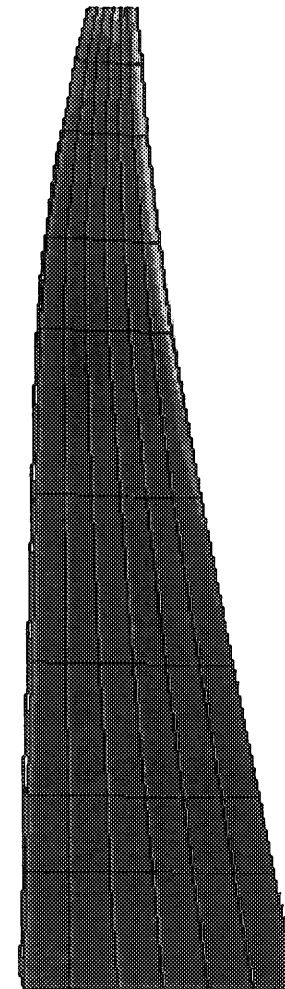
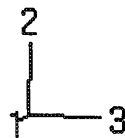


Figure E.17

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity Load

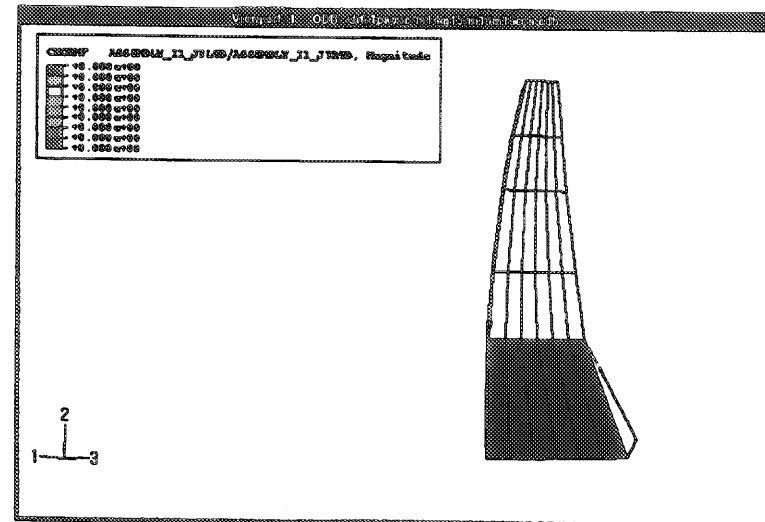
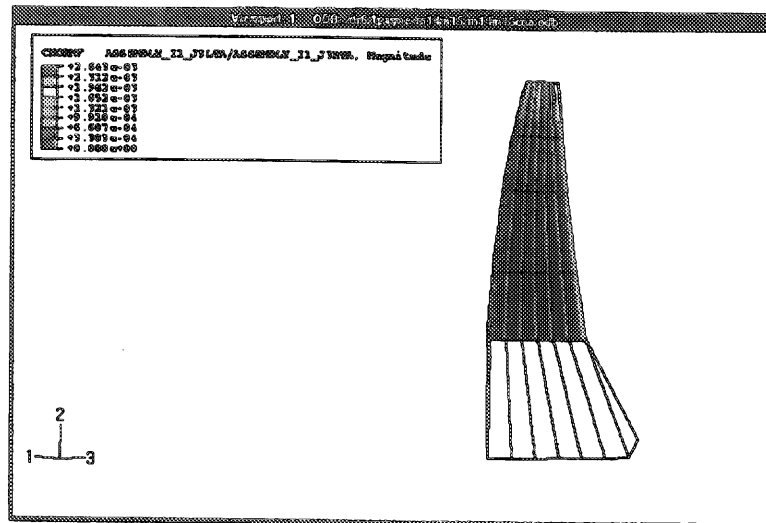
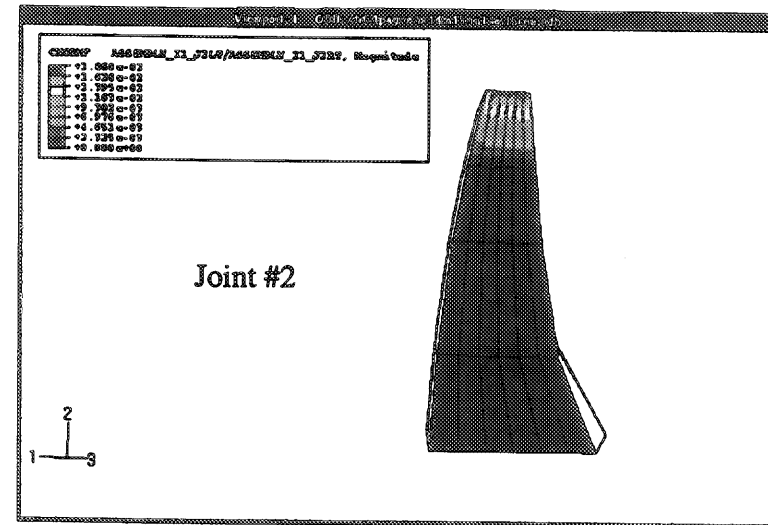
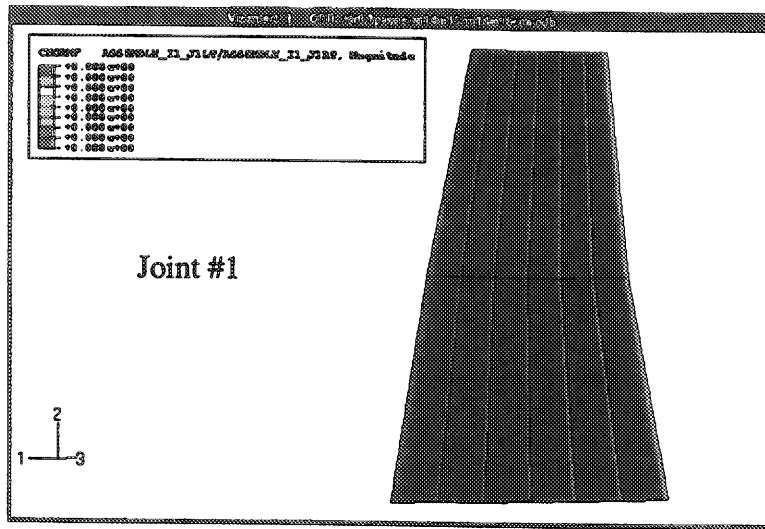


Figure E.18

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Load

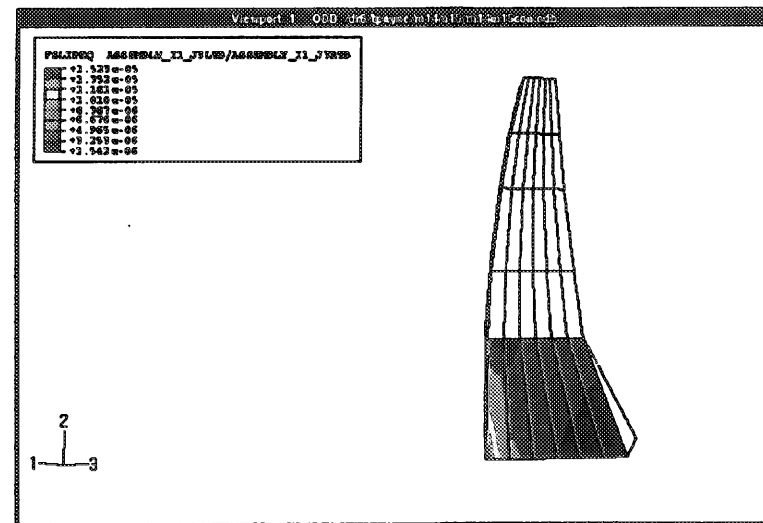
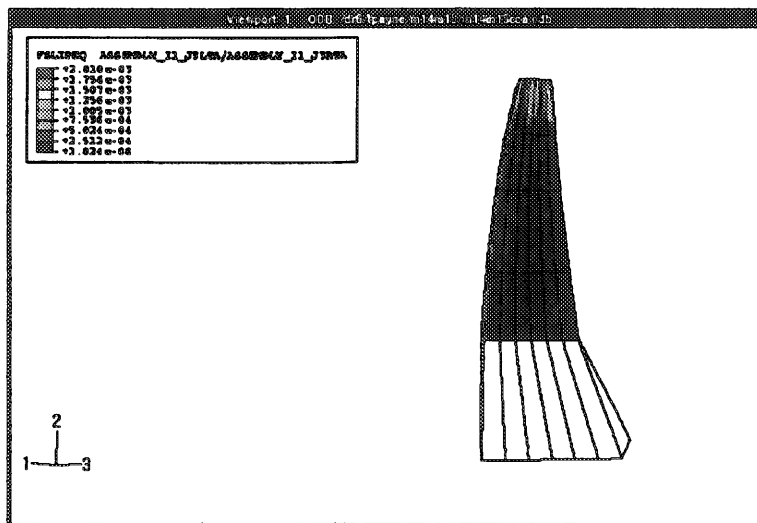
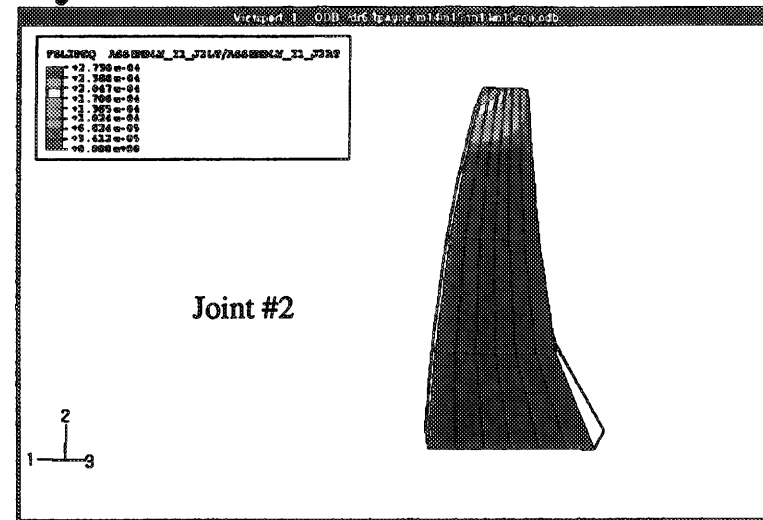
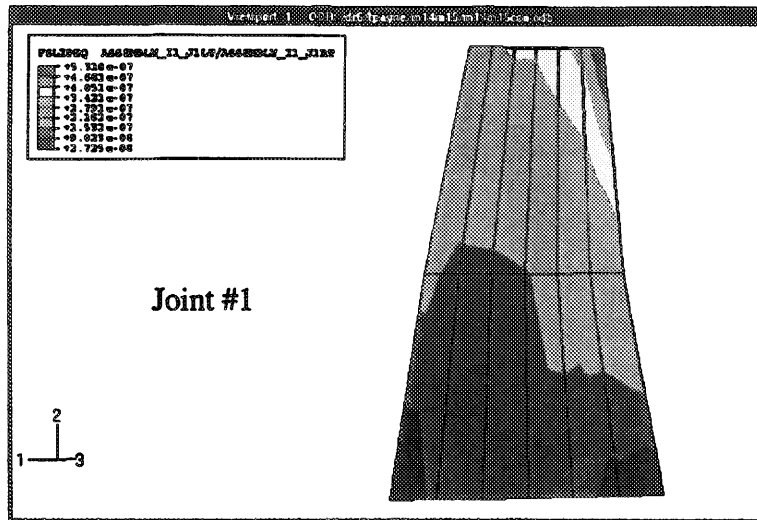


Figure E.19

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity Plus Reservoir Load

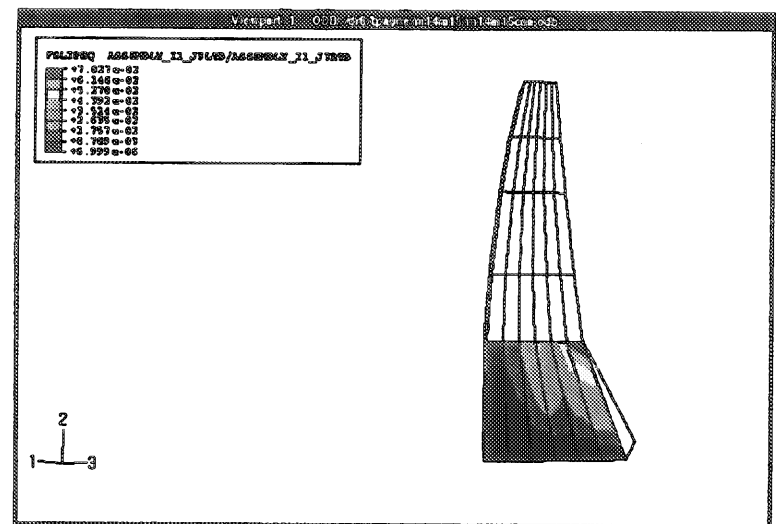
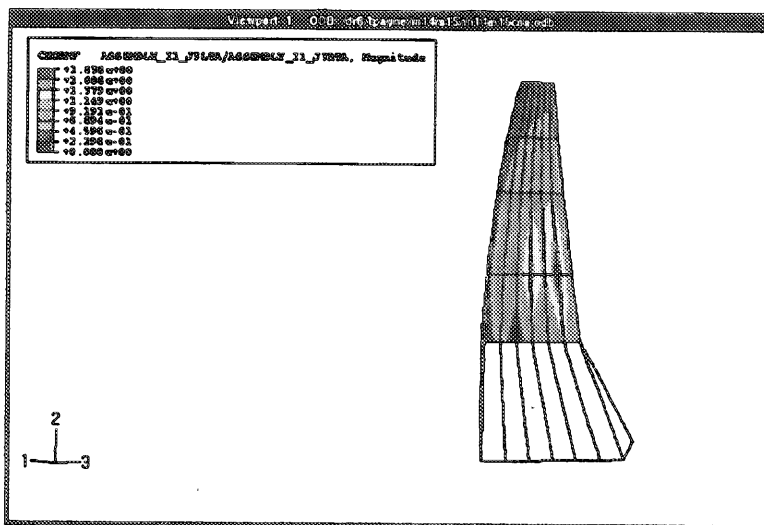
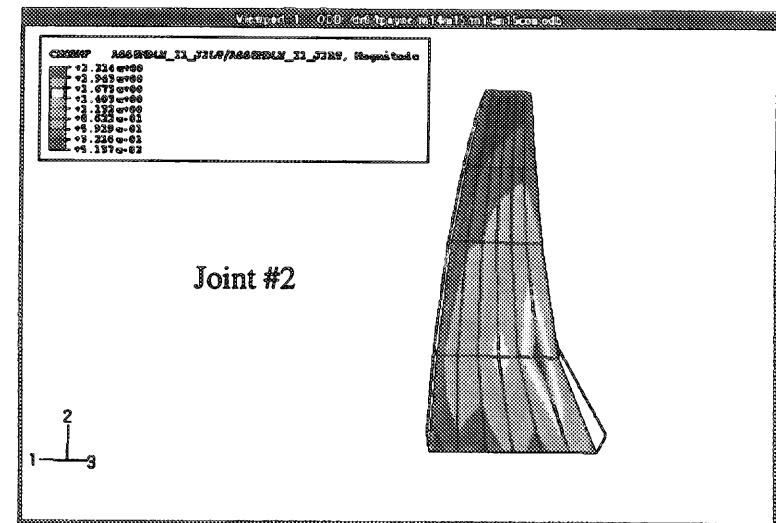
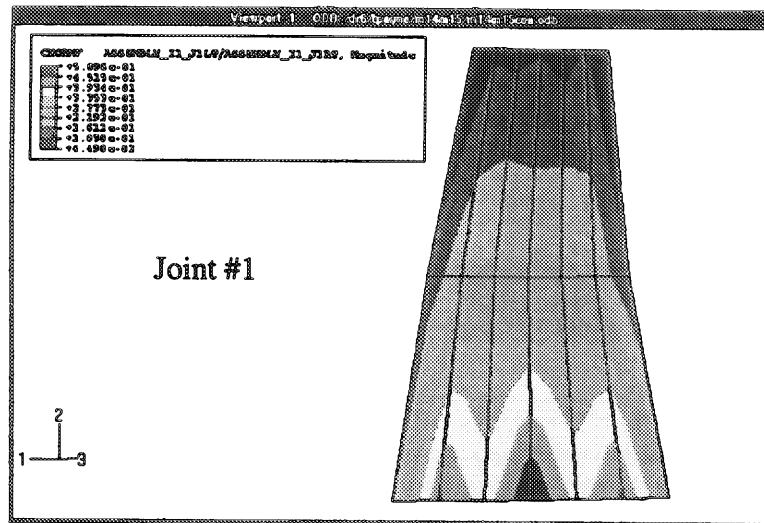


Figure E.20

Figure E.21

The figure displays four contour plots arranged in a 2x2 grid, showing the stress distribution on a tapered, three-dimensional structure. Each plot is labeled with a joint number and includes a legend and a coordinate system.

Joint #1 (Top Left): The legend shows stress values ranging from -1.275×10^{-04} to -1.082×10^{-05} . The structure is shown in a perspective view, with the stress distribution concentrated along the edges.

Joint #2 (Top Right): The legend shows stress values ranging from -9.734×10^{-02} to -1.932×10^{-06} . The structure is shown in a perspective view, with the stress distribution concentrated along the edges.

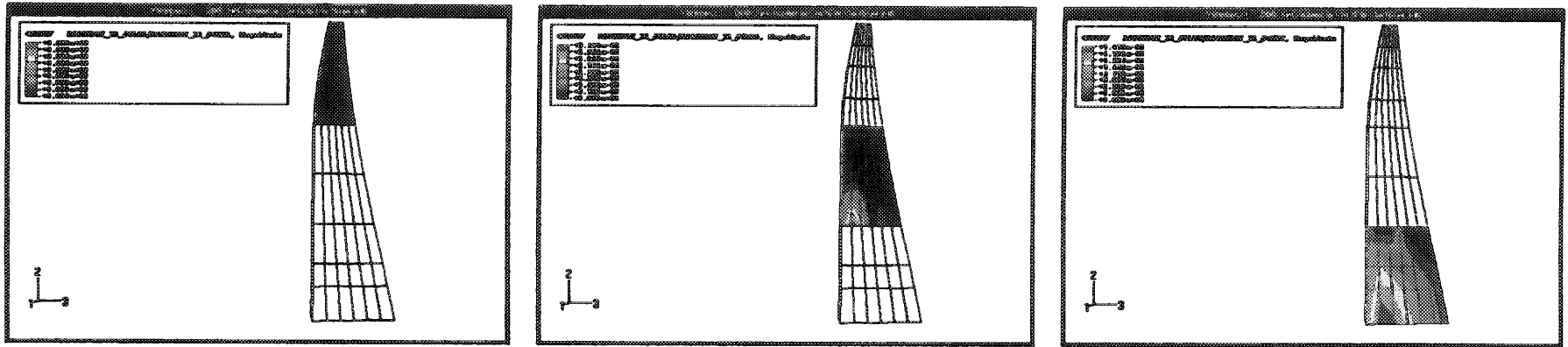
Joint #3 (Bottom Left): The legend shows stress values ranging from -9.926×10^{-02} to -1.282×10^{-06} . The structure is shown in a perspective view, with the stress distribution concentrated along the edges.

Joint #4 (Bottom Right): The legend shows stress values ranging from -7.627×10^{-02} to -6.999×10^{-06} . The structure is shown in a perspective view, with the stress distribution concentrated along the edges.

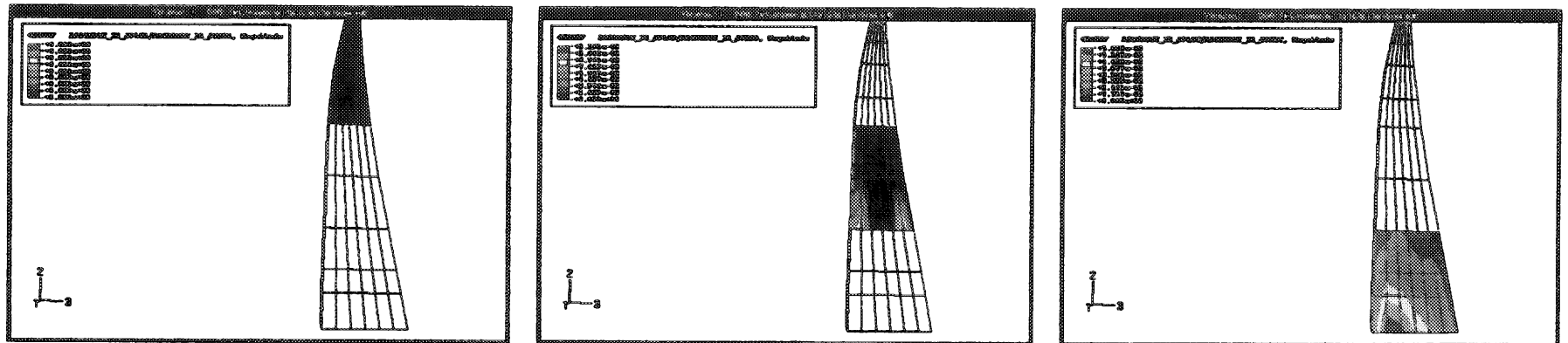
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity Load



Joint #8

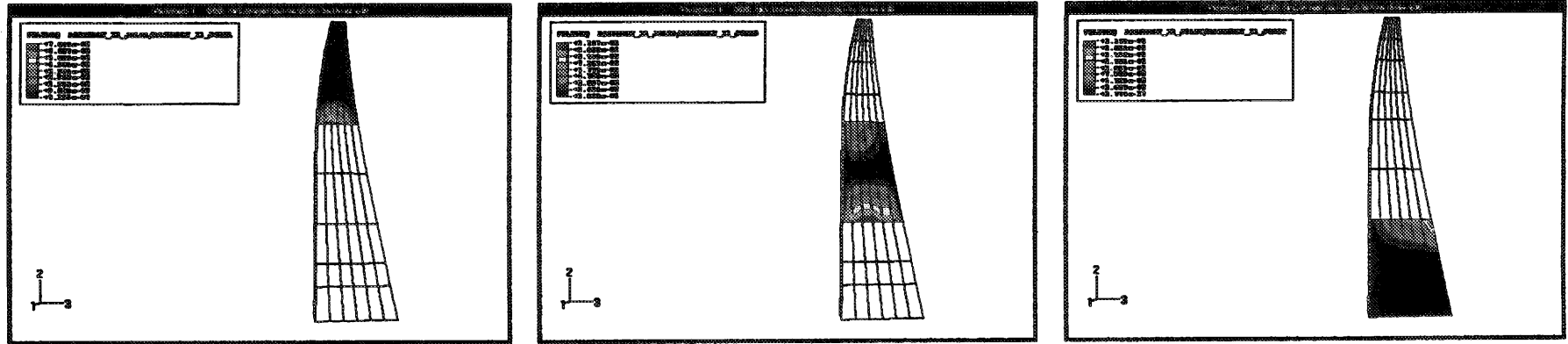


Joint #9

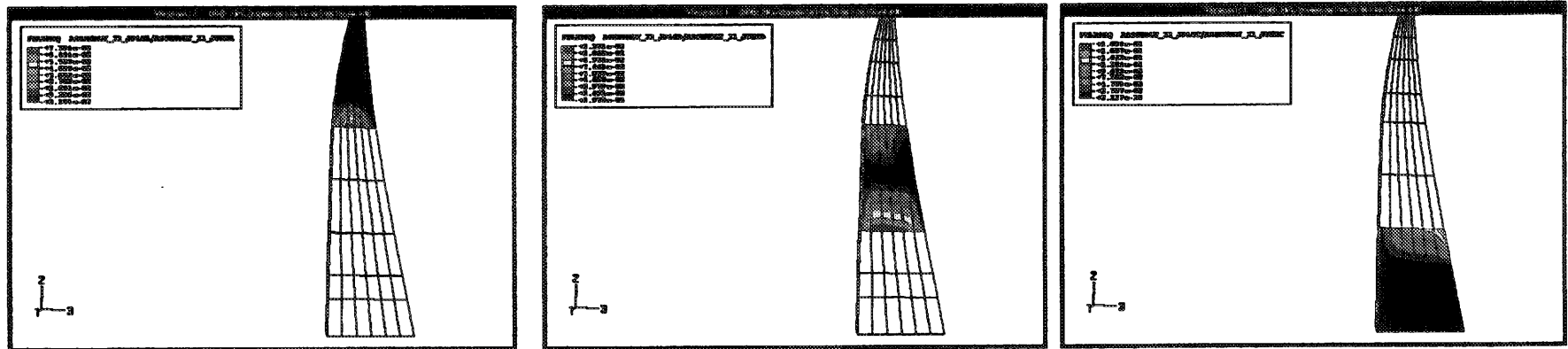
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Plus Reservoir Load



Joint #8

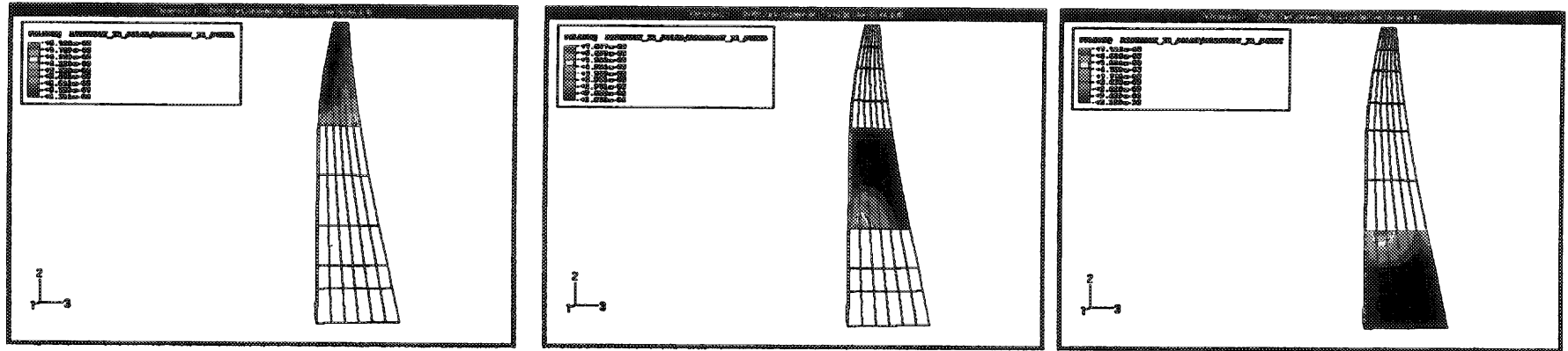


Joint #9

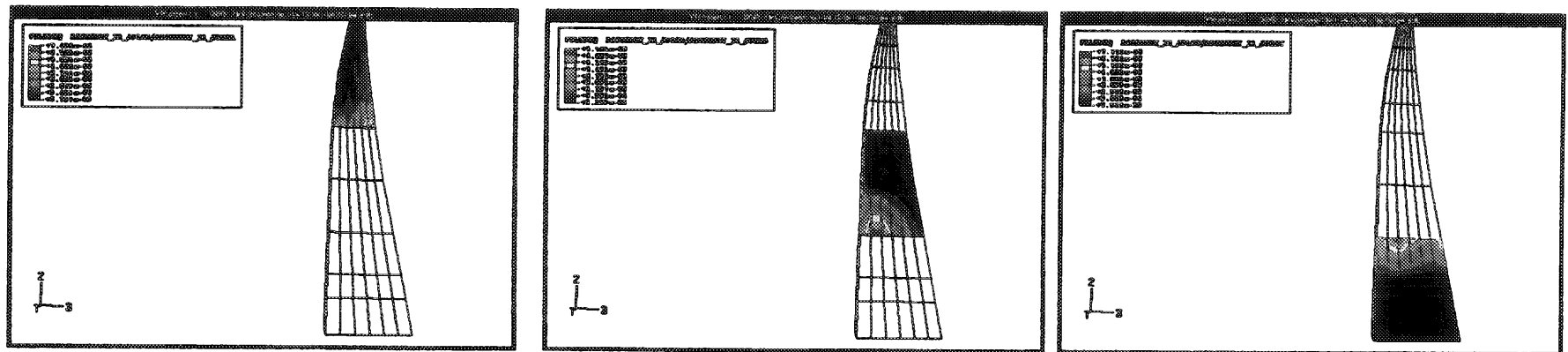
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Load



Joint #8

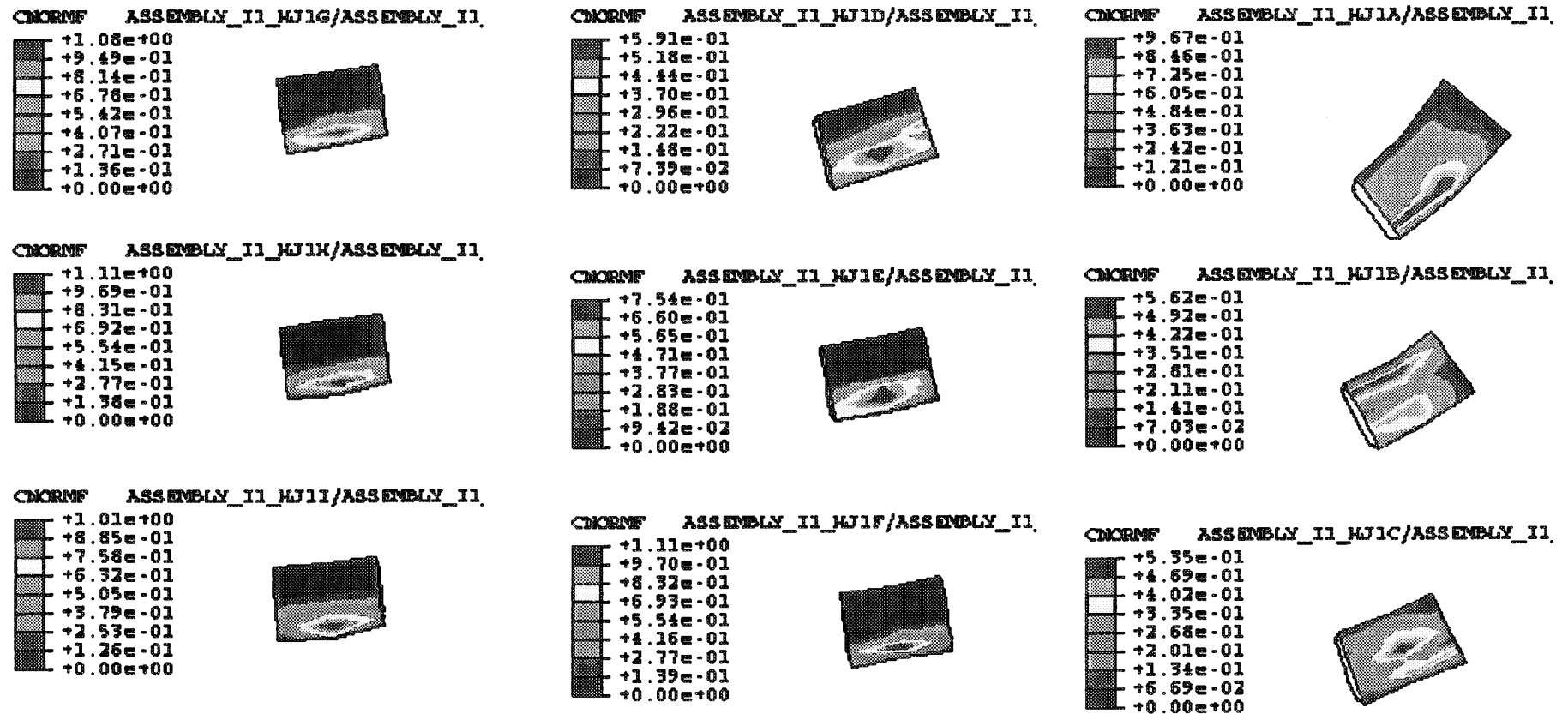


Joint #9

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load



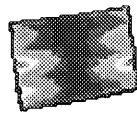
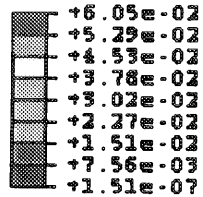
View is looking down on surfaces making up the upper horizontal joint

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

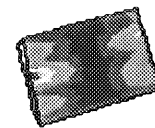
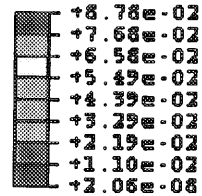
Slip Magnitude on Joint Surfaces

Under Gravity + Reservoir Load

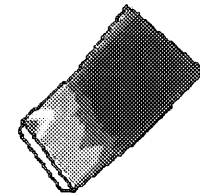
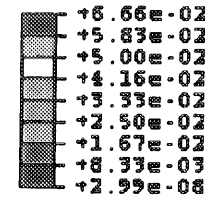
FSLIPEQ ASSEMBLY_I1_MJ1G/ASSEMBLY_I1.



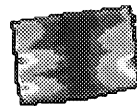
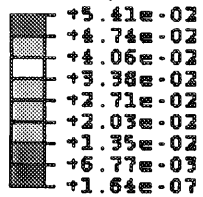
FSLIPEQ ASSEMBLY_I1_MJ1D/ASSEMBLY_I1.



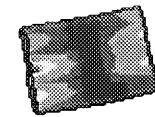
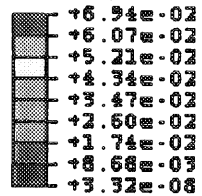
FSLIPEQ ASSEMBLY_I1_MJ1A/ASSEMBLY_I1.



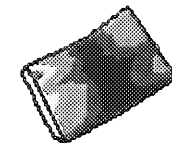
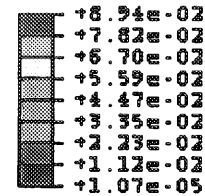
FSLIPEQ ASSEMBLY_I1_MJ1H/ASSEMBLY_I1.



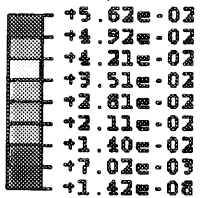
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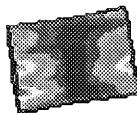
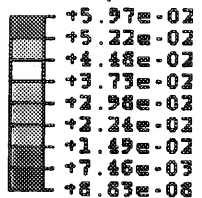
FSLIPEQ ASSEMBLY_I1_MJ1B/ASSEMBLY_I1.



FSLIPEQ ASSEMBLY_I1_MJ1I/ASSEMBLY_I1.



FSLIPEQ ASSEMBLY_I1_MJ1F/ASSEMBLY_I1.



FSLIPEQ ASSEMBLY_I1_MJ1C/ASSEMBLY_I1.

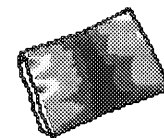
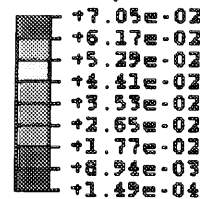


Figure E.26 View is looking down on surfaces making up the upper horizontal joint

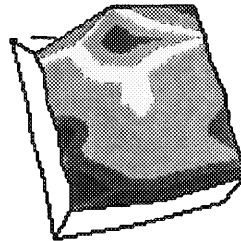
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load

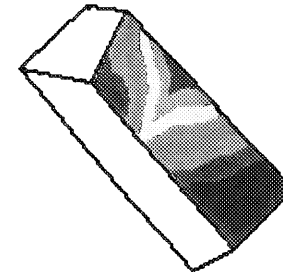
CNORMF ASSEMBLY_I1_HJ3F/ASSEMBLY_I1.

+1.52e+00
+1.33e+00
+1.14e+00
+9.49e-01
+7.59e-01
+5.69e-01
+3.80e-01
+1.90e-01
+0.00e+00



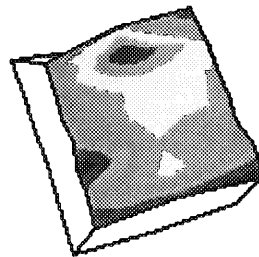
CNORMF ASSEMBLY_I1_HJ3K/ASSEMBLY_I1_HJ

+1.36e+00
+1.19e+00
+1.02e+00
+8.47e-01
+6.78e-01
+5.08e-01
+3.39e-01
+1.69e-01
+0.00e+00



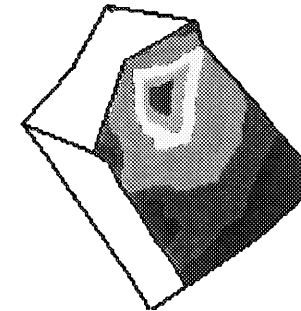
CNORMF ASSEMBLY_I1_HJ3G/ASSEMBLY_I1.

+1.39e+00
+1.22e+00
+1.04e+00
+8.69e-01
+6.95e-01
+5.21e-01
+3.48e-01
+1.74e-01
+0.00e+00



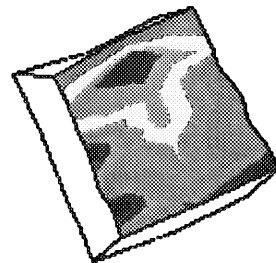
CNORMF ASSEMBLY_I1_HJ3J/ASSEMBLY_I1.

+2.41e+00
+2.11e+00
+1.81e+00
+1.51e+00
+1.21e+00
+9.05e-01
+6.03e-01
+3.02e-01
+0.00e+00



CNORMF ASSEMBLY_I1_HJ3H/ASSEMBLY_I1.

+1.25e+00
+1.10e+00
+9.40e-01
+7.83e-01
+6.27e-01
+4.70e-01
+3.13e-01
+1.57e-01
+0.00e+00



CNORMF ASSEMBLY_I1_HJ3I/ASSEMBLY_I1_HJ

+1.53e+00
+1.34e+00
+1.15e+00
+9.58e-01
+7.66e-01
+5.75e-01
+3.83e-01
+1.92e-01
+0.00e+00

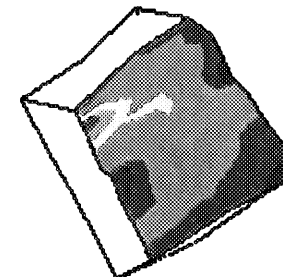


Figure E.27

View is looking down on surfaces making up the lower horizontal joint

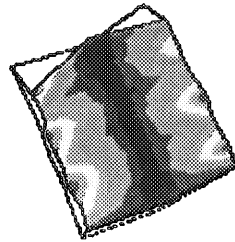
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity + Reservoir Load

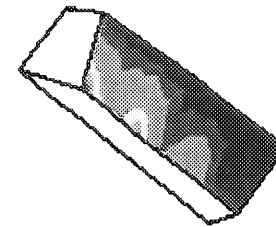
FSLIPEQ ASSEMBLY_I1_MJ3F/ASSEMBLY_I1.

+1.26e-01
+1.11e-01
+9.58e-02
+8.07e-02
+6.56e-02
+5.06e-02
+3.55e-02
+2.04e-02
+5.33e-03



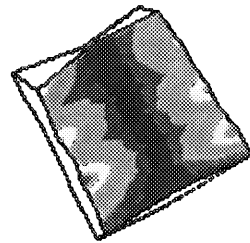
FSLIPEQ ASSEMBLY_I1_MJ3K/ASSEMBLY_I1.

+5.82e-02
+5.09e-02
+4.37e-02
+3.64e-02
+2.91e-02
+2.18e-02
+1.46e-02
+7.28e-03
+2.58e-17



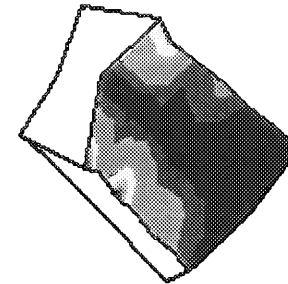
FSLIPEQ ASSEMBLY_I1_MJ3G/ASSEMBLY_I1.

+1.37e-01
+1.21e-01
+1.05e-01
+8.85e-02
+7.22e-02
+5.59e-02
+3.96e-02
+2.33e-02
+6.96e-03



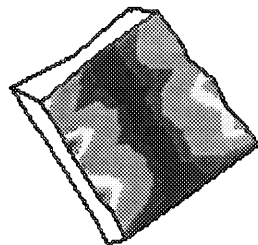
FSLIPEQ ASSEMBLY_I1_MJ3J/ASSEMBLY_I1.

+1.40e-01
+1.22e-01
+1.05e-01
+8.77e-02
+7.04e-02
+5.31e-02
+3.57e-02
+1.84e-02
+1.05e-03



FSLIPEQ ASSEMBLY_I1_MJ3H/ASSEMBLY_I1.

+1.31e-01
+1.16e-01
+1.00e-01
+8.43e-02
+6.87e-02
+5.30e-02
+3.74e-02
+2.17e-02
+6.10e-03



FSLIPEQ ASSEMBLY_I1_MJ3I/ASSEMBLY_I1.

+1.69e-01
+1.49e-01
+1.28e-01
+1.08e-01
+8.75e-02
+6.72e-02
+4.69e-02
+2.66e-02
+6.22e-03

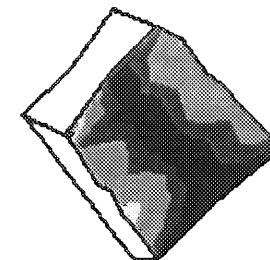


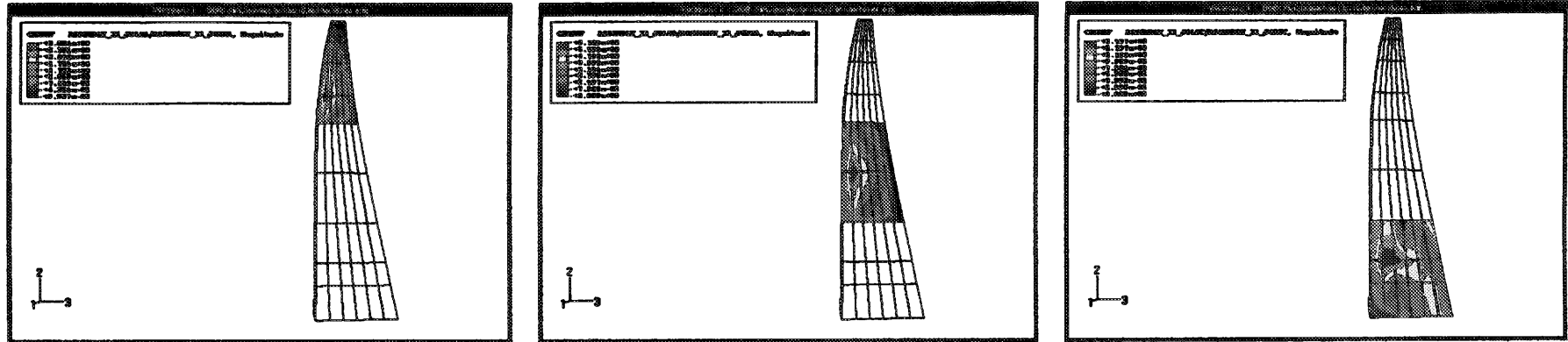
Figure E.28

View is looking down on surfaces making up the lower horizontal joint

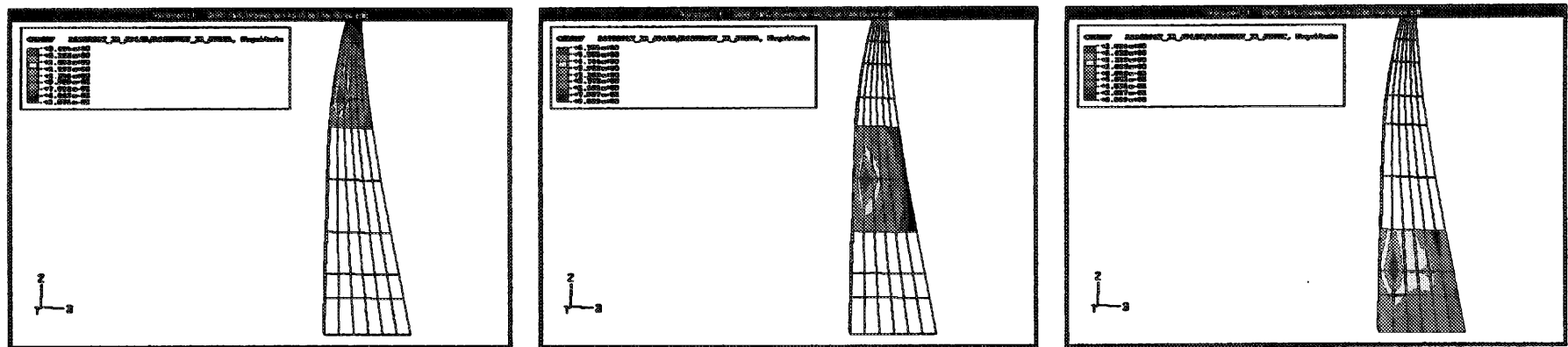
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

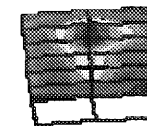
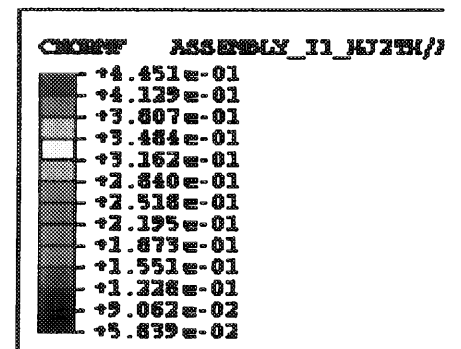
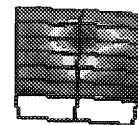
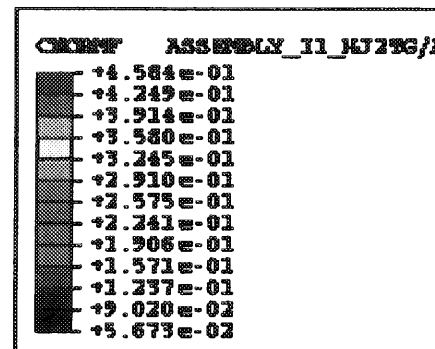
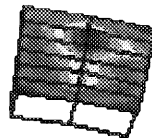
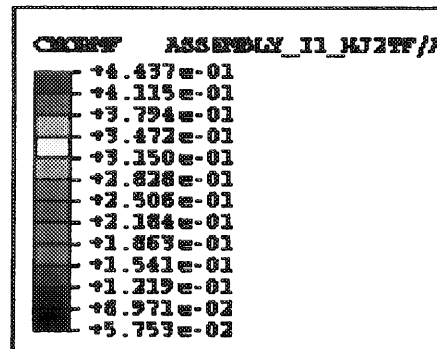
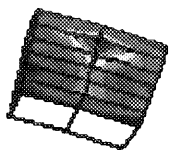
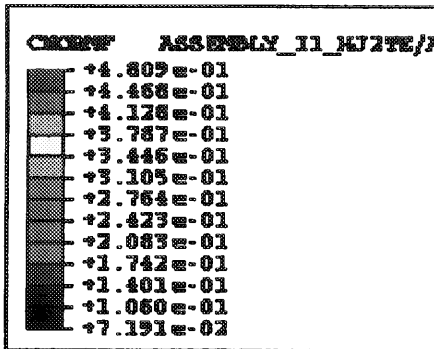
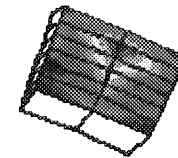
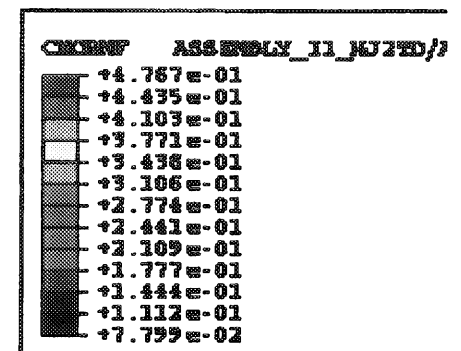
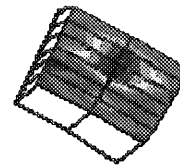
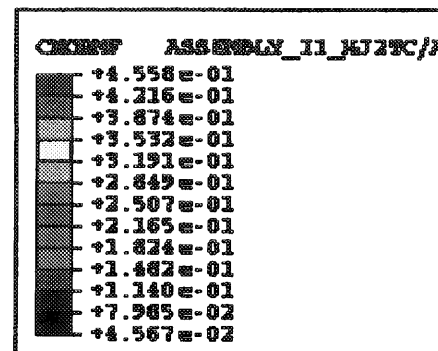
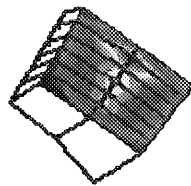
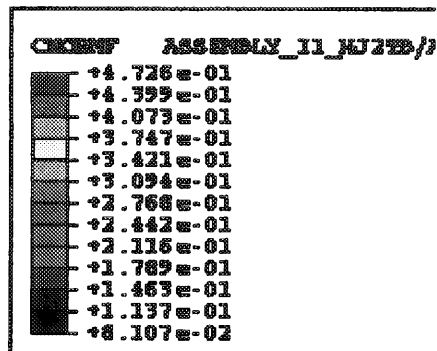
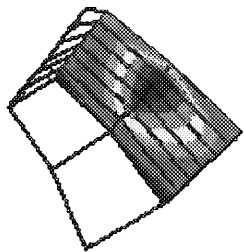
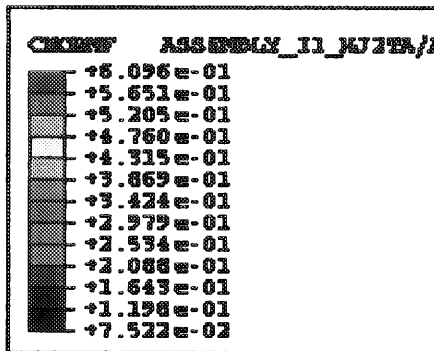
Under Gravity Plus Reservoir Load



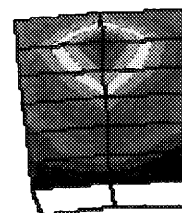
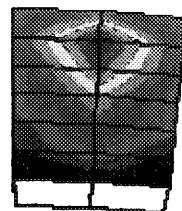
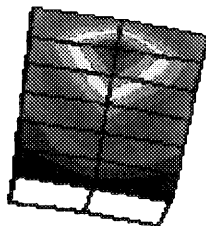
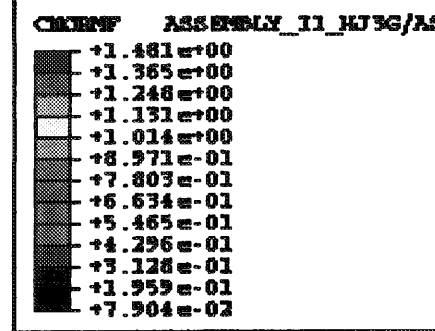
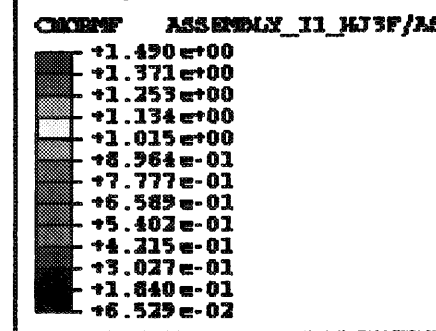
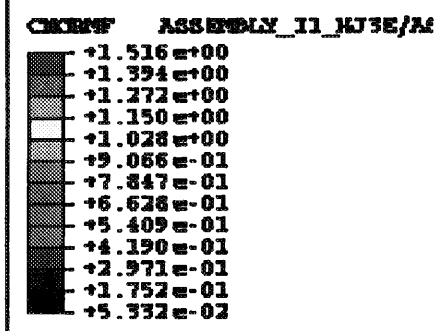
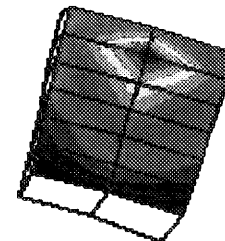
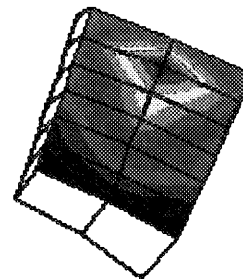
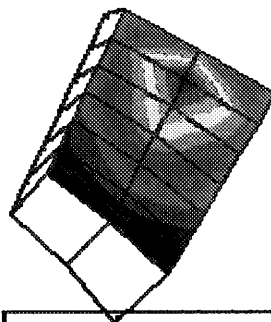
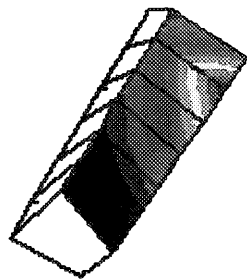
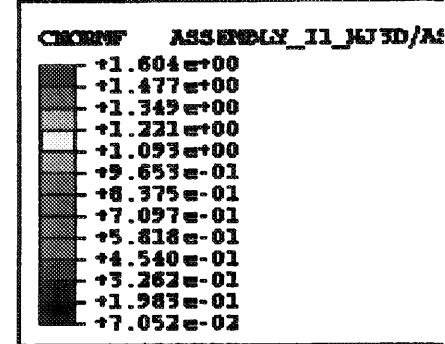
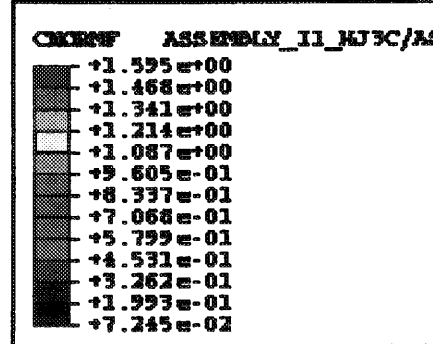
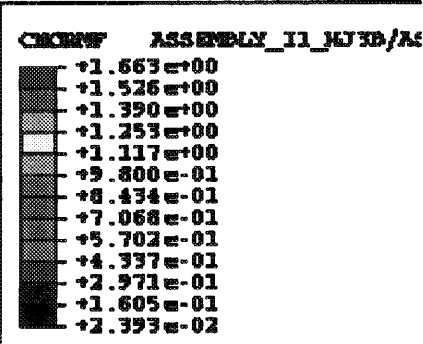
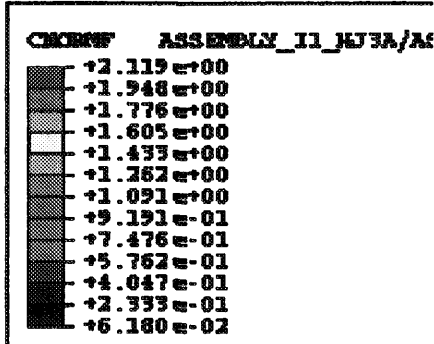
Joint #8



Joint #9

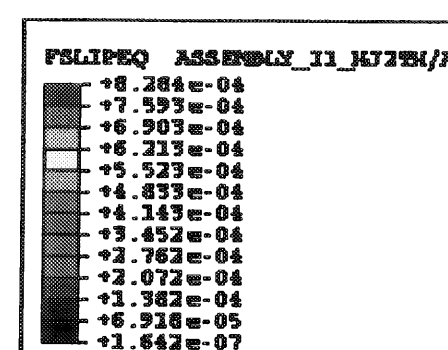
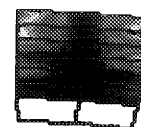
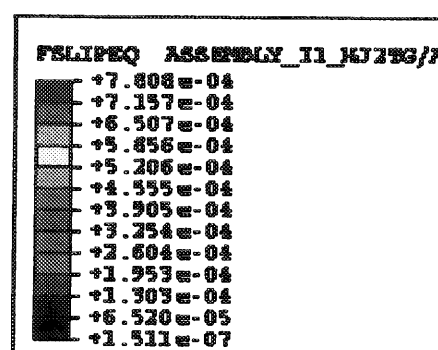
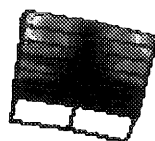
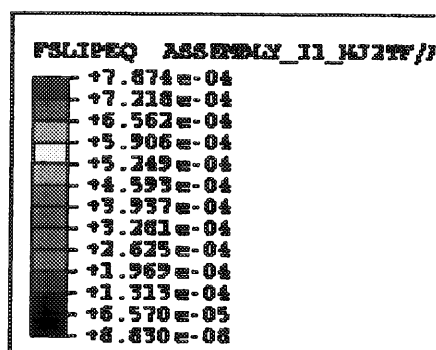
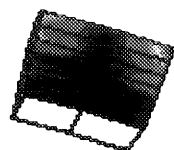
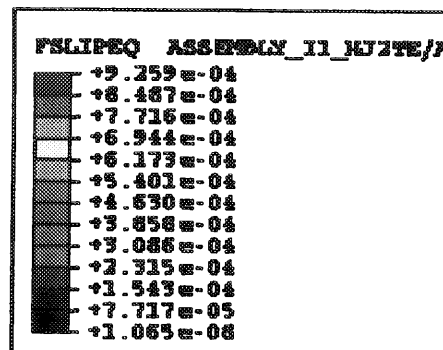
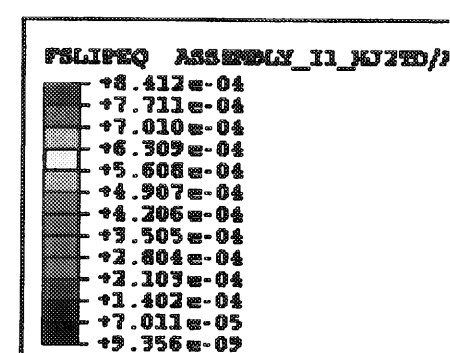
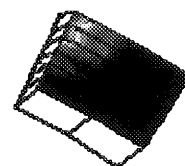
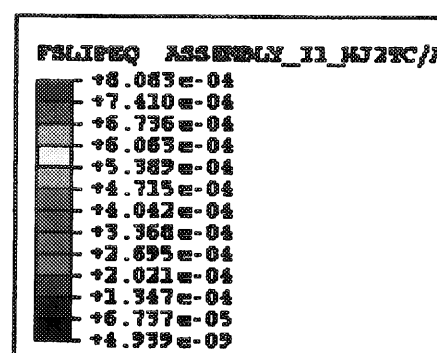
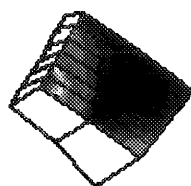
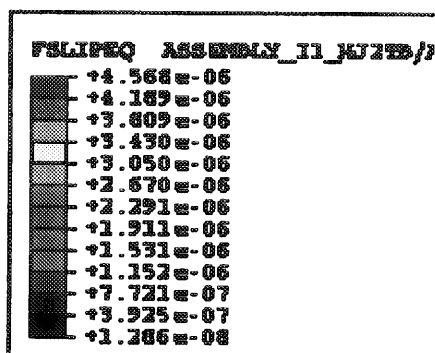
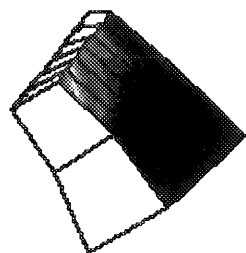
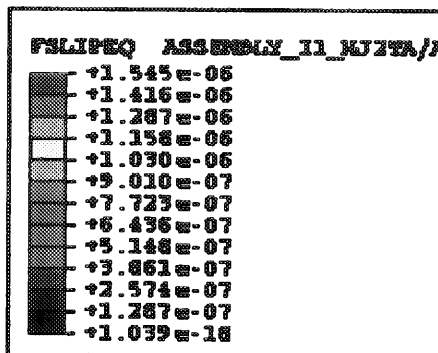


Seventeen Vertical & Two Horizontal Joint Model : M14 M15
Normal Force On Surfaces Of the Upper Horizontal Joint
Gravity Load



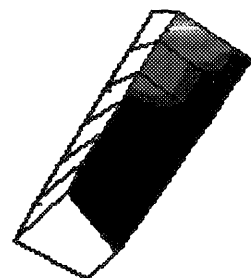
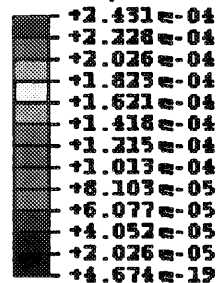
Seventeen Vertical &
Two Horizontal Joint Model
M14 M15
Normal Force On
Surfaces Of the
Lower Horizontal Joint
Gravity + Reservoir Load

Figure E.31

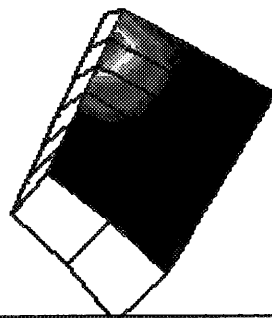
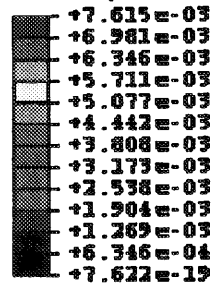


Seventeen Vertical & Two Horizontal Joint Model : M14 M15
Slip Magnitude On Surfaces Of the Upper Horizontal Joint
Gravity Load

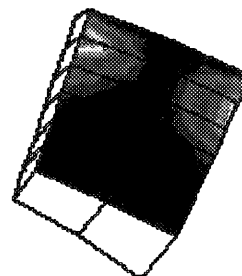
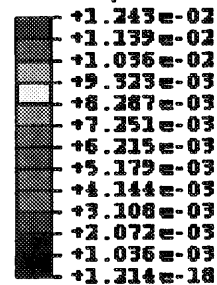
FSLIPEQ ASSEMBLY_I1_MJ3A/A2



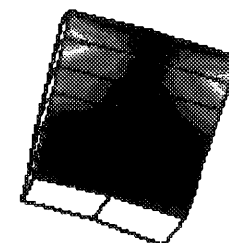
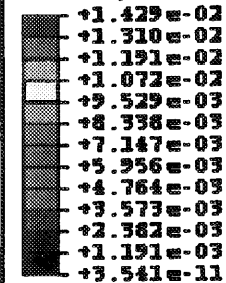
FSLIPEQ ASSEMBLY_I1_MJ3B/A2



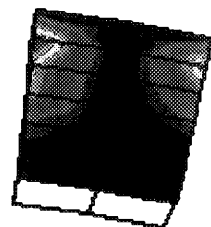
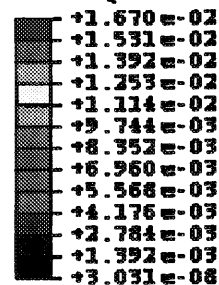
FSLIPEQ ASSEMBLY_I1_MJ3C/A2



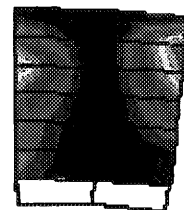
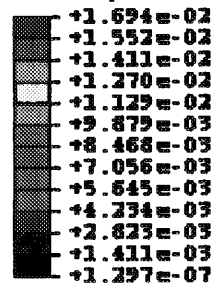
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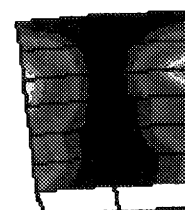
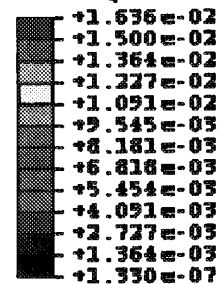
FSLIPEQ ASSEMBLY_I1_MJ3E/A2



FSLIPEQ ASSEMBLY_I1_MJ3F/A2



FSLIPEQ ASSEMBLY_I1_MJ3G/A2



Seventeen Vertical &
Two Horizontal Joint Model
M14 M15
Slip Magnitude On
Surfaces Of the
Lower Horizontal Joint
Gravity + Reservoir Load

Monolithic Model : M2 & M8

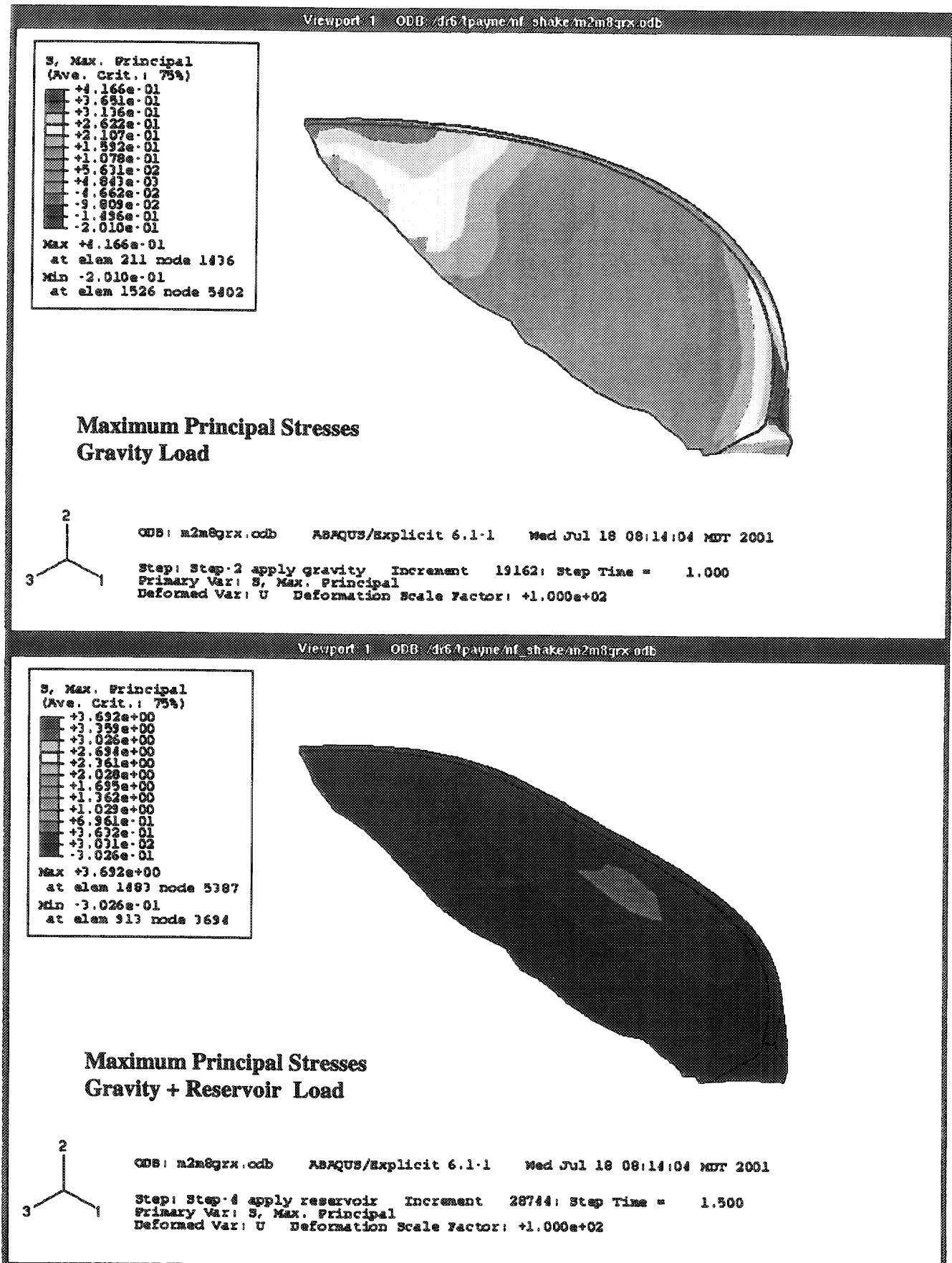


Figure E.34

Monolithic Model : M2 & M8

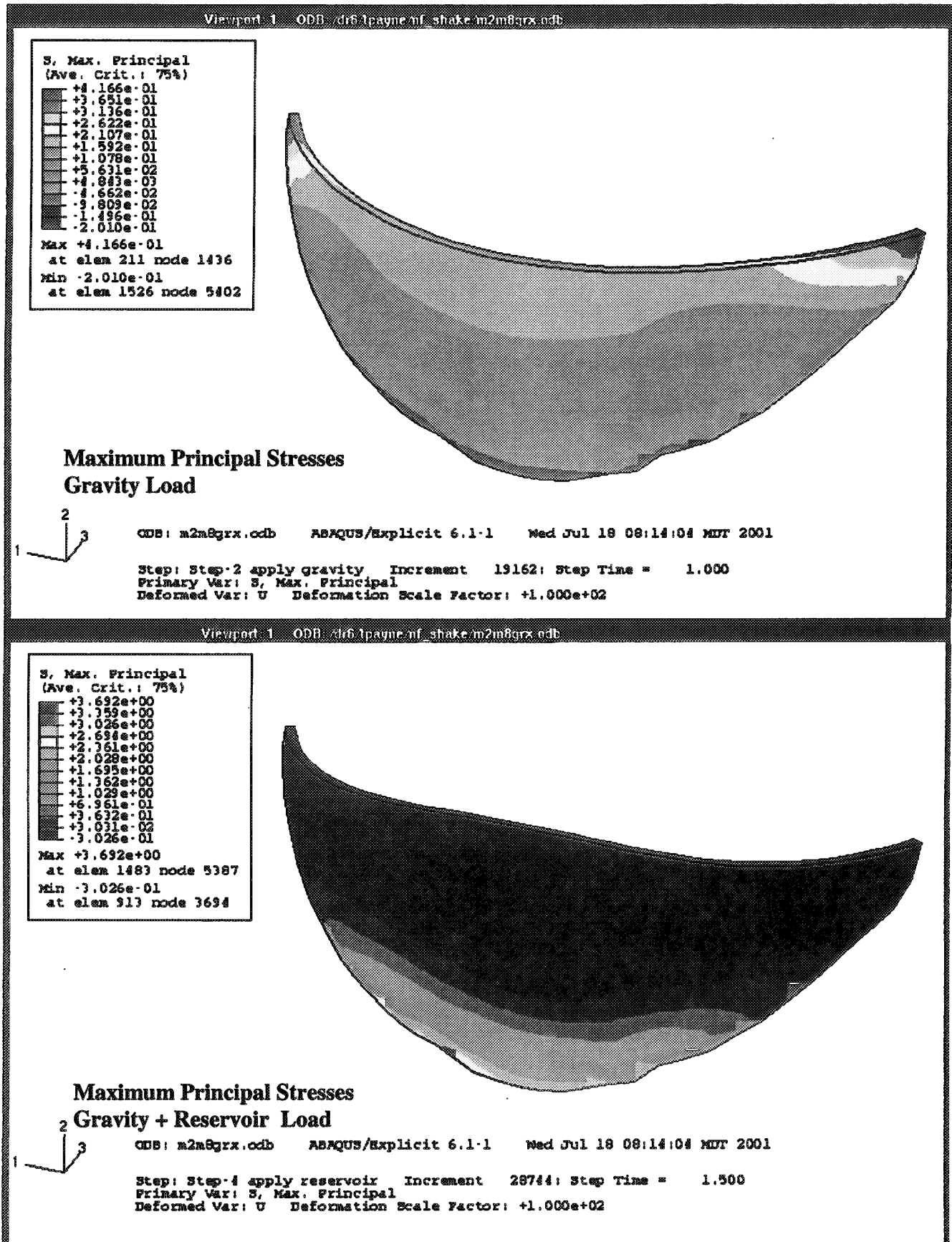


Figure E.35

Single Vertical Joint Model : M6 & M11

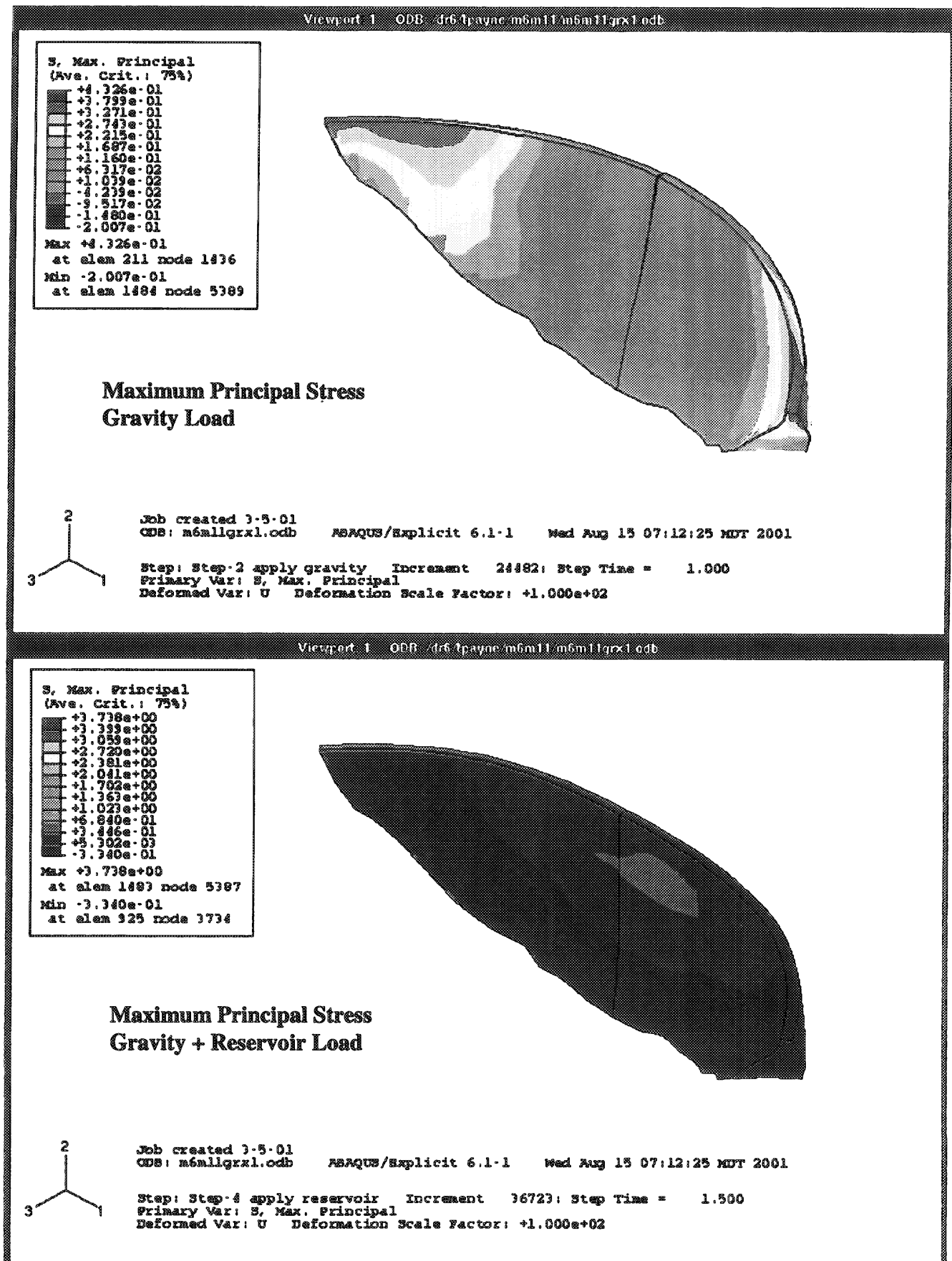


Figure E.36

Single Vertical Joint Model : M6 & M11

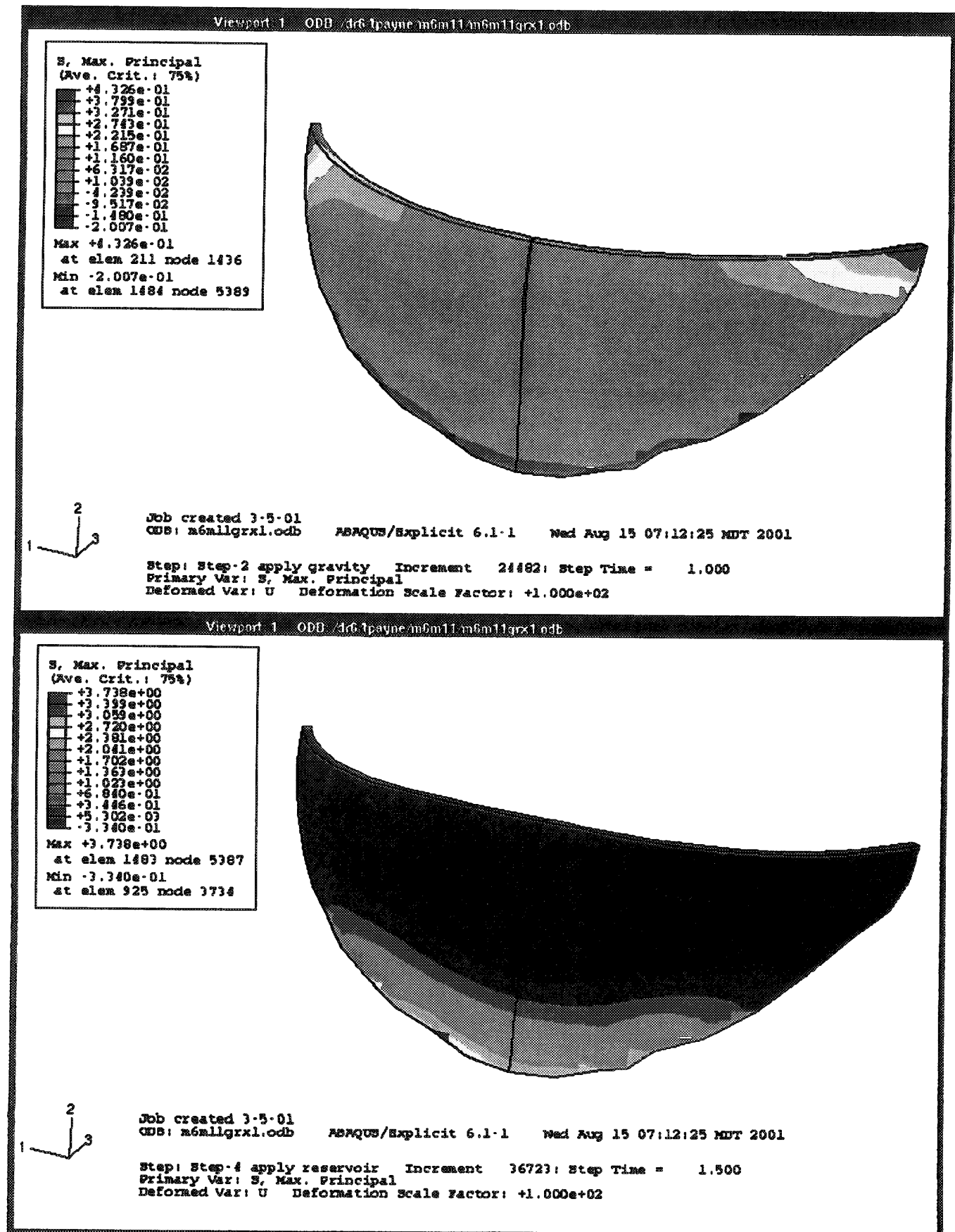


Figure E.37

Single Horizontal Joint Model : M9 & M10

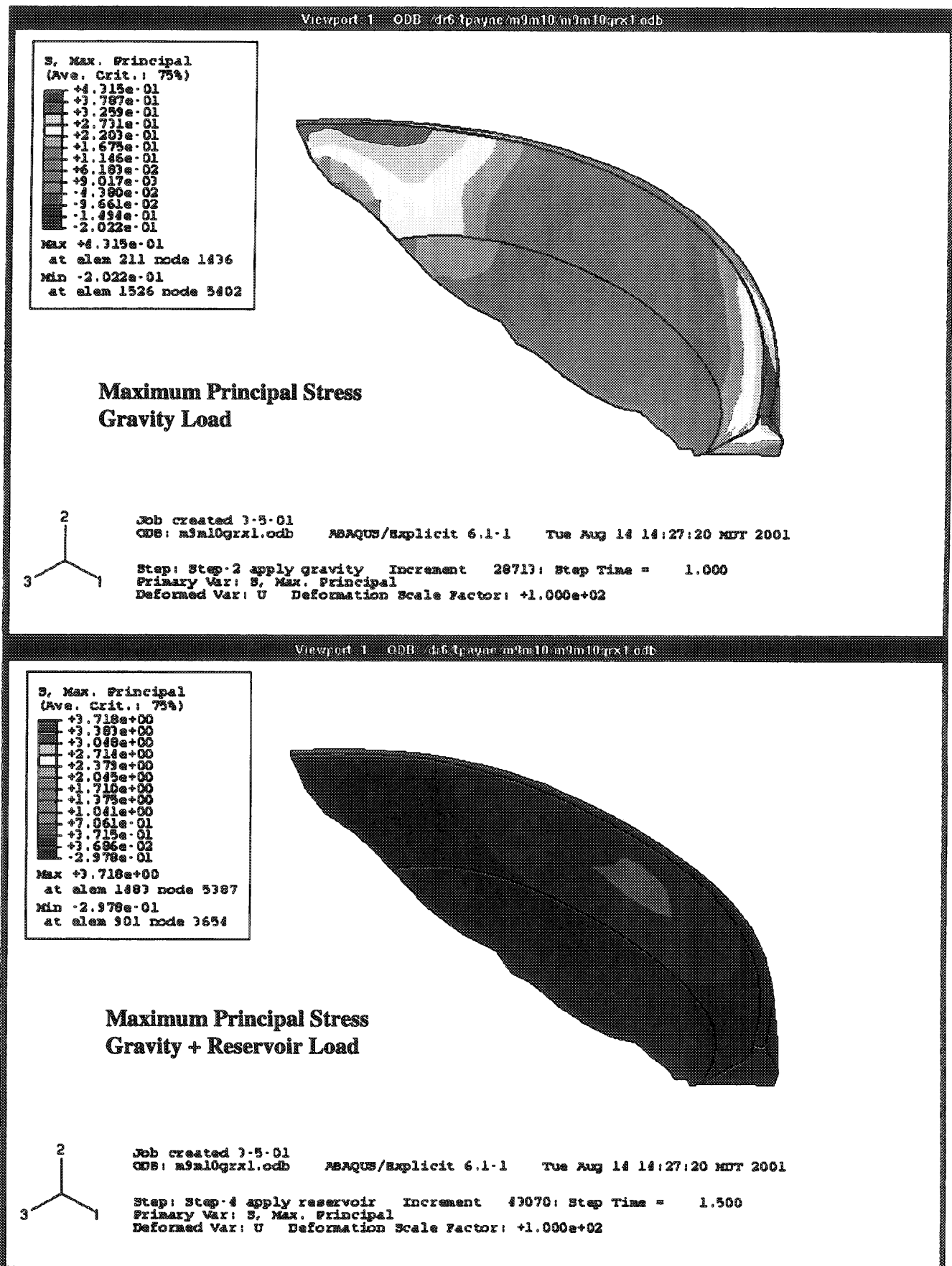


Figure E.38

Single Horizontal Joint Model : M9 & M10

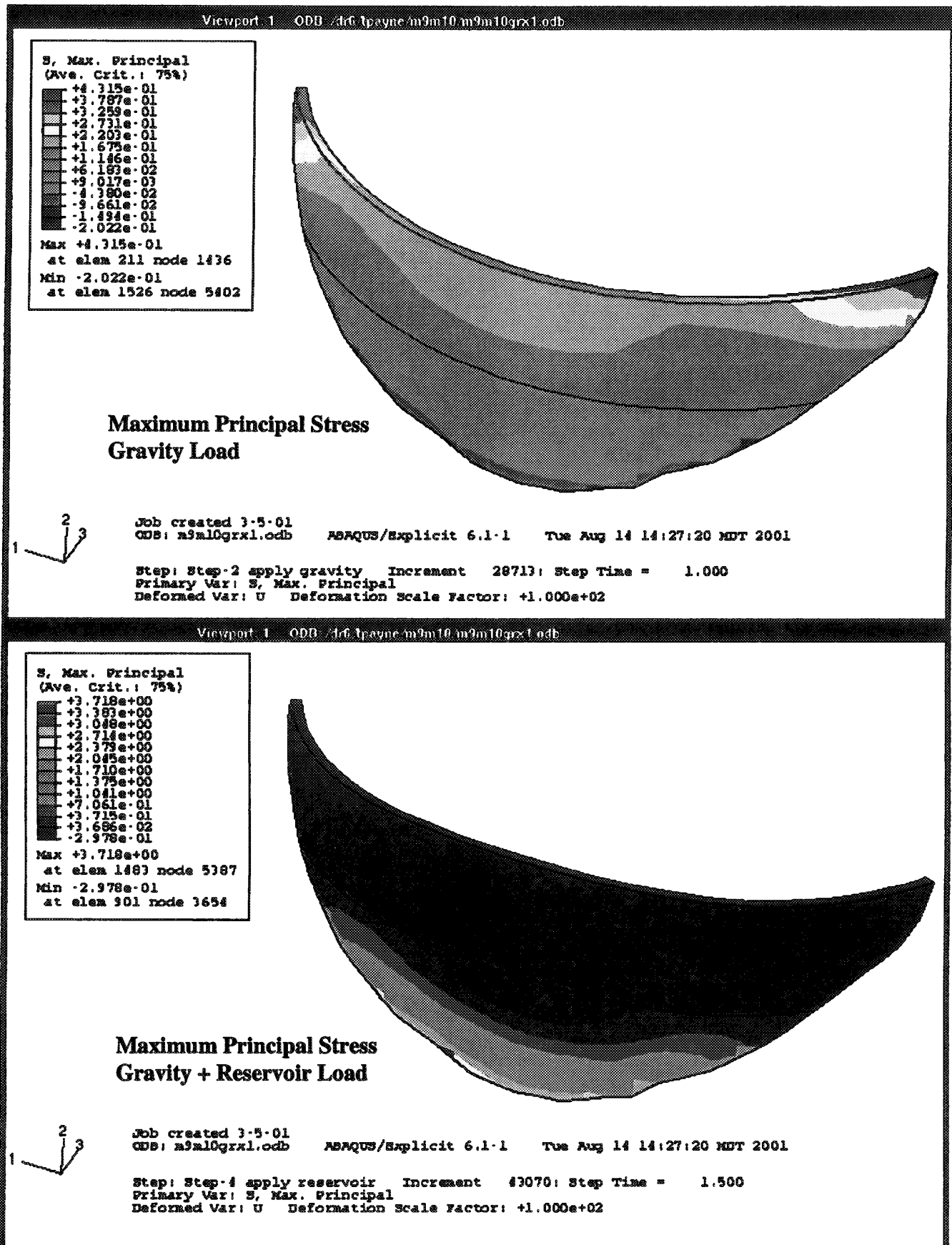


Figure E.39

Seventeen Vertical Joint Model : M12 & M13

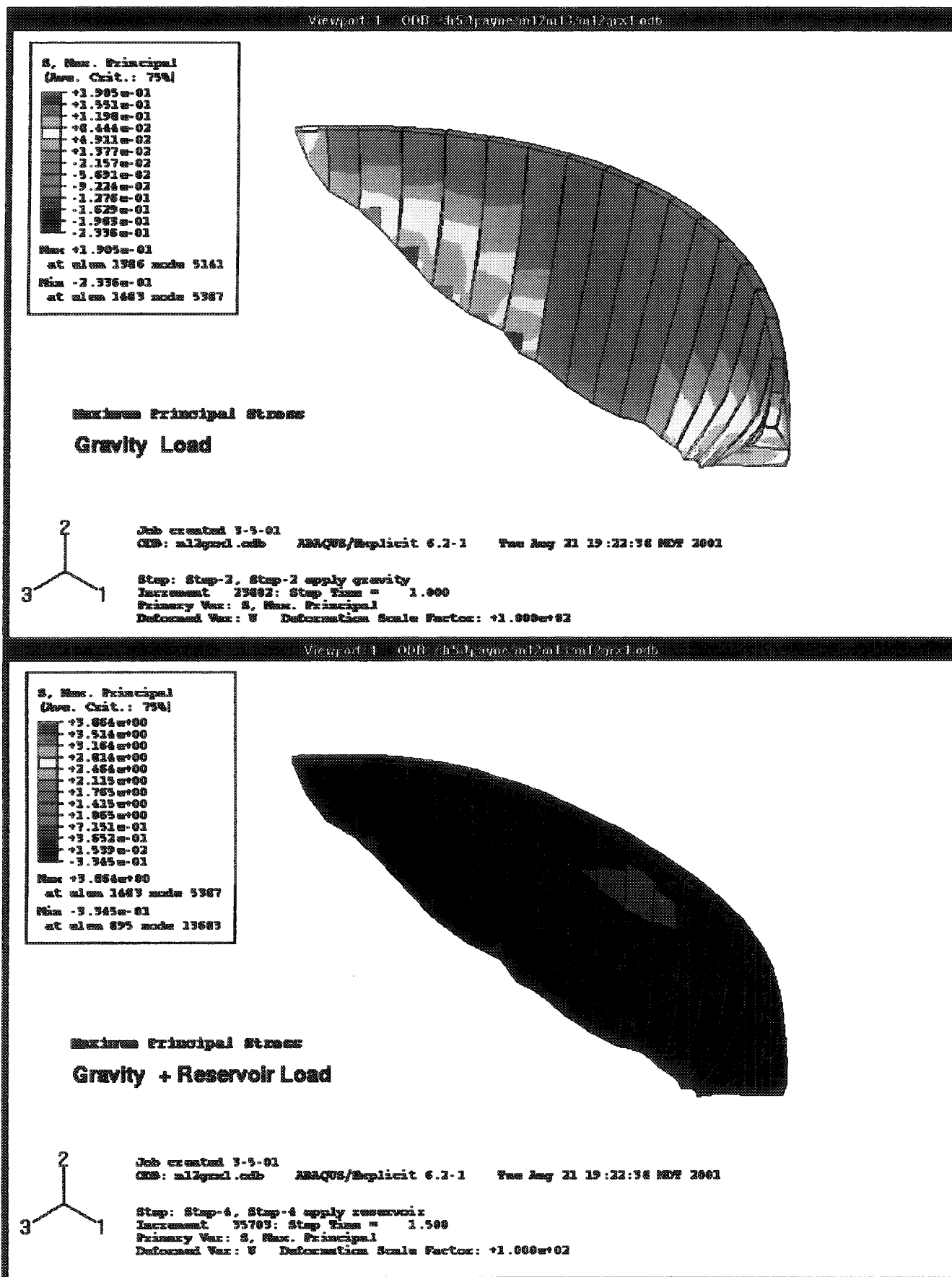


Figure E.40

Seventeen Vertical Joint Model : M12 & M13

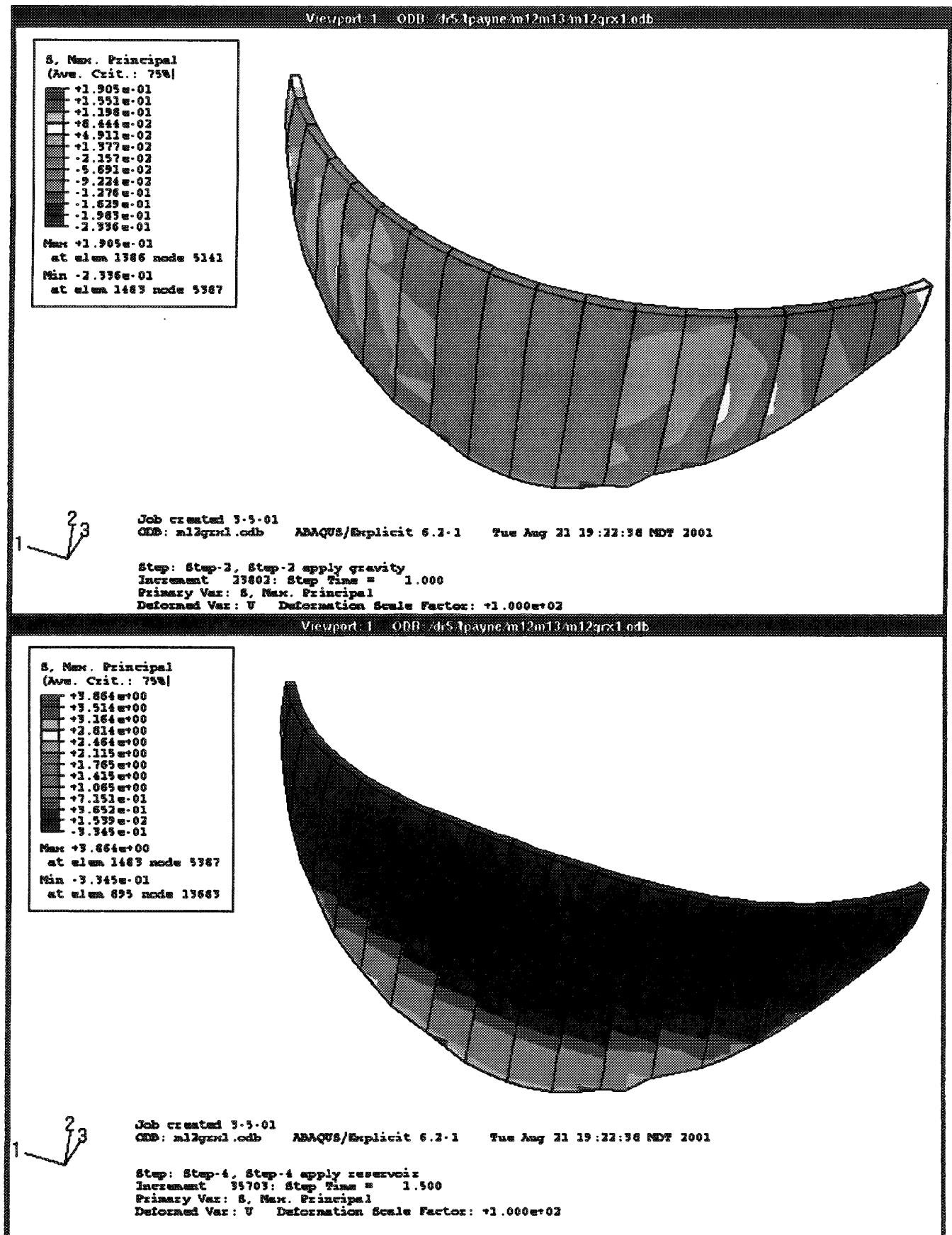


Figure E.41

Seventeen Vertical & Two Horizontal Joint Model M14 & M15

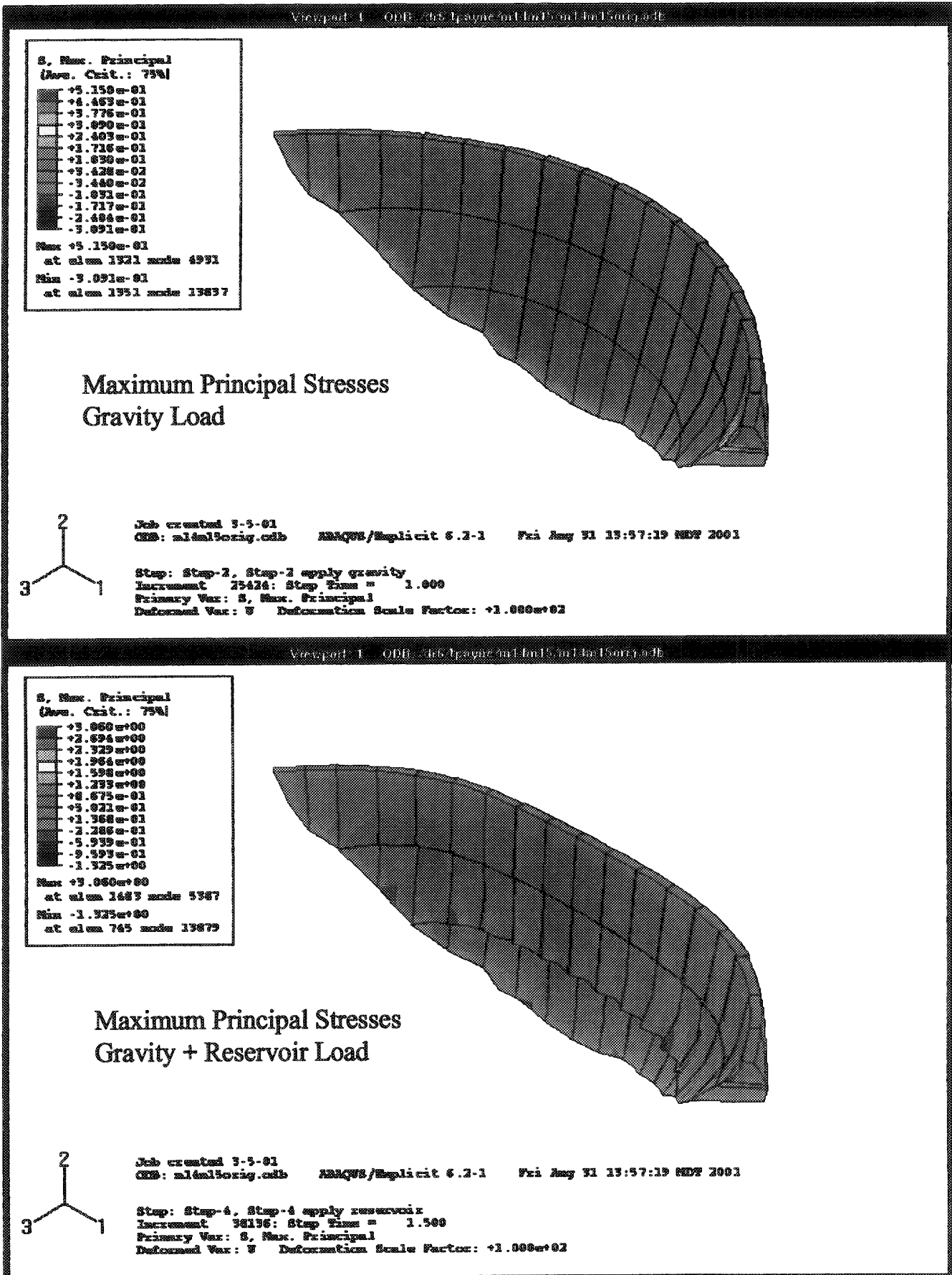


Figure E.42

Seventeen Vertical & Two Horizontal Joint Model M14 & M15

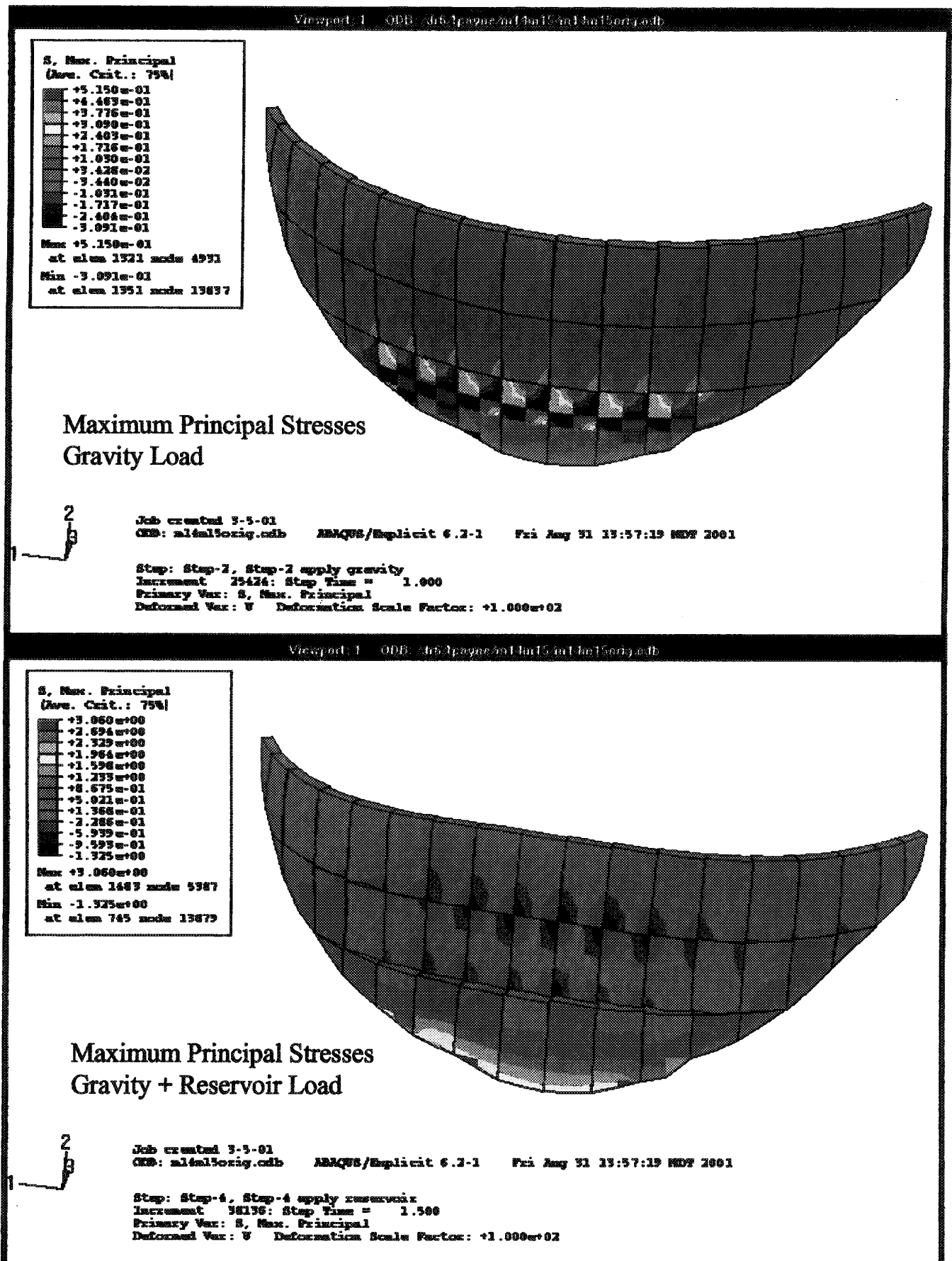
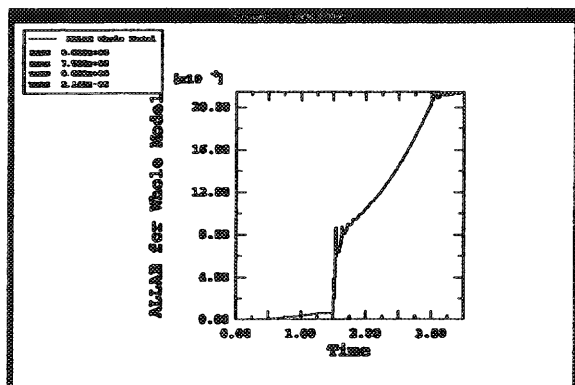


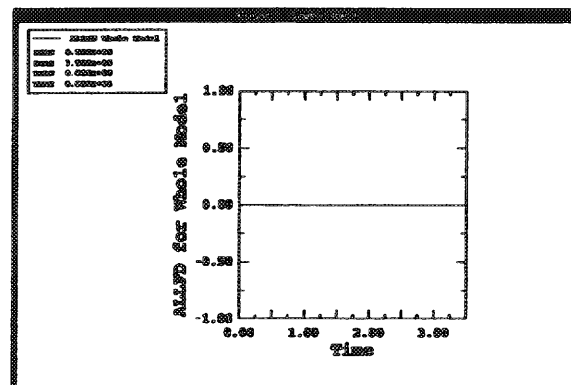
Figure E.43

Monolithic Model : M2 & M8

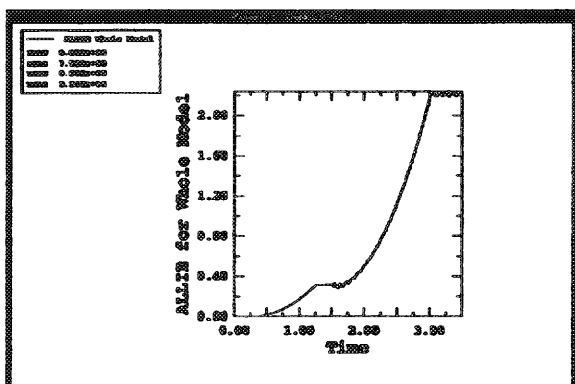
Energy Levels During Static Load Steps



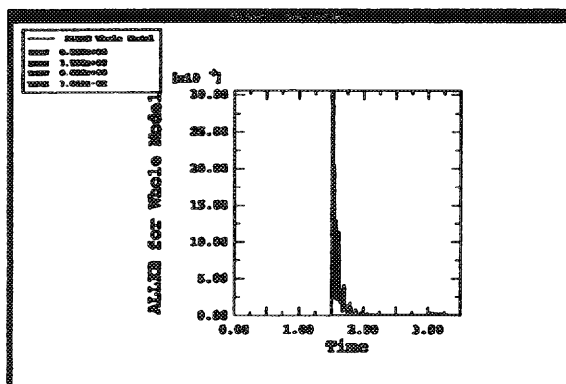
Artificial Strain Energy
"Hourglassing"



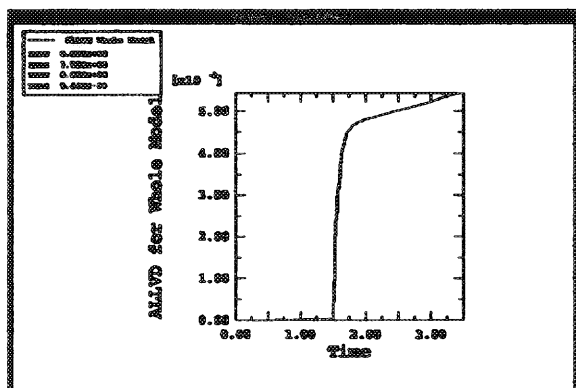
Energy Dissipated through Frictional Effects



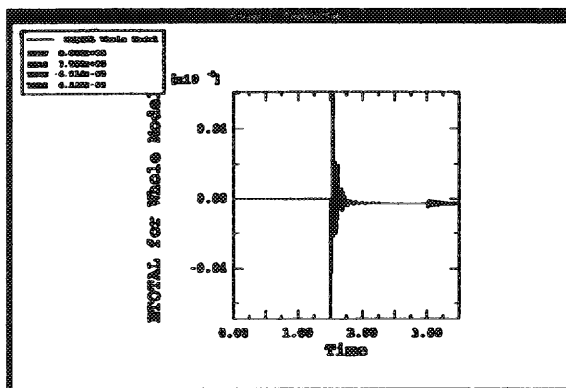
Total Strain Energy



Kinetic Energy



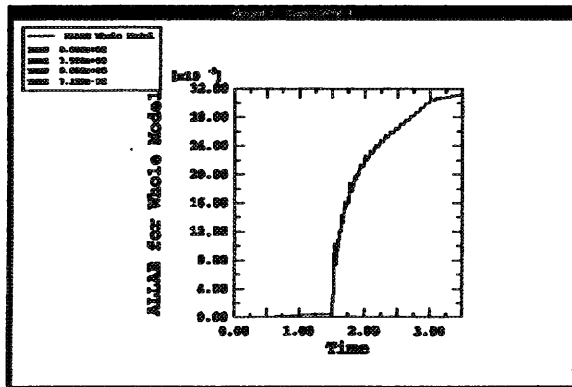
Energy Dissipated by Viscous Effects



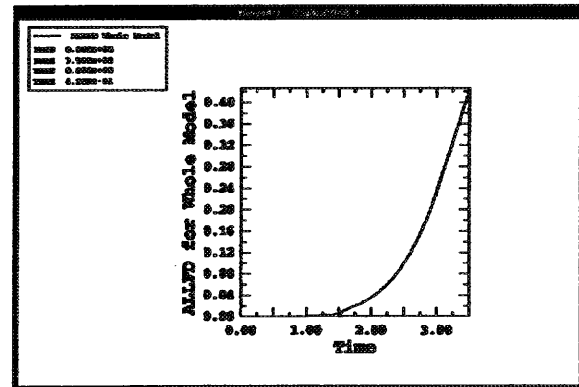
Energy Balance
"Total" Energy

Single Vertical Joint Model : M6 & M11

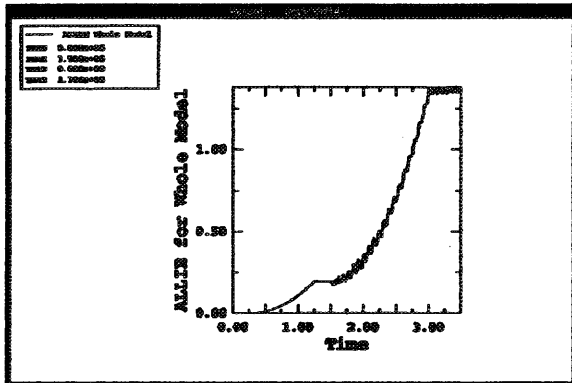
Energy Levels During Static Load Steps



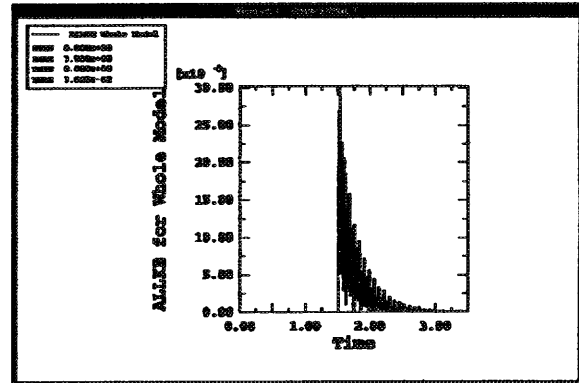
Artificial Strain Energy
"Hourglassing"



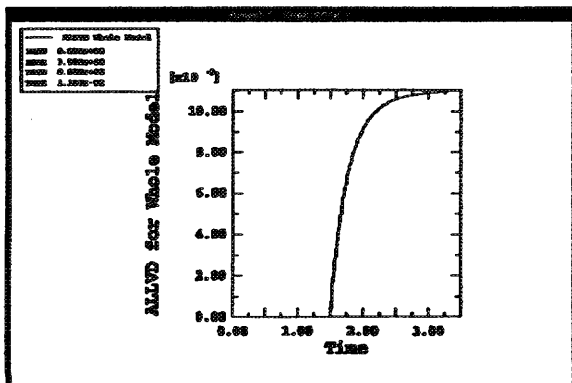
Energy Dissipated through Frictional Effects



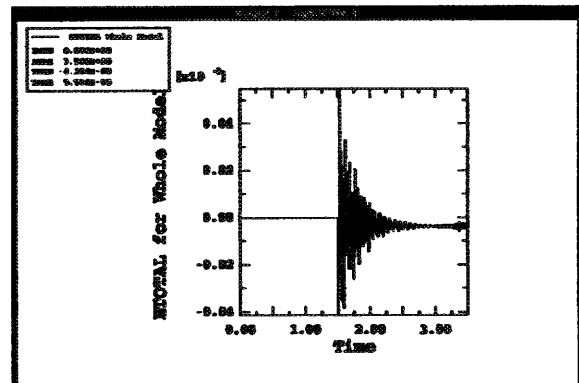
Total Strain Energy



Kinetic Energy



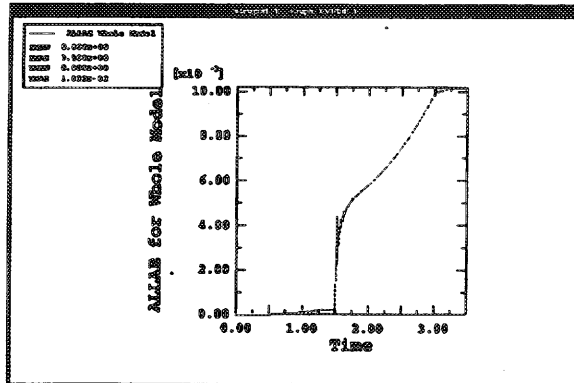
Energy Dissipated by Viscous Effects



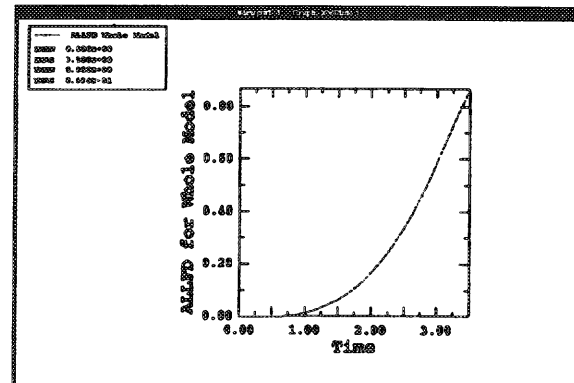
Energy Balance
"Total" Energy

Single Horizontal Joint Model : M9 & M10

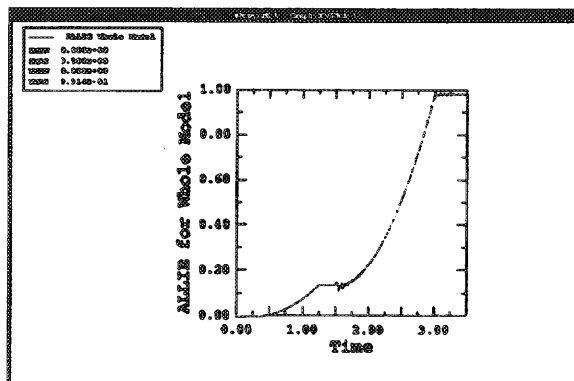
Energy Levels During Static Load Steps



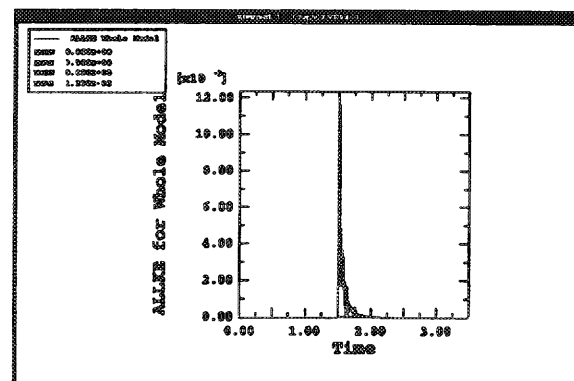
Artificial Strain Energy
"Hourglassing"



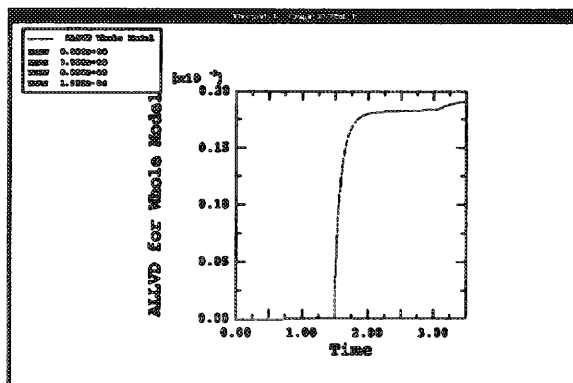
Energy Dissipated through Frictional Effects



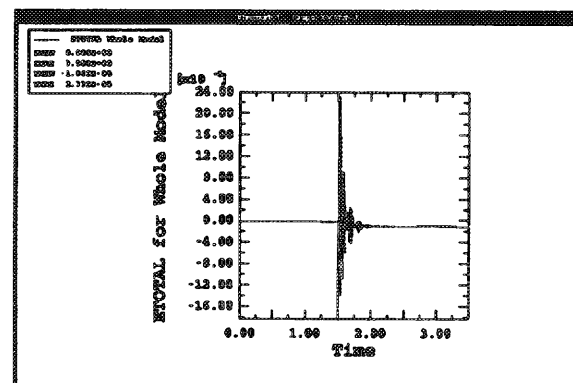
Total Strain Energy



Kinetic Energy



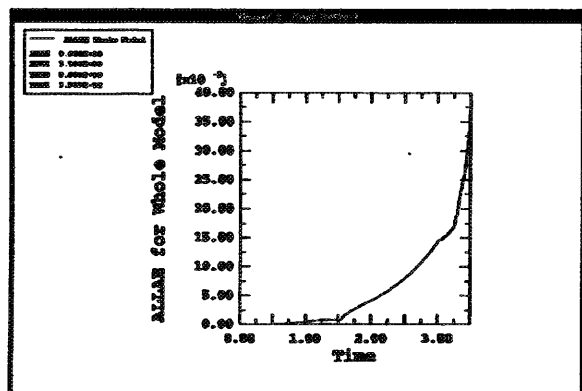
Energy Dissipated by Viscous Effects



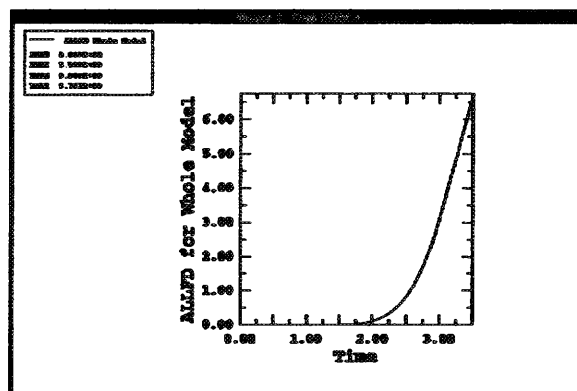
Energy Balance
"Total" Energy

Seventeen Vertical Joint Model : M12 & M13

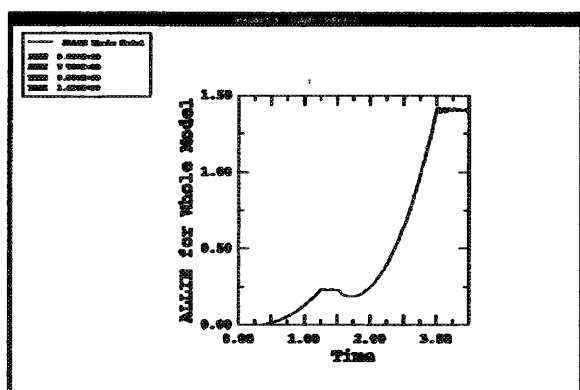
Energy Levels During Static Load Steps



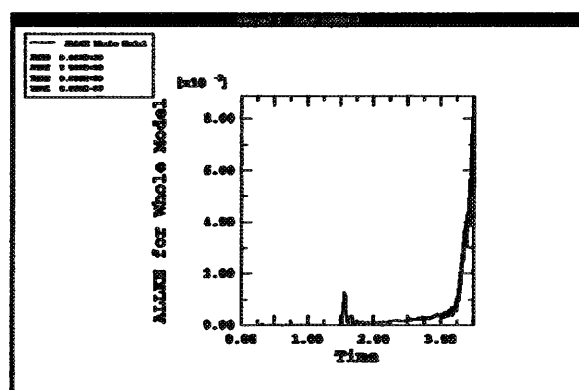
Artificial Strain Energy
"Hourglassing"



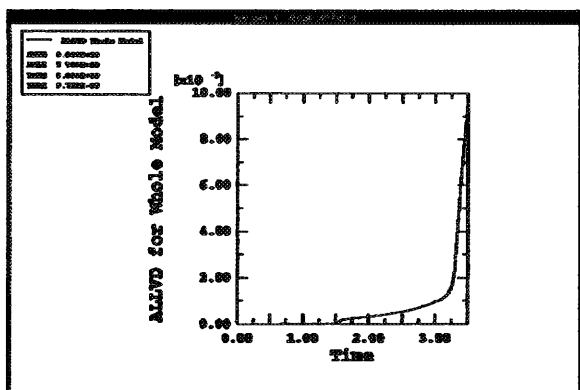
Energy Dissipated through Frictional Effects



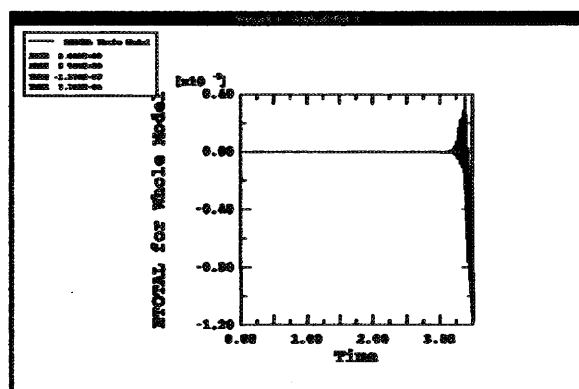
Total Strain Energy



Kinetic Energy



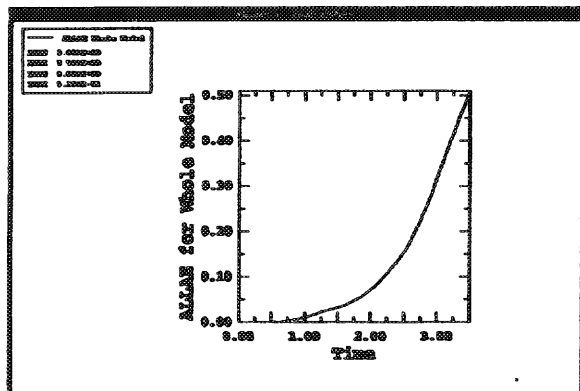
Energy Dissipated by Viscous Effects



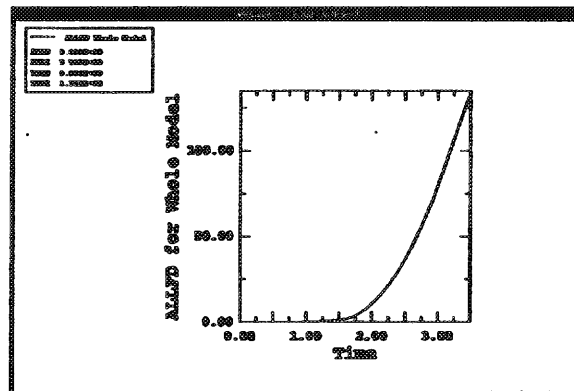
Energy Balance
"Total" Energy

Seventeen Vertical & Two horizontal Joint Model : M14 & M15

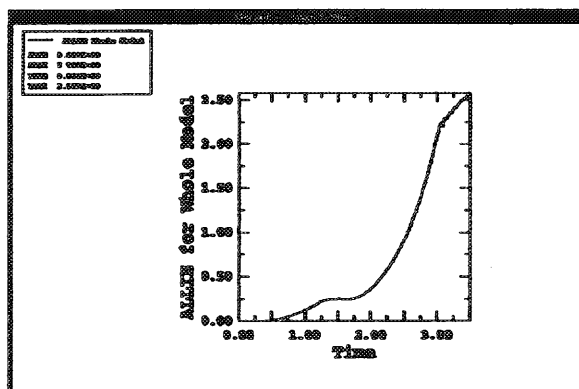
Energy Levels During Static Load Steps



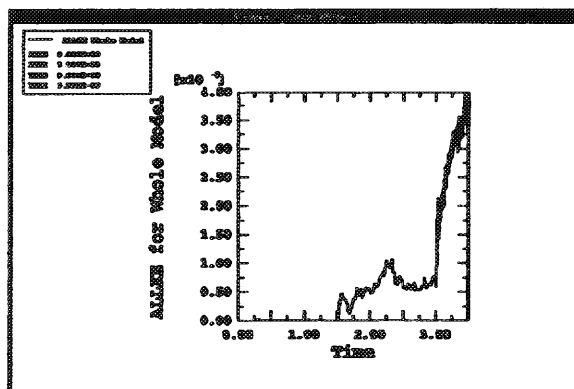
Artificial Strain Energy
"Hourglassing"



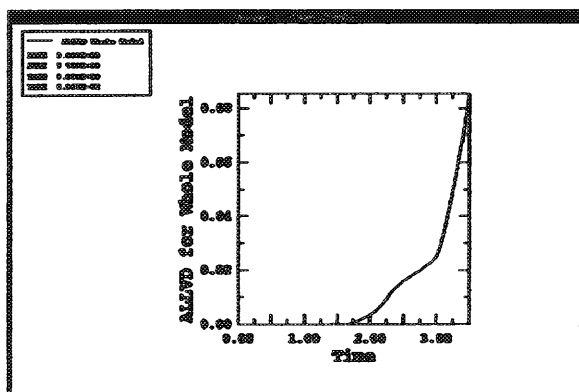
Energy Dissipated through Frictional Effects



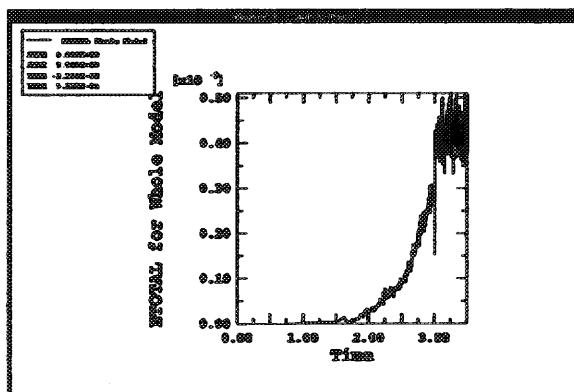
Total Strain Energy



Kinetic Energy



Energy Dissipated by Viscous Effects



Energy Balance
"Total" Energy

Appendix F

Dynamic Results of Linear Elastic Analyses for Five Different Joint Configurations

Monolithic Model M2
Deformation At
Five Equal Spaced Intervals
Of A Single Sinusoidal
Acceleration Load
Cycle
1.0 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

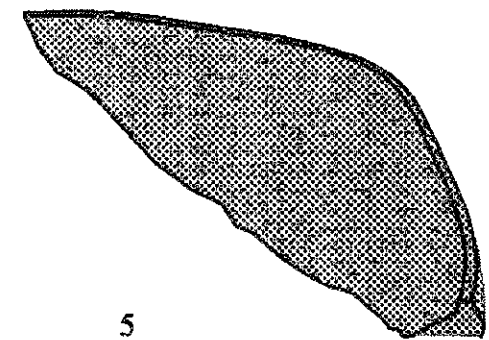
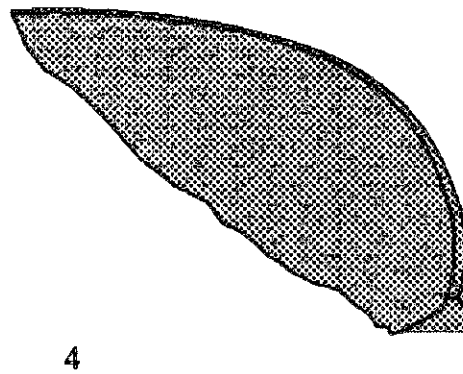
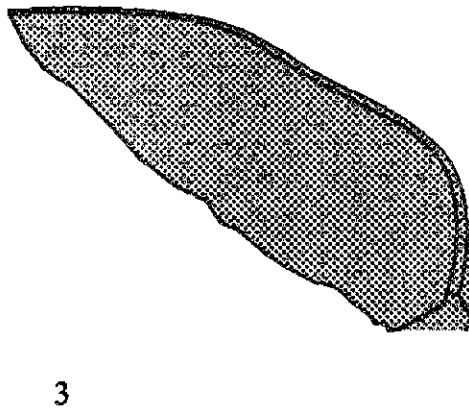
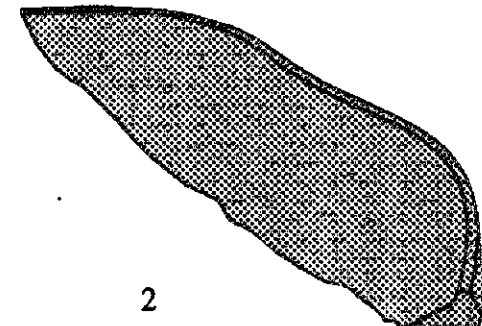
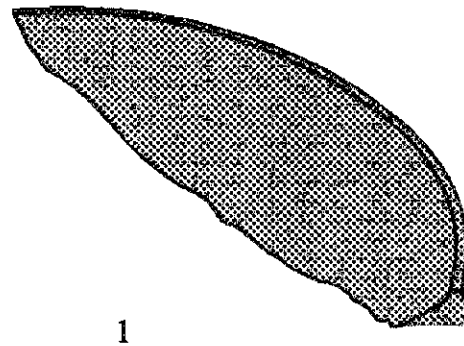


Figure F.1

Single Vertical Joint Model M6
Deformation At
Five Equal Spaced Intervals
Of A Single Sinusoidal
Acceleration Load
Cycle
1.0 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

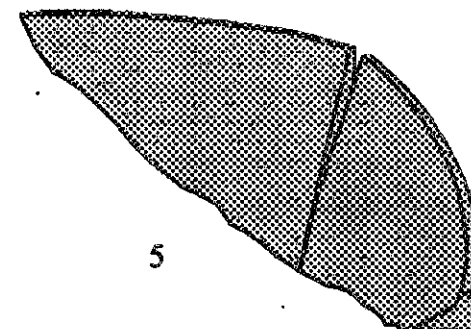
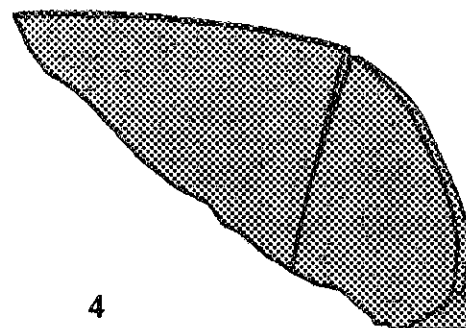
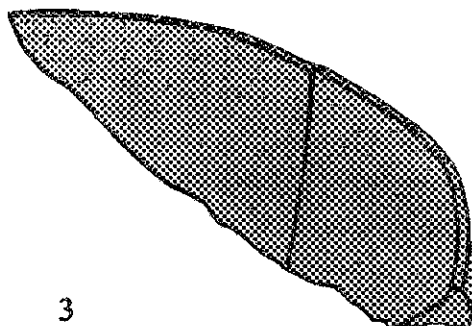
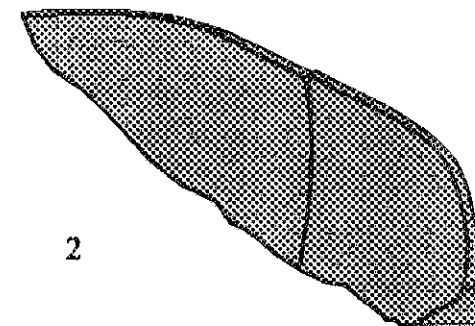
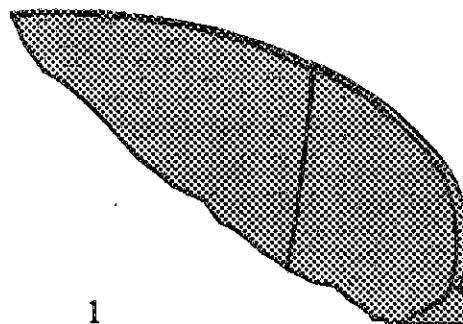
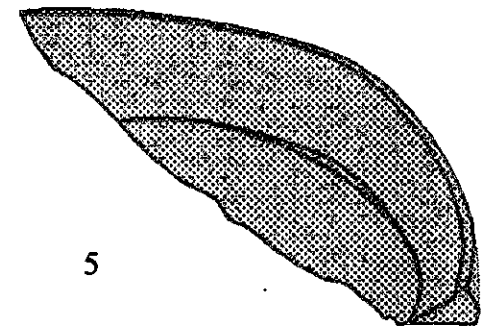
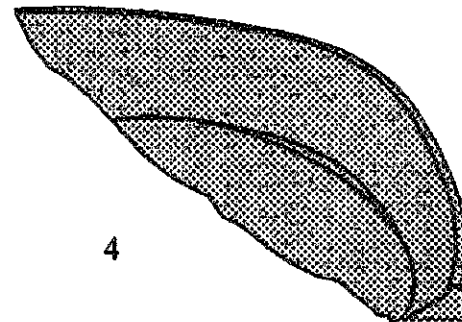
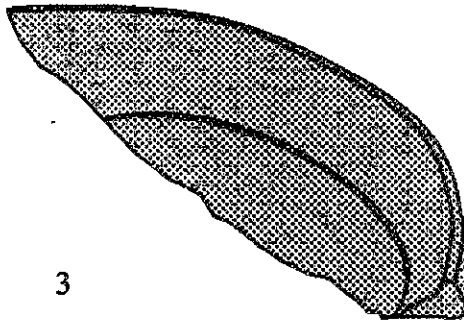
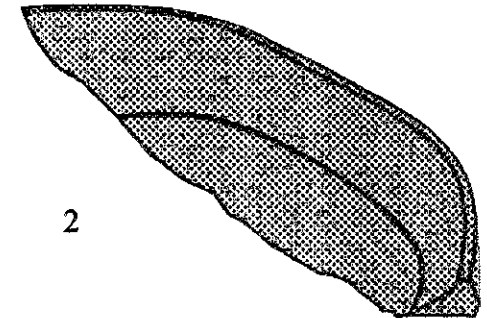
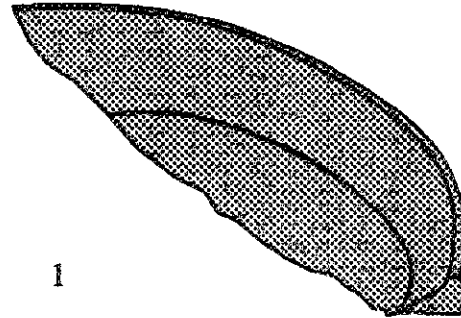


Figure F.2

Single Horizontal Joint Model M10

Deformation At
Five Equal Spaced Intervals
Of A Single Sinusoidal
Acceleration Load
Cycle

1.0 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10



Seventeen Vertical Joint Model M12
Deformation At
Five Equal Spaced Intervals
Of A Single Sinusoidal
Acceleration Load
Cycle
1.0 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

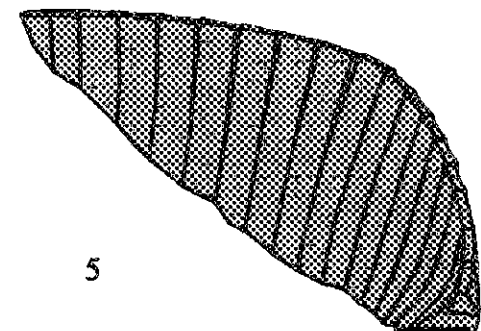
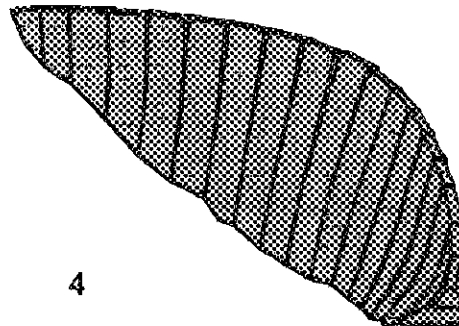
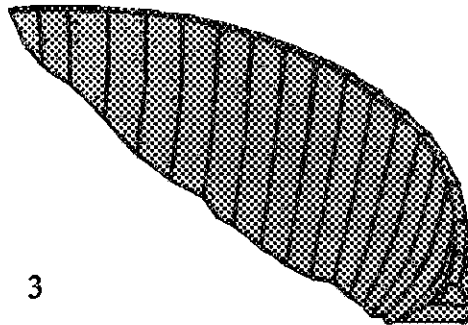
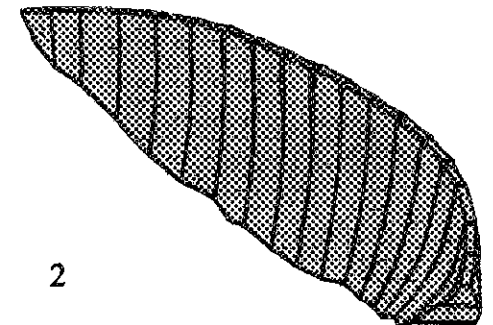
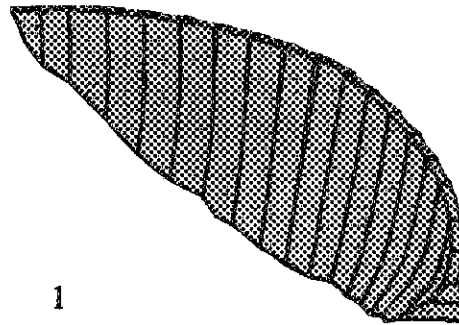


Figure F.4

Seventeen Vertical & Two Horizontal
Joint Model M14
Deformation At
Five Equal Spaced Intervals
Of A Single Sinusoidal
Acceleration Load
Cycle
1.0 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

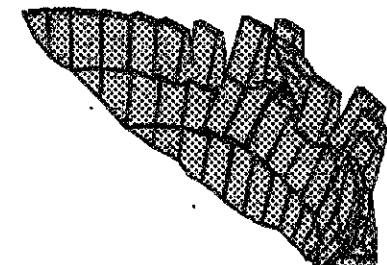
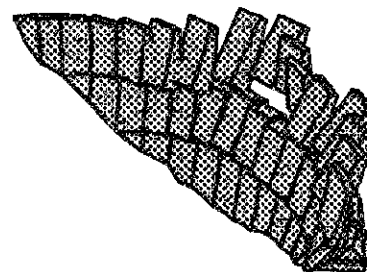
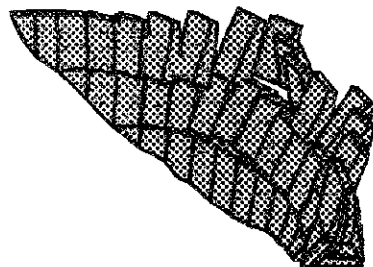
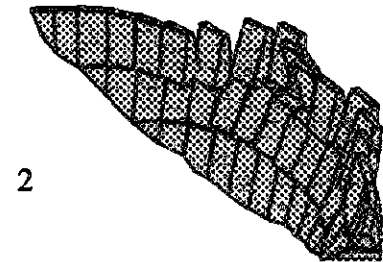
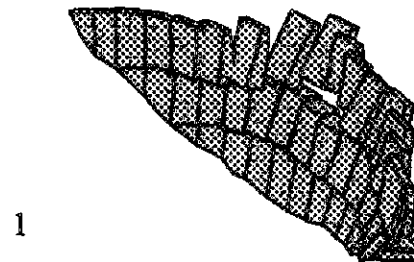
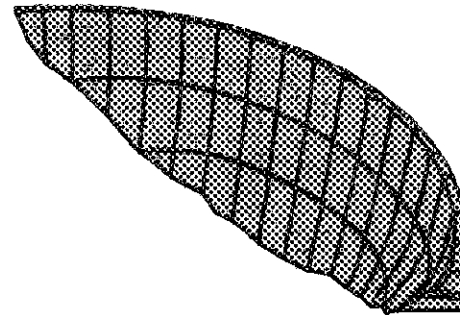
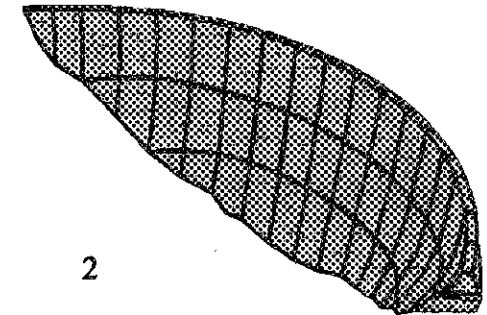


Figure F.5

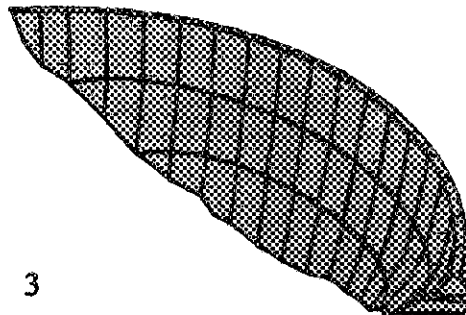
Seventeen Vertical & Two Horizontal
Joint Model M14
Deformation At
Five Equal Spaced Intervals
Of The First Sinusoidal
Acceleration Load
Cycle
0.25 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10



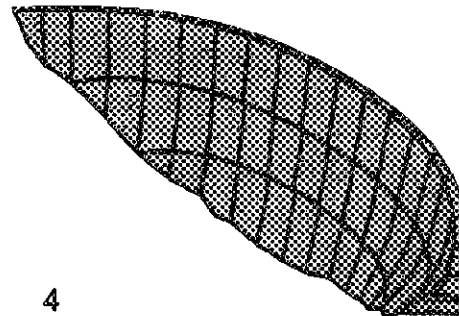
1



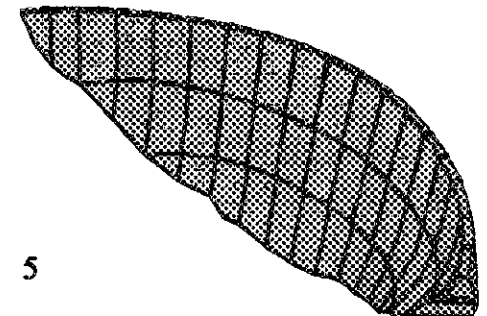
2



3



4



5

Figure F.6

Seventeen Vertical & Two Horizontal
Joint Model M14
Deformation At
Five Equal Spaced Intervals
A Single Sinusoidal
Acceleration Load
Cycle
0.25 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

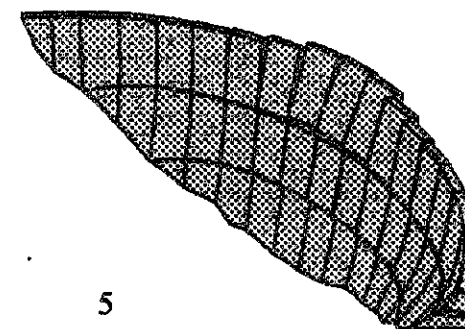
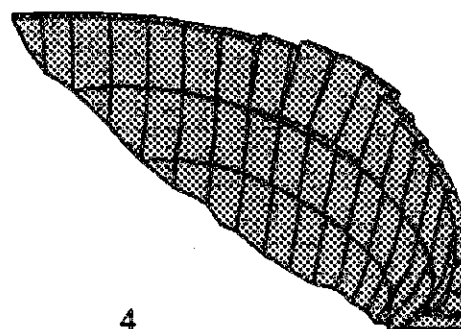
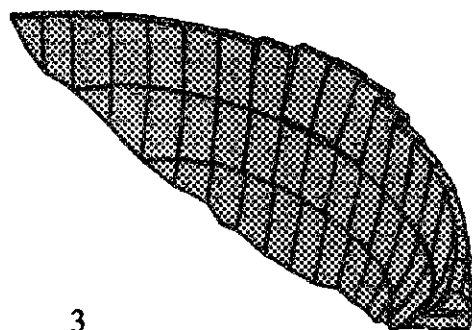
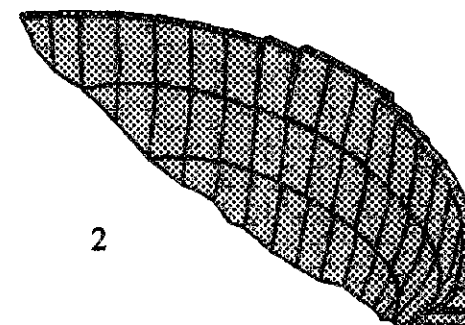
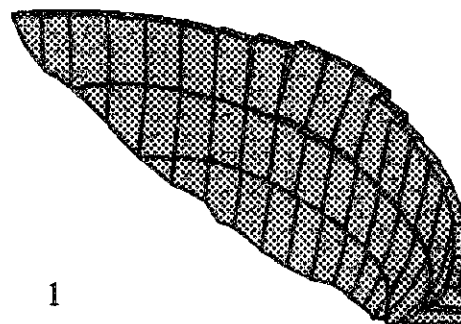


Figure F.7

Seventeen Vertical & Two Horizontal
Joint Model M14
Deformation At
Five Equal Spaced Intervals
A Single Sinusoidal
Acceleration Load
Cycle
0.50 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

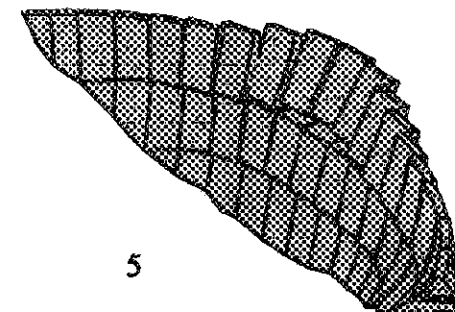
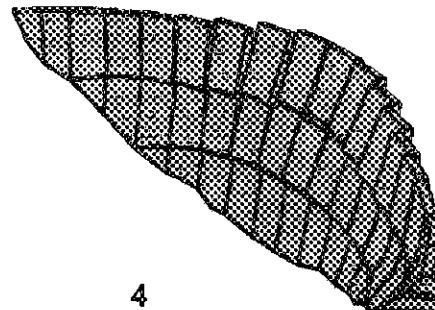
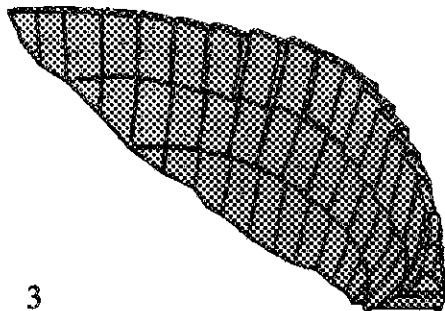
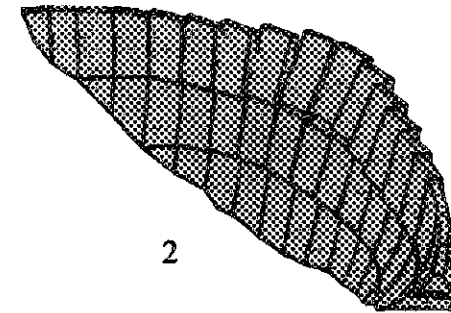
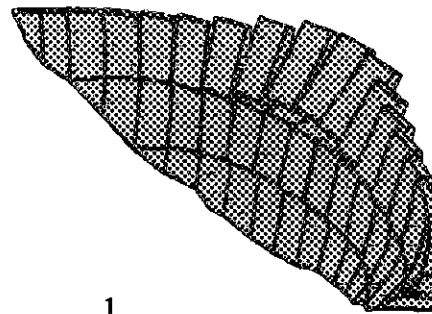


Figure F.8

Seventeen Vertical & Two Horizontal
Joint Model M14
Deformation At
Five Equal Spaced Intervals
A Single Sinusoidal
Acceleration Load
Cycle
0.75 g Peak Amplitude
Frequency = 14 Hertz
Magnification Factor = 10

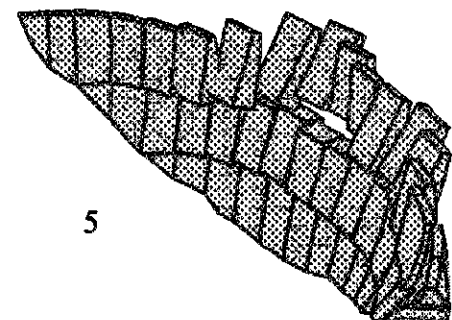
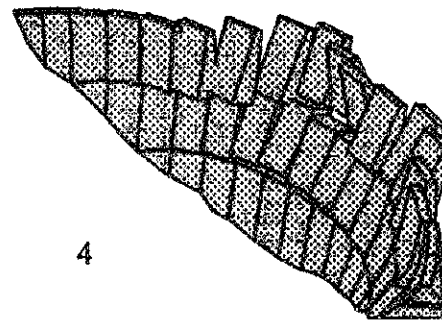
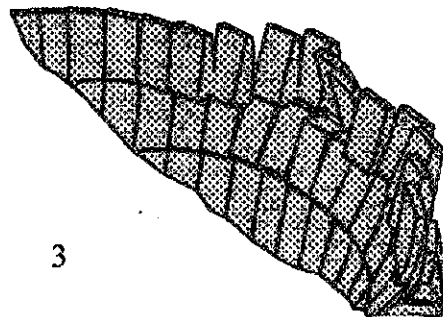
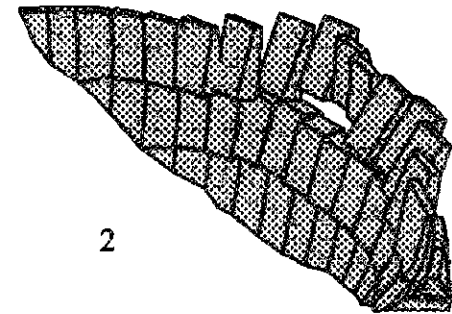
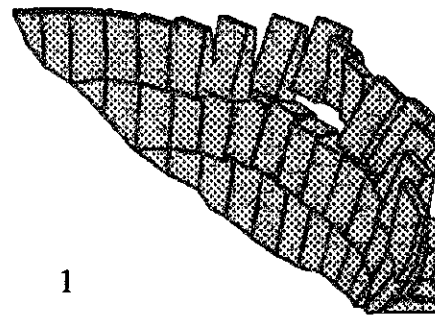
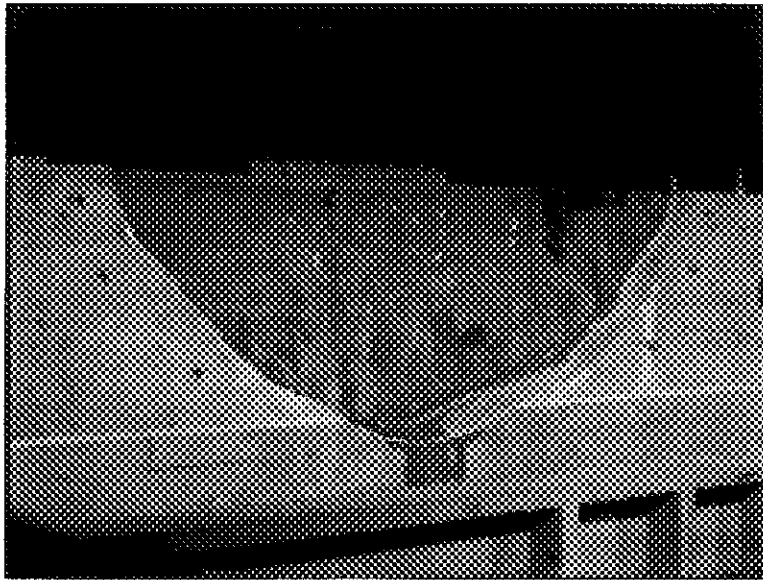
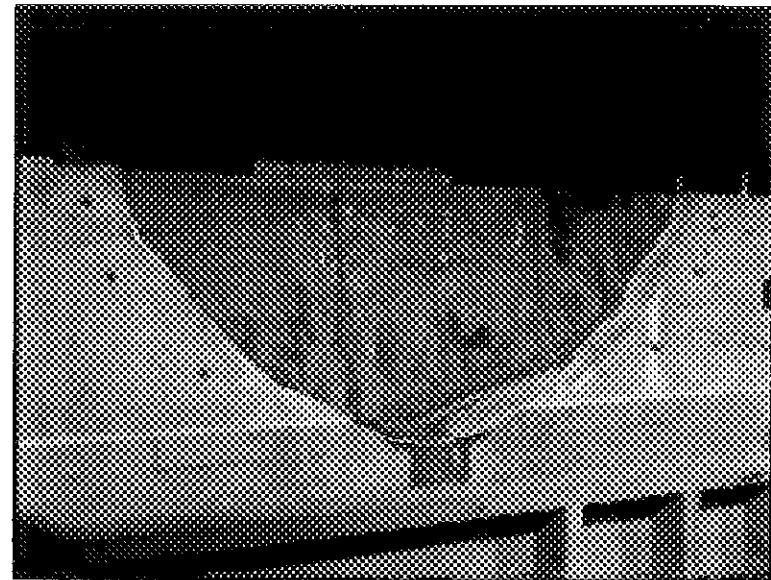


Figure F.9

Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



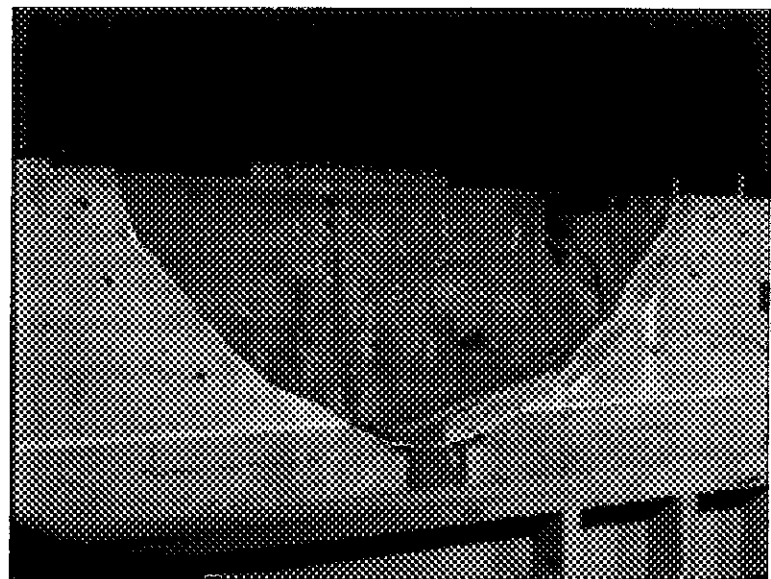
Time = 00.00 second.frame



Time = 00.33 second.frame



Time = 00.66 second.frame

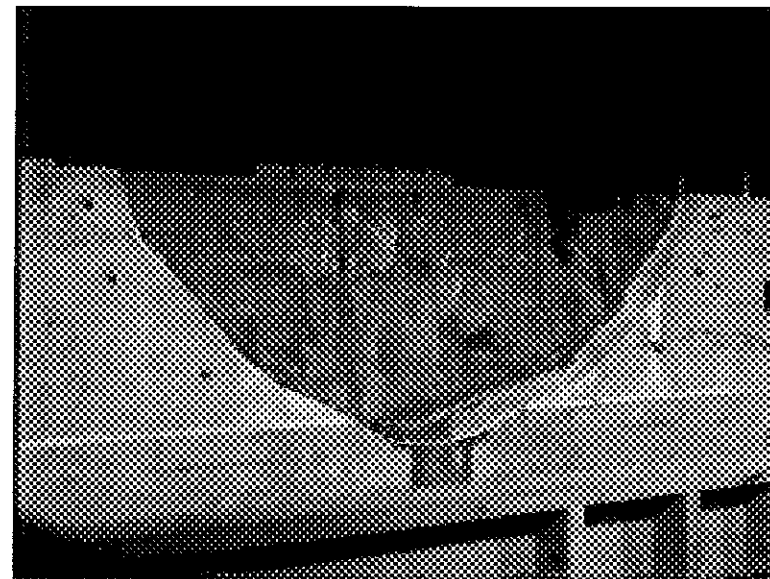


Time = 01.00 second.frame

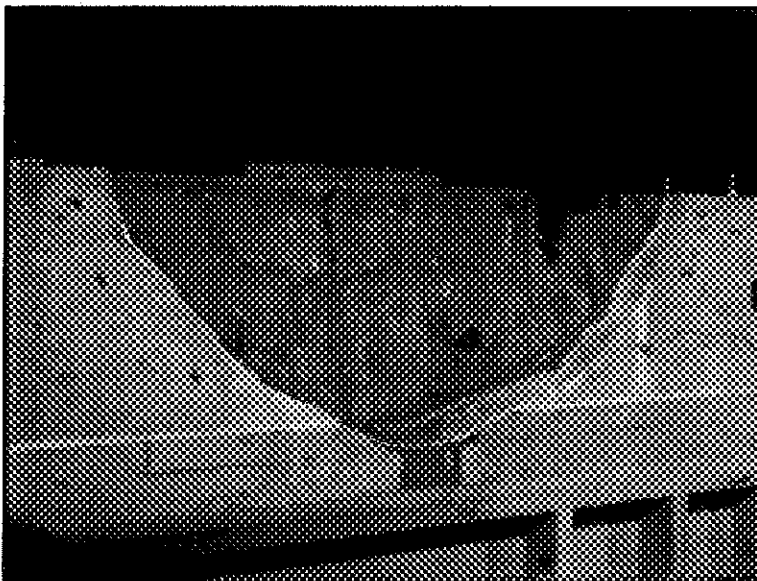
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



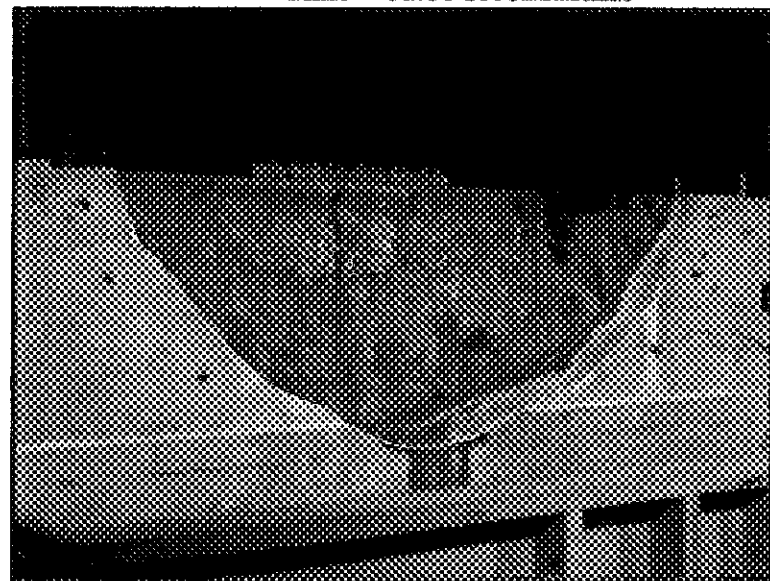
Time = 01.33 second.frame



Time = 01.66 second.frame



Time = 02.00 second.frame



Time = 02.33 second.frame

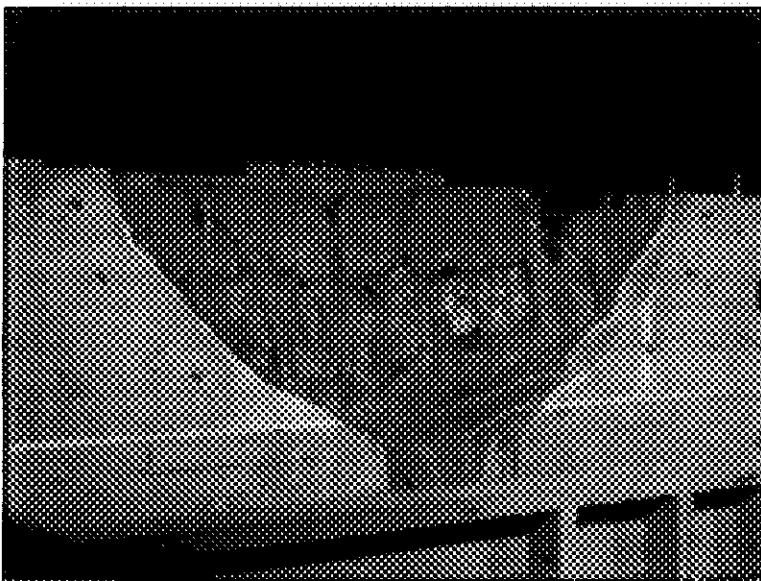
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



Time = 09.33 second.frame



Time = 09.66 second.frame

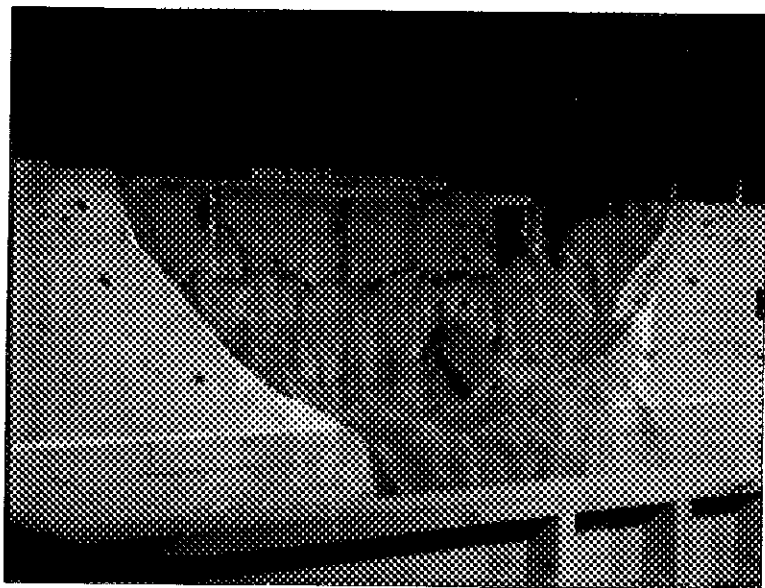


Time = 10.00 second.frame

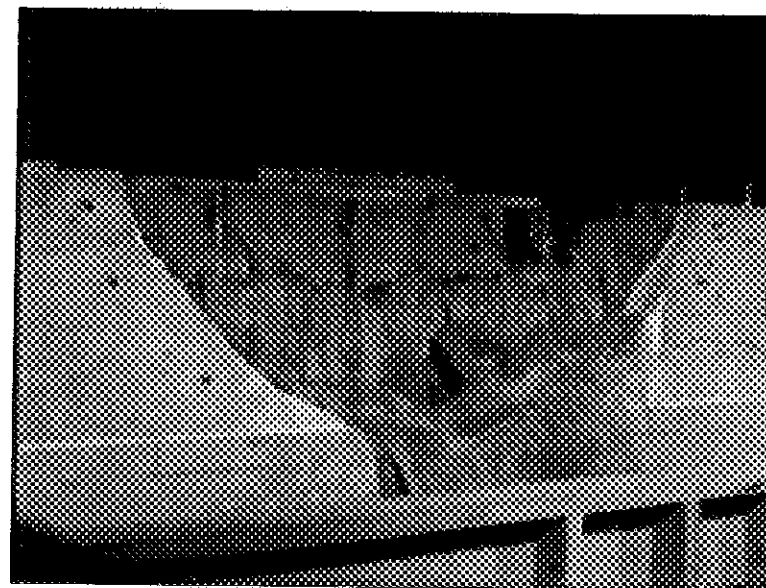


Time = 10.33 second.frame

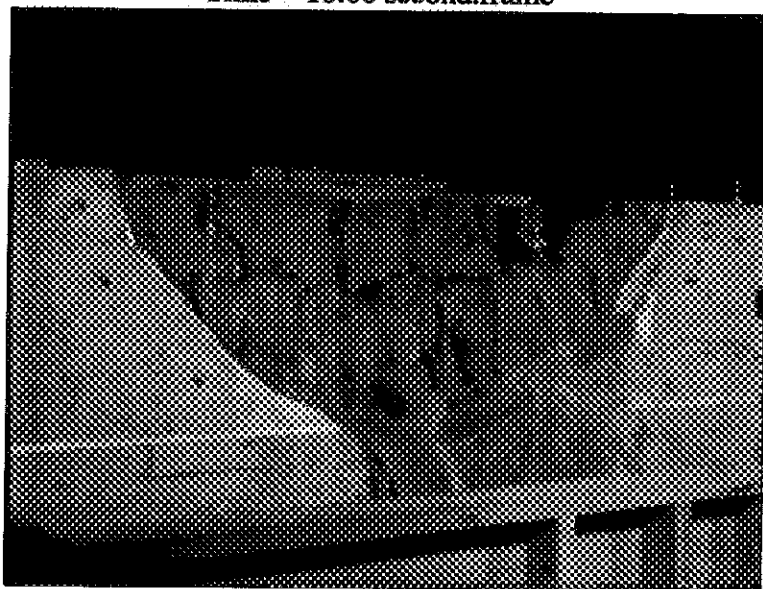
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



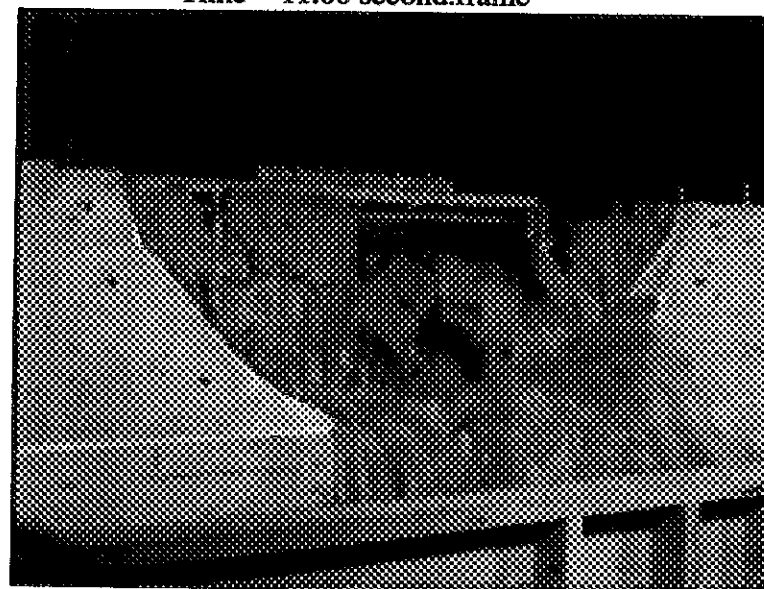
Time = 10.66 second.frame



Time = 11.00 second.frame



Time = 11.33 second.frame



Time = 11.66 second.frame

Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



Time = 15.00 second.frame



Time = 15.33 second.frame



Time = 15.66 second.frame

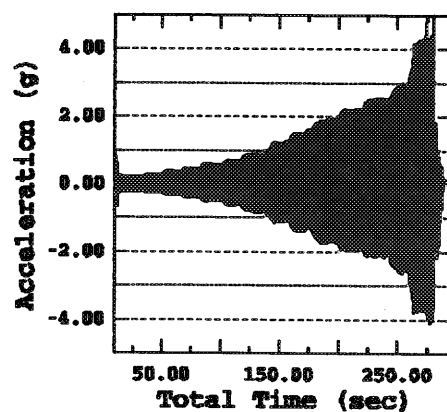


Time = 16.00 second.frame

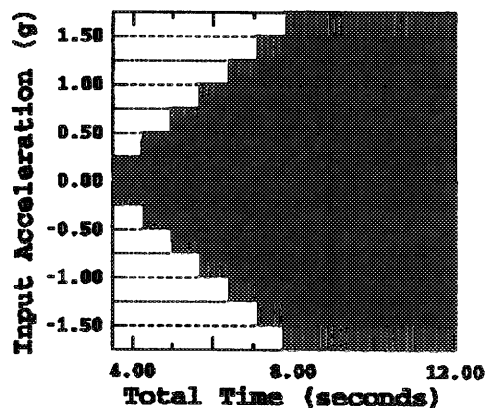
Input Accelerations : Model M2

Monolithic Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .50 g

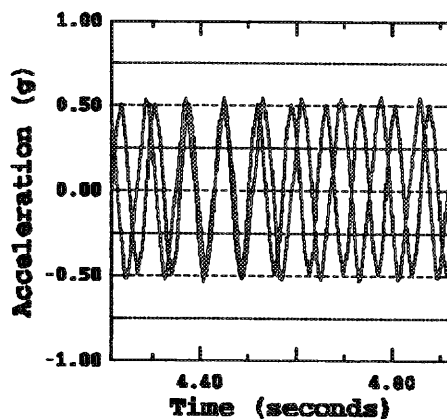
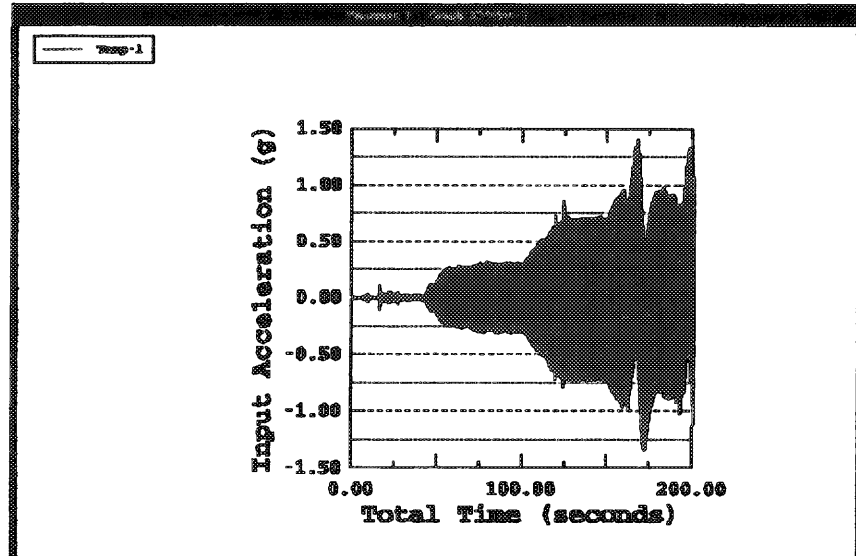


Figure F.15

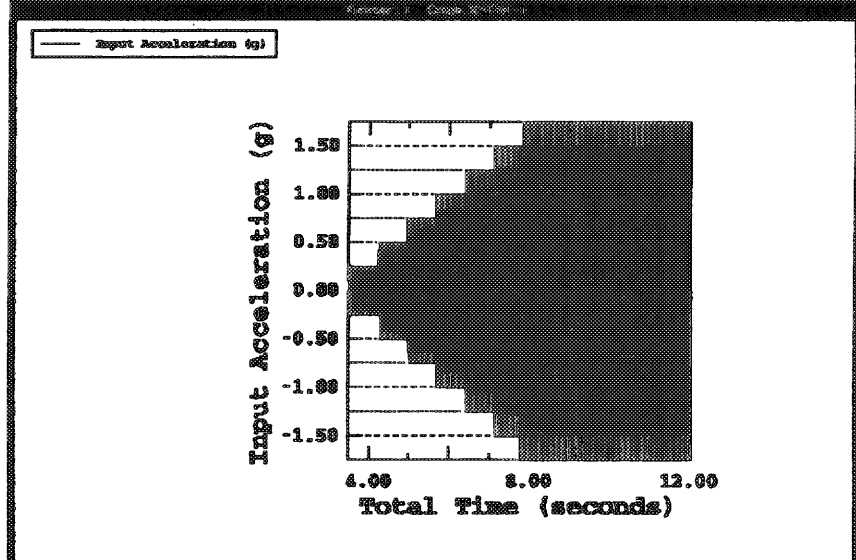
Input Accelerations : Model M6

Single Vertical Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .25 g

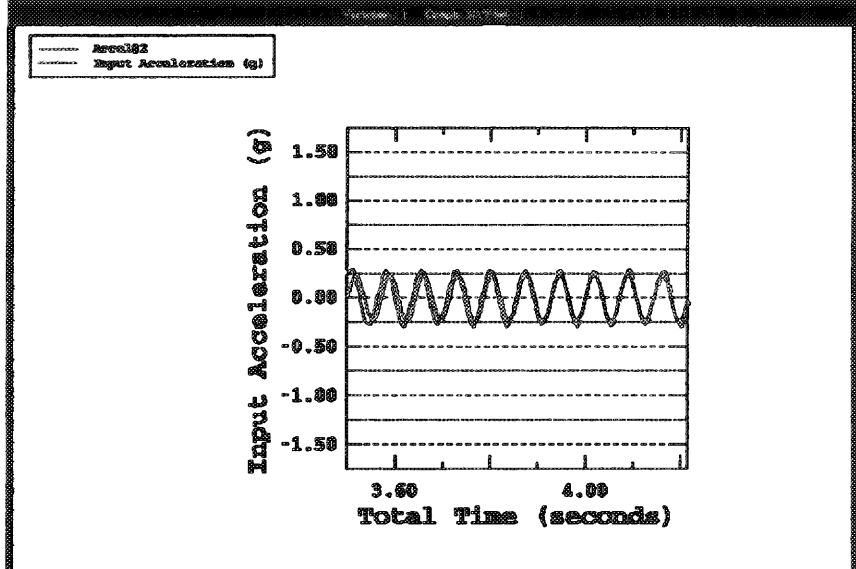
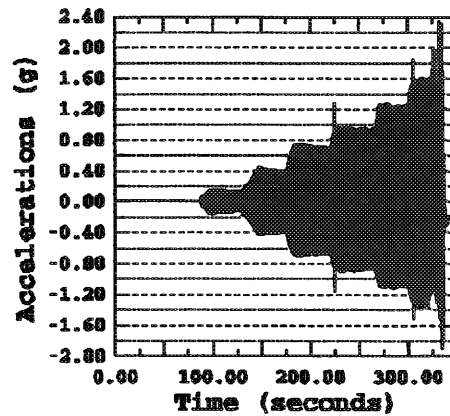


Figure F.16

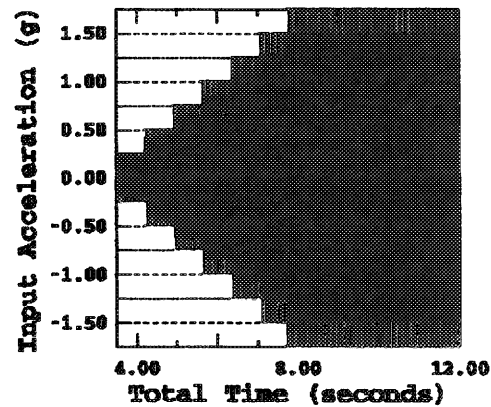
Input Accelerations : Model M10

Single Horizontal Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ 1.0 g

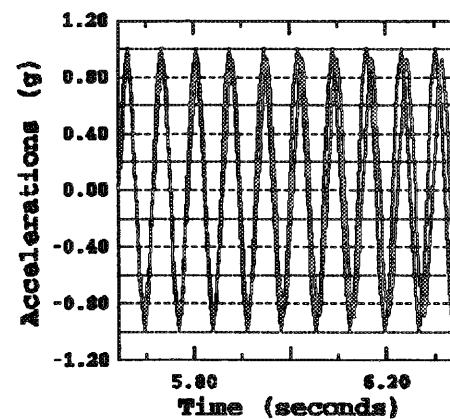
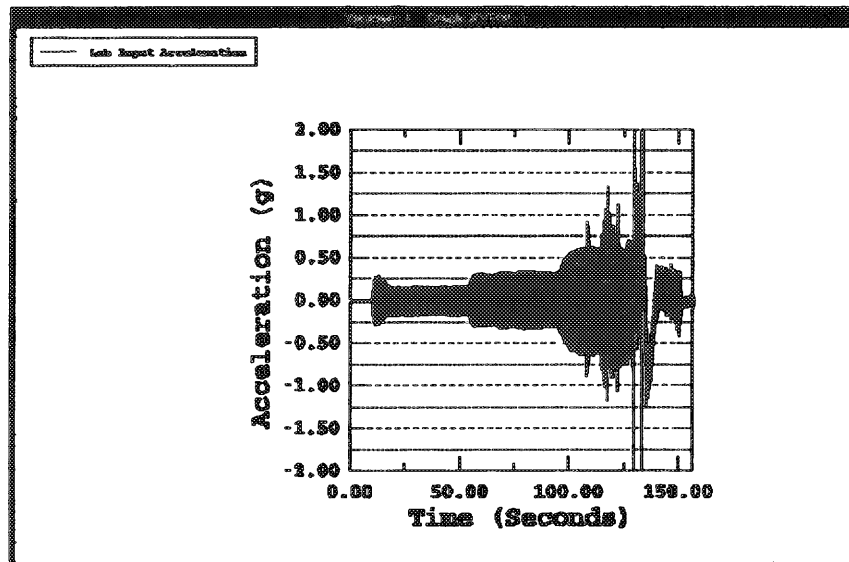


Figure F.17

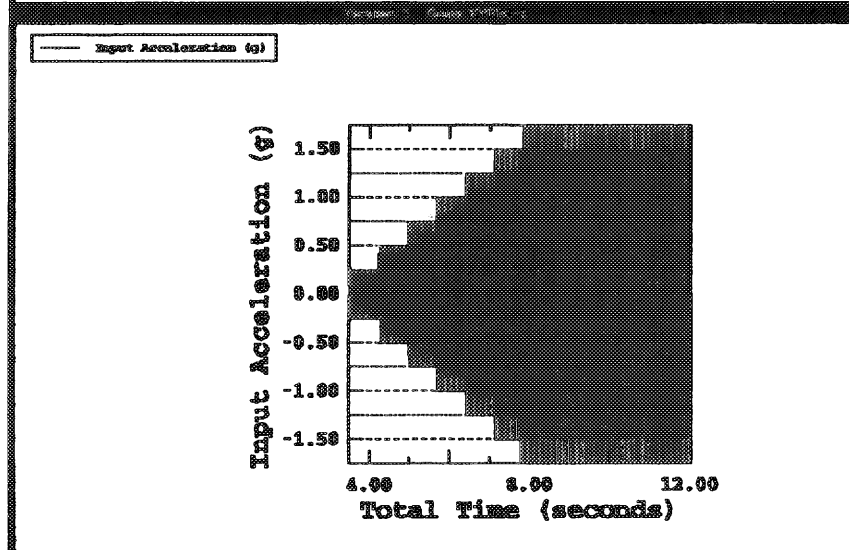
Input Accelerations : Model M13

Seventeen Vertical Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .25 g

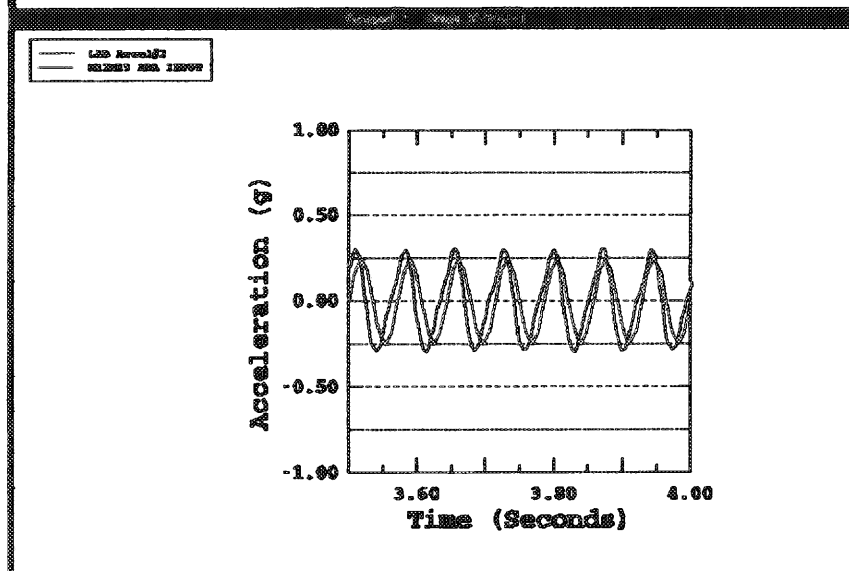
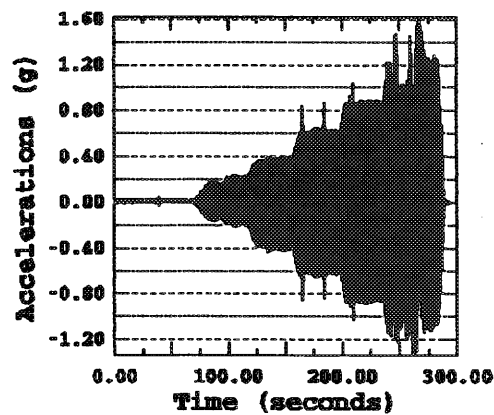


Figure F.18

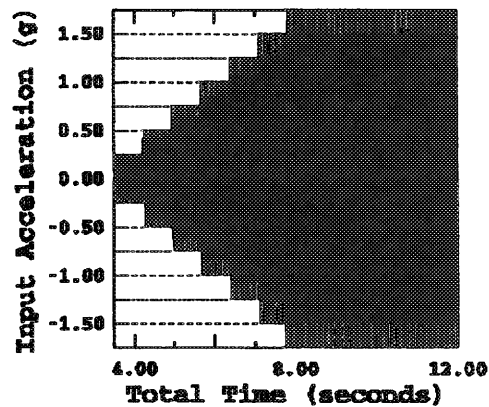
Input Accelerations : Model M14

Seventeen Vertical & Two Horizontal Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .50 g

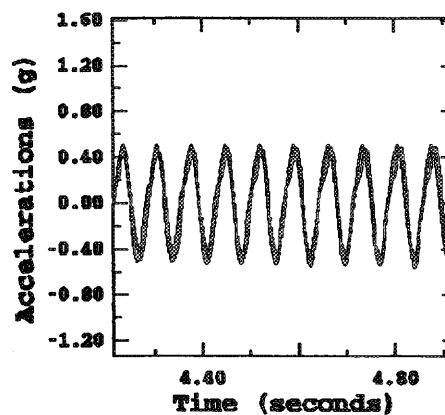
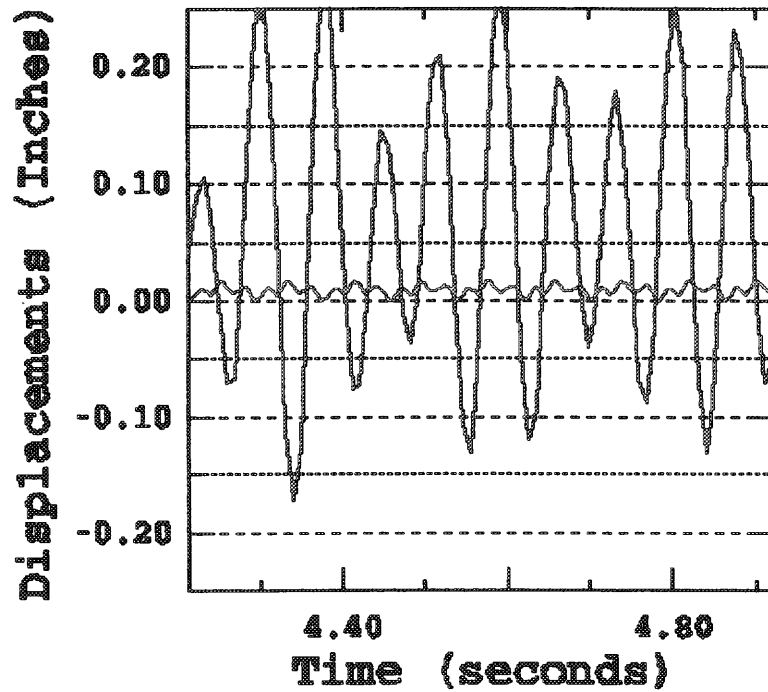


Figure F.19

Displacements Measured Versus Calculated Monolithic Model : M2

Input Acceleration Amplitude = 0.50 g

— ABAQUS LVDT#2
— LAS LVDT#2



— ABAQUS LVDT#1
— LAS LVDT#1

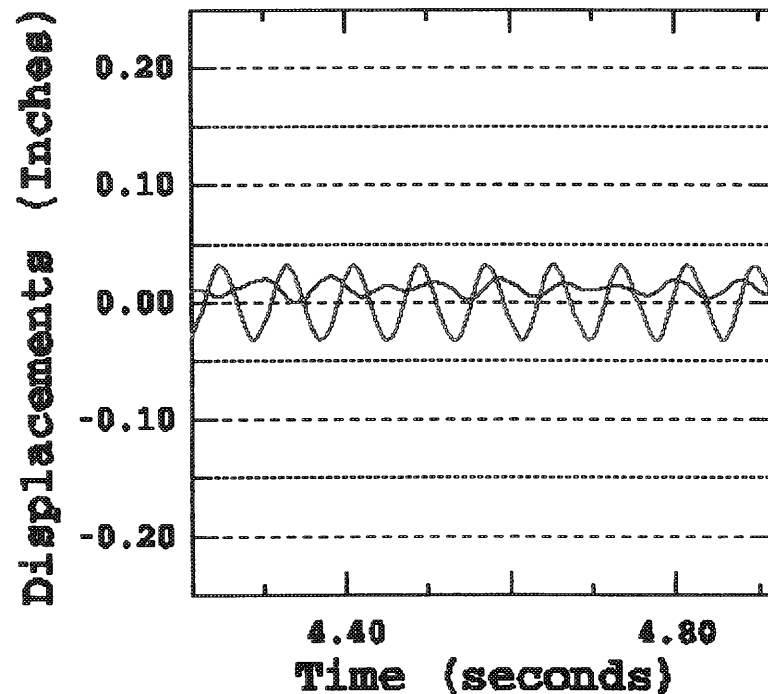
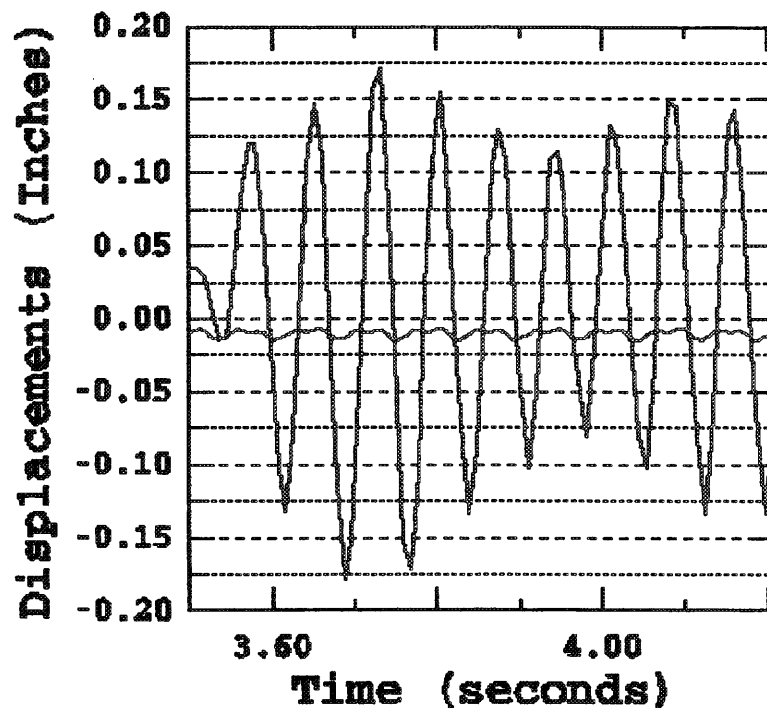


Figure F.20

Displacements Measured Versus Calculated Single Vertical Joint Model : M6

Input Acceleration Amplitude = 0.25 g

— ABAQUS LVDT#2
— LAB LVDT#2



— ABAQUS LVDT#1
— LAB LVDT#1

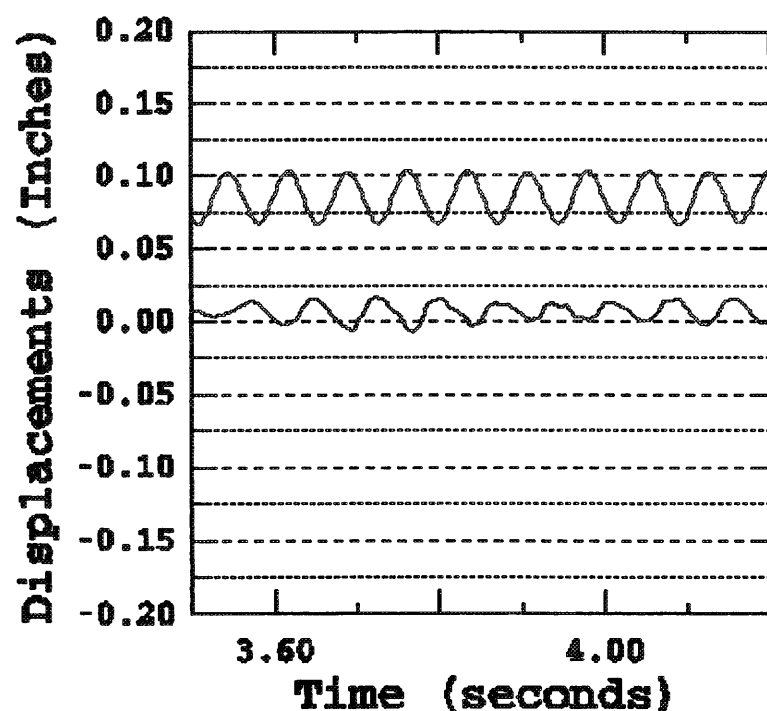
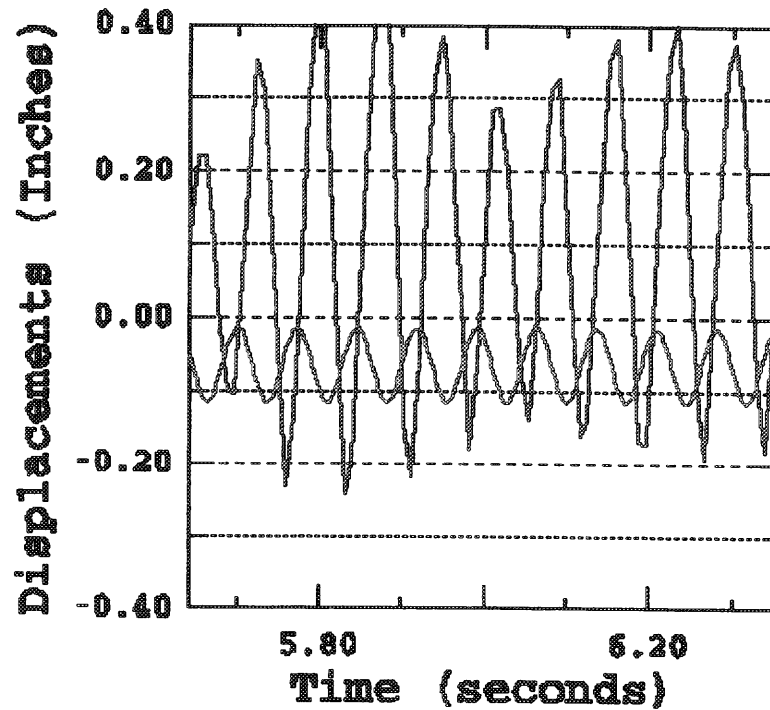


Figure F.21

Displacements Measured Versus Calculated Single Horizontal Joint Model : M10

Input Acceleration Amplitude = 1.0 g

— ABAQUS LVDT#2
— LAB LVDT#2



— ABAQUS LVDT#1
— LAB LVDT#1

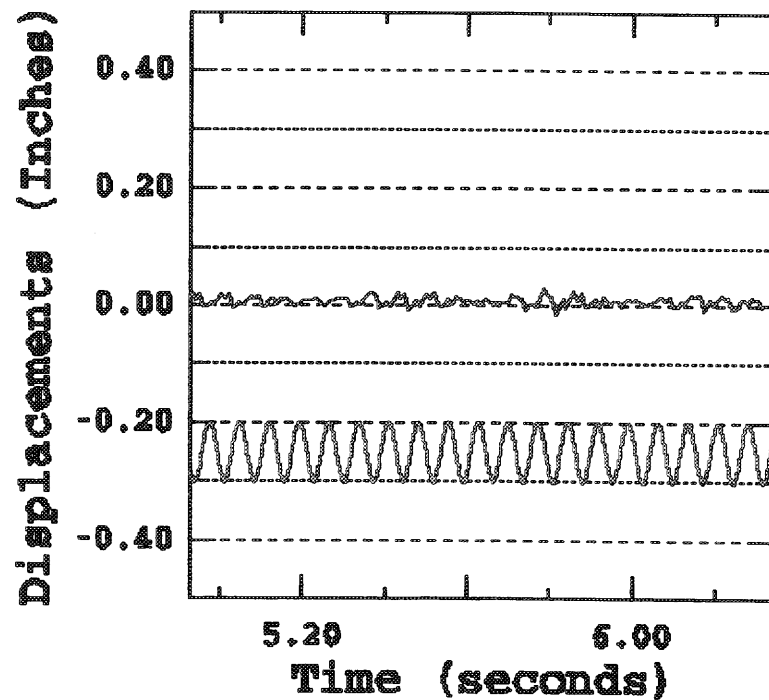
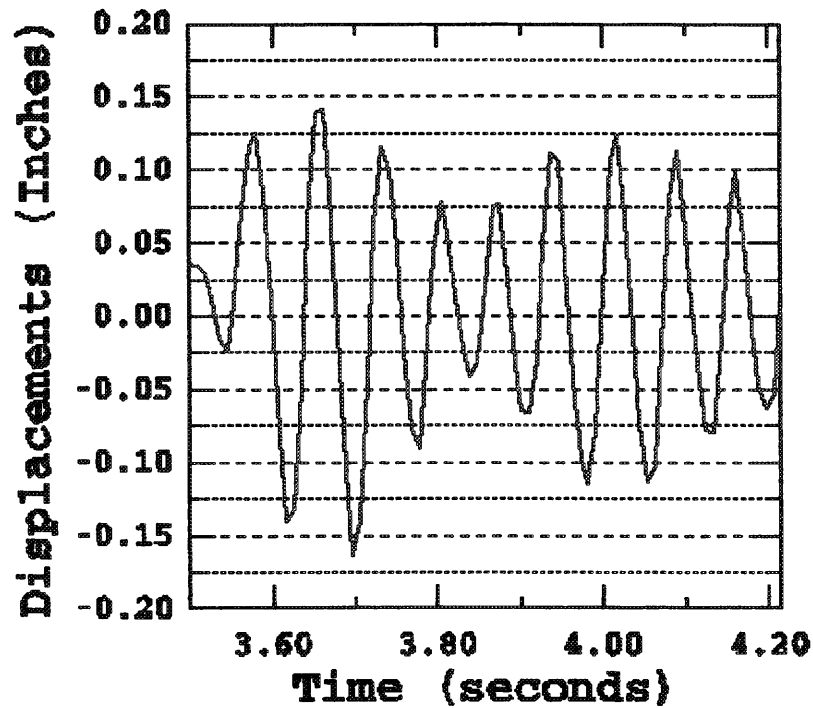


Figure F.22

Displacements Measured Versus Calculated Seventeen Vertical Joint Model : M13

Input Acceleration Amplitude = 0.25 g

— ABAQUS LVDT#2



— ABAQUS LVDT#1
- - - LAB LVDT#1

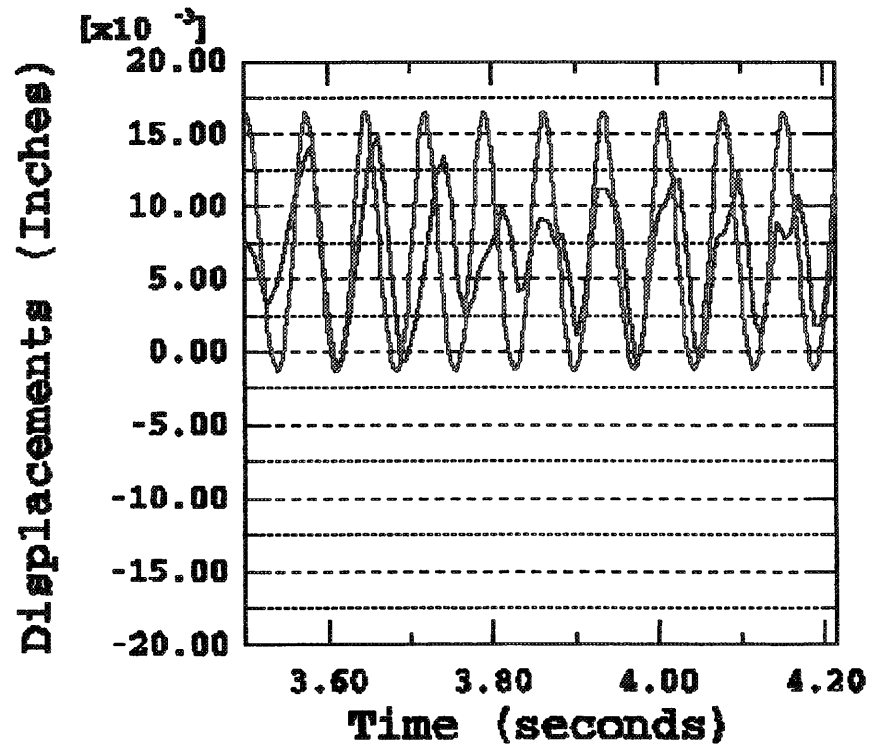
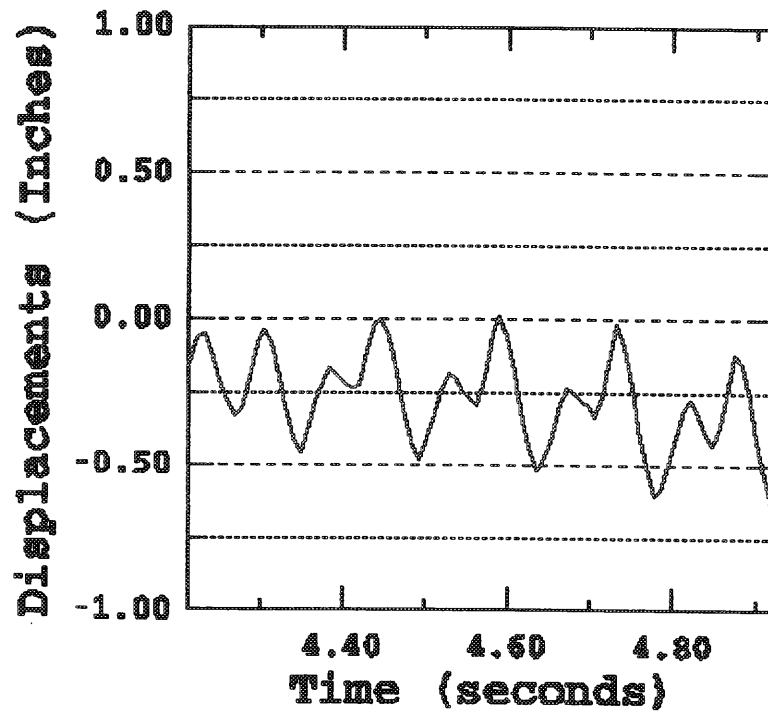


Figure F.23

Displacements Measured Versus Calculated Seventeen Vertical & Two Horizontal Joint Model : M14

Input Acceleration Amplitude = 0.50 g

— ABAQUS LVDT#2



— ABAQUS LVDT#1
— LAB LVDT#1

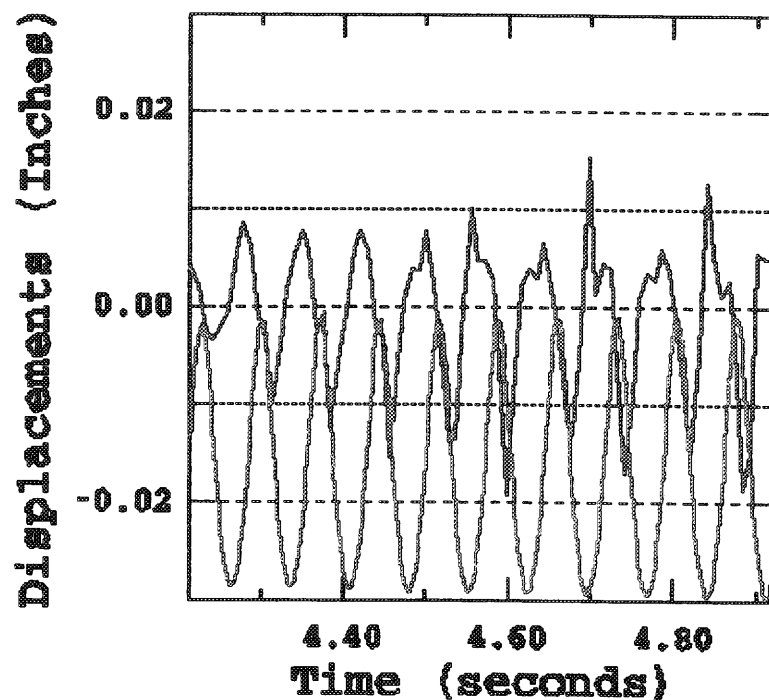
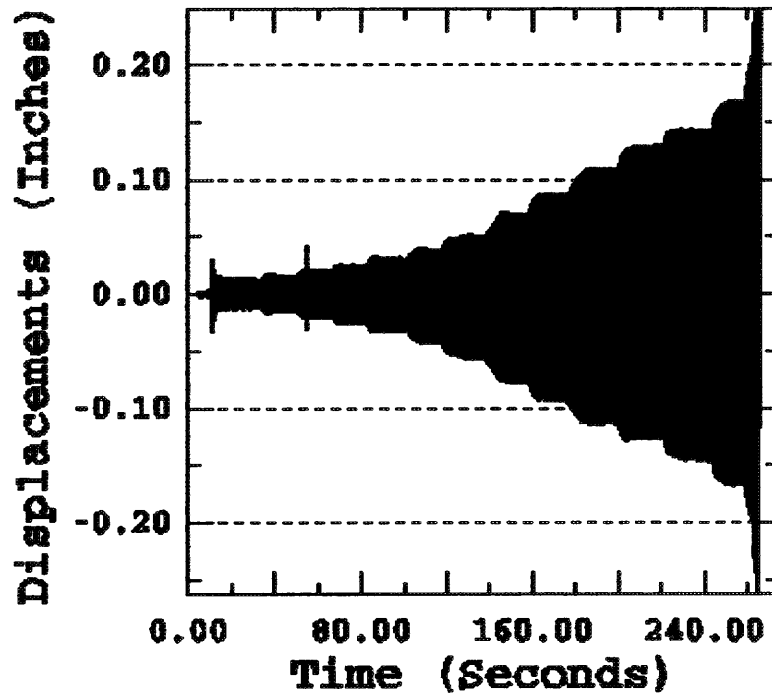


Figure F.24

Displacements Measured During Shake Table Test Monolithic Model : M2

Model M2 LVDT#1

LVDT#1



Model M2 LVDT#2

LVDT#2

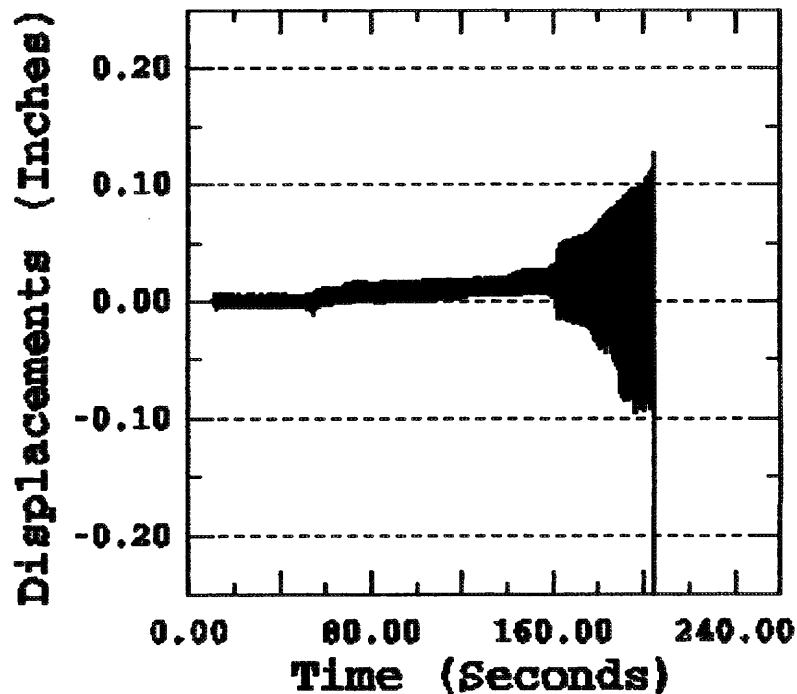
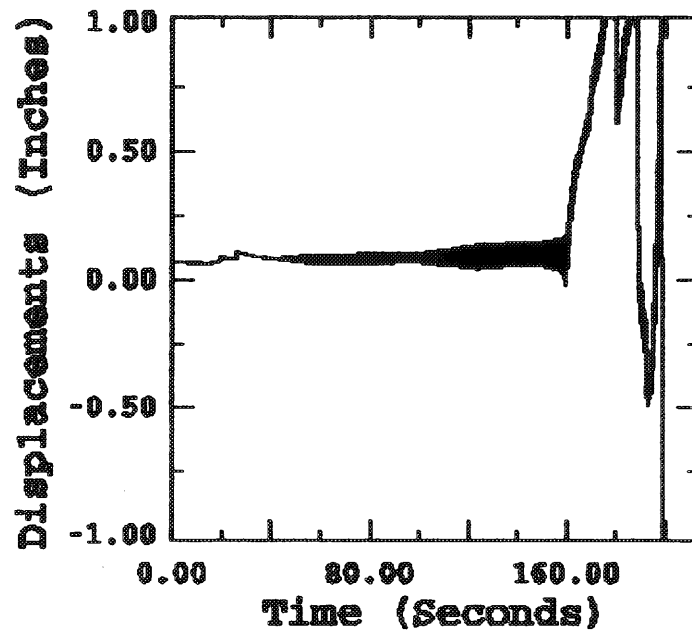


Figure F.25

Displacements Measured During Shake Table Test Single Vertical Joint Model : M6

Lab 1WDT01

LVDT#1



Lab 1WDT02

LVDT#2

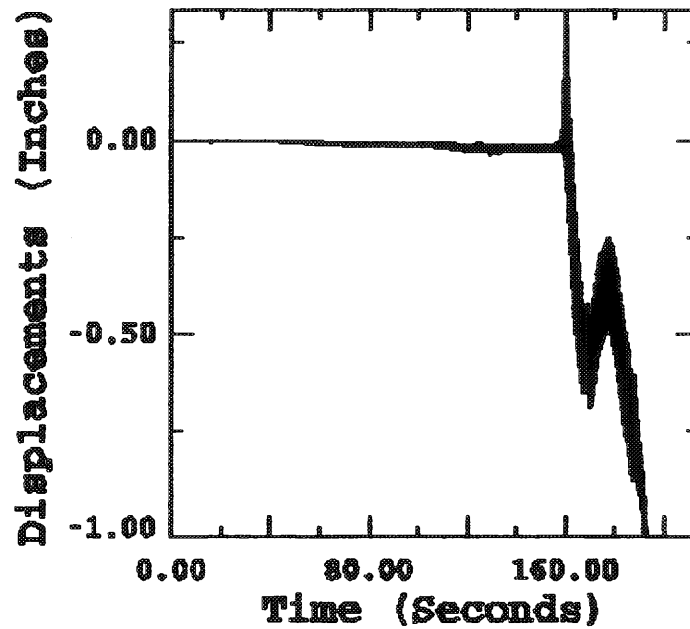
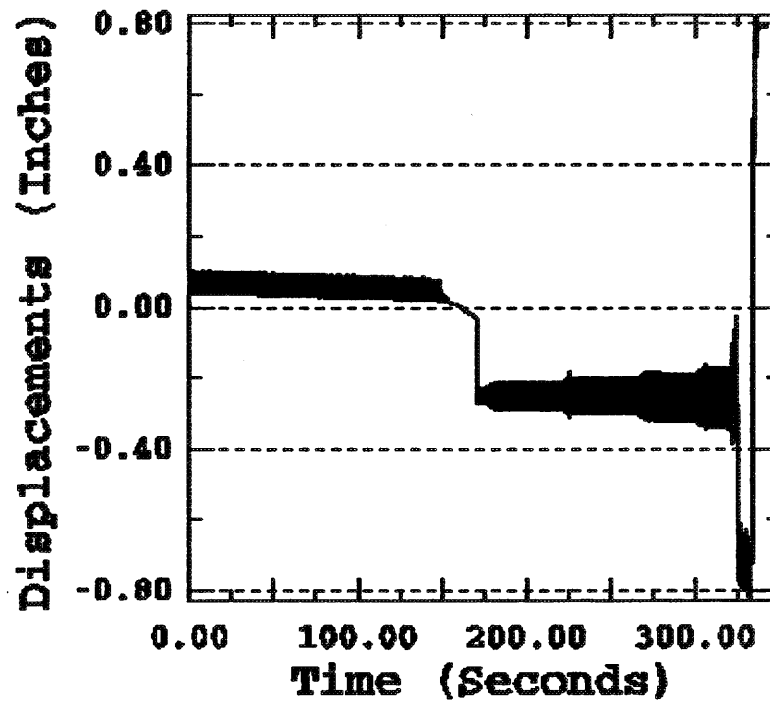


Figure F.26

Displacements Measured During Shake Table Test Single Horizontal Joint Model : M10

— LVDT#1

LVDT#1



— LVDT#2

LVDT#2

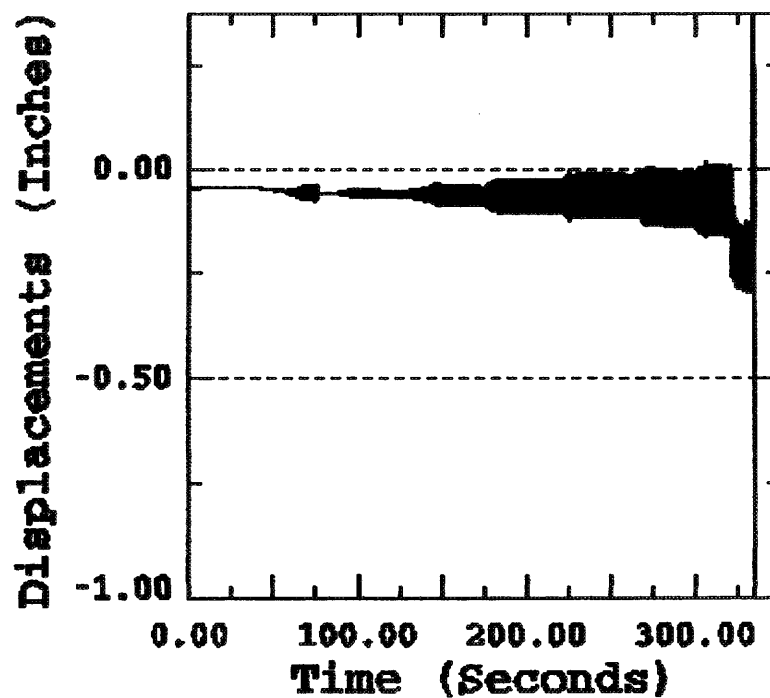
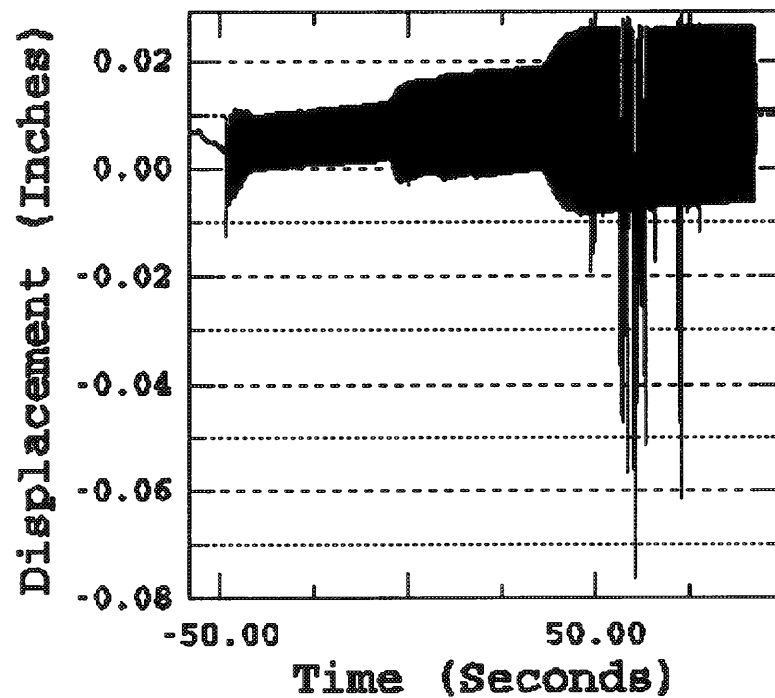


Figure F.27

Displacements Measured During Shake Table Test Seventeen Vertical Joint Model : M13

— LAB LVDT#1

LVDT#1



— LAB LVDT#2

LVDT#2

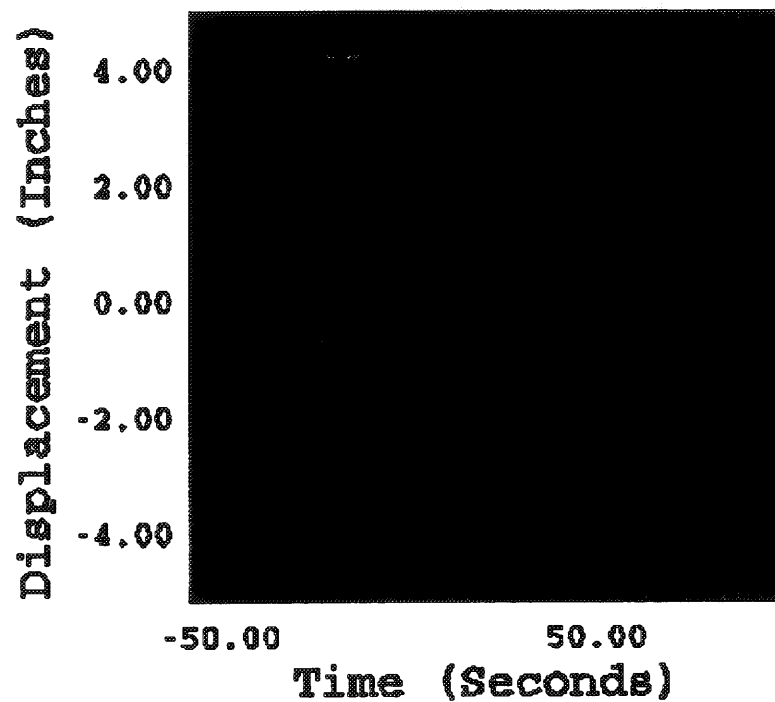
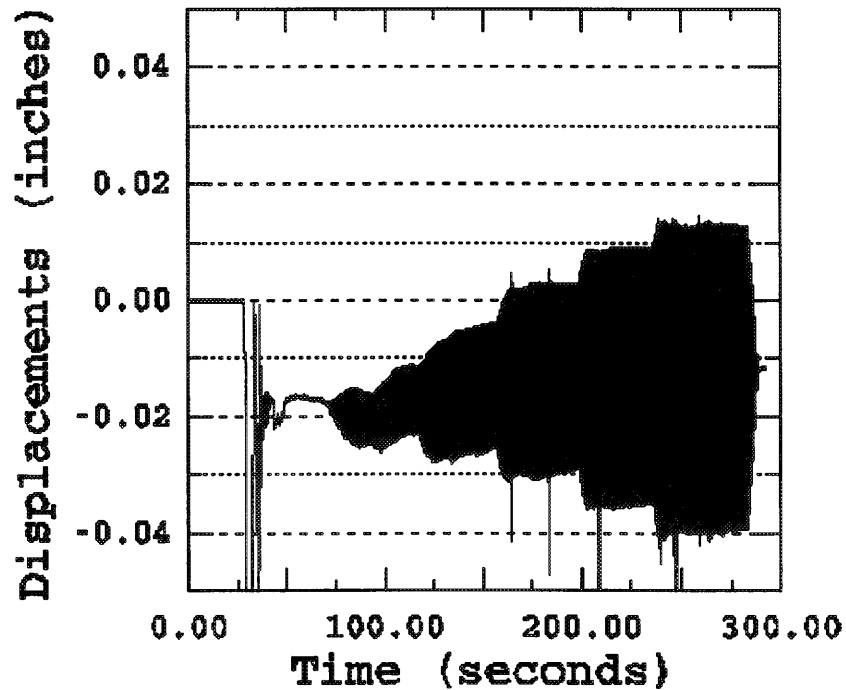


Figure F.28

Displacements Measured During Shake Table Test Seventeen Vertical & Two horizontal Joint Model : M14

Model M14 LVDT#1

LVDT#1



Model M14 LVDT#2

LVDT#2

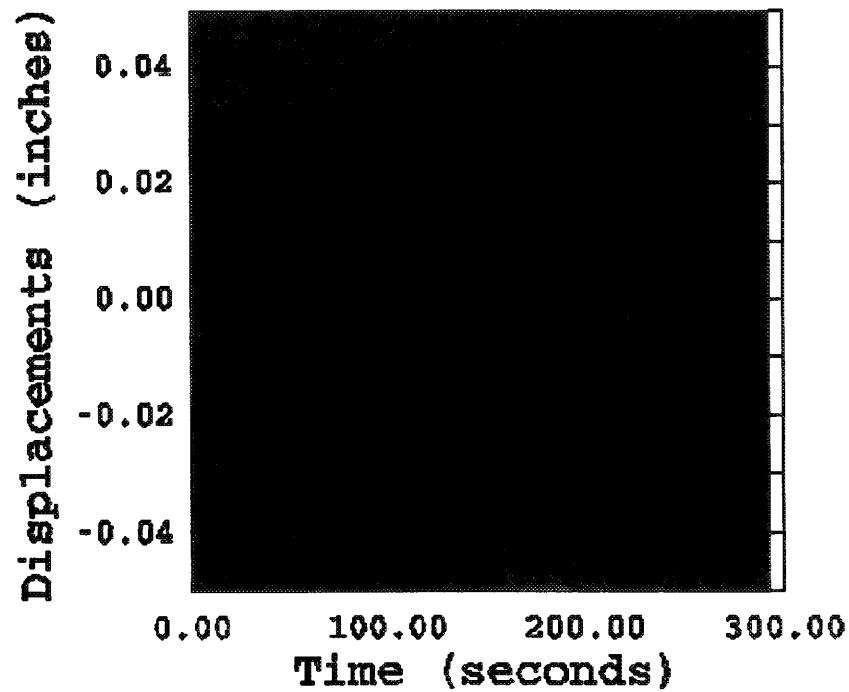
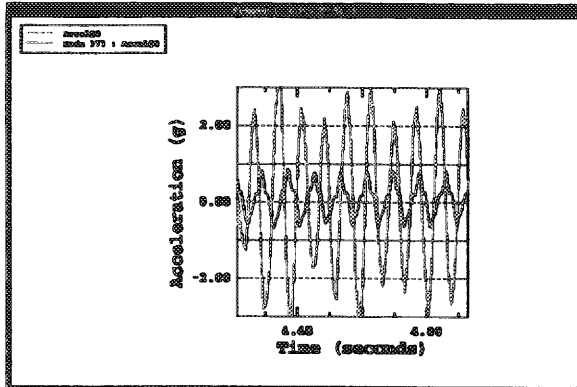


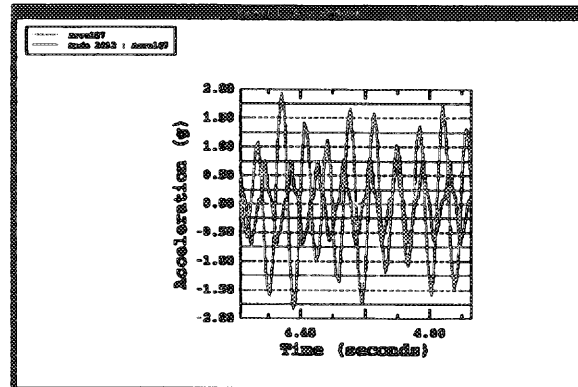
Figure F.29

Monolithic Model : M2

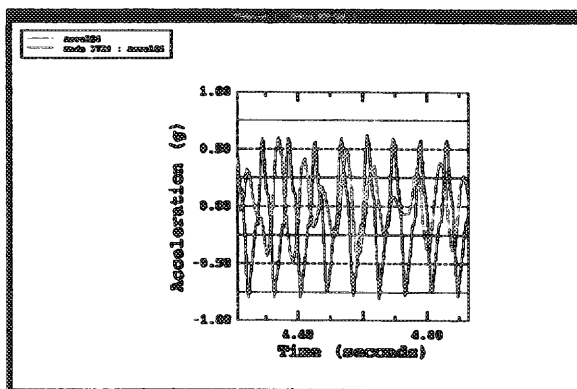
Comparison of Measured Versus Calculated Accelerations



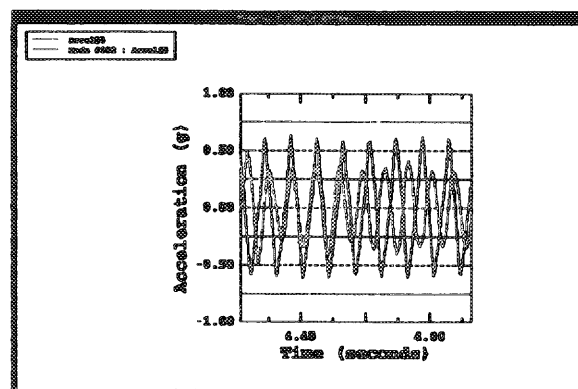
Accel #8



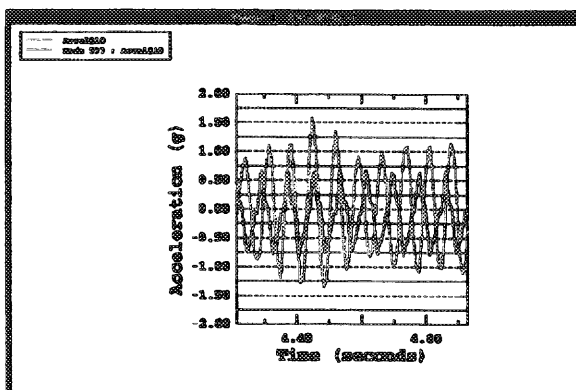
Accel #7



Accel #6

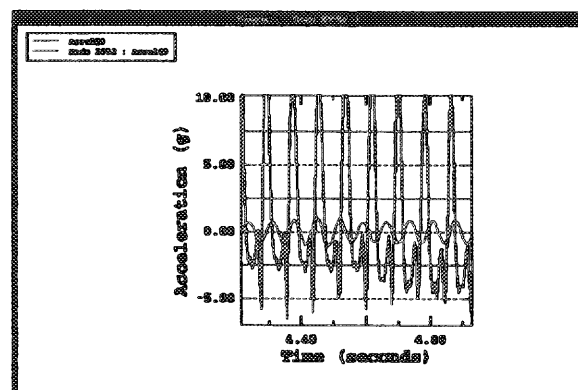


Accel #5



Accel #10

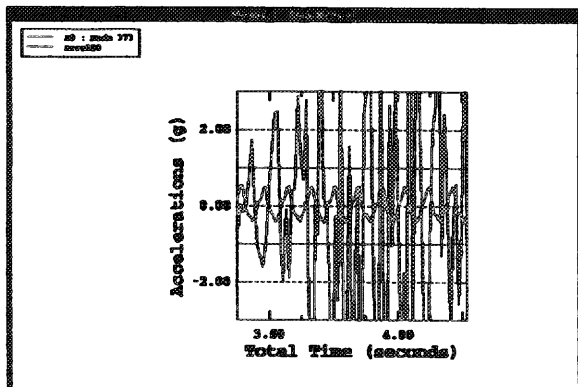
Green = Analysis
Red = Laboratory



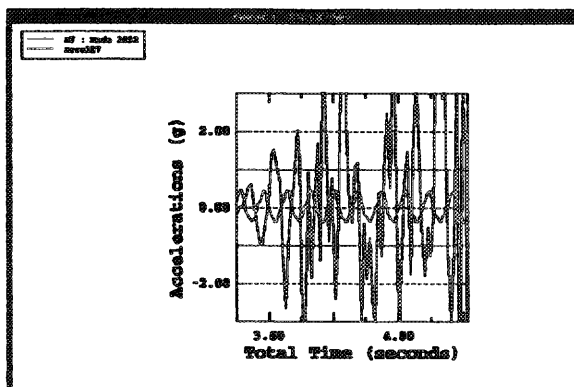
Accel #9

Single Vertical Joint Model : M6

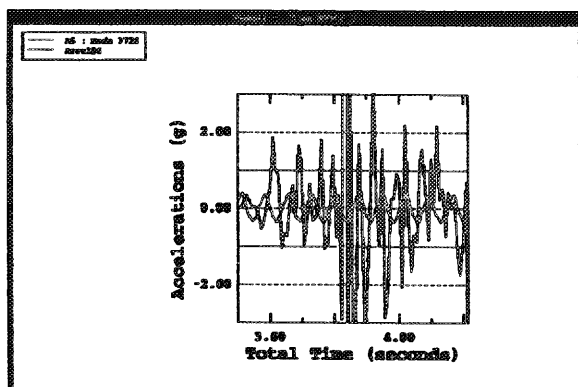
Comparison of Measured Versus Calculated Accelerations



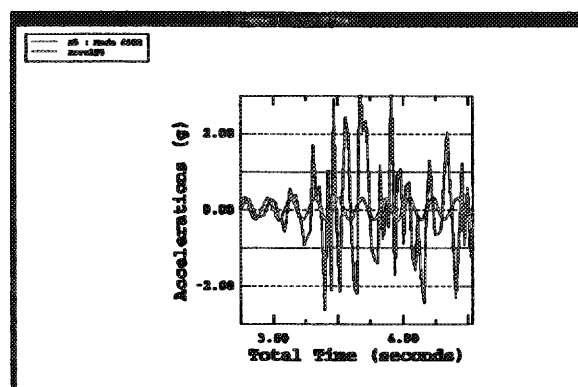
Accel #8



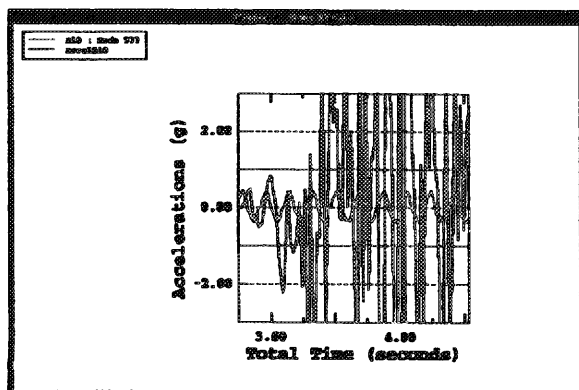
Accel #7



Accel #6

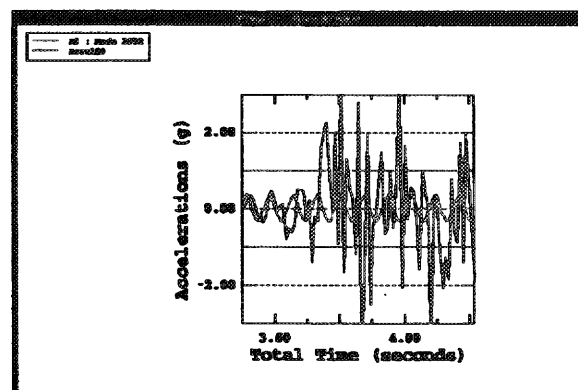


Accel #5



Accel #10

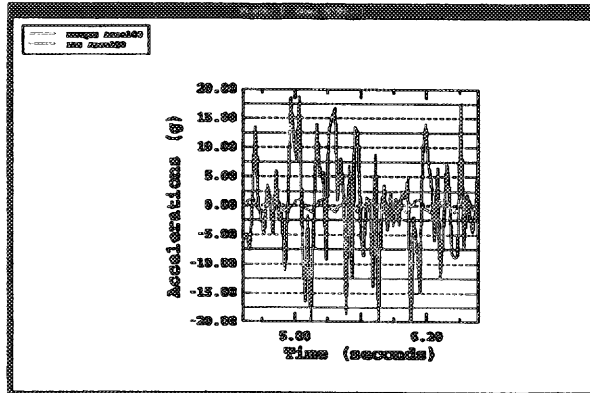
Red = Analysis
Green = Laboratory



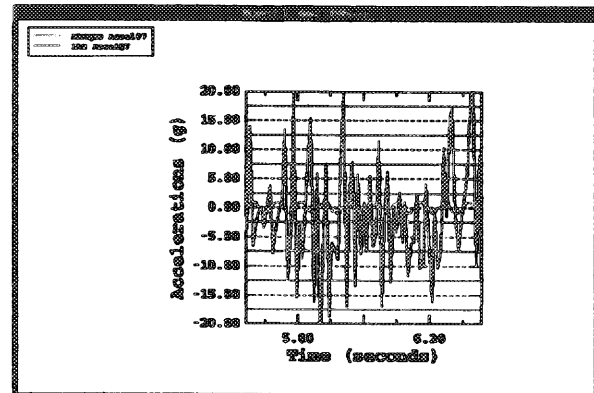
Accel #9

Single Horizontal Joint Model : M10

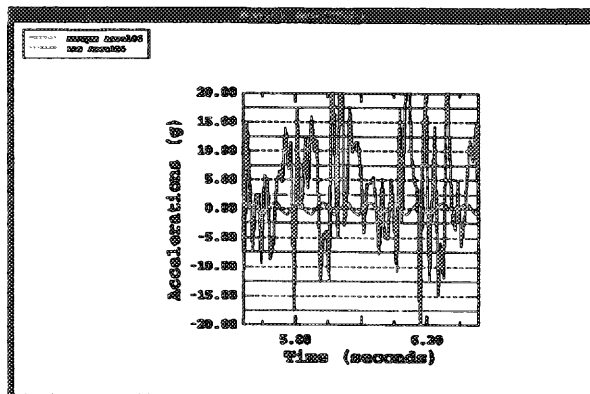
Comparison of Measured Versus Calculated Accelerations



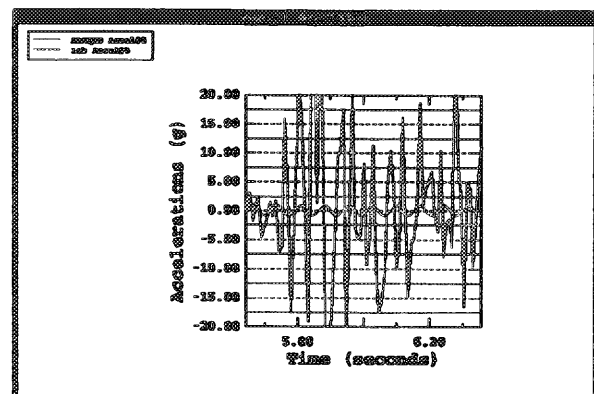
Accel #8



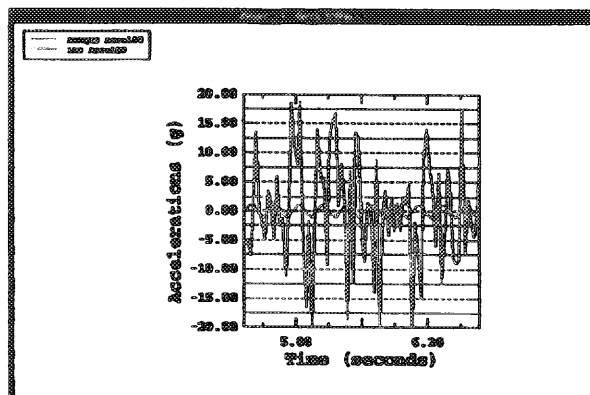
Accel #7



Accel #6

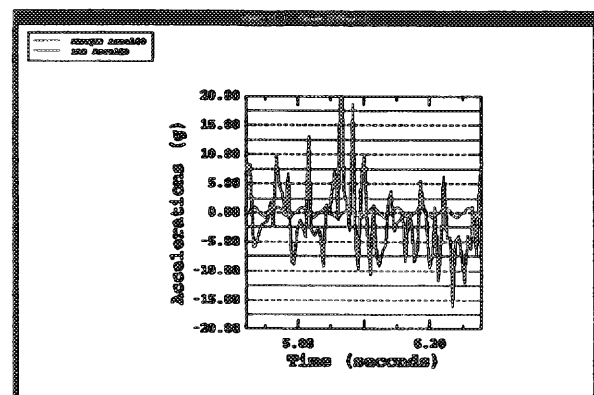


Accel #5



Accel #10

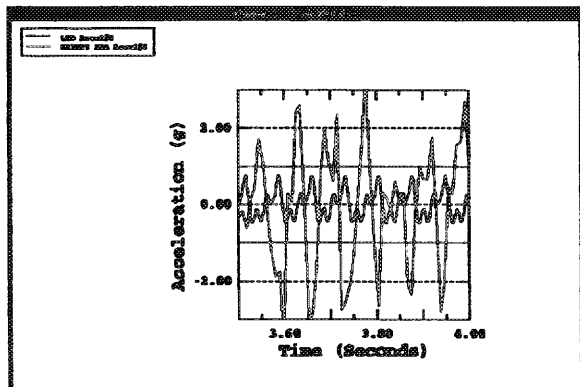
Red = Analysis
Green = Laboratory



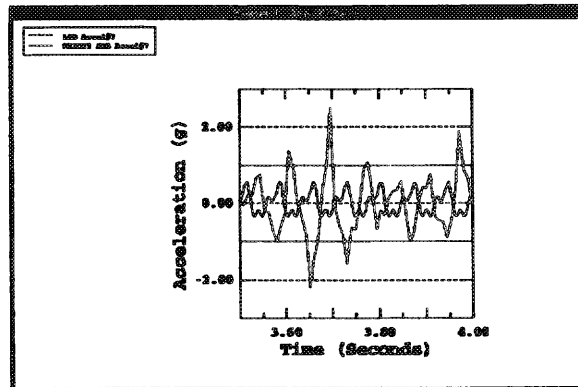
Accel #9

Seventeen Vertical Joint Model : M13

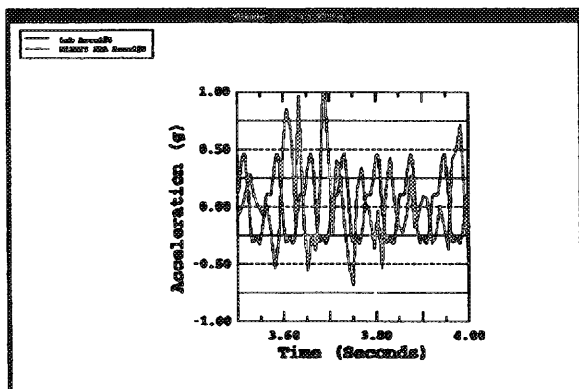
Comparison of Measured Versus Calculated Accelerations



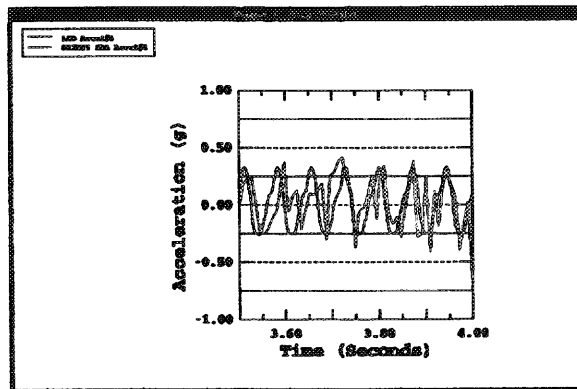
Accel #8



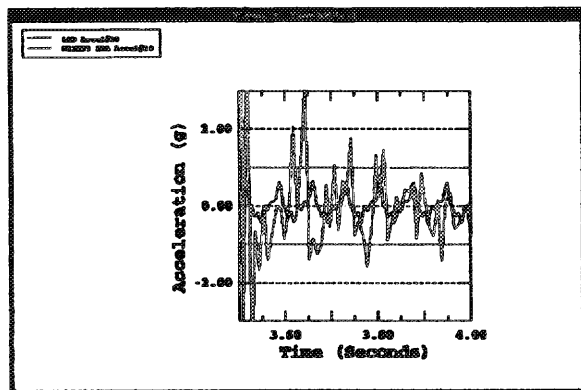
Accel #7



Accel #6

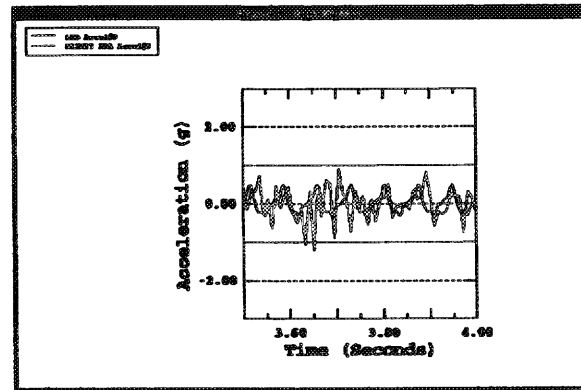


Accel #5



Accel #10

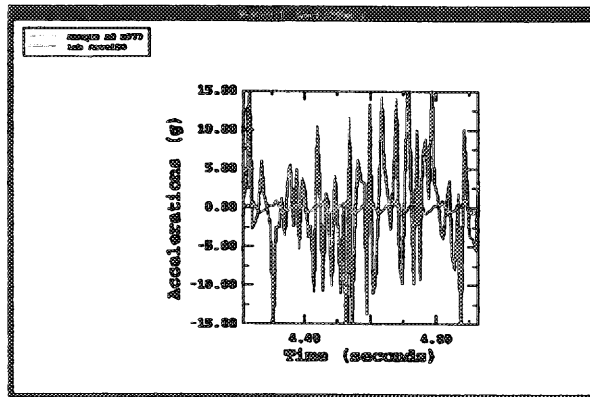
Green = Analysis
Red = Laboratory



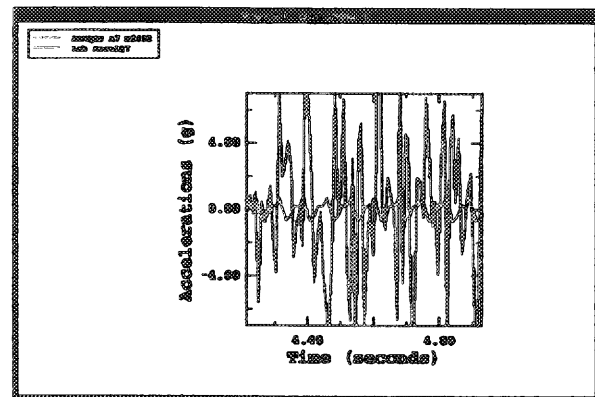
Accel #9

Seventeen Vertical & Two Horizontal Joint Model : M14

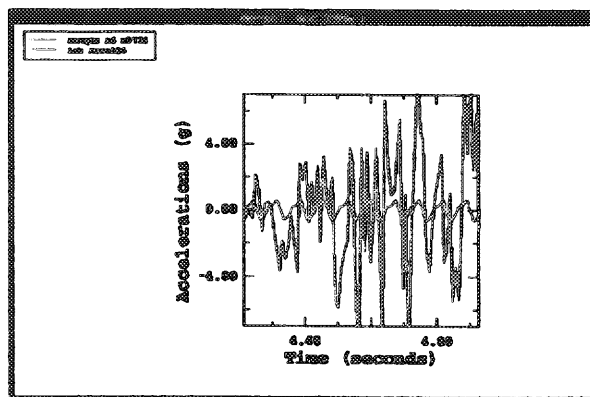
Comparison of Measured Versus Calculated Accelerations



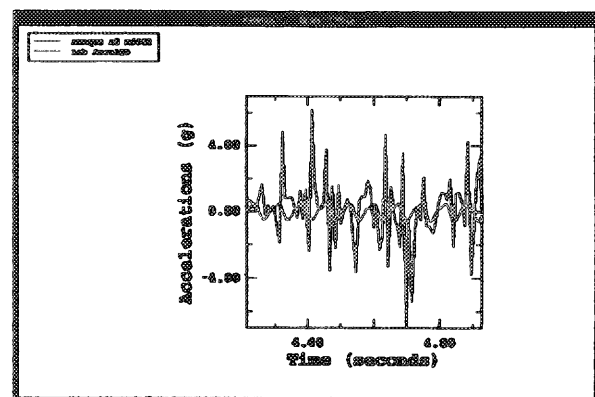
Accel #8



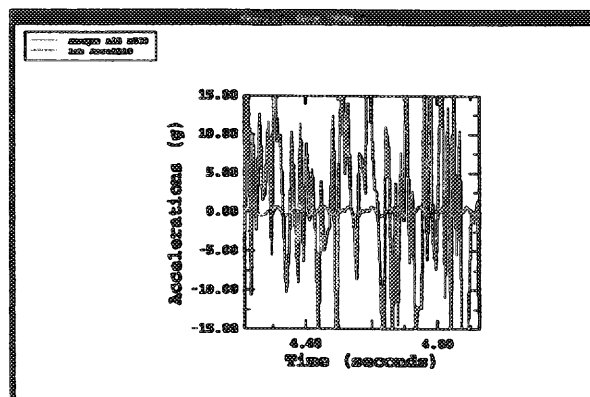
Accel #7



Accel #6

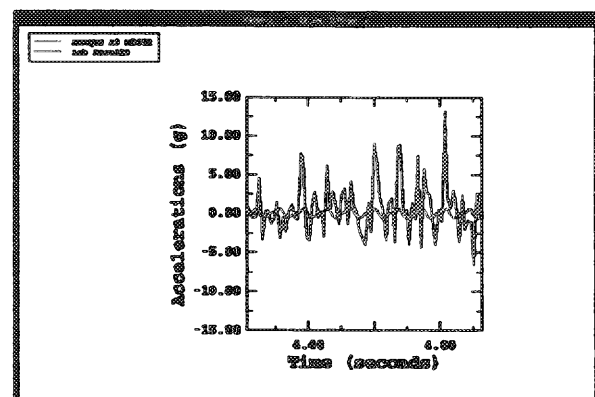


Accel #5



Accel #10

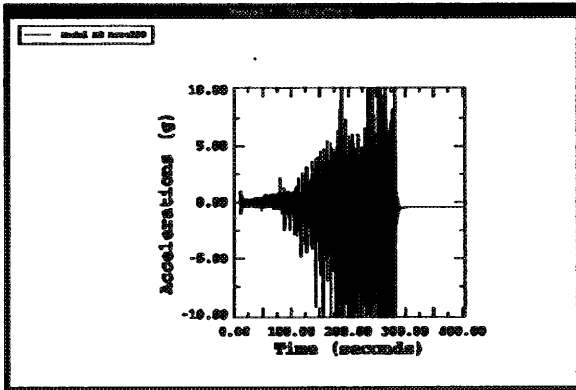
Red = Analysis
Green = Laboratory



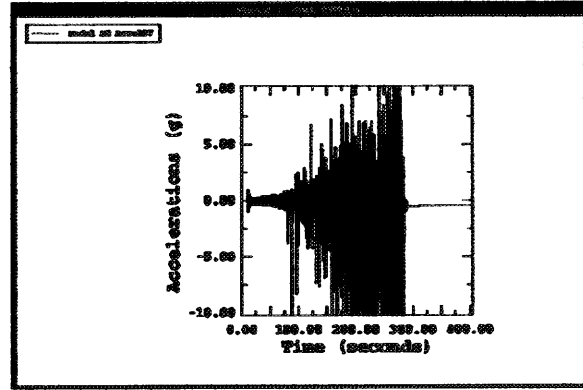
Accel #9

Measured Acceleration Records

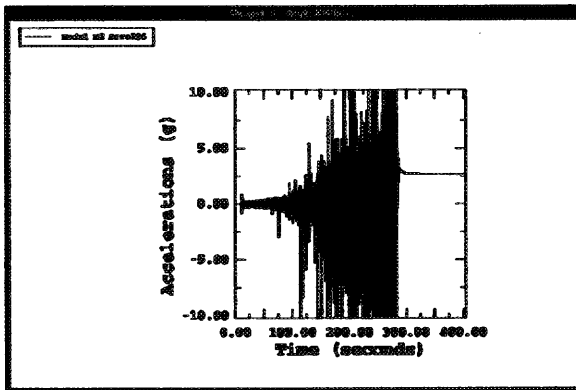
Monolithic Model : M2



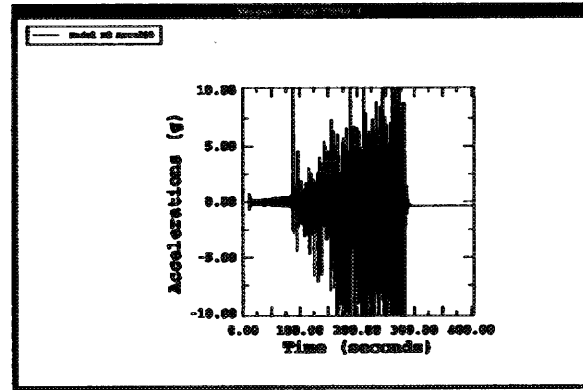
Accel #8



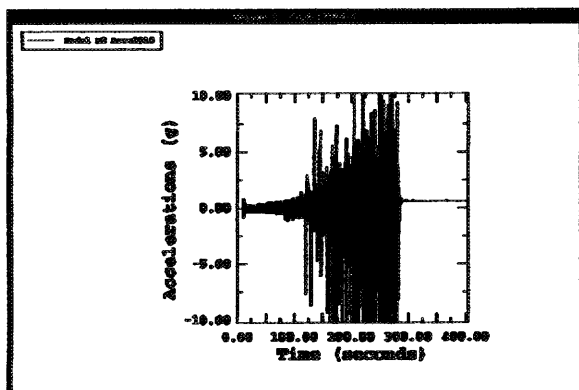
Accel #7



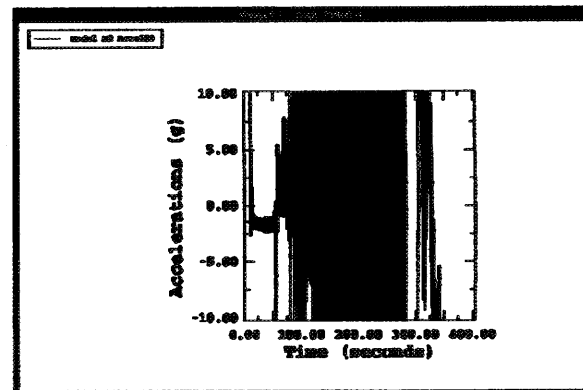
Accel #6



Accel #5



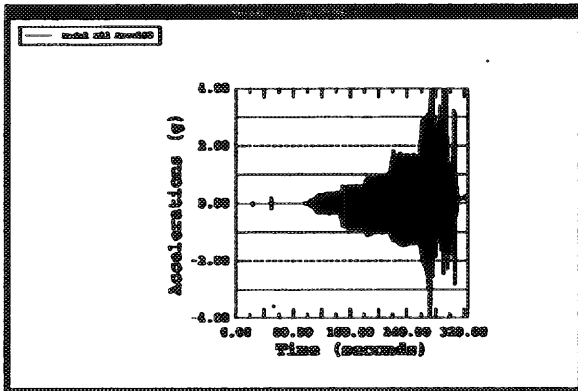
Accel #10



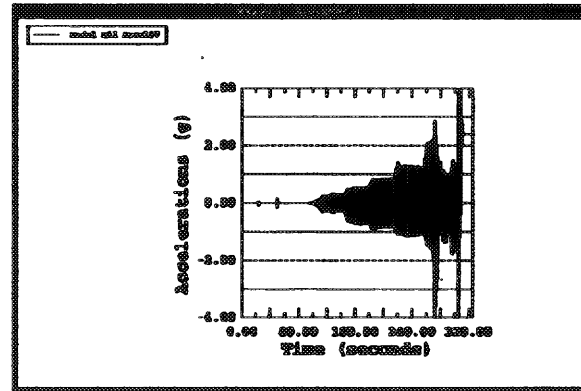
Accel #9

Measured Acceleration Records

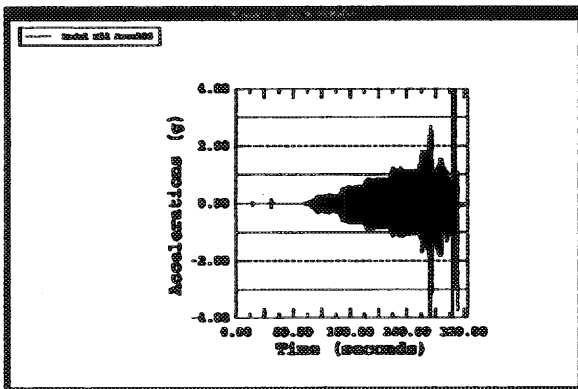
Single Vertical Joint Model : M6



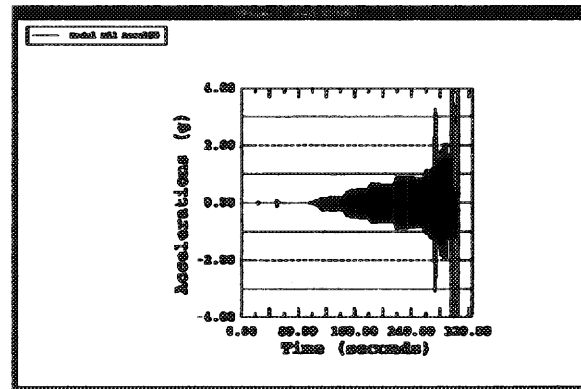
Accel #8



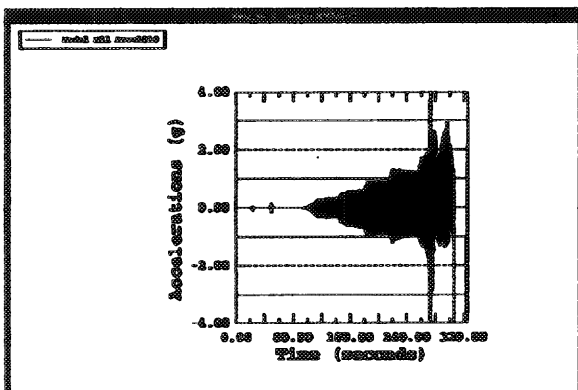
Accel #7



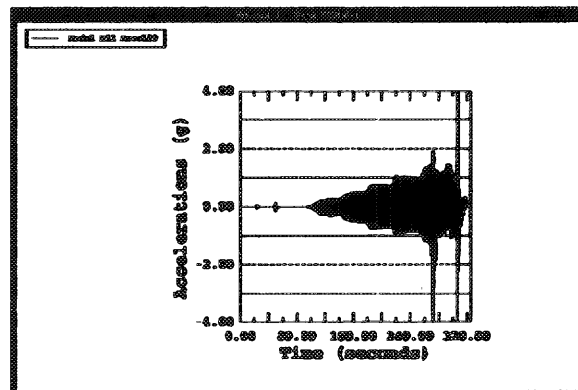
Accel #6



Accel #5



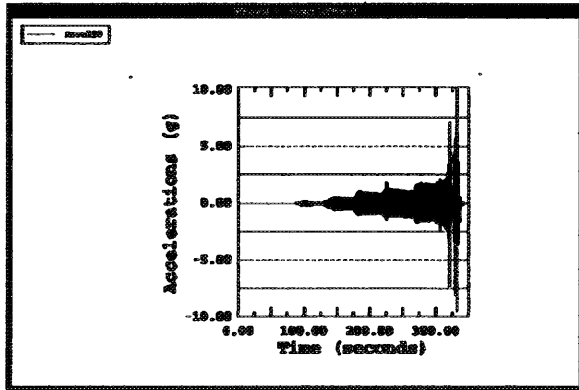
Accel #10



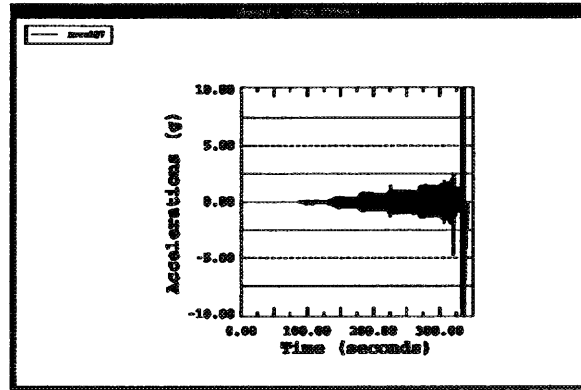
Accel #9

Measured Acceleration Records

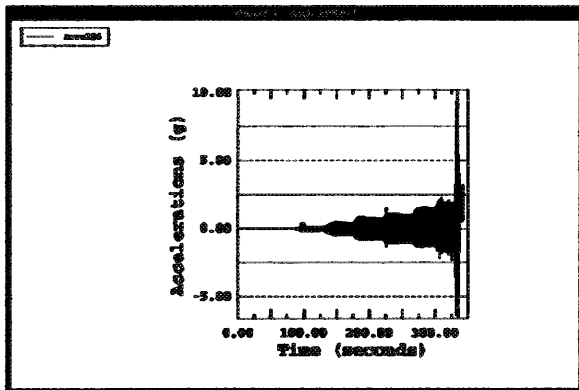
Single Horizontal Joint Model : M10



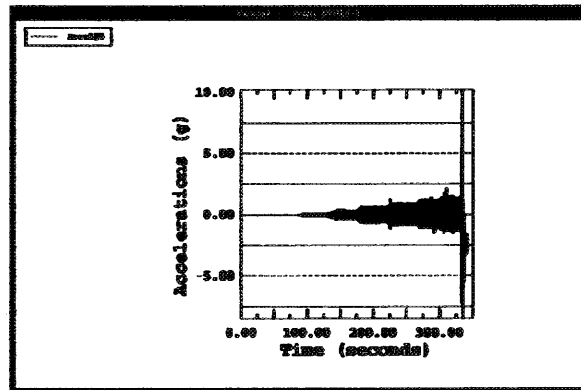
Accel #8



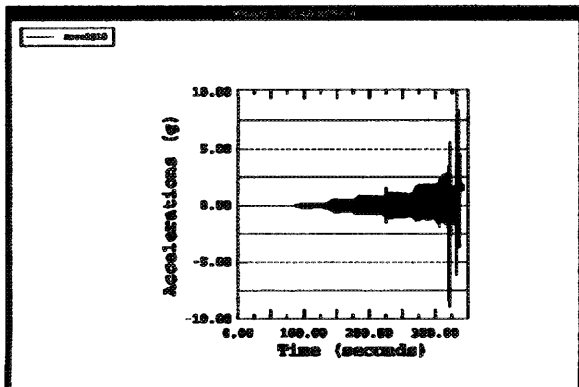
Accel #7



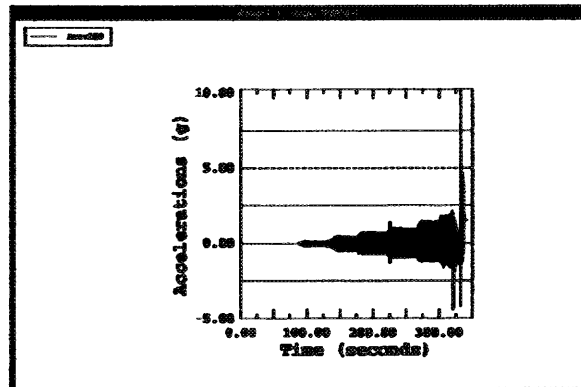
Accel #6



Accel #5



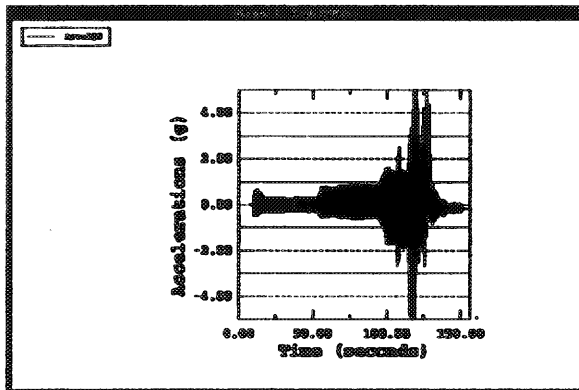
Accel #10



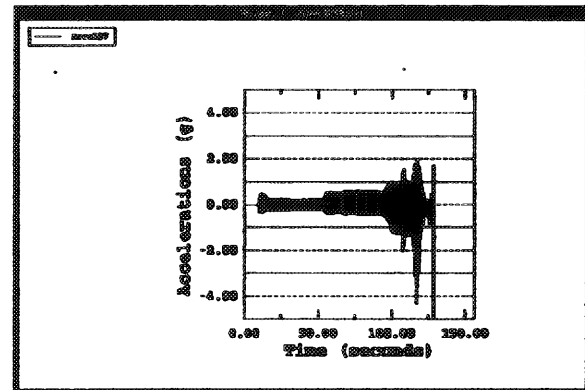
Accel #9

Measured Acceleration Records

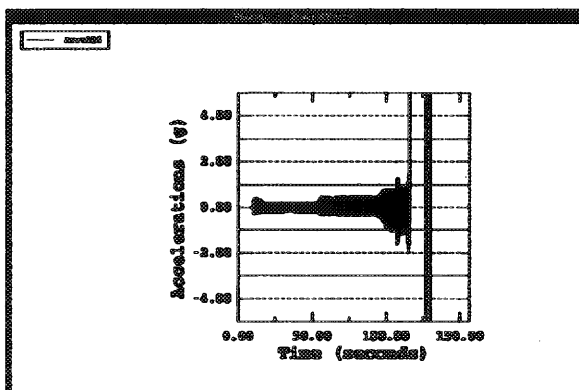
Seventeen Vertical Joint Model : M13



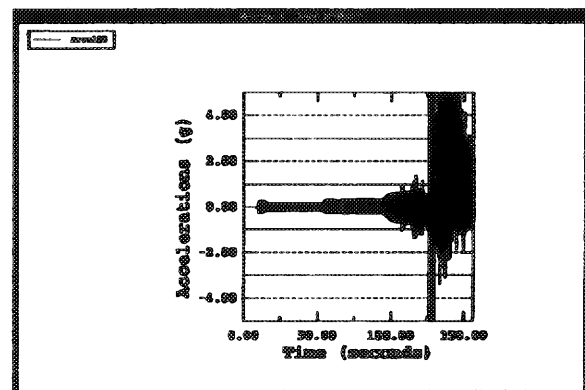
Accel #8



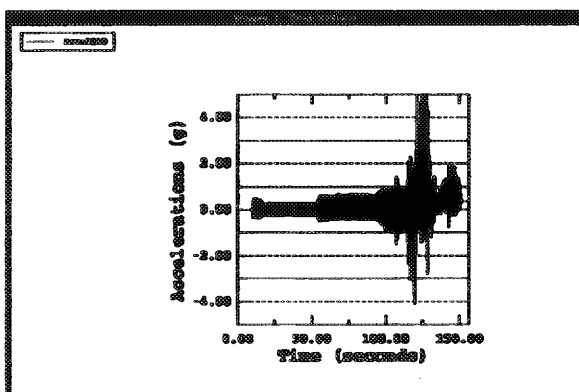
Accel #7



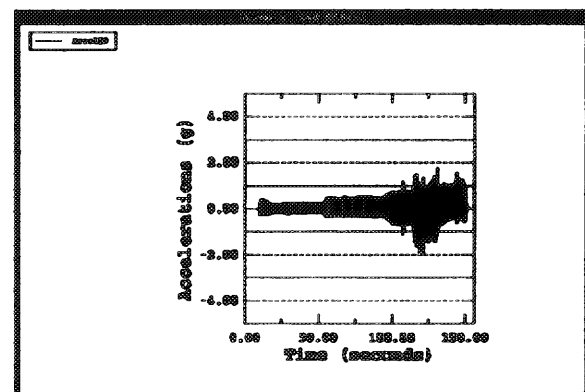
Accel #6



Accel #5



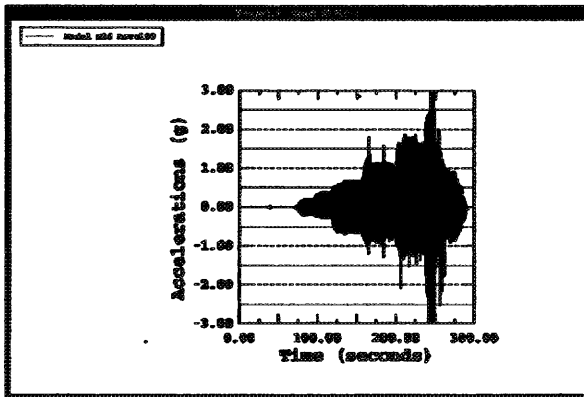
Accel #10



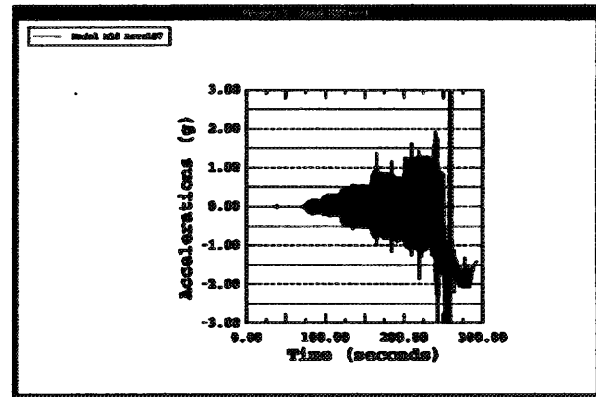
Accel #9

Measured Acceleration Records

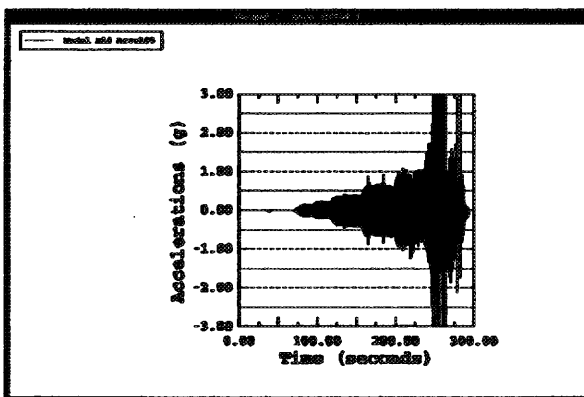
Seventeen Vertical & Two Horizontal Joint Model : M14



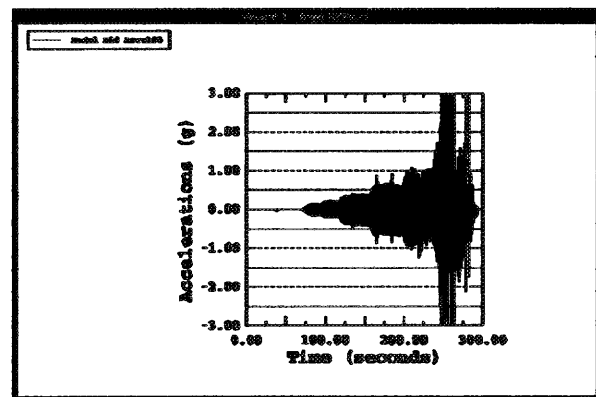
Accel #8



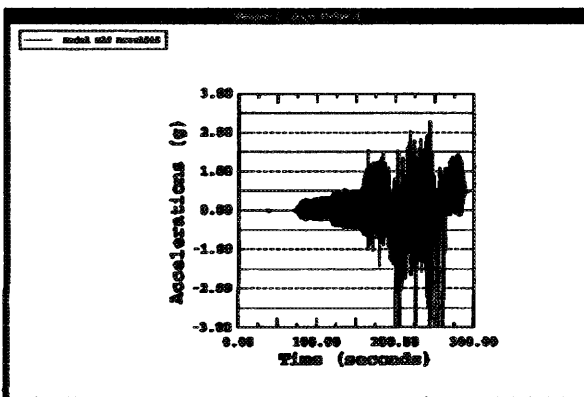
Accel #7



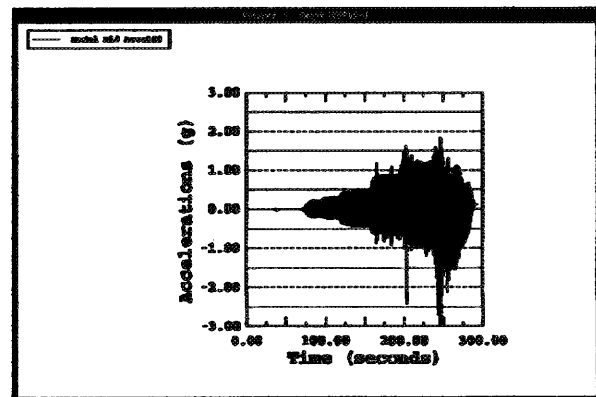
Accel #6



Accel #5



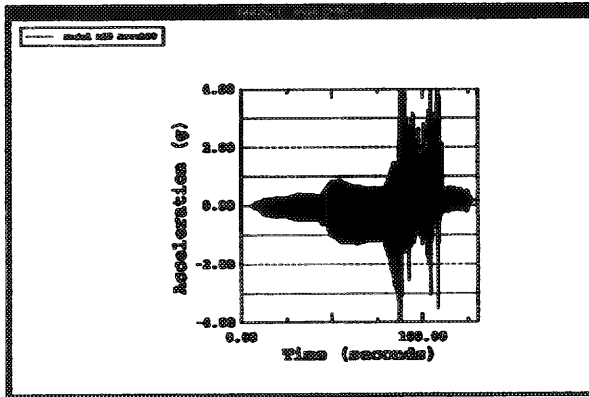
Accel #10



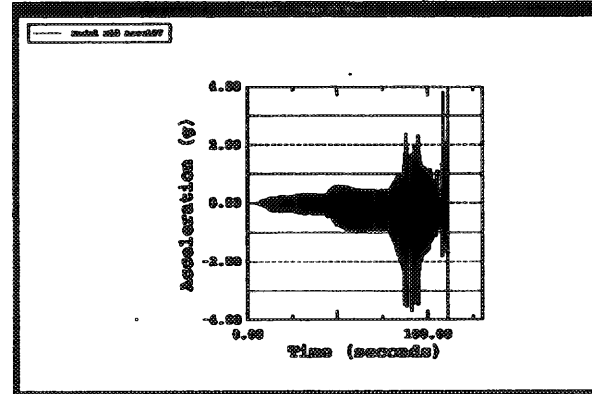
Accel #9

Measured Acceleration Records

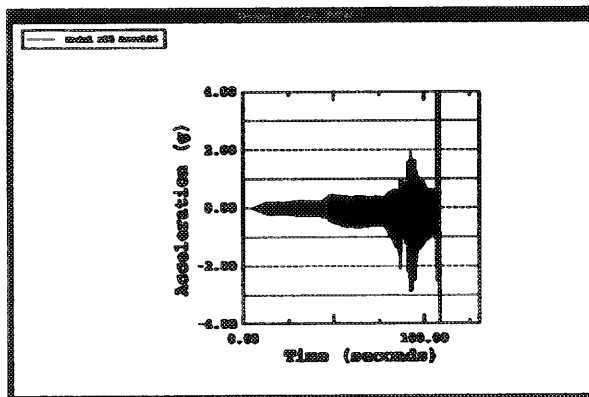
Seventeen Vertical & Two Horizontal Joint Model : M15



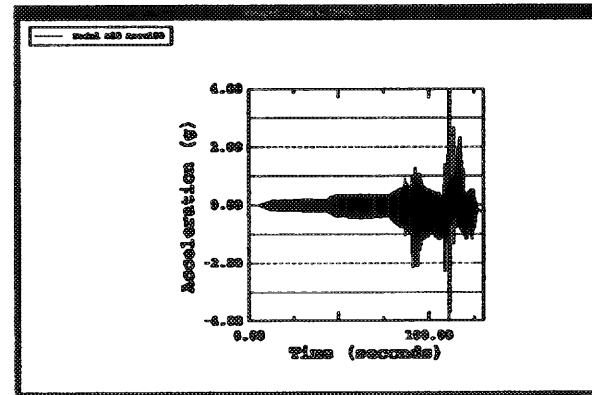
Accel #8



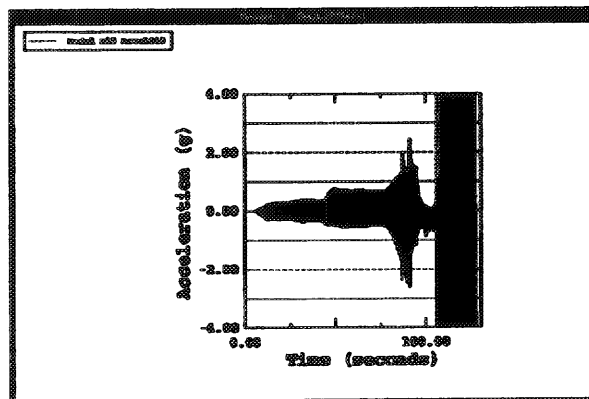
Accel #7



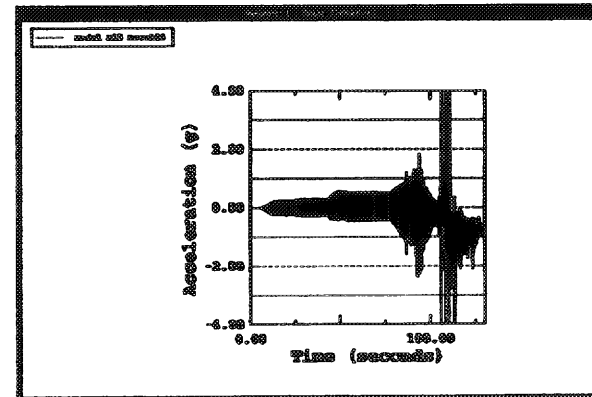
Accel #6



Accel #5



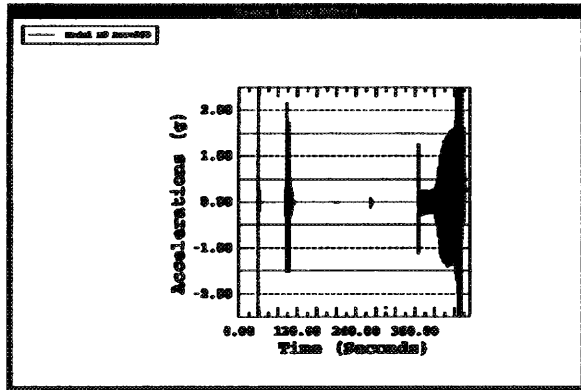
Accel #10



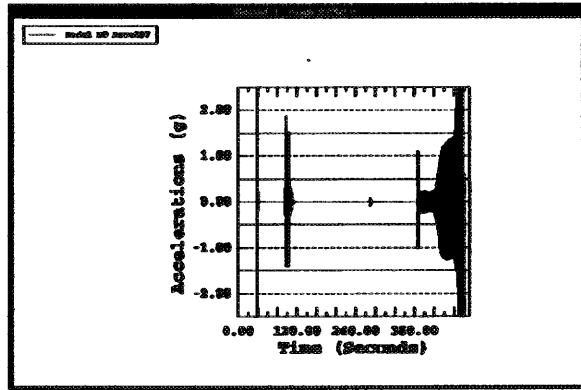
Accel #9

Measured Acceleration Records

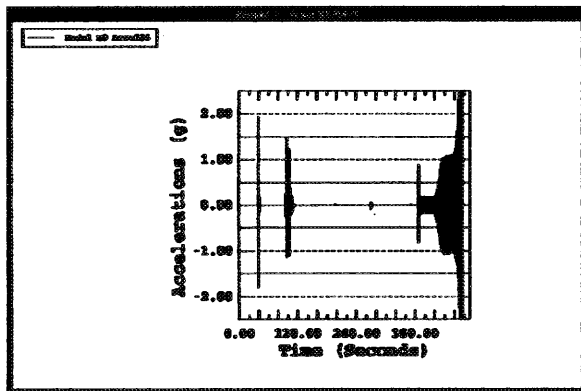
Monolithic Model : M8



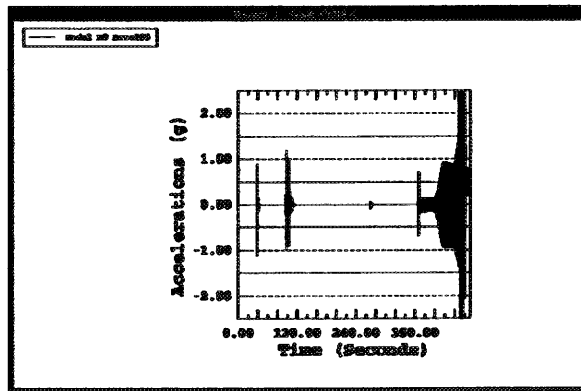
Accel #8



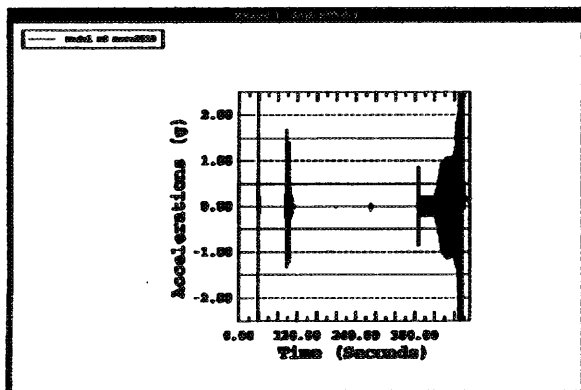
Accel #7



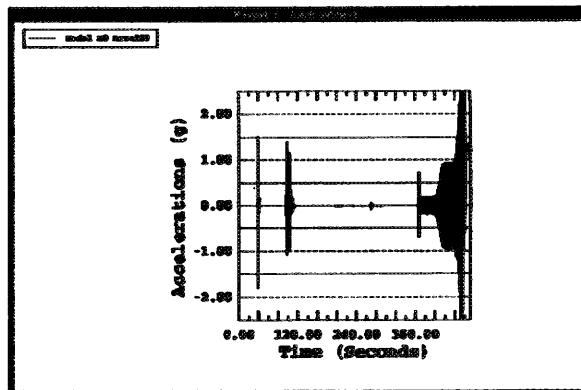
Accel #6



Accel #5



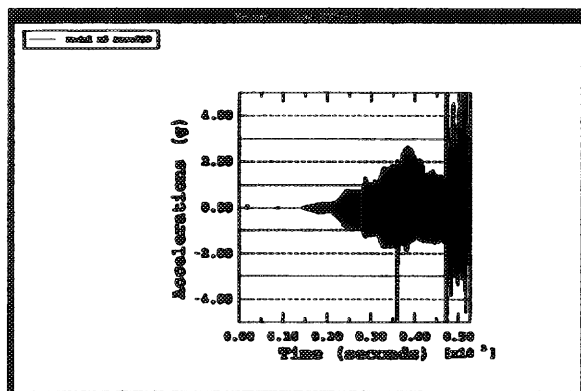
Accel #10



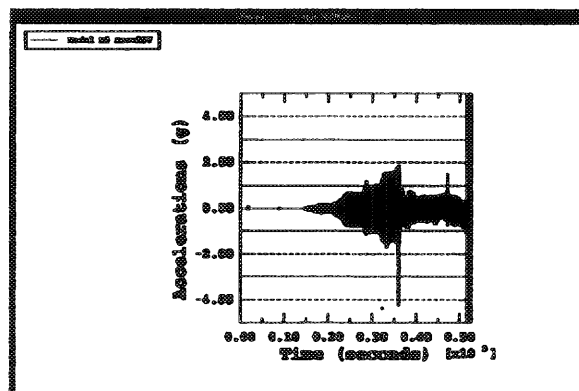
Accel #9

Measured Acceleration Records

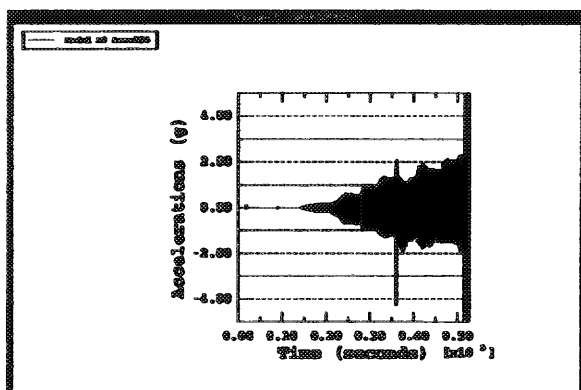
Single Horizontal Joint Model : M9



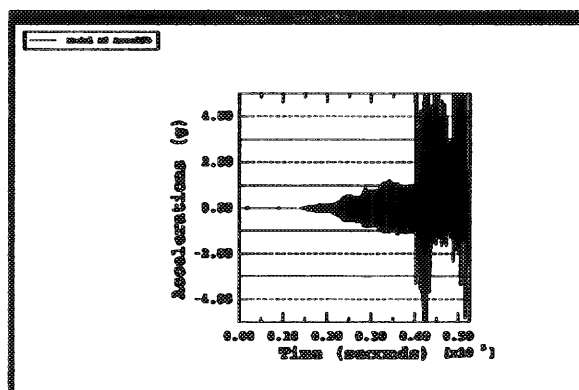
Accel #8



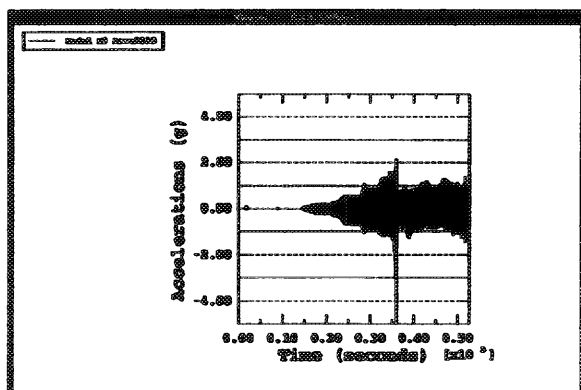
Accel #7



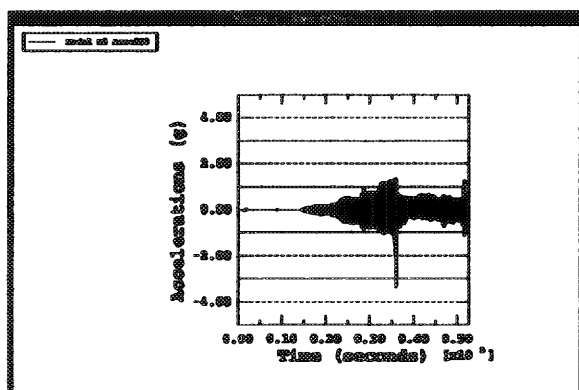
Accel #6



Accel #5



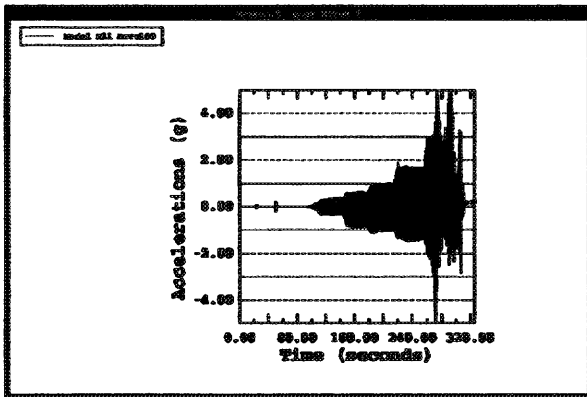
Accel #10



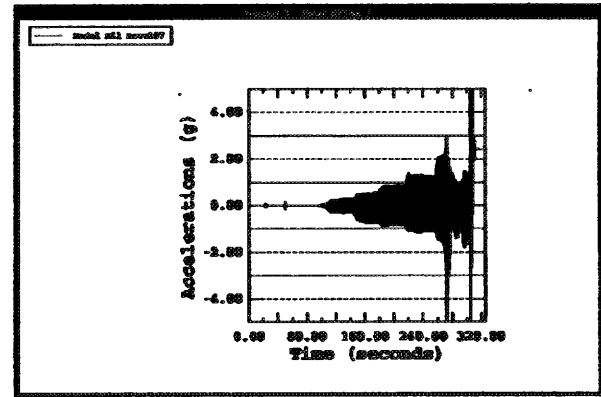
Accel #9

Measured Acceleration Records

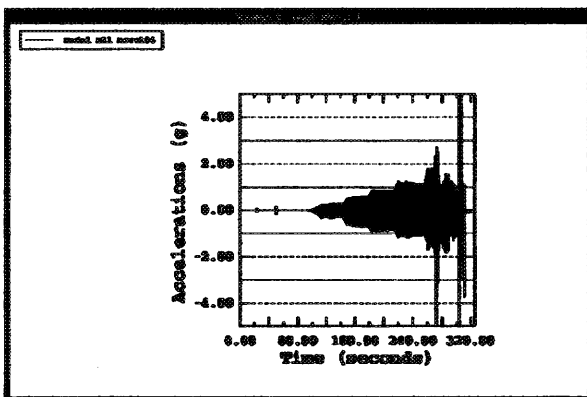
Single Vertical Joint Model : M11



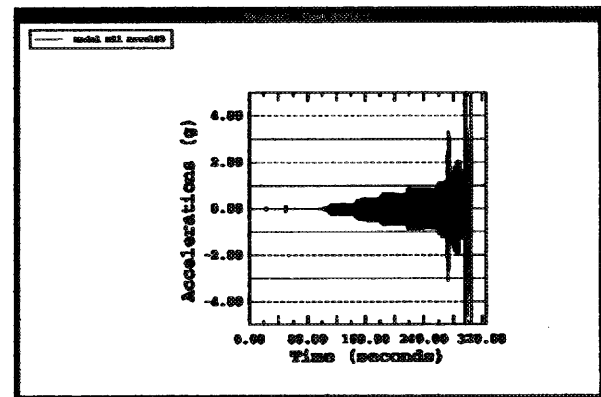
Accel#8



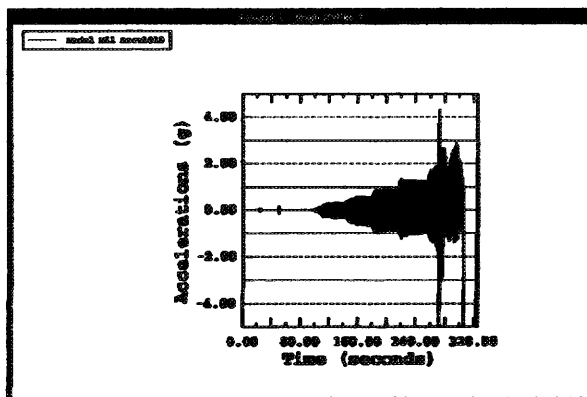
Accel#7



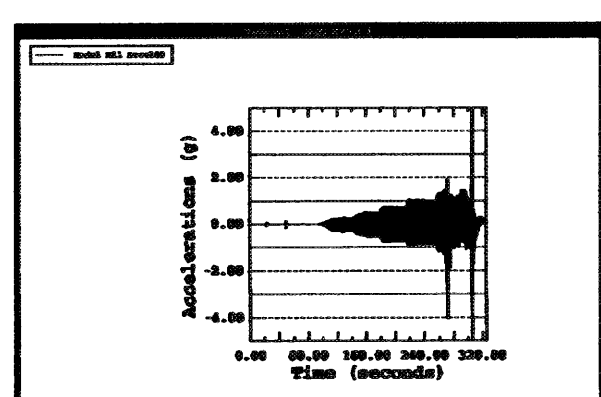
Accel#6



Accel#5



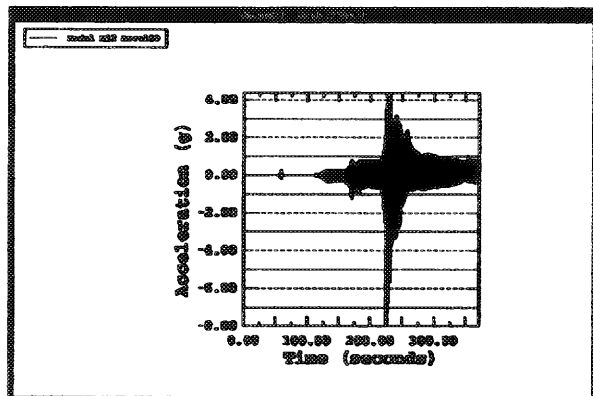
Accel#10



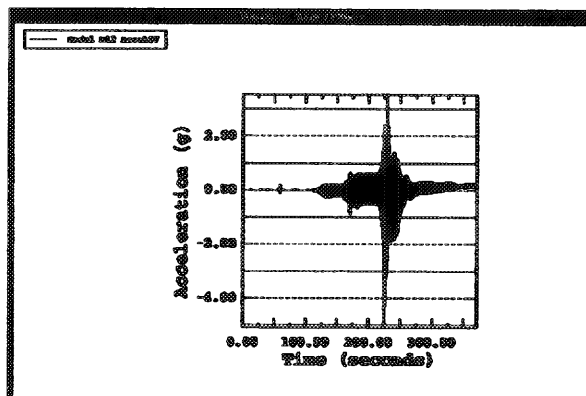
Accel#9

Measured Acceleration Records

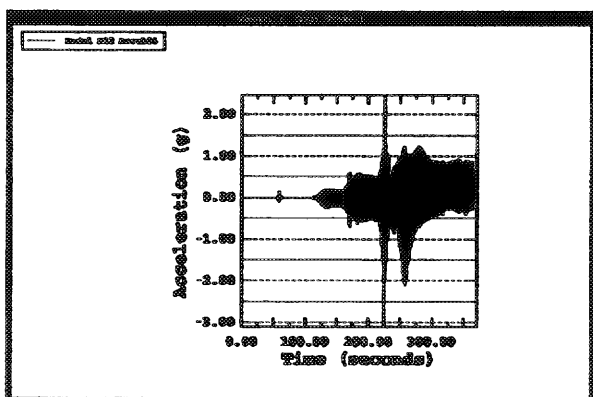
Seventeen Vertical Joint Model : M12



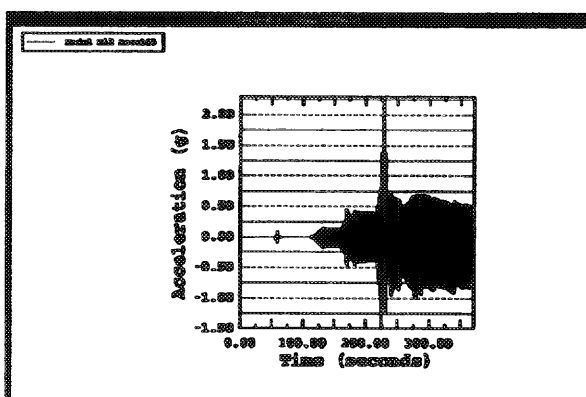
Accel #8



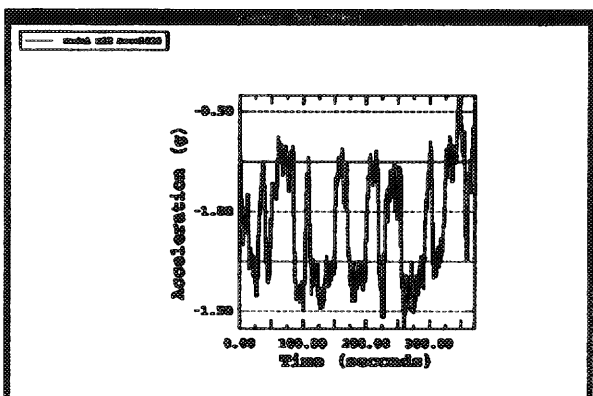
Accel #7



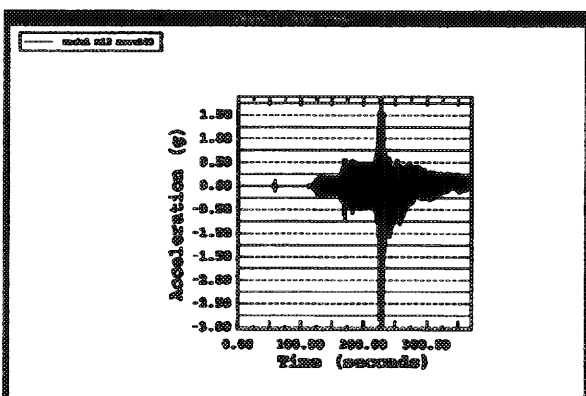
Accel #6



Accel #5



Accel #10



Accel #9

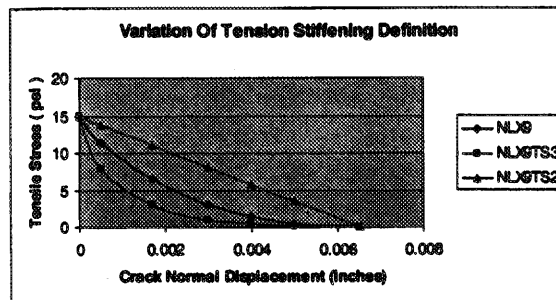
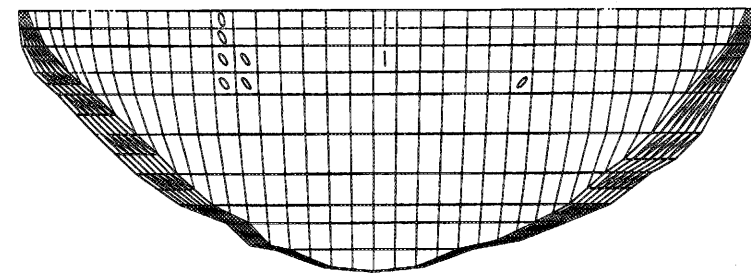
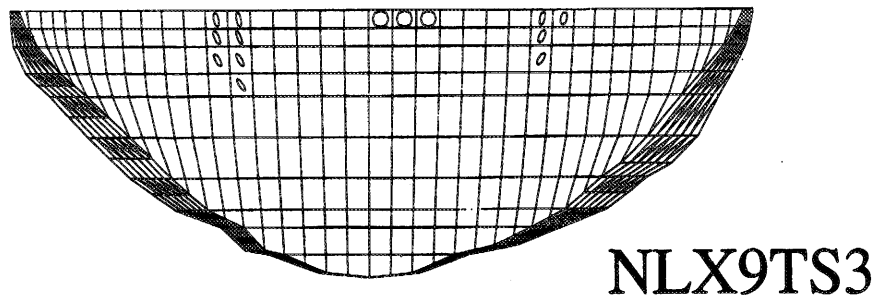
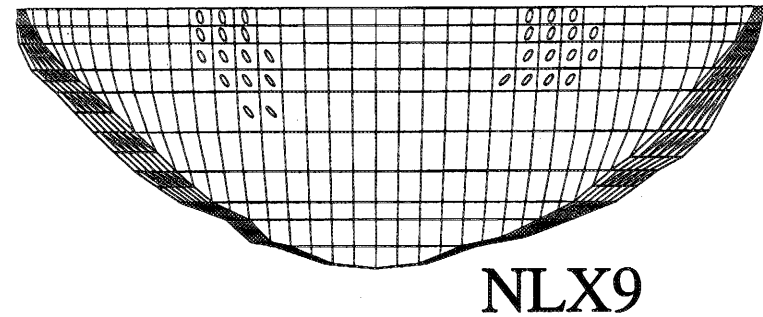
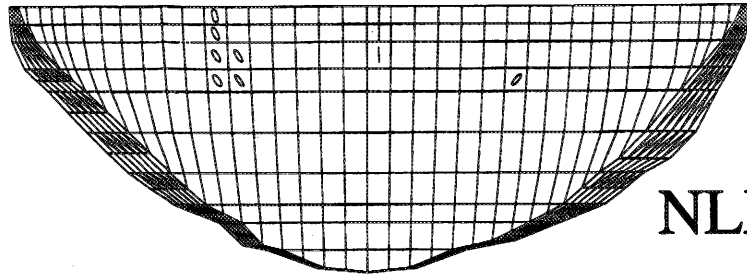
Appendix G

Dynamic Results of Non-Linear Analyses for Five Different Joint Configurations

Variation of Tension Stiffening Definition

Monolithic Model

Resulting Crack Pattern On Downstream face



NLX9GF

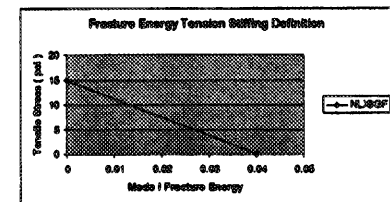
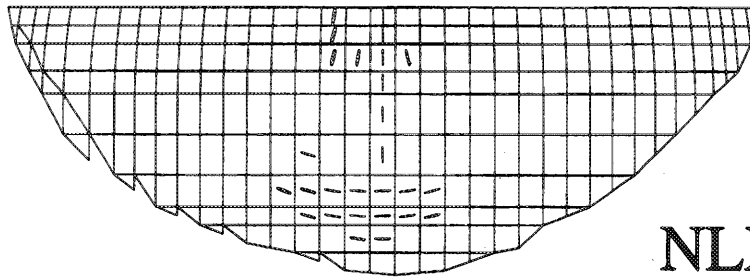


Figure G.11

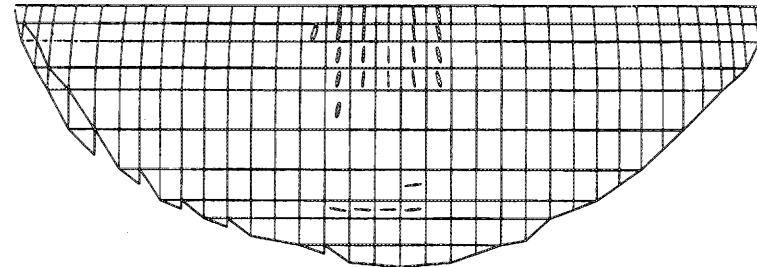
Variation of Tension Stiffening Definition

Monolithic Model

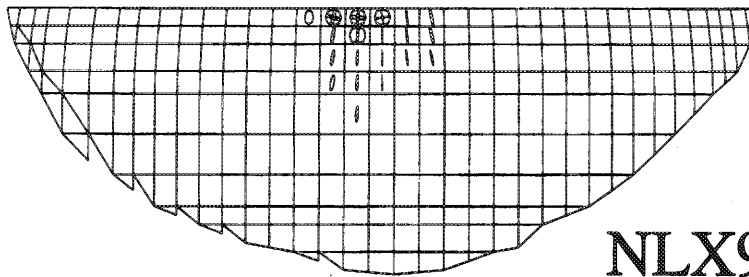
Resulting Crack Pattern On Downstream face



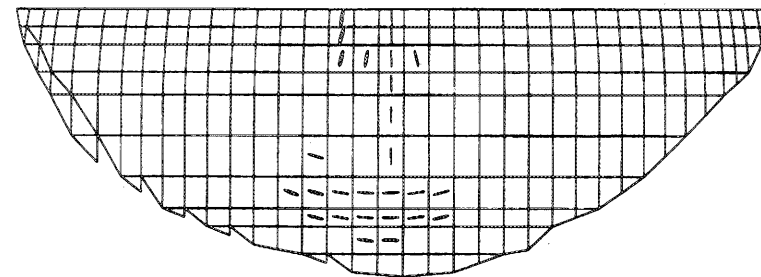
NLX9TS2



NLX9



NLX9TS3



NLX9GF

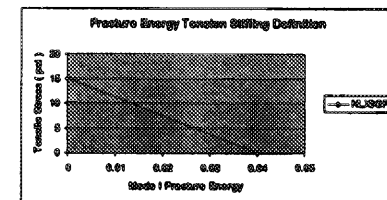
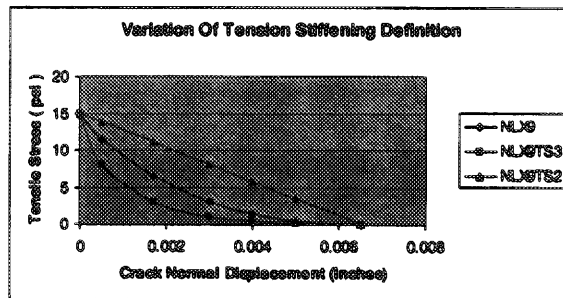
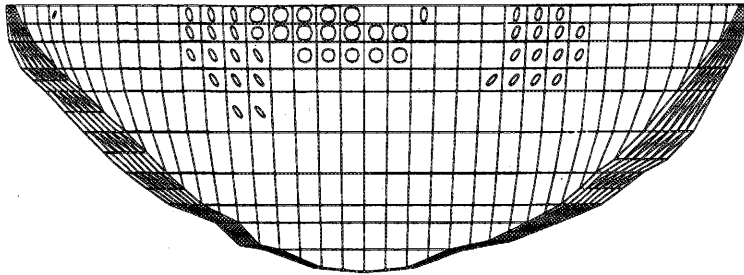


Figure G.12

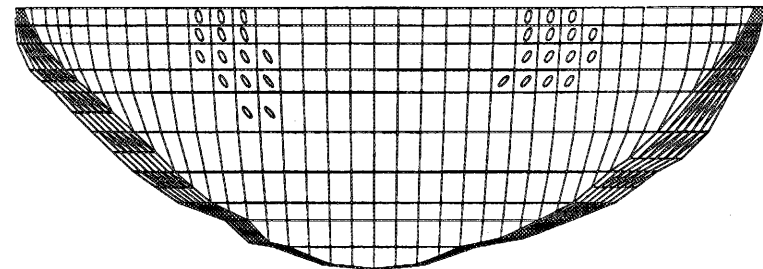
Variation in Definition Of the Shear Reduction Curve

Monolithic Model

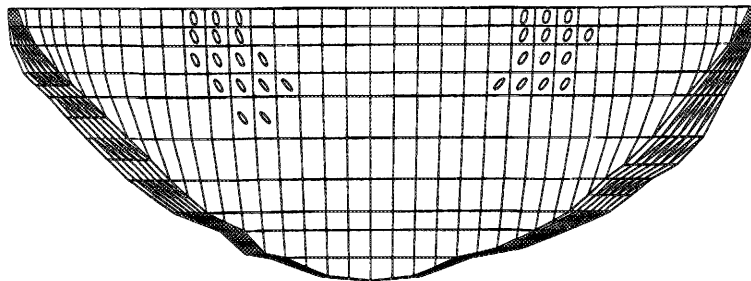
Resulting Crack Pattern On Downstream Face



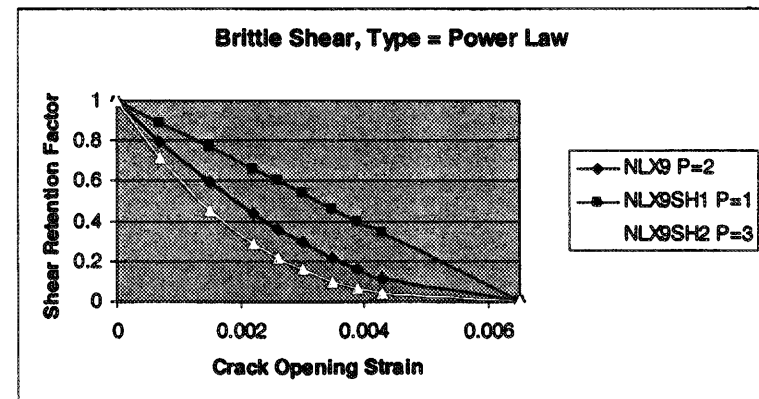
NLX9SH1



NLX9



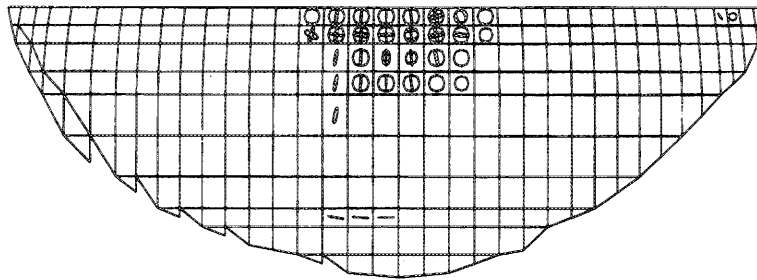
NLX9SH2



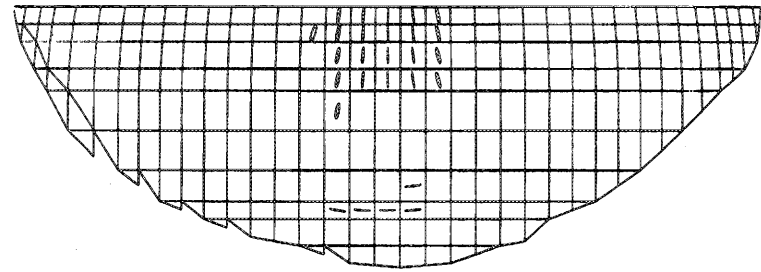
Variation in Definition Of the Shear Reduction Curve

Monolithic Model

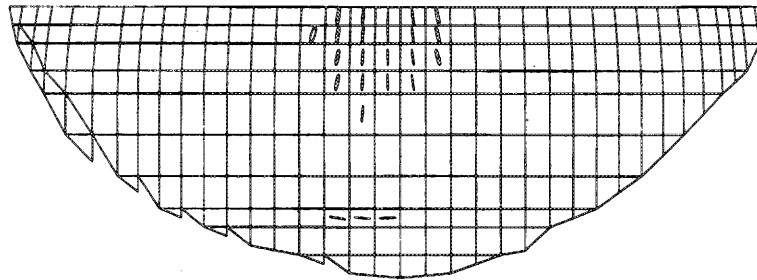
Resulting Crack Pattern On Upstream Face



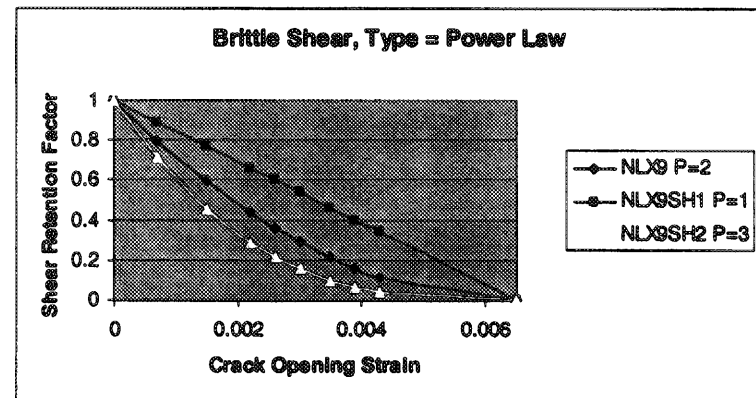
NLX9SH1

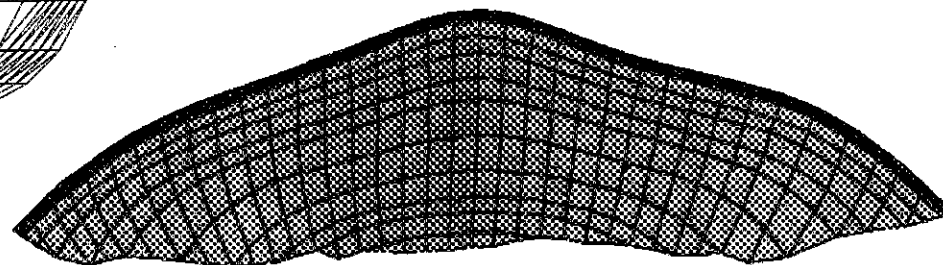
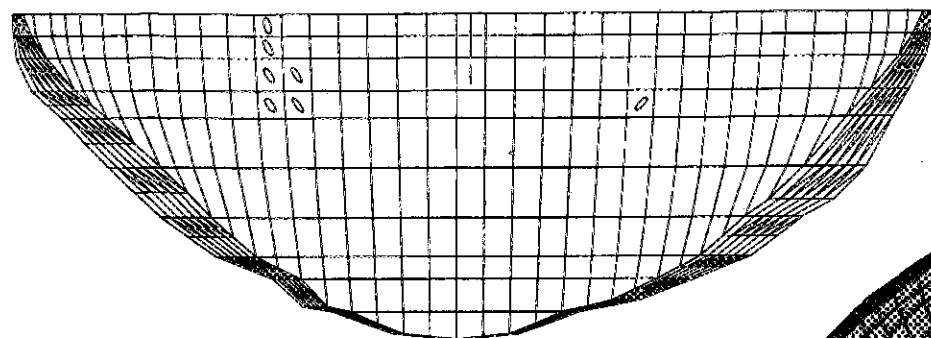


NLX9



NLX9SH2





Monolithic Model – M2M8
Crack Patterns and Deformed Shape
Deformation Magnification = 20

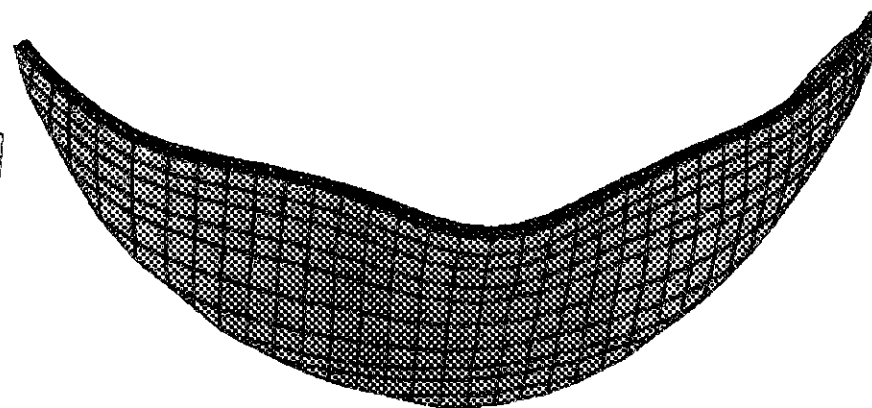
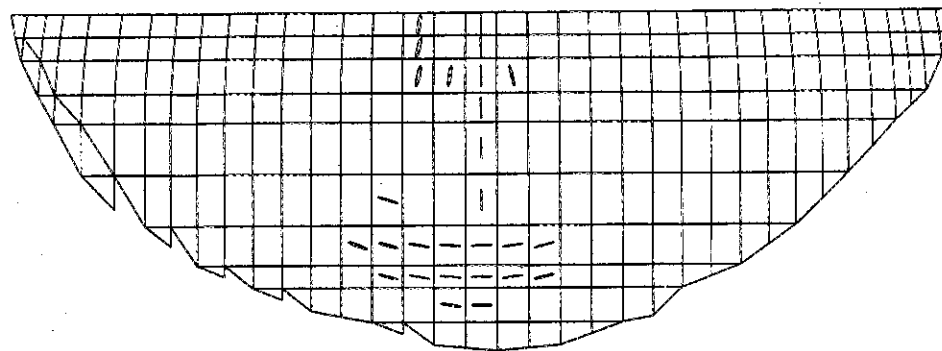
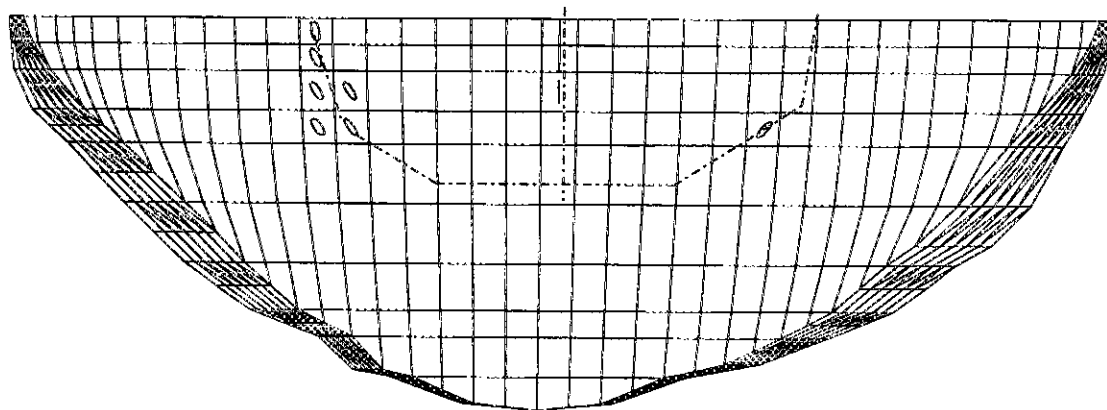


Figure G.15



Monolithic Model
Analysis M2M8
Laboratory Model M2
Predicted
Versus
Actual Crack Patterns

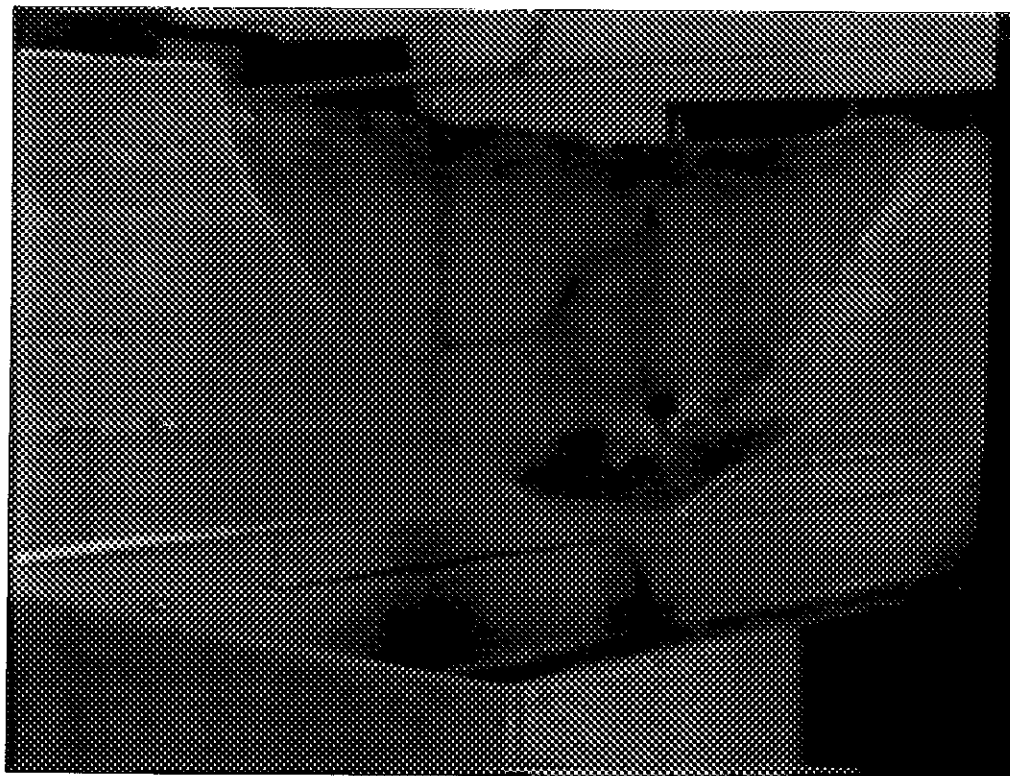
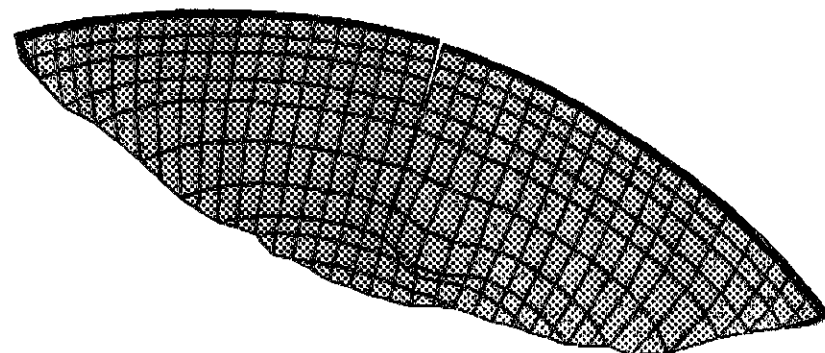
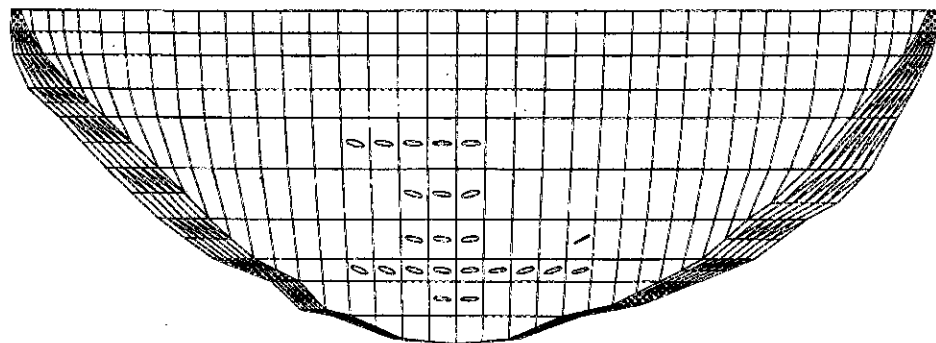
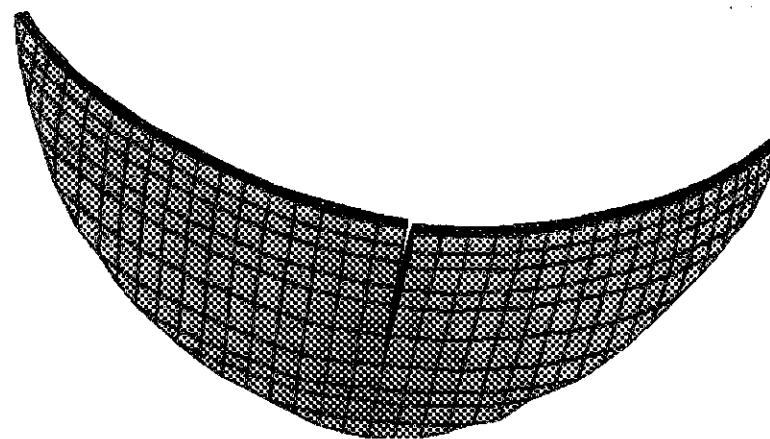
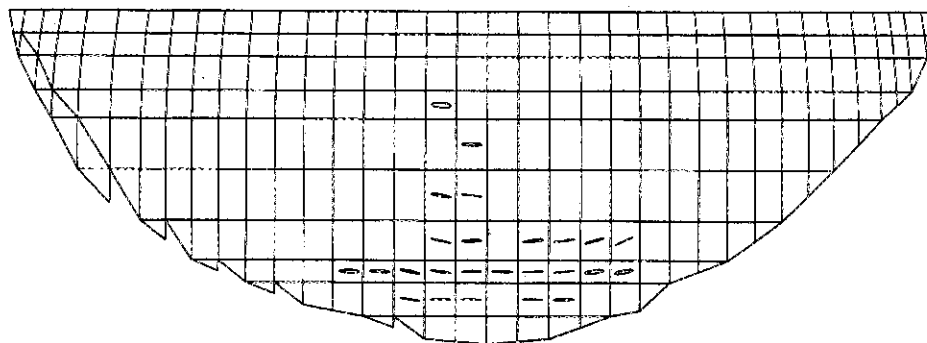


Figure G.16



Single Vertical Joint Model – M6M11
 Crack Patterns and Deformed Shape
 Deformation Magnification = 2



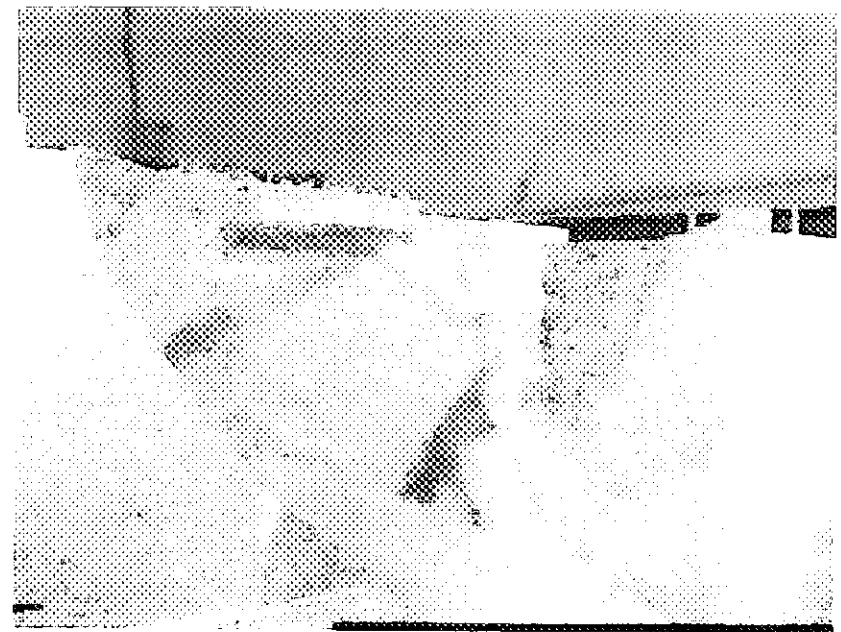
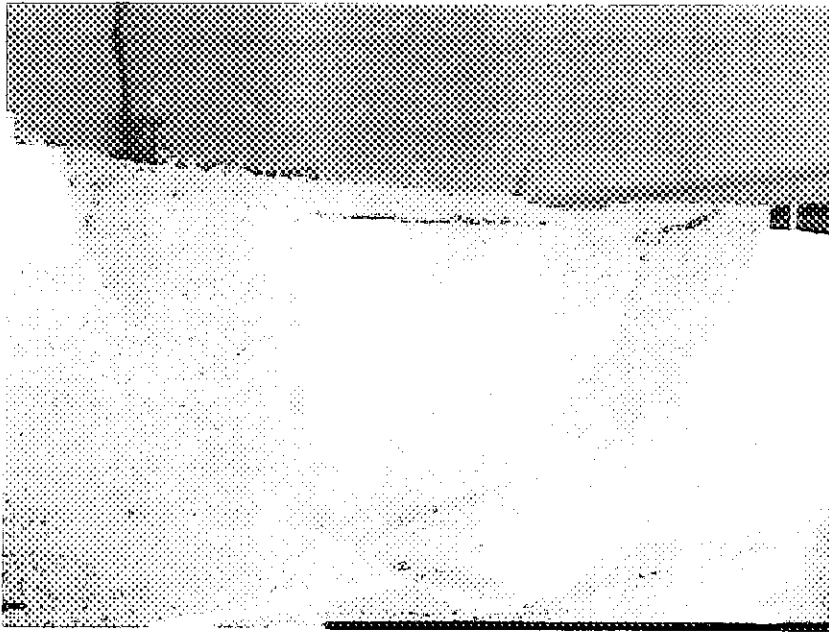
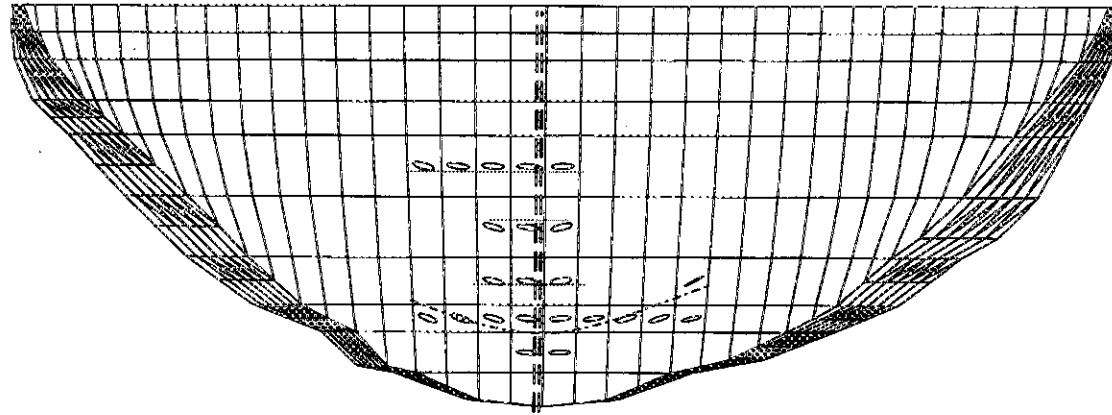
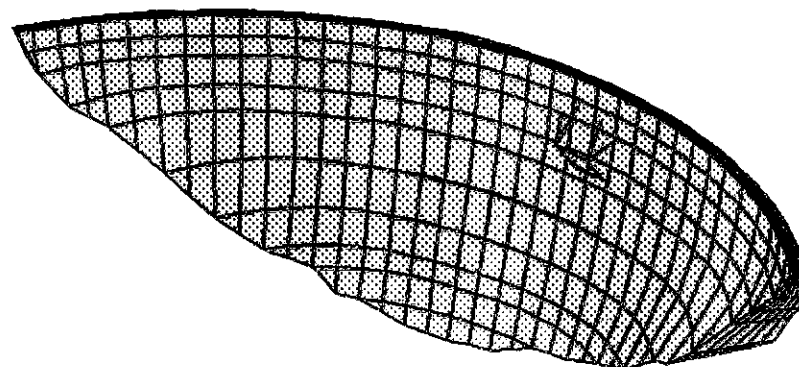
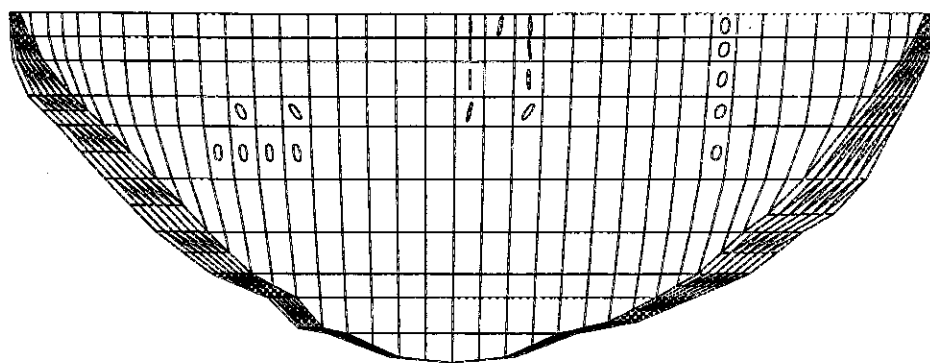


Figure G.18

Single Vertical Joint Model – Analysis M6M11 – Laboratory Model M11
Predicted Versus Actual Crack Pattern



Single Horizontal Joint Model – M9M10
 Crack Patterns and Deformed Shape
 Deformation Magnification = 2

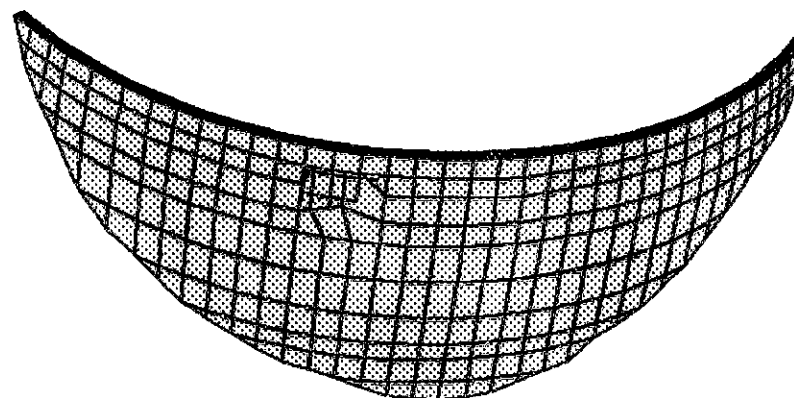
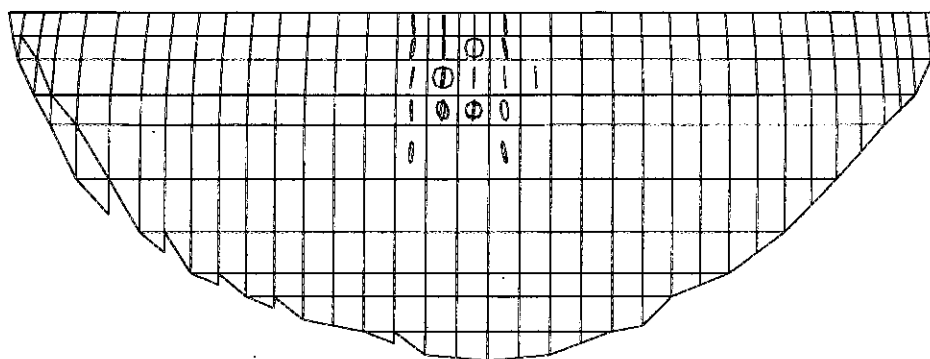


Figure G.19

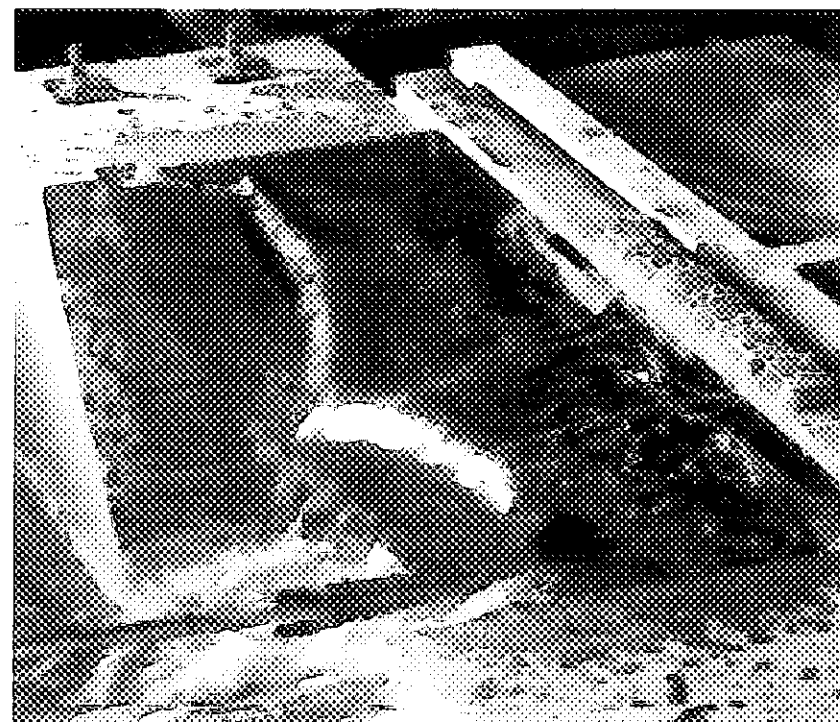
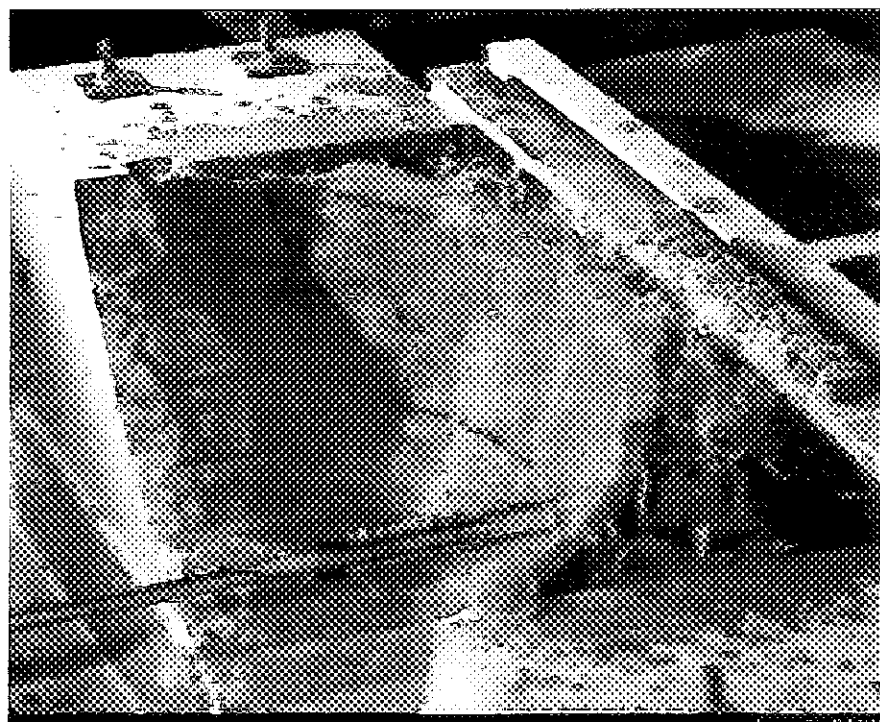
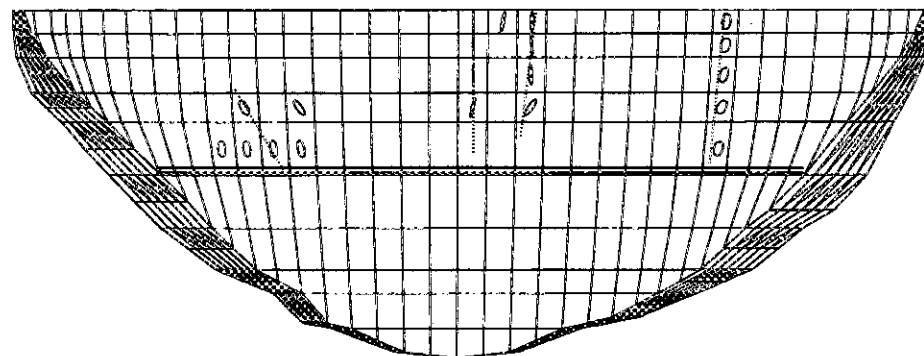
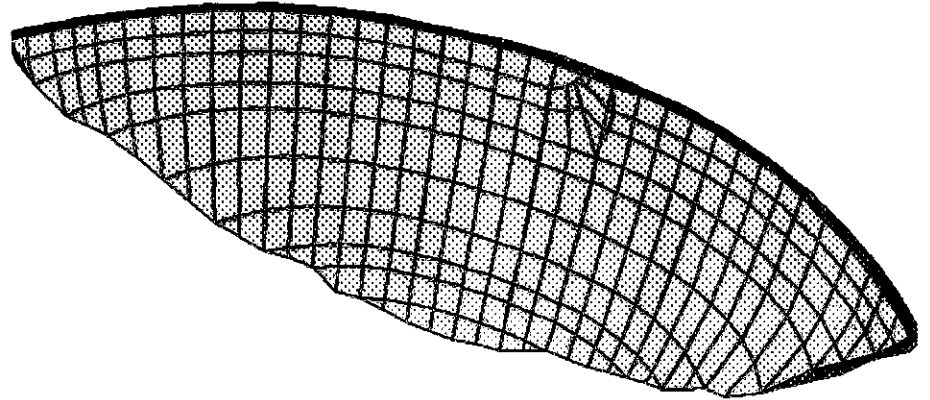
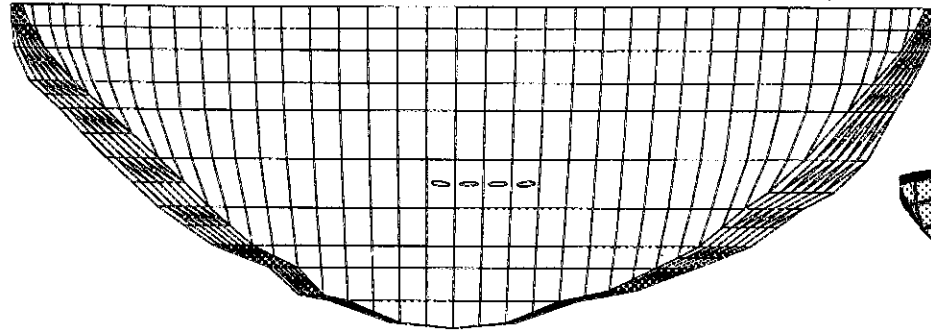


Figure G.20

Single Horizontal Joint Model – Analysis M9M10 – Laboratory Model M10
Predict versus Actual Crack Patterns



Seventeen Vertical Joint Model M12M13

Crack Patterns and Deformed Shape
Deformation Magnification = 2

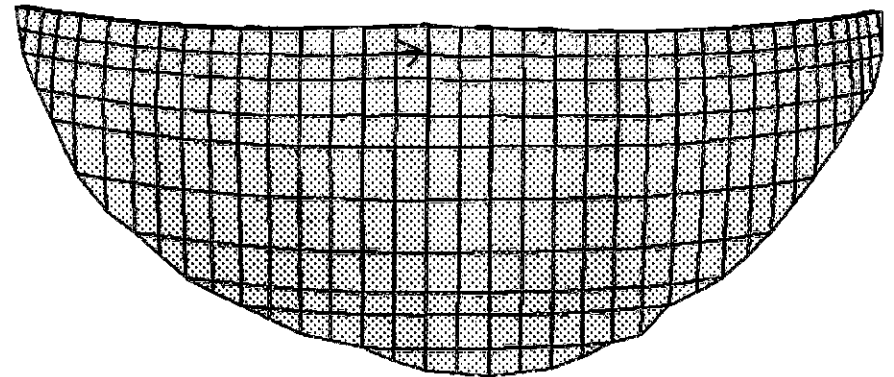
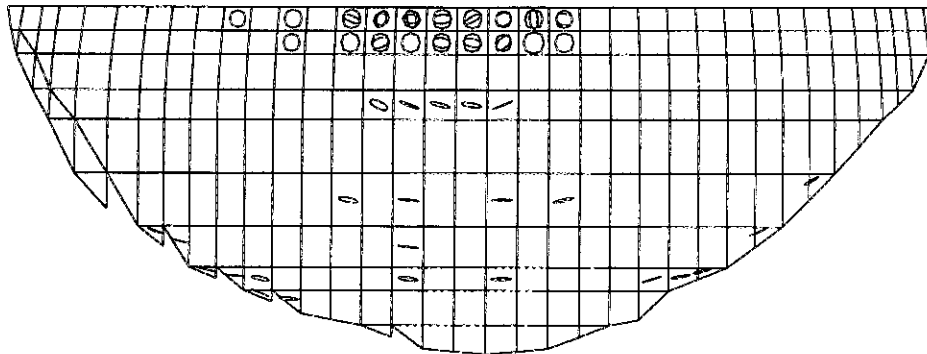
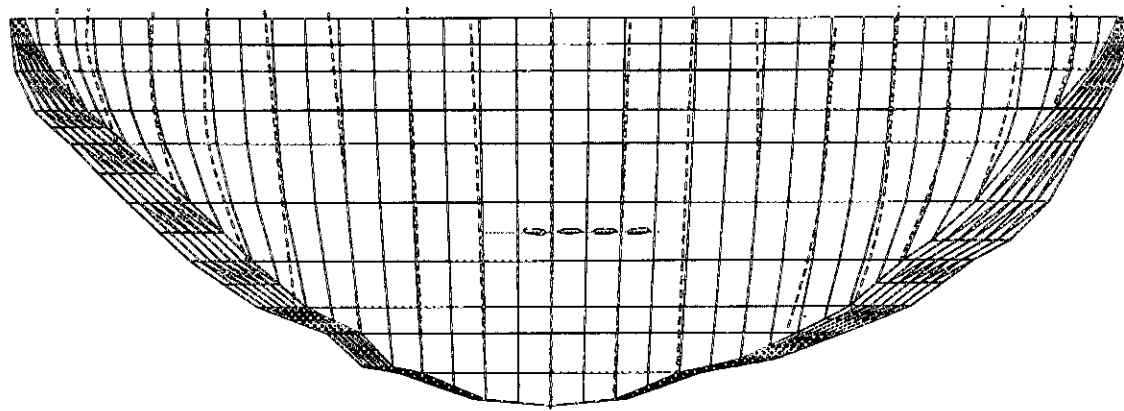
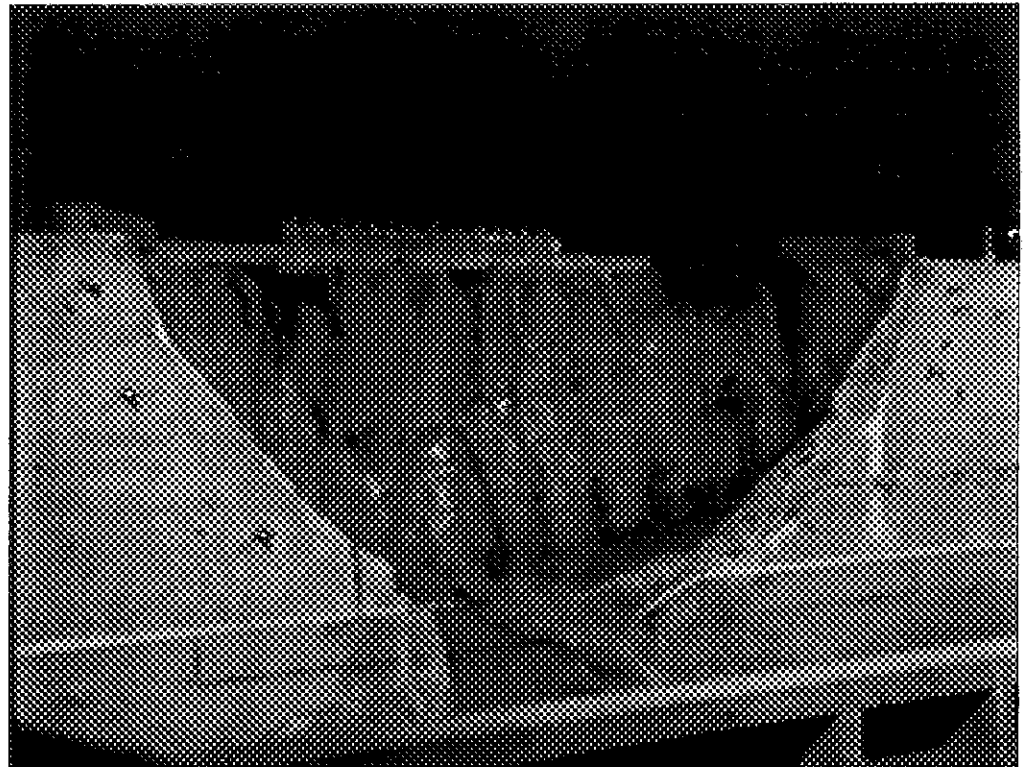
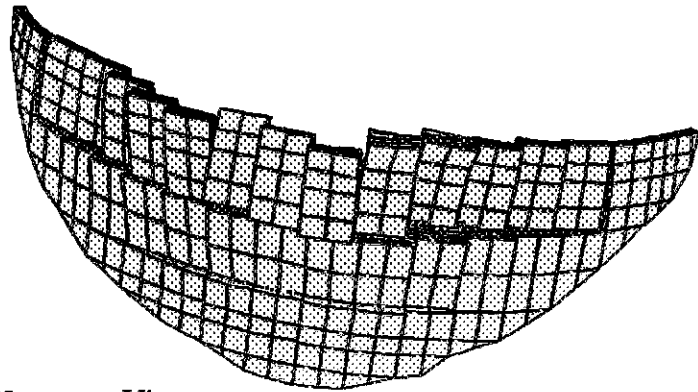


Figure G.21

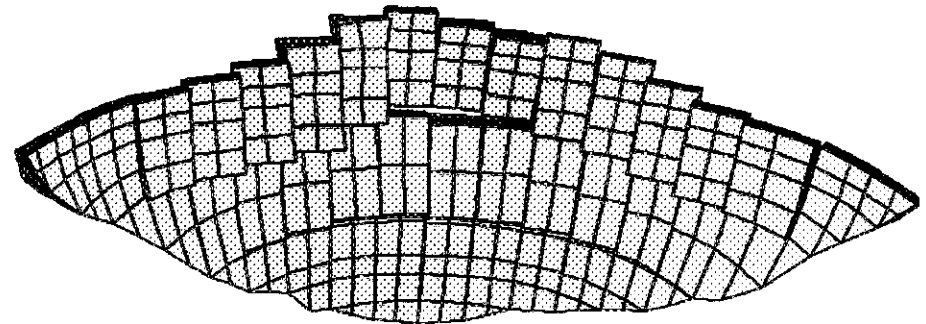


**Seventeen Vertical Joint Model
Analysis M12M13
Laboratory Model M13
Predicted versus Actual Crack Patterns**





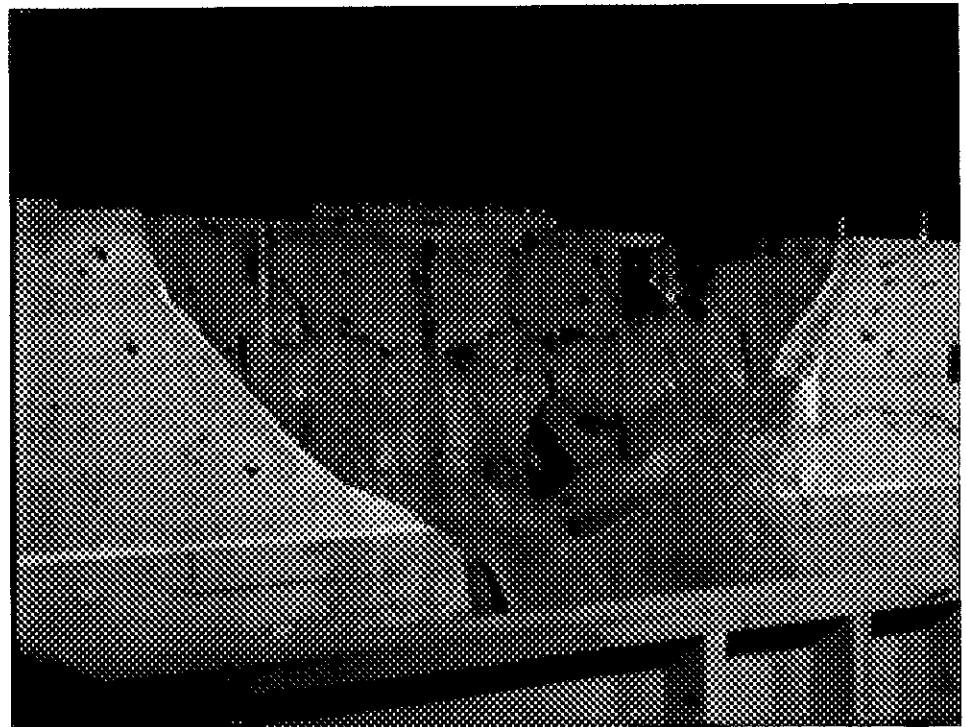
Upstream View

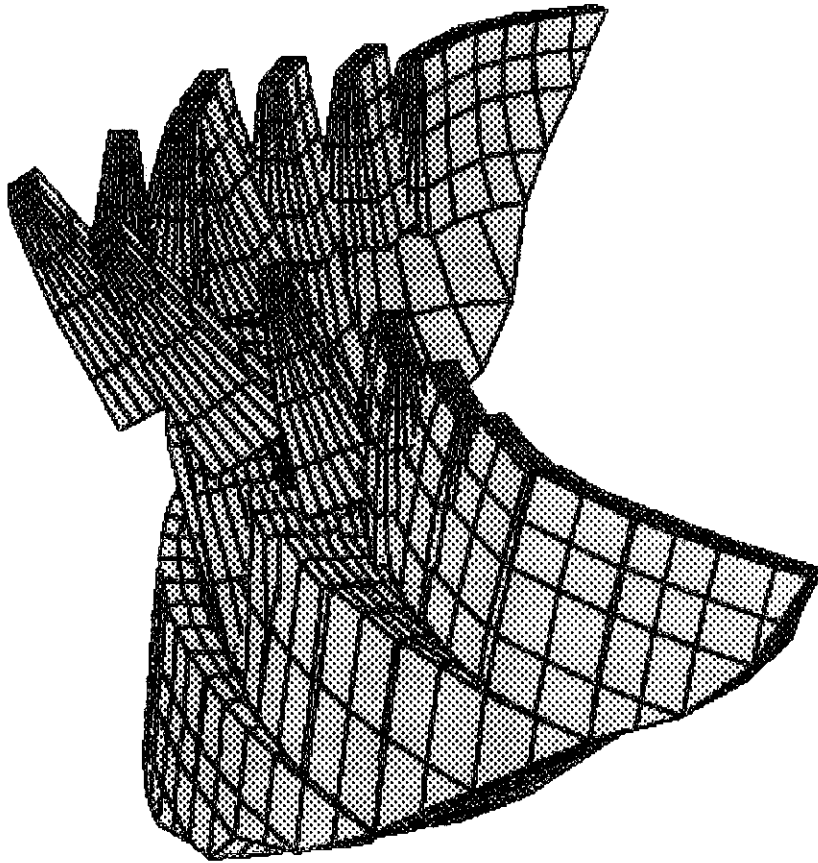


Seventeen Vertical and Two Horizontal Joint Model

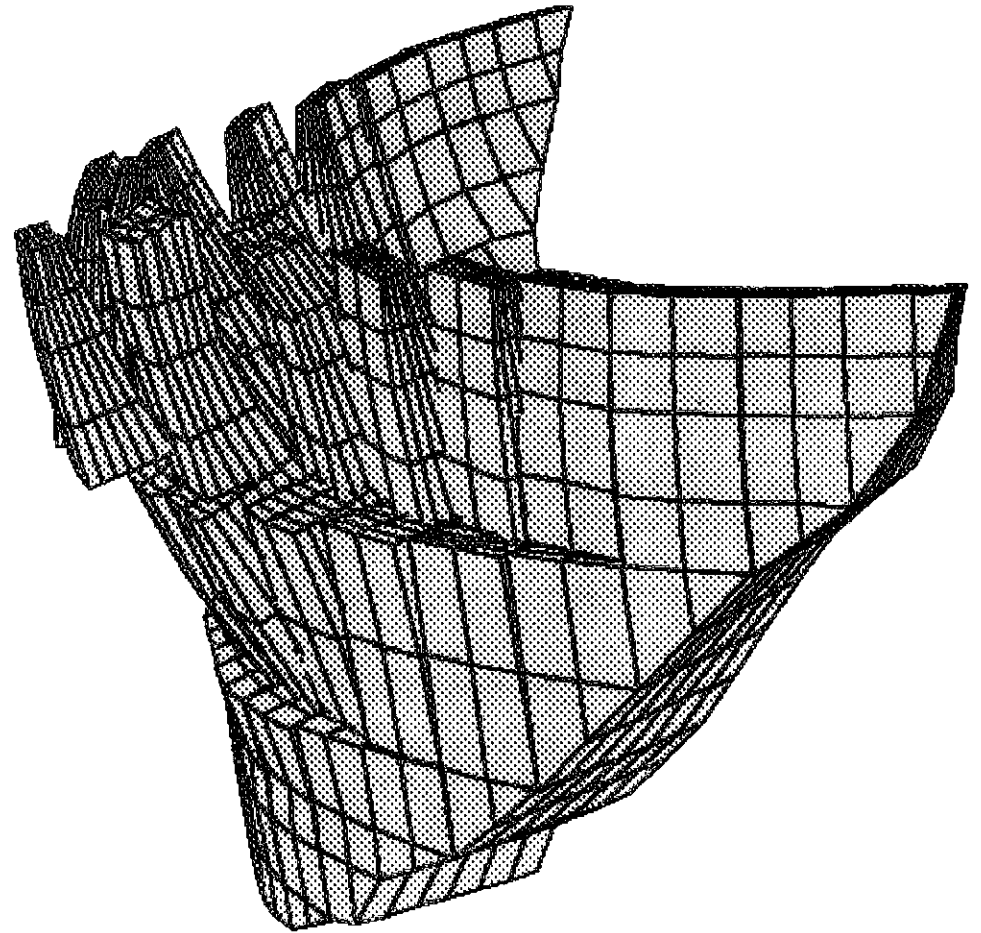
Analysis - M14M15
Laboratory – M15

Deformation Magnification Factor = 10 for Analysis Plots





Linear Elastic Analysis



Non-Linear Analysis

Appendix H

Procedure for Post Processing Cracking Results From ABAQUS/EXPLICIT Versions 6.11 and 6.21

Procedure for Post Processing Cracks in ABAQUS/EXPLICIT; Versions 6.11 and 6.21

A Fortran subroutine must be written to read the ABAQUS results file. There are instructions for writing this type of subroutine in the ABAQUS user manual. The subroutine used for post processing crack information in this analysis (subroutine "writeData") is included in this appendix. This subroutine was written to search for data from either two or three dimensional analyses from either ABAQUS/EXPLICIT or ABAQUS/STANDARD; although, only the section written for three dimensional analyses in ABAQUS/EXPLICIT has been tested. Crack output data must initially be written to the selected results file. Then the selected results file must be converted using the command "aba611 j=job_name convert=select". The user subroutine must be linked to ABAQUS by entering the following command: "aba611 make j=subroutine_name". The subroutine used in this study was written with a required input name of "test.fil", so the job_name.fil file created during the convert step must be copied into a file named "test.file". Then this file is read, and cracking information is written to a file named "test.out", by executing the following command "aba611 subroutine_name > test.out". This output file is then reformatted into the proper input file format for use in a two dimensional plotting program. The program "srchds4", written at Reclamation by Larry Nuss, was modified and renamed "crkhds4" to add ABAQUS crack plotting capabilities. The fortran program written to reformat the crack data was named "reformat_abacr", and this file is also included in Appendix H. The two-dimensional plotting program (crkhds4) also requires the creation of universal geometry files. A program has also been written to generate these files from the ABAQUS input file.

MISSION STATEMENTS

The Mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Physical Models

Tests were completed in the Bureau of Reclamation, Materials Engineering and Research Laboratory. A one dimensional shake table (horizontal acceleration only) was constructed for these experiments. The model scale chosen for these models was a 1/150 scale. The maximum height of the scaled dam was 23 11/16 inches, and the crest length was 81 13/16 inches. A sealed chamber on the upstream side of the dam was filled with water to simulate a reservoir loading. A similitude simulation of an earthquake motion was not used. Rather, for practical reasons associated with the table and for simplicity in numerical model calibration, a 14 Hz sinusoidal motion was selected. 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 modeled were: (1) monolithic (identified as tests M2 and M8), (2) a single vertical joint at the arch center (tests M6 and M11), (3) a single horizontal joint at mid height (tests M9 and M10), (4) 17 vertical joints spaced evenly along the arch (tests M12 and M13), and (5) 17 evenly spaced vertical joints combined with 2 horizontal joints (tests M14 and M15). The models were placed in a concrete block foundation on the table. A photo of a typical experiment setup is shown in figure 1.

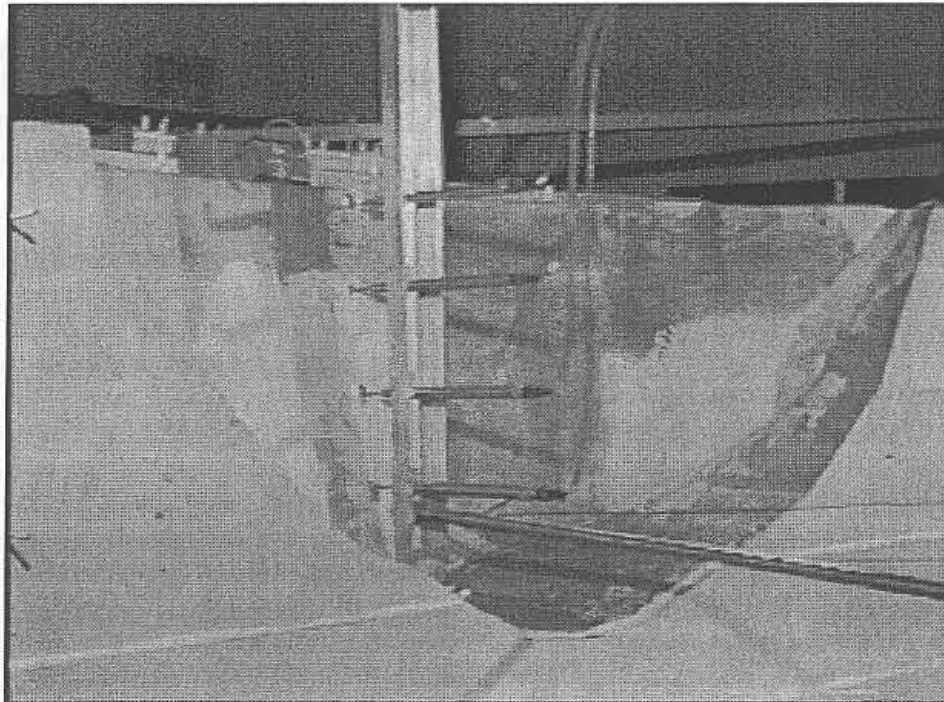


Figure 1.—Typical Experiment Setup.

The models were instrumented on the downstream face to record accelerations at six locations and displacements at two locations as shown in Appendix A, figure A.1. Figure A.2 shows the corresponding Node numbers at which acceleration time histories were recorded in the analyses.

Reservoir Load

Applied to the Upstream Face

As Stepped Uniform Pressure Loads

Water Surface Elevation = 35.48 inches

ELEVATIONS
INCHES

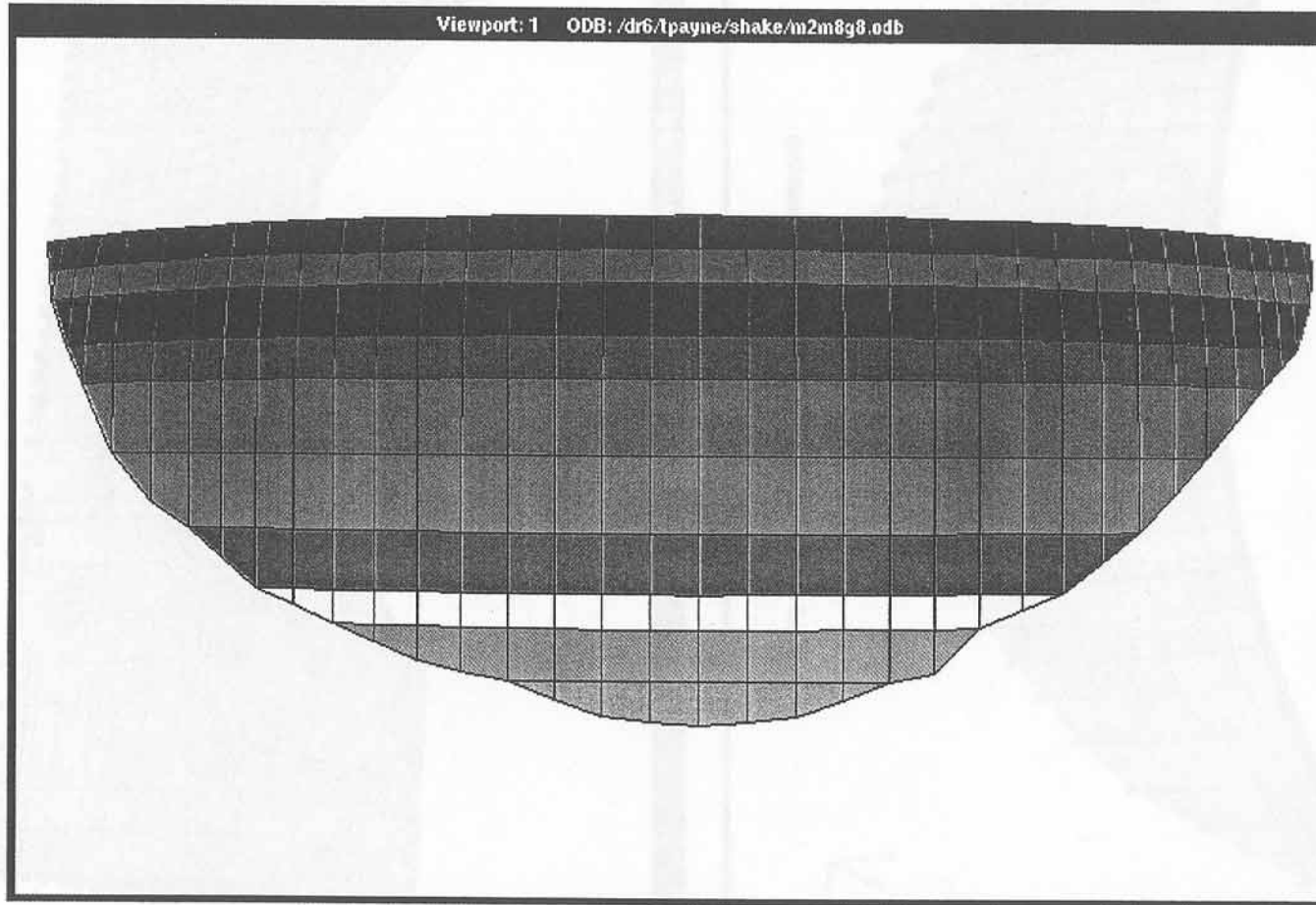
36.48
34.87
33.27
30.86
28.85

25.24

21.63
18.82
17.22

14.81
12.80

Viewport: 1 ODB: /dr6/1payne/shake/m2m8g8.odb



UNIFORM
PRESSURE
LOADS
LB/IN²

.0042
.0508
.1232
.2031

.3047

.4350
.5508

.6305
.7030
.7828

Figure A.4

Mini Dam Materials - Mix M-1 - (3/2/99)

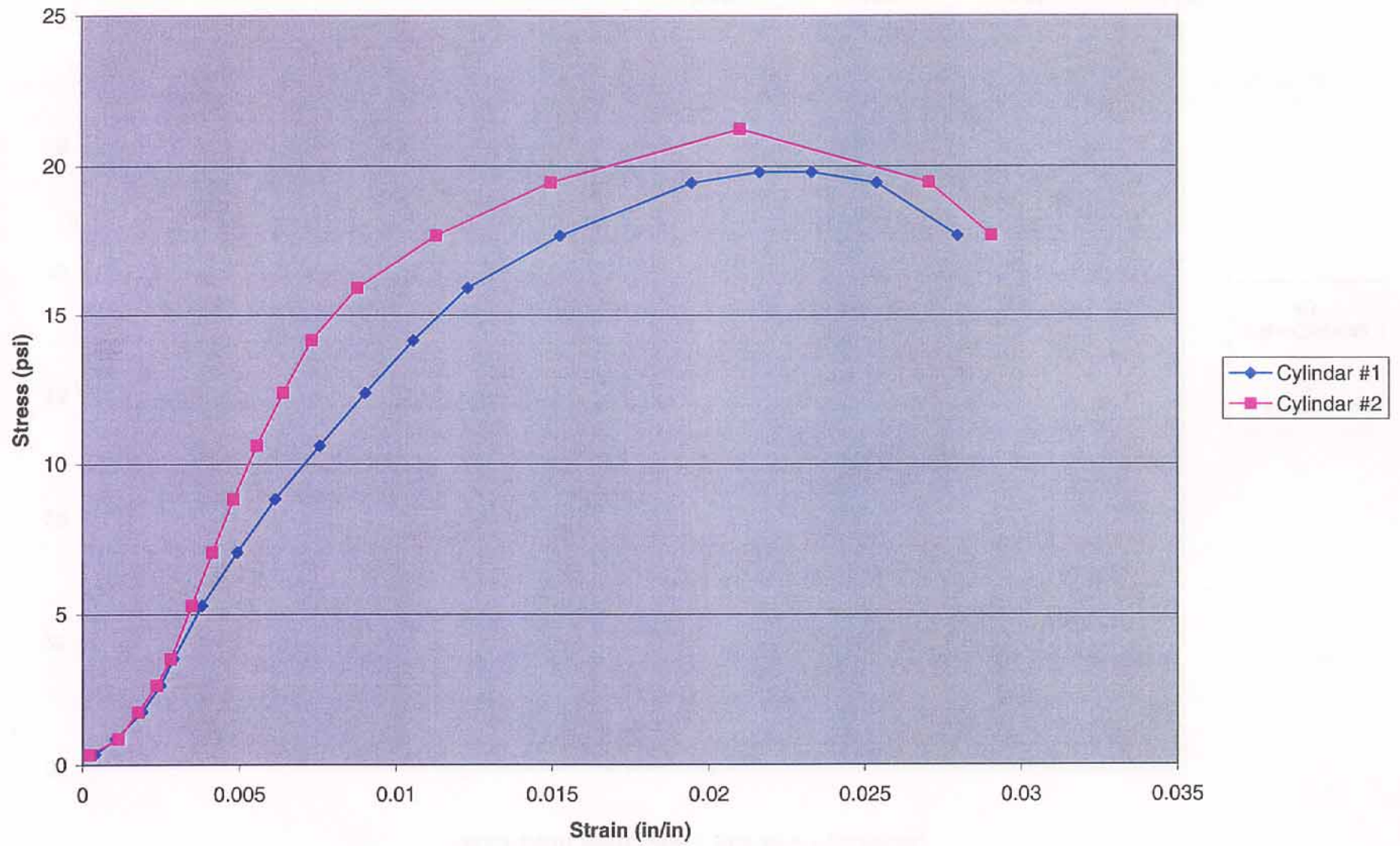


Figure B.10

Mini Dam Materials - Mix M-2 - (3/24/99)

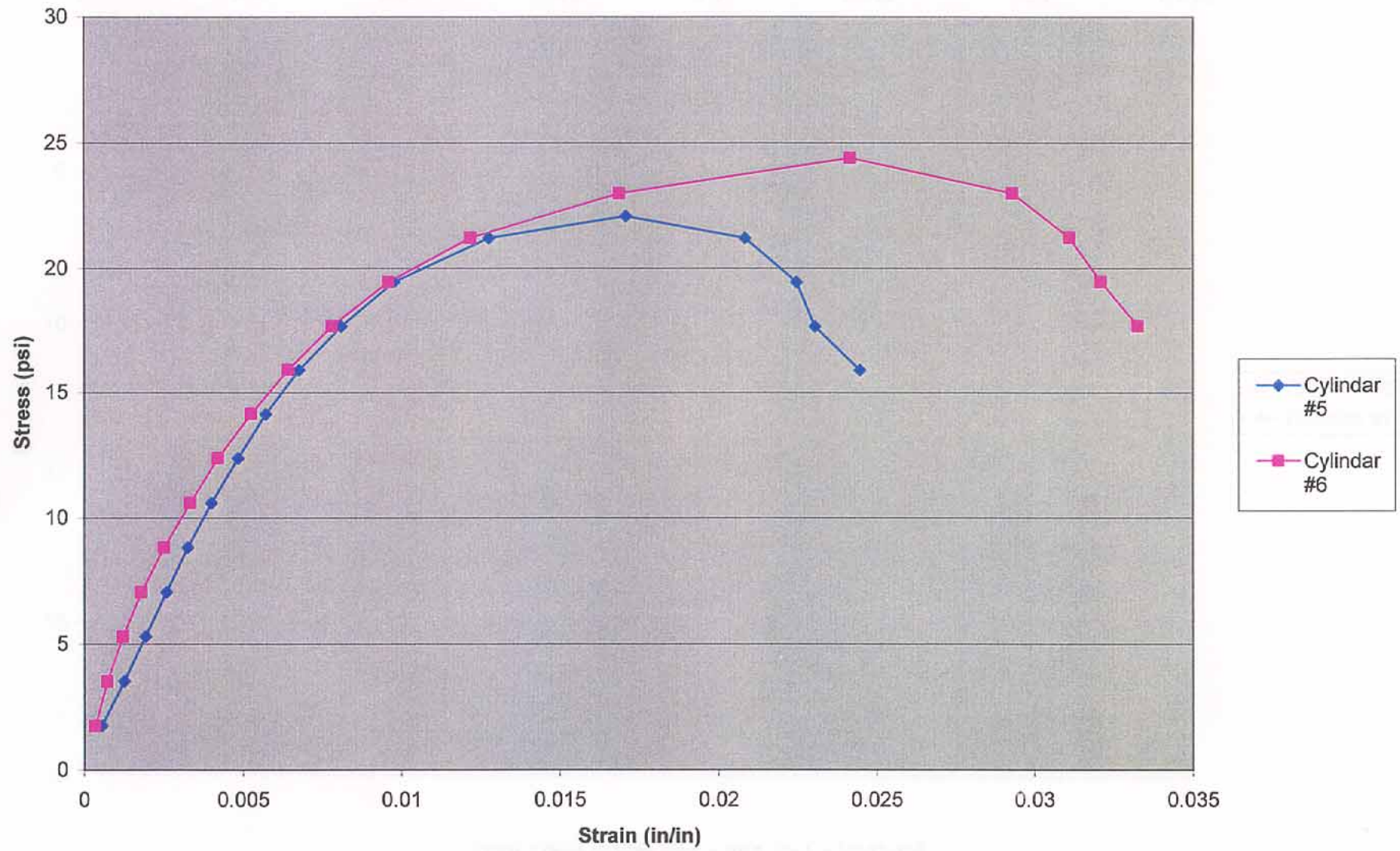


Figure B.13

Mini Dam Materials - M-4 - (7/28/99)

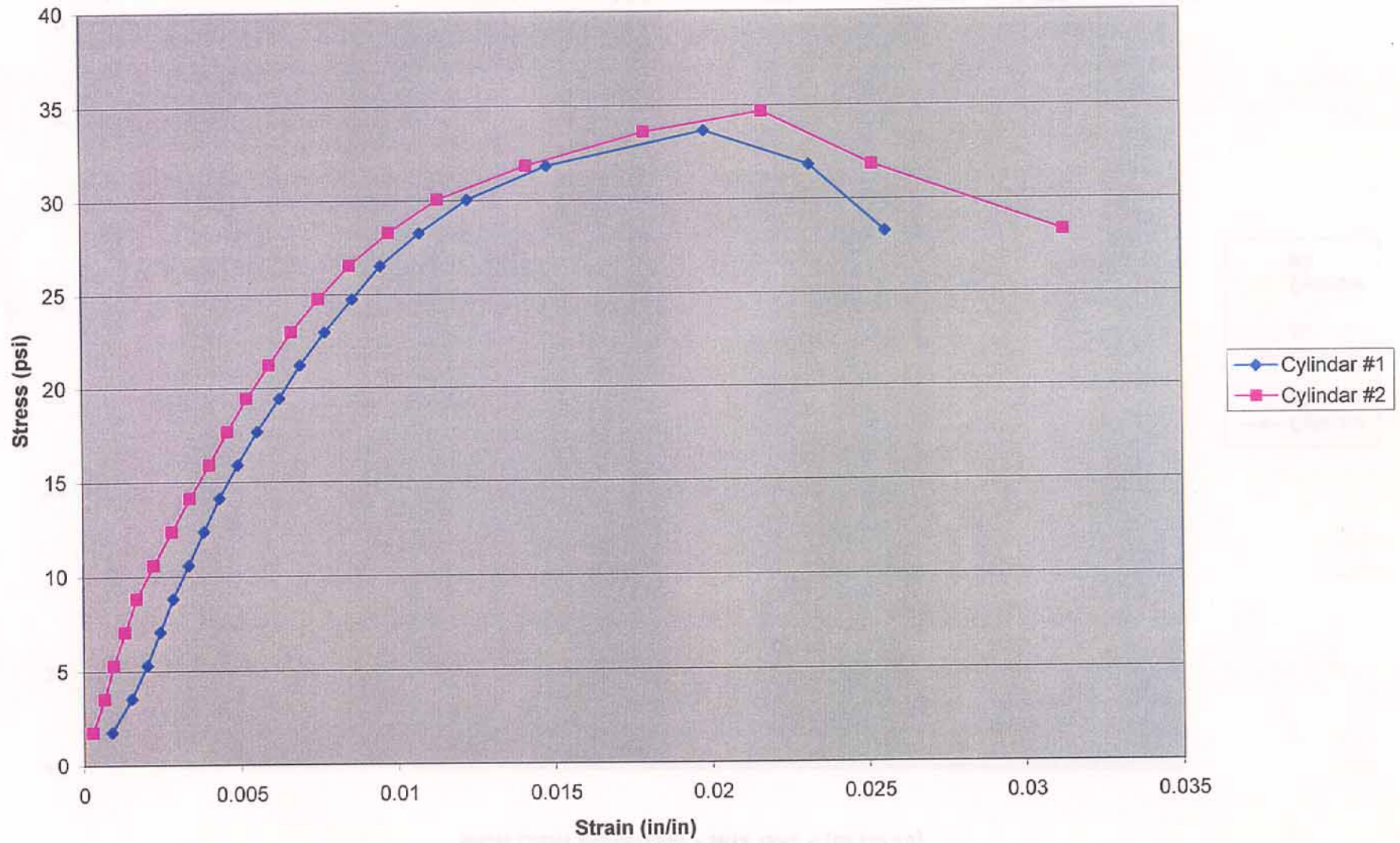


Figure B.16

Mini Dam Materials - Mix M-5 - (8/12/99)

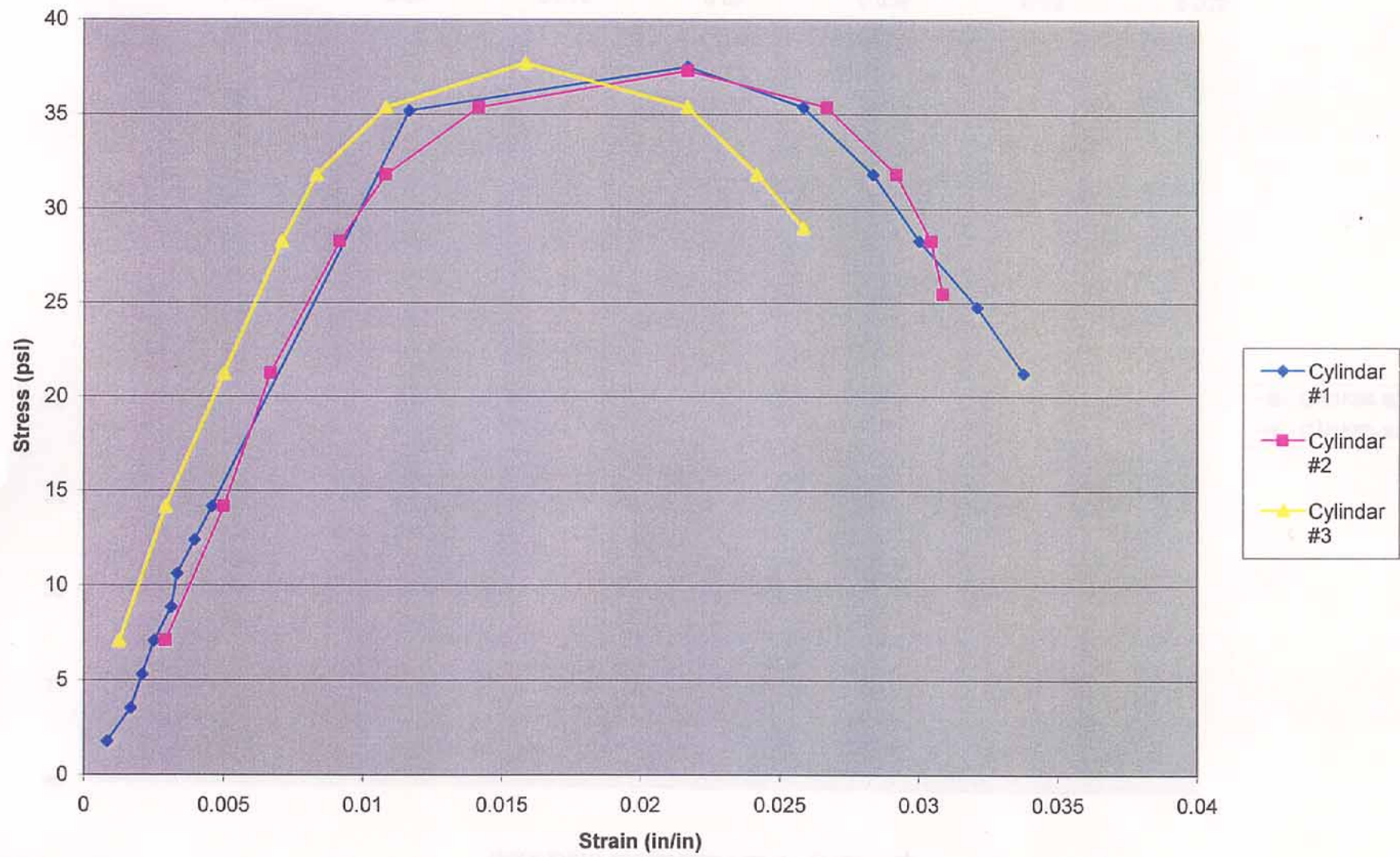


Figure B.20

Mini Dam Materials - M-10 - (7/27/00)

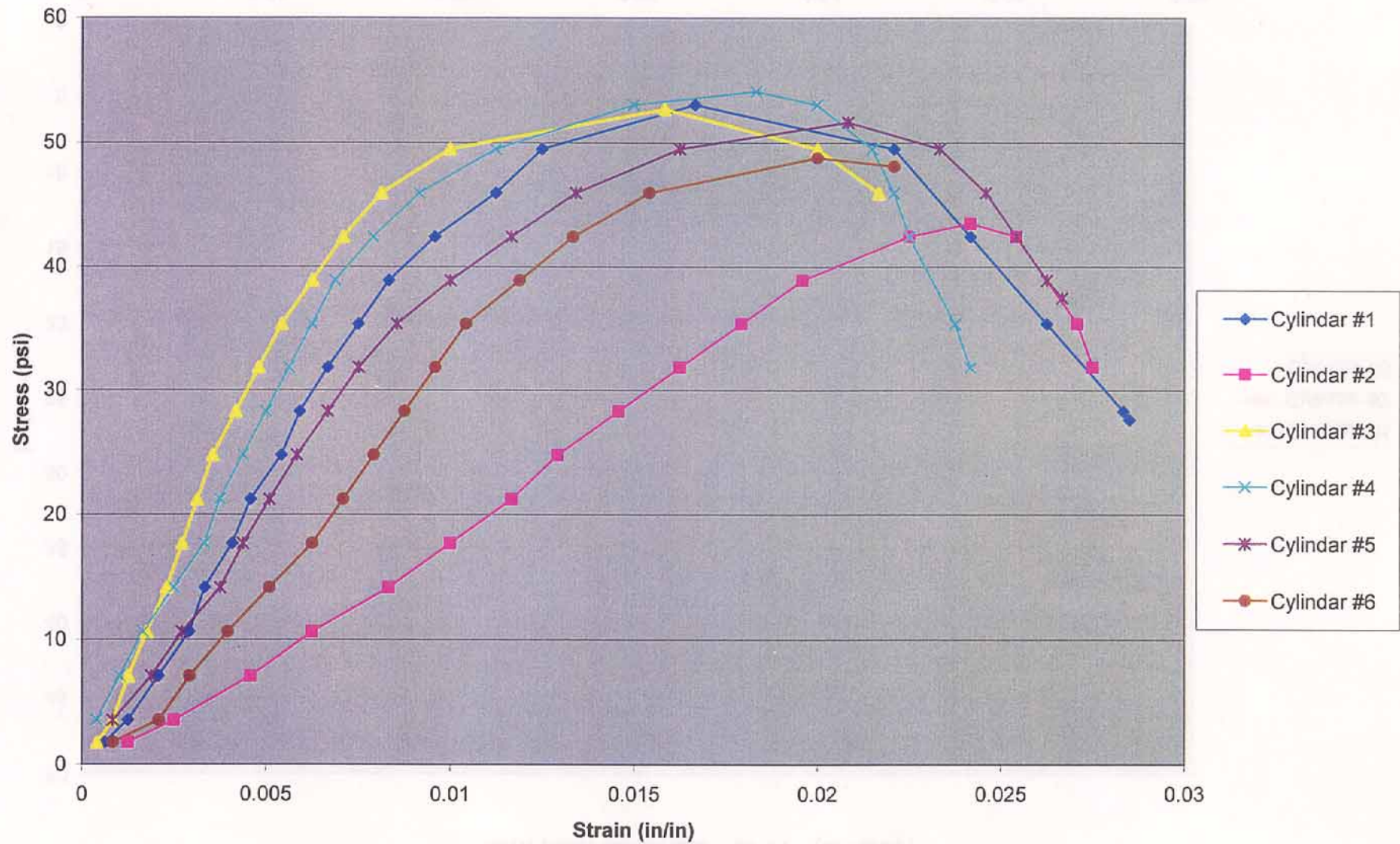


Figure B.24

Mini Dam Materials - M-11 - (8/16/00)

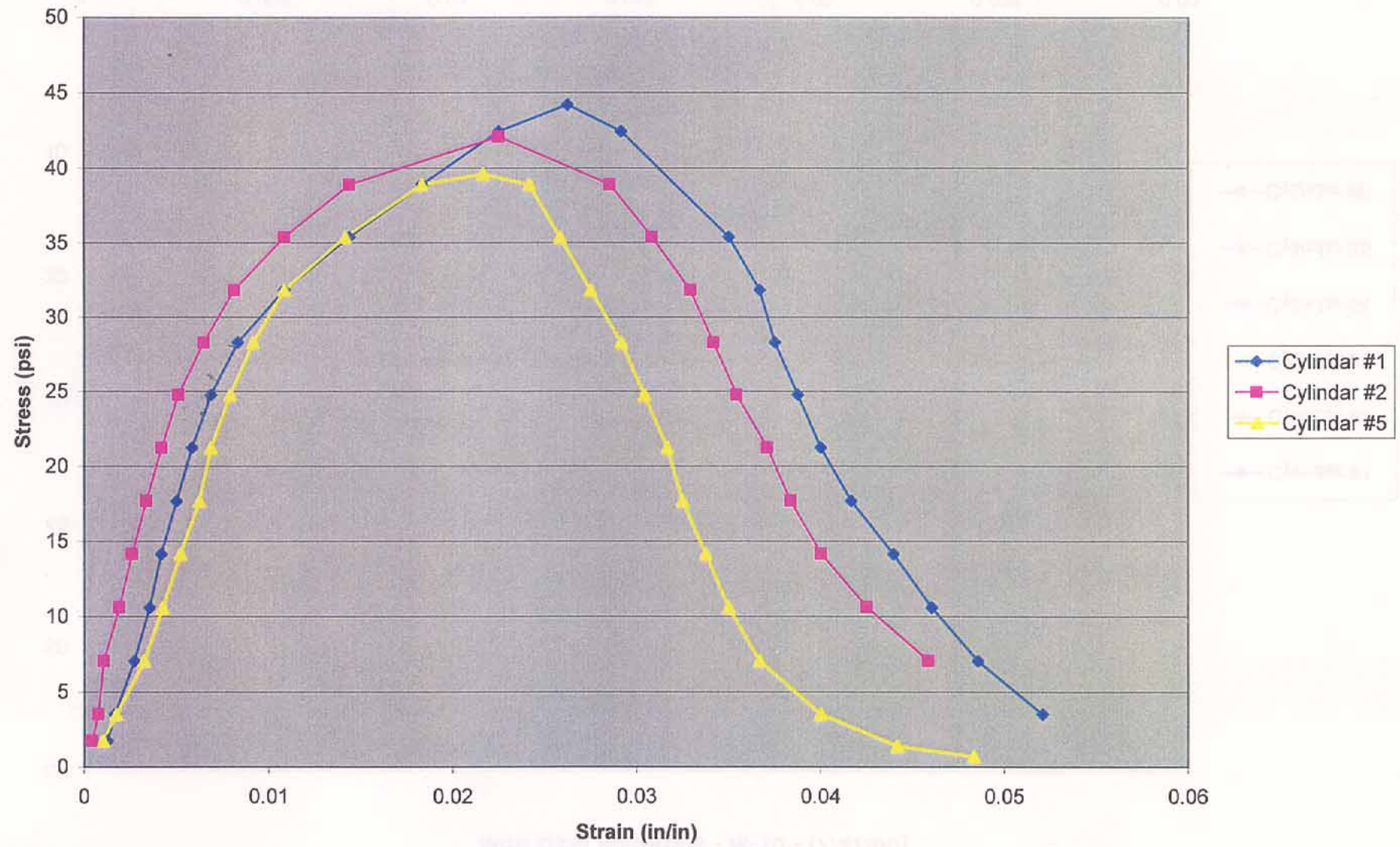


Figure B.27

Mix M-12

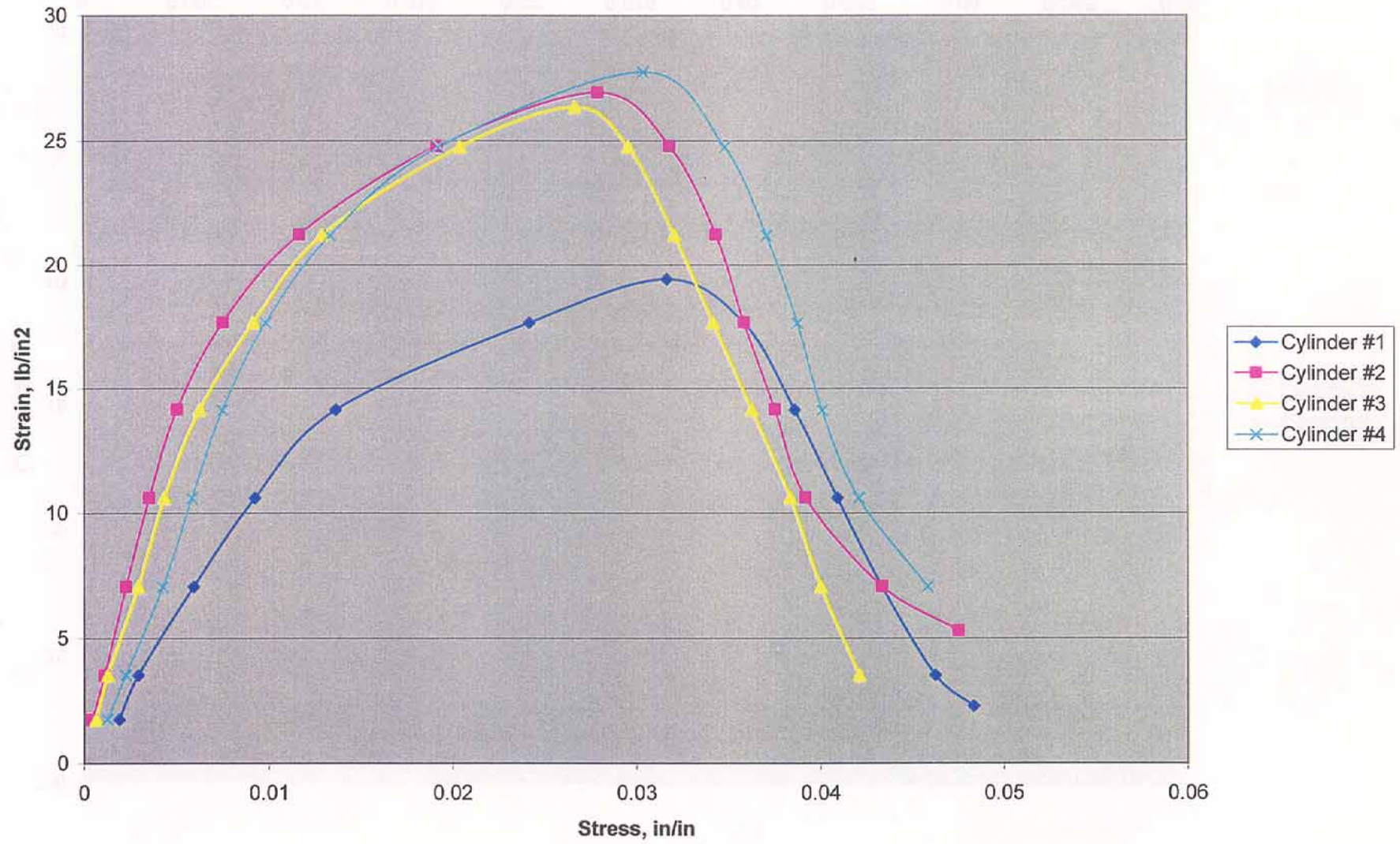


Figure B.30

M-13 6x12 Compression Tests

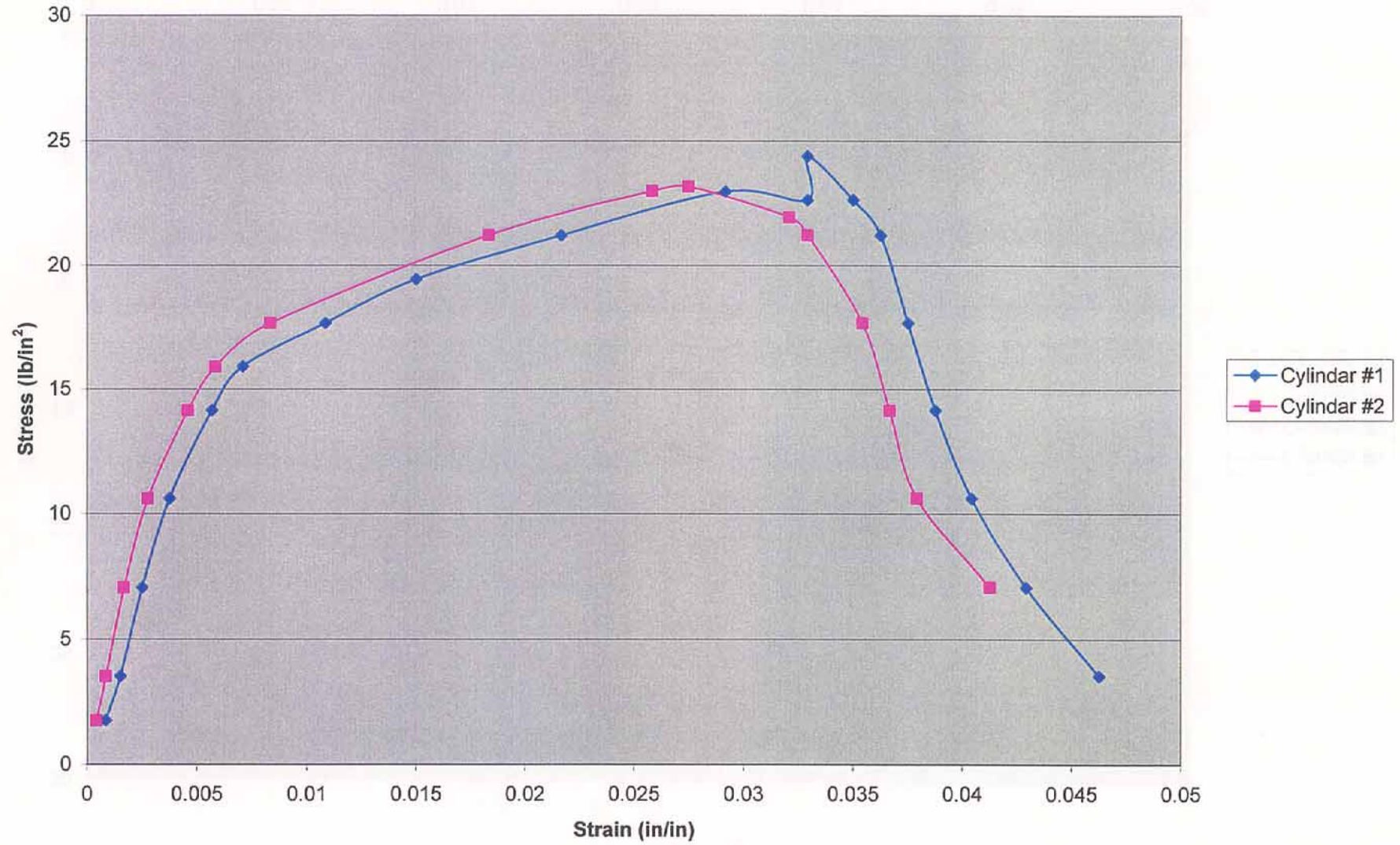


Figure B.32

Mix M-14 6x12 Compression Tests

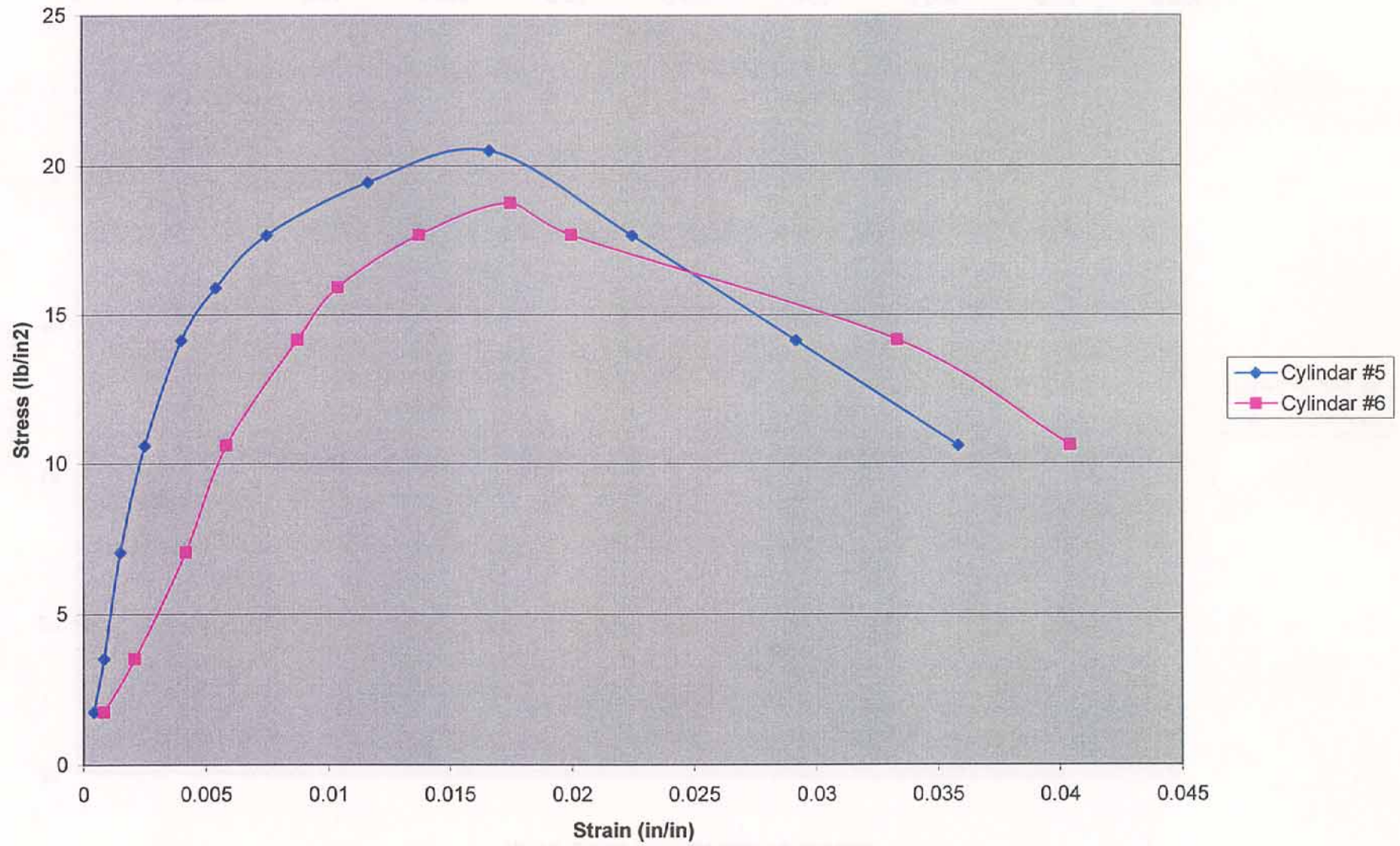


Figure B.34

M-15 6x12 Compressive Stress

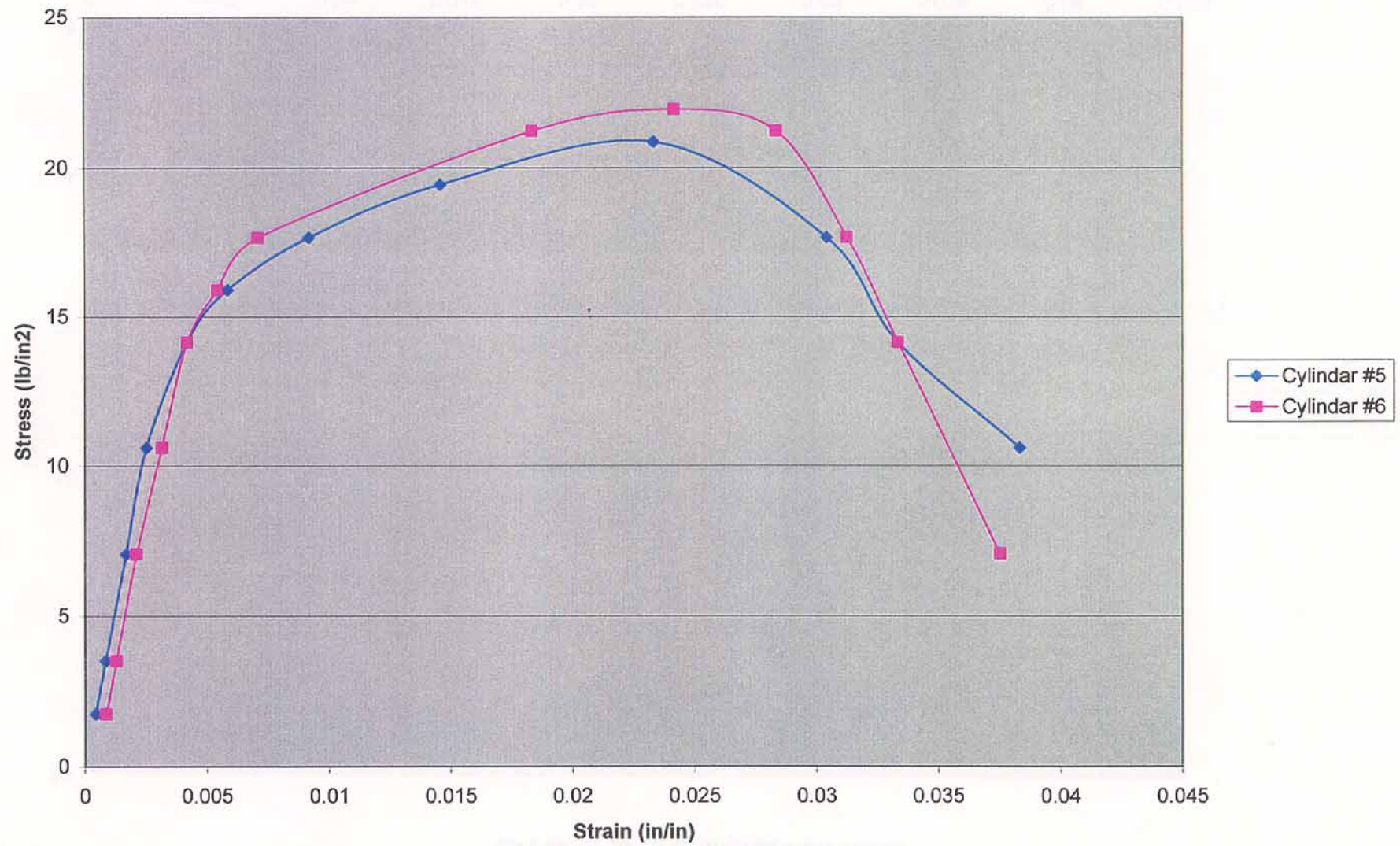


Figure B.36

Comparison of Displacements With & Without Foundation Model

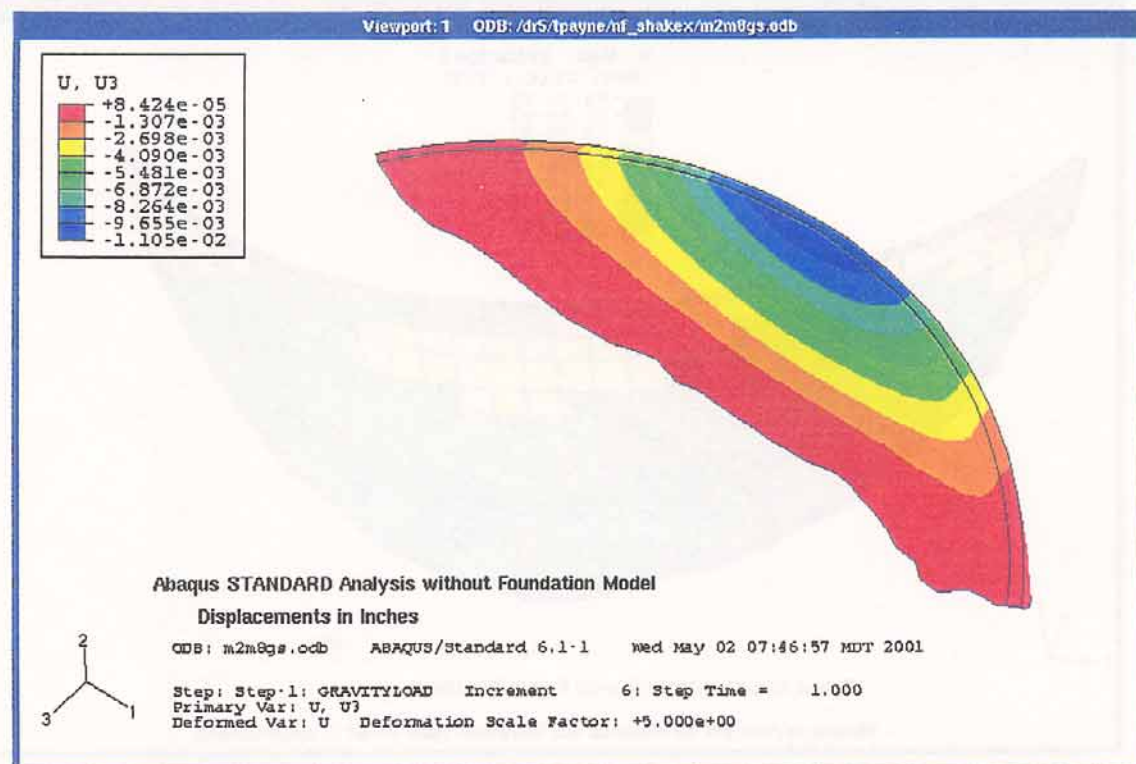
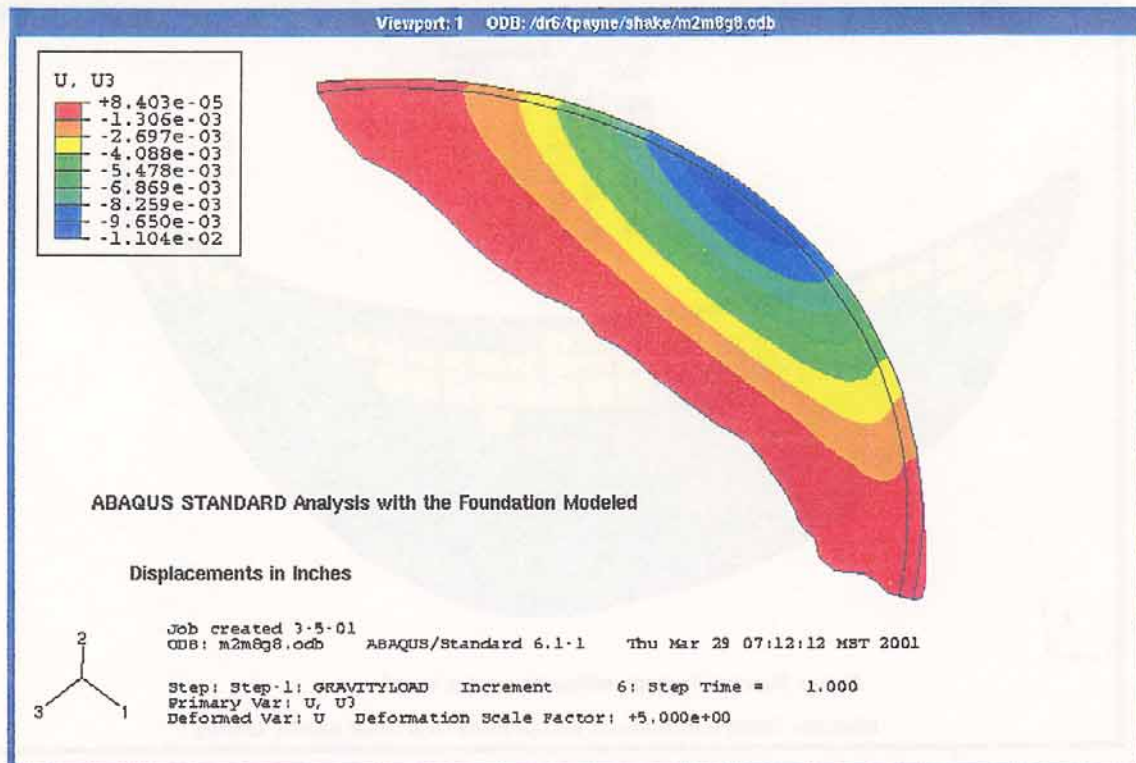


Figure C.1

Comparison of Max. Principal Stresses With & Without Foundation Model

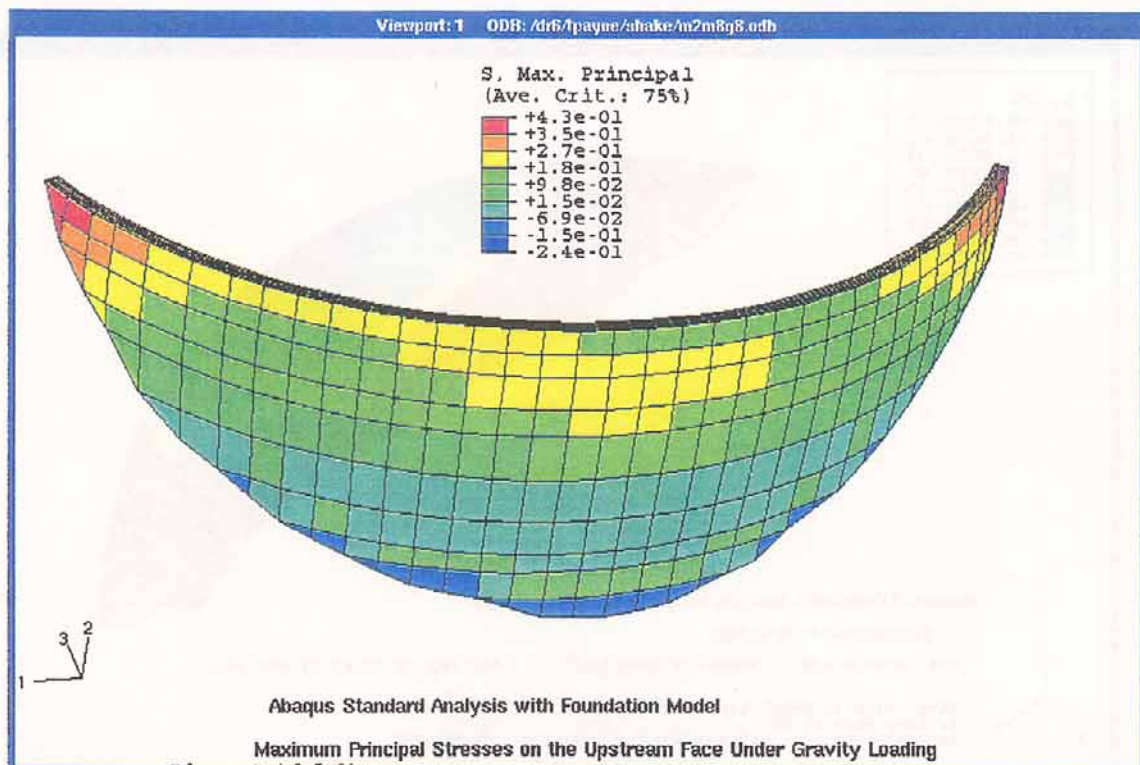
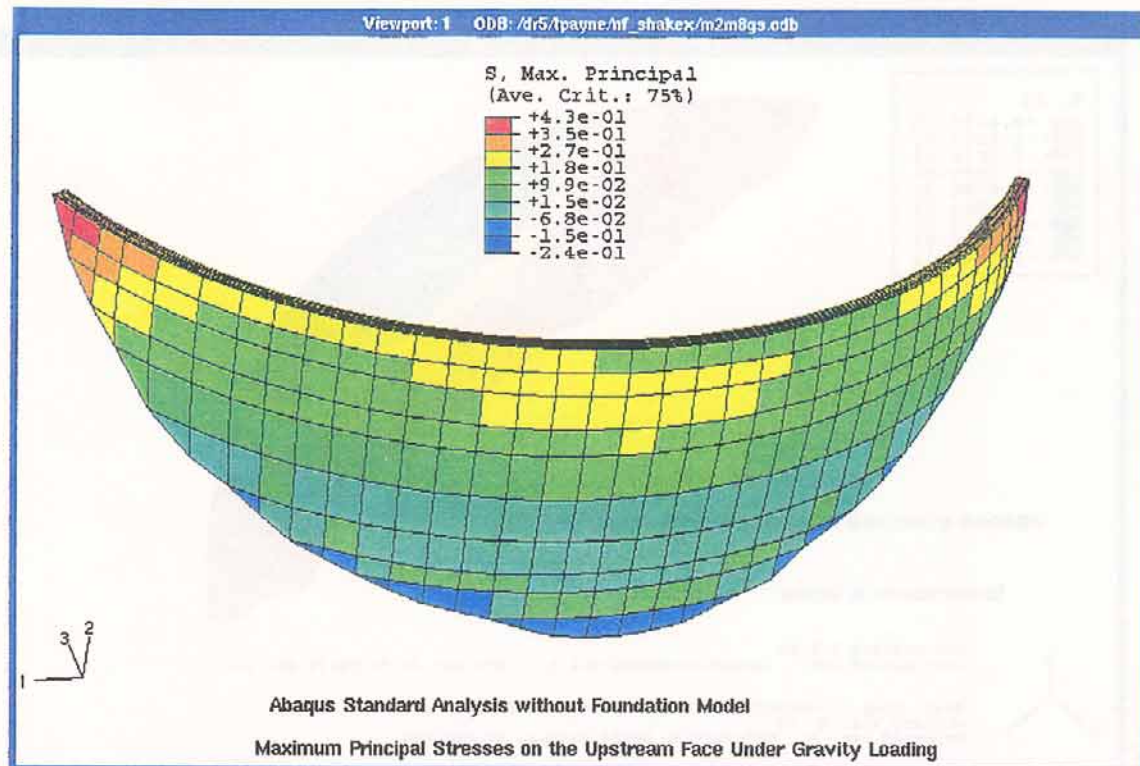


Figure C.2

Comparison of Displacements

Models With & Without Foundations

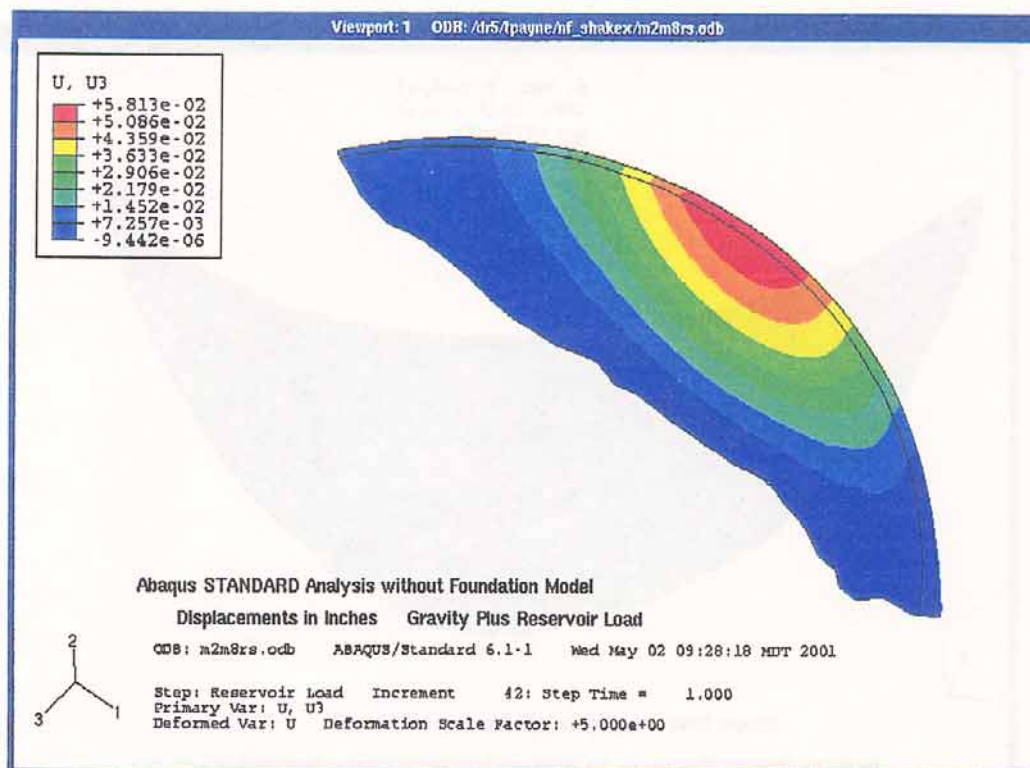
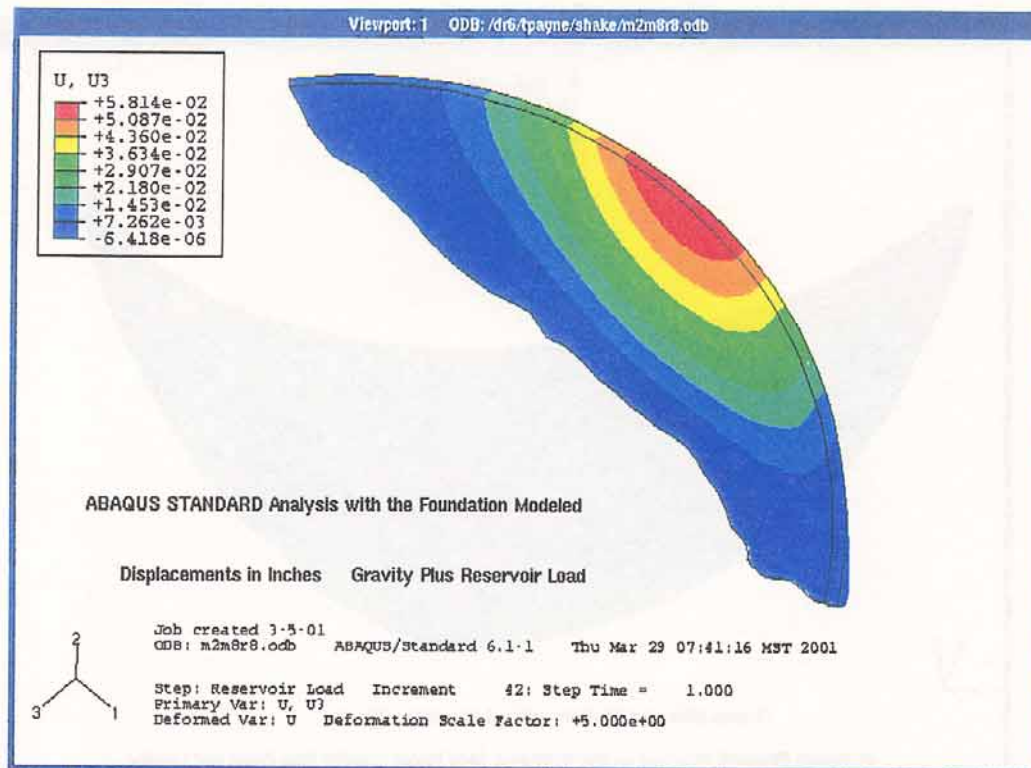


Figure C.3

Comparison of Max. Principal Stresses With & Without Foundation Model

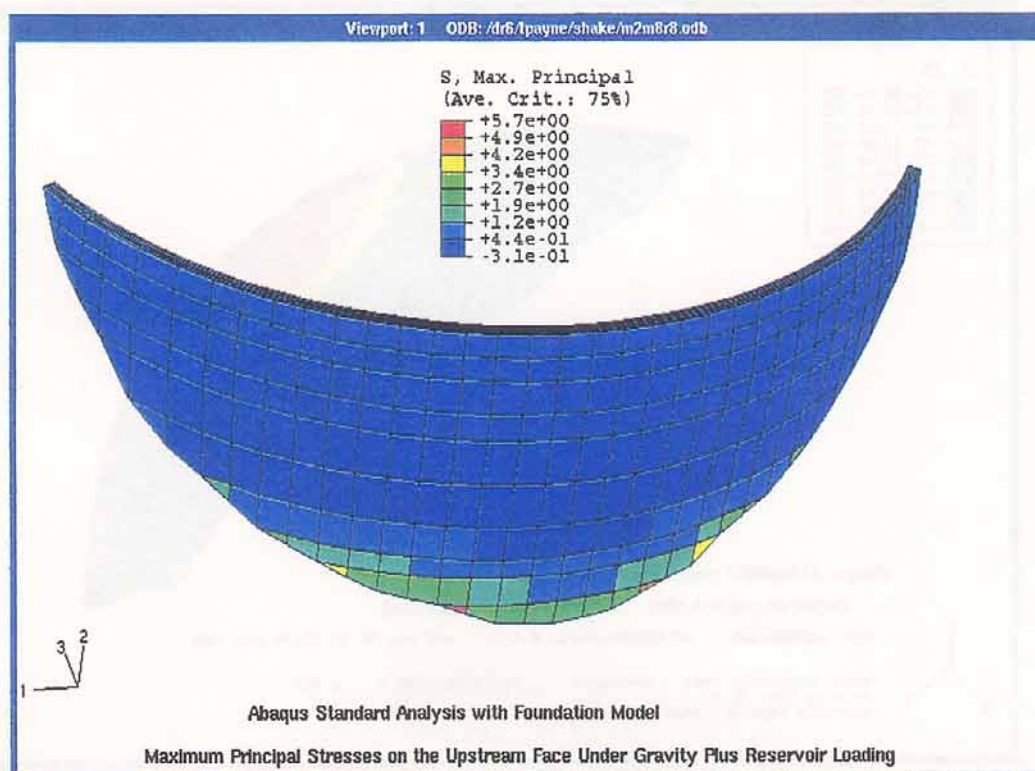
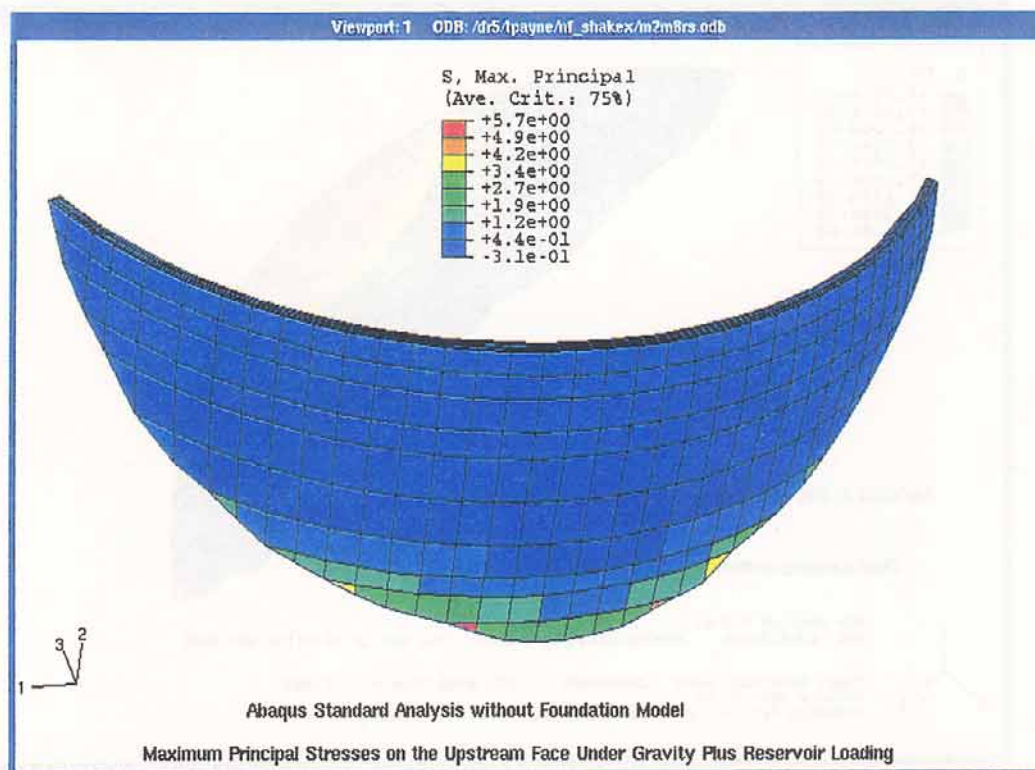
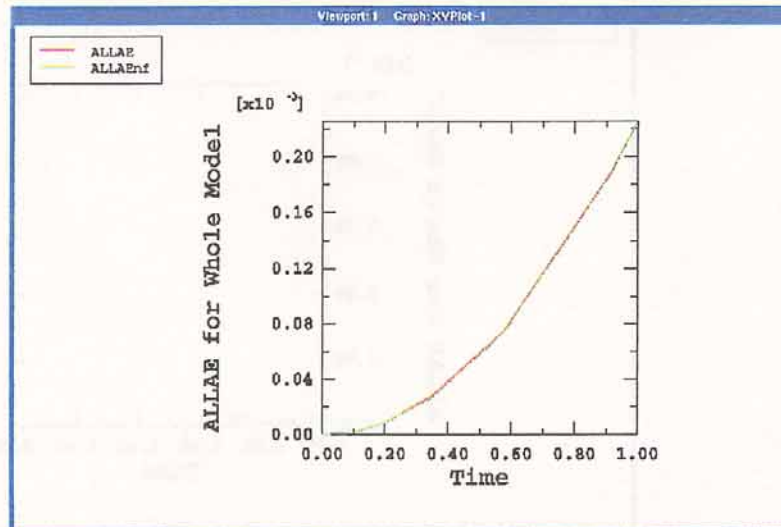


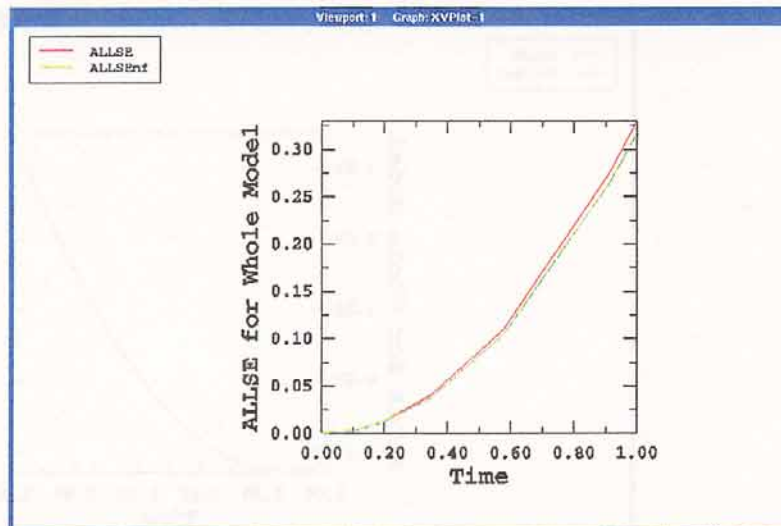
Figure C.4

Comparison of Energy Levels
ABAQUS STANDARD Analyses
Gravity Load
With and With Foundation Models

Artificial
Strain
Energy



Strain
Energy



Total
Energy

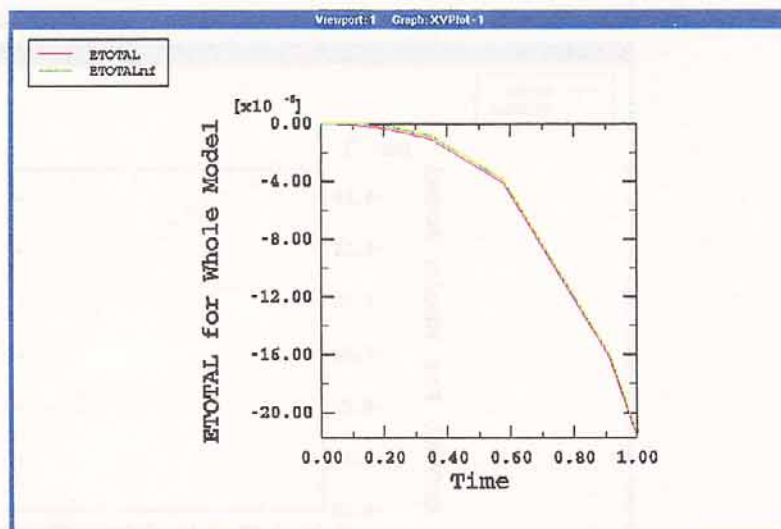
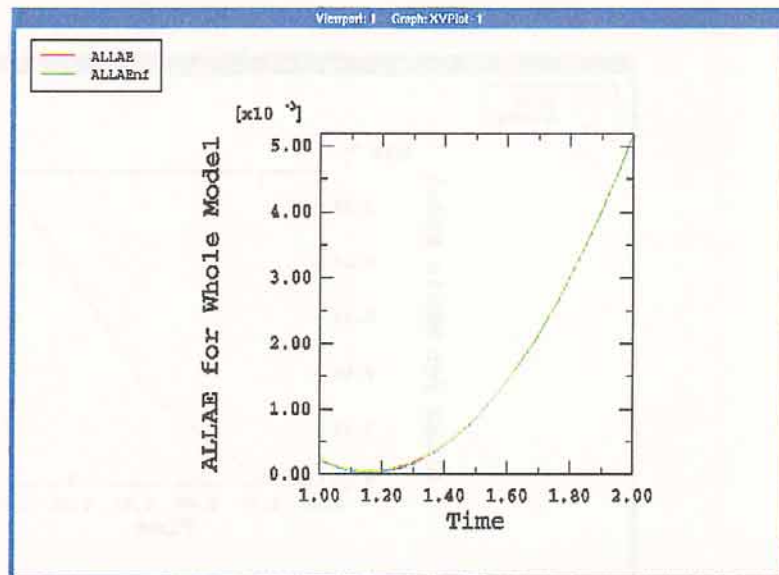


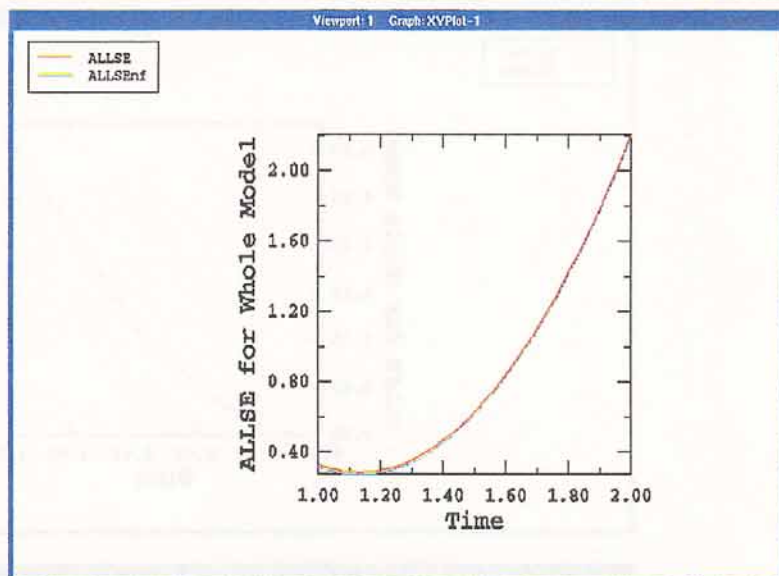
Figure C.5

Comparison of Energy Levels
 ABAQUS STANDARD Analyses
 Gravity + Reservoir loads
 With and Without A Foundation Model

Artificial
 Strain
 Energy



Strain
 Energy



Total
 Energy

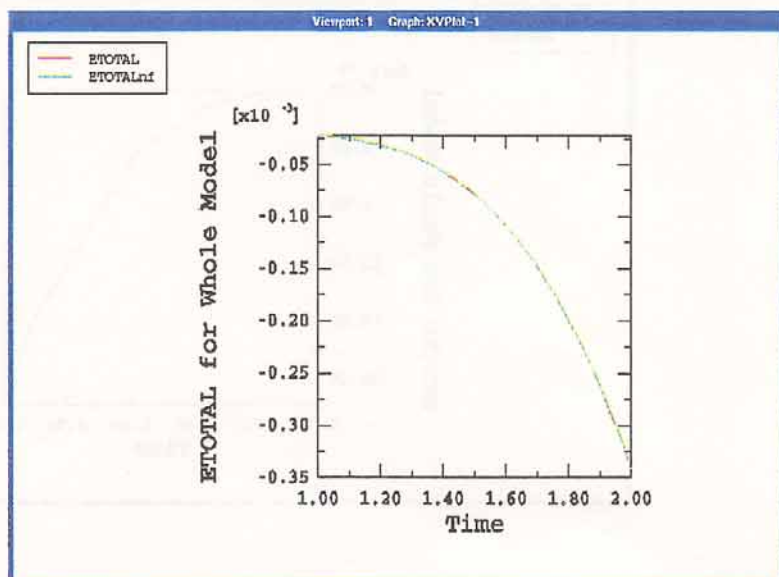


Figure C.6

Preliminary Analyses With Foundation Model

Modal Analyses

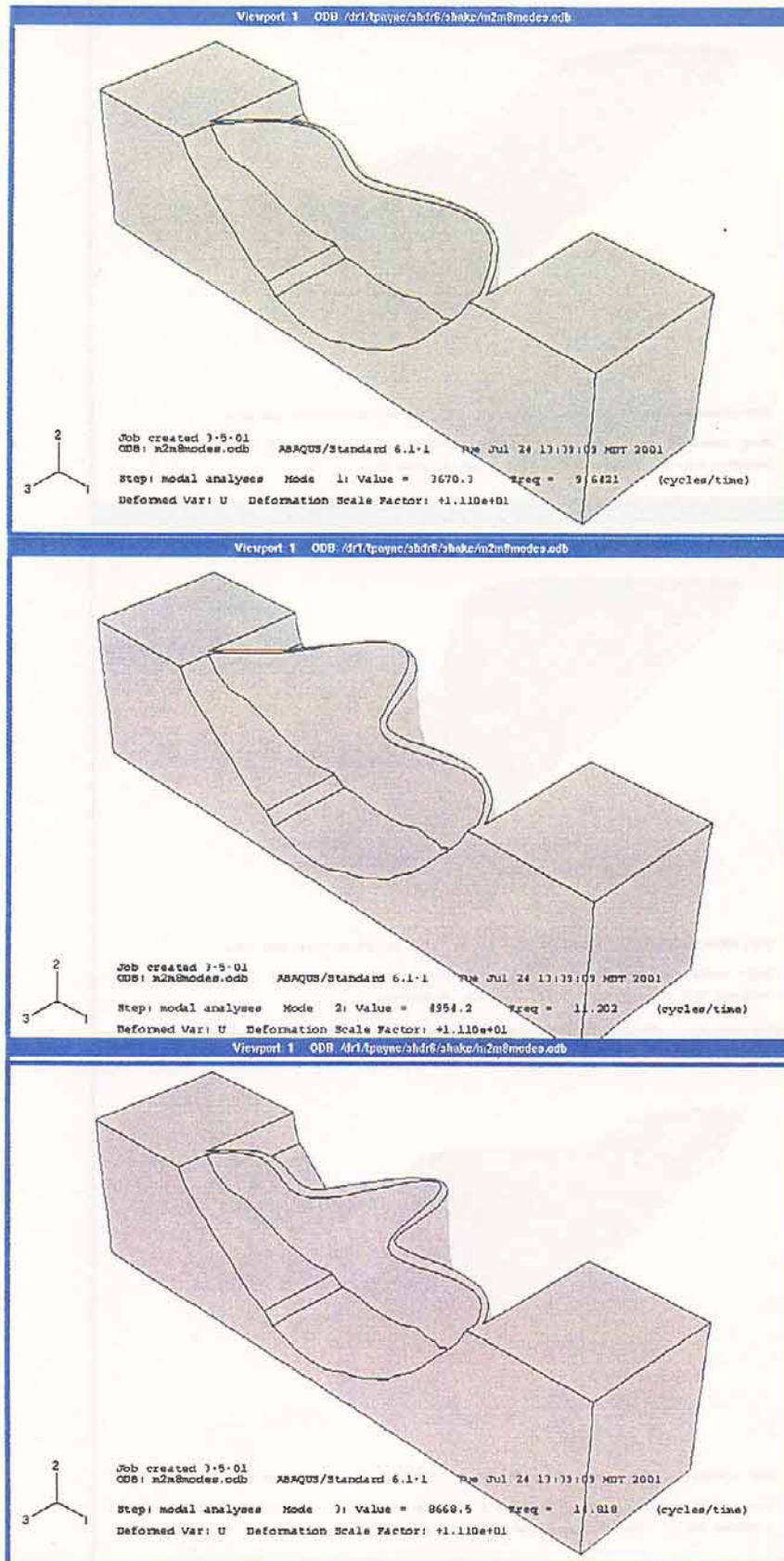


Figure C.7

Preliminary Analyses With Out Foundation Model

Modal Analyses

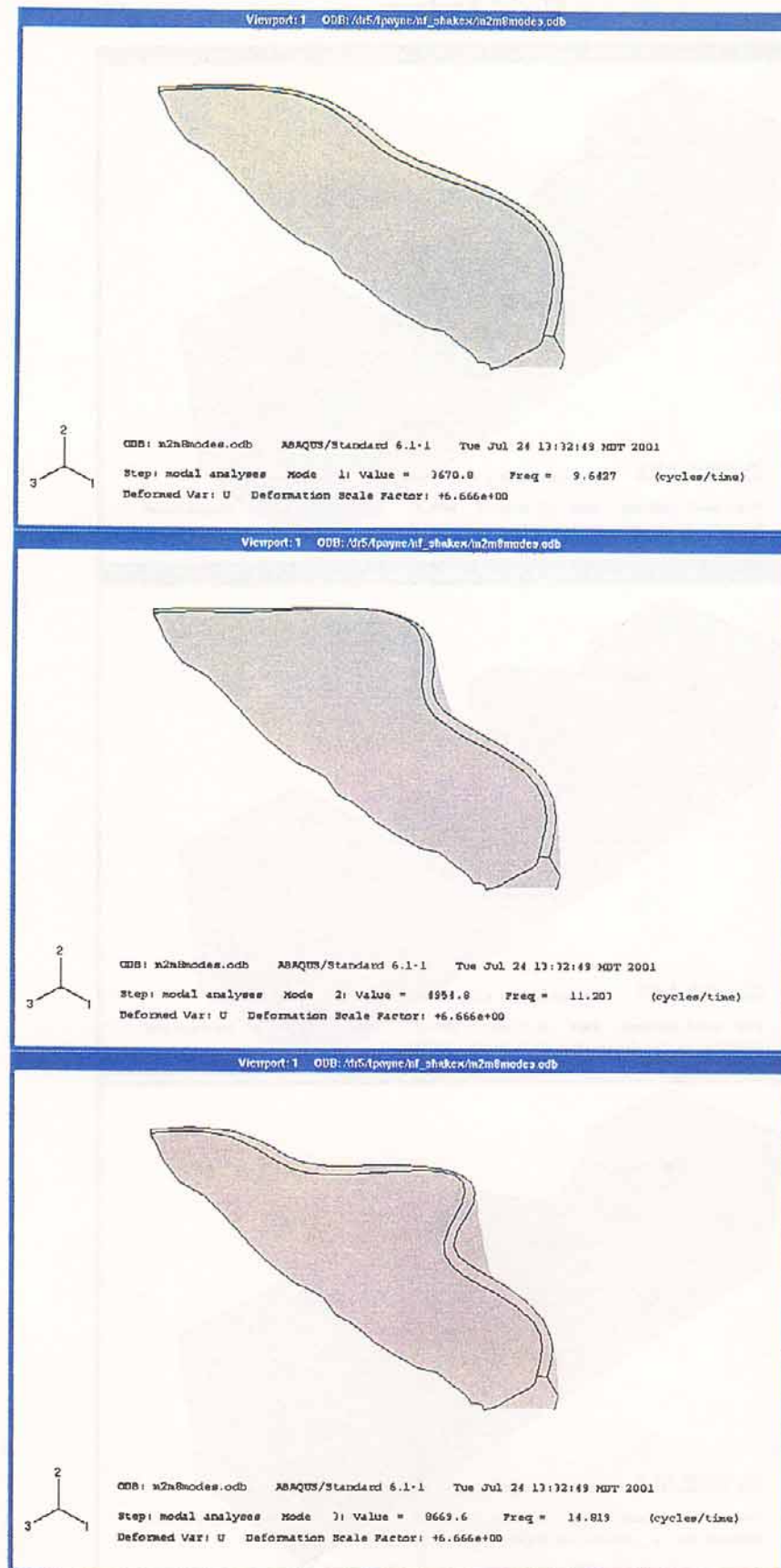


Figure C.8

Comparison of Displacements With & Without Foundation Models

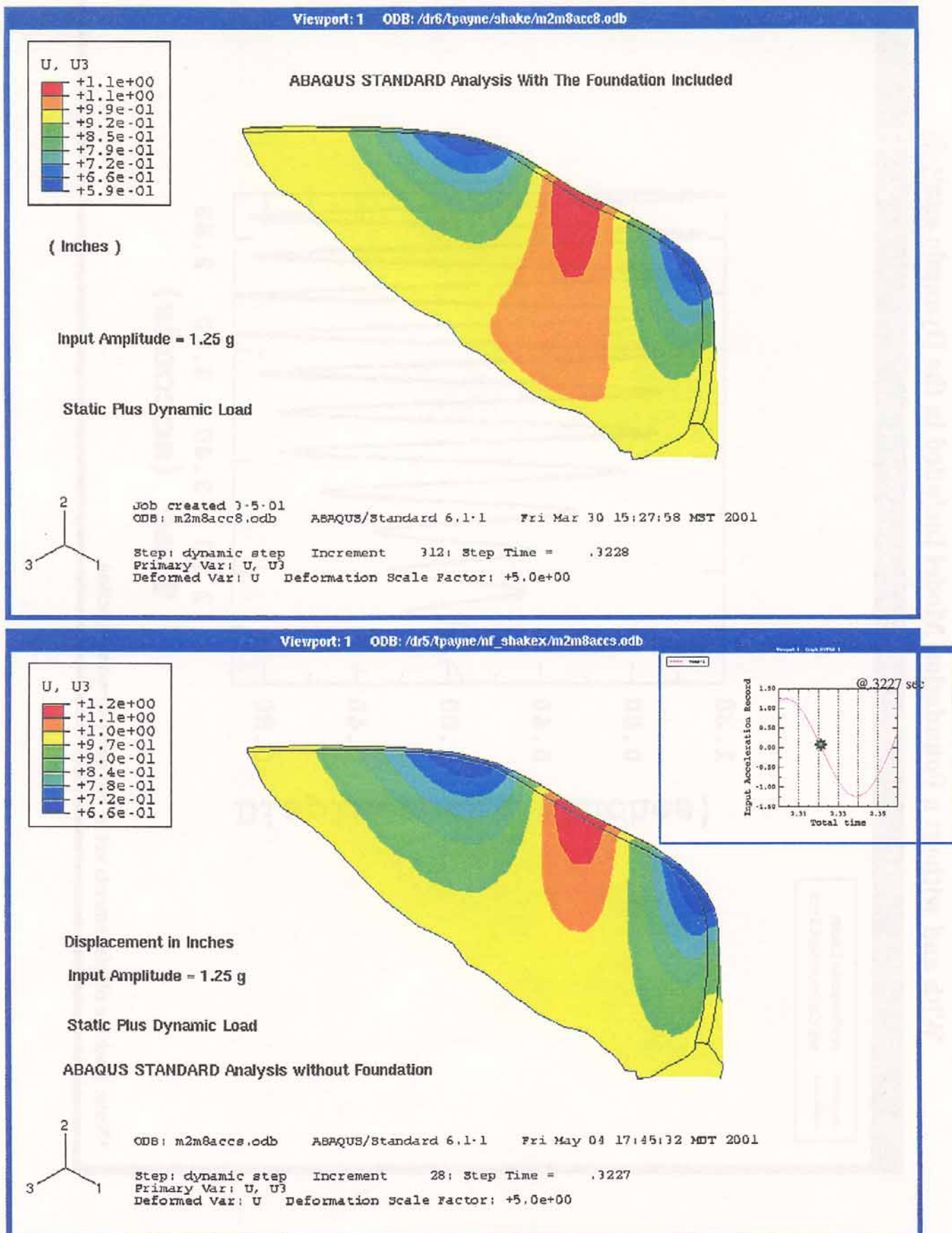


Figure C.9

Upstream/Downstream Relative Displacement Time Histories at the Dam Crest With and without a Foundation Model Included in the Dynamic analysis

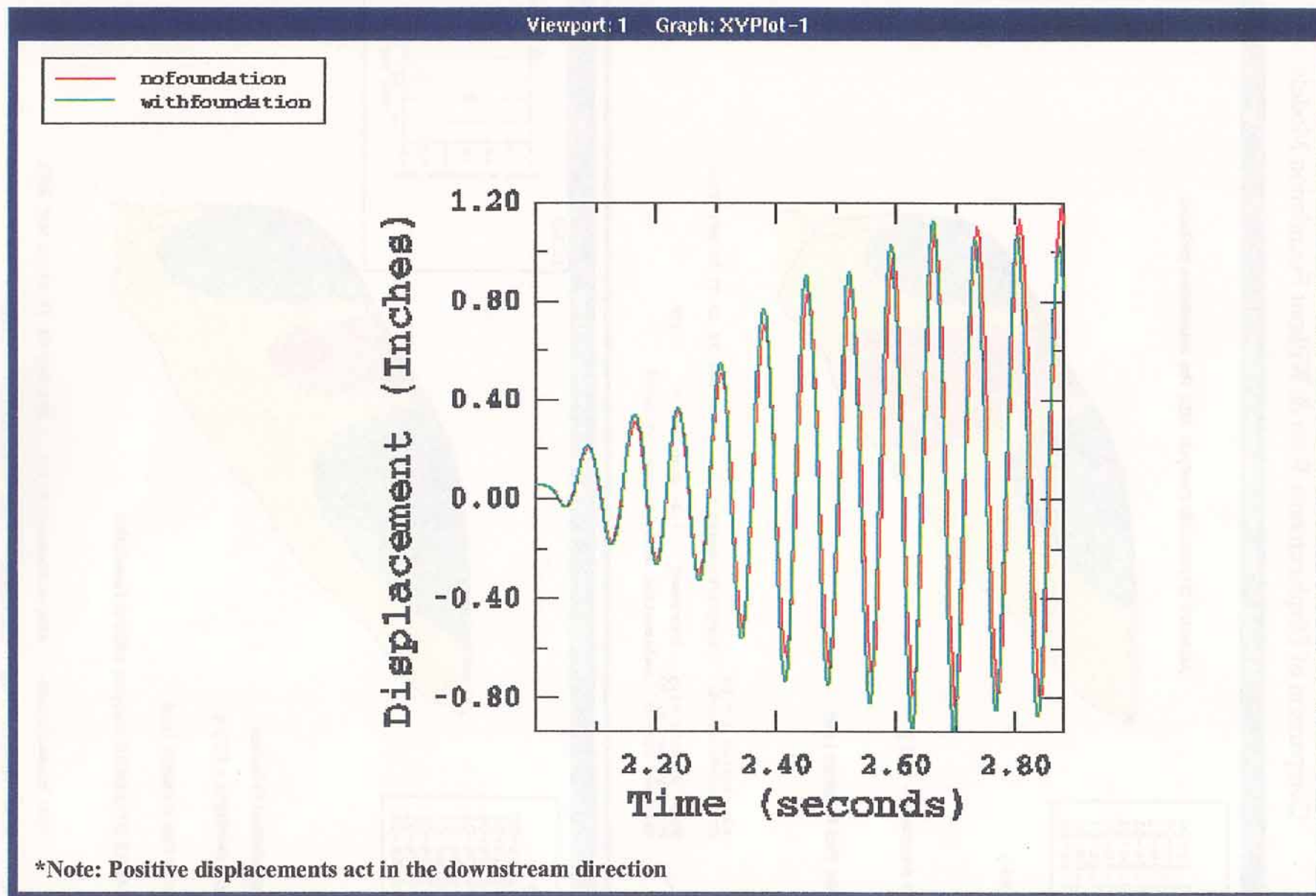


Figure C.10

Comparison of Max. Principal Stresses With & Without Foundation Models

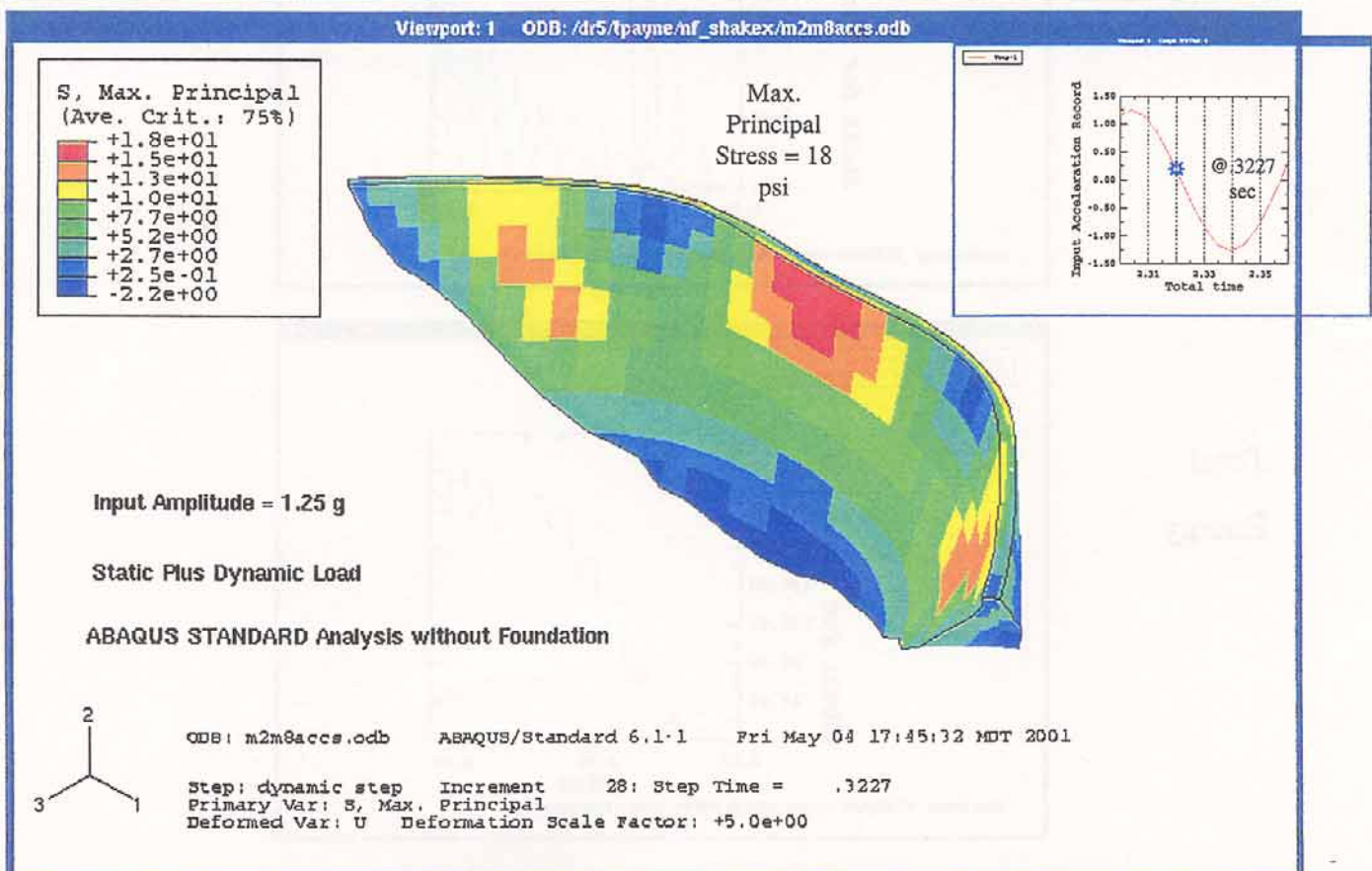
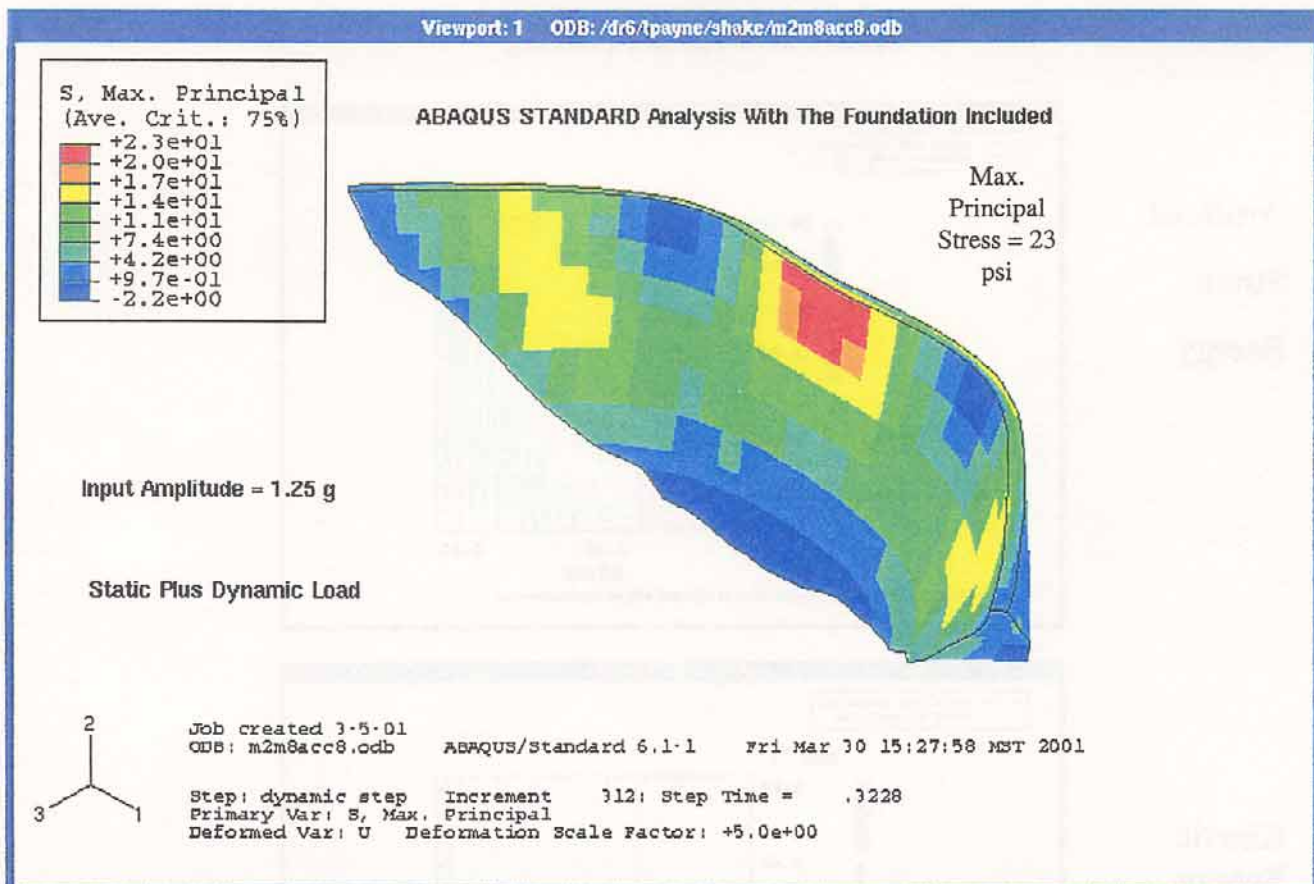
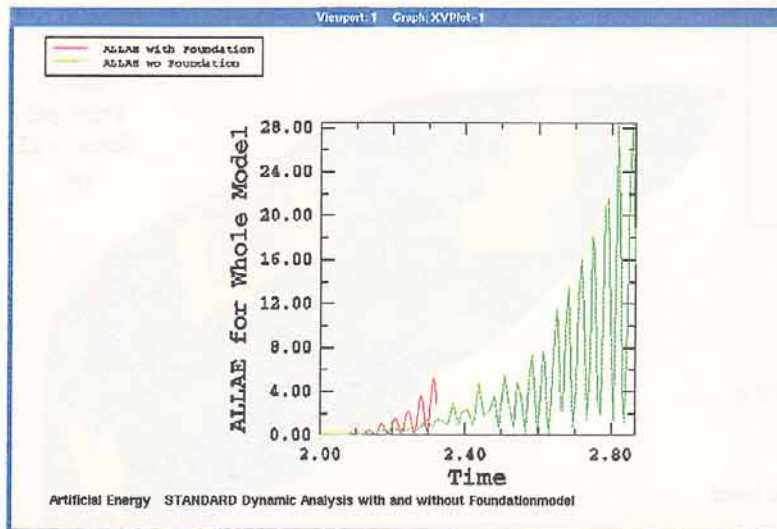


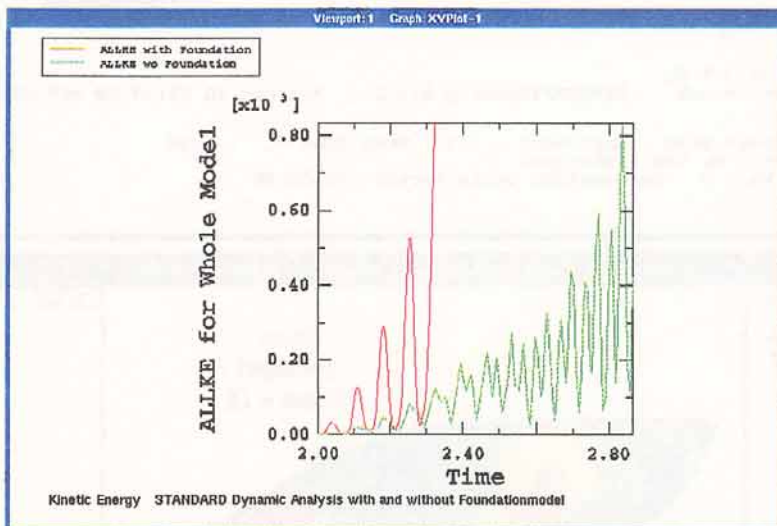
Figure C.11

Comparison of Energy Levels **ABAQUS STANDARD Analyses with/without Foundations** **Static Plus Dynamic Loading**

Artificial
Strain
Energy



Kinetic
Energy



Total
Energy

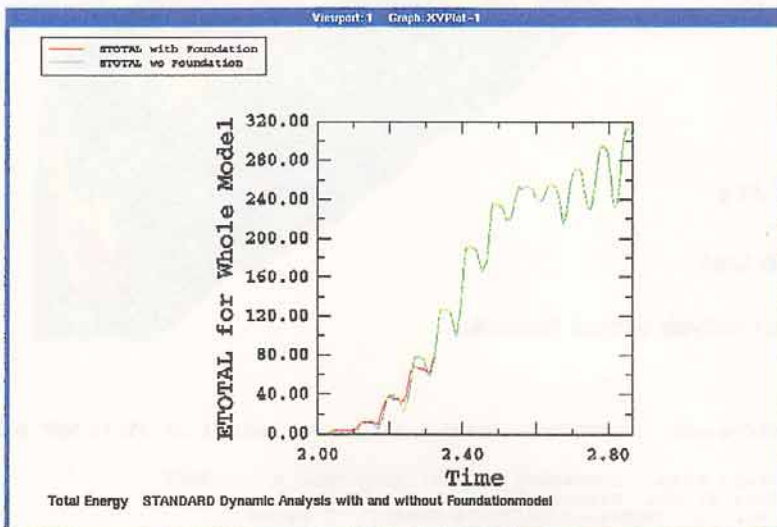


Figure C.12

Comparison of Displacement STANDARD versus EXPLICIT

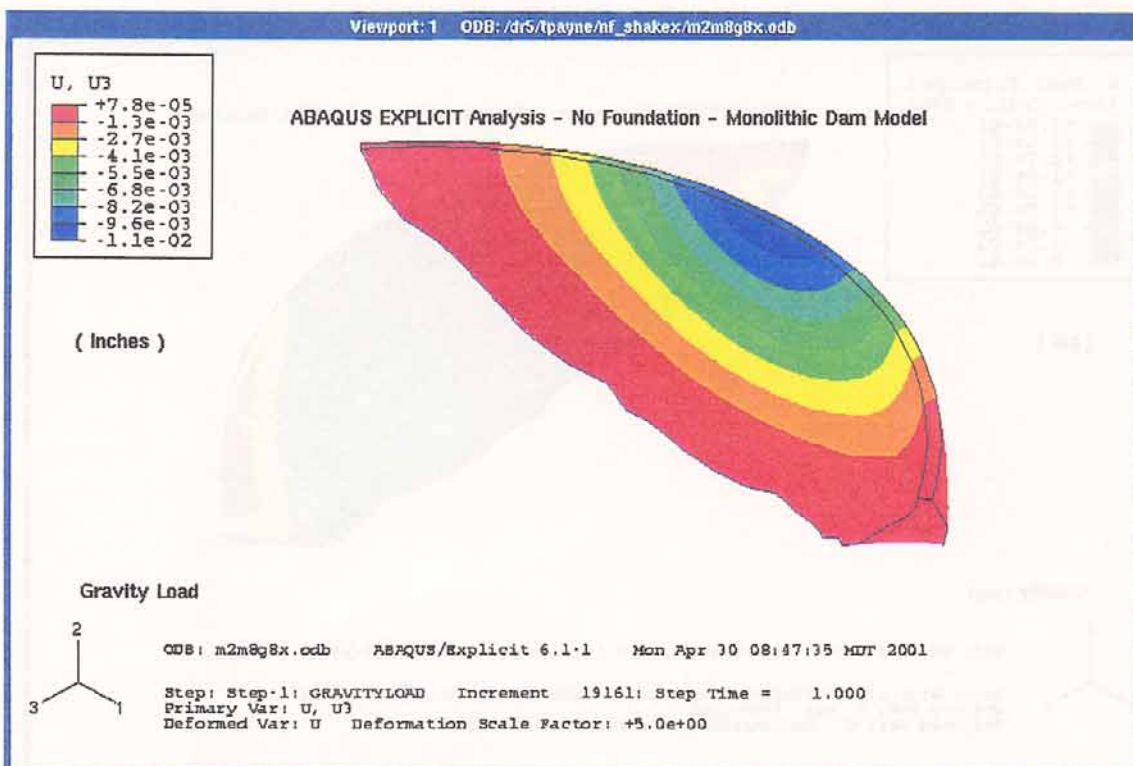
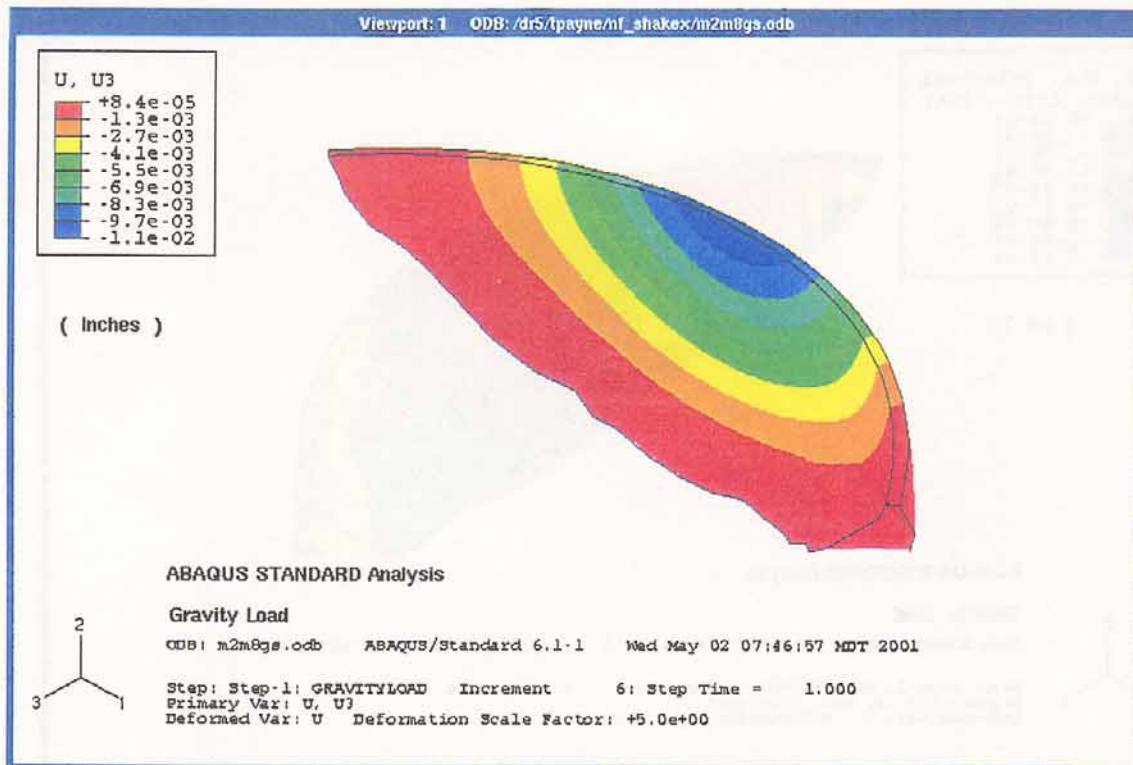


Figure C.13

Comparison of Max. Principal Stresses

STANDARD versus EXPLICIT

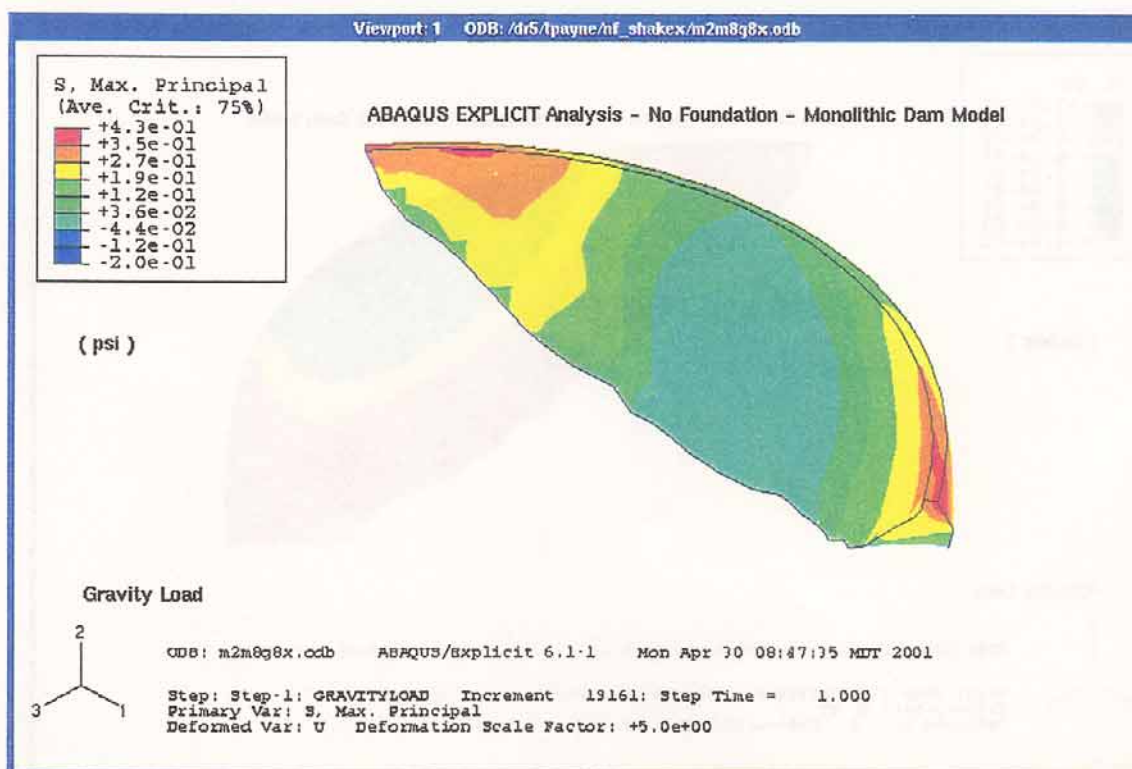
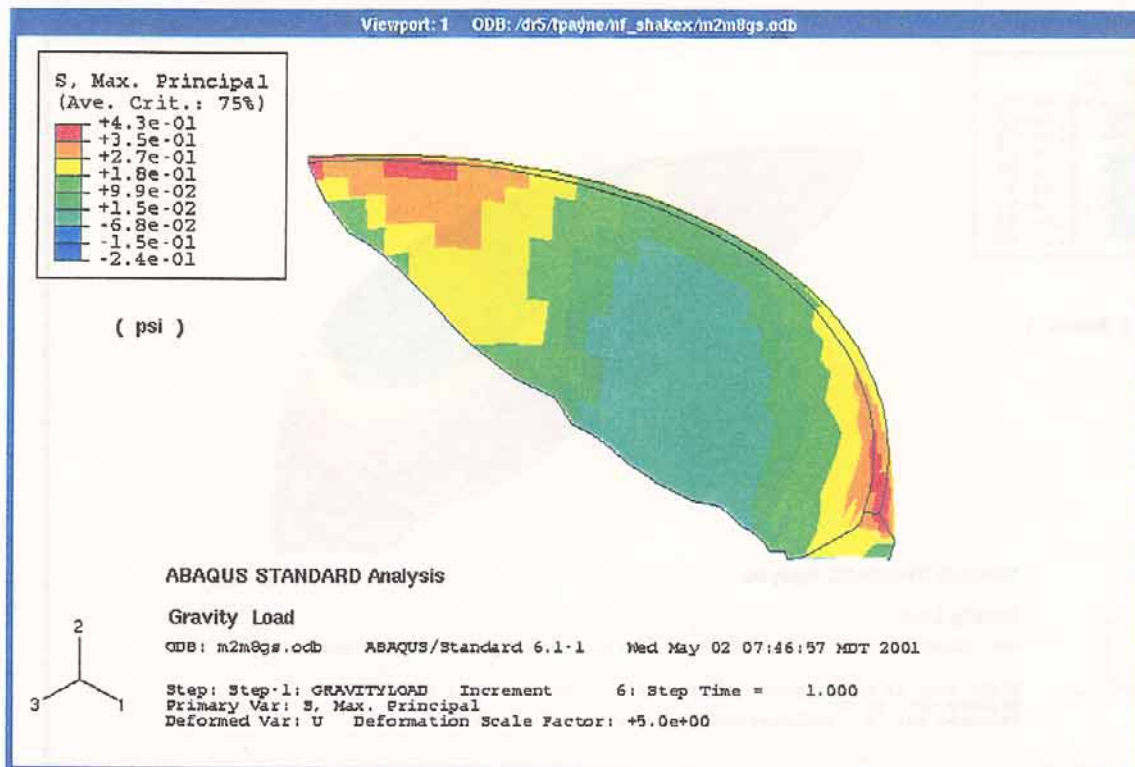


Figure C.14

Comparison of Displacements

STANDARD versus EXPLICIT

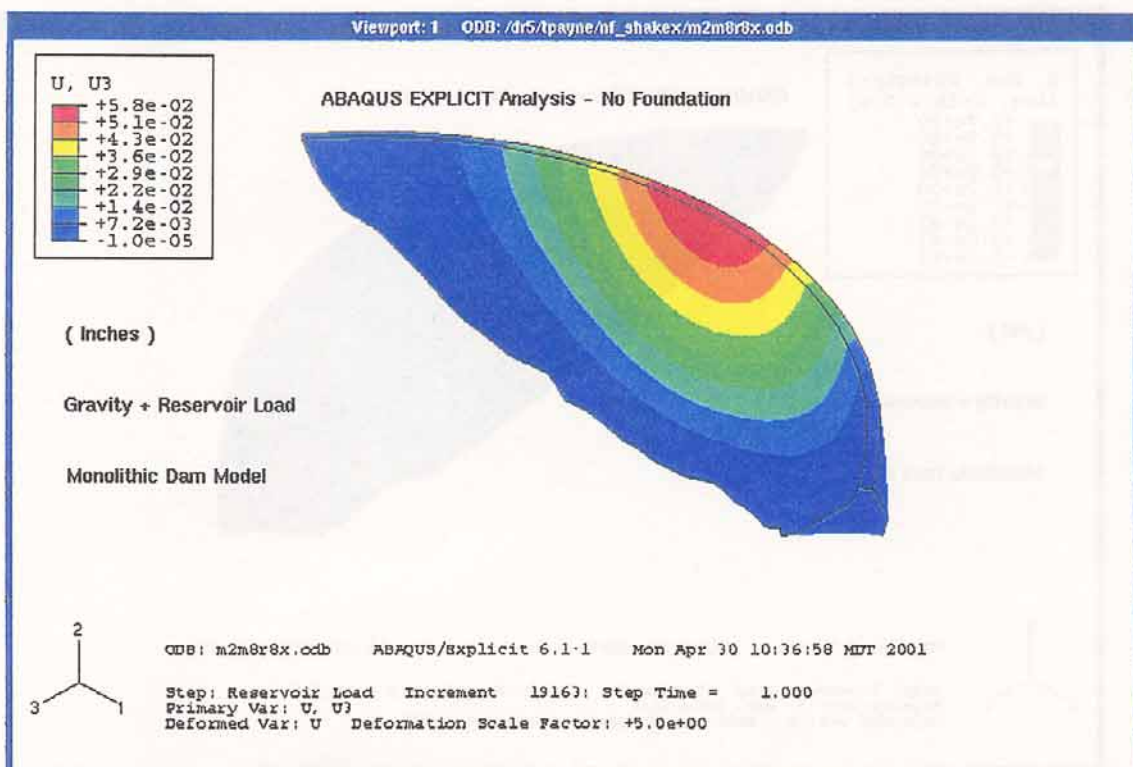
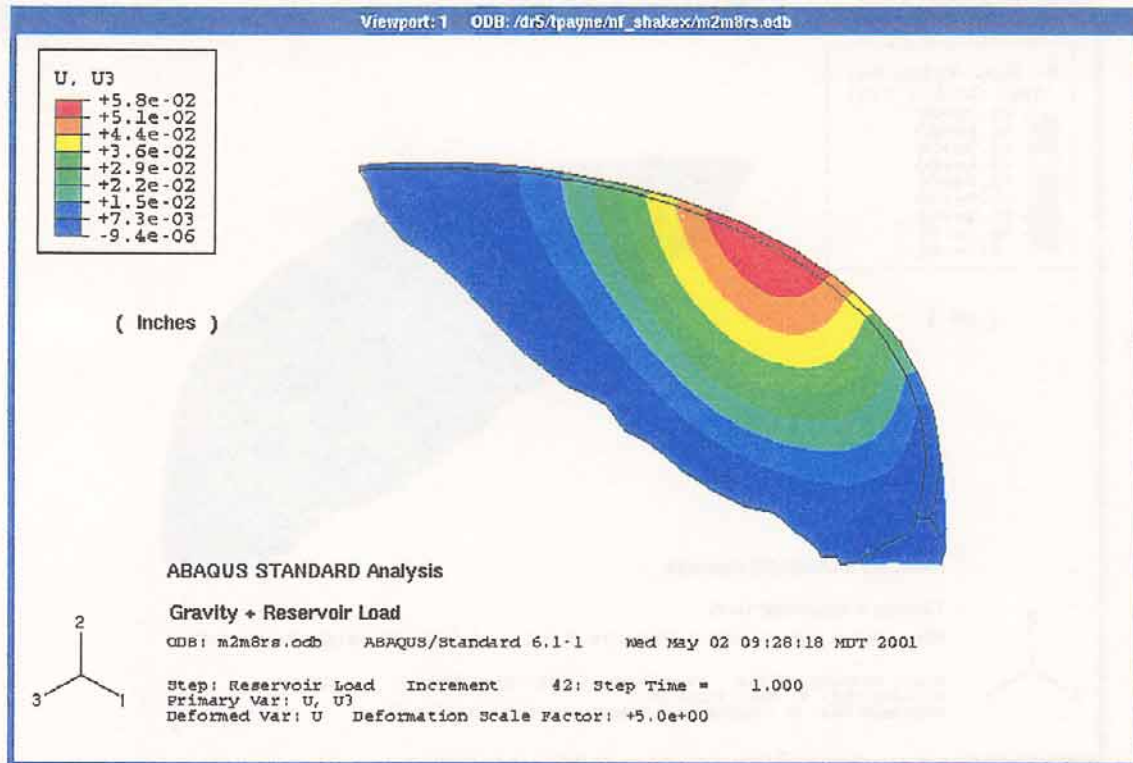


Figure C.15

Comparison of Max. Principal Stresses

STANDARD versus EXPLICIT

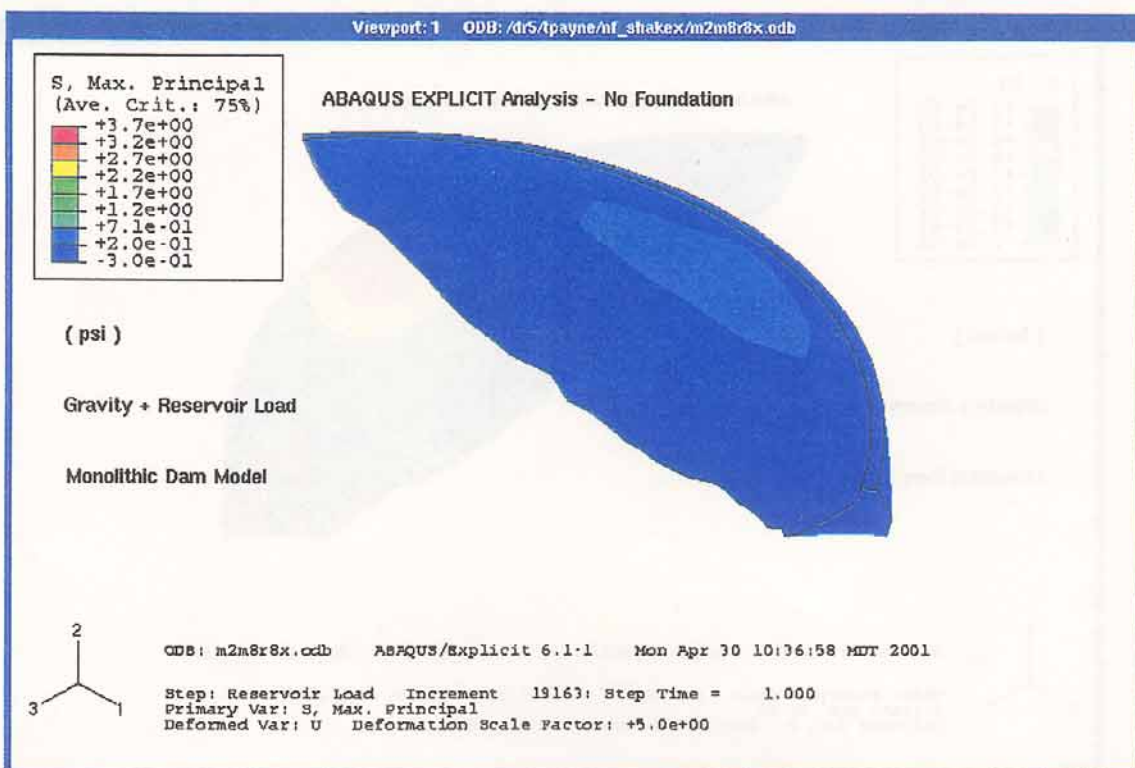
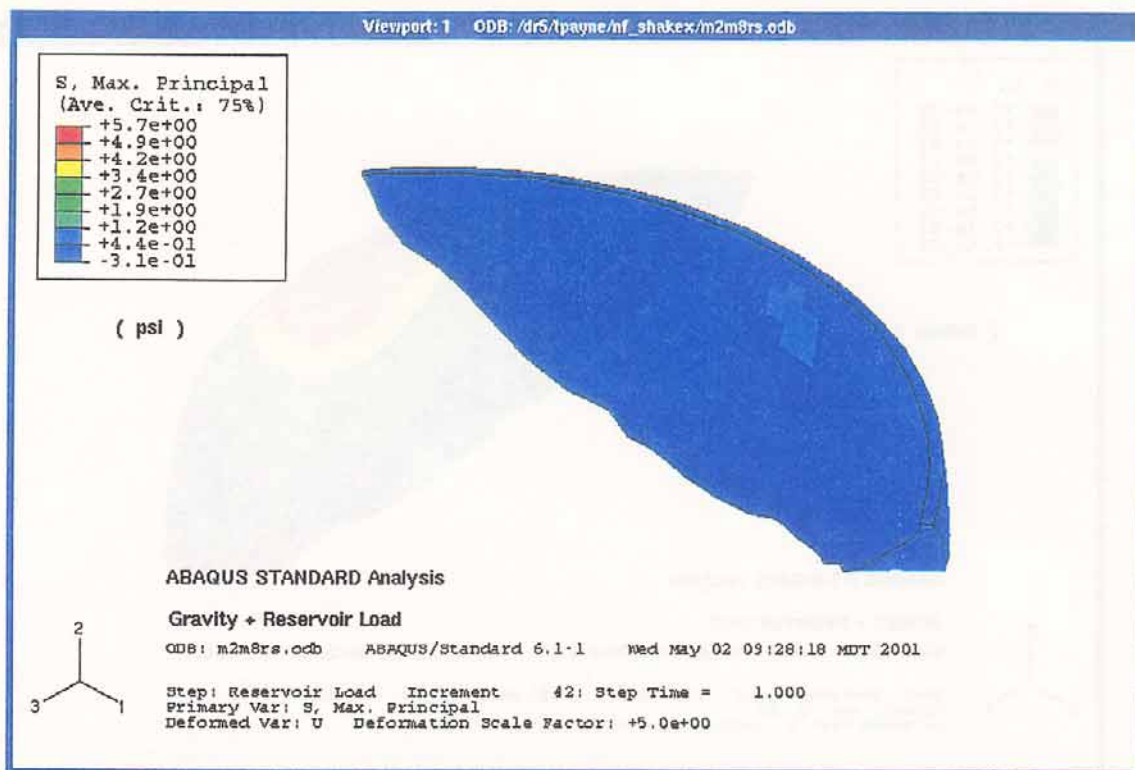
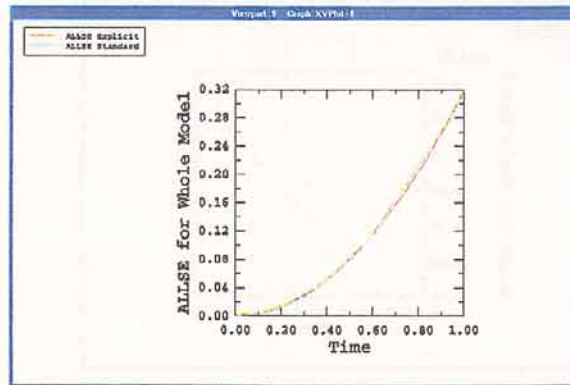


Figure C.16

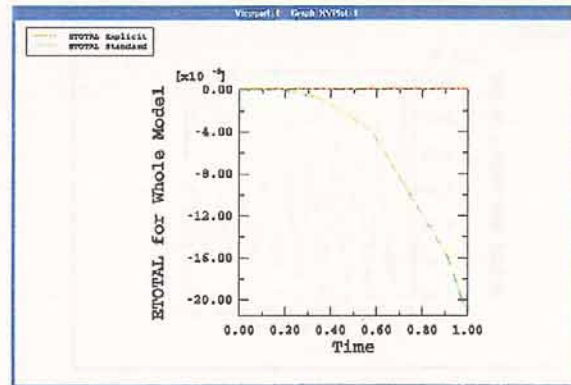
Comparison of Energy Levels

STANDARD versus EXPLICIT

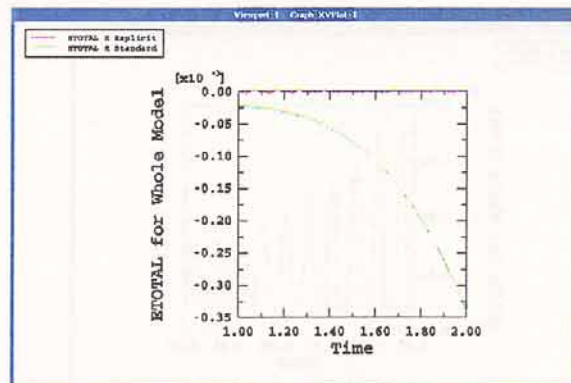
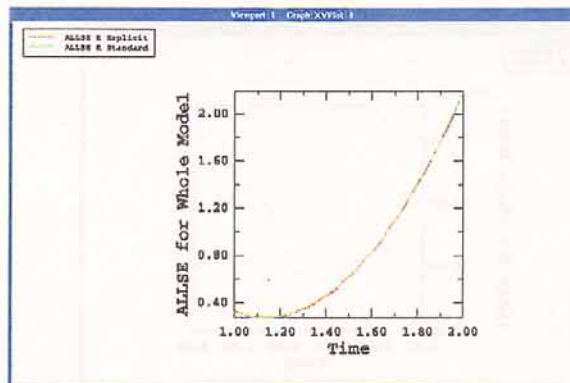
Strain Energy



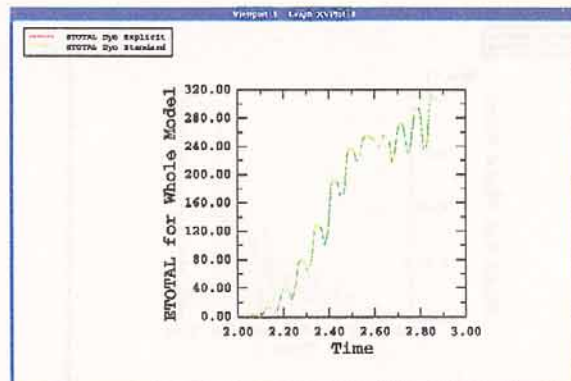
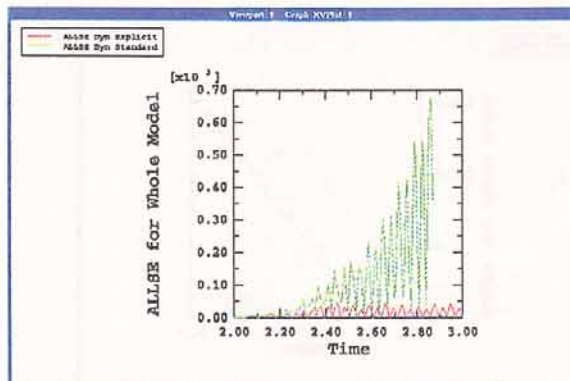
Total Energy



Gravity Load Step



Reservoir Load Step



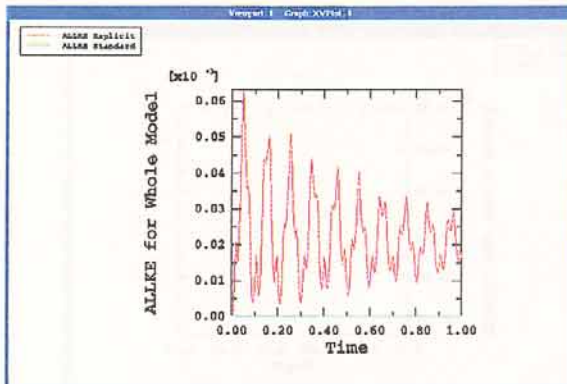
Dynamic Load Step

Figure C.17

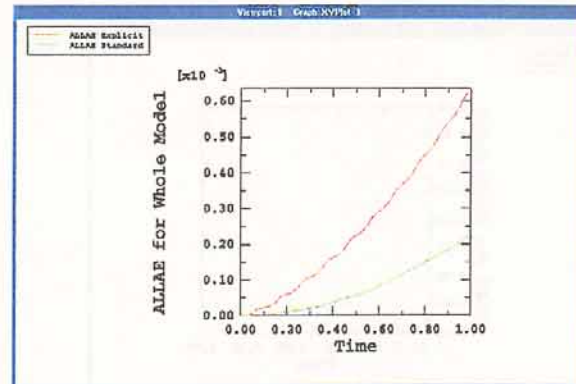
Comparison of Energy levels

STANDARD versus EXPLICIT

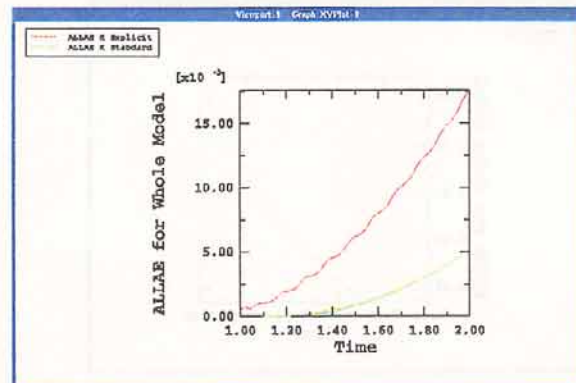
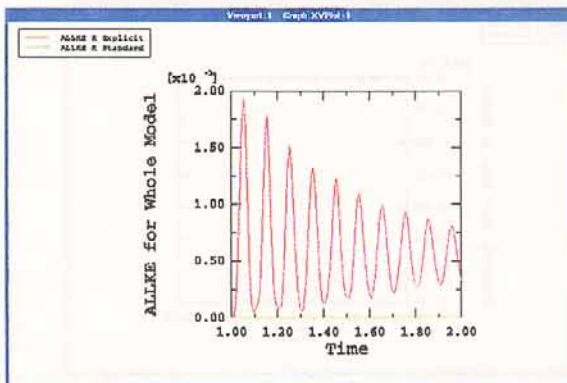
Kinetic Energy



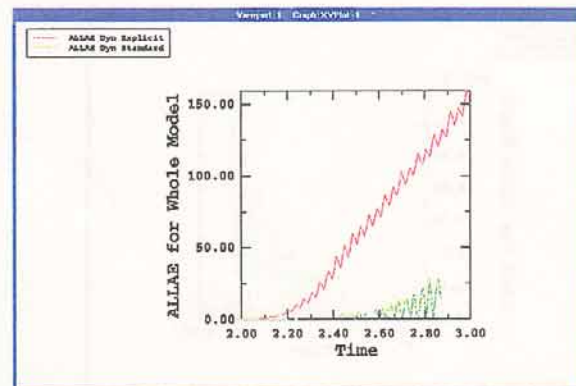
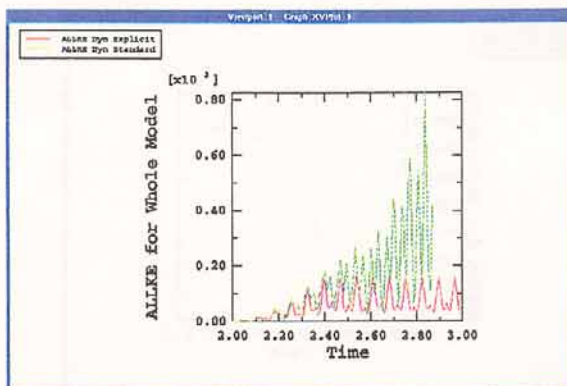
Artificial Strain Energy



Gravity Load Step



Reservoir Load Step



Dynamic Load Step

Figure C.18

Comparison of Displacements

STANDARD versus EXPLICIT

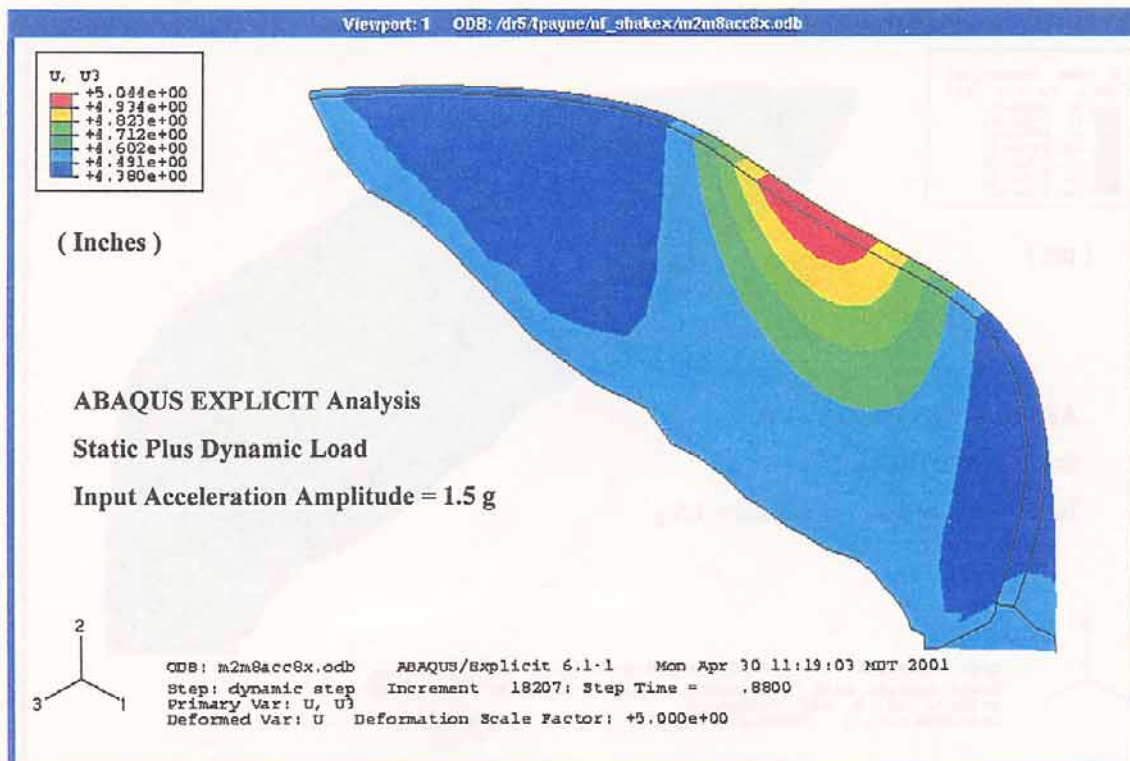
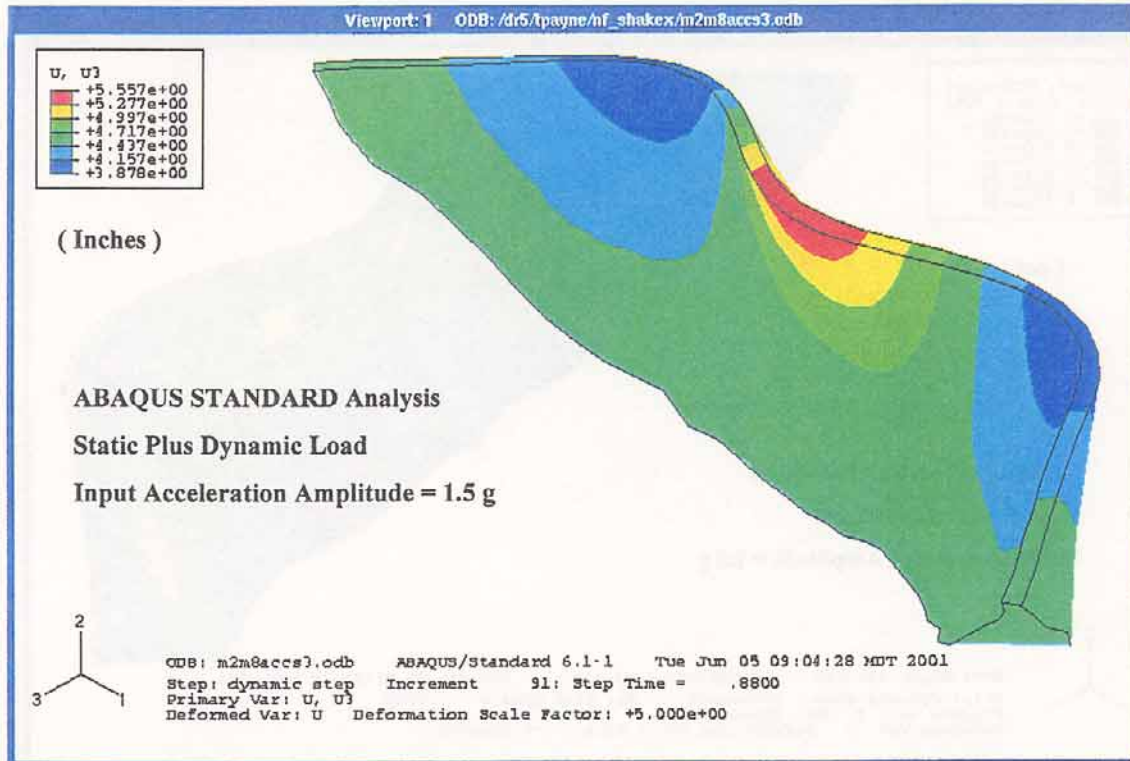


Figure C.19

Comparison of Max. Principal Stresses

STANDARD versus EXPLICIT

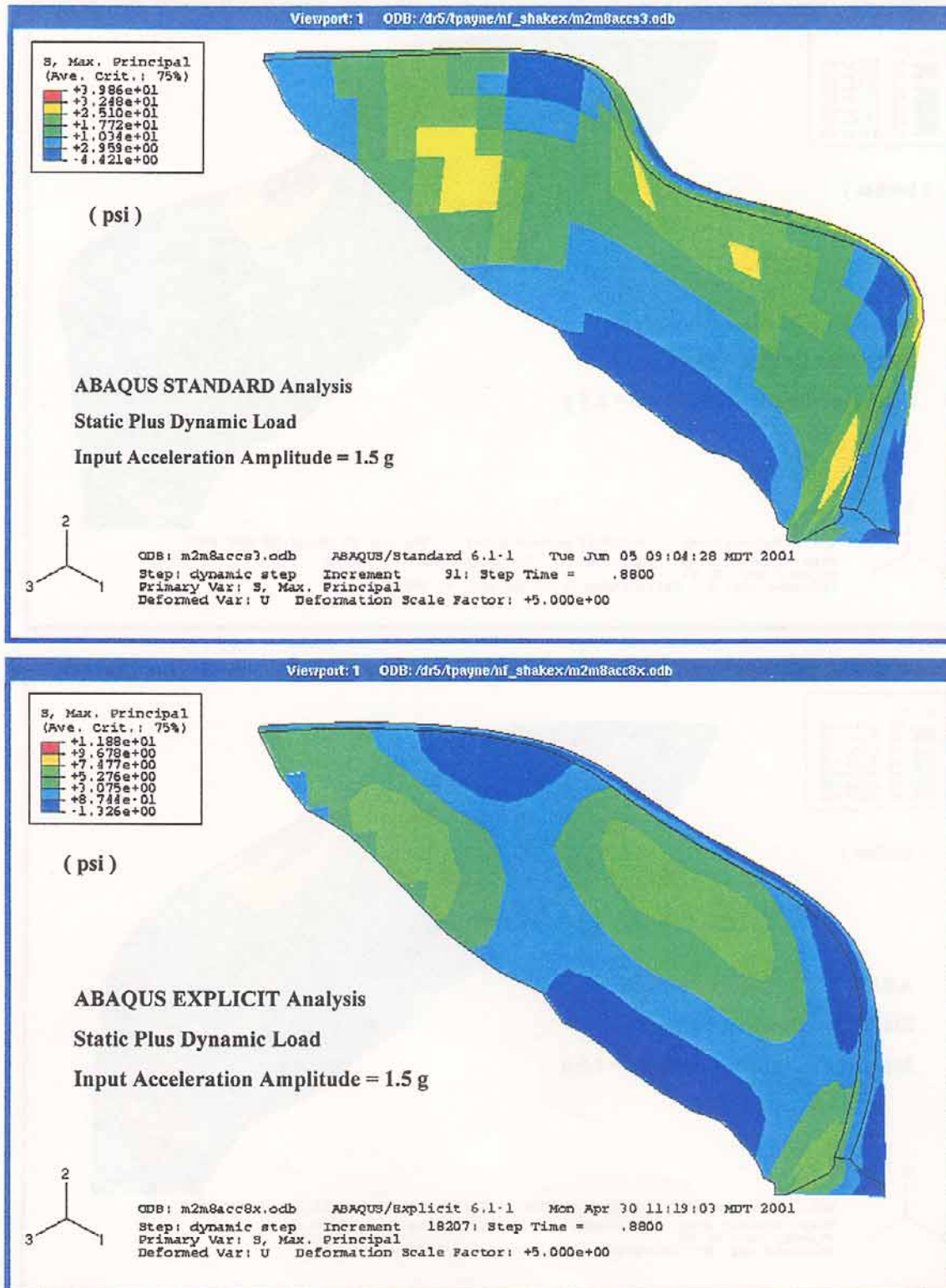
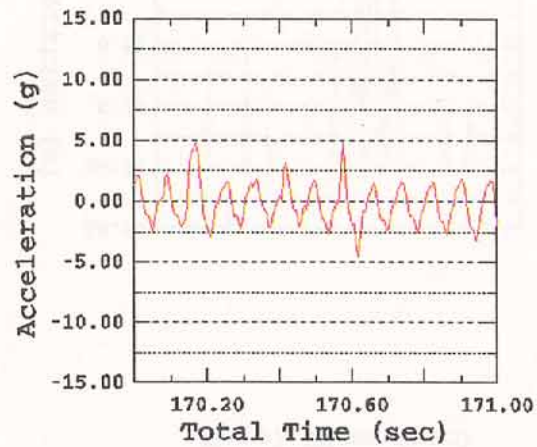


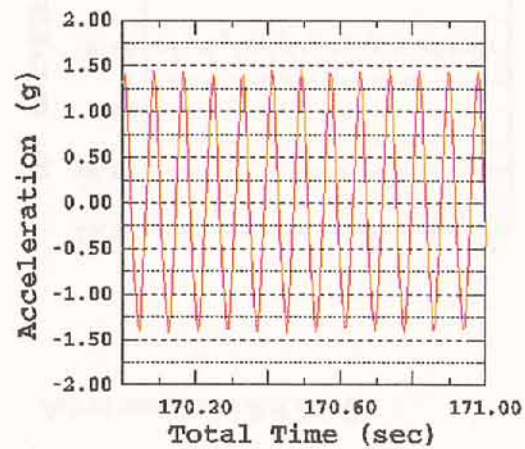
Figure C.20

Accelerations Measured in the Laboratory Experiment
Accelerometer #8 @ Dam Crest on Crown Cantilever

Temp:1

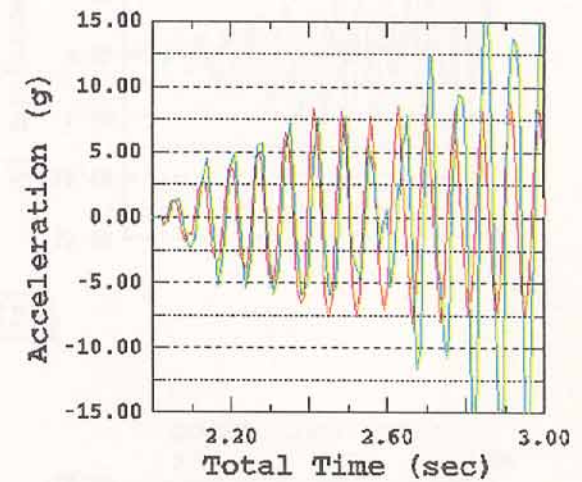


Temp:1

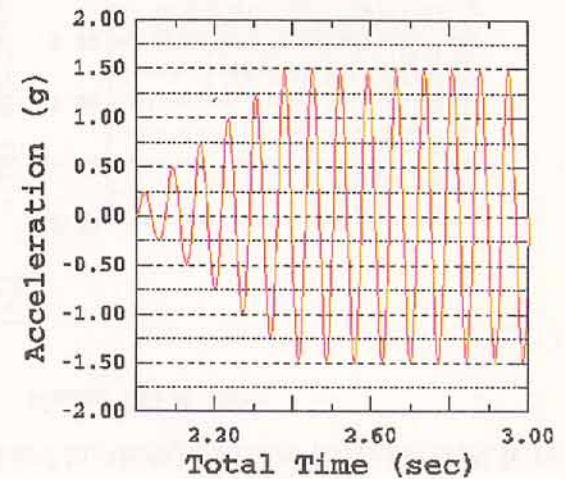


Accelerations Calculated in ABAQUS STANDARD & EXPLICIT
Node 373 @ Dam Crest on Crown Cantilever

Explicit A3 Node 373 g
STANDARD A3 Node 373 g



Temp:1



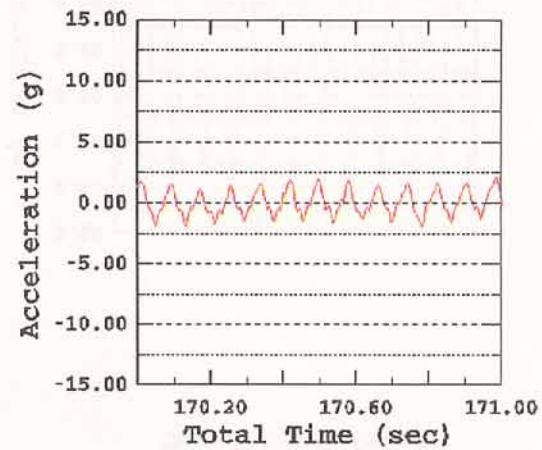
Monolithic
Model M2

Corresponding
Input Accelerations

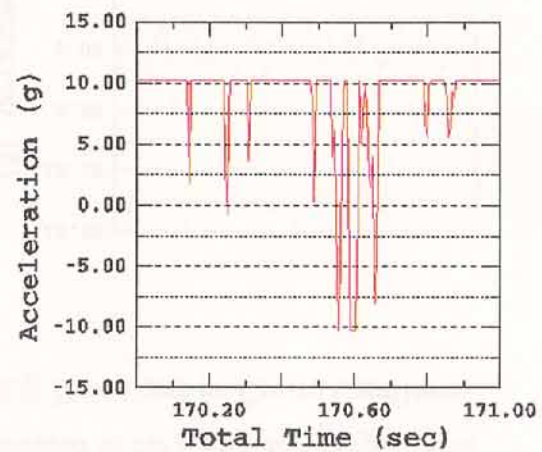
Accelerations Measured in the Laboratory Experiment

Accelerometers # 9 & 10

Temp-1



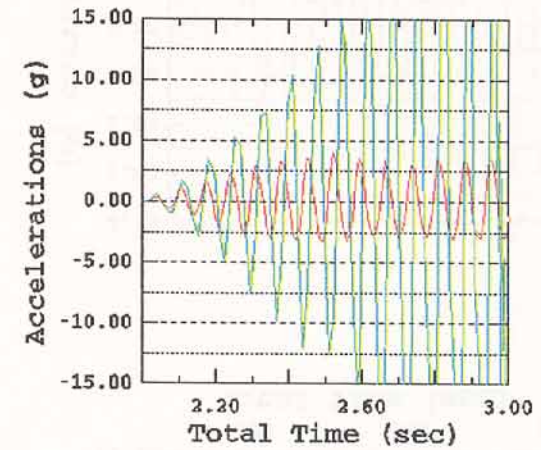
Temp-1



Accelerations Calculated in ABAQUS STANDARD/EXPLICIT

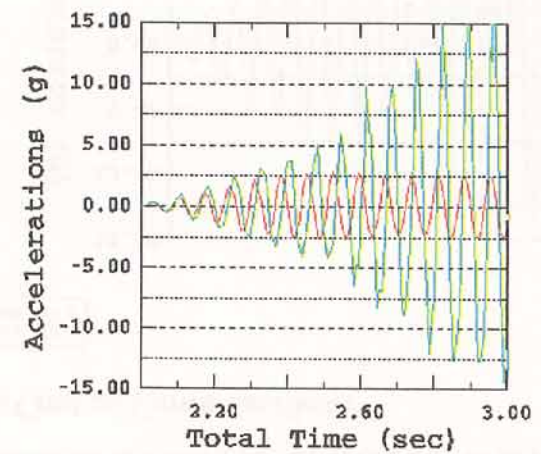
Nodes 533 & 2652

EXPLICIT Node 533 A3 g
STANDARD Node 533 A3 g



Monolithic
Model M2

EXPLICIT Node 2652 A3 g
STANDARD Node 2652 A3 g



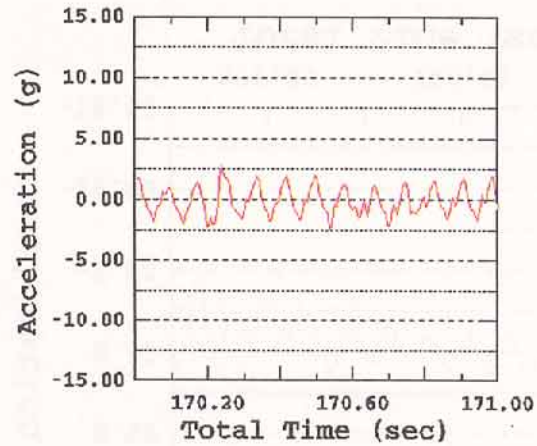
Accelerations Measured in the Laboratory Experiment

Accelerometers # 6 & 7

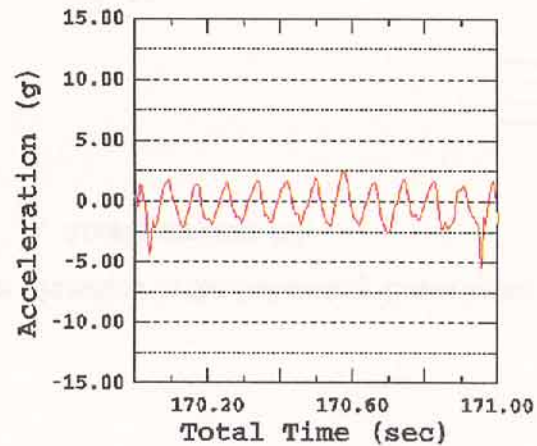
Accelerations Calculated in ABAQUS STANDARD/EXPLICIT

Nodes 3724 & 2492

Temp:1

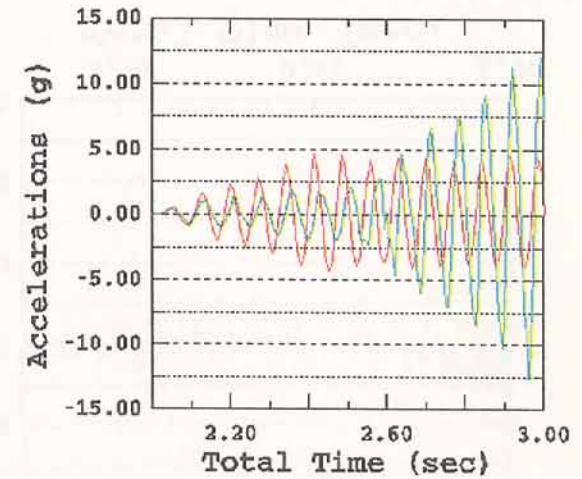


Temp:1

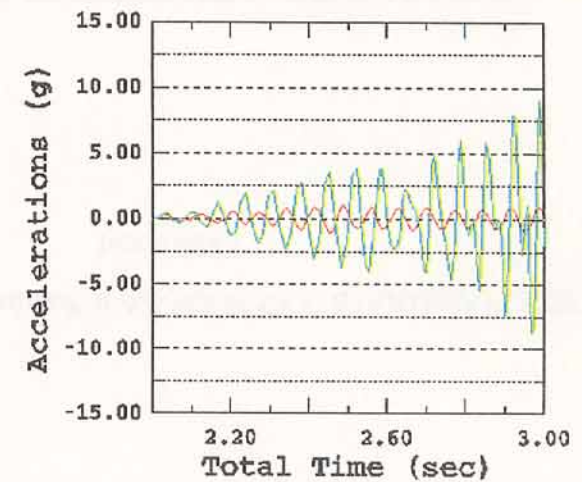


Monolithic
Model M2

EXPLICIT Node 2492 A3 g
STANDARD Node 2492 A3 g



EXPLICIT Node 3724 A3 g
STANDARD Node 3724 A3 g



Accelerations Measured in the Laboratory Experiment

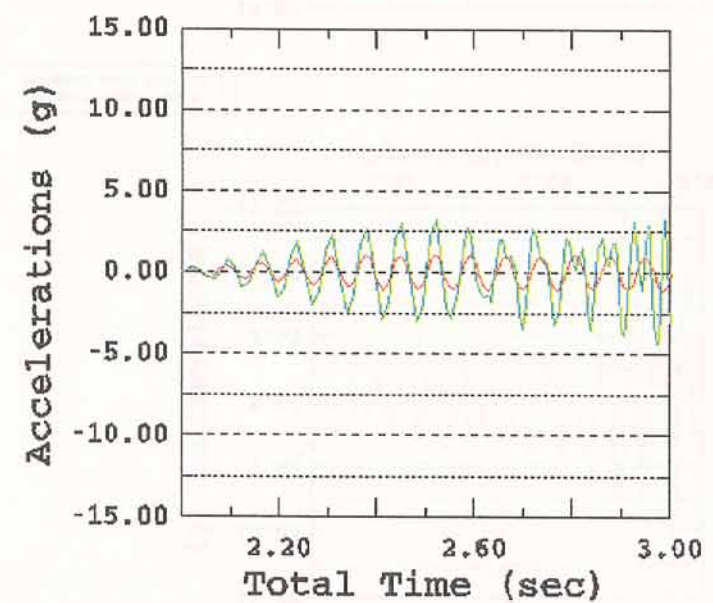
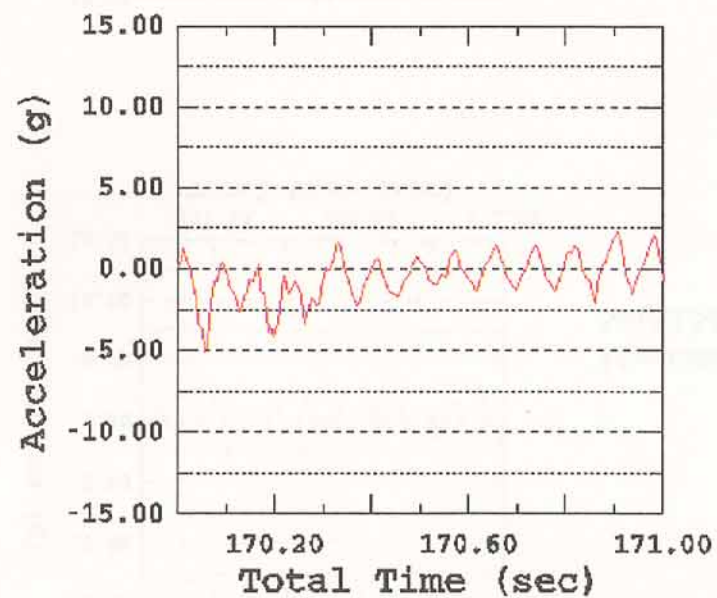
Accelerometers # 5

Accelerations Calculated in ABAQUS STANDARD/EXPLICIT

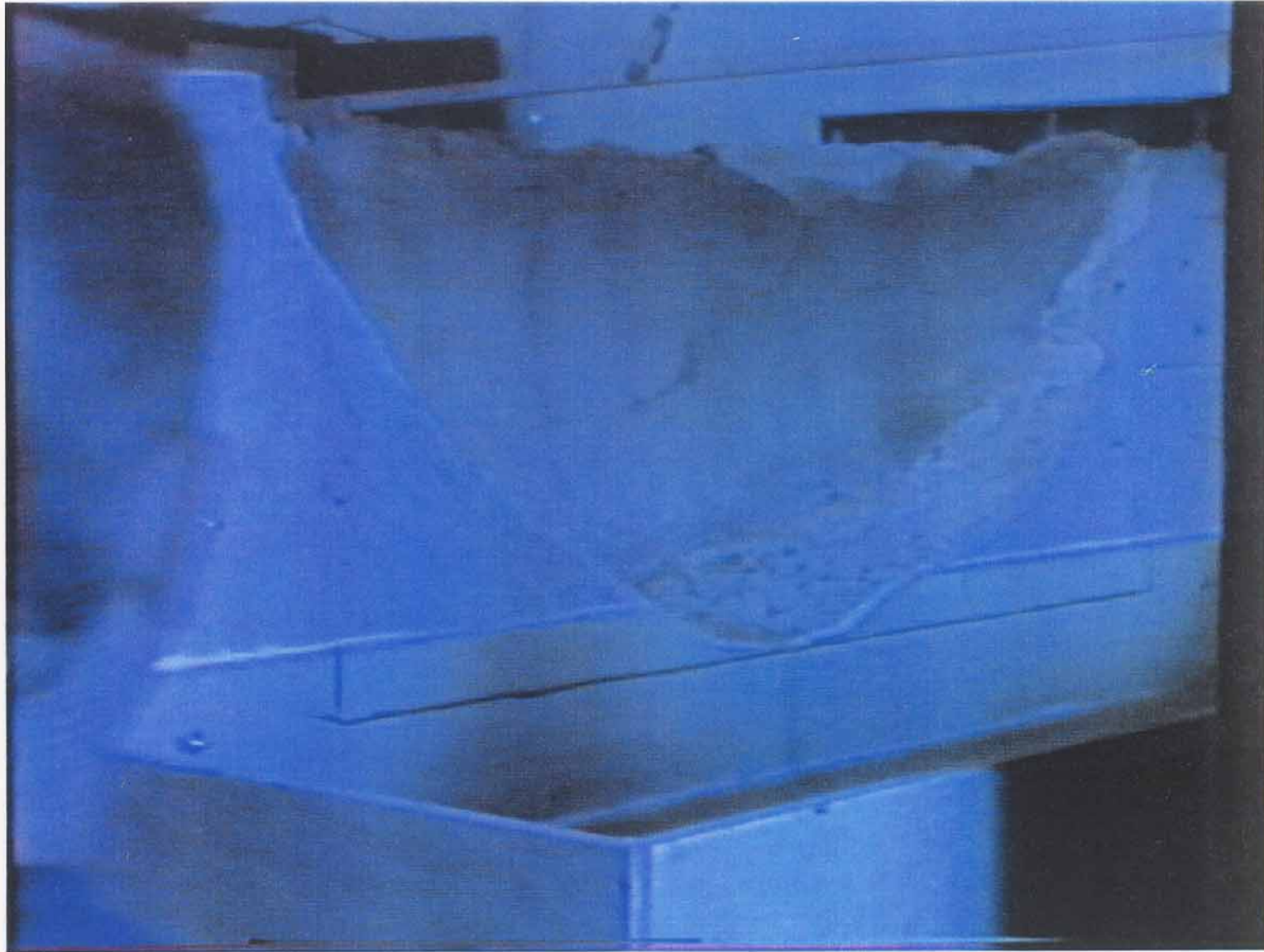
Node 4682

Temp-1

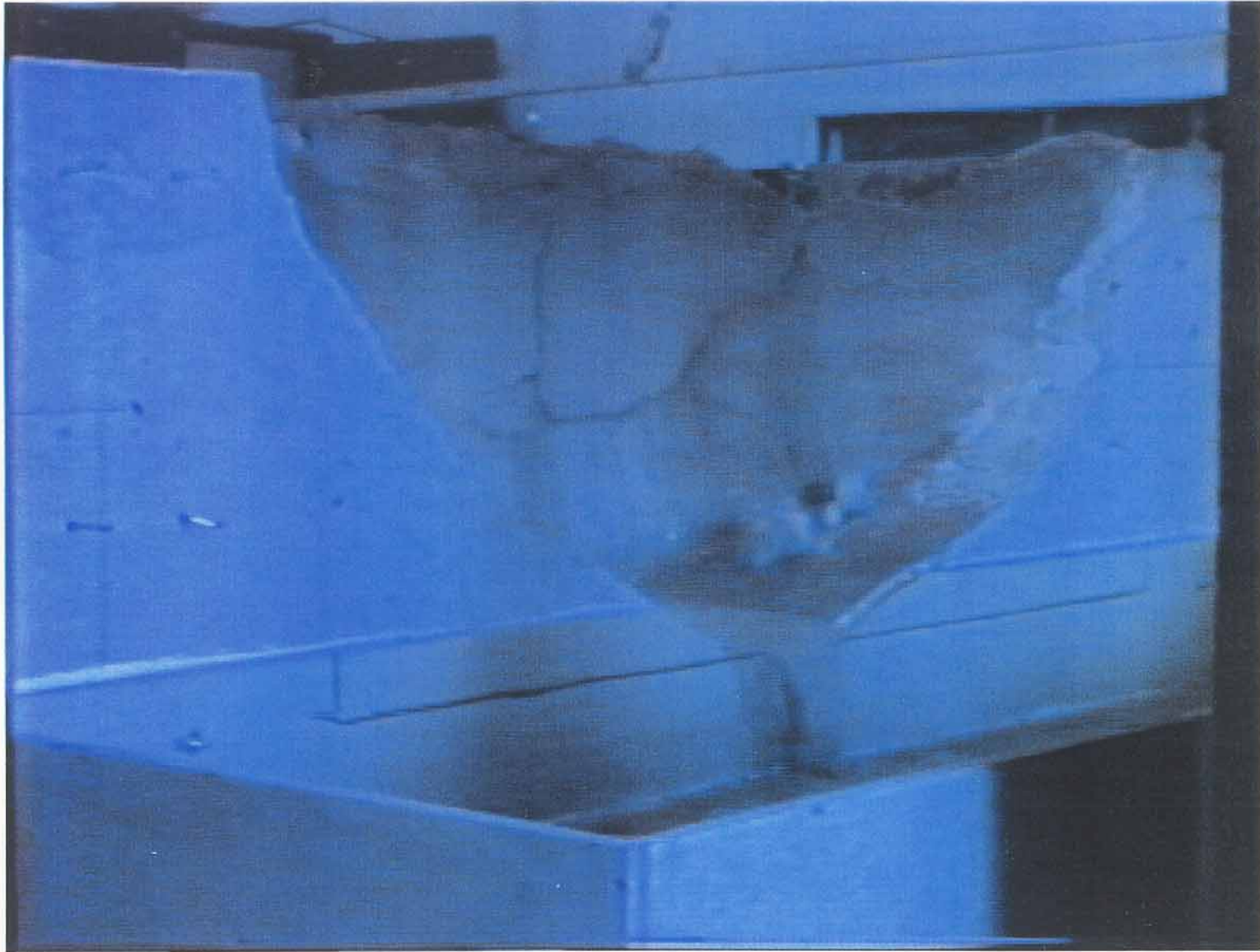
EXPLICIT Node 4682 A3 g
STANDARD Node 4682 A3 g



Monolithic
Model M2



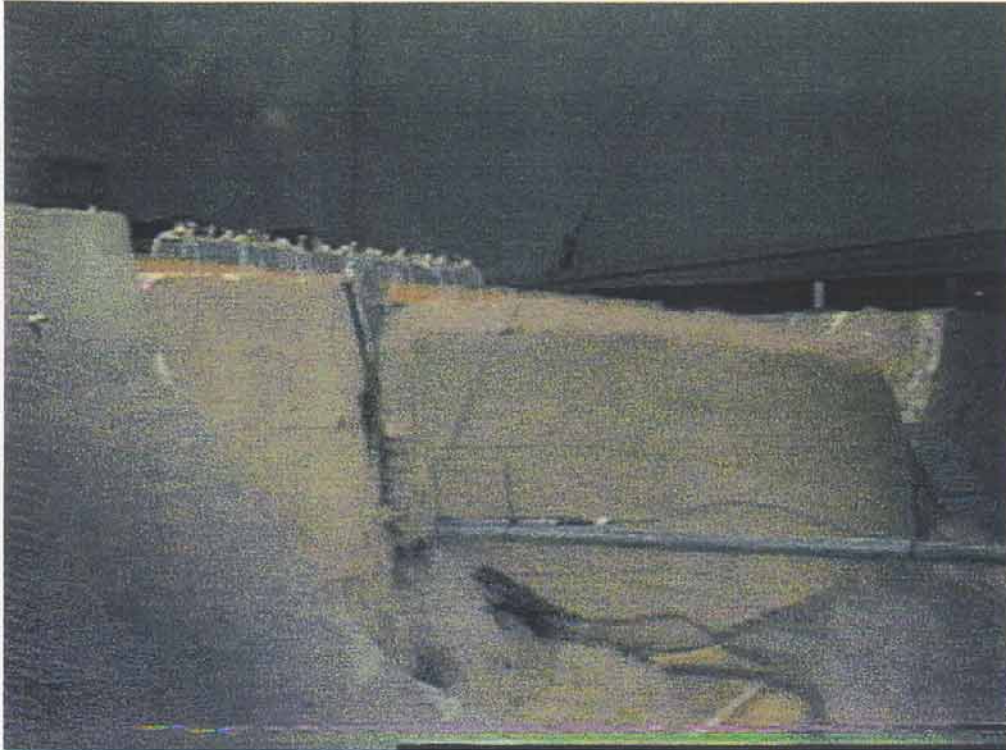
Initial Crack Pattern - Model M2 - Test Date 3/31/99



Crack Pattern - Model M2 - Test Date 3/31/99



Final Crack Pattern - Model M2 - Test Date 3/31/99



Model M8 -- 6/21/00 South view, final failure



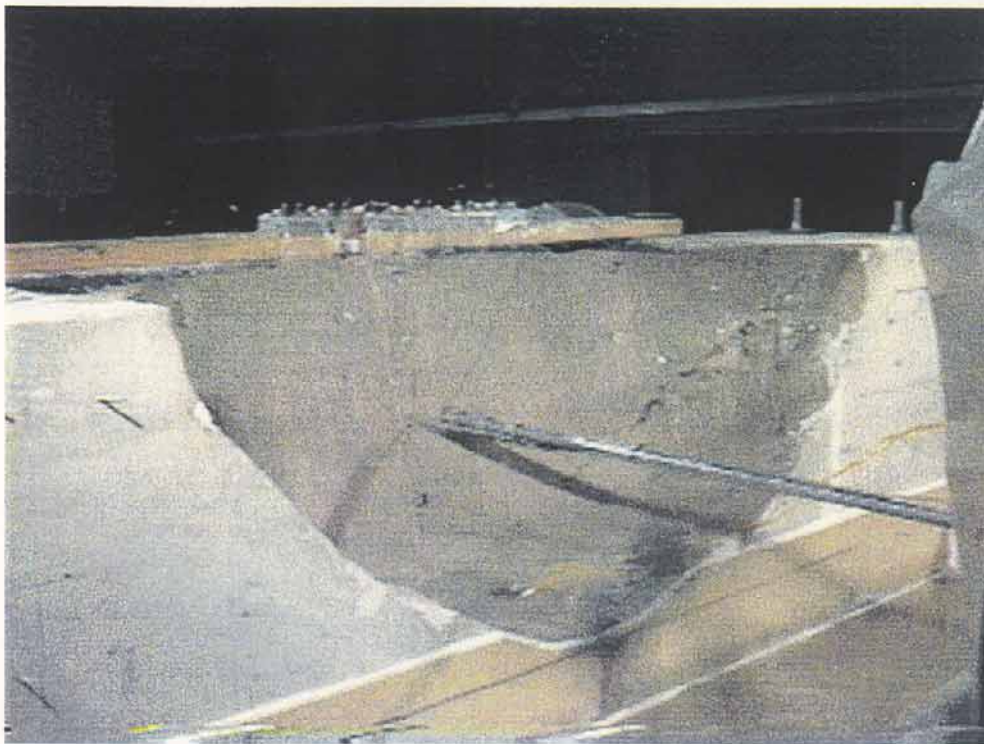
Model M8 -- 6/21/00, South view, initial cracking



Model M8 -- 6/21/00, North view, final failure



Model M8 -- 6/21/00 North view, initial cracking

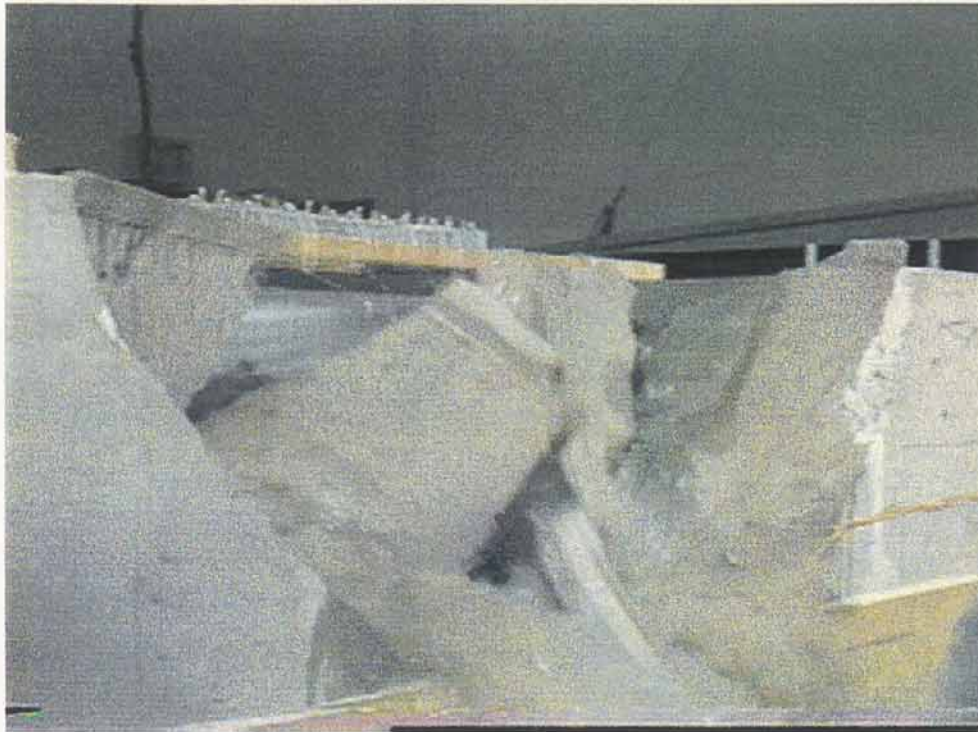


Model M6 -- August 27, 2000 -- South, initial cracking

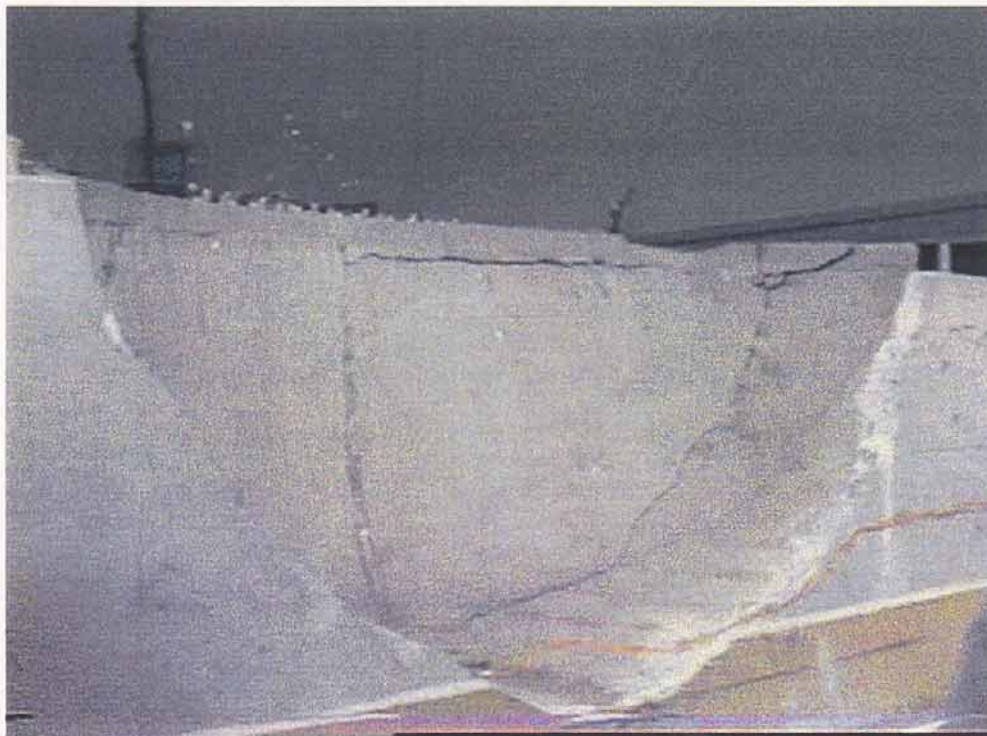


Model M6 -- August 27, 1999 -- South, final failure

Figure D.6



Model M11 -- 8/22/00 South view, final failure



Model M11 -- 8/22/00 South view, initial cracking



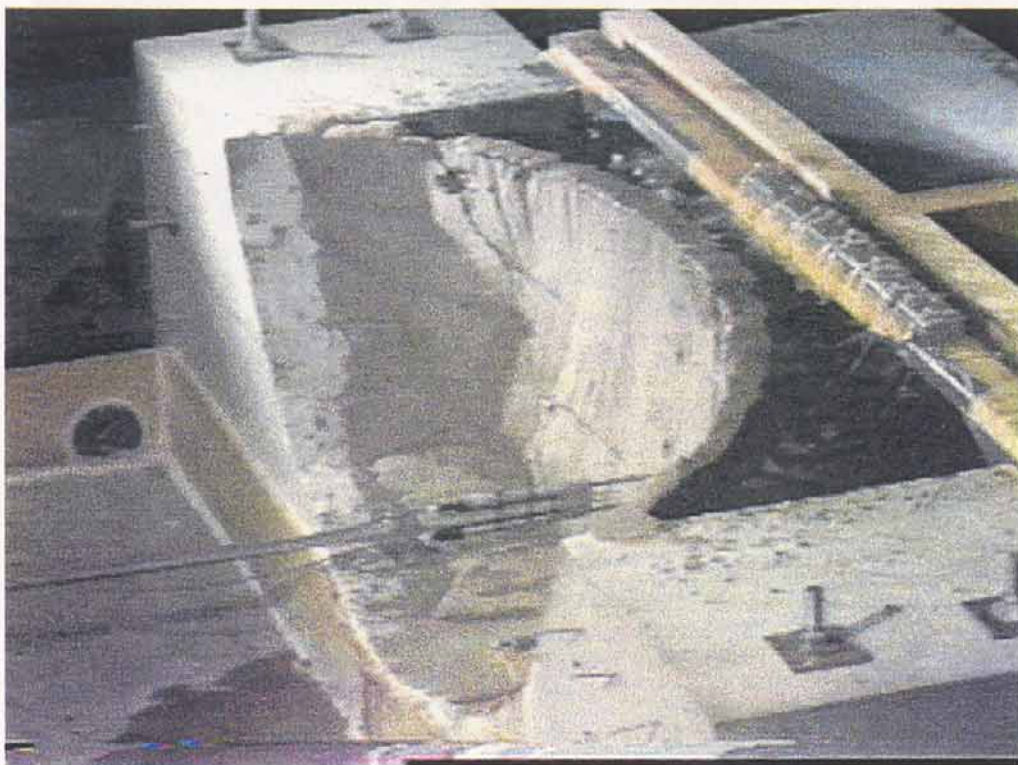
Model M11 -- 8/22/00 North view, final failure



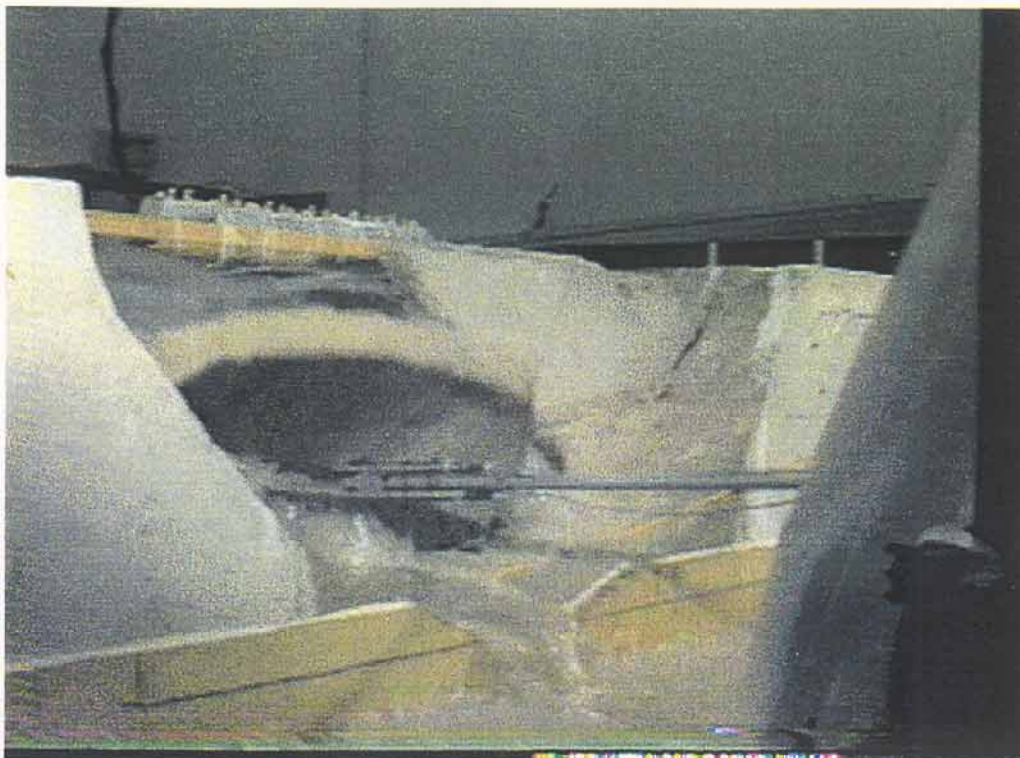
Model M11 -- 8/22/00 North view, initial cracking



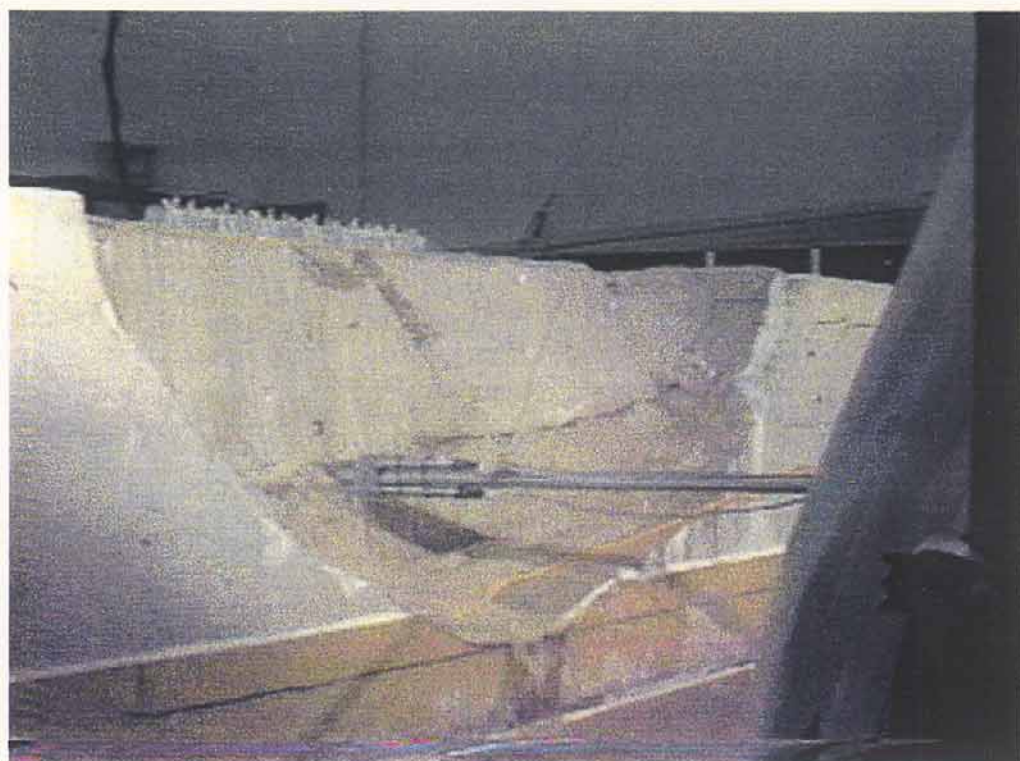
Model M9 -- 7/19/00 North view, final failure



Model M9 -- 7/19/00 North view, initial cracking



Model M9 -- 7/19/00, South view - final failure



Model M9 -- 7/19/00, South view, initial cracking



Model M10 -- 8/2/00, North view, initial cracking



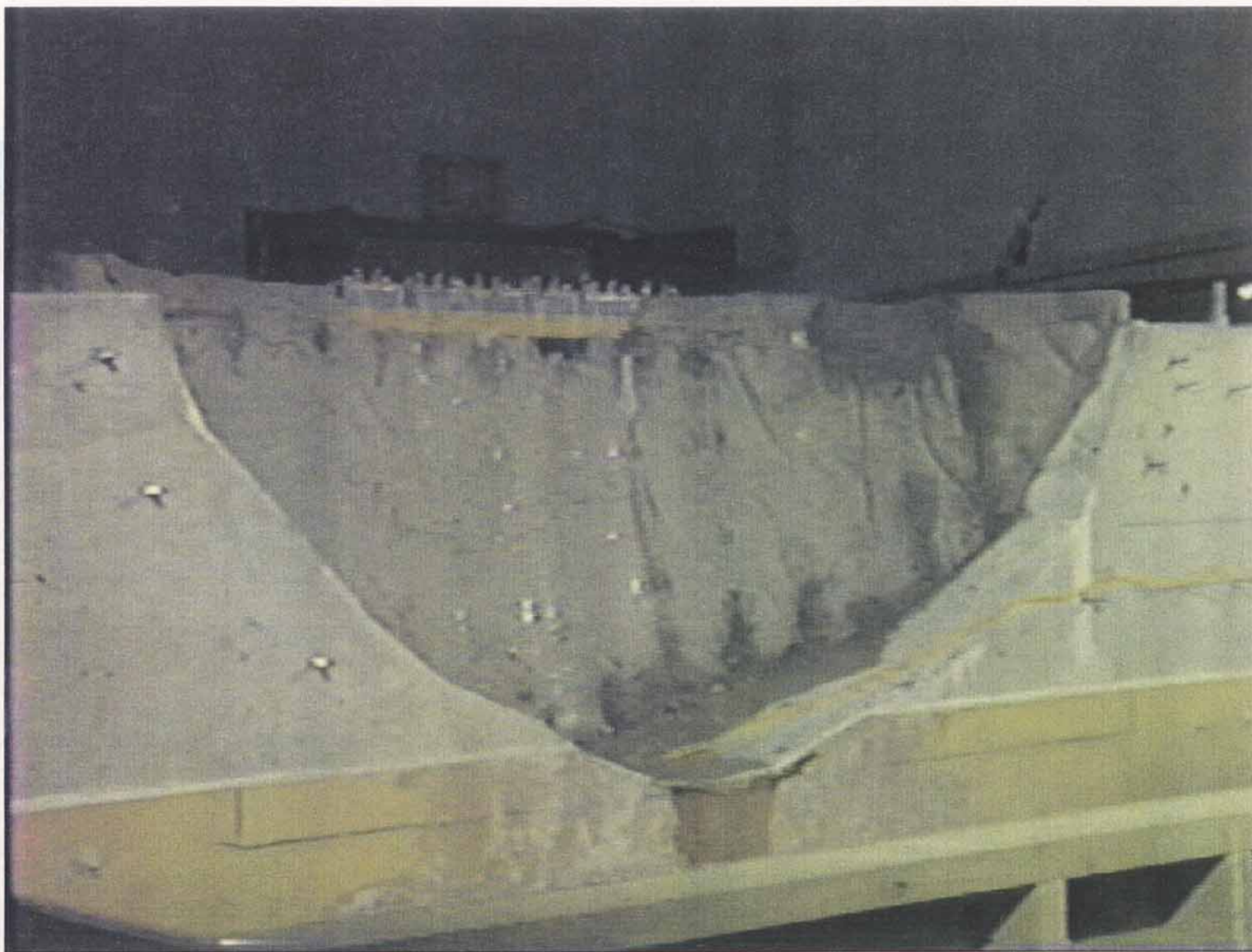
Model 10 -- 8/2/00 North view, final failure



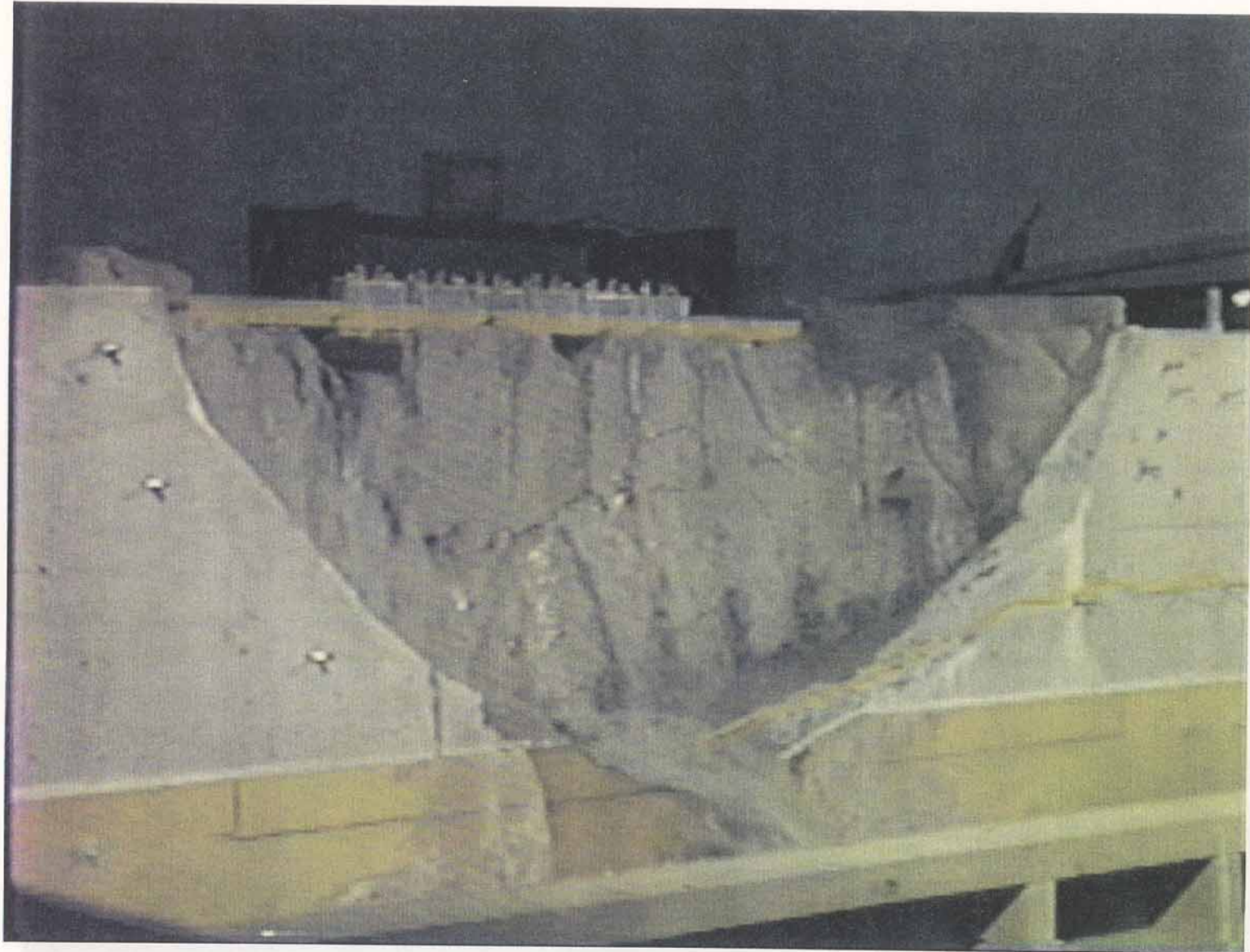
Model M10 – 8/2/00, South view camera final failure



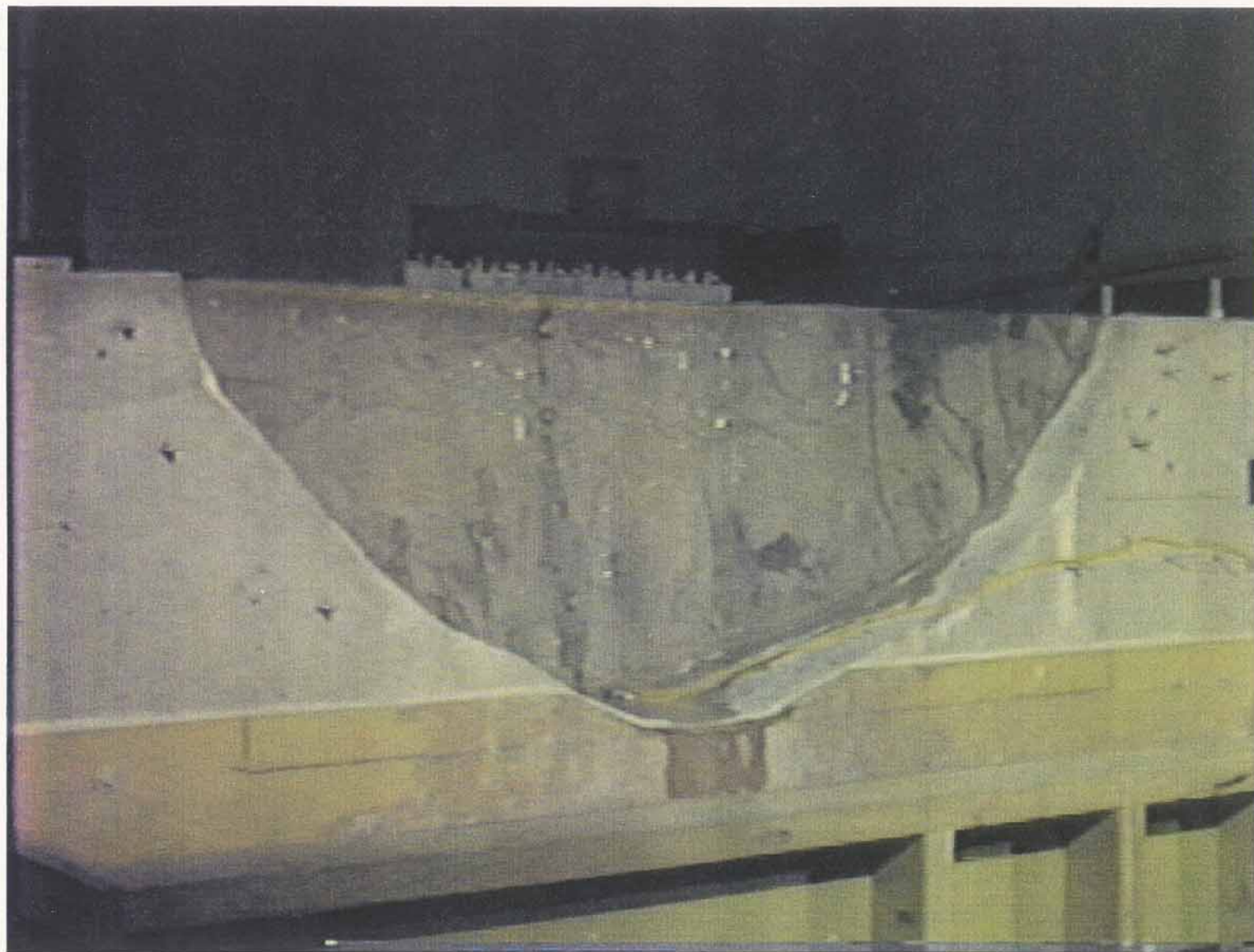
Model M10 – 8/2/00, South view camera initial cracking



Initial Crack Pattern – Model M13 – Test Date 4/10/01



Final Crack Pattern – Model M13 – Test Date 4/10/01



Initial Crack Pattern – Model M15 – Test Date 5/1/01

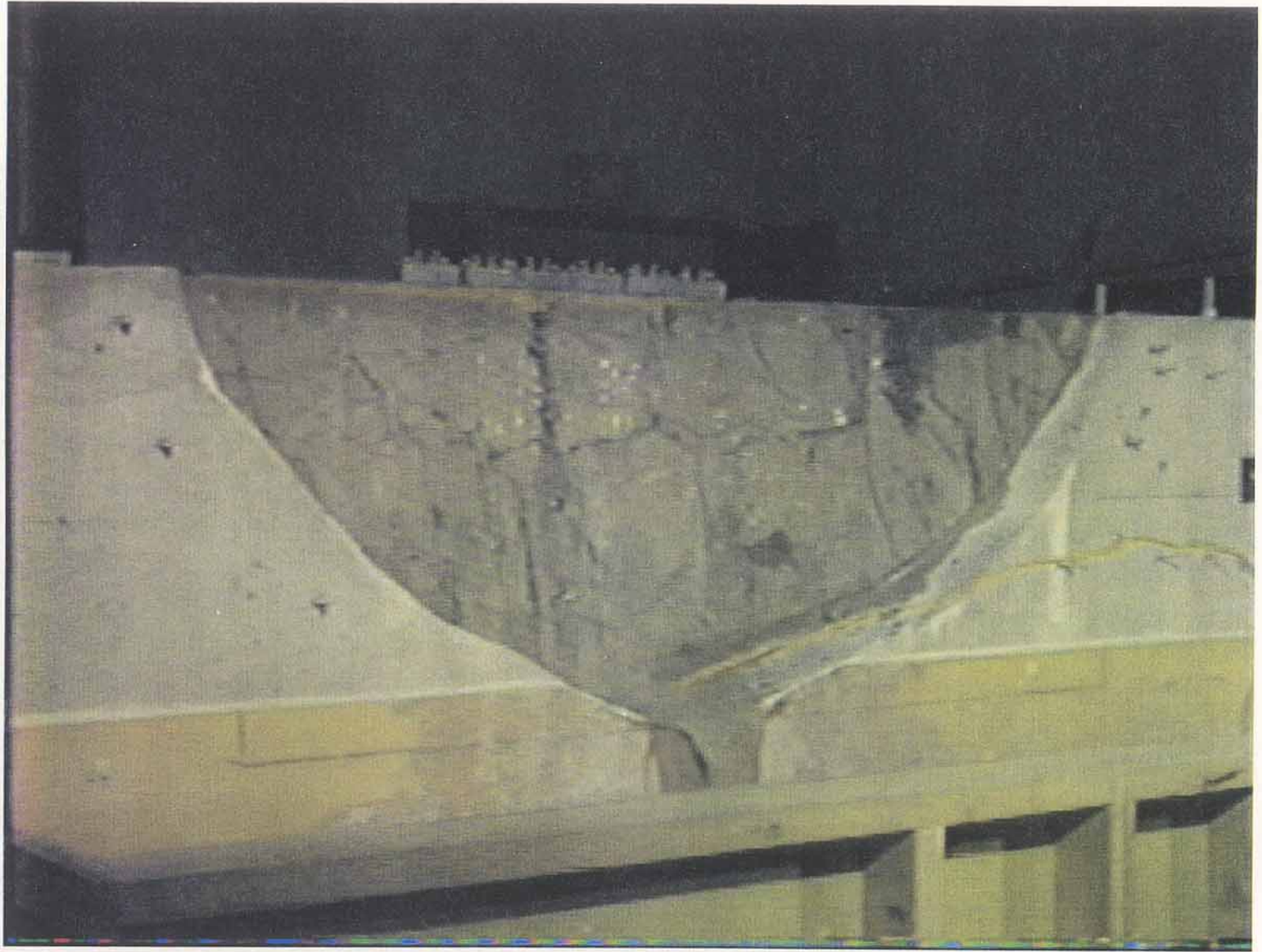


Figure D.16

5.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

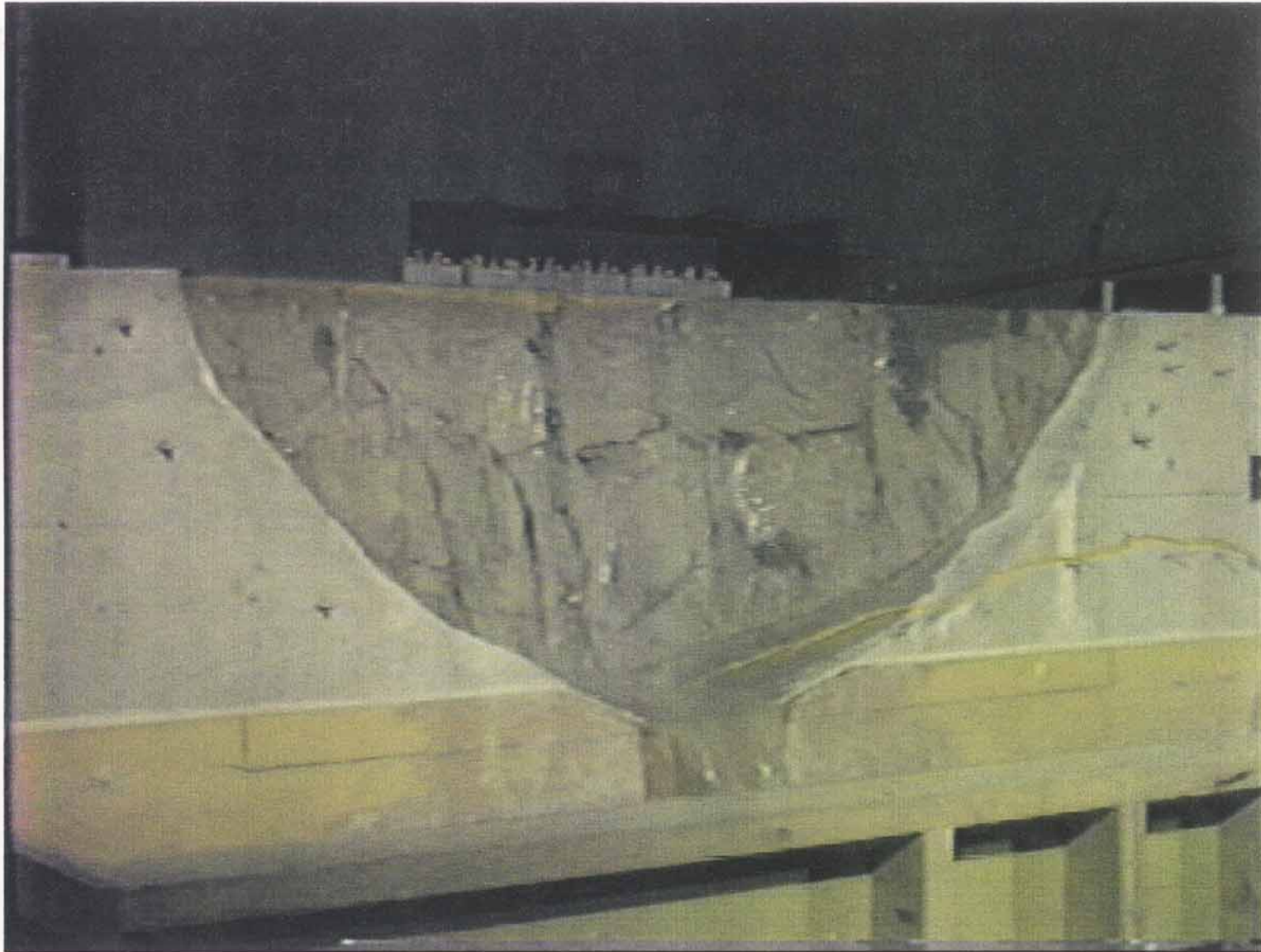


Figure D.17

8.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

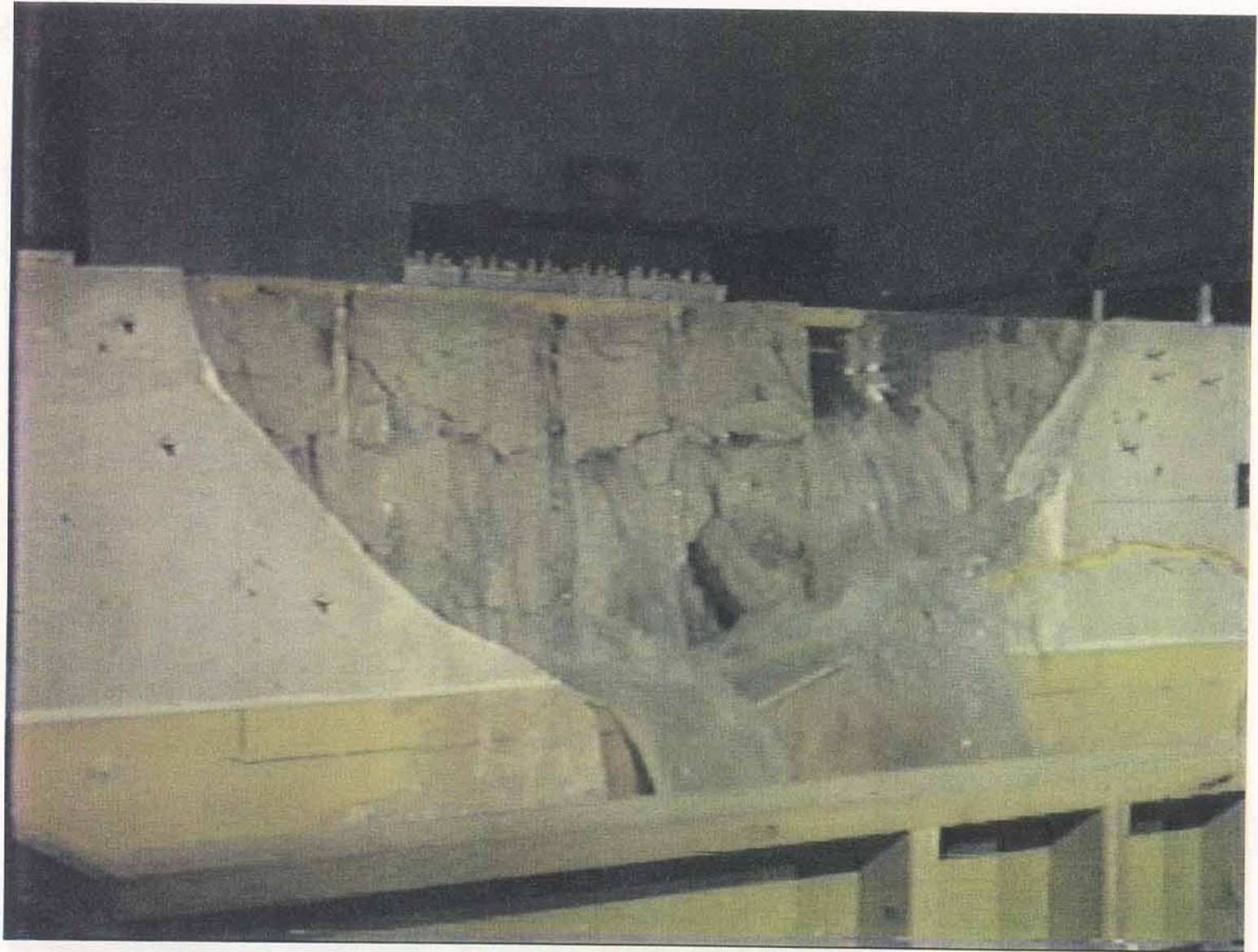


Figure D.18

11.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

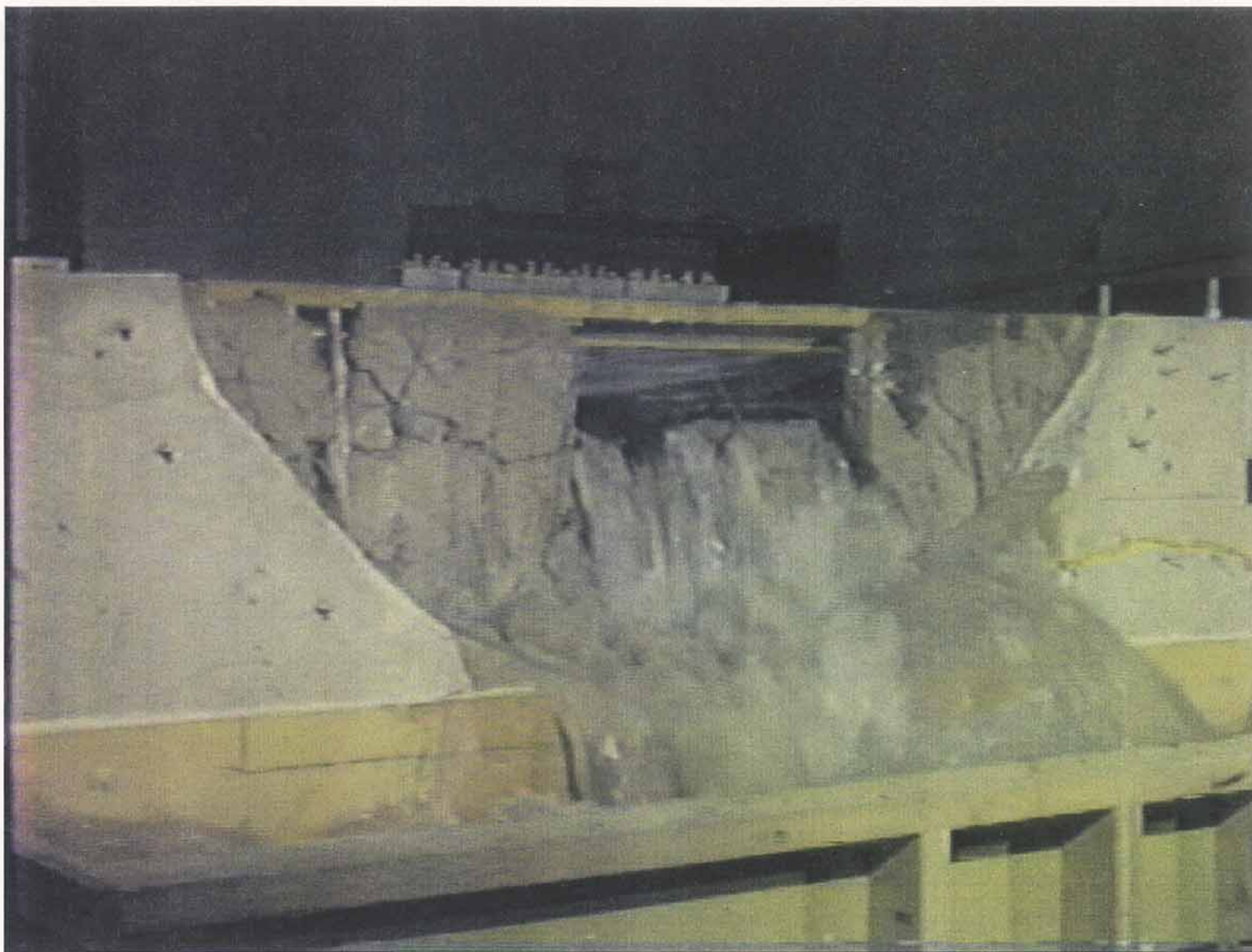


Figure D.19

12.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

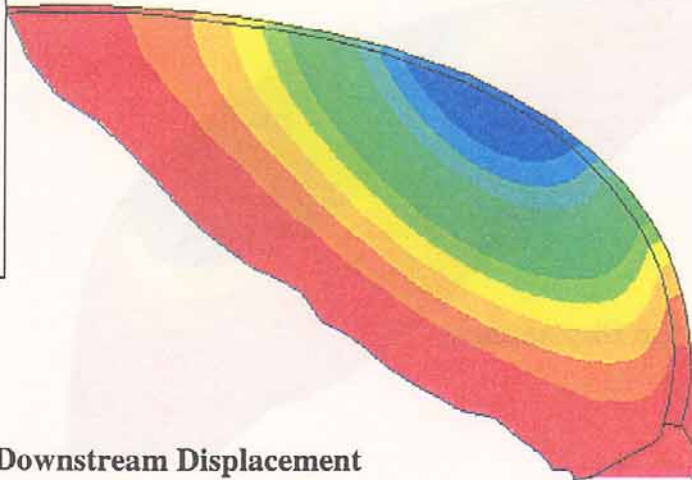
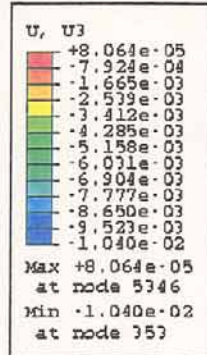


Figure D.20

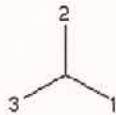
14.0 seconds After Initial Cracking – Model M15 – Test Date 5/1/01

Monolithic Model : M2 & M8

Viewport: 1 ODB: /dr6/tpayne/nf_shake/m2m8grx.odb



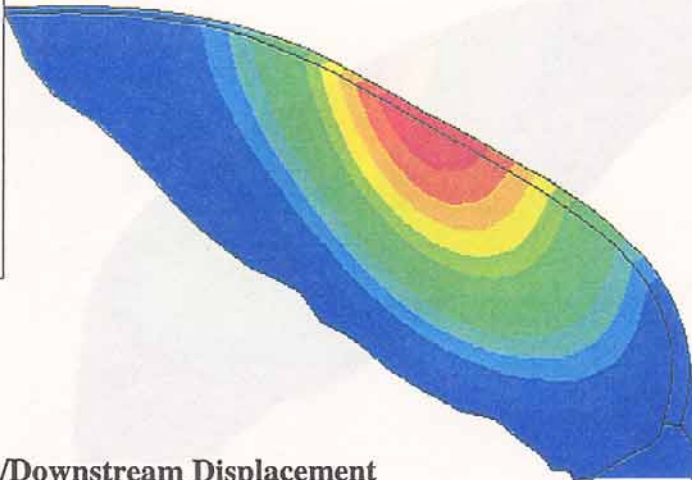
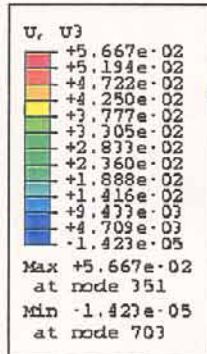
Upstream/Downstream Displacement
Gravity Load



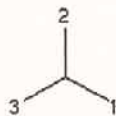
ODB: m2m8grx.odb ABAQUS/Explicit 6.1.1 Wed Jul 18 08:14:04 MDT 2001

Step: Step-2 apply gravity Increment 19162; Step Time = 1.000
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport: 1 ODB: /dr6/tpayne/nf_shake/m2m8grx.odb



Upstream/Downstream Displacement
Gravity + Reservoir Load



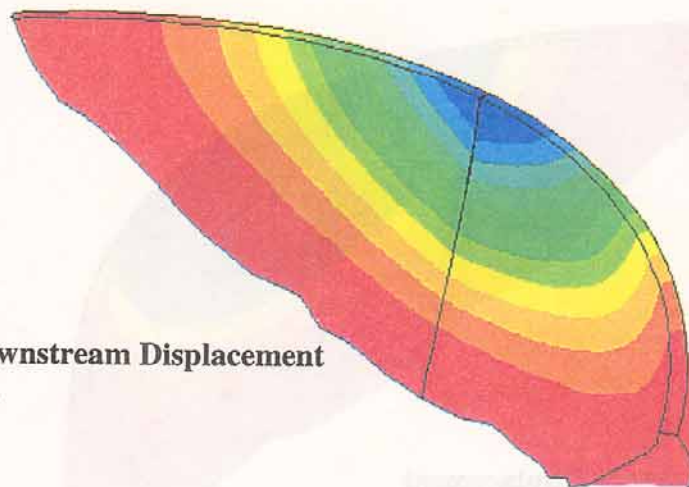
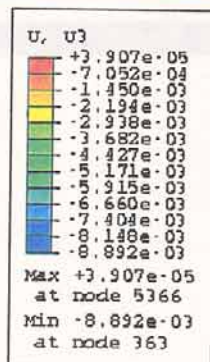
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Step: Step-4 apply reservoir Increment 28744; Step Time = 1.500
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

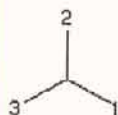
Figure E.1

Single Vertical Joint Model : M6 & M11

Viewport: 1 ODB: /dr6/tpayne/m6m11/m6m11grx1.odb

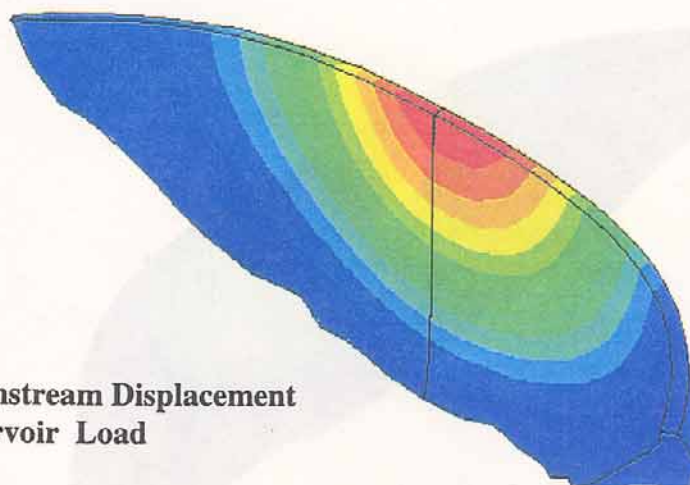
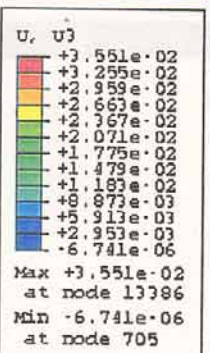


Upstream/Downstream Displacement
Gravity Load

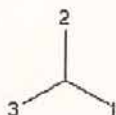


Job created 3-5-01
ODB: m6m11grx1.odb ABAQUS/Explicit 6.1.1 Wed Aug 15 07:12:25 MDT 2001
Step: Step-2 apply gravity Increment 24482; Step Time = 1.000
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport: 1 ODB: /dr6/tpayne/m6m11/m6m11grx1.odb



Upstream/Downstream Displacement
Gravity + Reservoir Load



Job created 3-5-01
ODB: m6m11grx1.odb ABAQUS/Explicit 6.1.1 Wed Aug 15 07:12:25 MDT 2001
Step: Step-4 apply reservoir Increment 36723; Step Time = 1.500
Primary Var: U, U3
Deformed Var: U Deformation Scale Factor: +1.000e+02

Figure E.2

Single Horizontal Joint Model : M9 & M10

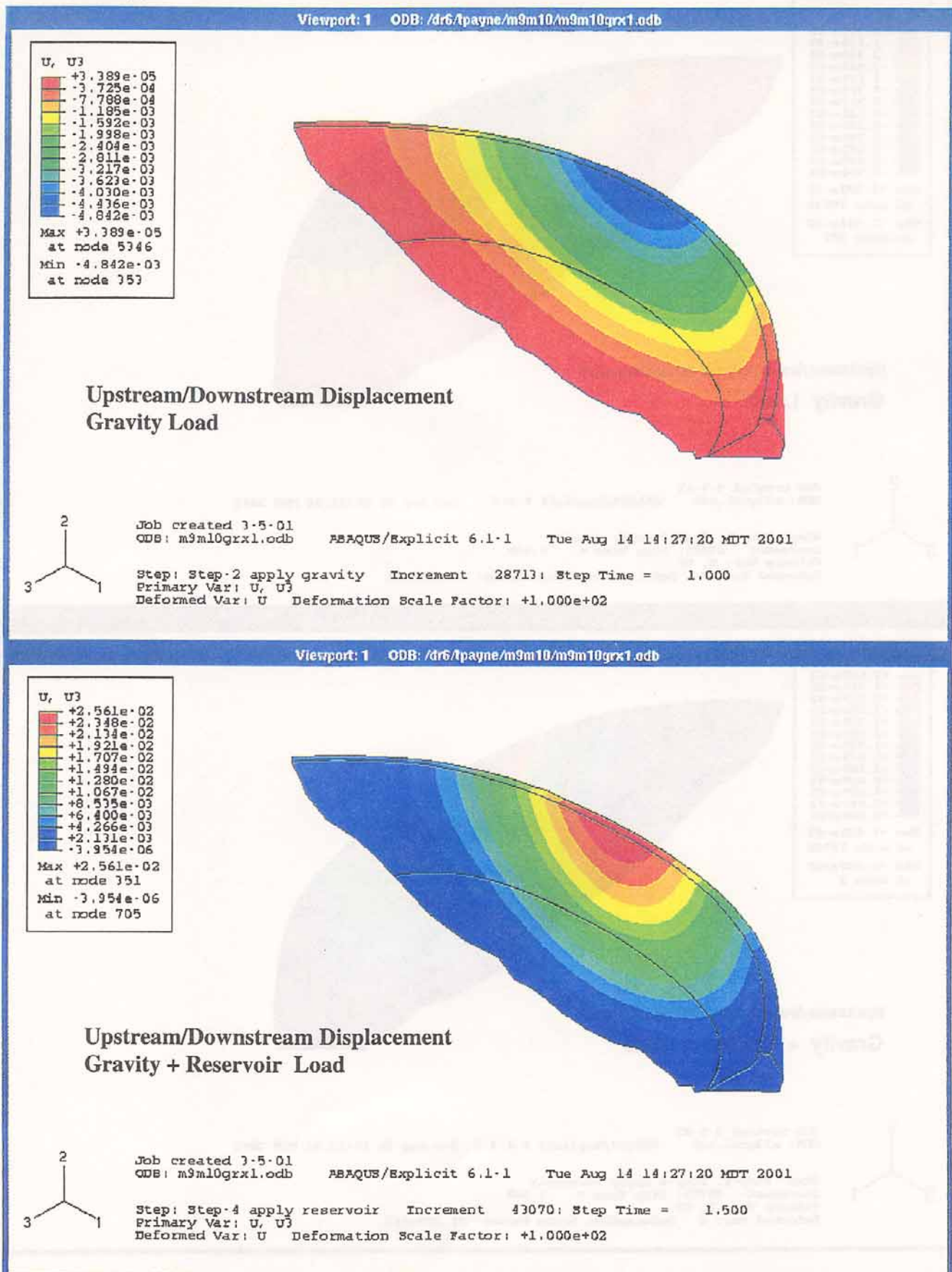


Figure E.3

Seventeen Vertical Joint Model : M12 & M13

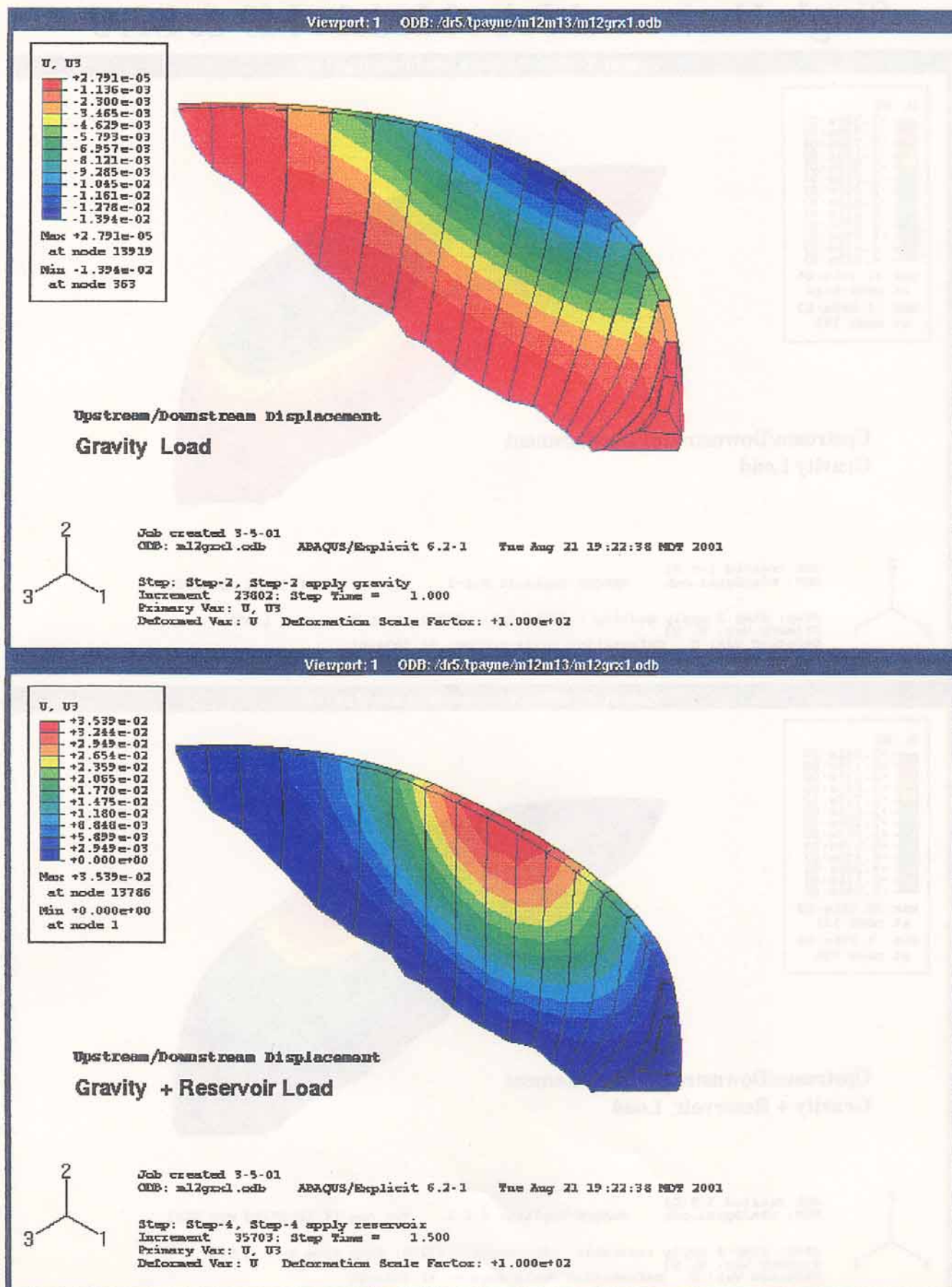


Figure E.4

Seventeen Vertical & Two Horizontal Joint Model M14 & M15

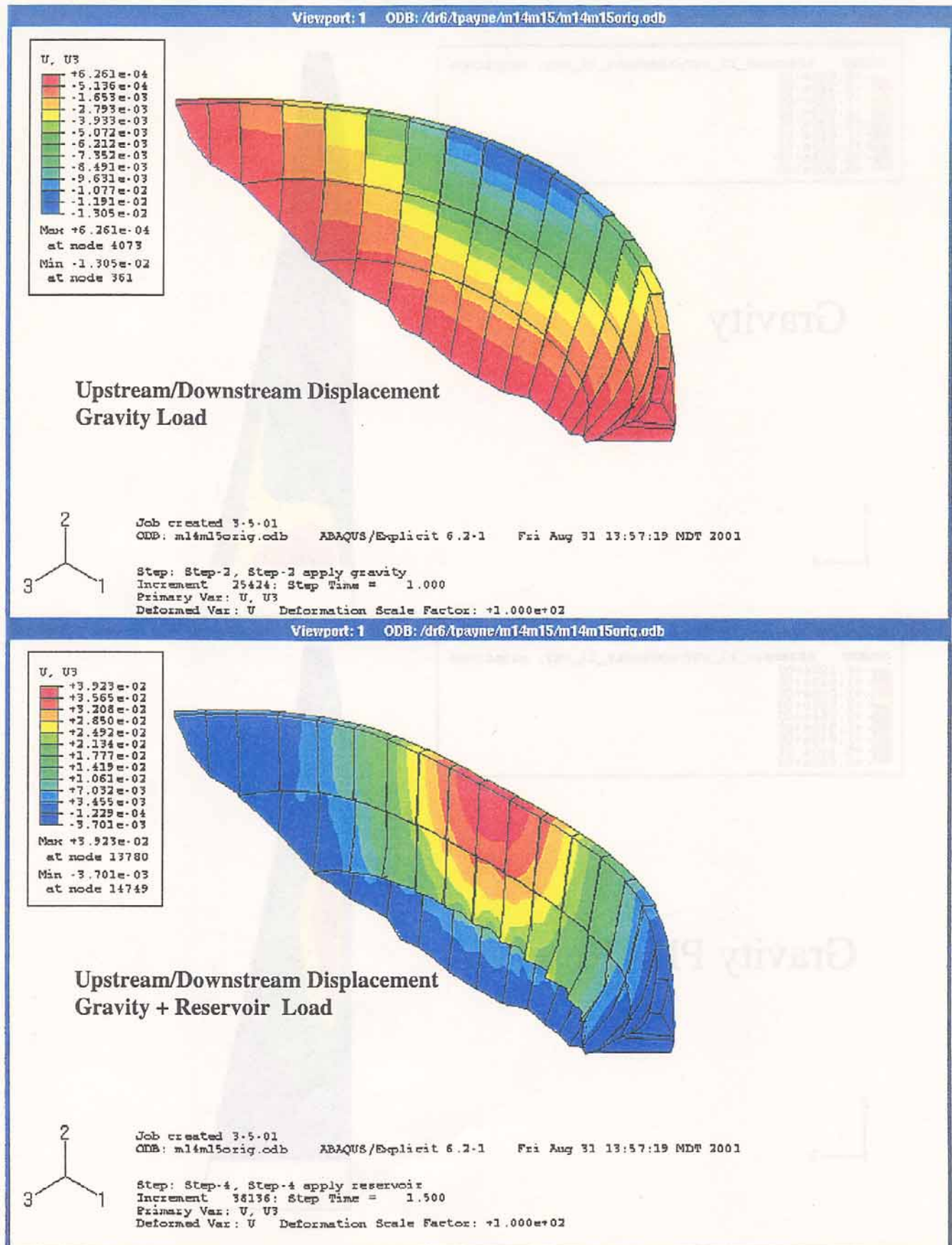
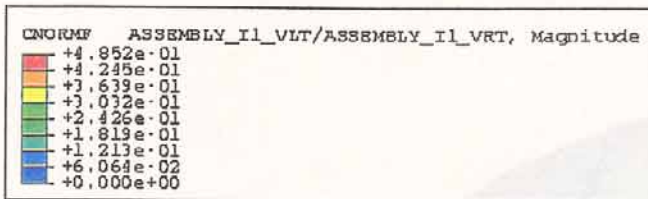


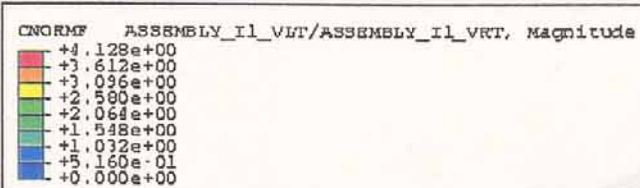
Figure E.5

Single Vertical Joint Model : M6M11

Force on Contact Surface



Gravity



Gravity Plus Reservoir

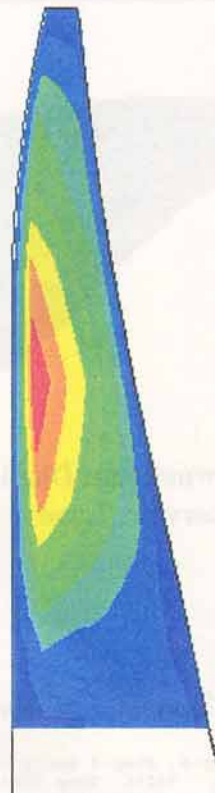
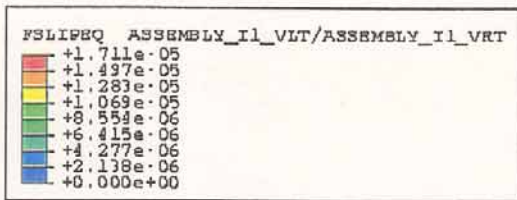


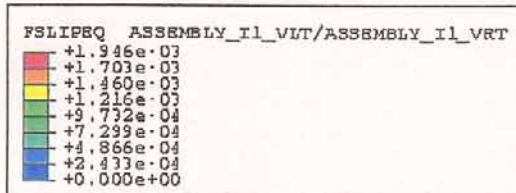
Figure E.6

Single Vertical Joint Model : M6M11

Slip Magnitude on Contact Surface



Gravity



Gravity Plus Reservoir

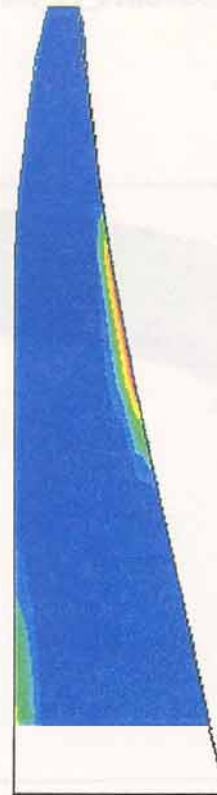
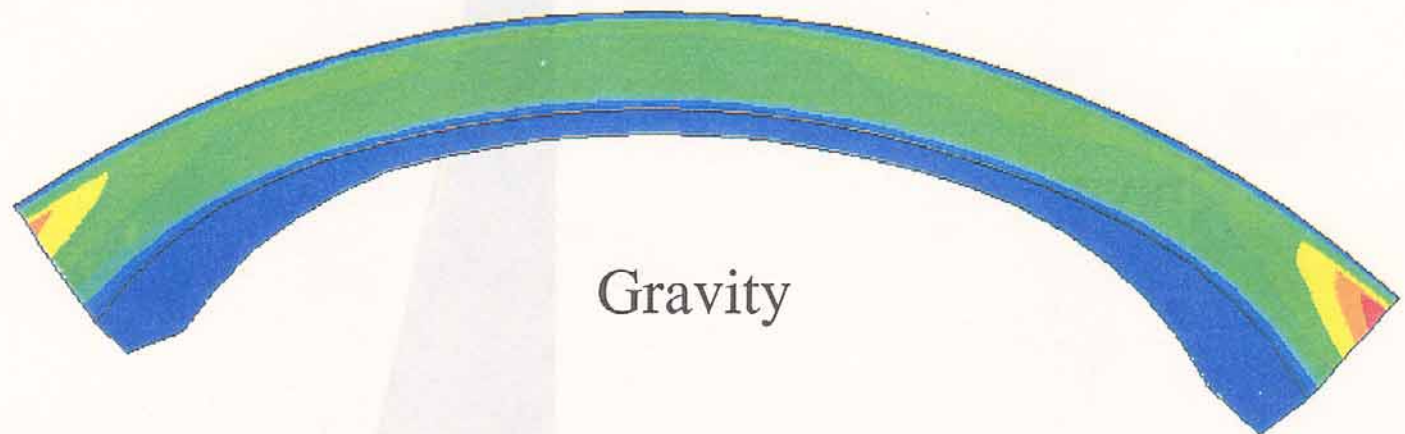
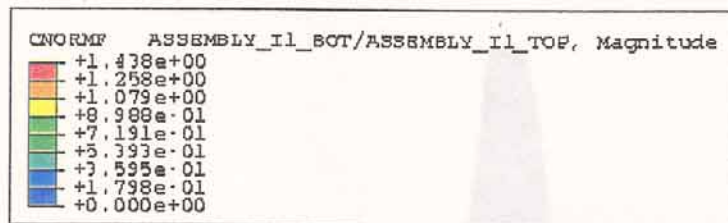


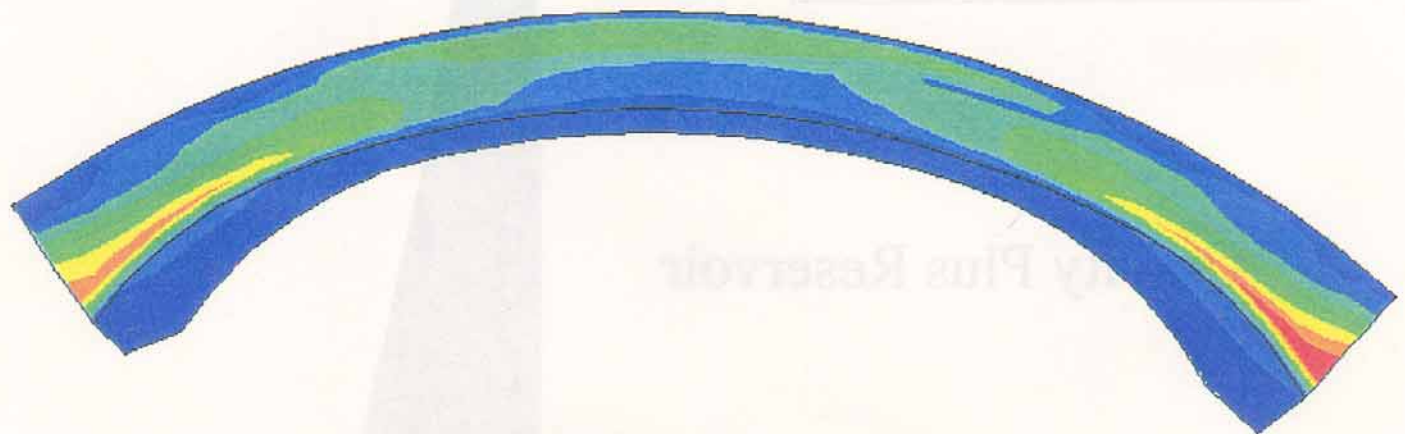
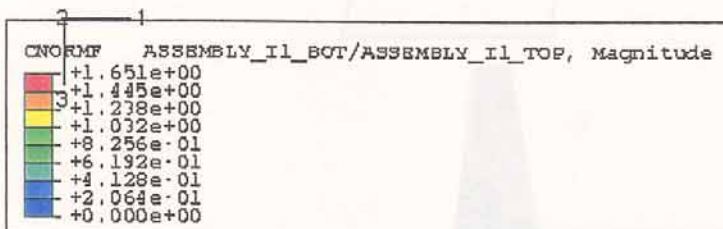
Figure E.7

Single Horizontal Joint Model : M9M10

Force on Contact Surface



Gravity



Gravity Plus Reservoir

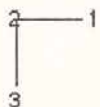
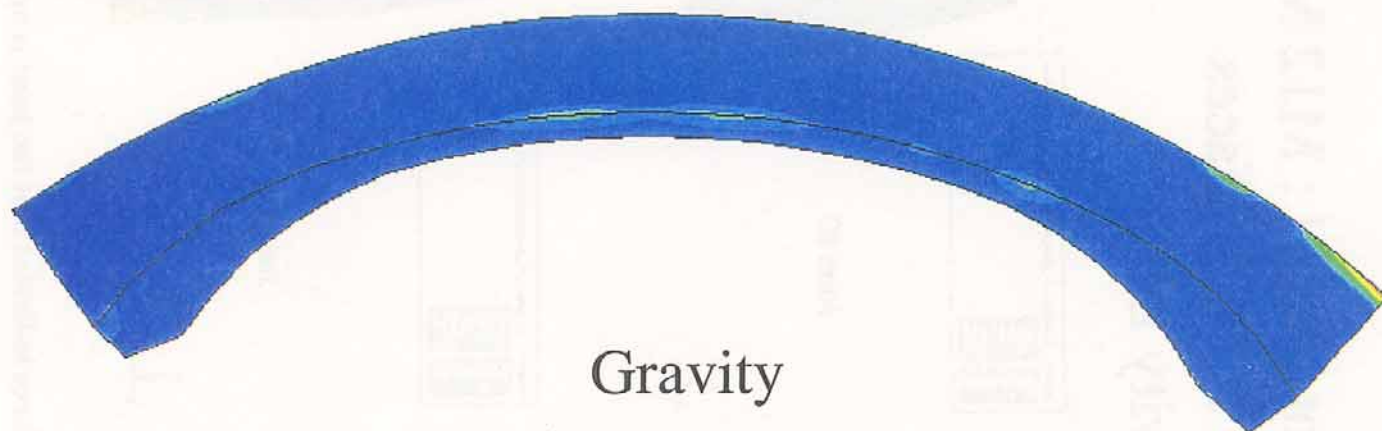
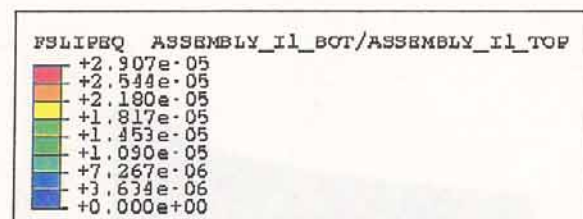


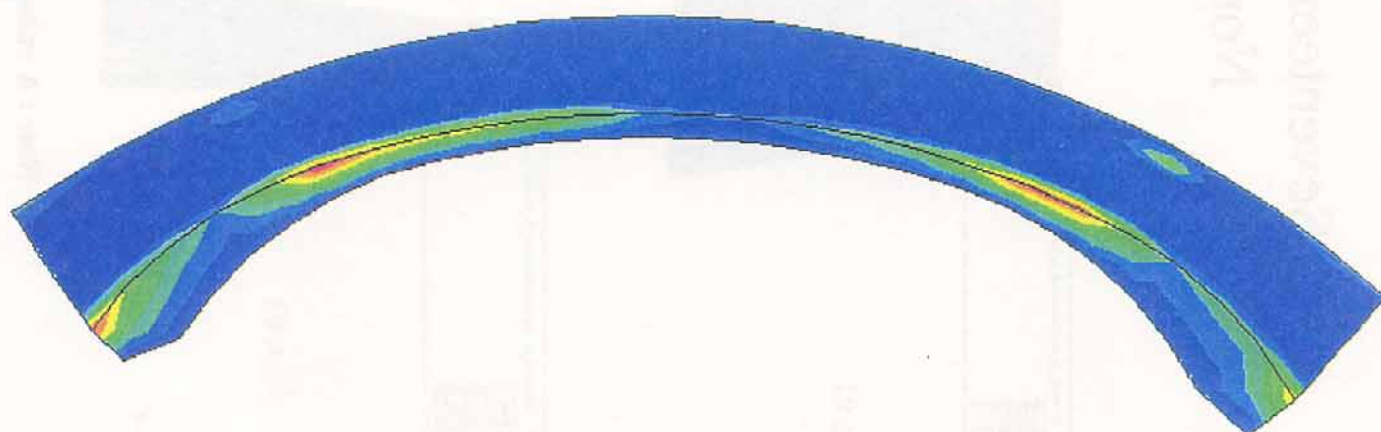
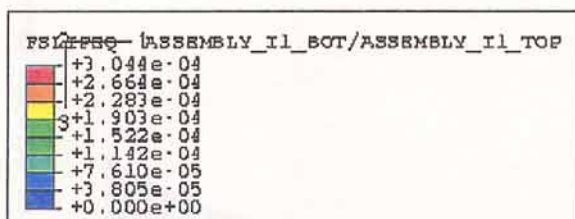
Figure E.8

Single Horizontal Joint Model : M9M10

Slip Magnitude on Contact Surface



Gravity



Gravity Plus Reservoir

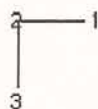
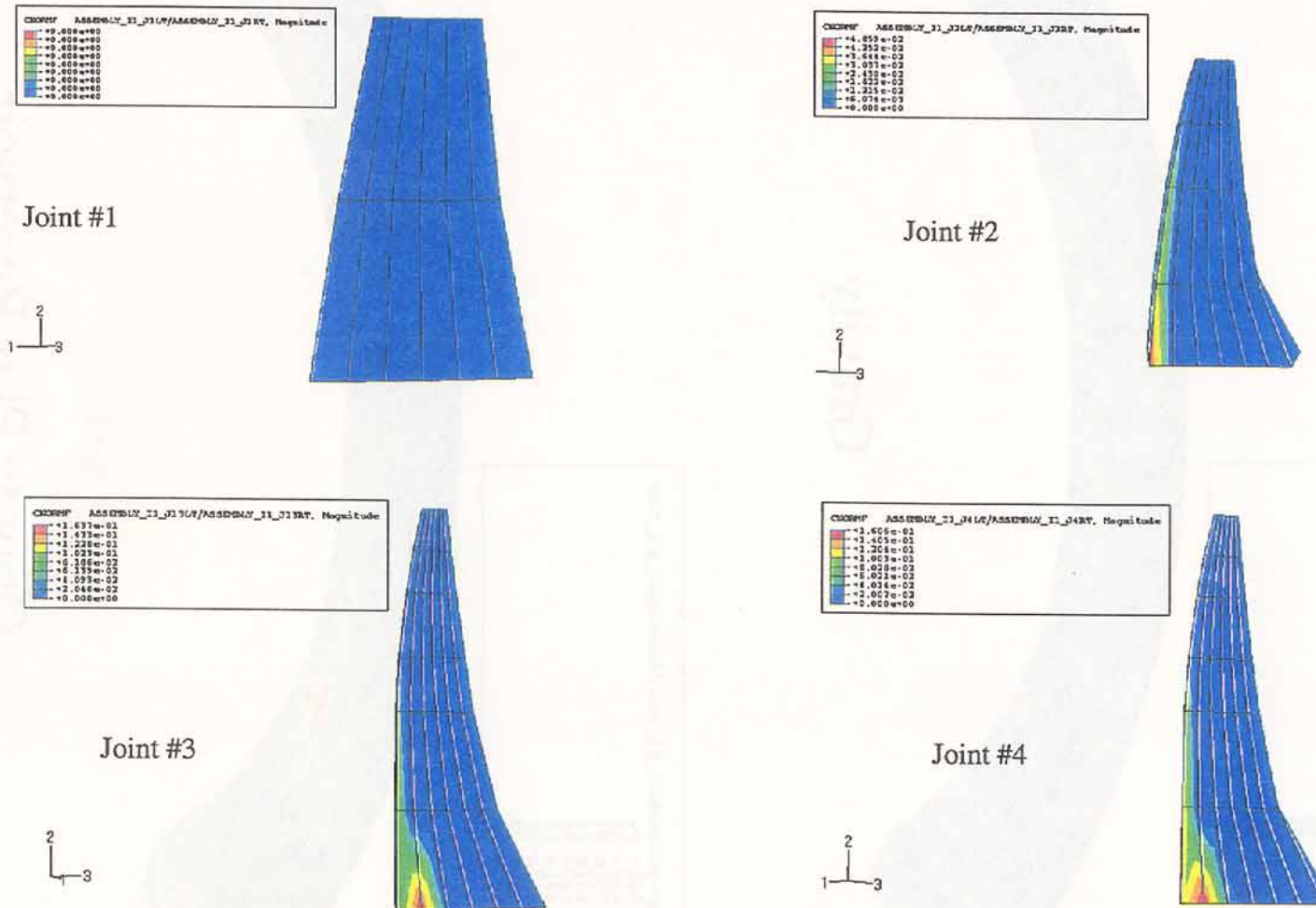


Figure E.9

Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity Load



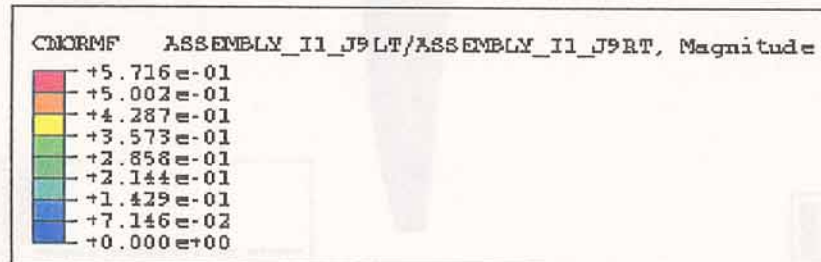
Note : A value of zero for the contact force indicates that the joint is open.

Figure E.10

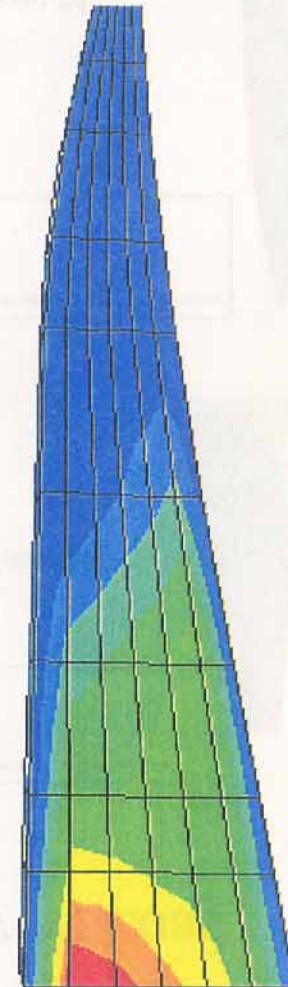
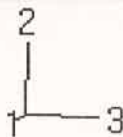
Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity Load



Joint #9
Center joint

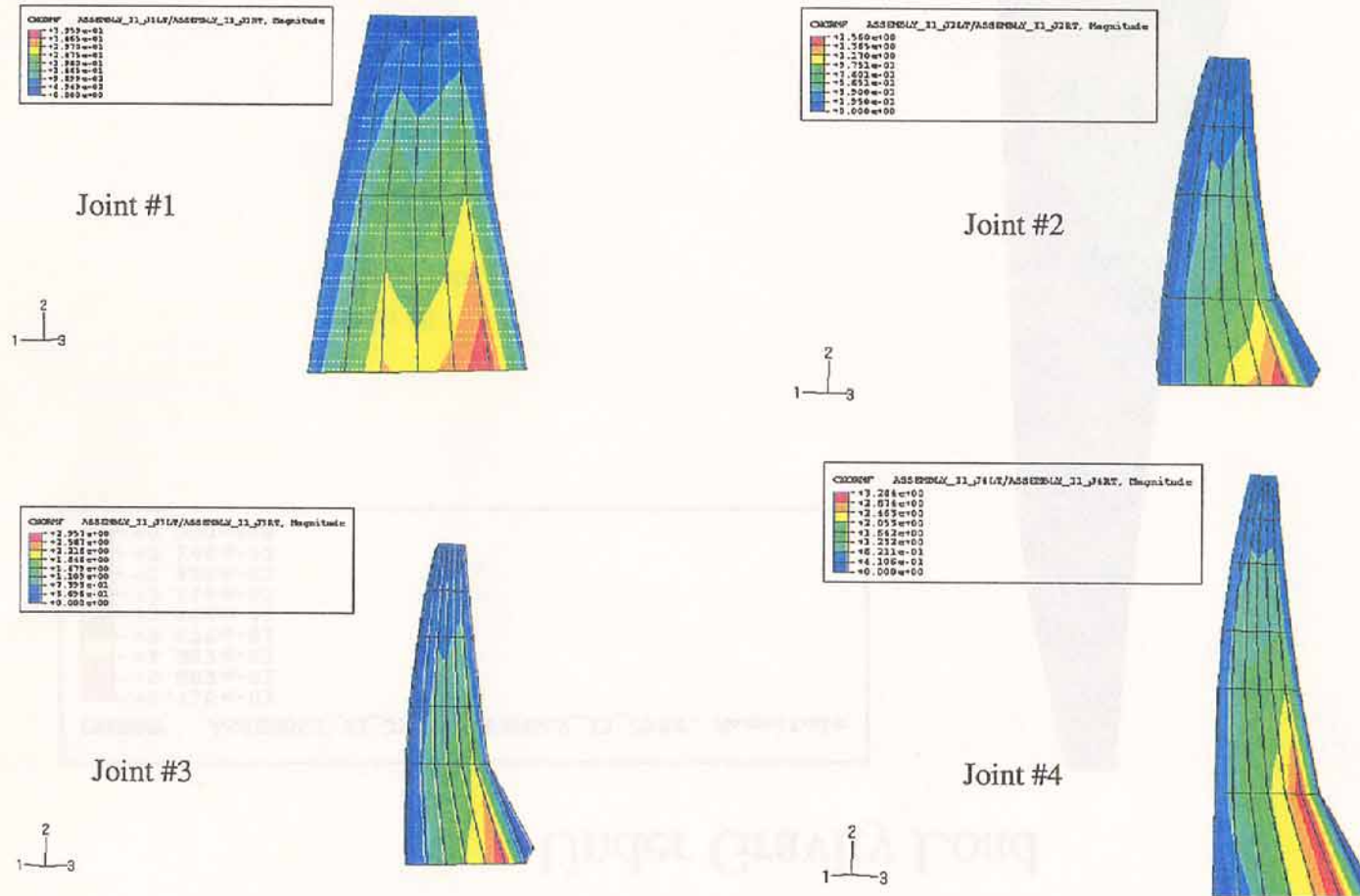


Note : A value of zero for the contact force indicates that the joint is open.

Figure E.11

Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces Under Gravity + Reservoir Load



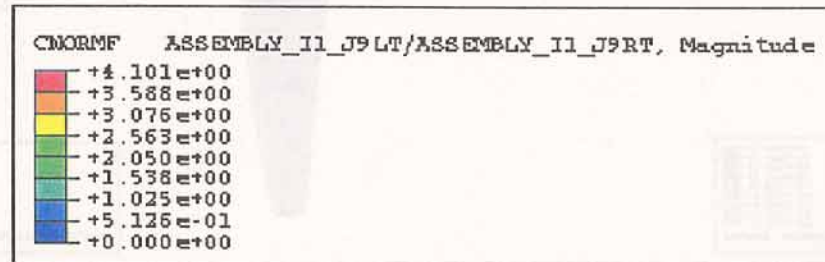
Note : A value of zero for the contact force indicates that the joint is open.

Figure E.12

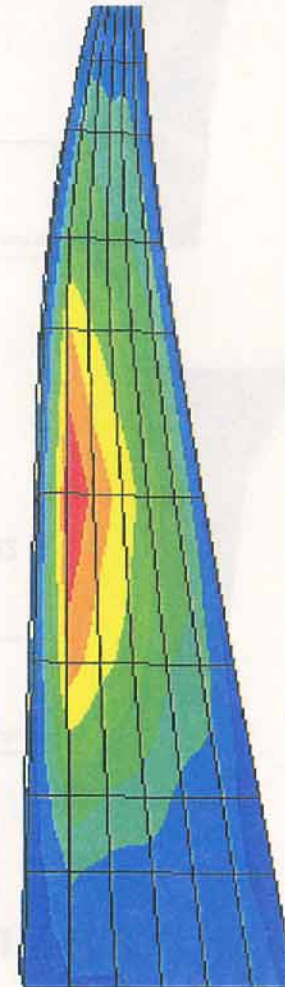
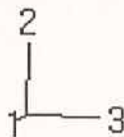
Seventeen Vertical Joint Model : M12 M13

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load



Joint #9
Center joint



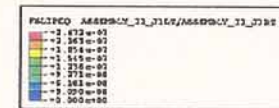
Note : A value of zero for the contact force indicates that the joint is open.

Figure E.13

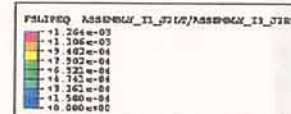
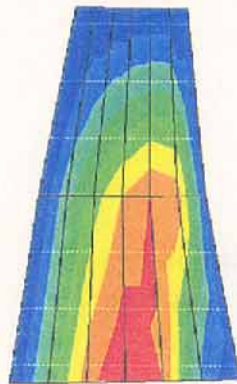
Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

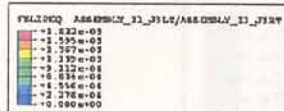
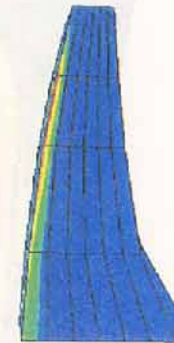
Under Gravity Load



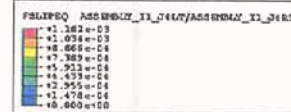
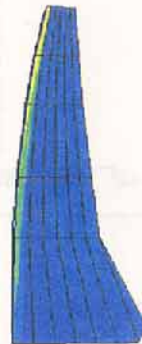
Joint #1



Joint #2



Joint #3



Joint #4

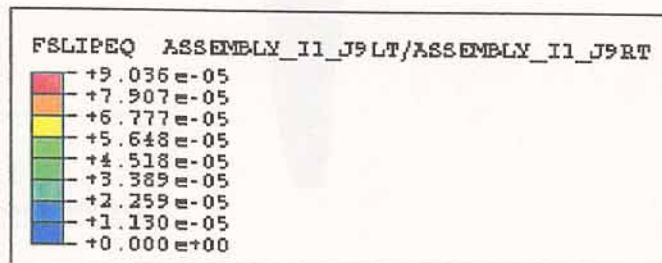


Figure E.14

Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

Under Gravity Load



Joint #9
Center joint

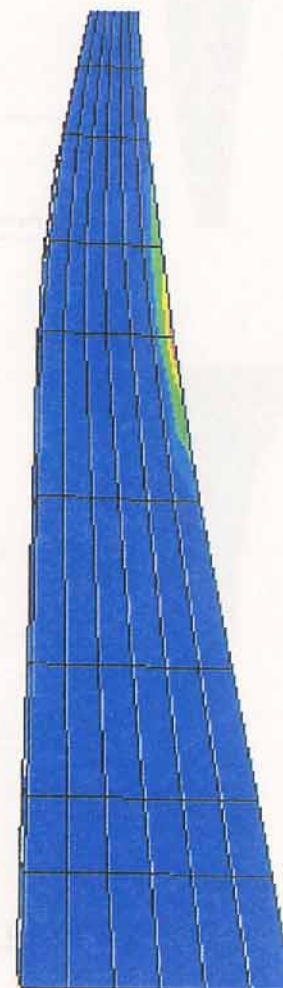
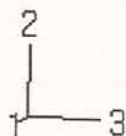
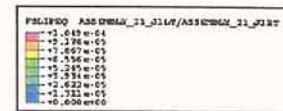


Figure E.15

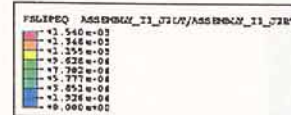
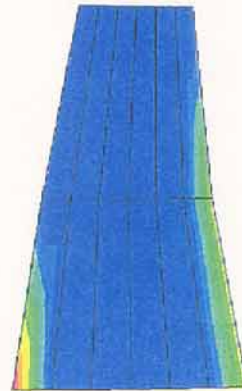
Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

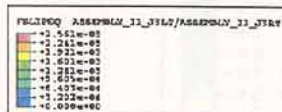
Under Gravity + Reservoir Load



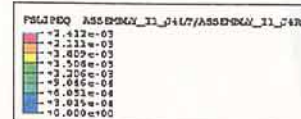
Joint #1



Joint #2



Joint #3



Joint #4

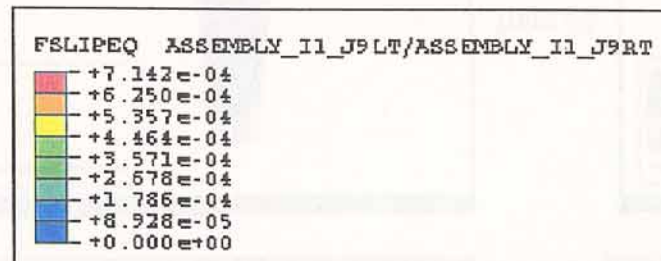


Figure E.16

Seventeen Vertical Joint Model : M12 M13

Slip Magnitude on Joint Surfaces

Under Gravity + Reservoir Load



Joint #9
Center joint

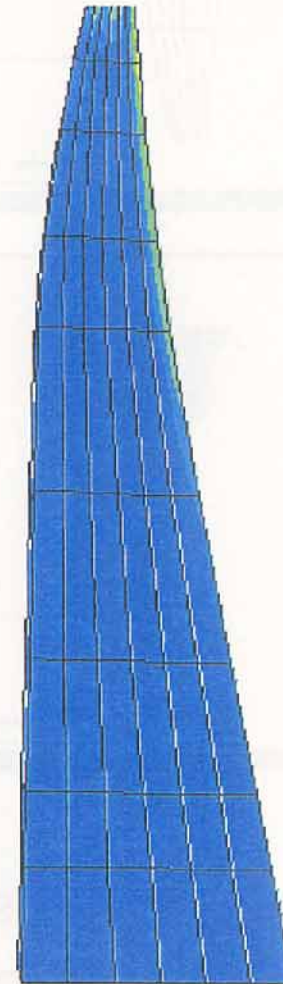
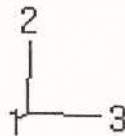


Figure E.17

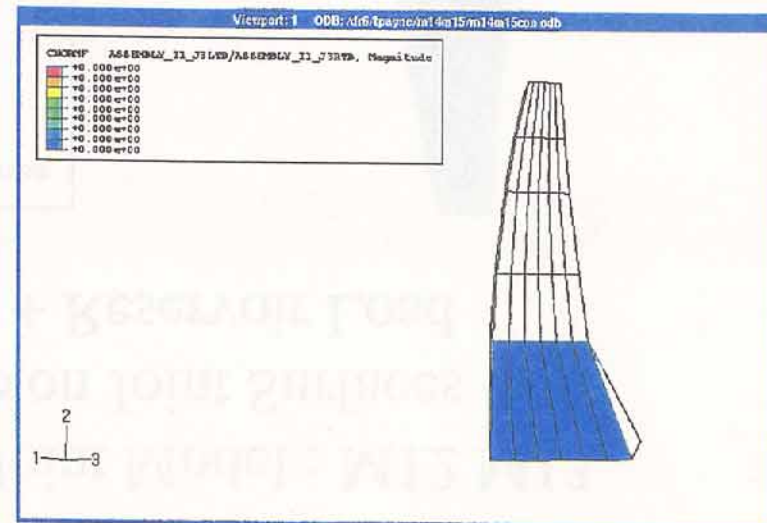
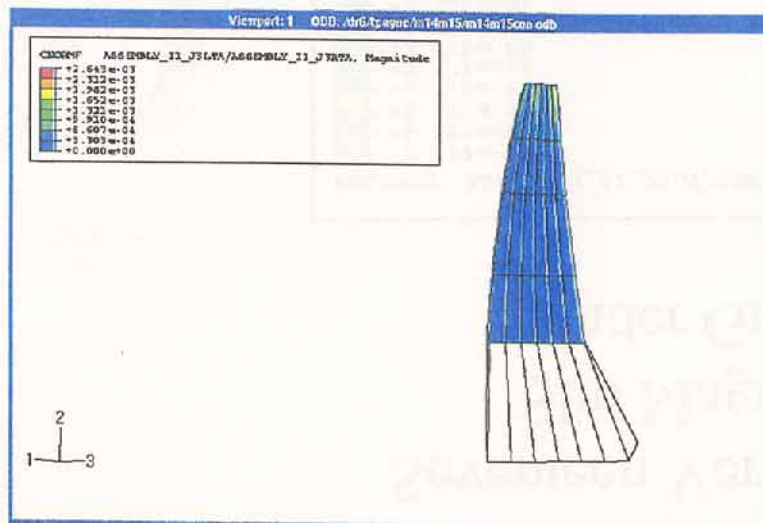
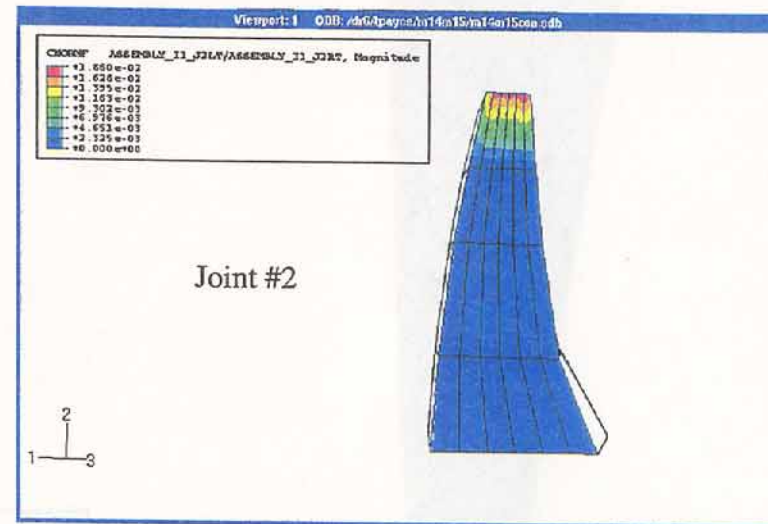
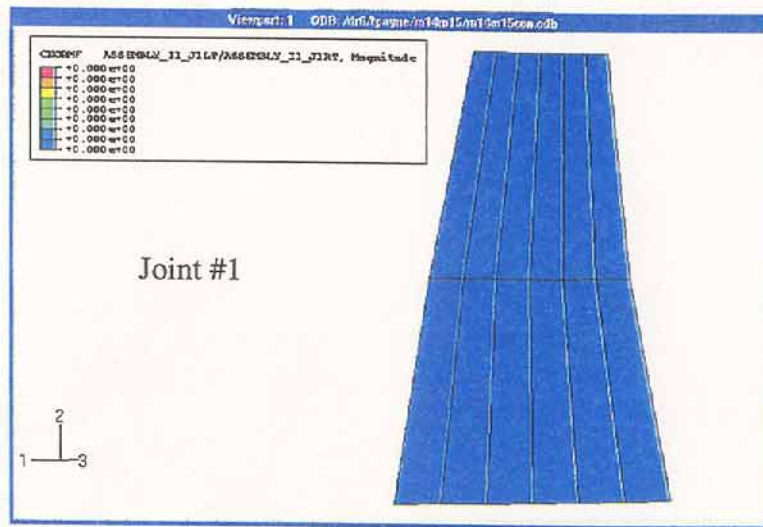


Figure E.18

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Load

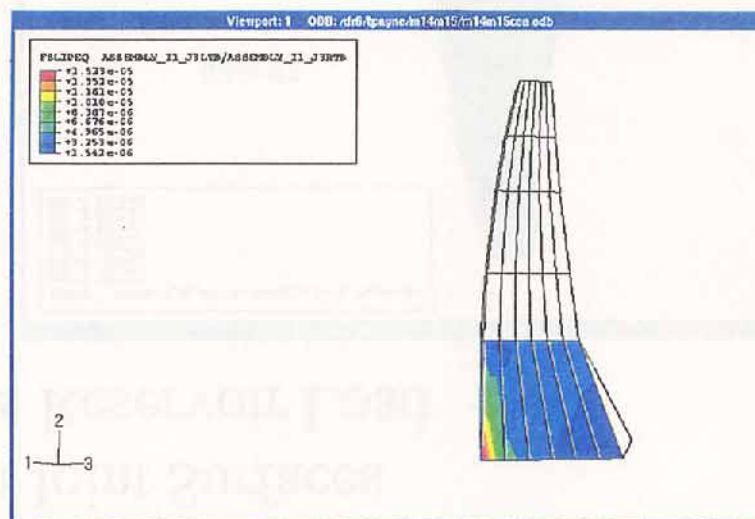
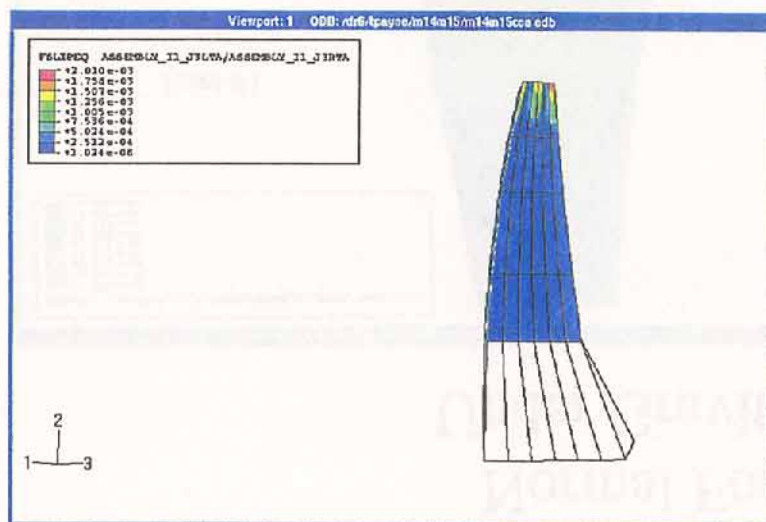
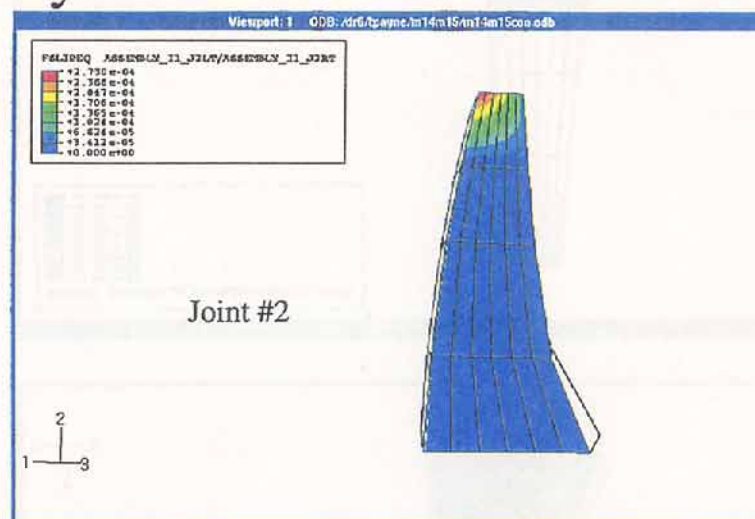
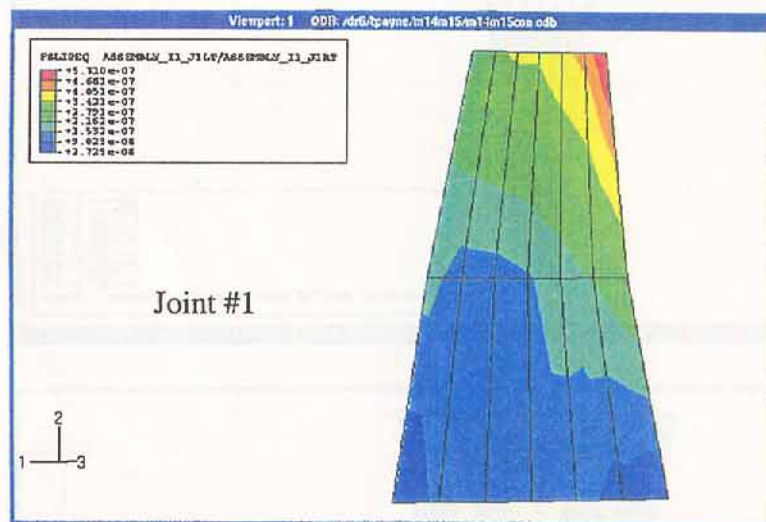


Figure E.19

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity Plus Reservoir Load

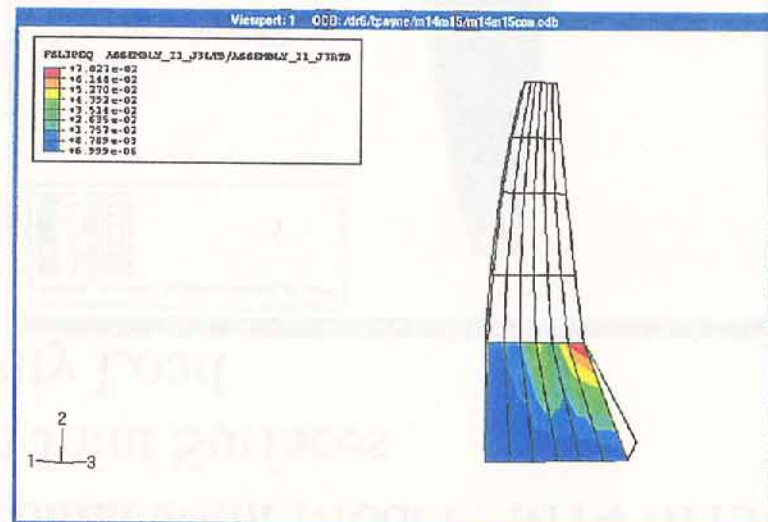
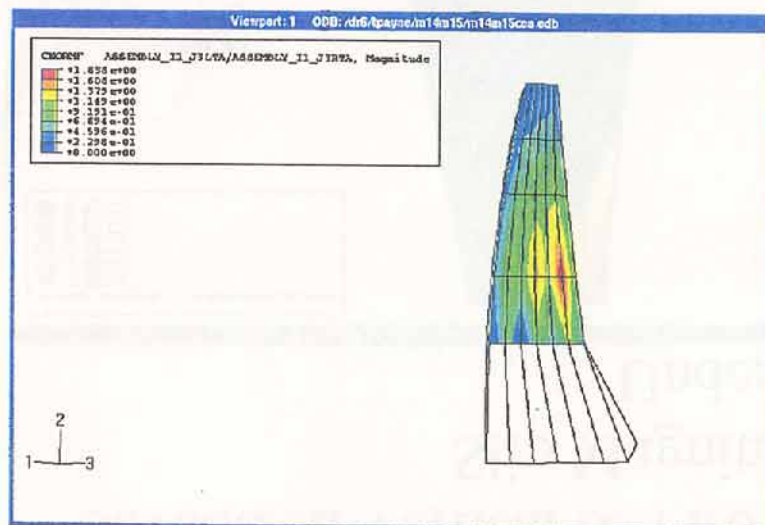
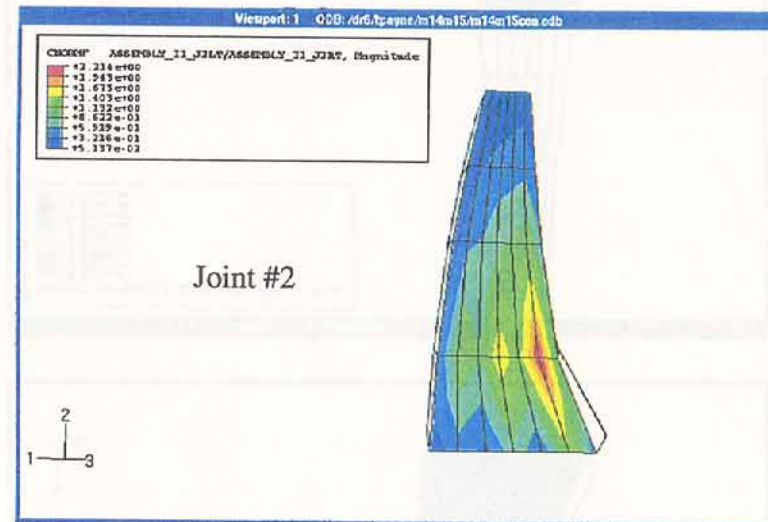
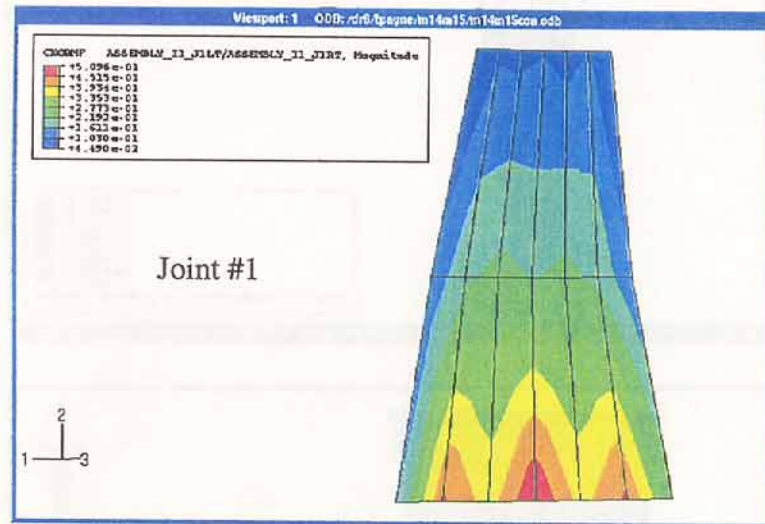


Figure E.20

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Plus Reservoir Load

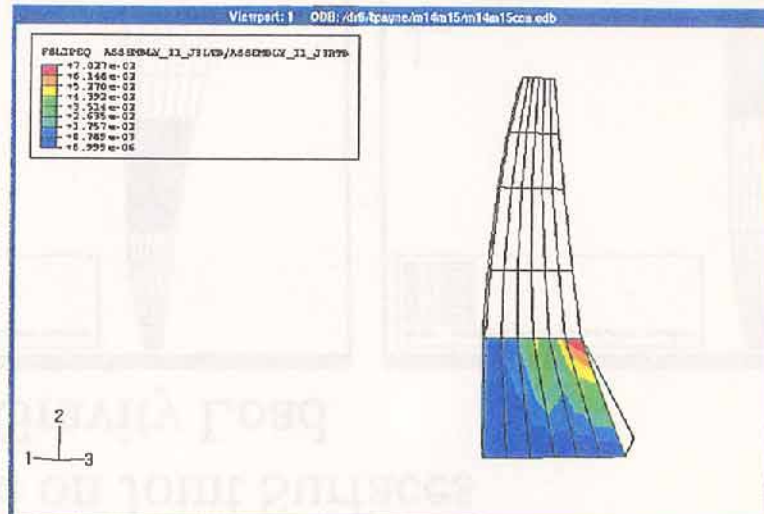
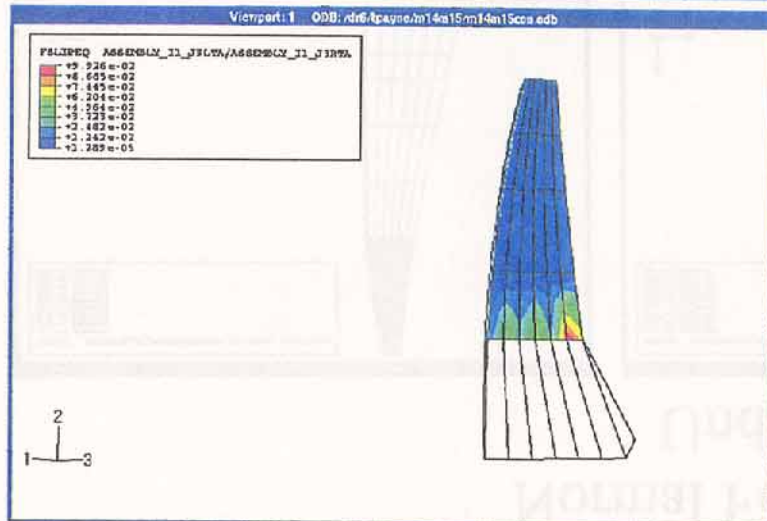
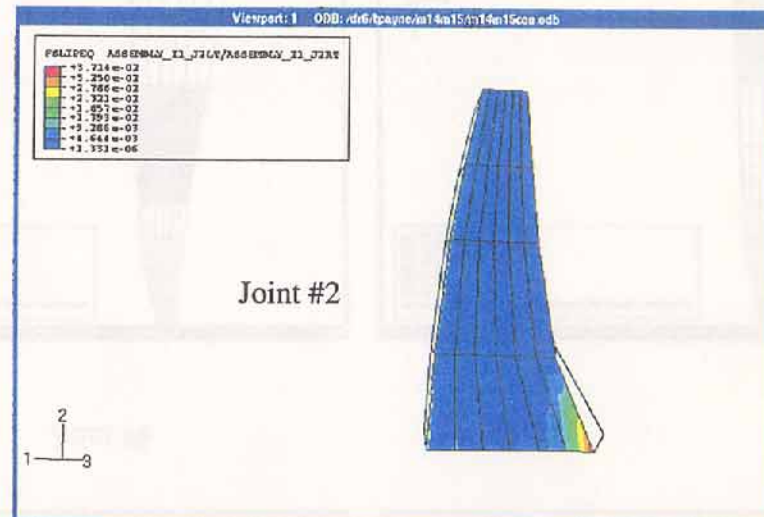
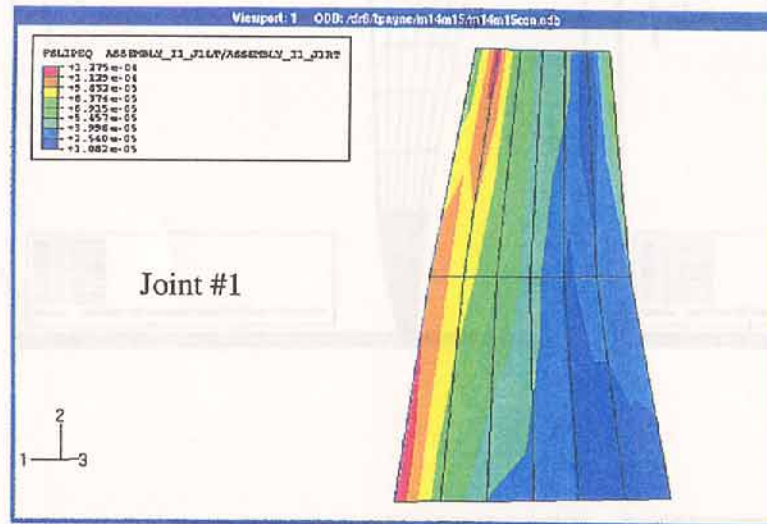
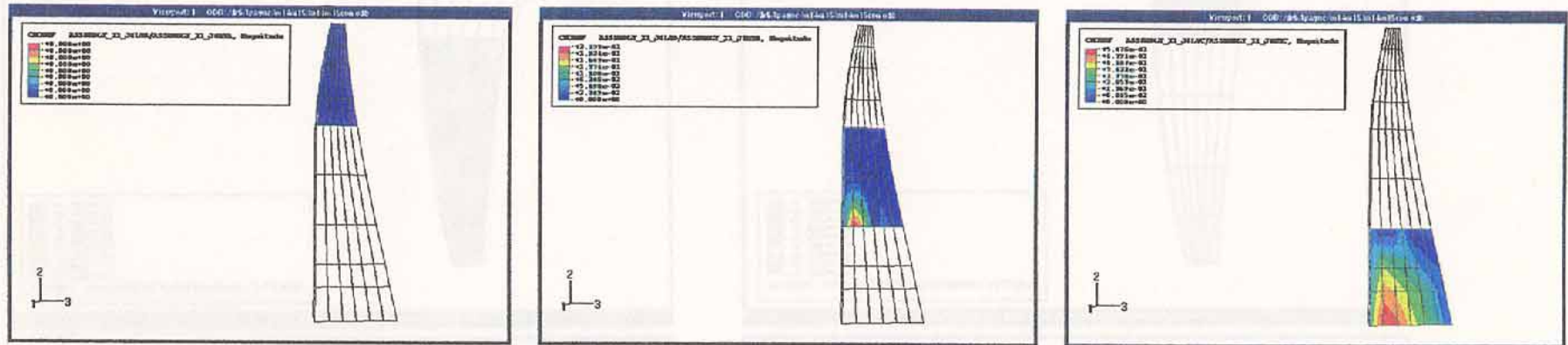


Figure E.21

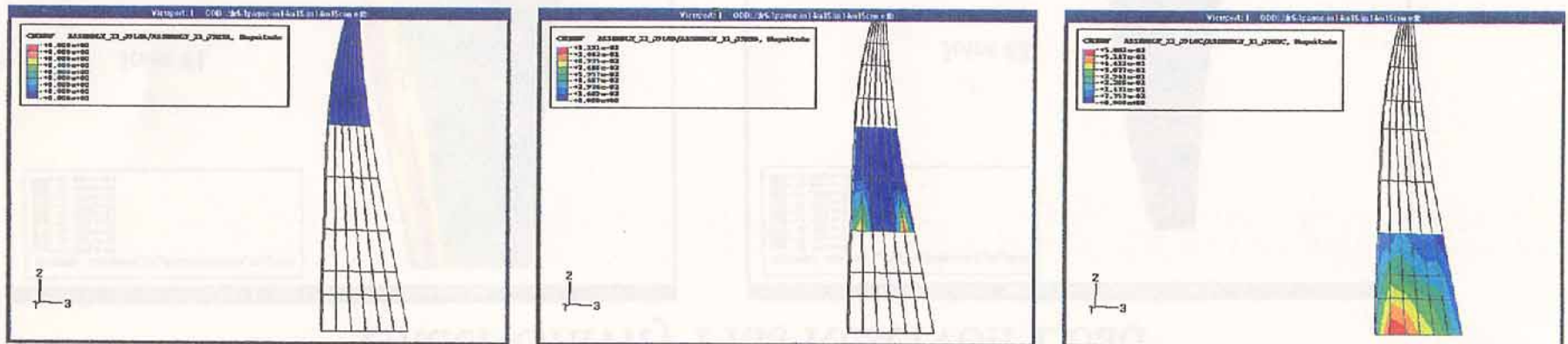
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity Load



Joint #8

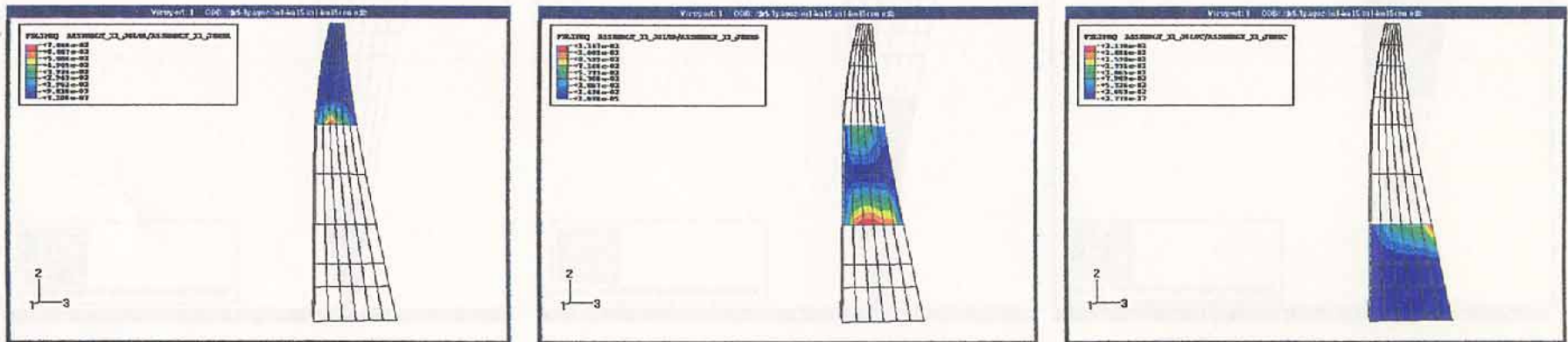


Joint #9

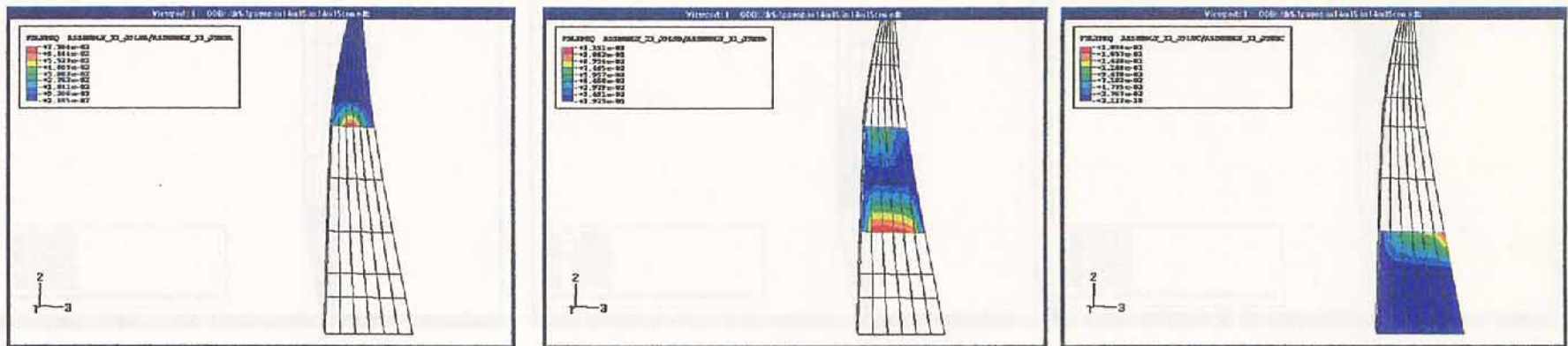
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Plus Reservoir Load



Joint #8

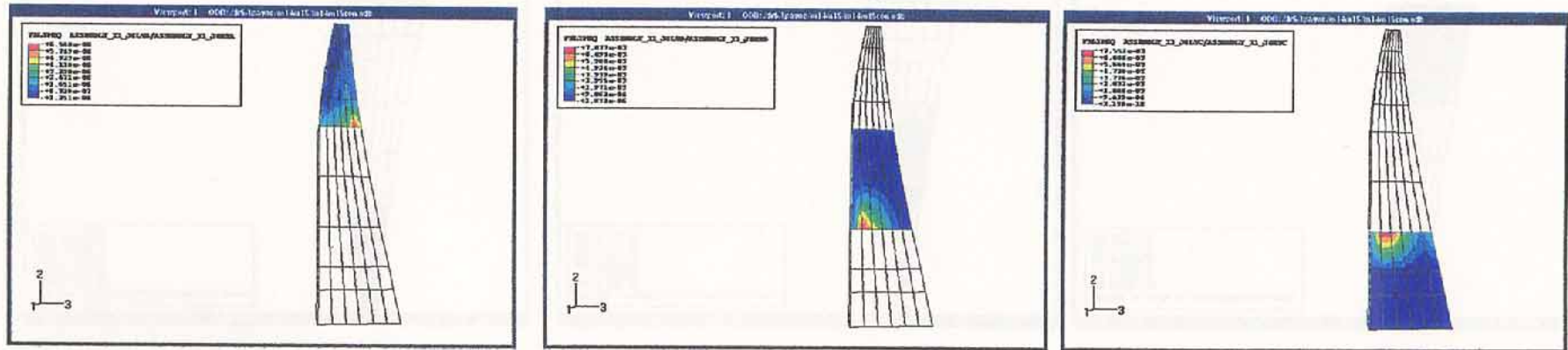


Joint #9

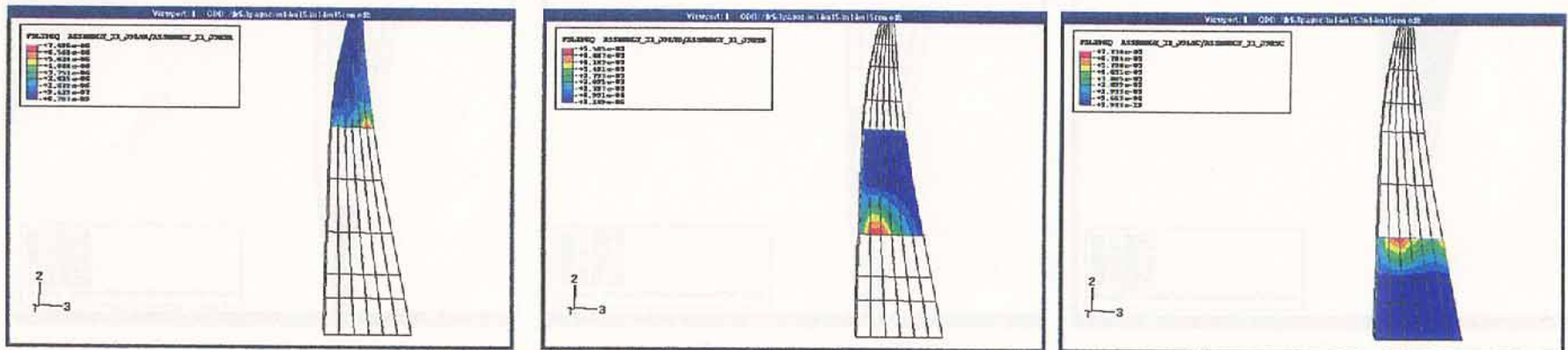
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity Load



Joint #8

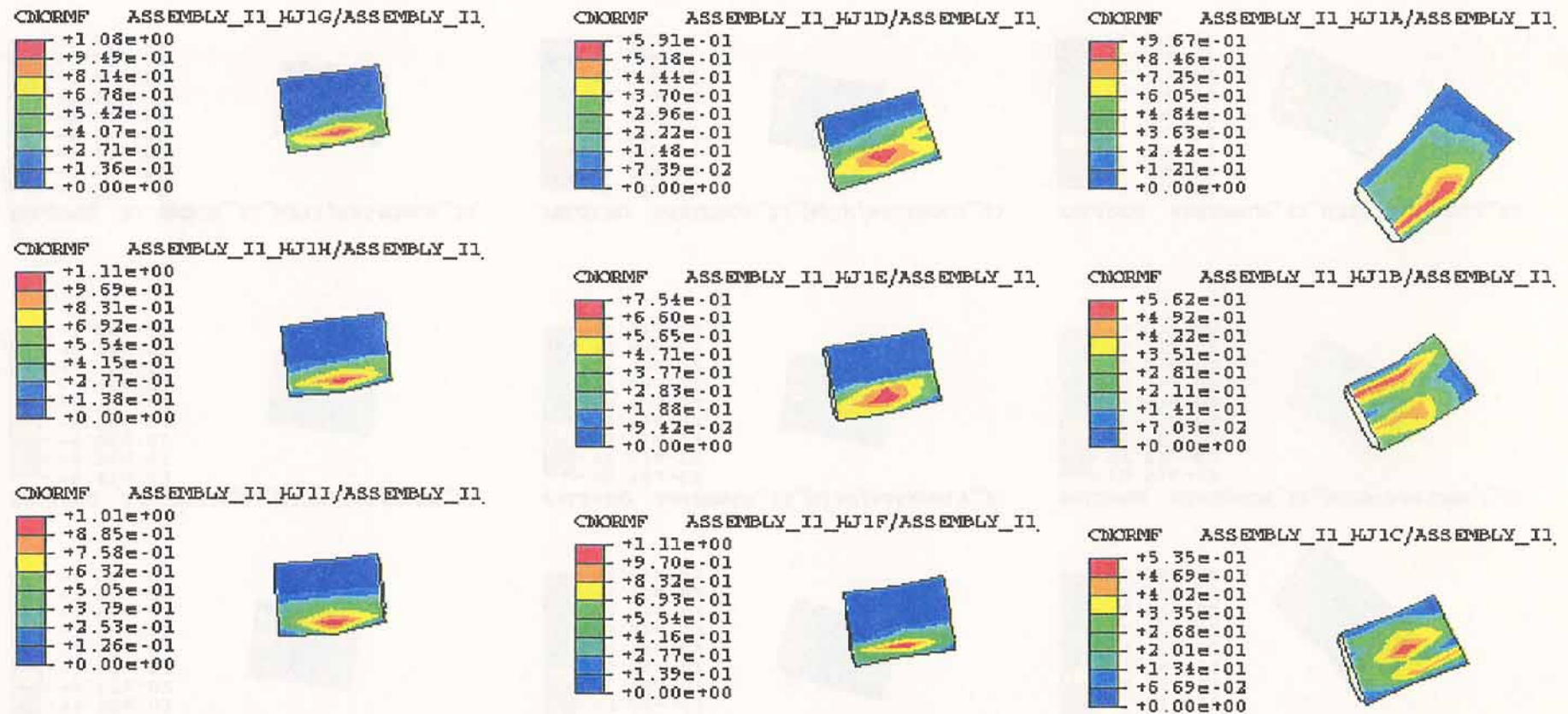


Joint #9

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load



View is looking down on surfaces making up the upper horizontal joint

Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity + Reservoir Load

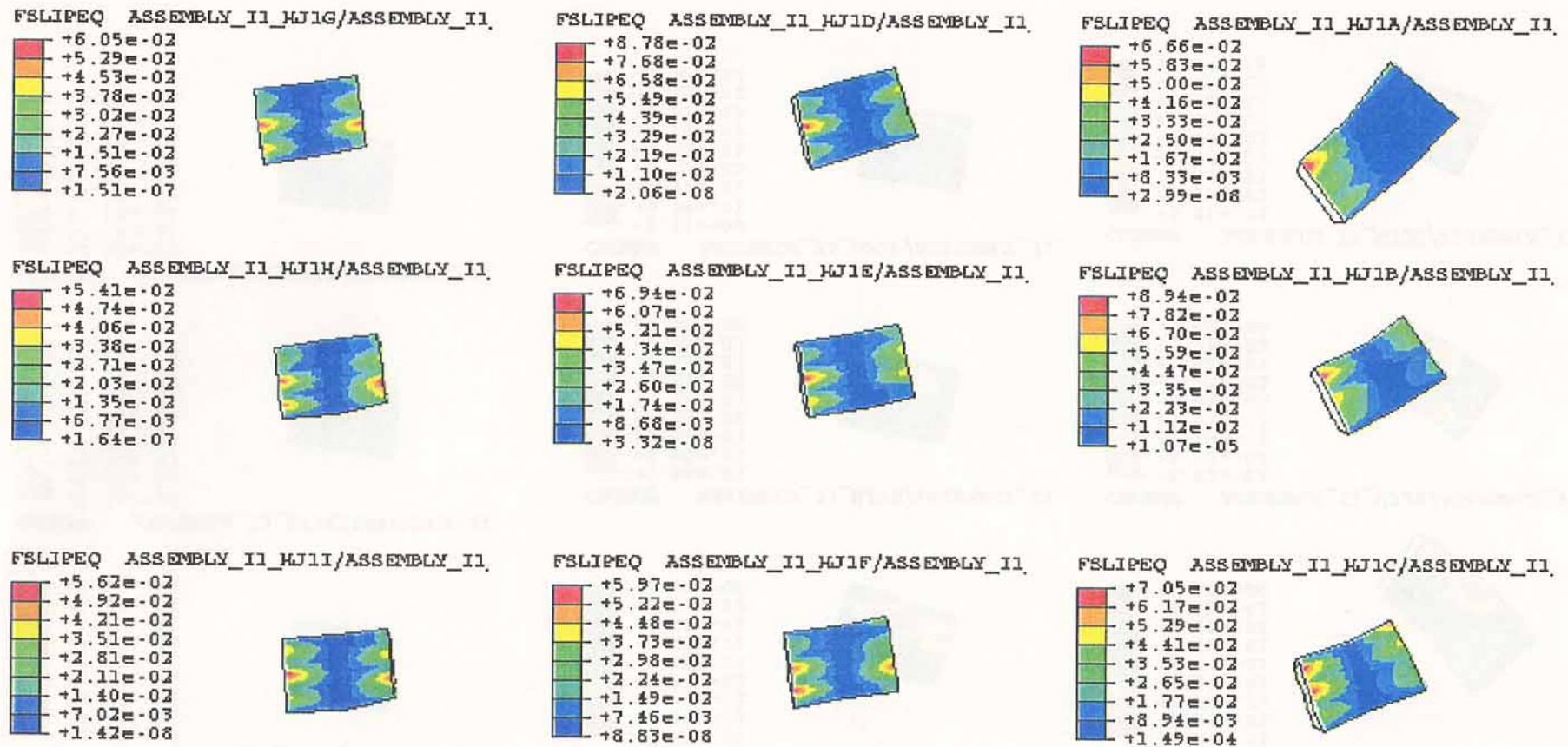


Figure E.26 View is looking down on surfaces making up the upper horizontal joint

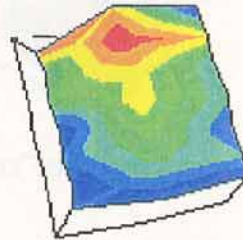
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity + Reservoir Load

CNORMF ASSEMBLY_I1_HJ3F/ASSEMBLY_I1

+1.52e+00
+1.33e+00
+1.14e+00
+9.49e-01
+7.59e-01
+5.69e-01
+3.80e-01
+1.90e-01
+0.00e+00



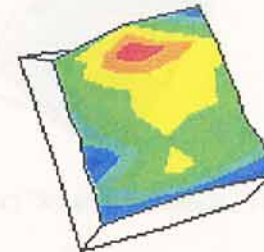
CNORMF ASSEMBLY_I1_HJ3K/ASSEMBLY_I1_HJ

+1.36e+00
+1.19e+00
+1.02e+00
+8.47e-01
+6.78e-01
+5.08e-01
+3.39e-01
+1.69e-01
+0.00e+00



CNORMF ASSEMBLY_I1_HJ3G/ASSEMBLY_I1

+1.39e+00
+1.22e+00
+1.04e+00
+8.69e-01
+6.95e-01
+5.21e-01
+3.48e-01
+1.74e-01
+0.00e+00



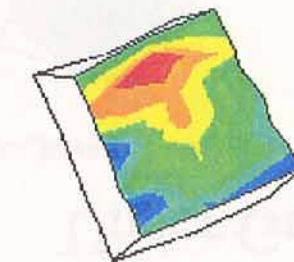
CNORMF ASSEMBLY_I1_HJ3J/ASSEMBLY_I1

+2.41e+00
+2.11e+00
+1.81e+00
+1.51e+00
+1.21e+00
+9.05e-01
+6.03e-01
+3.02e-01
+0.00e+00



CNORMF ASSEMBLY_I1_HJ3H/ASSEMBLY_I1

+1.25e+00
+1.10e+00
+9.40e-01
+7.83e-01
+6.27e-01
+4.70e-01
+3.13e-01
+1.57e-01
+0.00e+00



CNORMF ASSEMBLY_I1_HJ3I/ASSEMBLY_I1_HJ

+1.53e+00
+1.34e+00
+1.15e+00
+9.58e-01
+7.66e-01
+5.75e-01
+3.83e-01
+1.92e-01
+0.00e+00

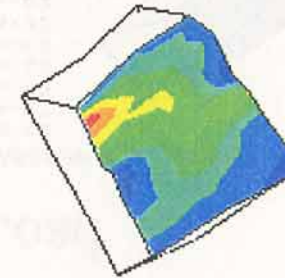


Figure E.27

View is looking down on surfaces making up the lower horizontal joint

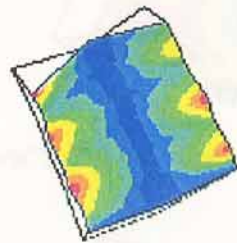
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Slip Magnitude on Joint Surfaces

Under Gravity + Reservoir Load

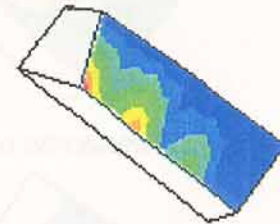
FSLIPEQ ASSEMBLY_I1_HJ3F/ASSEMBLY_I1.

+1.26e-01
+1.11e-01
+9.58e-02
+8.07e-02
+6.56e-02
+5.06e-02
+3.55e-02
+2.04e-02
+5.33e-03



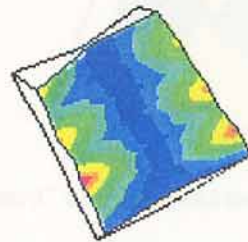
FSLIPEQ ASSEMBLY_I1_HJ3K/ASSEMBLY_I1.

+5.82e-02
+5.09e-02
+4.37e-02
+3.64e-02
+2.91e-02
+2.18e-02
+1.46e-02
+7.28e-03
+2.58e-17



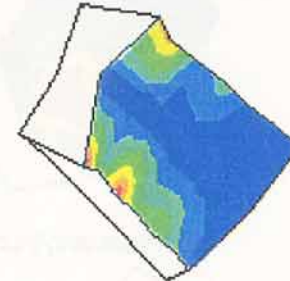
FSLIPEQ ASSEMBLY_I1_HJ3G/ASSEMBLY_I1.

+1.37e-01
+1.21e-01
+1.05e-01
+8.85e-02
+7.22e-02
+5.59e-02
+3.96e-02
+2.33e-02
+6.96e-03



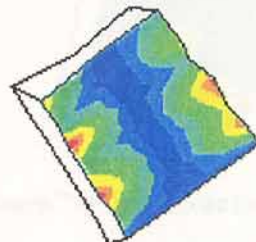
FSLIPEQ ASSEMBLY_I1_HJ3J/ASSEMBLY_I1.

+1.40e-01
+1.22e-01
+1.05e-01
+8.77e-02
+7.04e-02
+5.31e-02
+3.57e-02
+1.84e-02
+1.05e-03



FSLIPEQ ASSEMBLY_I1_HJ3H/ASSEMBLY_I1.

+1.31e-01
+1.16e-01
+1.00e-01
+8.43e-02
+6.87e-02
+5.30e-02
+3.74e-02
+2.17e-02
+6.10e-03



FSLIPEQ ASSEMBLY_I1_HJ3I/ASSEMBLY_I1.

+1.69e-01
+1.49e-01
+1.28e-01
+1.08e-01
+8.75e-02
+6.72e-02
+4.69e-02
+2.66e-02
+6.22e-03

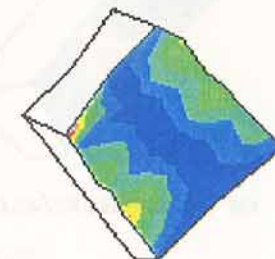


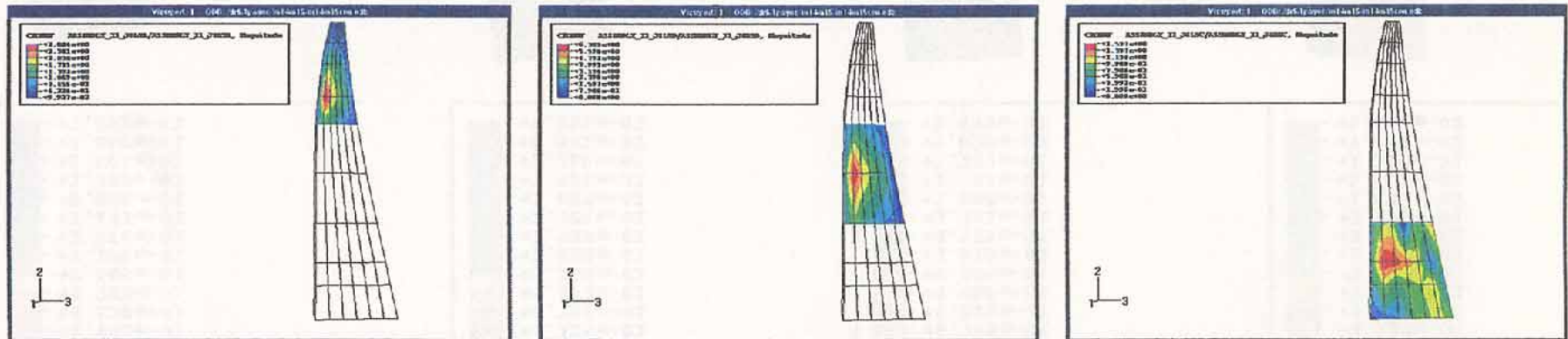
Figure E.28

View is looking down on surfaces making up the lower horizontal joint

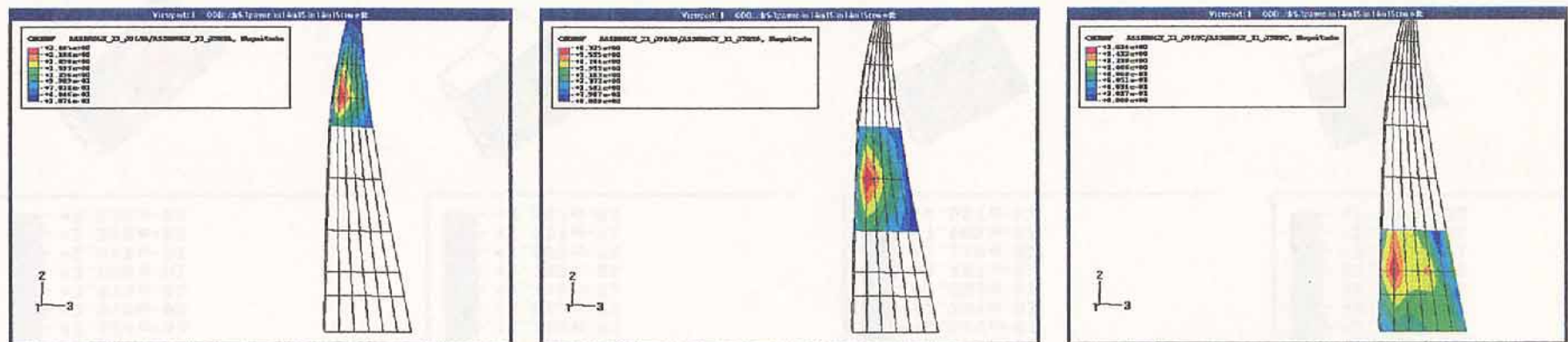
Seventeen Vertical & Two Horizontal Joint Model : M14 M15

Normal Force on Joint Surfaces

Under Gravity Plus Reservoir Load

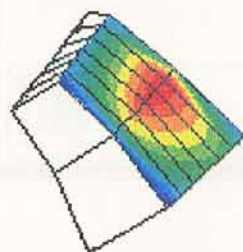
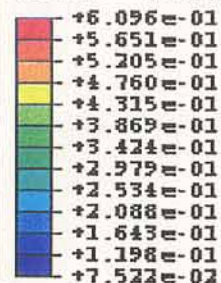


Joint #8

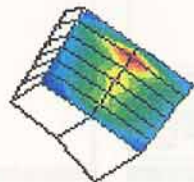
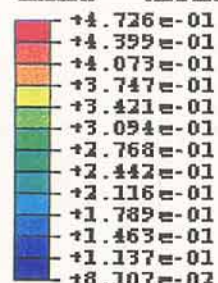


Joint #9

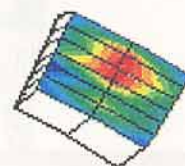
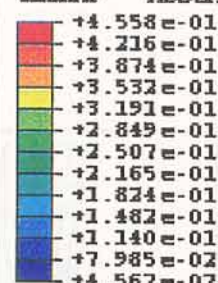
CNORMF ASSEMBLY_I1_HJ2TA//



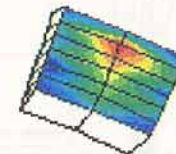
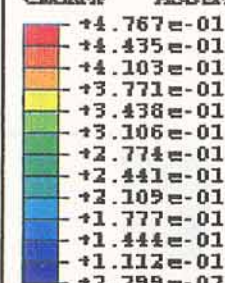
CNORMF ASSEMBLY_I1_HJ2TB//



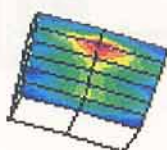
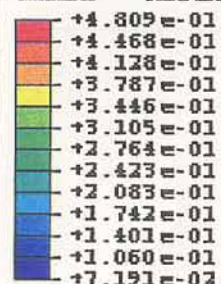
CNORMF ASSEMBLY_I1_HJ2TC//



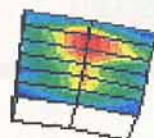
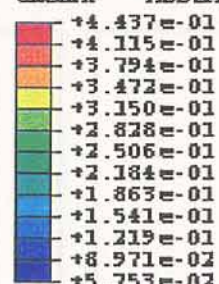
CNORMF ASSEMBLY_I1_HJ2TD//



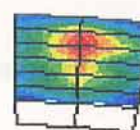
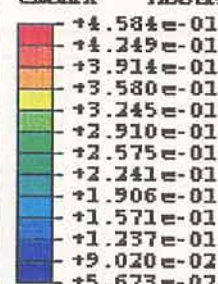
CNORMF ASSEMBLY_I1_HJ2TE//



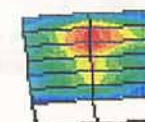
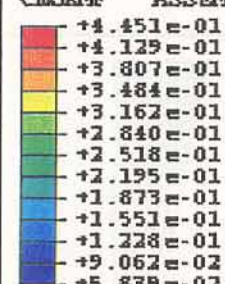
CNORMF ASSEMBLY_I1_HJ2TF//



CNORMF ASSEMBLY_I1_HJ2TG//



CNORMF ASSEMBLY_I1_HJ2TH//



Seventeen Vertical & Two Horizontal Joint Model : M14 M15
Normal Force On Surfaces Of the Upper Horizontal Joint
Gravity Load

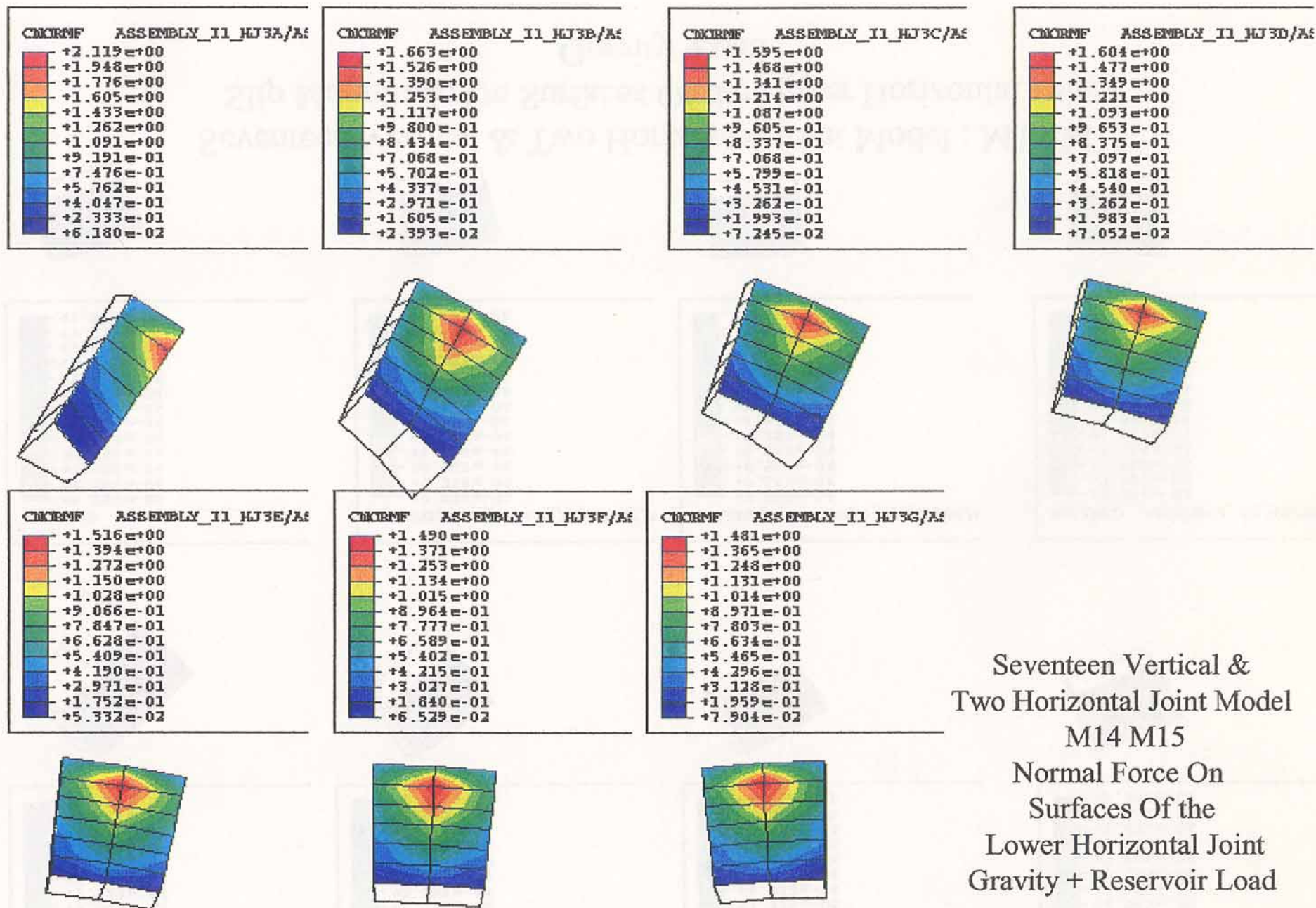
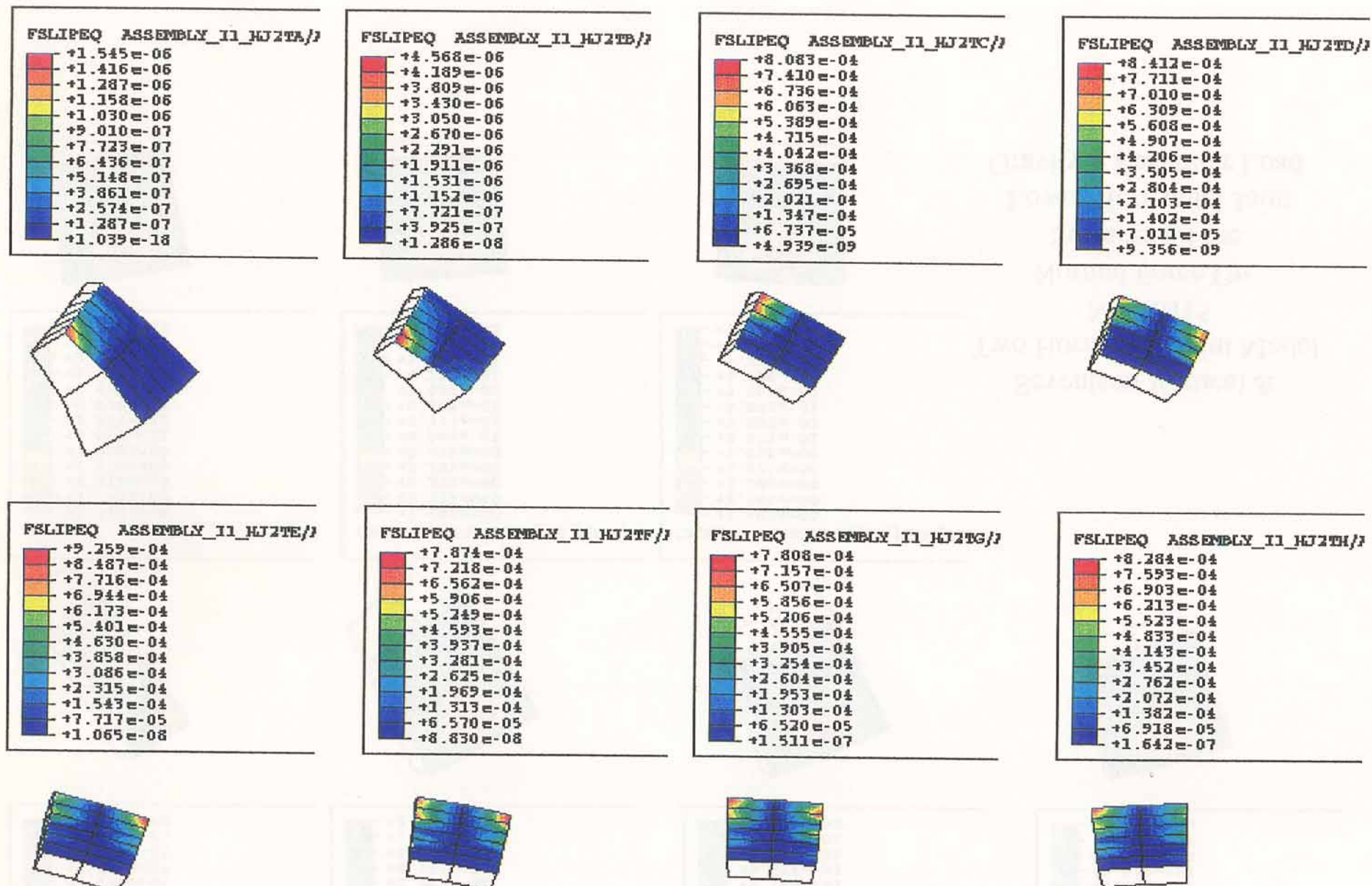
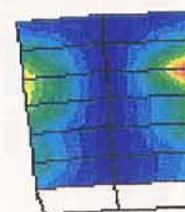
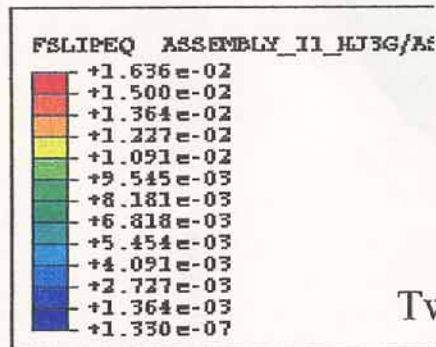
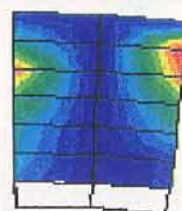
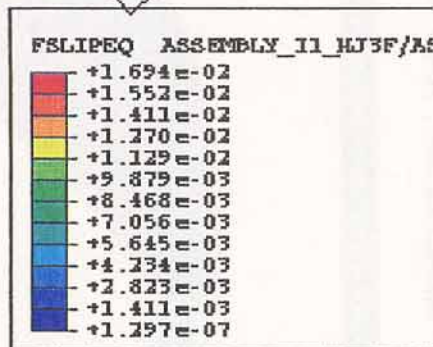
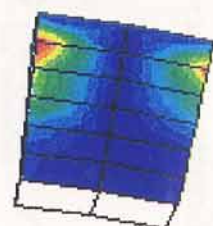
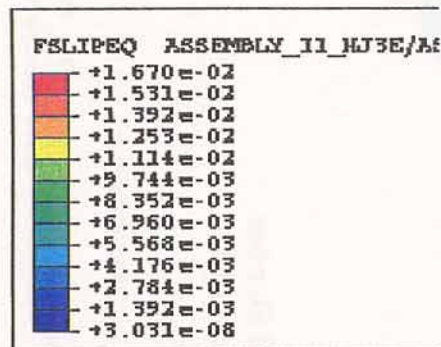
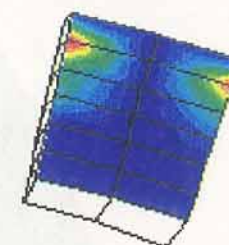
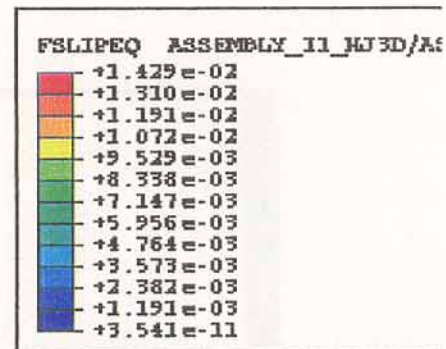
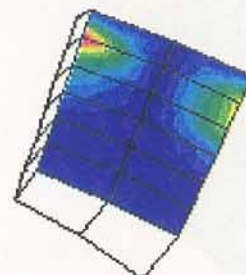
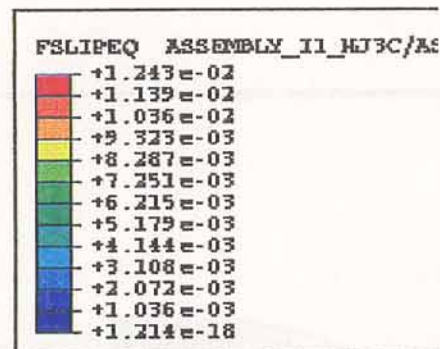
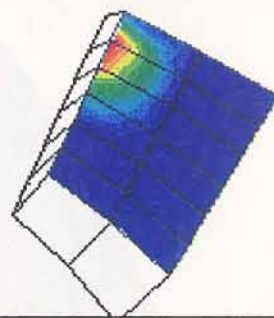
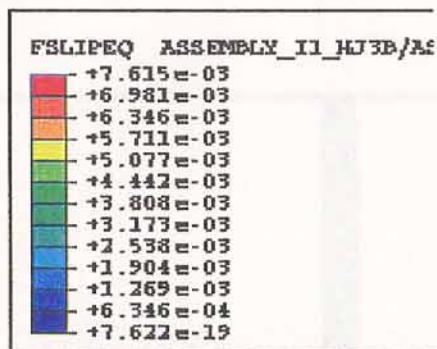
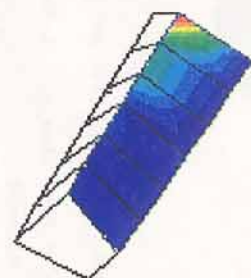
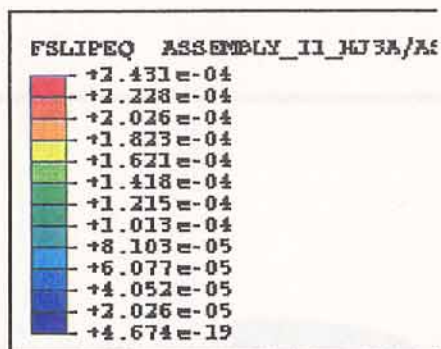


Figure E.31



Seventeen Vertical & Two Horizontal Joint Model : M14 M15
Slip Magnitude On Surfaces Of the Upper Horizontal Joint
Gravity Load



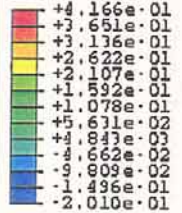
Seventeen Vertical &
Two Horizontal Joint Model
M14 M15
Slip Magnitude On
Surfaces Of the
Lower Horizontal Joint
Gravity + Reservoir Load

Figure E.33

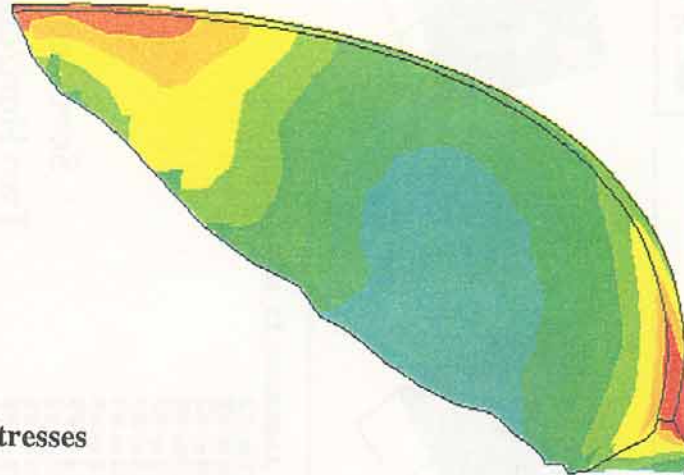
Monolithic Model : M2 & M8

Viewport: 1 ODB: /dr6/tpayne/nf_shake/m2m8grx.odb

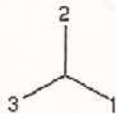
S, Max. Principal
(Ave. Crit.: 75%)



Max +4.166e-01
at elem 211 node 1436
Min -2.010e-01
at elem 1526 node 5402



Maximum Principal Stresses
Gravity Load

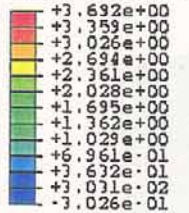


ODB: m2m8grx.odb ABAQUS/Explicit 6.1.1 Wed Jul 18 08:14:04 MDT 2001

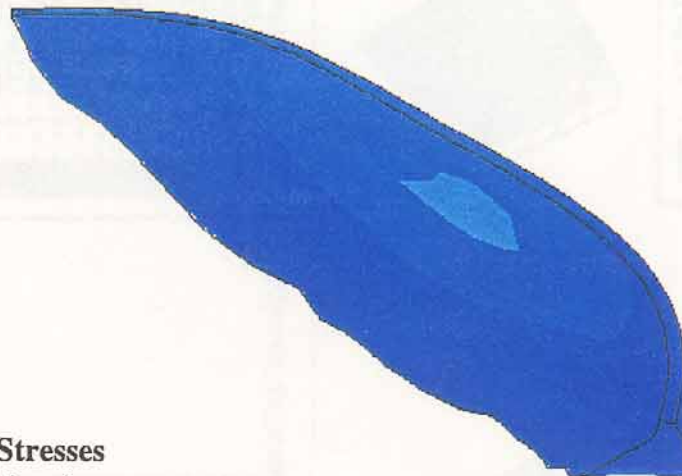
Step: Step-2 apply gravity Increment 19162; Step Time = 1.000
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport: 1 ODB: /dr6/tpayne/nf_shake/m2m8grx.odb

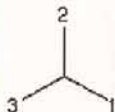
S, Max. Principal
(Ave. Crit.: 75%)



Max +3.692e+00
at elem 1487 node 5387
Min -3.026e-01
at elem 917 node 7694



Maximum Principal Stresses
Gravity + Reservoir Load



ODB: m2m8grx.odb ABAQUS/Explicit 6.1.1 Wed Jul 18 08:14:04 MDT 2001

Step: Step-4 apply reservoir Increment 28744; Step Time = 1.500
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+02

Figure E.34

Monolithic Model : M2 & M8

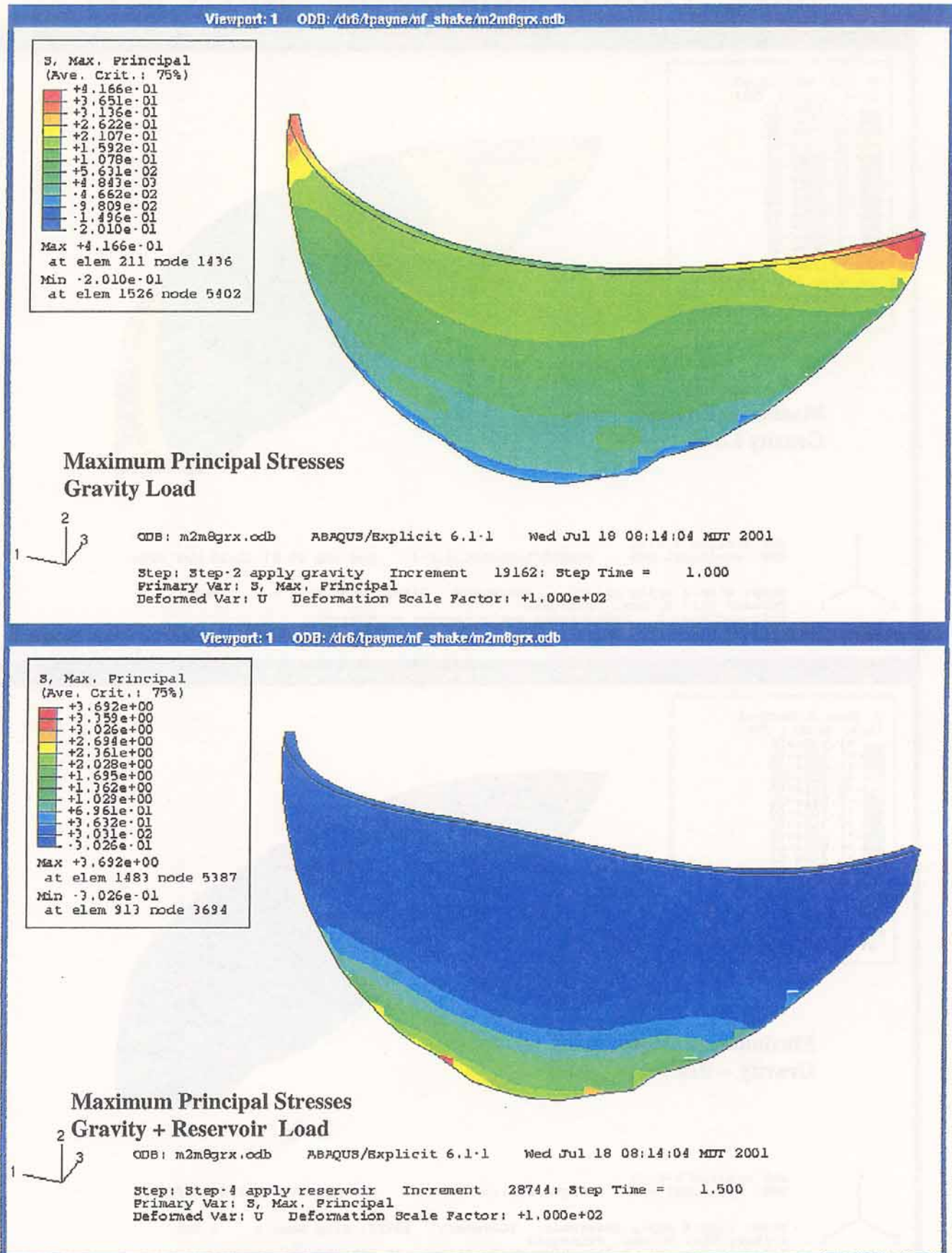


Figure E.35

Single Vertical Joint Model : M6 & M11

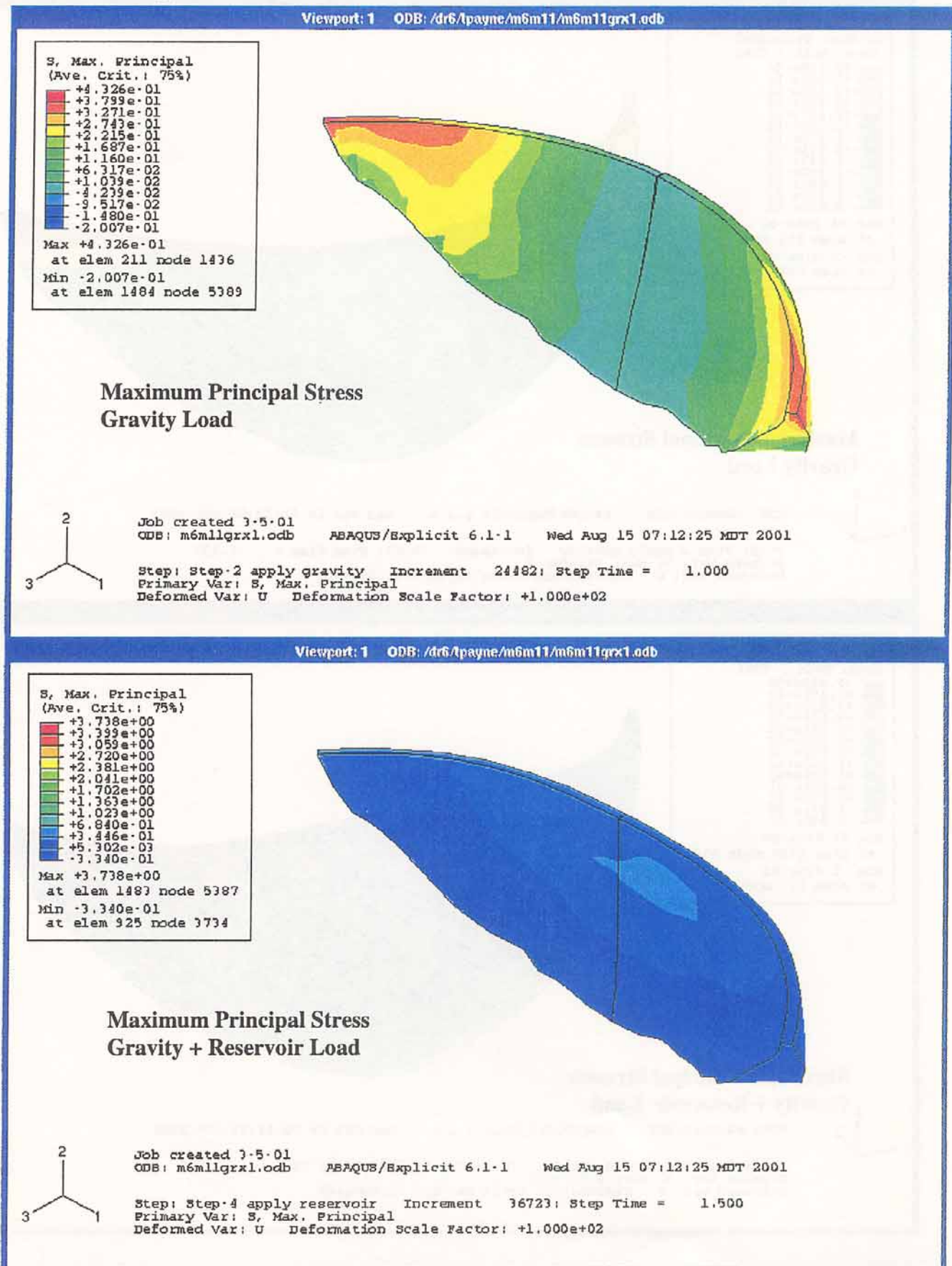


Figure E.36

Single Vertical Joint Model : M6 & M11

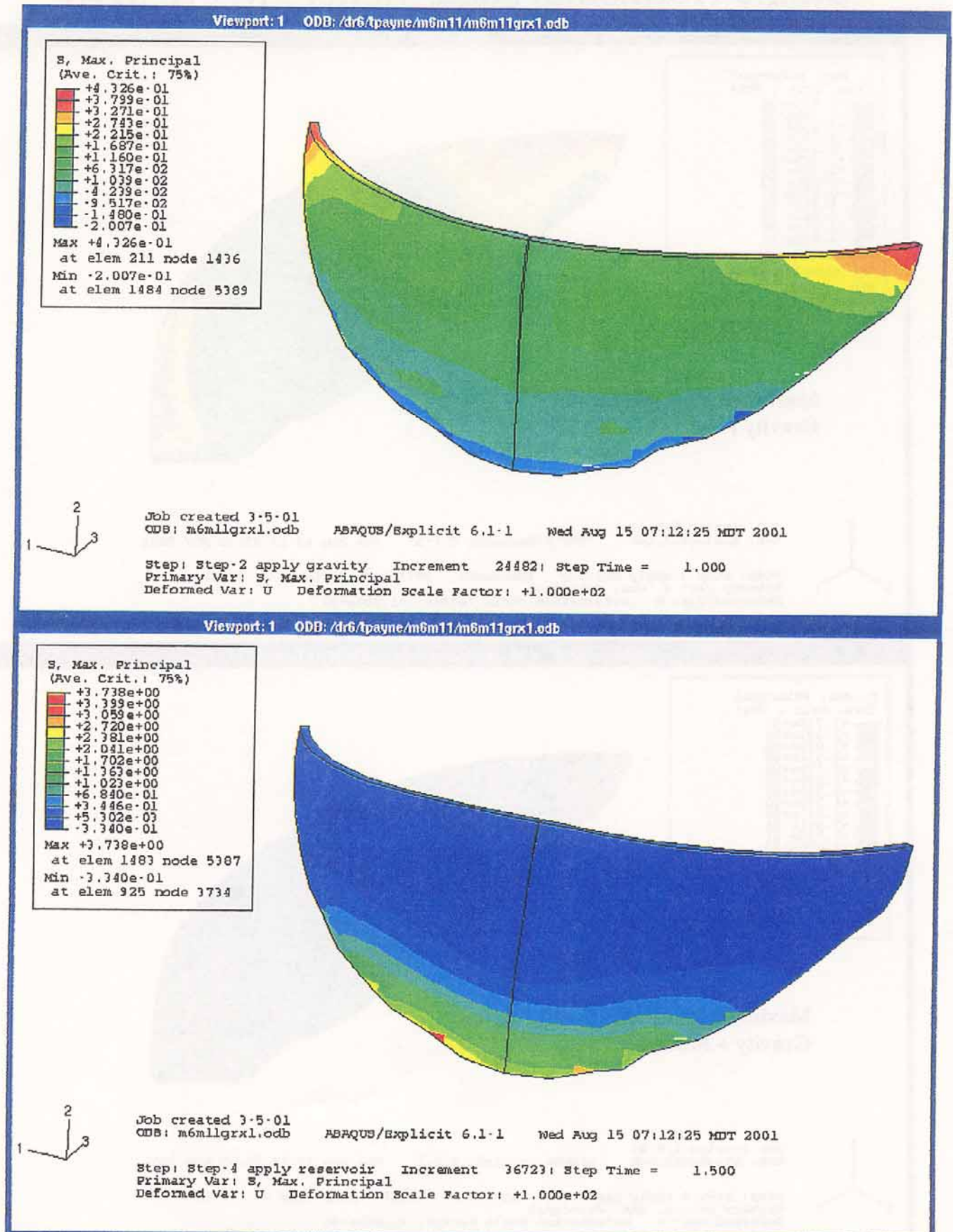


Figure E.37

Single Horizontal Joint Model : M9 & M10

Viewport: 1 ODB: /dr6/lpayne/m9m10/m9m10grx1.odb

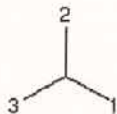
S, Max. Principal
(Ave. Crit.: 75%)

+4.315e-01
+3.787e-01
+3.259e-01
+2.711e-01
+2.203e-01
+1.675e-01
+1.146e-01
+6.183e-02
+9.017e-03
-4.380e-02
-9.661e-02
-1.494e-01
-2.022e-01

Max +4.315e-01
at elem 211 node 1436
Min -2.022e-01
at elem 1526 node 5402



Maximum Principal Stress
Gravity Load



Job created 3-5-01
ODB: m9m10grx1.odb

ABAQUS/Explicit 6.1-1

Tue Aug 14 14:27:20 MDT 2001

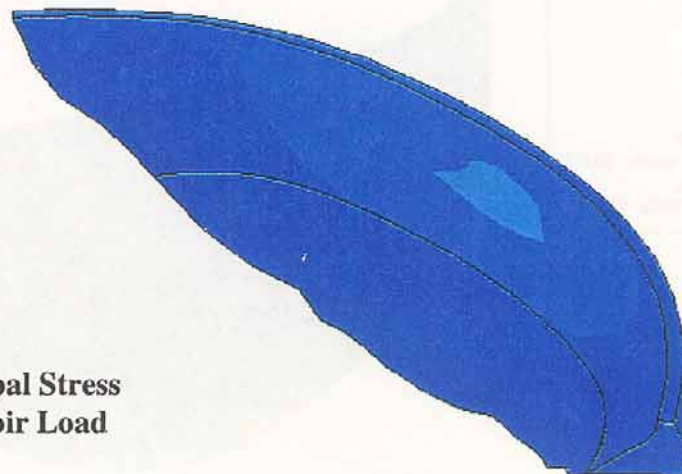
Step: Step-2 apply gravity Increment 28713; Step Time = 1.000
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport: 1 ODB: /dr6/lpayne/m9m10/m9m10grx1.odb

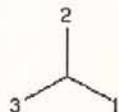
S, Max. Principal
(Ave. Crit.: 75%)

+3.718e+00
+3.383e+00
+3.048e+00
+2.714e+00
+2.379e+00
+2.045e+00
+1.710e+00
+1.375e+00
+1.041e+00
+7.061e-01
+3.715e-01
+3.686e-02
-2.978e-01

Max +3.718e+00
at elem 1483 node 5387
Min -2.978e-01
at elem 901 node 3654



Maximum Principal Stress
Gravity + Reservoir Load



Job created 3-5-01
ODB: m9m10grx1.odb

ABAQUS/Explicit 6.1-1

Tue Aug 14 14:27:20 MDT 2001

Step: Step-4 apply reservoir Increment 43070; Step Time = 1.500
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+02

Figure E.38

Single Horizontal Joint Model : M9 & M10

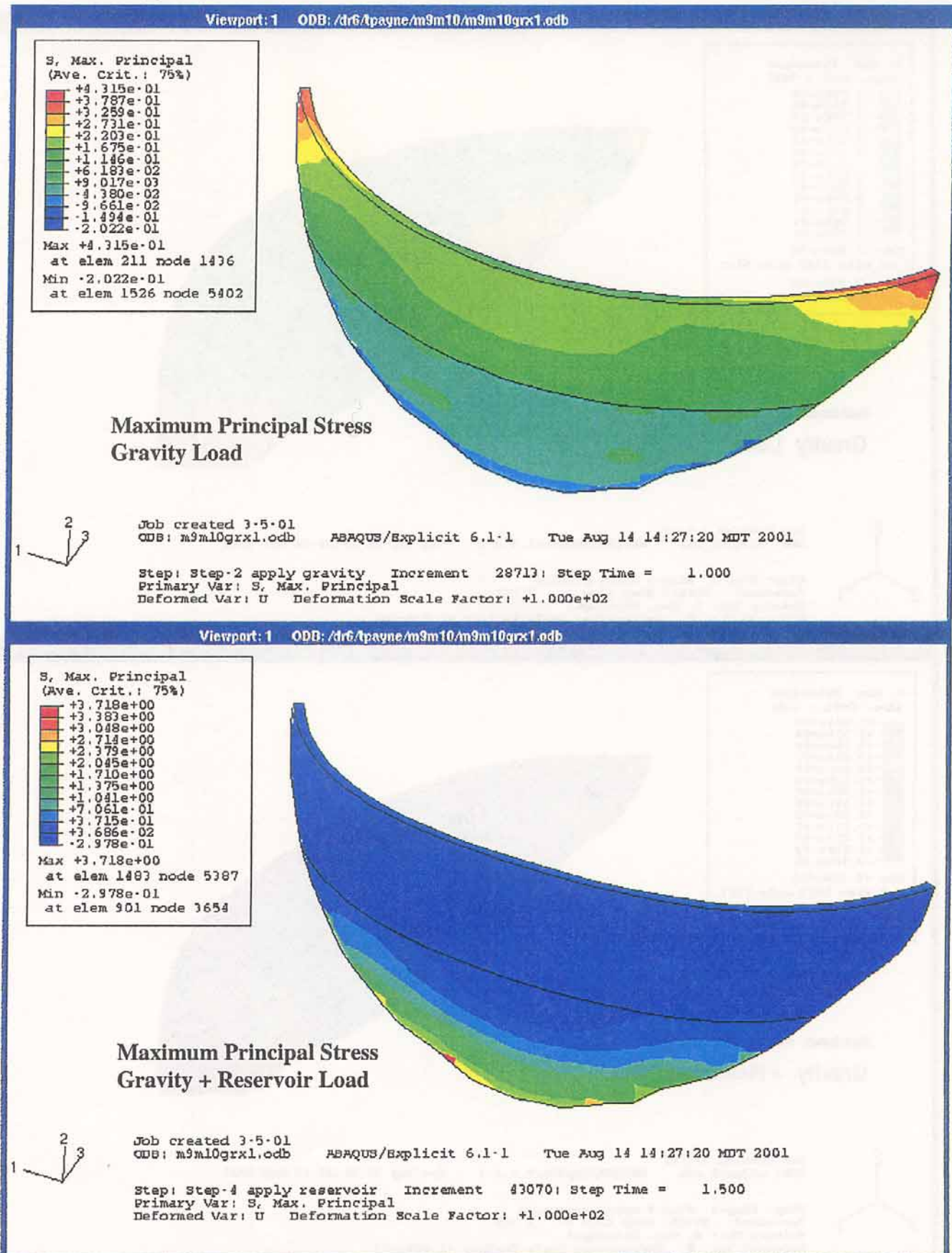


Figure E.39

Seventeen Vertical Joint Model : M12 & M13

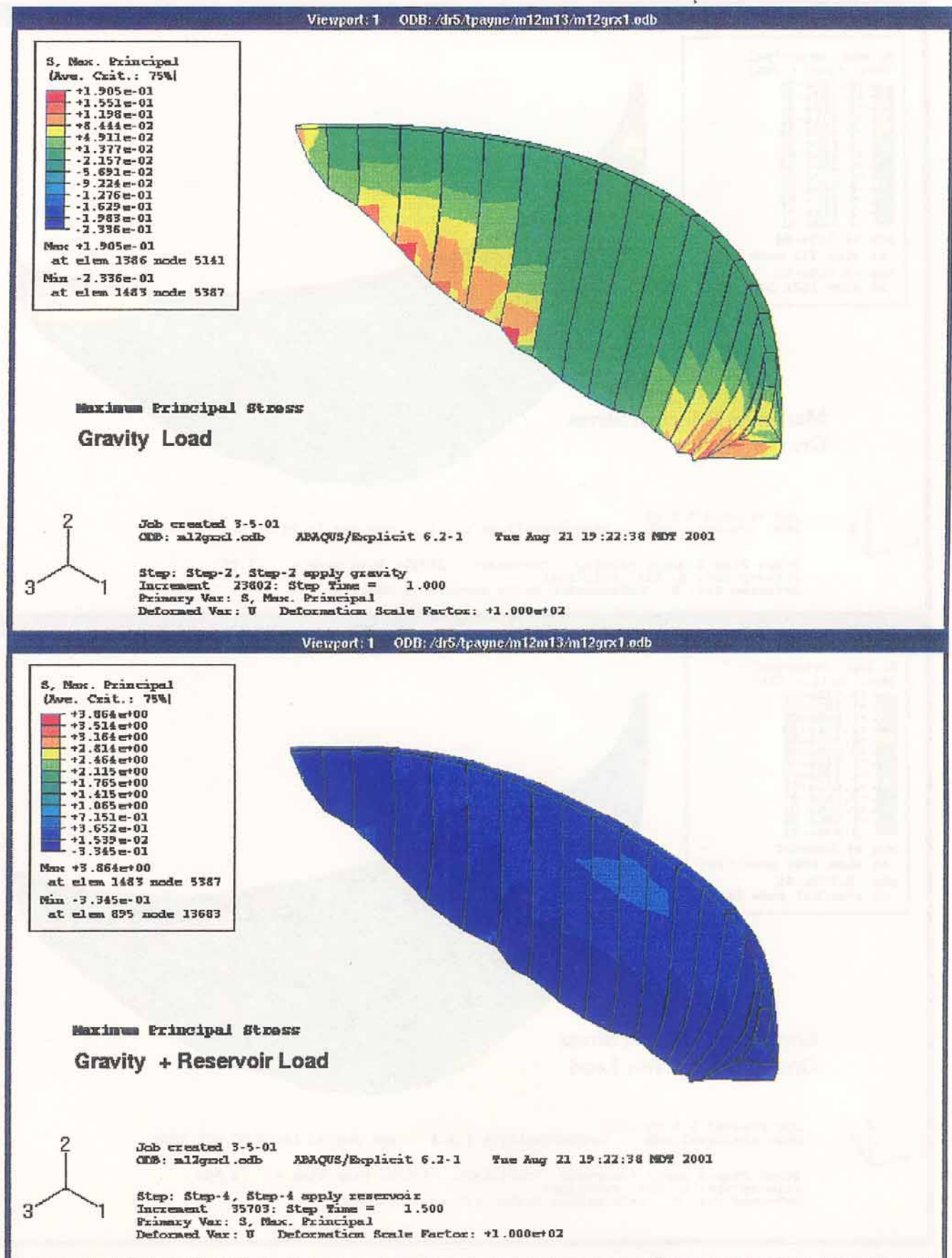


Figure E.40

Seventeen Vertical Joint Model : M12 & M13

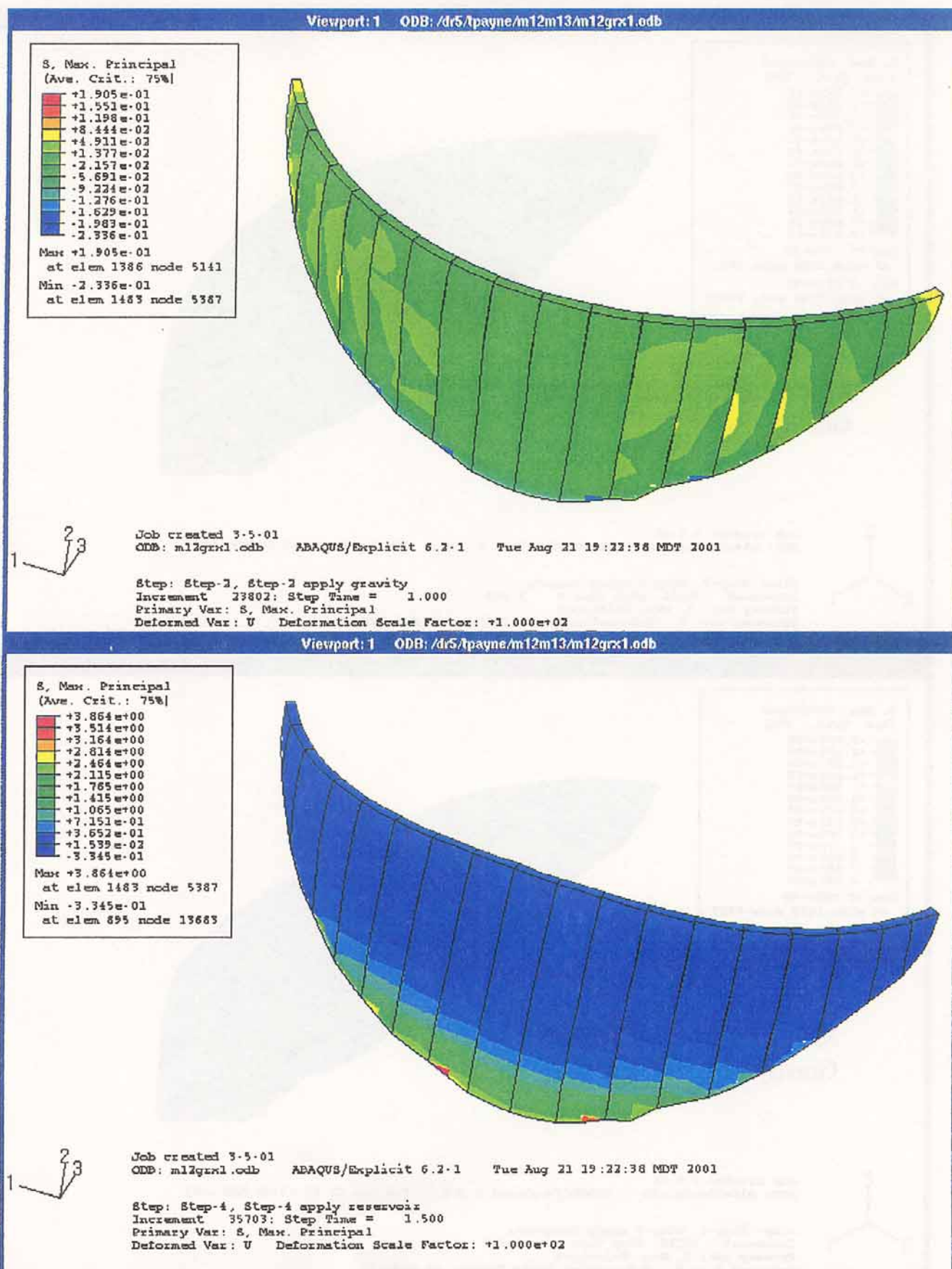
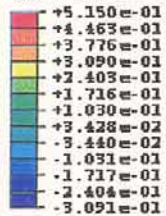


Figure E.41

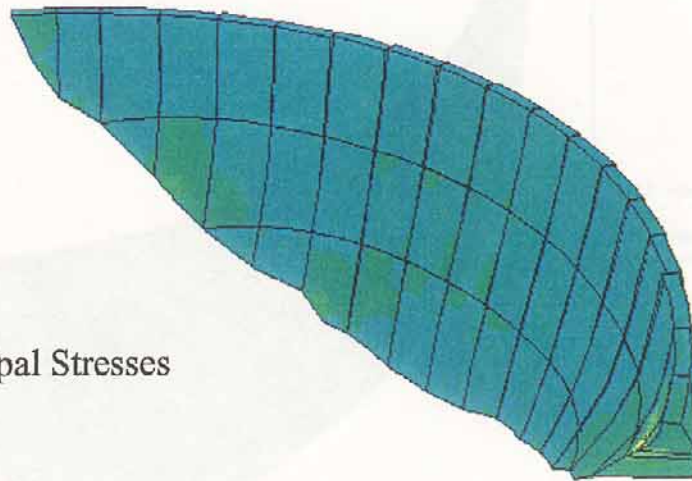
Seventeen Vertical & Two Horizontal Joint Model M14 & M15

Viewport: 1 ODB: /dr6/apayne/m14m15/m14m15orig.odb

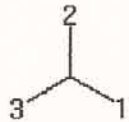
S, Max. Principal
(Ave. Crat.: 75%)



Max +5.150e-01
at elem 1321 node 4931
Min -3.091e-01
at elem 1351 node 13837



Maximum Principal Stresses
Gravity Load

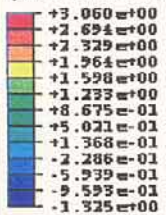


Job created 3-5-01
ODB: m14m15orig.odb ABAQUS/Explicit 6.2-1 Fri Aug 31 13:57:19 MDT 2001

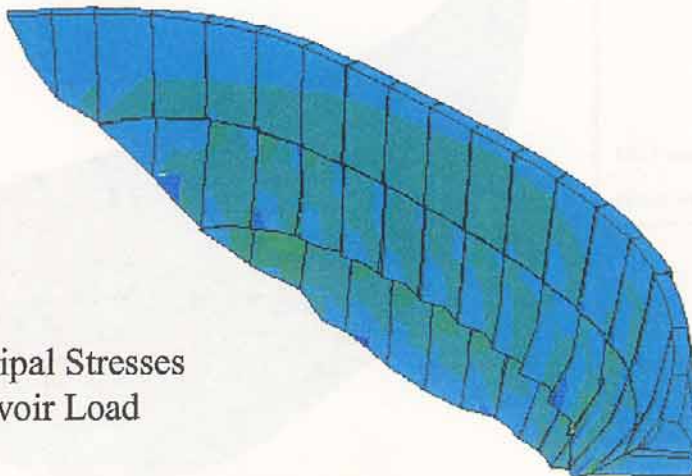
Step: Step-2, Step-2 apply gravity
Increment 25424: Step Time = 1.000
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+02

Viewport: 1 ODB: /dr6/apayne/m14m15/m14m15orig.odb

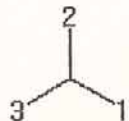
S, Max. Principal
(Ave. Crat.: 75%)



Max +3.060e+00
at elem 1483 node 5387
Min -1.325e+00
at elem 745 node 13879



Maximum Principal Stresses
Gravity + Reservoir Load



Job created 3-5-01
ODB: m14m15orig.odb ABAQUS/Explicit 6.2-1 Fri Aug 31 13:57:19 MDT 2001

Step: Step-4, Step-4 apply reservoir
Increment 38136: Step Time = 1.500
Primary Var: S, Max. Principal
Deformed Var: U Deformation Scale Factor: +1.000e+02

Figure E.42

Seventeen Vertical & Two Horizontal Joint Model M14 & M15

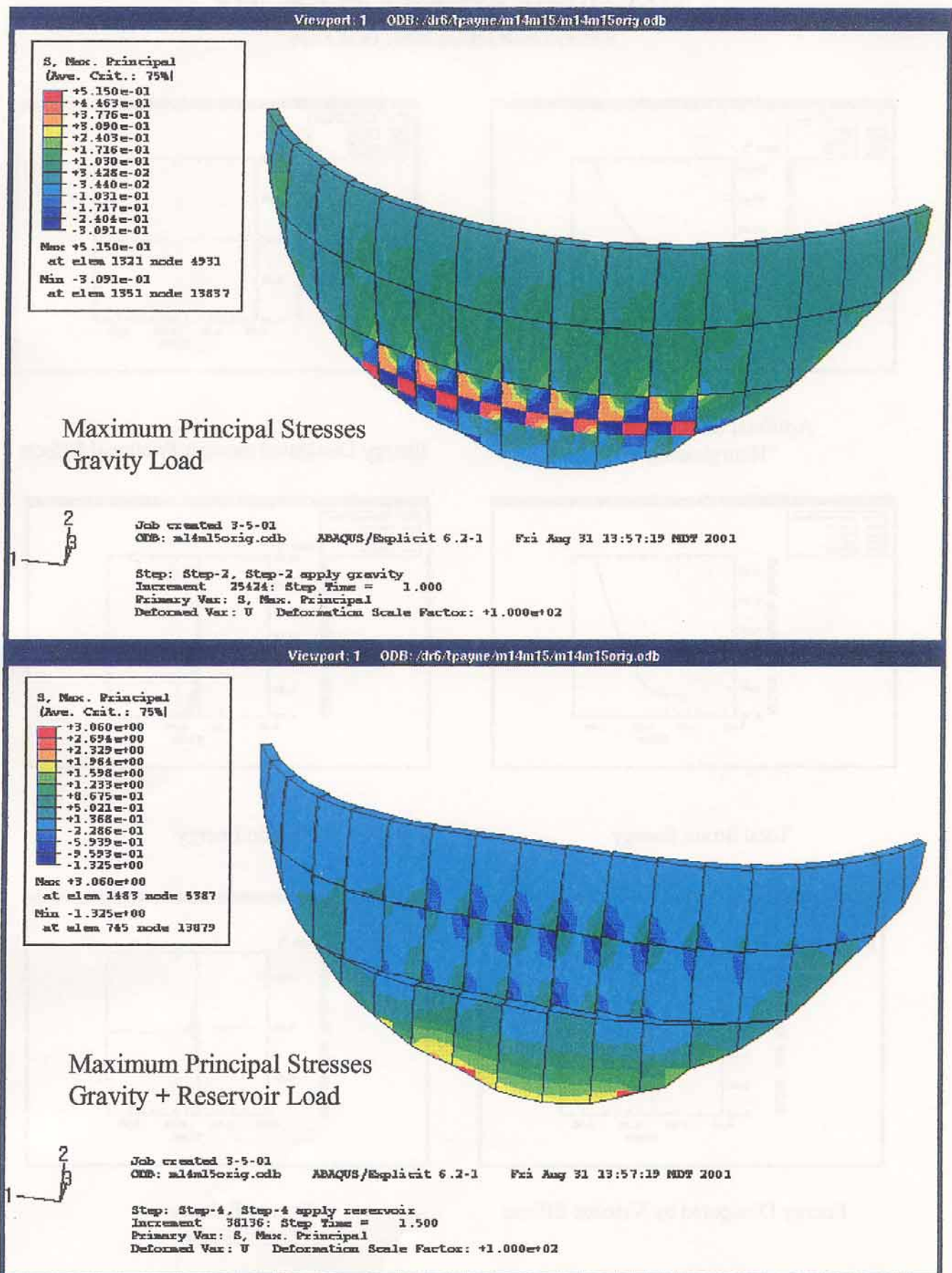
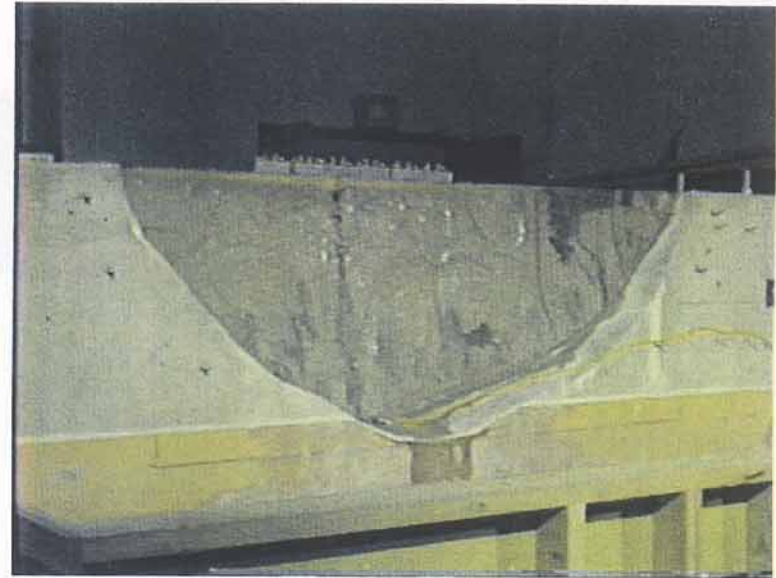


Figure E.43

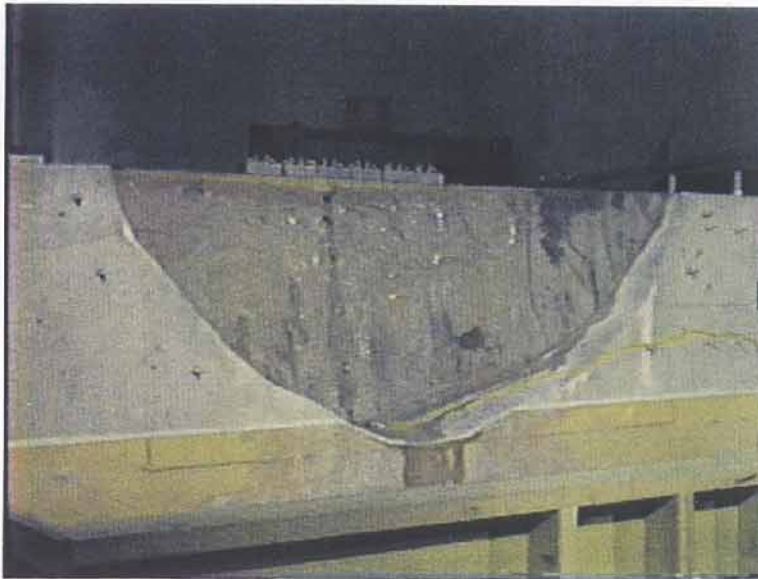
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



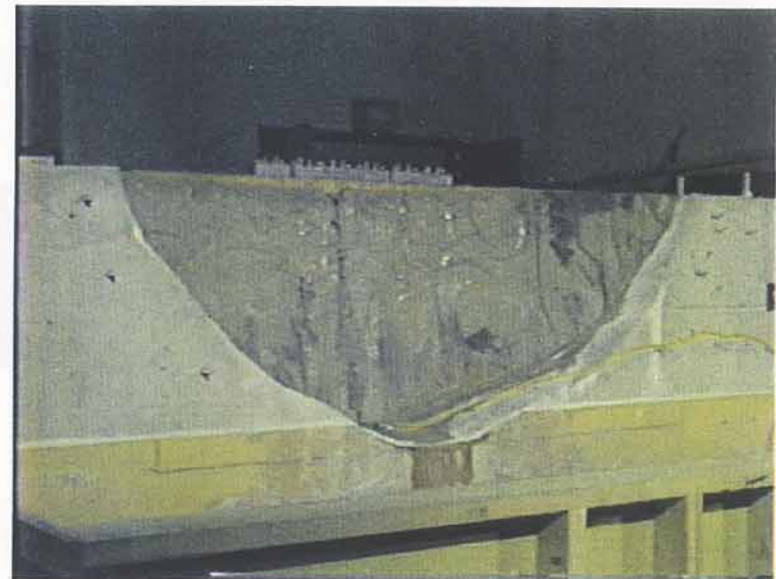
Time = 00.00 second.frame



Time = 00.33 second.frame



Time = 00.66 second.frame

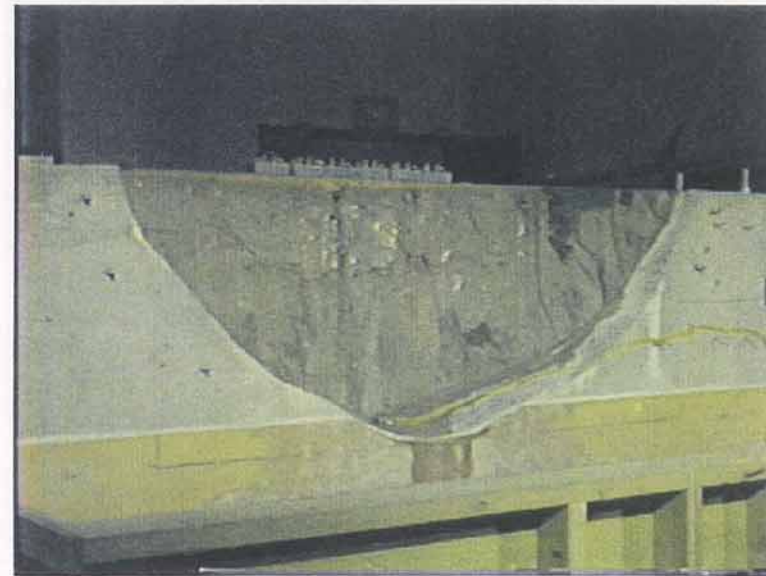


Time = 01.00 second.frame

Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



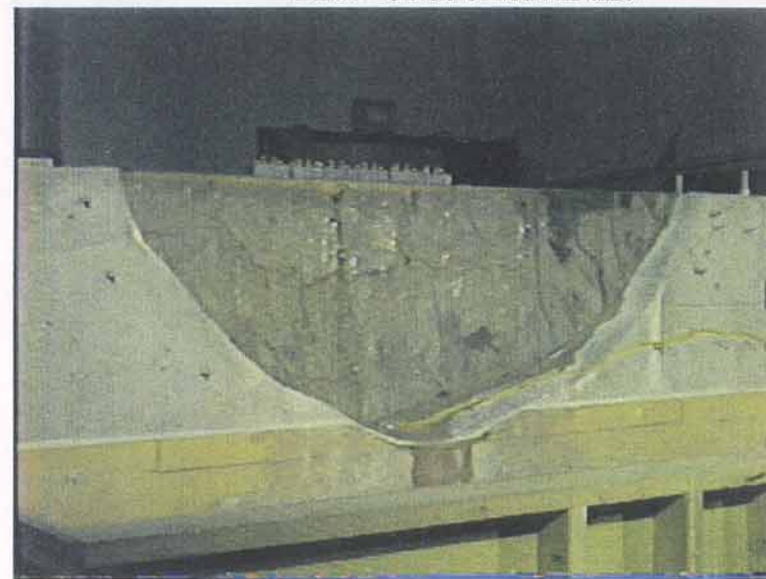
Time = 01.33 second.frame



Time = 01.66 second.frame



Time = 02.00 second.frame

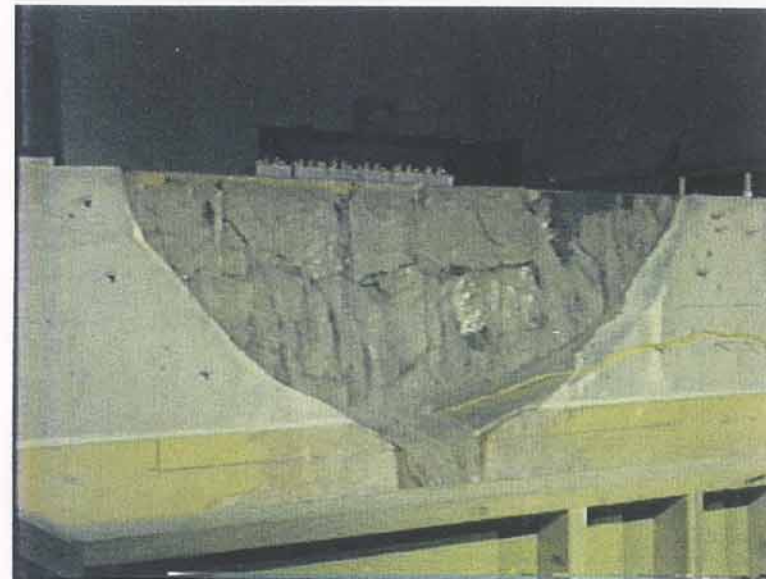


Time = 02.33 second.frame

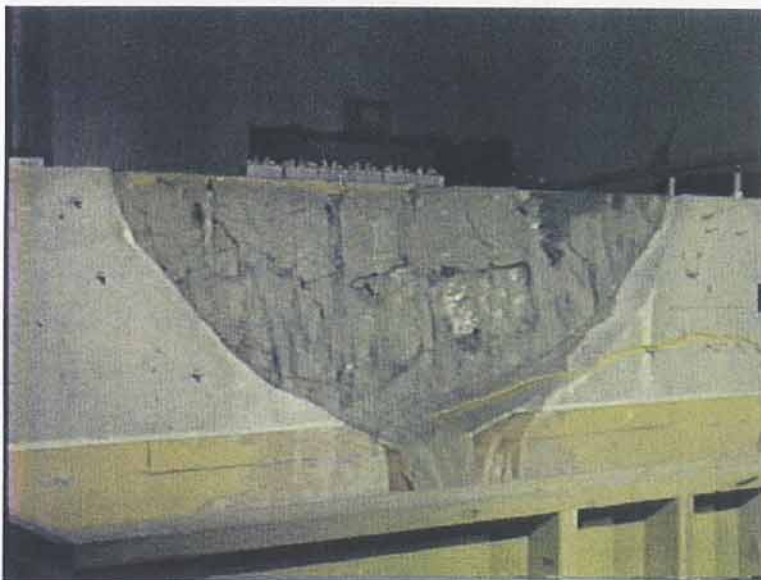
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



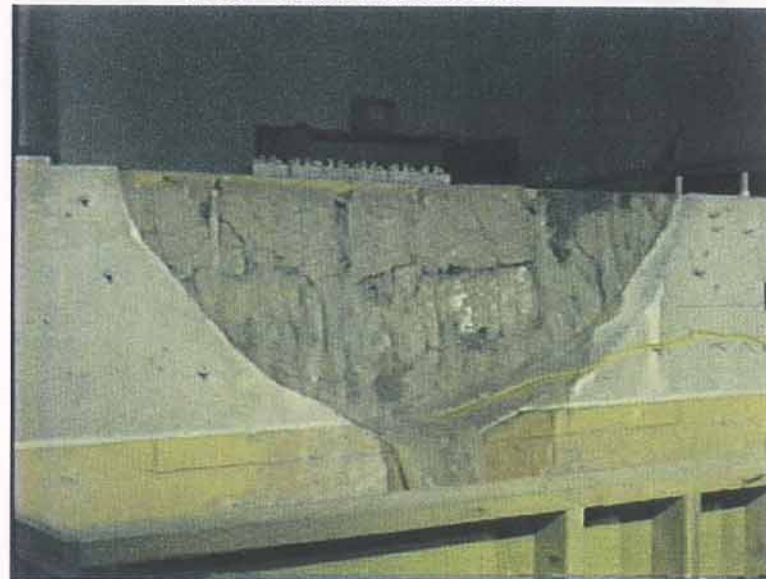
Time = 09.33 second.frame



Time = 09.66 second.frame



Time = 10.00 second.frame

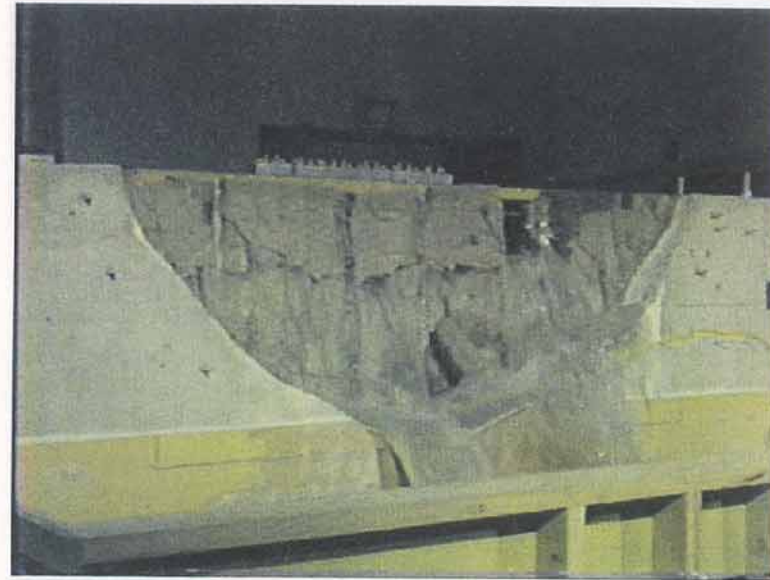


Time = 10.33 second.frame

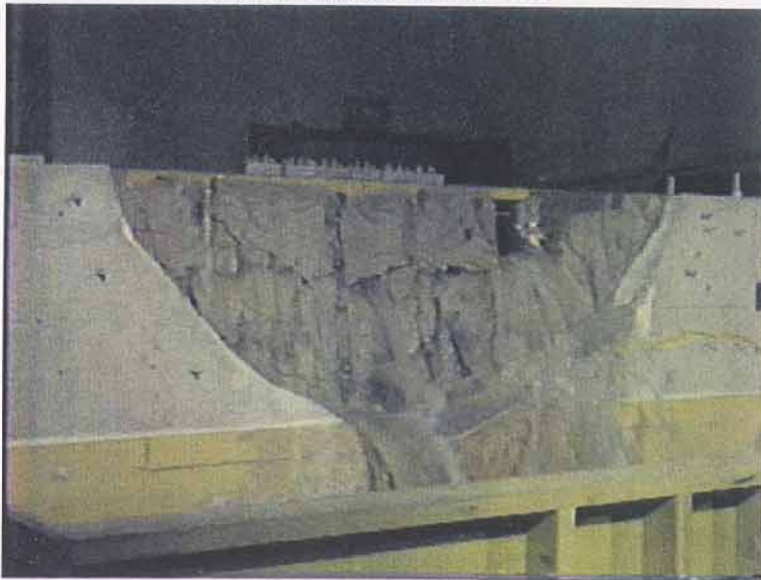
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



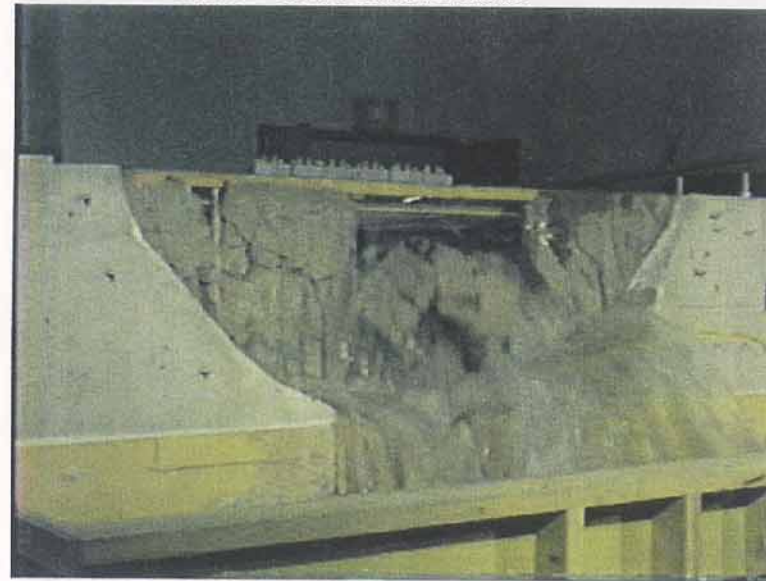
Time = 10.66 second.frame



Time = 11.00 second.frame



Time = 11.33 second.frame



Time = 11.66 second.frame

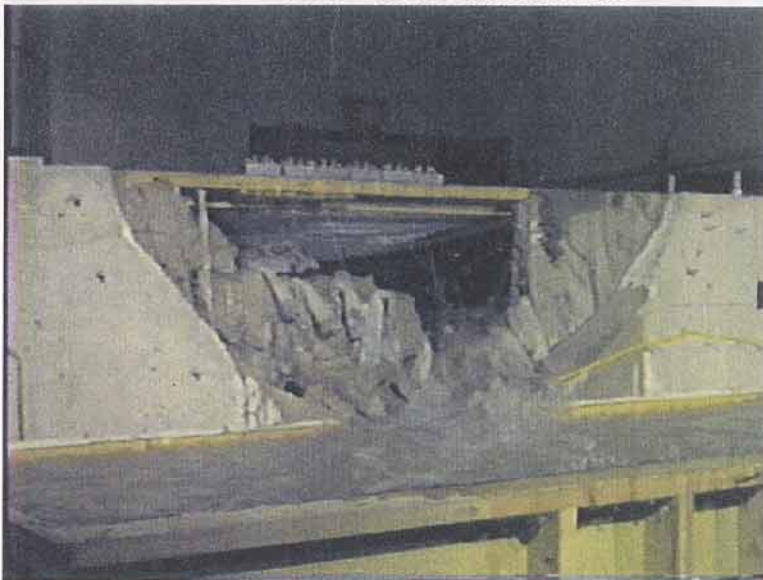
Crack patterns which developed during the shake table test of seventeen vertical & two horizontal joint model : Model M15



Time = 15.00 second.frame



Time = 15.33 second.frame



Time = 15.66 second.frame

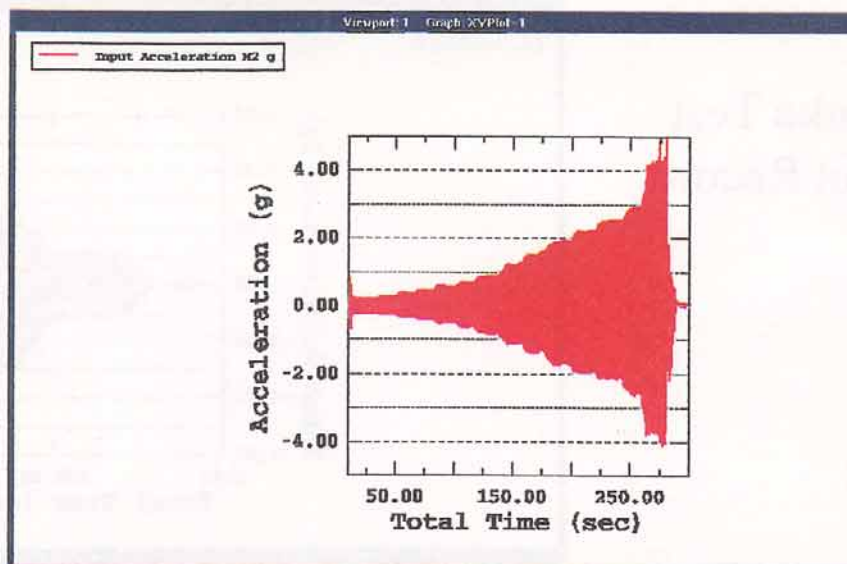


Time = 16.00 second.frame

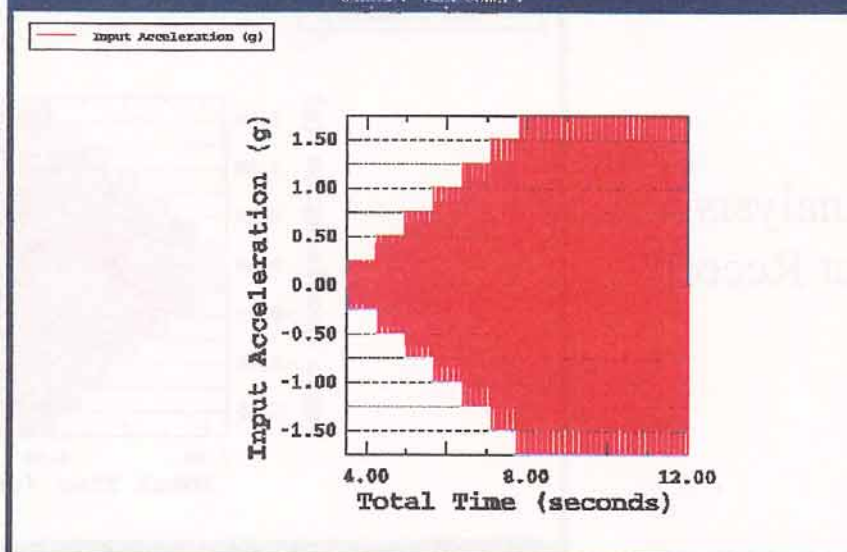
Input Accelerations : Model M2

Monolithic Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .50 g

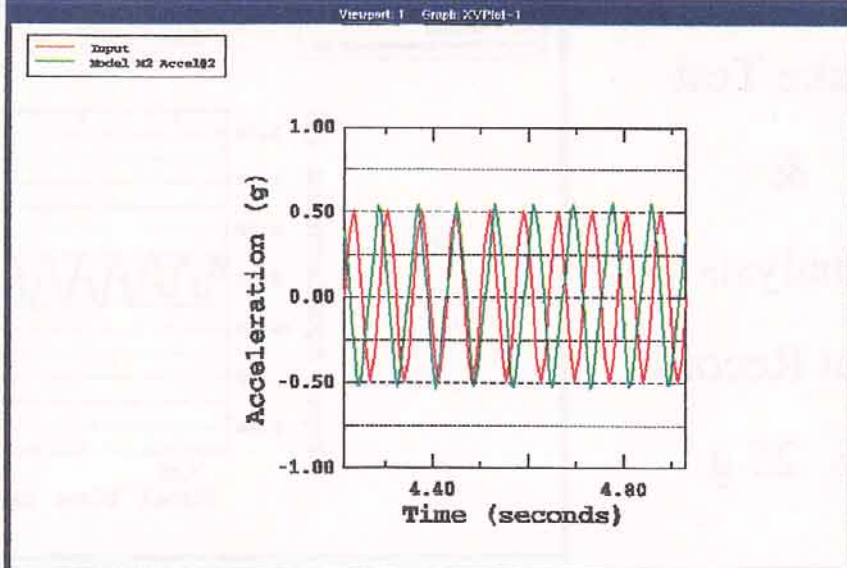
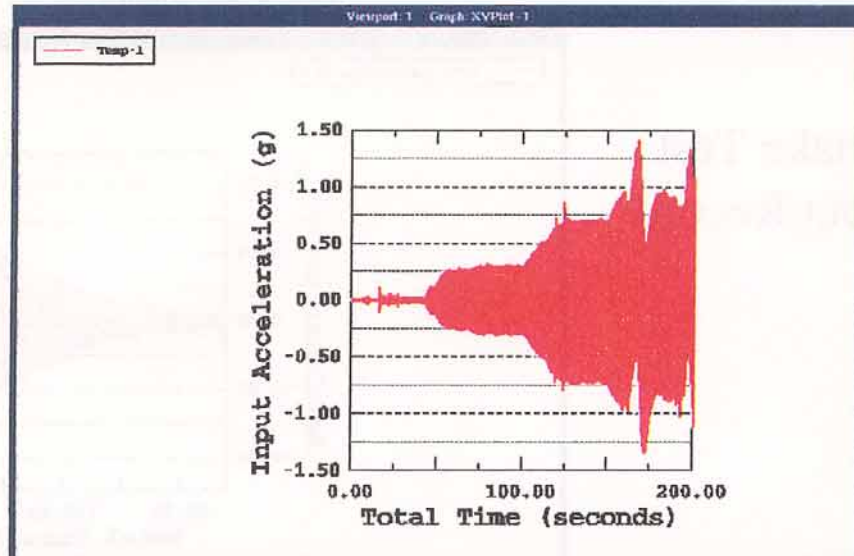


Figure F.15

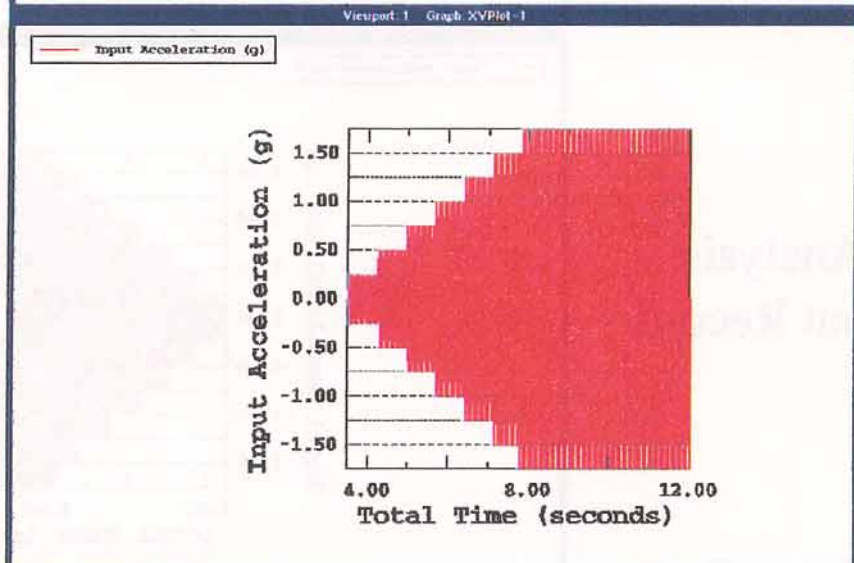
Input Accelerations : Model M6

Single Vertical Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .25 g

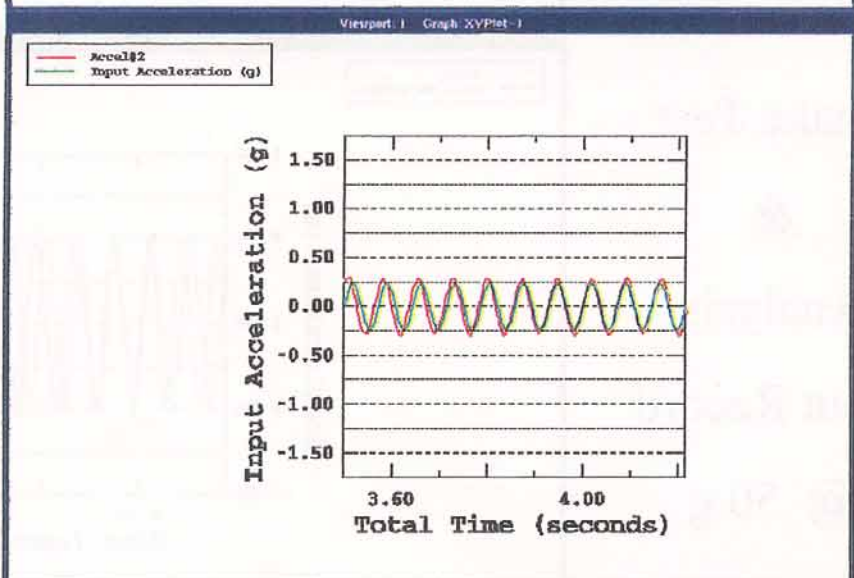
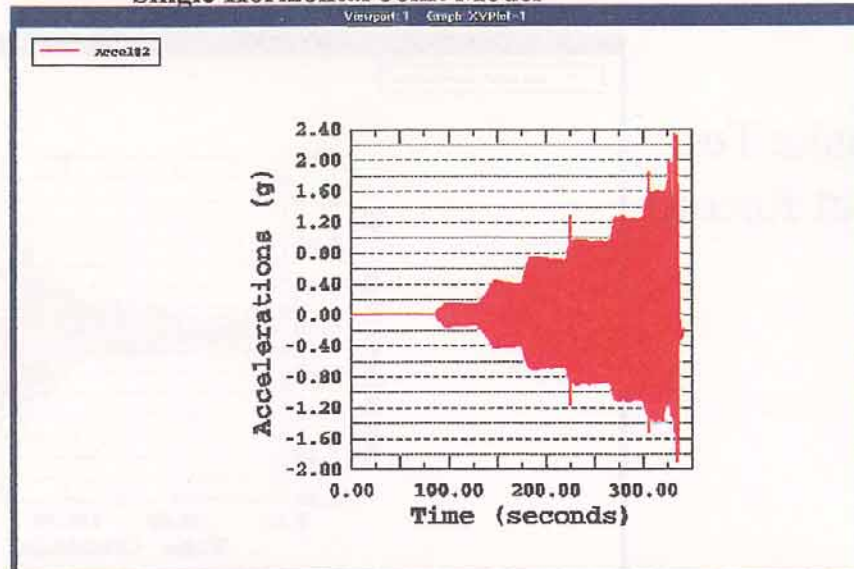


Figure F.16

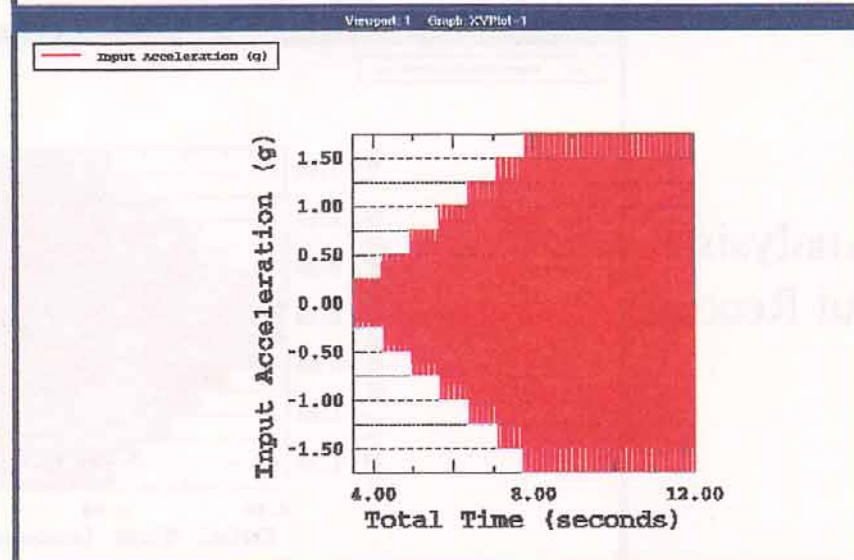
Input Accelerations : Model M10

Shake Test
Input Record

Single Horizontal Joint Model



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ 1.0 g

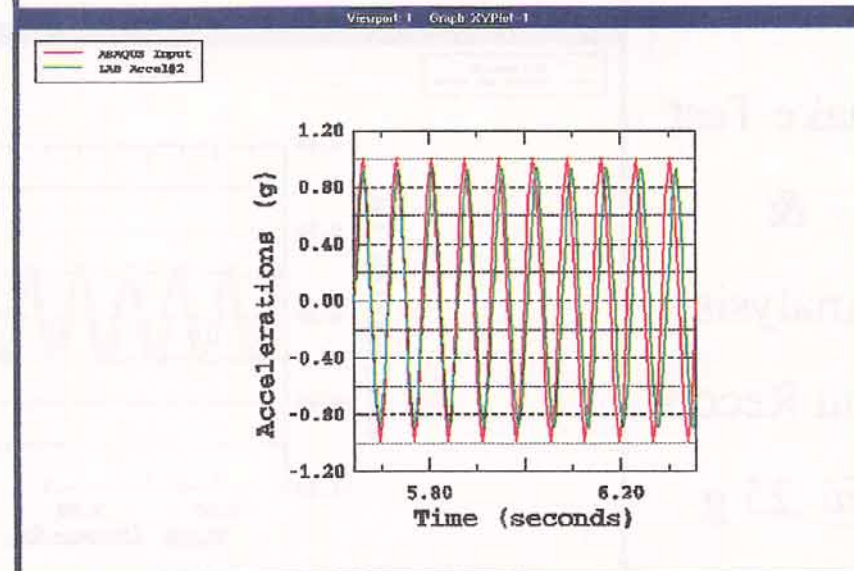
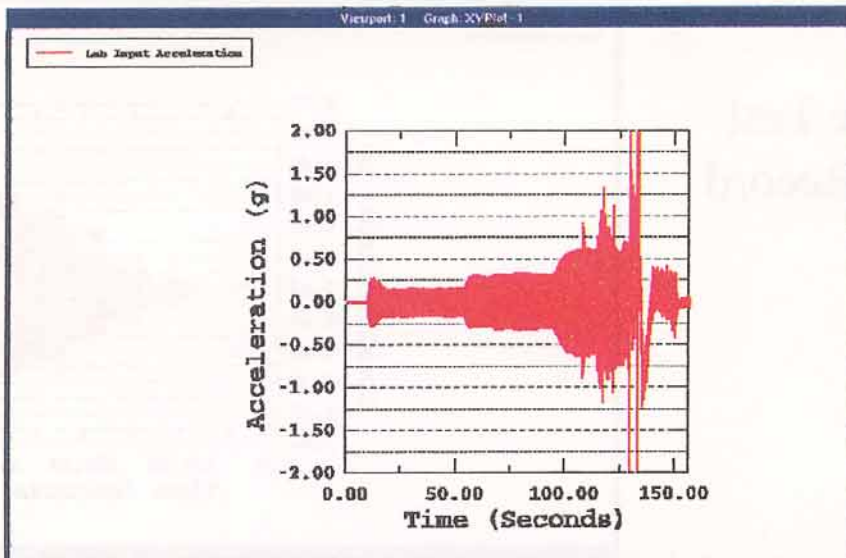


Figure F.17

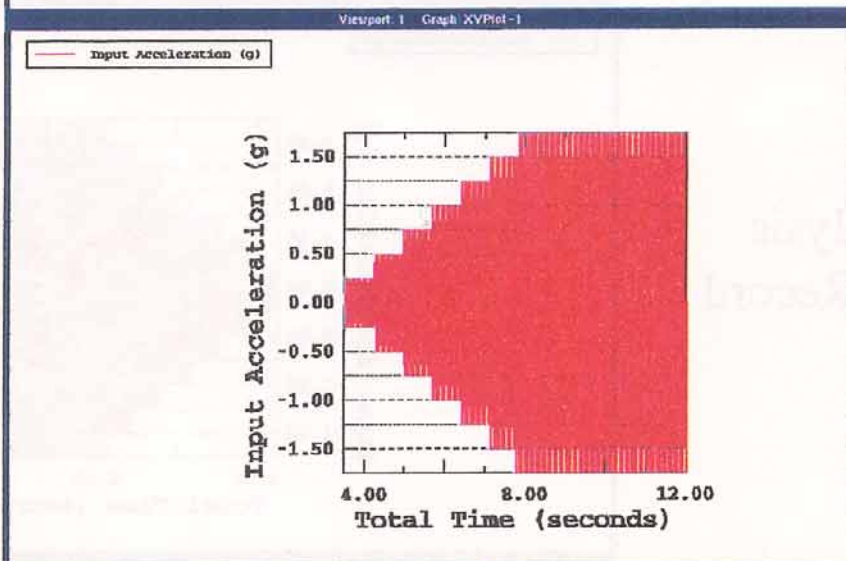
Input Accelerations : Model M13

Seventeen Vertical Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .25 g

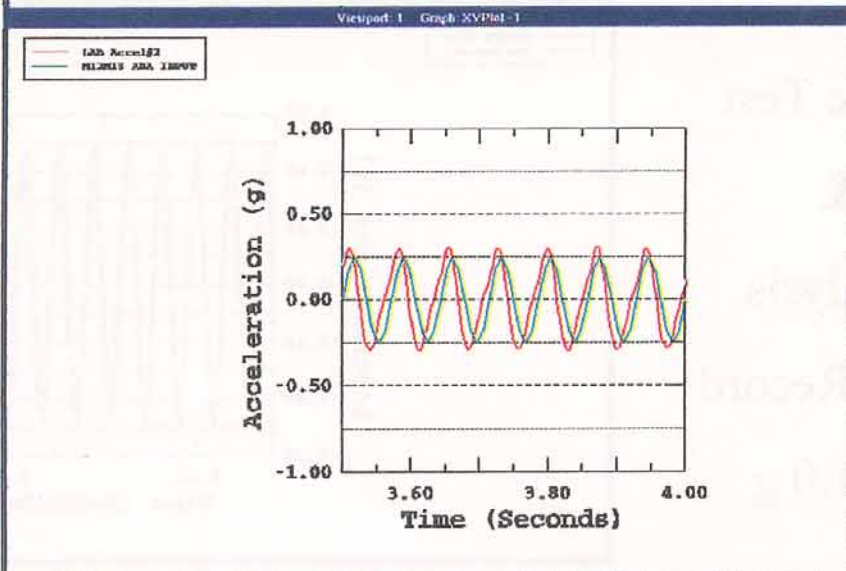
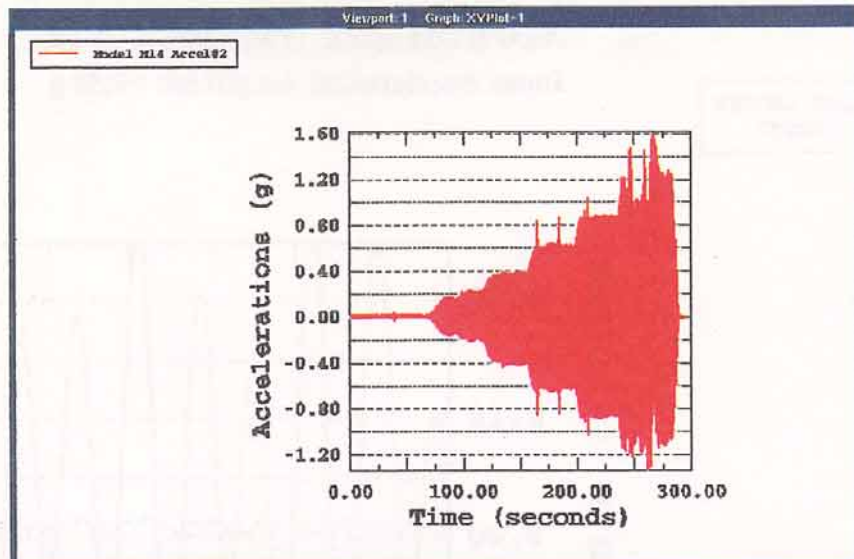


Figure F.18

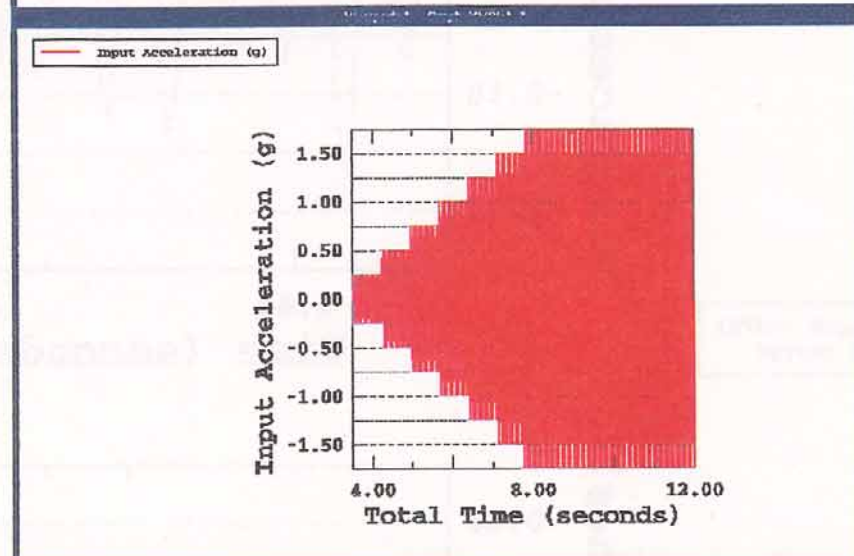
Input Accelerations : Model M14

Seventeen Vertical & Two Horizontal Joint Model

Shake Test
Input Record



Analysis
Input Record



Shake Test
&
Analysis
Input Record
@ .50 g

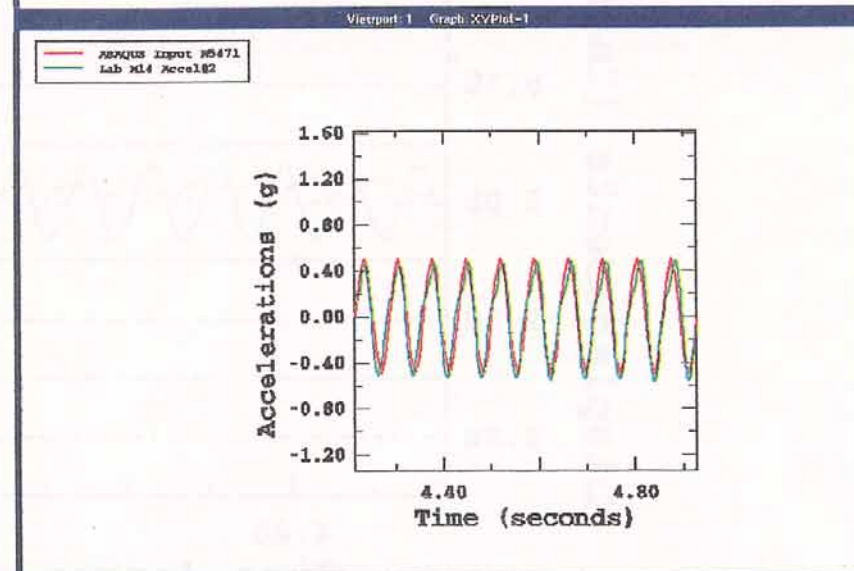
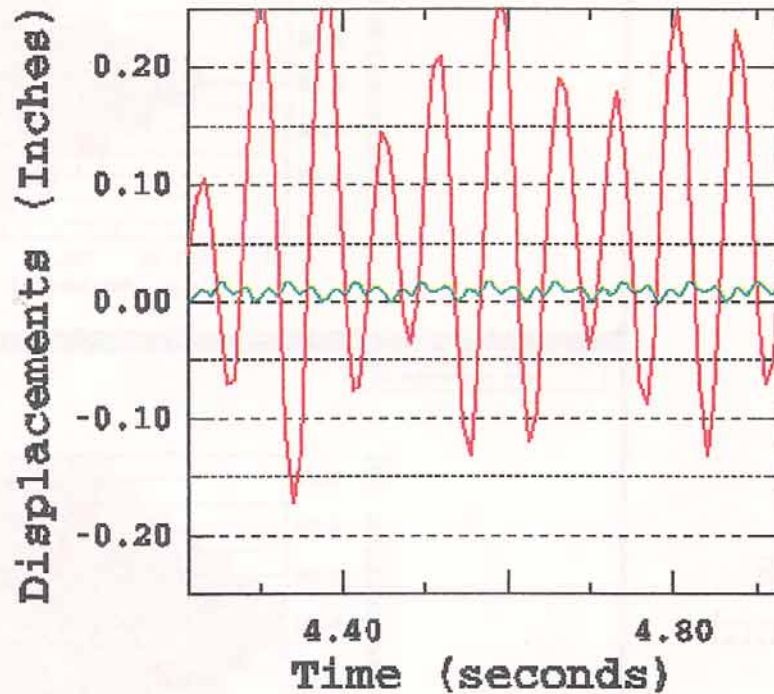


Figure F.19

Displacements Measured Versus Calculated Monolithic Model : M2

Input Acceleration Amplitude = 0.50 g

ABAQUS LVDT#2
LAB LVDT#2



ABAQUS LVDT#1
LAB LVDT#1

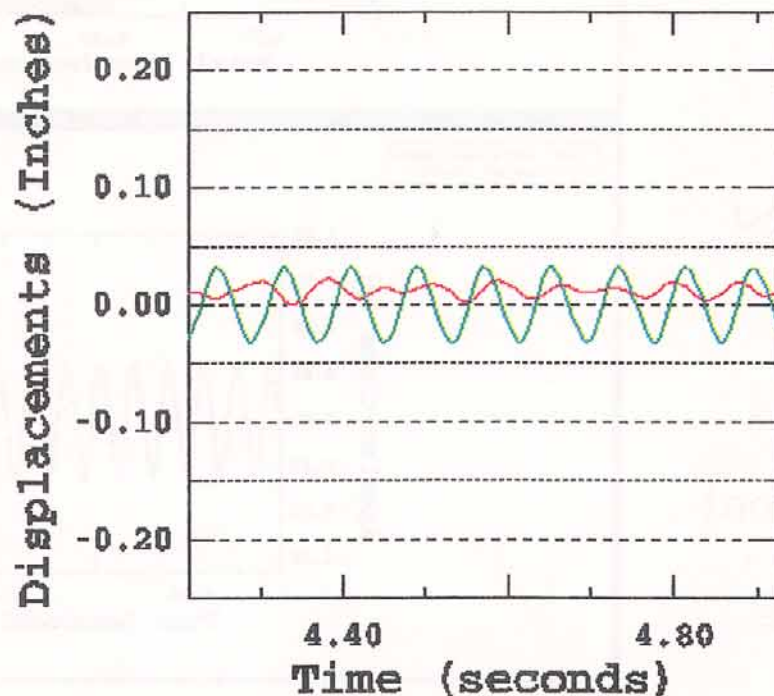
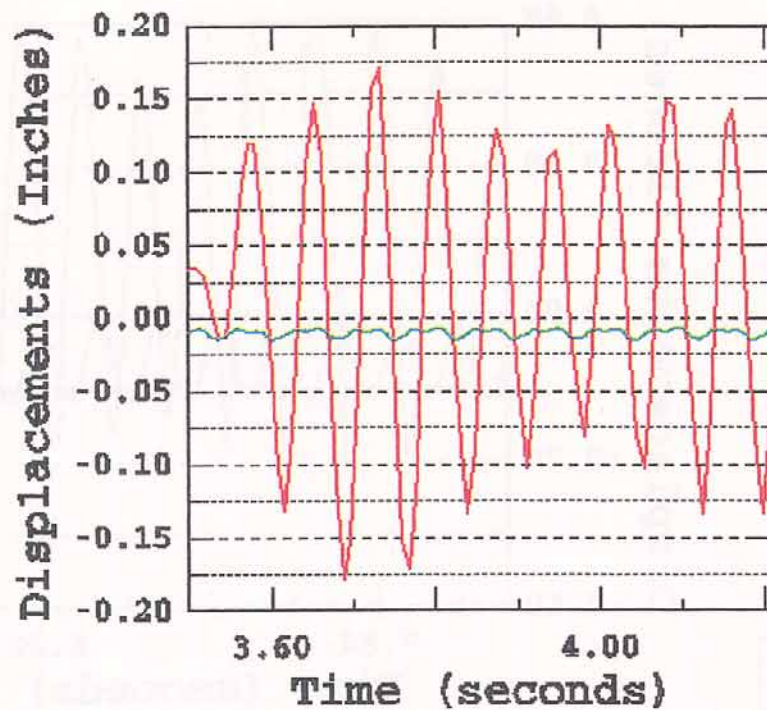


Figure F.20

Displacements Measured Versus Calculated Single Vertical Joint Model : M6

Input Acceleration Amplitude = 0.25 g

ABAQUS LVD1#2
LAB LVD1#2



ABAQUS LVD1#1
LAB LVD1#1

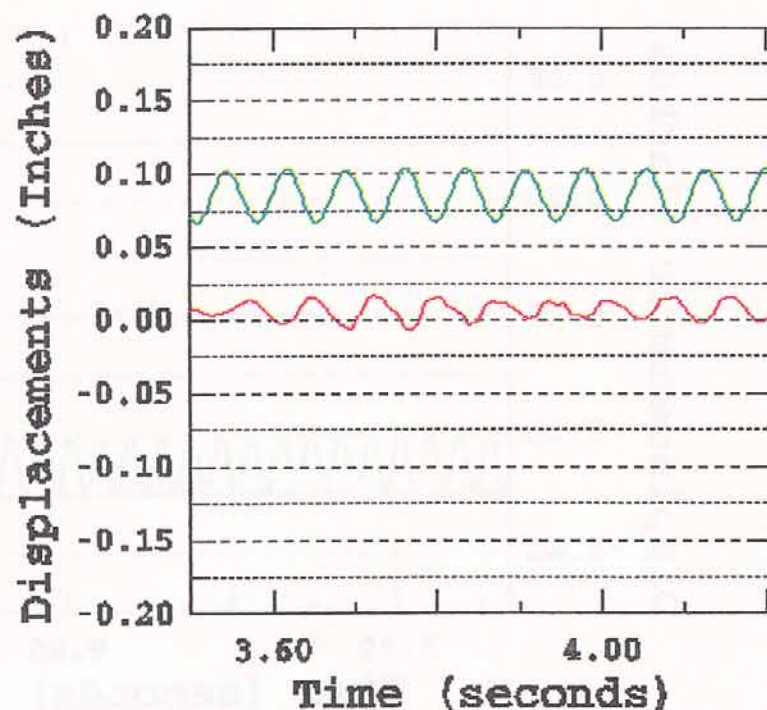


Figure F.21

Displacements Measured Versus Calculated Single Horizontal Joint Model : M10

Input Acceleration Amplitude = 1.0 g

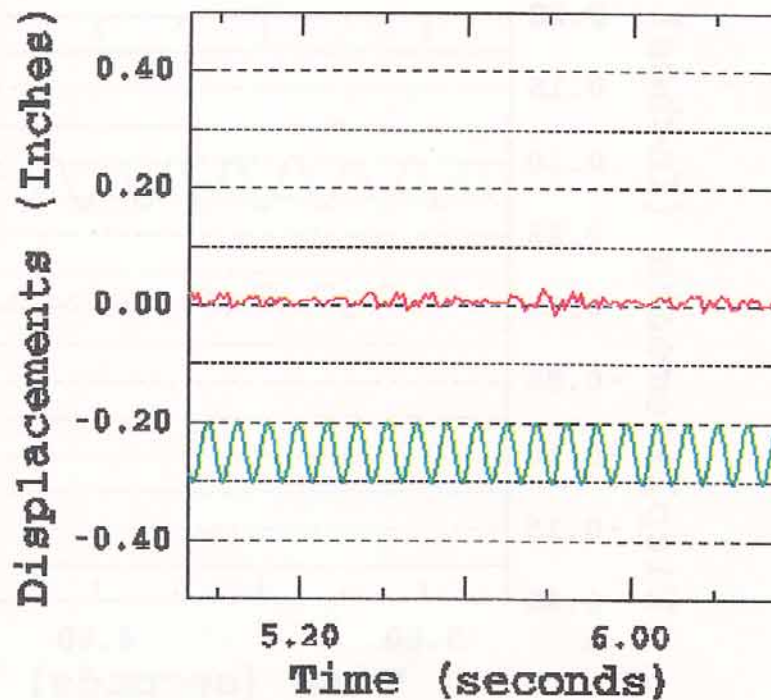
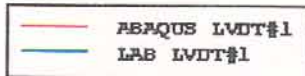
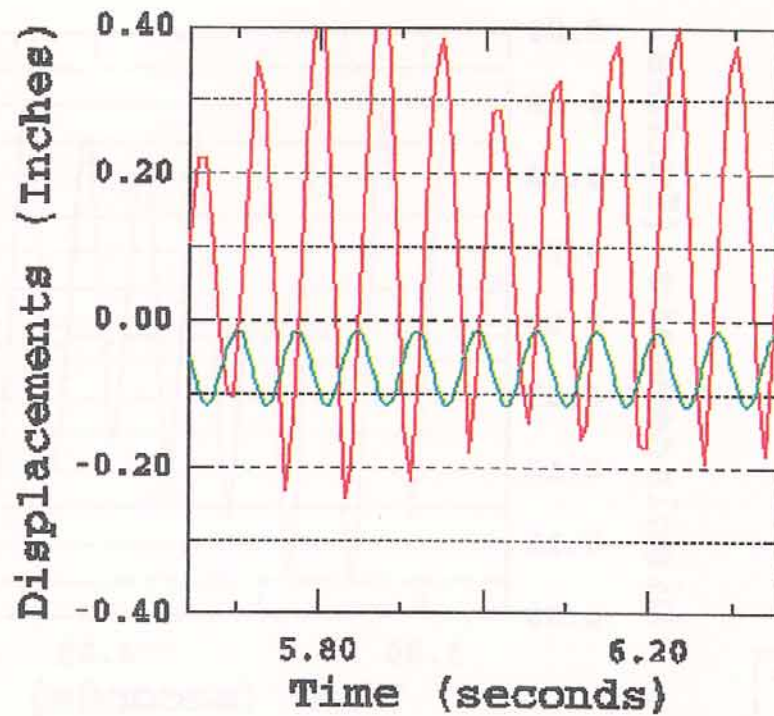
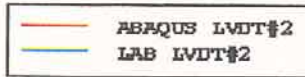
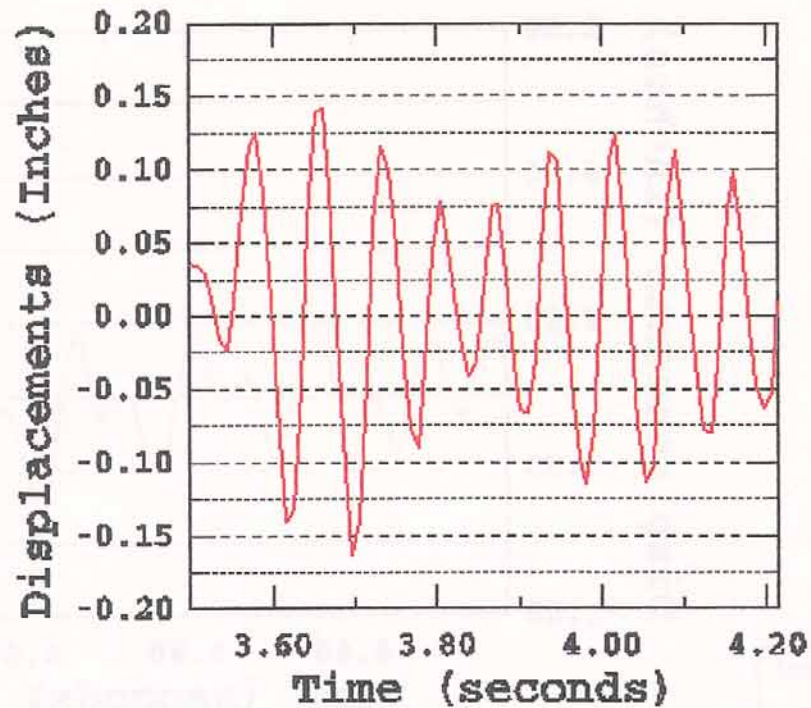


Figure F.22

Displacements Measured Versus Calculated Seventeen Vertical Joint Model : M13

Input Acceleration Amplitude = 0.25 g

ABAQUS LVDT#2



ABAQUS LVDT#1
LAS LVDT#1

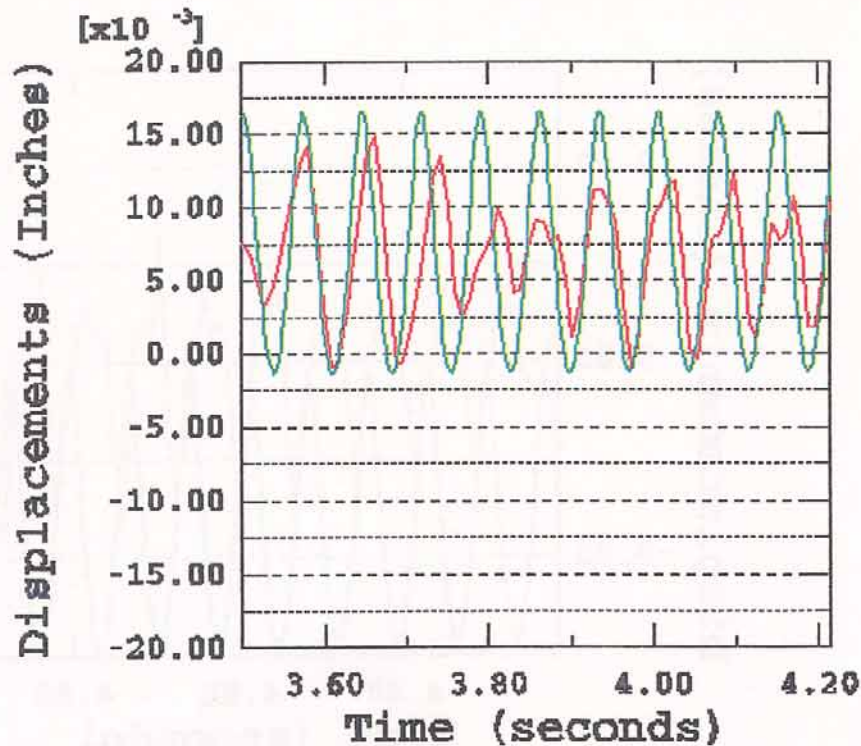


Figure F.23

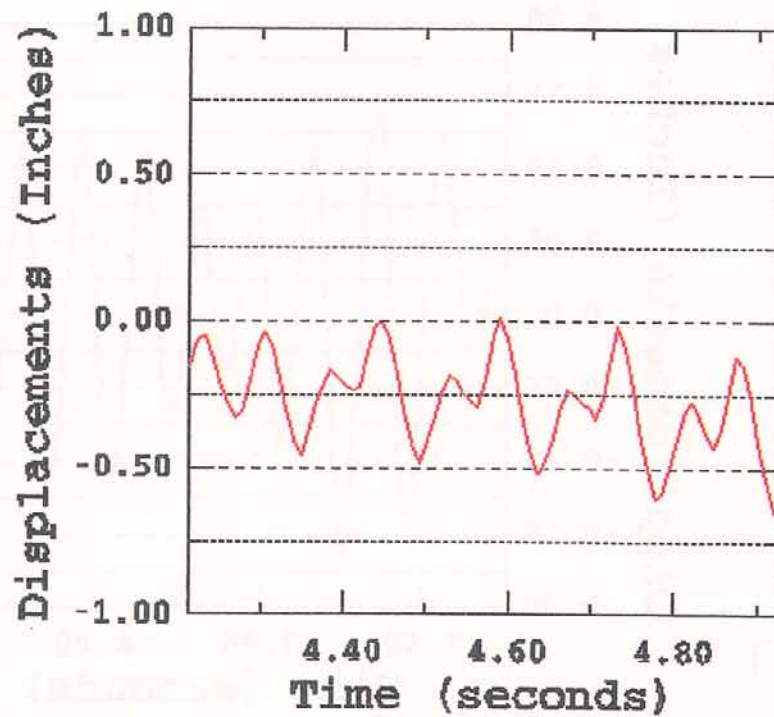
Displacements

Measured Versus Calculated

Seventeen Vertical & Two Horizontal Joint Model : M14

Input Acceleration Amplitude = 0.50 g

ABAQUS LVDT#2



ABAQUS LVDT#1
LAB LVDT#1

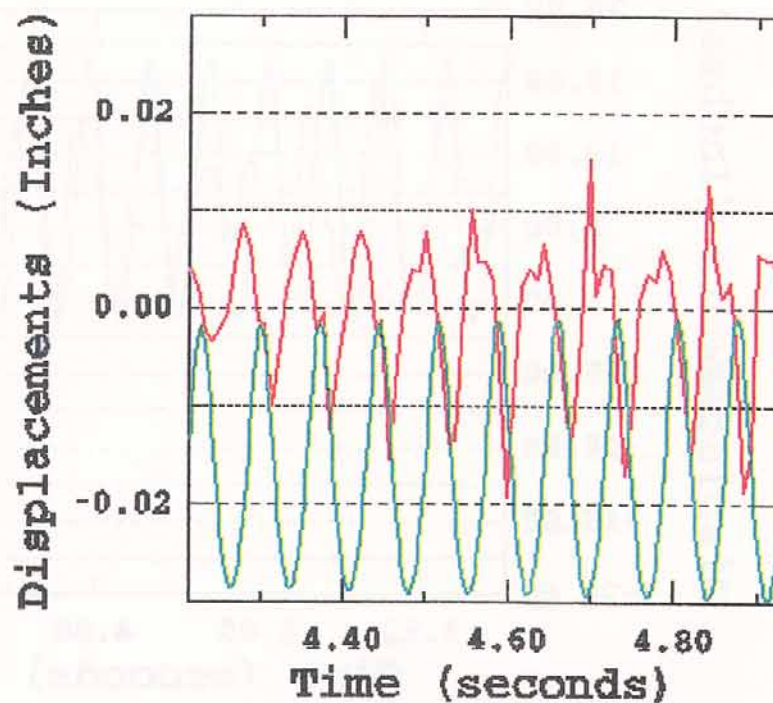
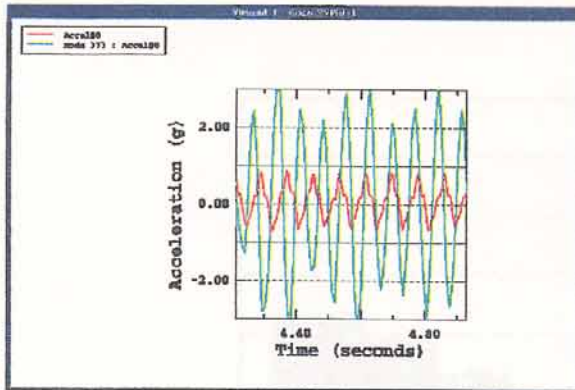


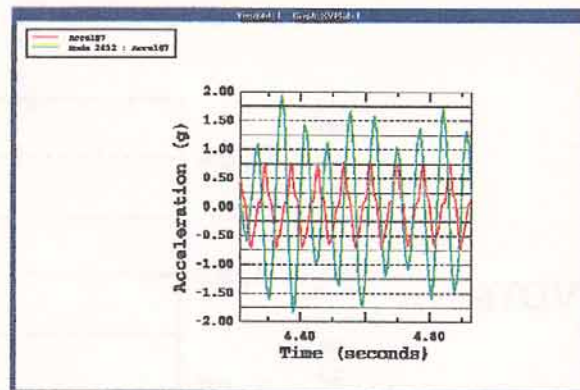
Figure F.24

Monolithic Model : M2

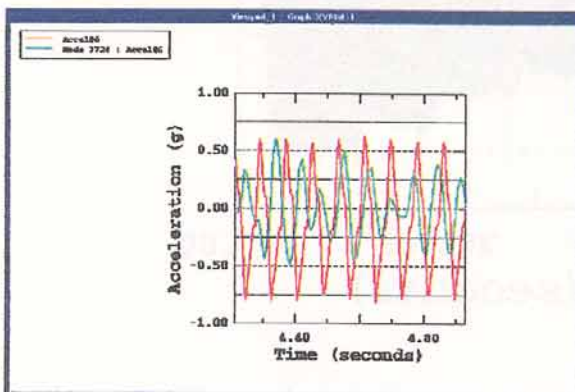
Comparison of Measured Versus Calculated Accelerations



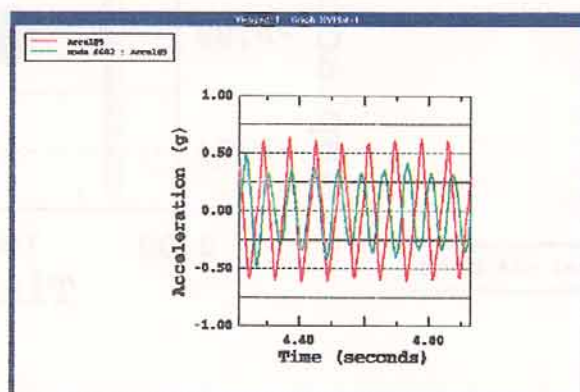
Accel #8



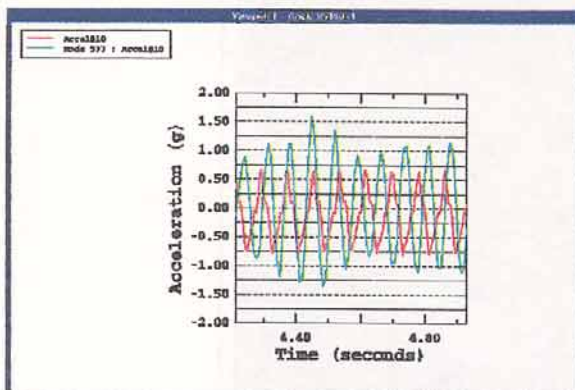
Accel #7



Accel #6

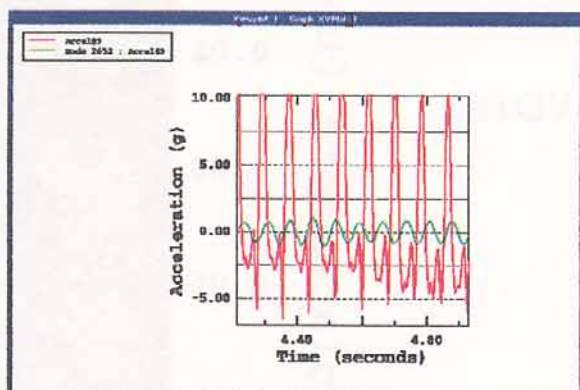


Accel #5



Accel #10

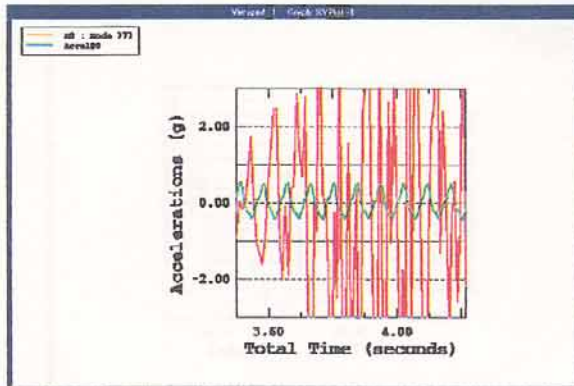
Green = Analysis
Red = Laboratory



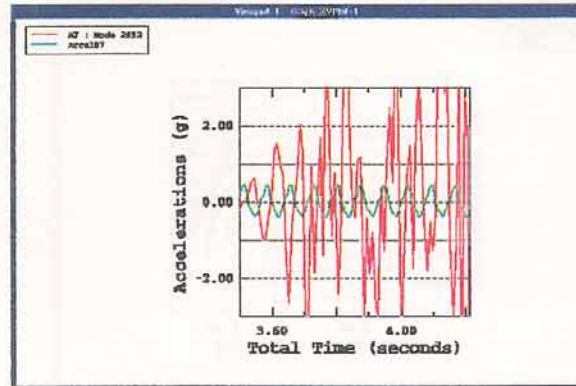
Accel #9

Single Vertical Joint Model : M6

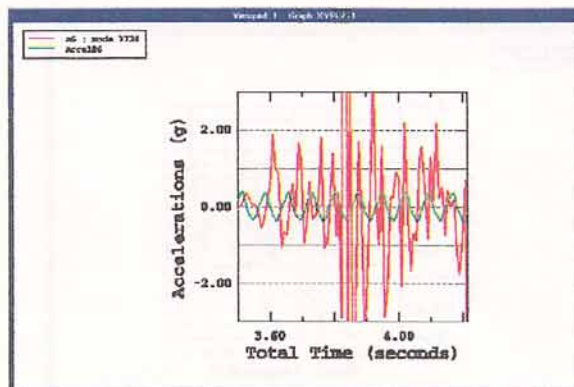
Comparison of Measured Versus Calculated Accelerations



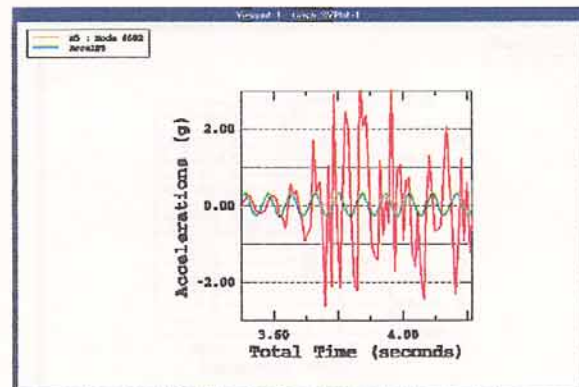
Accel #8



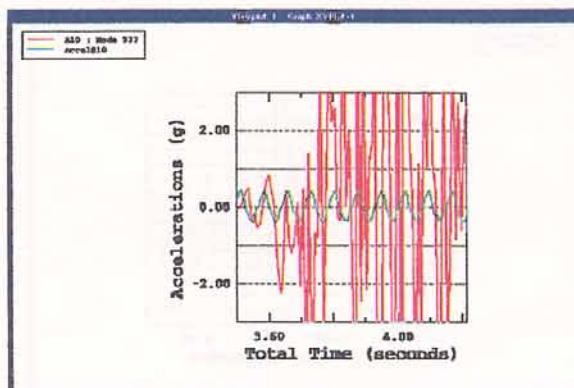
Accel #7



Accel #6

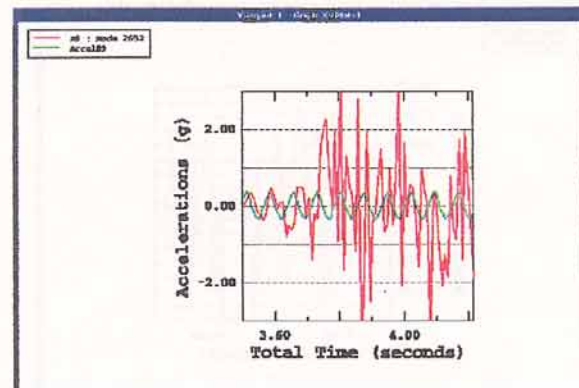


Accel #5



Accel #10

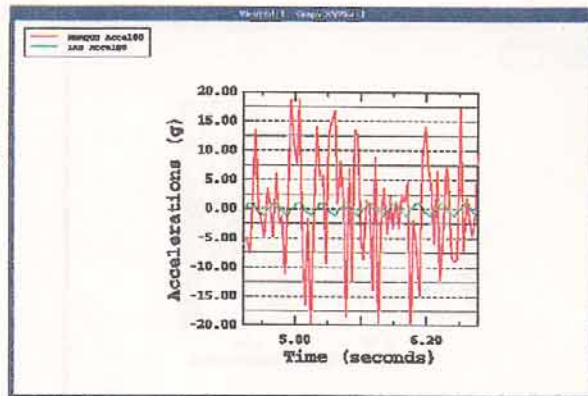
Red = Analysis
Green = Laboratory



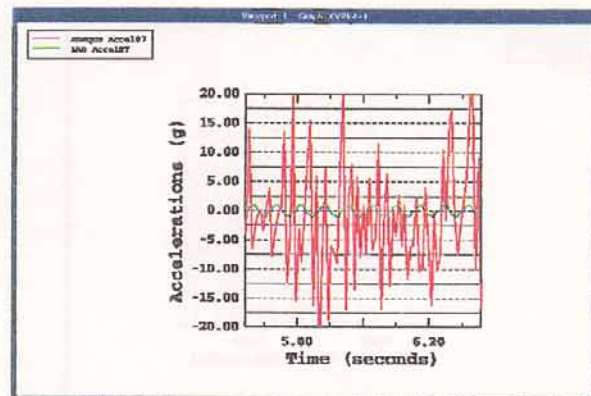
Accel #9

Single Horizontal Joint Model : M10

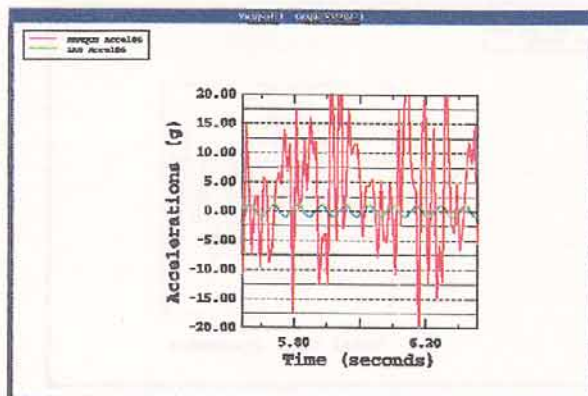
Comparison of Measured Versus Calculated Accelerations



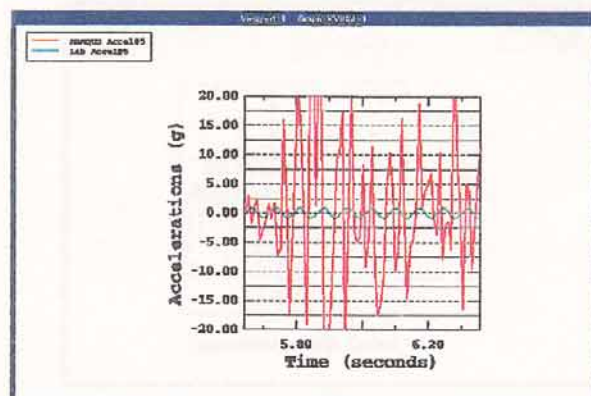
Accel #8



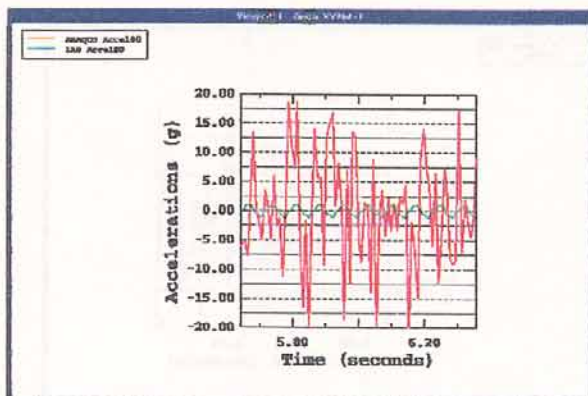
Accel #7



Accel #6

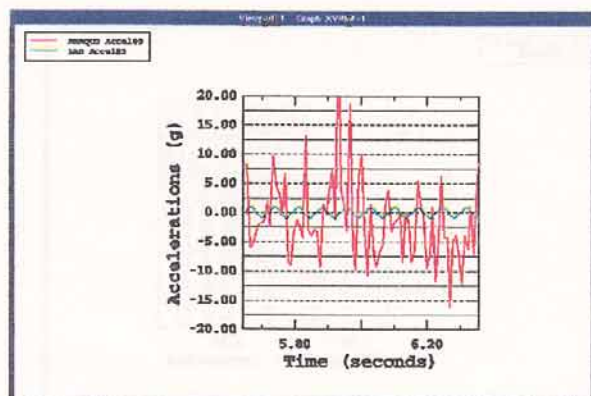


Accel #5



Accel #10

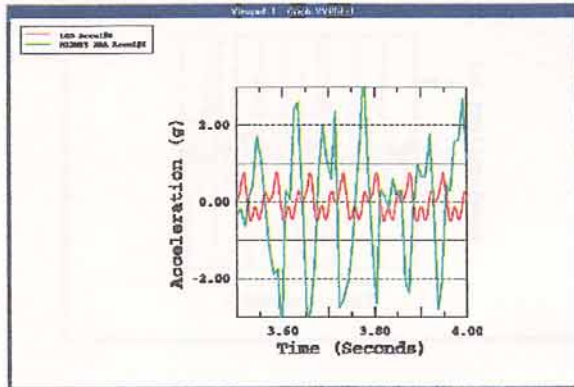
Red = Analysis
Green = Laboratory



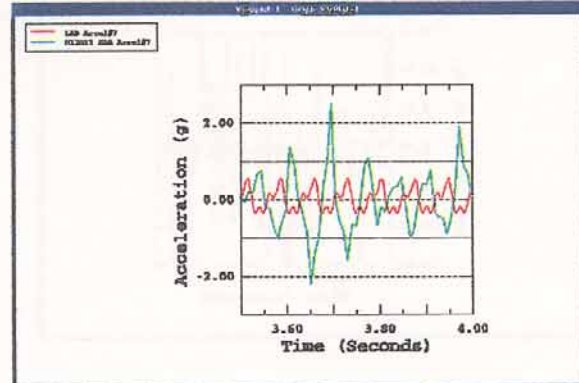
Accel #9

Seventeen Vertical Joint Model : M13

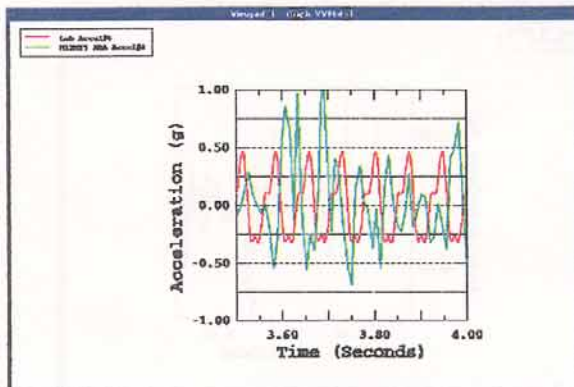
Comparison of Measured Versus Calculated Accelerations



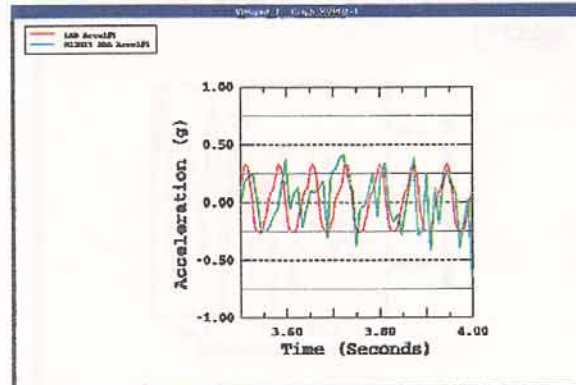
Accel #8



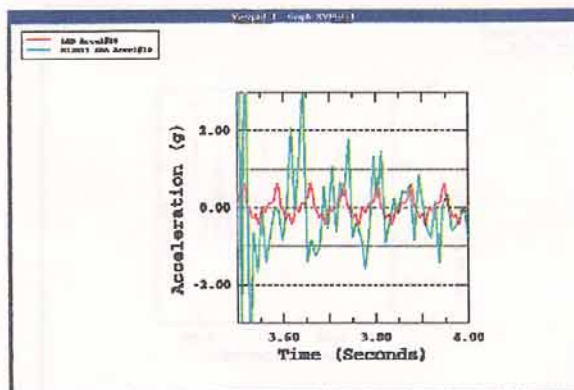
Accel #7



Accel #6

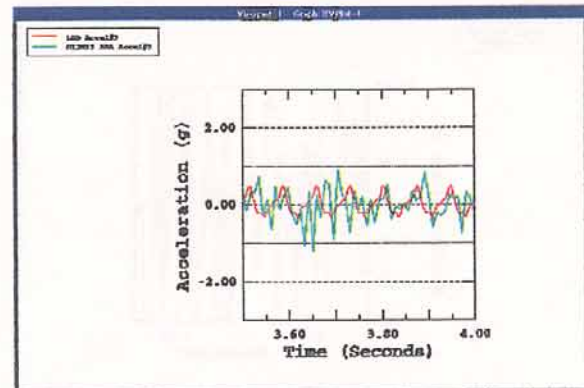


Accel #5



Accel #10

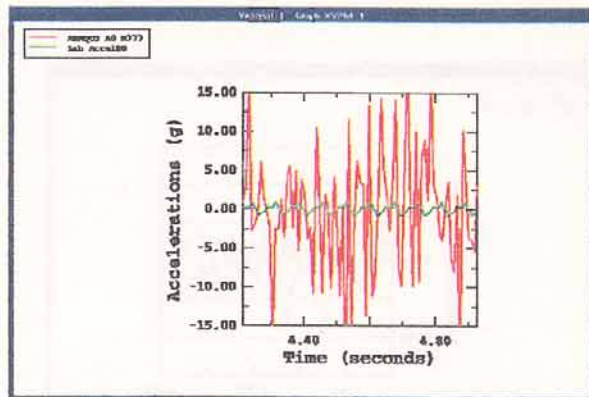
Green = Analysis
Red = Laboratory



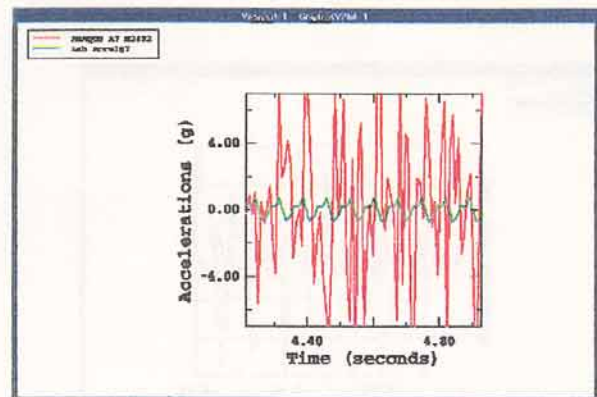
Accel #9

Seventeen Vertical & Two Horizontal Joint Model : M14

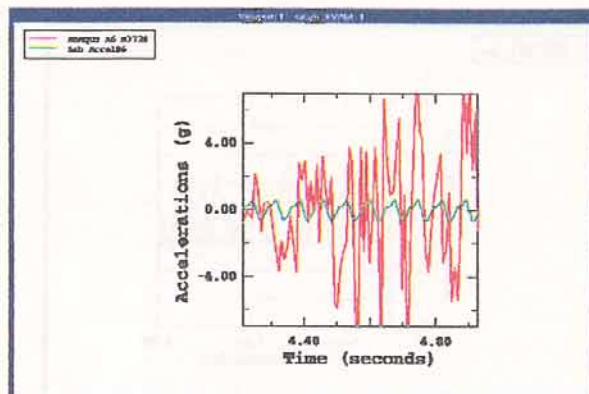
Comparison of Measured Versus Calculated Accelerations



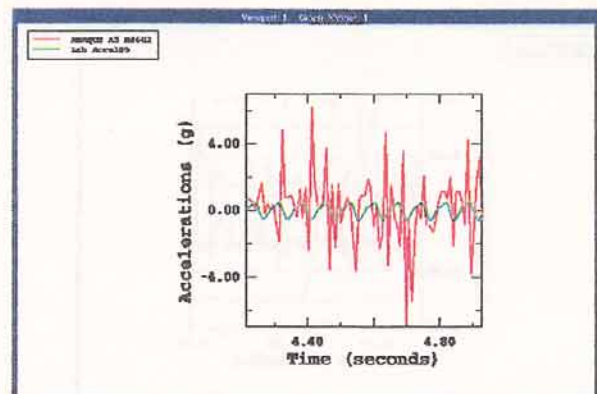
Accel #8



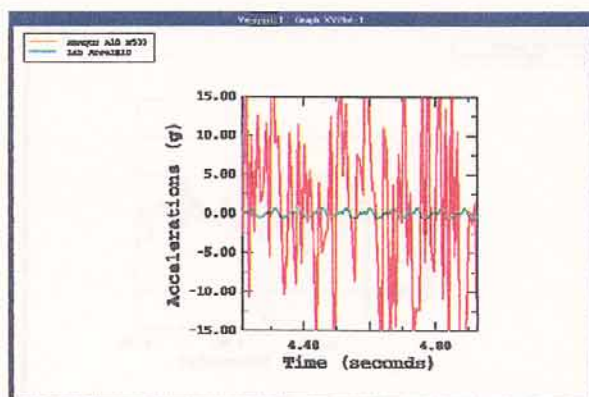
Accel #7



Accel #6

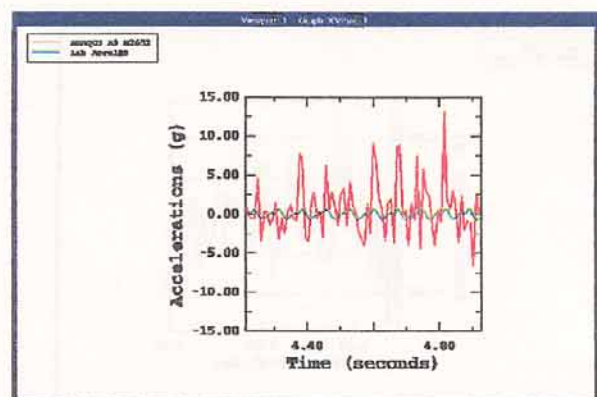


Accel #5

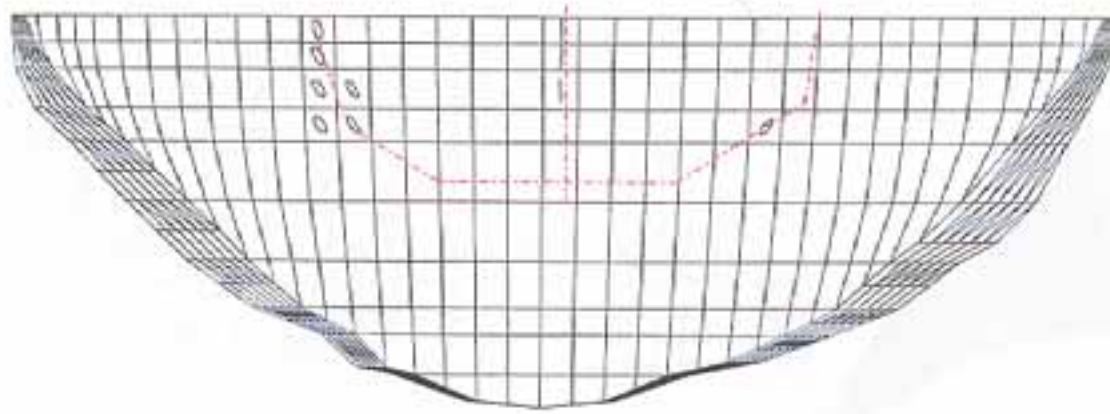


Accel #10

Red = Analysis
Green = Laboratory



Accel #9



Monolithic Model
Analysis M2M8
Laboratory Model M2
Predicted
Versus
Actual Crack Patterns



Figure G.16



Single Vertical Joint Model – Analysis M6M11 – Laboratory Model M11
Predicted Versus Actual Crack Pattern

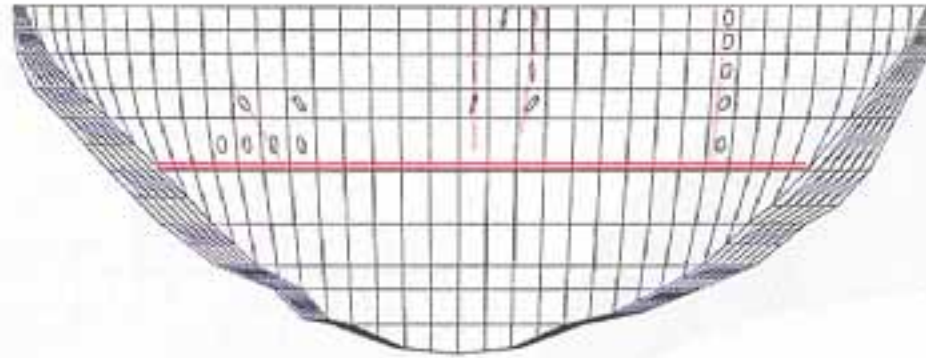
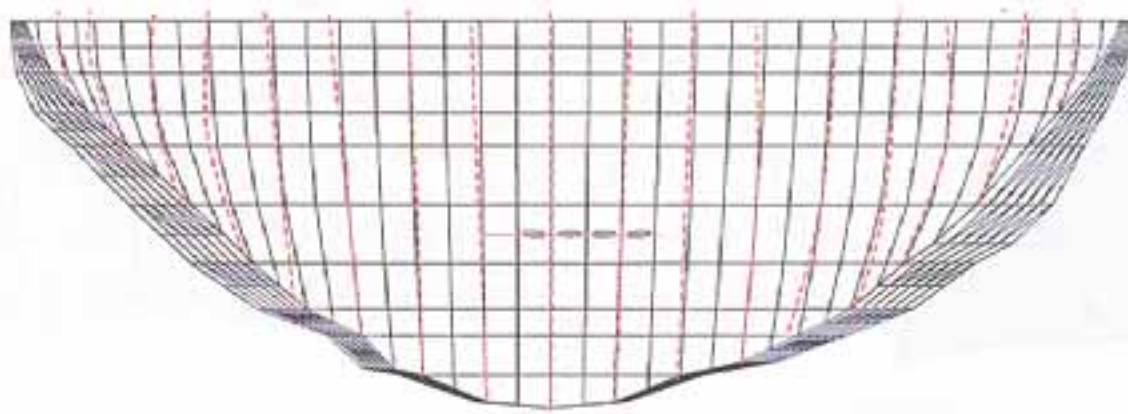


Figure G.20

Single Horizontal Joint Model – Analysis M9M10 – Laboratory Model M10
Predict versus Actual Crack Patterns



**Seventeen Vertical Joint Model
Analysis M12M13
Laboratory Model M13
Predicted versus Actual Crack Patterns**

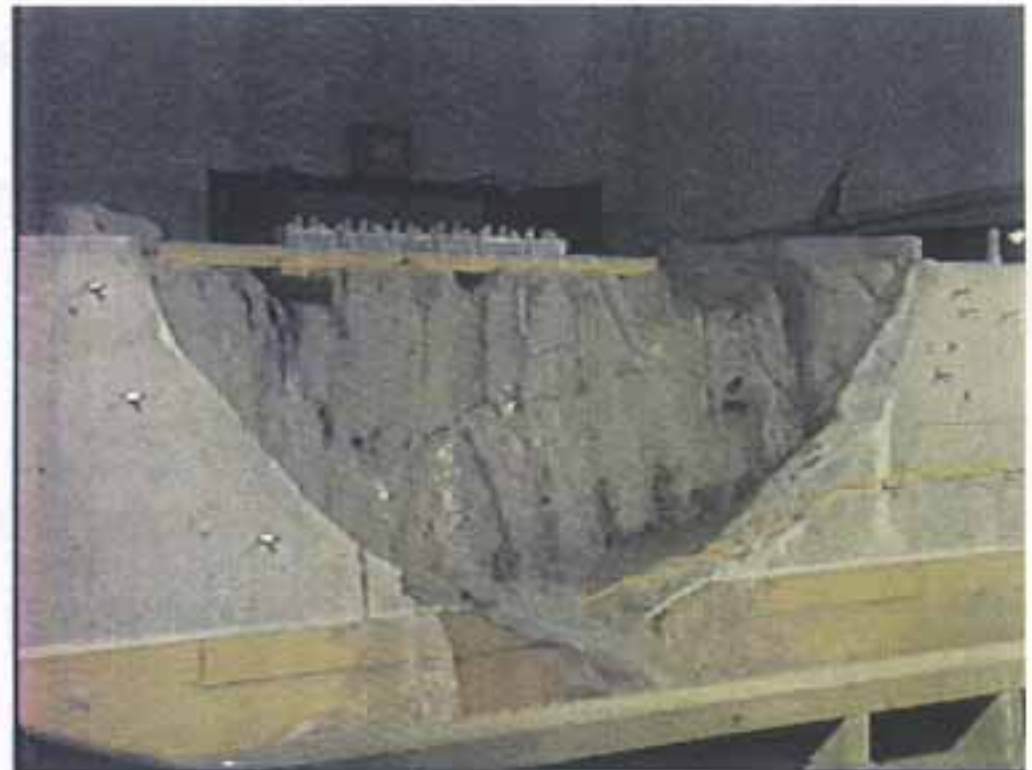
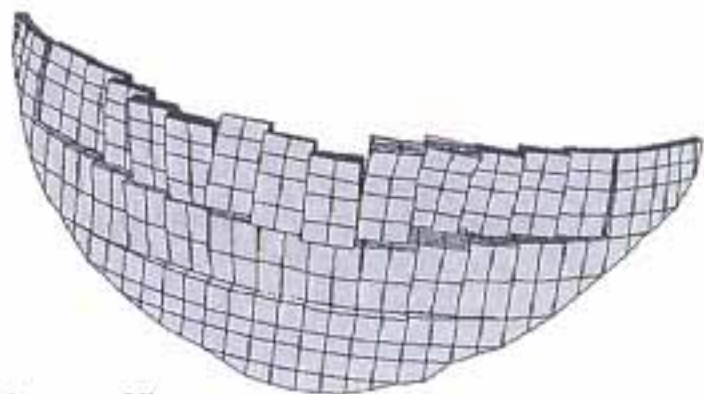


Figure G.22



Upstream View



Seventeen Vertical and Two Horizontal Joint Model

Analysis - M14M15
Laboratory – M15

Deformation Magnification Factor = 10 for Analysis Plots

