

Response of Isotropic and Laminated Plates to Close Proximity Blast Loads

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(ABSTRACT)

The transient response of various plate structures subject to blast loads is analyzed. In particular, simply supported isotropic and laminated composite plates are modeled using the commercial finite element code NASTRAN, and the method of modal superposition. Both analysis procedures are used to quantify the linear transient response of such plates subject to uniform and patch blast loads. Furthermore, NASTRAN is used to study the nonlinear response of plates subject to close proximity explosions. Also considered here is the case for which a blast loaded plate impacts another closely neighboring plate. The NASTRAN solution used here accounts for nonlinearities due to large plate deflections, plasticity, and plate-to-plate contact.

Many studies are currently available in which the blast load is considered to be spatially uniform across the plate; with a temporal distribution described by step, N-pulse, or Friedlander equations. The novel aspect considered here is the case for which the blast pressure is due to a close proximity explosion, and is therefore taken to be both spatially and temporally varying. A FORTRAN program is described which automates the application of an arbitrary blast load to a generic finite element mesh. The results presented here are a collection of analyses performed for a variety of parameters important to the dynamic response of blast loaded contacting plates. Conclusions are drawn concerning the influence of the various parameters on the nature of the plate response and the quality of the solution.

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Chapter 1

Introduction

Structures in close proximity to an explosion experience high intensity-short duration pressures that vary in time and space. Predicting the structural response to such an explosion requires accurate prediction of the applied pressures and a solution procedure that is adequate for such transient phenomena. The efforts of Chock (1999) resulted in a FORTRAN program that calculates the spatial and time varying blast pressure for a given set of blast parameters. This program is utilized in the work here; however, details are left to that reference. The work presented here focuses on the structural response to such close proximity explosions. In particular, the structures considered include isotropic, composite, and contacting plates subject to mine blasts. Both a linear and a nonlinear solution is developed for these simulations.

1.1 Literature Review

Transient plate response to high intensity loads is often investigated in the context of sonic booms, explosive blasts, and other shock type pressure loads. Sonic booms and explosions that are initiated sufficiently far from a structure are often idealized as arriving at all points on the structure's surface simultaneously. Most of the literature available concerning plate response to short-duration, high intensity pressures make this assumption. Experimental evidence

supporting this assumption is provided by Houlston (1985). In many of these works, the time history of the spatially uniform pressure is described by step-pulse, N-pulse, or Friedlander equations (Librescu; 1990, Rajamani, 1979; Reddy, 1997). The particular equation used for the pressure-time history of the load is often chosen to best match the particular phenomenon; considered. The time history of overpressures due to explosions are often represented by the modified Friedlander exponential decay equation (Gupta, 1985).

In the references listed thus far, the blast pressures are of arbitrary magnitude and are applied uniformly across the structure. Methods presented by Baker (1973), use experimental data from explosive tests to develop expressions for the blast overpressure as a function of time and distance from the blast, as well as charge weight and other important blast parameters. In a paper by Chock (1999), these methods are reviewed and implemented into a FORTRAN program for quickly calculating blast pressures due to an explosion. Very few papers make use of such a realistic blast load, a few exceptions are presented by Molyneaux (1994), Turkmen et. al. (1998), Zhuk et. al. (1994). The papers by Turkmen and Zhuk utilize shock tube experiments for determining the blast pressure. The paper by Molyneaux utilizes a numerical simulation of an explosive charge.

Most of the literature available concerning impulsively loaded plates considers a linear solution for isotropic plates. There are also many linear solutions available for impulsively loaded composite plates, and some of the references listed thus far are of this type (Reddy, 1975; Librescu & Nosier et. al., 1990). Mallikarjuna (1993) provides a good review of solutions for composite plates. A few papers consider the geometric and material nonlinear solution (Yang & Saigal, 1984; Louca et. al., 1997). The paper by Yang and Saigal considers the geometric and material nonlinear solution of a step-loaded isotropic plate where the material constitutive behavior is elastic-perfectly-plastic. Some papers examine the response of stiffened panels to explosive loading, the paper by Turkmen et. al., (1998), and the one by Mukhopadhyay et. al., (1995), are such examples.

There is much available in the literature concerning contact analysis. A good collection of contact problems in elasticity is provided in a book by Kikuchi and Oden (1990). One of the most relevant examples considers the static analysis of an elastic plate forced into contact with a rigid foundation by a uniform pressure. Some papers deal with the dynamic response of

contacting systems where the contact occurs at a single location (Lee & Byrne, 1998). There are several authors that consider the transient response of composite plates subject to impact loads. They often consider low velocity impact, known contact areas, and hertzian contact laws. Nosier, Kapania, and Reddy (1994) provide a good review of such investigations, as well as some analytical methods using higher order plate theories. One paper presented by Hilding (1999) considers the optimization of structures in unilateral contact.

1.2 Investigative Procedure

In order to model the transient response of composite plates subject to impulsive loads, both a modal superposition and a NASTRAN finite element solution procedure are developed for linear analysis. These two analysis methods are compared to each other and to results available in the literature. Both analysis procedures are verified within the framework of classical laminated plate theory for N-pulse and Friedlander blast loads. Furthermore, a finite element analysis incorporating first order transverse shear effects is verified for a step-loaded composite plate.

In addition to the linear analyses of composite plates, a NASTRAN solution is also developed for a geometric and material nonlinear analysis of isotropic plates. After verifying the nonlinear finite element solution for a spatially uniform step load, mesh and time-step convergence studies were performed for isotropic plates subject to a mine blast. In performing these verifications and convergence studies, many of the parameters important to a nonlinear transient analysis were evaluated independently. These single plate studies were a preliminary step towards the more difficult contact analyses.

High velocity contact between blast loaded plates is likely to have a significant amount of high frequency response due to repetitive contact between the elastic plates. This high frequency response, called chatter, requires that a very small integration time step be used. This small time step allows for frequent updates of the stiffness matrix based on the rapidly changing deformation. Other elements important to a contact analysis also need to be selected carefully; namely the closed gap stiffness. Other factors could also be important, such as sliding friction. As a starting point, the only plate-to-plate contact example found in the literature is performed using a range of closed gap stiffnesses. From this point, time step convergence studies are

performed on blast loaded contacting plates, and finally, analyses are performed to investigate the various parameters.

An accurate mine blast simulation requires that both temporal and spatial variations in the blast wave be accounted for in the transient analysis. Mesh convergence studies indicate that a fine mesh is needed for accurate solutions, which requires that a large number of elements be loaded with a variety of pressure histories. In order to facilitate the application of these complex loads using MSC NASTRAN, a FORTRAN code was developed. This FORTRAN code, called the blast load preprocessor, completely automates the manually intensive task of specifying a blast load using a finite element program such as NASTRAN. The blast load preprocessor takes as inputs blast size, distance, location, and the blast load calculation method; and returns a NASTRAN input deck that contains all the loading commands required for a blast load simulation. The preprocessor also returns the percent error in the applied load, as well as the values of the actual and applied impulse. A parametric study is performed in order to determine the percent error associated with a particular mesh discretization. These results and a summary of the blast preprocessor methodology is included in Chapters 5 and 6.

The information gathered from the verifications, convergence studies, and blast load studies provided a good starting point for the study of plates subject to close proximity explosions. With many of the important parameters identified, the blast preprocessor and NASTRAN solution procedure are used together in the investigation of plates subject to mine blasts. Isotropic, composite, and contacting plates are all subject to a five-pound T-N-T mine blast. Results are obtained using various plate configurations, solution procedures, and methods for calculating blast pressures. Solution outputs such as plate displacement, stress, and plastic strain are used for drawing conclusions concerning plate behavior. Conclusions are also drawn concerning which solution parameters are important for an accurate blast simulation.

Chapter 2

Solution Procedures

2.1 Linear Elastic Analysis of Composite Plates

A linear elastic transient analysis of composite plates using classical lamination theory (CLT) was developed using the NASTRAN finite element program and the method of modal superposition. The method of modal superposition and results from the literature were used to verify the NASTRAN solution within the framework of CLT. Next, a NASTRAN solution procedure was developed and verified within the framework of first order shear deformable theory (FSDT). A summary of the methodology and assumptions for the modal superposition and NASTRAN analyses are provided below. Appendix B provides details of a modal superposition example used for comparison to the literature.

2.1.1 Modal Superposition

The method of modal superposition for the transient response of composite plates was implemented using a routine written in the Mathematica (1996) programming language. First, classical lamination theory was utilized to calculate laminate properties for a given stacking sequence, material, and plate thickness (Gurdal, 1999). Next, these laminate properties were used to calculate the mode shapes and natural frequencies. The generalized forces were found by exact integration of the product of the mode shape and time dependent force over the area of the plate. Finally, a solution was found by exact integration of the first “n” modes of the infinite series solution with respect to time. The number of modes necessary for a converged solution was then determined by comparing results for various values of n.

2.1.2 NASTRAN Finite Element Code

The NASTRAN “direct transient response” solution procedure was used to perform linear elastic transient analysis of blast loaded composite plates. The CQUAD4 isoparametric quadrilateral shell element was used in conjunction with the MAT8 and PCOMP entries to define a composite plate based on stacking sequence and orthotropic laminae properties (NASTRAN Quick Reference Guide, 1997). This 2-D composite shell element accounts for in plane, bending, and transverse shear behavior. First order shear flexibility is achieved by providing a value for the transverse shear moduli G_{13} and G_{23} (NASTRAN Quick Reference Guide, 1997), which effectively removes the assumption that transverse normals remain perpendicular to the mid-plane. A shear correction factor defined in terms of transverse strain energy is internally calculated (MSC/NASTRAN Reference Manual, 1997).

2.2 Nonlinear Analysis of Isotropic Contacting Plates

The direct transient response solution procedure of the NASTRAN finite element code was used to predict the nonlinear response of isotropic contacting plates. The CQUAD4 isoparametric quadrilateral shell element was used for the verification studies and plate studies. This is NASTRAN’s most commonly used element for modeling plates and shells. It can represent in plane, bending, and transverse shear behavior. Both geometric and material nonlinearities are modeled. The material nonlinearity is implemented using an elastic-perfectly-plastic constitutive relation. For the case of contacting plates, a nonlinear gap element is also used for the analysis. The CGAP element is a line element that connects the nodes of contacting surfaces. The stiffness of this element is taken to be zero when the gap is open, and of a specified nonzero value when the gap is closed. NASTRAN recommends that the closed gap stiffness be 1000 times the stiffness at neighboring grid points. However, NASTRAN’s gap element also has adaptive features that can be activated when an allowable penetration depth is specified for the contacting surfaces. When the allowable penetration depth is exceeded, the gap stiffness is automatically increased to keep the plate deflections kinematically acceptable. This allows for the use of small gap stiffnesses while preserving good results. Determination of the appropriate gap parameters will be the focus of the contact studies, presented subsequently.

Chapter 3

Verification of Solution Procedures

3.1 Linear Analysis of Composite Plates

The two solution procedures used here were compared to results available from the literature before conducting the parametric studies. Three examples are considered, and each one assumes that the pressure is applied uniformly across the plate, and that the material is linear elastic. The material properties, plate dimensions, and load parameters unique to each example are detailed below.

Verification 1

In this example taken from Librescu and Nosier (1990), a 4-layer (0/90/90/0) symmetric cross-ply laminate is subjected to an N-shaped pulse. The load parameters that define the symmetric N-pulse are:

$$t_p = .01 \text{ s}, r = 2, P_m = 2500 \text{ psi.}$$

These are used to describe the time history of the pulse via the equation

$$P(t) = \begin{cases} P_m (1 - t/t_p), & \text{for } 0 < t < r t_p \\ 0, & \text{for } t < 0 \text{ and } t > r t_p \end{cases}$$

The plate dimensions and laminae properties are taken to be:

$$E_1 = 19200 \text{ ksi}, E_2 = 1560 \text{ ksi}, G_{12} = 820 \text{ ksi}, \nu_{12} = .24,$$
$$G_{23} = 523 \text{ ksi}, a = b = 100 \text{ in.}, a/h = 10, \rho = .00013 \text{ lb-sec.}^2/\text{in.}^4$$

Figure 1 shows the center plate deflection vs. time for the two methods and the reference.

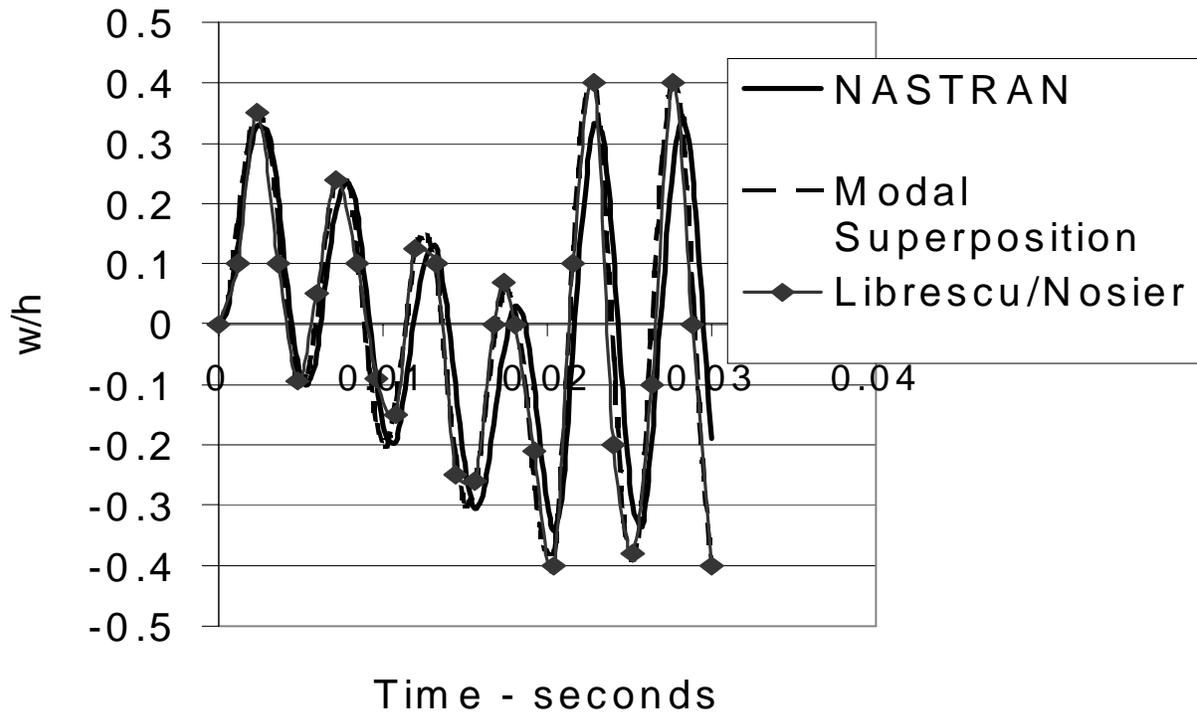


Figure 1. Verification of analysis techniques for an N-shaped pulse.

Verification 2

This example is also taken from Librescu (1990); a 4-layer (0/90/90/0) symmetric cross-ply laminate is subjected to a uniform blast described by the modified Friedlander exponential decay equation.

$$P(t) = P_m (1 - t/t_p) e^{(-a't/t_p)}$$

The load parameters that define the modified Friedlander exponential decay equation are:

$$t_p = .1 \text{ s}, a' = 2, P_m = 500 \text{ psi.}$$

The plate dimensions and laminae properties are the same as verification 1 except:

$$a/h = 15$$

Figure 2 shows the center plate deflection vs. time for the two methods and the reference.

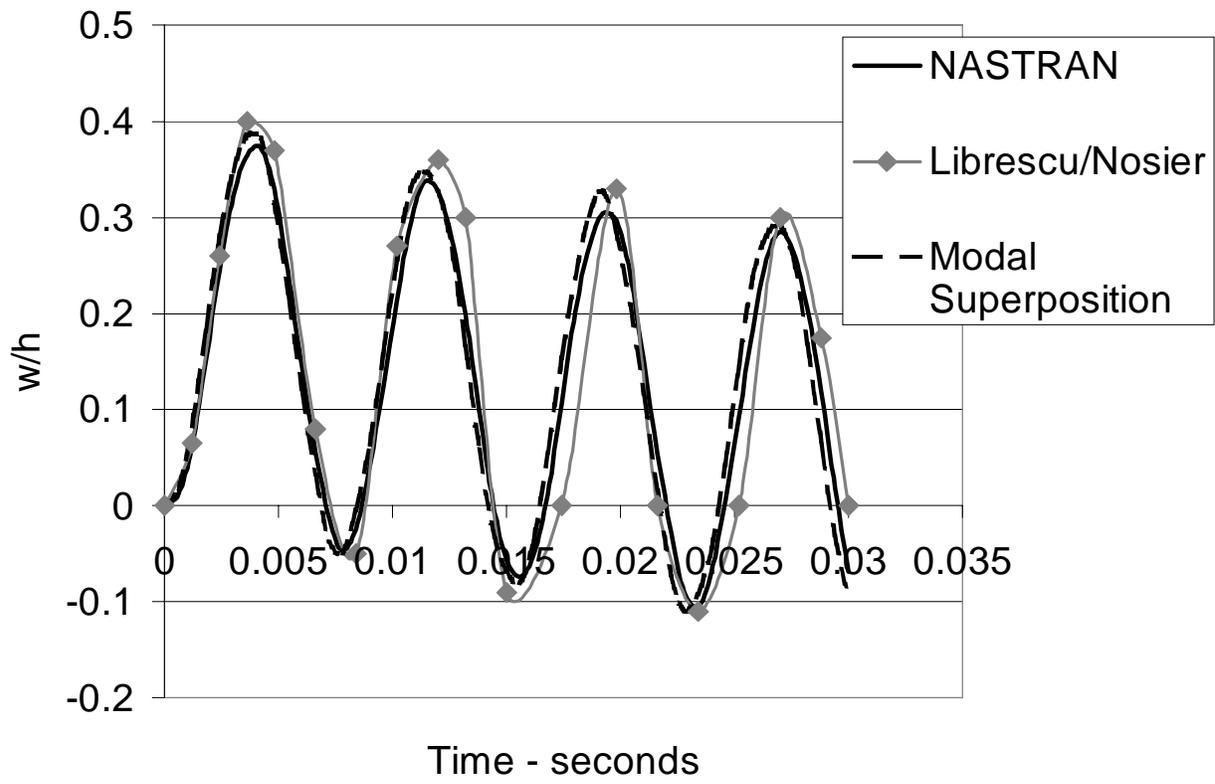


Figure 2. Verification of analysis techniques for a Friedlander blast.

Verification 3

In this example taken from Reddy (1997), a 2-layer (0/90) antisymmetric cross-ply laminate is subjected to a step pulse. The plate dimensions and laminae properties are taken to be:

$$E_1 = 25 E_2, E_2 = 2100 \text{ N/cm}^2, G_{12} = G_{13} = E_2/2, \nu_{12} = .25, \\ G_{23} = .2 E_2, a = b = 25 \text{ cm}, a/h = 10, \rho = .008 \text{ kN-s}^2/\text{cm}^4$$

Figure 3 compares the NASTRAN CLT and FSDT solutions to those of Reddy. The nondimensional center plate deflection is given by:

$$w' = 100 (w_0 E_2 h^3)/(q_0 a^4)$$

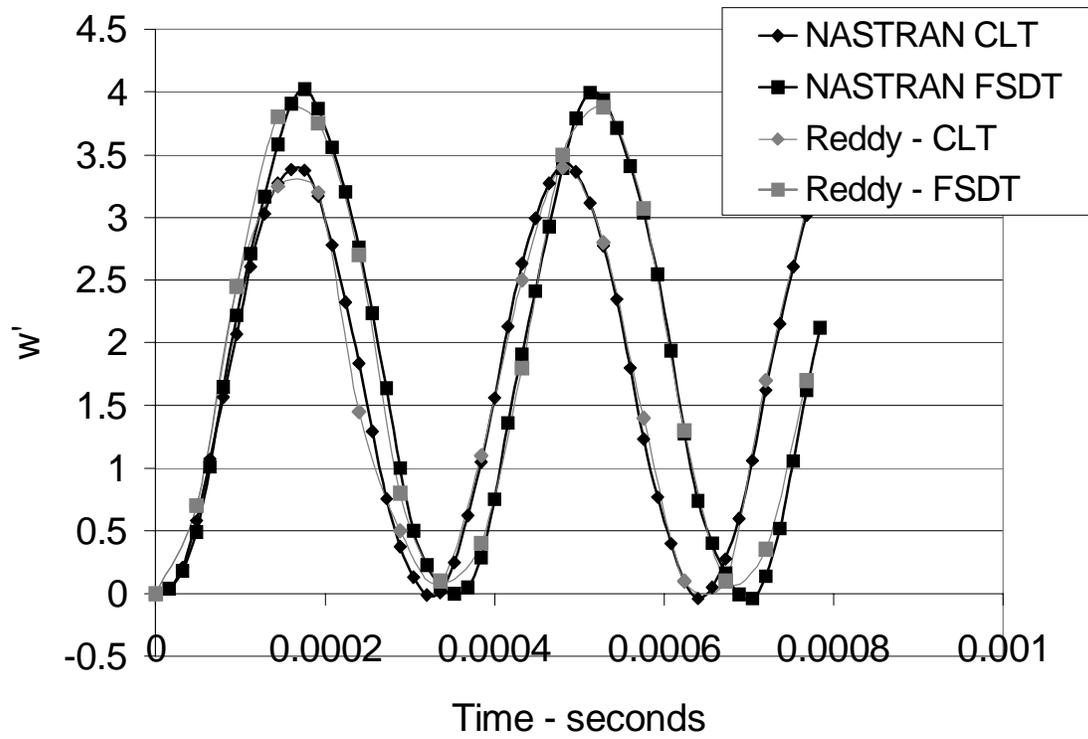


Figure 3. Center plate deflections vs. time for a step loaded composite plate. Verification using CLT and FSDT.

3.2 Nonlinear Analysis of Isotropic Plates

The first verification study is based on the results from a paper by T. Y. Yang and Sunil Saigal (1984). Geometric and material nonlinearities were verified for the dynamic analysis of a simply supported square plate subject to a uniform step pressure. The material nonlinearity was assumed to be elastic-perfectly-plastic. Material properties were taken to be: 1) modulus of elasticity $E = 10^7$ psi, 2) poisson's ratio $\nu = .3$, 3) mass density $\rho = .0002588$ lbs-sec²/in⁴, 4) yield strength $\sigma_y = 30,000$ psi. The 10 x 10 inch square plate had all edges on fixed hinges and the thickness of the plate was $\frac{1}{2}$ inch. Figure 4 shows the center plate deflections vs. time for the NASTRAN solution and the published results of Yang and Saigal. It can be seen that the frequencies and amplitudes are well matched for the two curves.

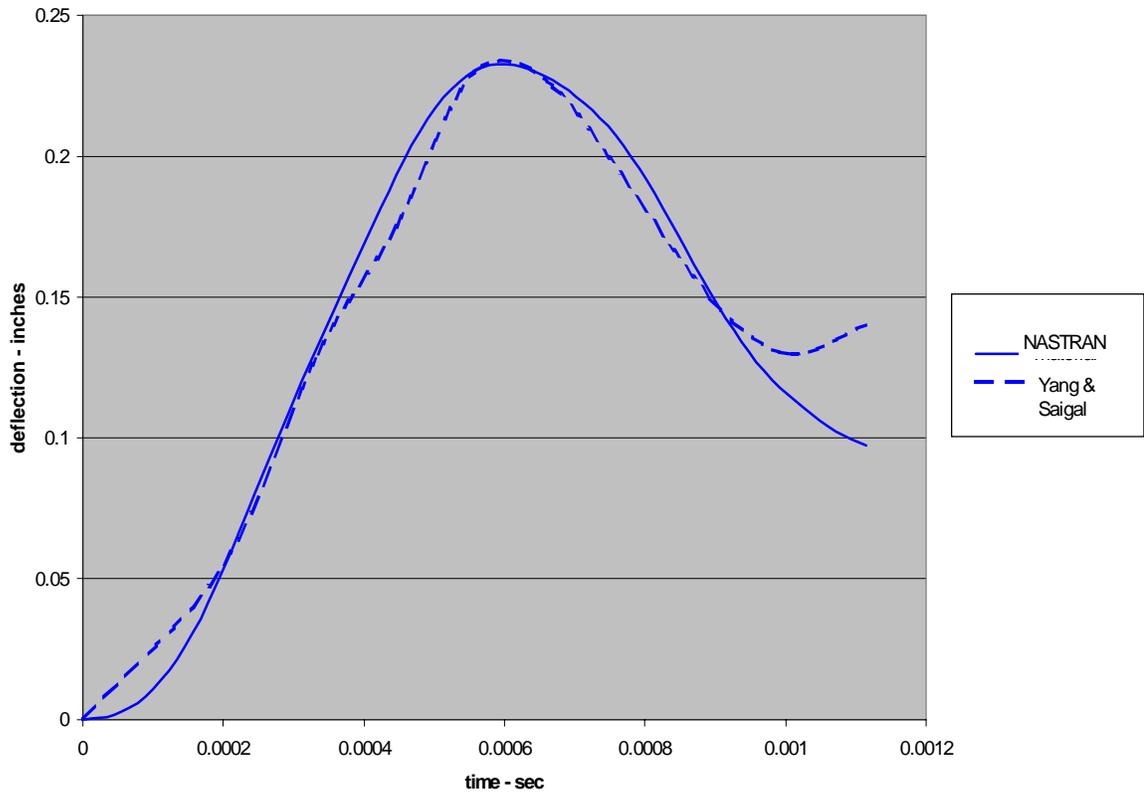


Figure 4. Verification of geometric and material nonlinear analysis. Center plate deflections vs. time.

3.3 Nonlinear Analysis of Contacting Plates

The next verification study was used to test NASTRAN's treatment of contact nonlinearities. In the comparison to Kikuchi and Oden (1990), shown below, a wide range of closed gap stiffnesses is evaluated. The base stiffness used here is equal to the modulus of the plate, therefore, a stiffness of "100 x" would refer to a value of 100 x E. The problem reproduced here is a nonlinear static analysis of a 120 x 120 x 2 mm square plate with fixed edges, separated from a rigid foundation by a gap of 2 mm. A non-dimensional uniform transverse pressure of 500 is applied across the plate to force it into contact with the rigid foundation. Material properties were taken to be: $E = 7000 \text{ kg/mm}^2$, and $\nu = .3$. For this analysis, a 256-element quarter plate was analyzed using symmetry boundary conditions. Figure 5 shows the shape of the deformed plate as viewed along the centerline of symmetry. The horizontal line located through a nondimensional displacement of 1.0 corresponds to contact with the rigid foundation. Displacements above this line are considered kinematically unacceptable. A good comparison to the results of Kikuchi and Oden is found for gap stiffnesses of between 1/10 and 10 x E.

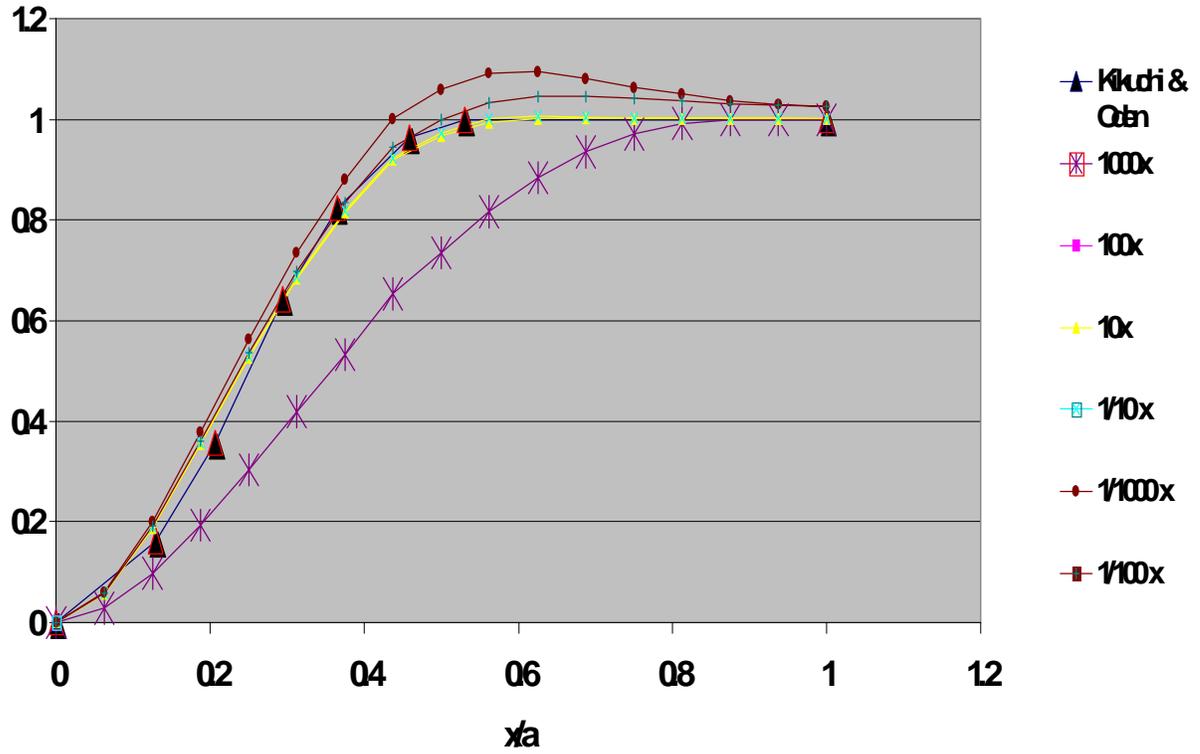


Figure 5. Deflections of the centerline of a square plate in contact with a rigid foundation. Rigid Foundation marked by the $w/t = 1.0$ line.

Chapter 4

Convergence Studies

In order to establish appropriate length and time scales for a mine blast analysis, simple plates subjected to dynamic pressure loads were analyzed using different mesh densities and integration time steps. Both the mesh and time convergence studies were carried out on an isotropic aluminum 2519 plate of dimension 2385 mm x 2385 mm x 17.5 mm. The dynamic pressure load applied uniformly across the plate was calculated using the methods of Kingery & Bulmash (Chock, 1999). The magnitude of the pressure was equal to the pressure at 16 inches normal to a 5-lb mine-blast. Since the loading is uniform, and the plate is square, symmetry conditions are used to analyze only a quarter plate section.

4.1 Mesh Convergence

The mesh convergence study was done using linear and nonlinear dynamic analyses. The figures below show these analyses for a quarter plate with varying mesh densities. The nonlinear analysis was done using a blast load of 15 times the magnitude used for the linear convergence study. The blast load was magnified in order to insure a plastic response in the plate. The plasticity model used is a bilinear hardening model with Young's modulus, the yield point, and the tangent modulus as defining parameters. The linear analysis shown in Figure 6 indicates that a mesh with as few as 16 elements is sufficient for an accurate solution. However, the nonlinear analysis shown in Figure 7 indicates that a refined mesh is necessary to accurately capture the maximum deflection and permanent set experienced by the plastically deformed plate.

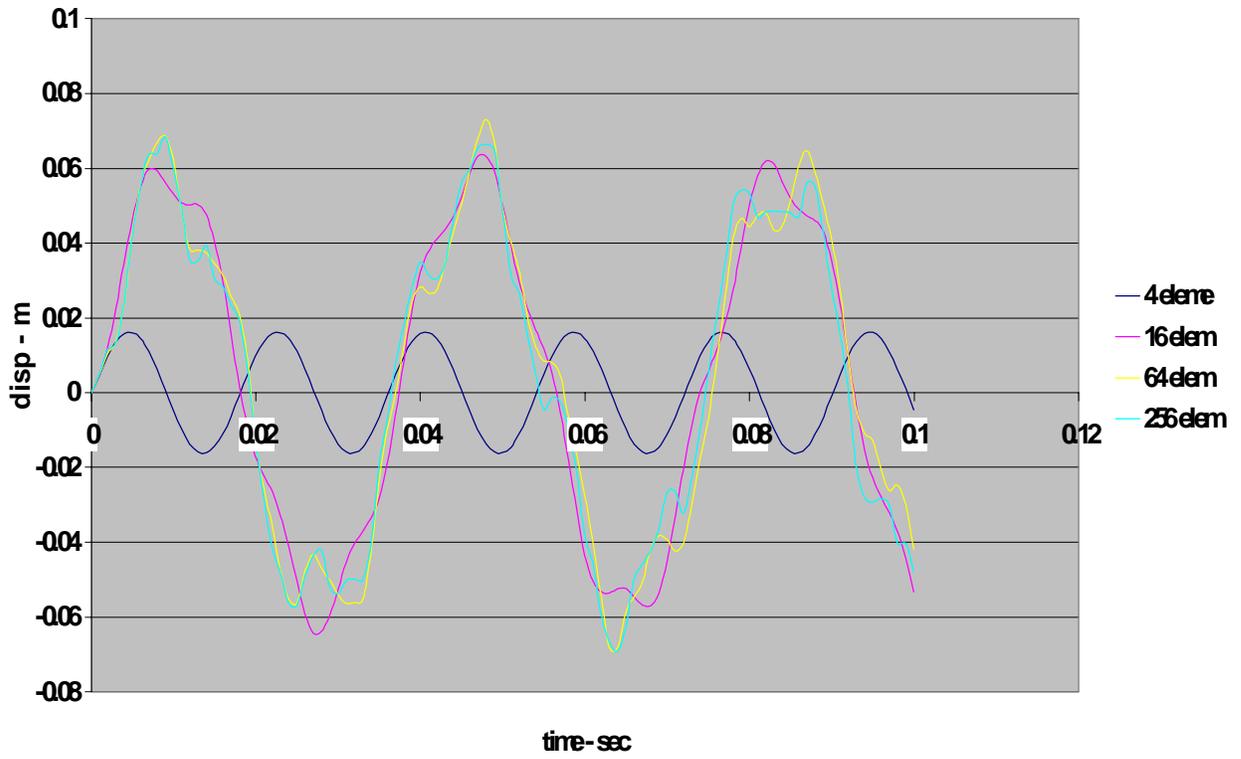


Figure 6. Mesh convergence study for a simply supported square plate subject to a blast load. Linear analysis, center plate deflection vs. time.

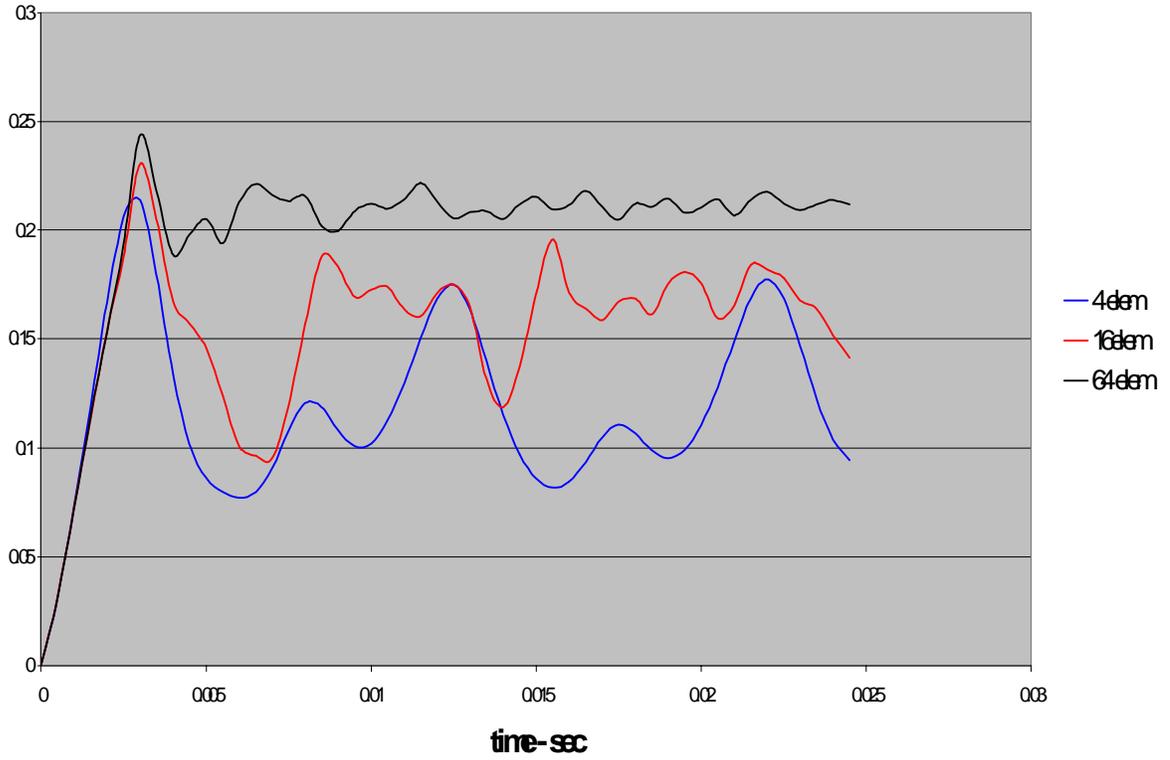


Figure 7. Mesh convergence study for a simply supported square plate subject to a blast load. Nonlinear analysis, center plate deflection vs. time.

In the following three figures, the mesh is refined one step further and the displacement, stress, and plastic strain at the center node are compared for the two finest meshes.

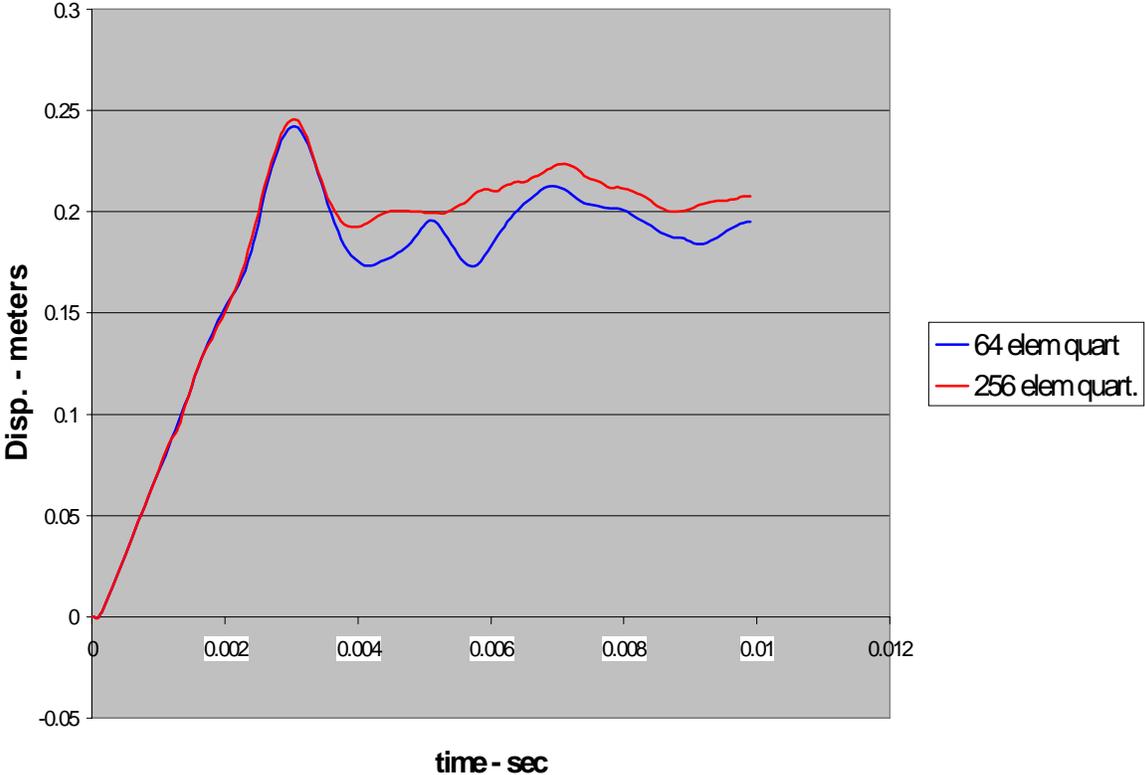


Figure 8. Displacement–vs-time for the center node of the two refined meshes.

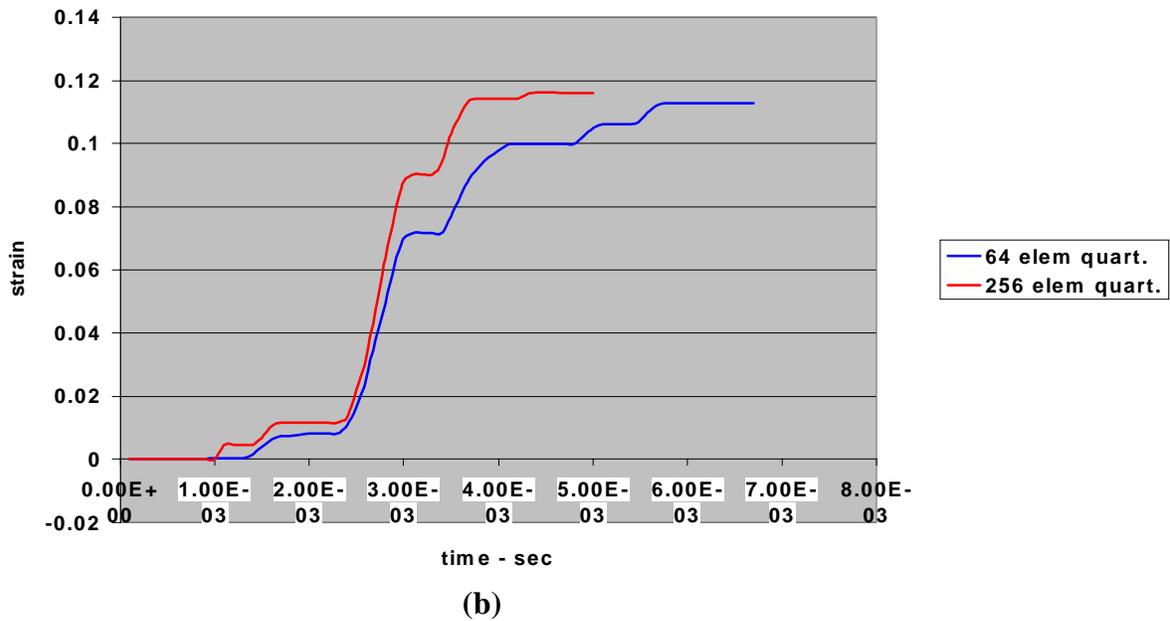
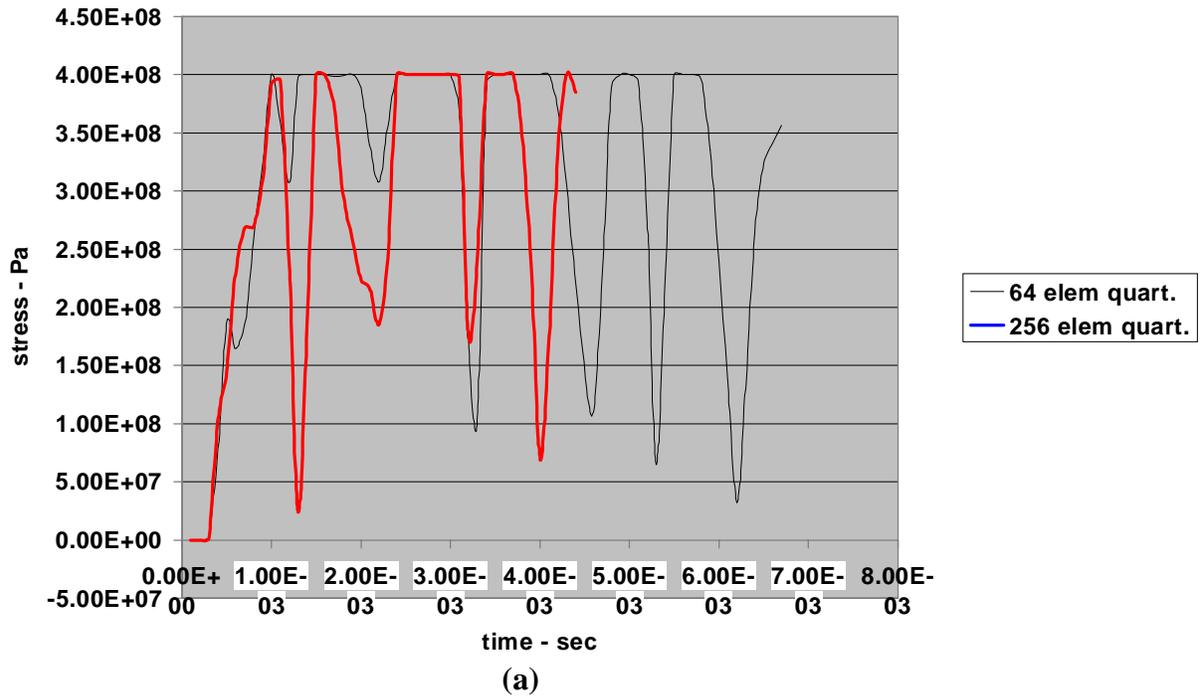


Figure 9. Equivalent stress (a), and plastic strain (b) plots for the center element of the two refined meshes.

The permanent deformation of the center node showed a 10% increase for the final mesh refinement. Stress and strain plots indicate that rise times and permanent plastic strain are reasonably close for the two finest meshes. These factors indicate that an element mesh on the order of the 256 elements in the quarter plate is adequate to properly model effects due to a mine blast. This refinement translates to elements with sides of about 2.9 inches for the plates subject to a mine blast.

4.2 Time step Convergence

The time step convergence studies were carried out using a geometric and material nonlinear analysis on the plate of section 4.1. Figure 10 shows the center plate deflections vs time for two values of the time step. It can be seen that the maximum deflection and permanent set for the time steps of 5 to 10 microseconds only differ by several percent.

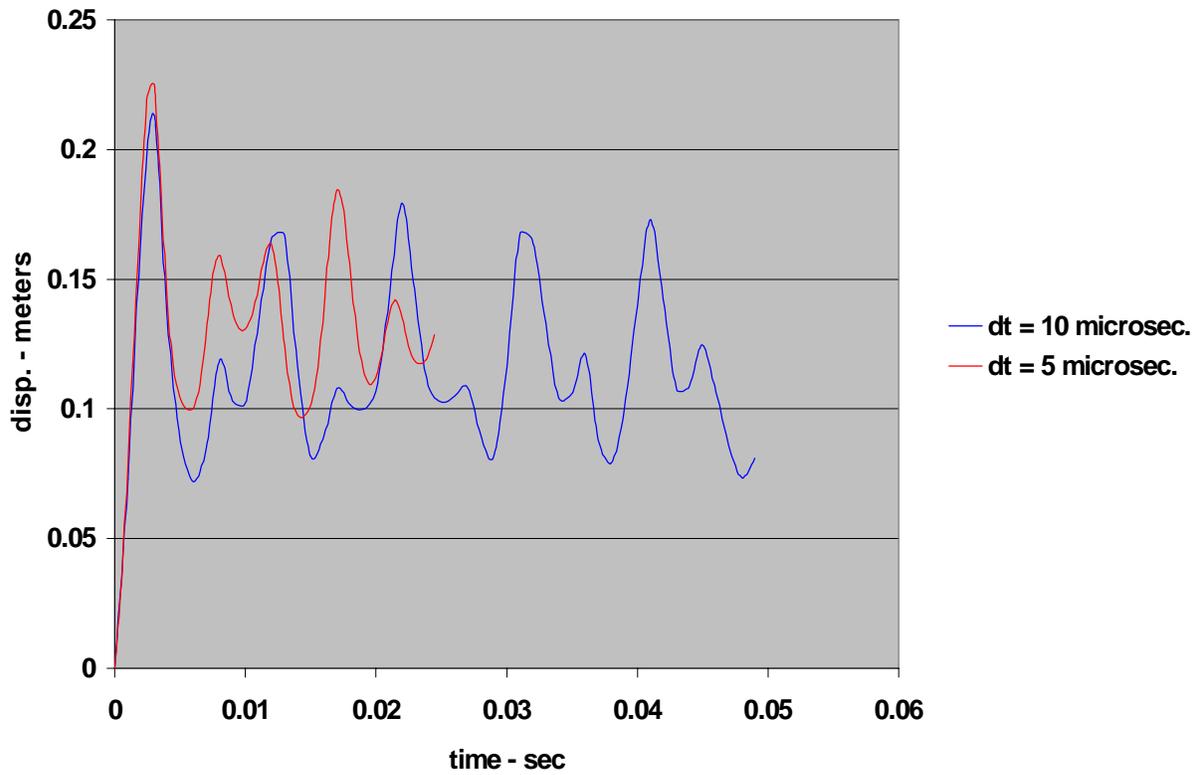


Figure 10. Center plate deflections vs. time for different values of the integration time step. Analysis is for a blast loaded elastic-perfectly-plastic plate, geometric and material nonlinear analysis.

Chapter 5

Blast Load Application

The diagram in Fig. 11 illustrates some of the assumptions and parameters involved in blast loading a finite element model of a plate structure. Once the blast distance is determined, elements within 45 degrees of the blast normal vector are divided into groups based upon their average distance to the center node. Next, the methods described by Chock (1999) are used to assign an individual pressure-time history to each element based on its distance from the blast. As an example, eight discretization rings were used to load a 100" x 100" plate with a 5-pound mine blast at a distance of 30 inches. The spatial distribution and pressure profiles are illustrated in Fig. 12 and Fig. 13, respectively.

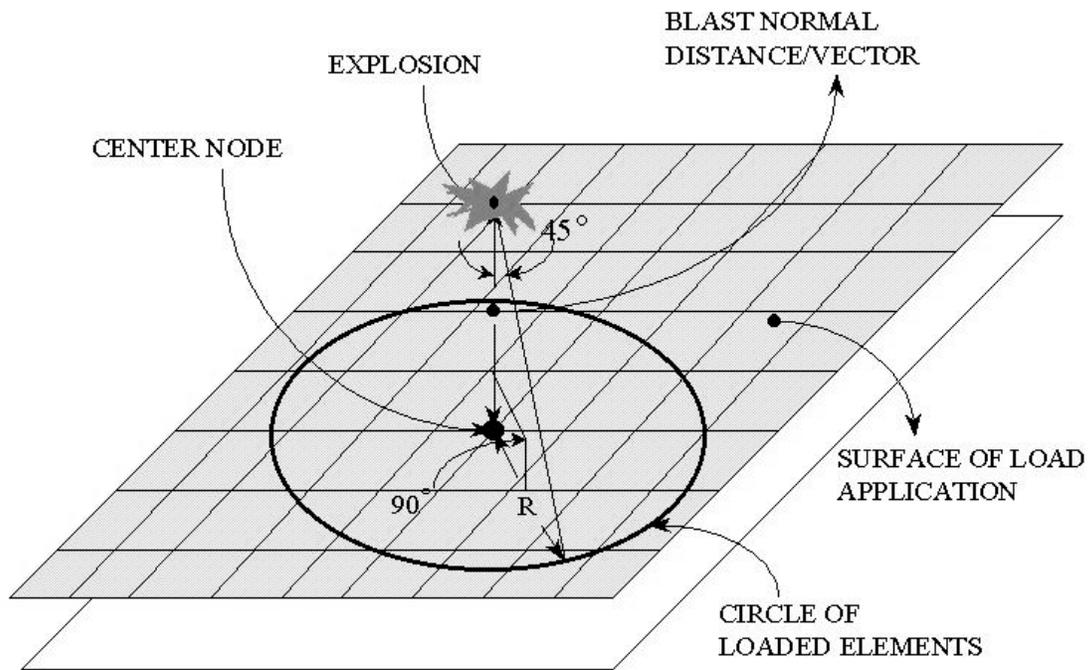


Figure 11. Application of a blast load to a finite element mesh. Only elements within the 45-degree cone are loaded.

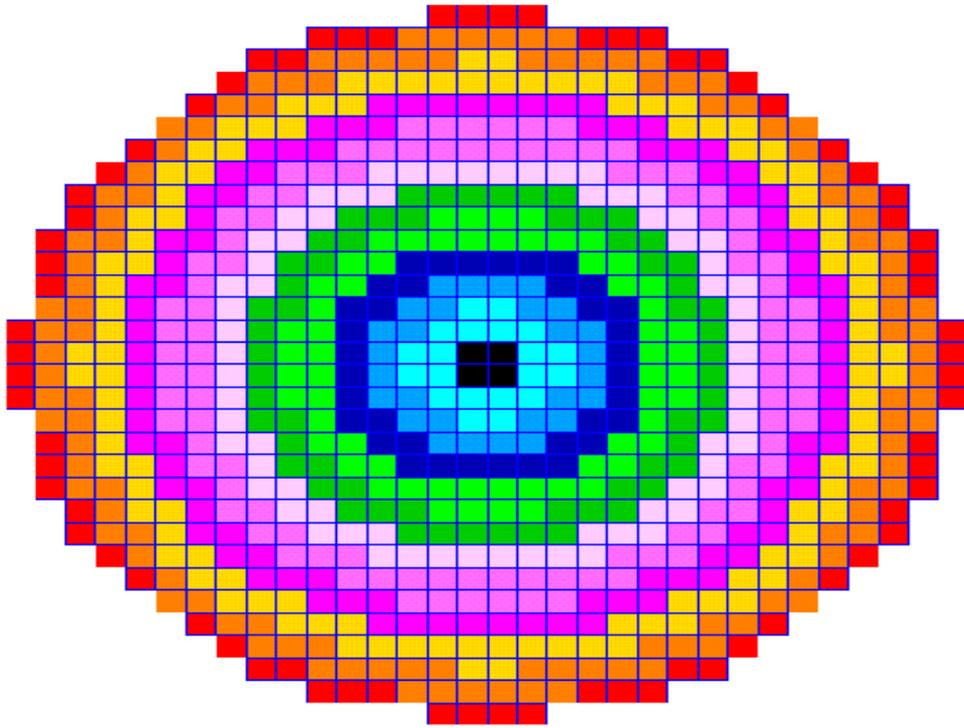


Figure 12. Spatial distribution of the blast load using eight load rings. Each ring has its own pressure-time history as shown in Fig. 13.

Pressure Profiles for an 8 Ring Discretization of a Kingery and Bulmash Calculated 5 lb. Mine Blast at 30"

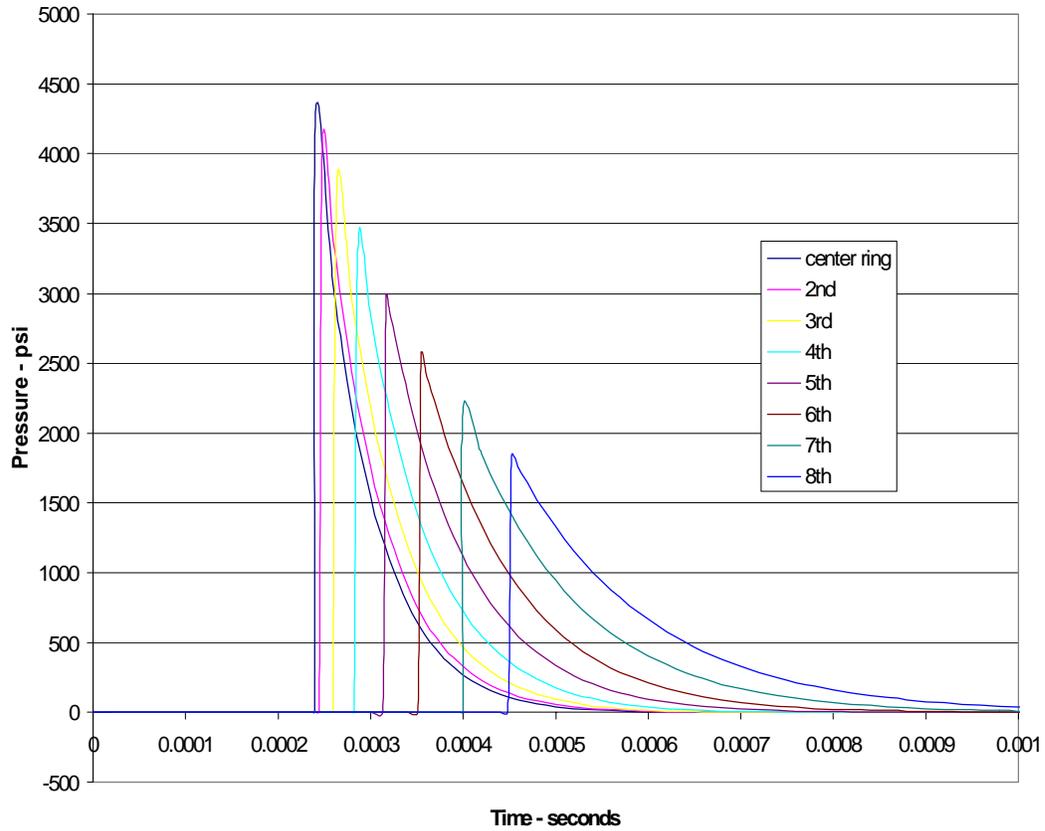


Figure 13. Pressure-time histories for the eight load rings.

Chapter 6

Blast Load Preprocessor

The blast load preprocessor integrates the methods described in Chapter 5 into a Fortran code. Given the parameters describing a blast, and the finite element model to be loaded, this code automatically determines which elements to load and the corresponding pressure-time histories for these elements. This loading information is then formatted and inserted into the original model's input deck. The total impulse of the load applied to the NASTRAN model is then compared to the actual impulse as calculated from the routine by Chock (1999). Good comparison between these impulses indicates that the finite element model has been loaded appropriately. The methodology for this preprocessor and a user's guide are presented in the following sections.

5.1 Methodology

The program begins by prompting the user to enter the blast parameters, the name and units associated with the NASTRAN model to be loaded, and information that specifies the blast location on the model. Blast parameters include: pounds of TNT, blast normal distance, blast calculation method, and number of discretization rings. The user specifies the location of the blast in relation to the finite element model by indicating three grid point identification numbers. The first grid point specifies the origin of the blast normal vector (refer back to Figure 11). The other two grid points are chosen to be on the surface of load application but not co-linear to the first point. The final input prompt requests that the user enters a number less than the distance to the next closest plane. This number is referred to as the plane tolerance and is used to ensure that all the appropriate elements are selected for loading. All the input information is then stored and utilized in the following steps.

The first step is to write the equation of the plane using the three specified grid points. To accomplish this, we must first determine the x, y, and z-coordinates of each grid point. The user specified geometry file is opened and searched for all lines that begin with the NASTRAN input command "GRID". All grid points and their coordinates are written to a new file called "grids.dat". In the process of writing "grids.dat", the coordinates of the user specified grid points are extracted and used to write the equation of the plane.

<p>Plane Equation in Terms of 3 points: P_1, P_2, P_3 Where $P_i = (x_i, y_i, z_i)$</p>	$X_n(x-x_1) + Y_n(y-y_1) + Z_n(z-z_1) = 0$ <p>where the coefficients $X_n, Y_n,$ and Z_n are computed via the following relations:</p> $\mathbf{F} = P_2 - P_1 \quad \mathbf{G} = P_3 - P_1$ <p>And: $\mathbf{N} = \mathbf{F} \times \mathbf{G} = X_n \mathbf{i} + Y_n \mathbf{j} + Z_n \mathbf{k}$</p> <p>*boldface indicates a vector</p>
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With the plane equation and the blast normal distance known, we can test each grid point in the model to see if it is in the plane and within the circular loaded area. The coordinates of each grid point in "grids.dat" are read and substituted into the plane equation. Ideally, all points on the surface of load application would satisfy the plane equation exactly. However, mesh generation software tends to create grid point coordinates that err from the ideal by some small amount. This small amount, which is certainly much less than the plane tolerance, puts the grid point on a plane that is parallel to the ideal plane. By allowing the plane equation to evaluate to some constant which is slightly less than the plane tolerance; we will capture all the appropriate grid points, and avoid grid points that comprise an unloaded closely neighboring plate (see Figure 11). In the same do-loop, the grid points are tested and retained if they are a distance that is less than or equal to the user specified blast normal distance. Grid points in the plane that are within the blast normal distance lie in the loaded area defined by the cone shown in Figure 11. Grid points that satisfy the plane equation and fall within the loaded area are retained in the new file "circle.dat".

The next step is to determine which elements have all their grid points in the file "circle.dat", and to determine the average radius of these elements. To accomplish this, the NASTRAN geometry file is read again and searched for lines containing the keywords "CQUAD4" and "CTRIA3". These keywords are the NASTRAN commands that specify the grid points that define quadrilateral and triangular plate elements. The grid points of each element are then read and compared with the list in "circle.dat". Any element that does not have all of its grid points in this list is discarded. Elements that have all of their grid points in this list are placed in the new file "elem.dat". The areas and average radii of these loaded elements are computed and placed in this file as well.

After collecting all the loaded elements in "elem.dat", we divide these elements into groups based upon their average radii. The blast normal distance is divided by the user specified, "number of discretization rings"; this increment is used to group the elements into the appropriate loading zone based on their distance from the center node. These loading zones, along with their characteristic radius, are written to the new file "zones.dat". The list of radii and the blast parameters are then written to a new file called "mineblast.inp". This new file is then utilized by a subprogram that applies the blast calculation techniques of Chock, 1999. This subprogram returns a file called "blast.out", which is a list of the characteristic radii and their particular pressure-vs- time histories (a set of ordered pairs).

Now that the loaded elements have been grouped and the loading for each group has been calculated, we can proceed in writing this information back into the NASTRAN geometry file. The first input deck created is "patranvis.dat". This file is used to visualize the spatial distribution of the load using MSC PATRAN, and cannot be utilized to perform a vehicle analysis. The second file created is used for the blast response analysis and is called "analysis1.dat". All of the NASTRAN commands required to describe this spatially and time varying load are inserted into the NASTRAN geometry file to create a complete NASTRAN input deck. These commands include the PLOAD4, DLOAD, TLOAD1, LSEQ, and TABLED1 of the bulk data section; as well as the LOADSET and DLOAD commands of the case control section.

In order to validate the loading applied to the finite element model, a comparison is made between the ideal impulse and the applied impulse. First, the impulse per unit area for each loading zone is calculated by numerically integrating the individual pressure-time histories via

the trapezoidal rule. Now consider the two spatially discretized loading zones shown in Figure 14.

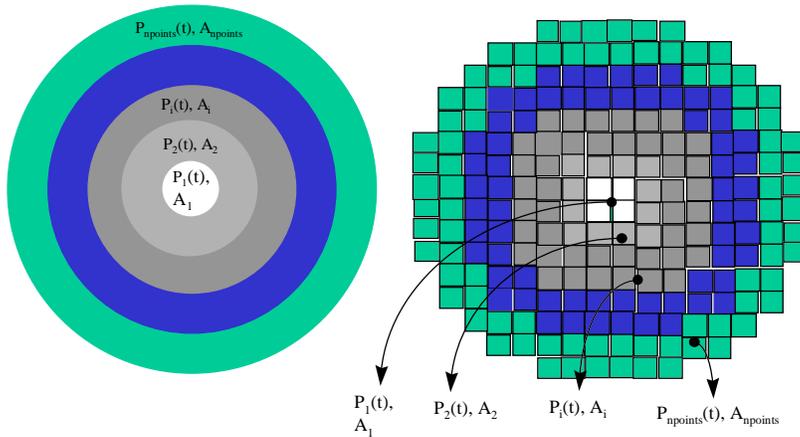


Figure 14. Two spatial discretization schemes used for calculating the ideal (left) and applied (right) impulses.

The ideal impulse is calculated using the discretization scheme on the left. The applied impulse is calculated using the scheme depicted on the right. The area of each of the ring zones on the left is easily calculated from the formula for the cross sectional area of a cylinder. These individual areas are then multiplied by the corresponding impulse per unit area to obtain the total ideal impulse. Ring areas for the scheme on the right are calculated by adding together the areas of all elements within a particular zone. These areas are then multiplied by the corresponding impulse per unit area to obtain the total applied impulse. Using the ideal and applied impulse values, a percent error for the applied impulse is determined.

As a last step, all the input and output quantities are assembled and written to the new file “results.dat”. This file can be used to verify the user input as well as the validity of the blast load applied to the finite element model.

5.2 User’s Guide

5.2.1 User Inputs

- All user-input numbers should be entered as real values that contain a decimal point, except for the following integer inputs: blast calculation method, units, # of rings, grid point ID's.
- A minimum of 8 discretization rings is suggested, a maximum of 23 rings allowed.
- The units chosen (lbs. & in, lbs. & ft, N & m, or N & mm), should be used to enter the blast distance and plane tolerance. The size of the explosion however, is always entered in pounds of TNT.
- The finite element model to be loaded must be in NASTRAN format. If the preprocessor is to create usable visualization (patranvis.dat) and analysis (analysis1.dat) decks, the following criteria must be met: 1) The submitted file should not contain any loading information in the case control or bulk data sections (i.e. LOADSET, DLOAD, LSEQ, PLOAD, TLOAD, TABLED1 commands are written by the preprocessor). 2) The user must insert all other information necessary to a successful NASTRAN analysis (i.e. iteration control, boundary conditions, etc.). 3) The section markers (i.e. BEGIN BULK, CEND, ENDDATA) must be included.

5.2.2 Preprocessor Outputs

The table in Figure 15 summarizes the files created and their contents.

File Name	Description
Grids.dat	Contains all grid points in the user specified NASTRAN geometry file.
Circle.dat	Contains all grid points that satisfy the plane equation and fall within the loaded area.
Elem.dat	Contains all CQUAD4 and CTRIA3 elements that have all of their grid points in the list of circle.dat. Also contains areas and average radii for these elements.
Zones.dat	Contains a list of the loaded elements, grouped into loading zones based upon their average radius.
Mineblast.inp	Contains all the blast parameters and list of loading zone characteristic radii. For use by the blast calculation subprogram in creating the pressure-time profiles.
Blast.out	Contains the pressure vs. time profiles for each loading zone. Profiles are described using sets of ordered pairs.
Filename.dat	Contains the NASTRAN geometry filename and the units system chosen by the user
Patranvis.dat	File used to visualize the spatial distribution of the blast load. Should be imported into PATRAN as a NASTRAN input deck.
Analysis1.dat	File to be used for the transient response analysis using NASTRAN
Integral	File containing information about the actual and applied impulse
Results	File detailing all of the user inputs and some useful information about the results of the run. i.e. # of elements loaded, actual impulse, applied impulse, % error in applied load.

Figure 15. A table describing the various files created by the blast load preprocessor.

5.2.3 Verifying the Applied Load

- Check the “results” file to see that input values were properly entered, and the number of grid points and elements in the loaded zone is reasonable.
- Check the error in the applied impulse to see that it is within the desired degree of accuracy. If the error is too large, increase the number of discretization rings or refine the finite element mesh itself.
- One source of error in the applied load could be due to the blast position selected in relation to the edge of a loaded surface. If the circular loading area overhangs the edge of the surface of load application, the applied impulse will be smaller than the actual impulse. This is because not all of the ideal impulse impacts the surface. The loading created should be accurate for such a blast placement, however, the error in the applied load is no longer a valid way to judge this. Import “patranvis.dat” into PATRAN in order to see that the spatial distribution of the applied load is reasonable.
- The files “circle.dat” and “zones.dat” can be used to determine information about the grid points and elements selected for loading by the preprocessor (i.e. coordinates, areas, average distance). Careful inspection of these files can reveal information about the applied load not contained in “results”.

In order to validate the newly applied blast load, the actual impulse of the load applied to the NASTRAN model is compared to an ideal impulse as calculated from the methods described above. The ideal impulse is calculated by numerically integrating the calculated blast pressure over the loaded area and for the duration of the blast. The impulse actually applied to the plate is calculated by first calculating the impulse per unit area for each loading zone. Then the area of all the elements in each load zone is calculated and multiplied by the corresponding impulse per unit area. This result is the total impulse actually applied to the NASTRAN model. A comparison between the ideal and applied impulses can then be made in order to determine the validity of the applied blast load. The chart in Fig. 16 shows the error in applied load for a 400 and 2500 element plate which was loaded using 4, 8, and 12 discretization rings.

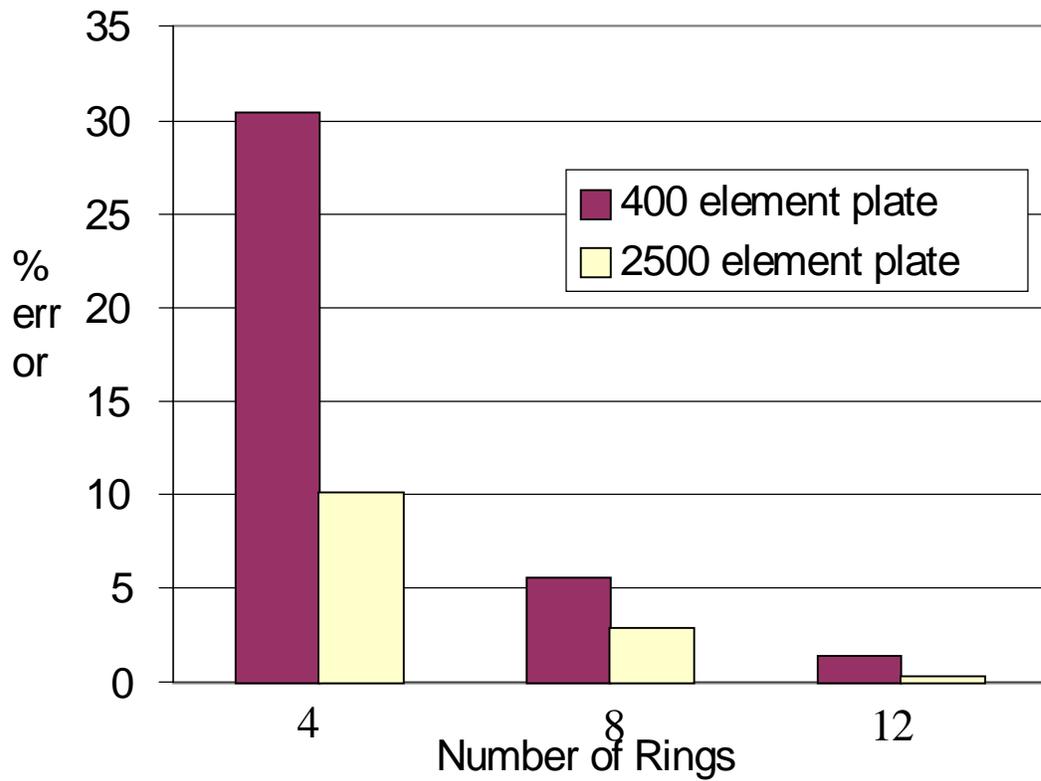


Figure 16. Percent error in applied load using a 400 and 2500 element plate, which was loaded using 4, 8, and 12 discretization rings.

Chapter 7

Linear Analysis of Composite Plates Subject to A Mine Blast

Results were generated using the NASTRAN finite element procedure and blast preprocessor described here. All studies were carried out within the framework of CLT on the same 4-layer (0/90/90/0) symmetric cross-ply laminate, unless otherwise noted. The plate dimensions and laminae material properties are:

$$E_1 = 26300 \text{ ksi}, E_2 = 1490 \text{ ksi}, G_{12} = G_{13} = G_{23} = 1040 \text{ ksi}, \\ \nu_{12} = .25, a = b = 100 \text{ in.}, a/h = 50, \rho = .00475 \text{ lb- s}^2/\text{in}^4$$

Figures 17 through 21 provide a comparison between the two blast calculation methods by monitoring the plate response as a function of blast parameters. These plots show center plate deflections vs. time for several blast distances and charge weights. Figures 22 and 23 illustrate how the ideal impulse varies with blast distance and charge weight, respectively. Figure 24 shows how stacking sequence affects plate response. Figure 25 provides a comparison between the NASTRAN CLT and FSDT solution procedures for a thick plate subject to a 20-pound mine blast.

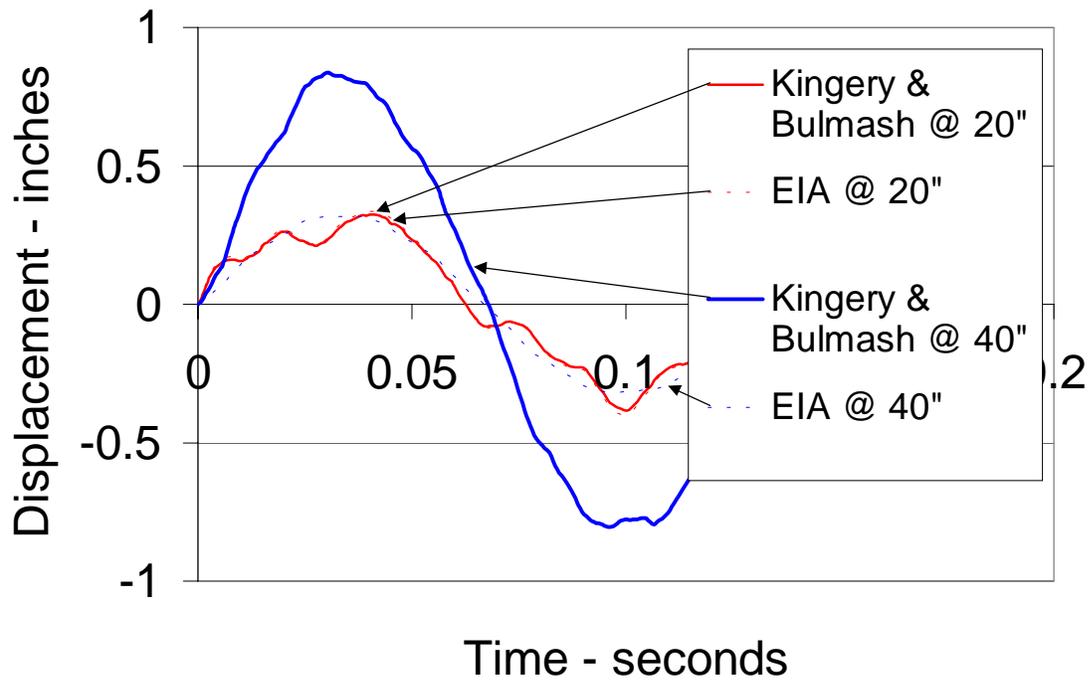


Figure 17. Comparison of blast calculation methods for a 5-lb mine blast at 20" and 40".

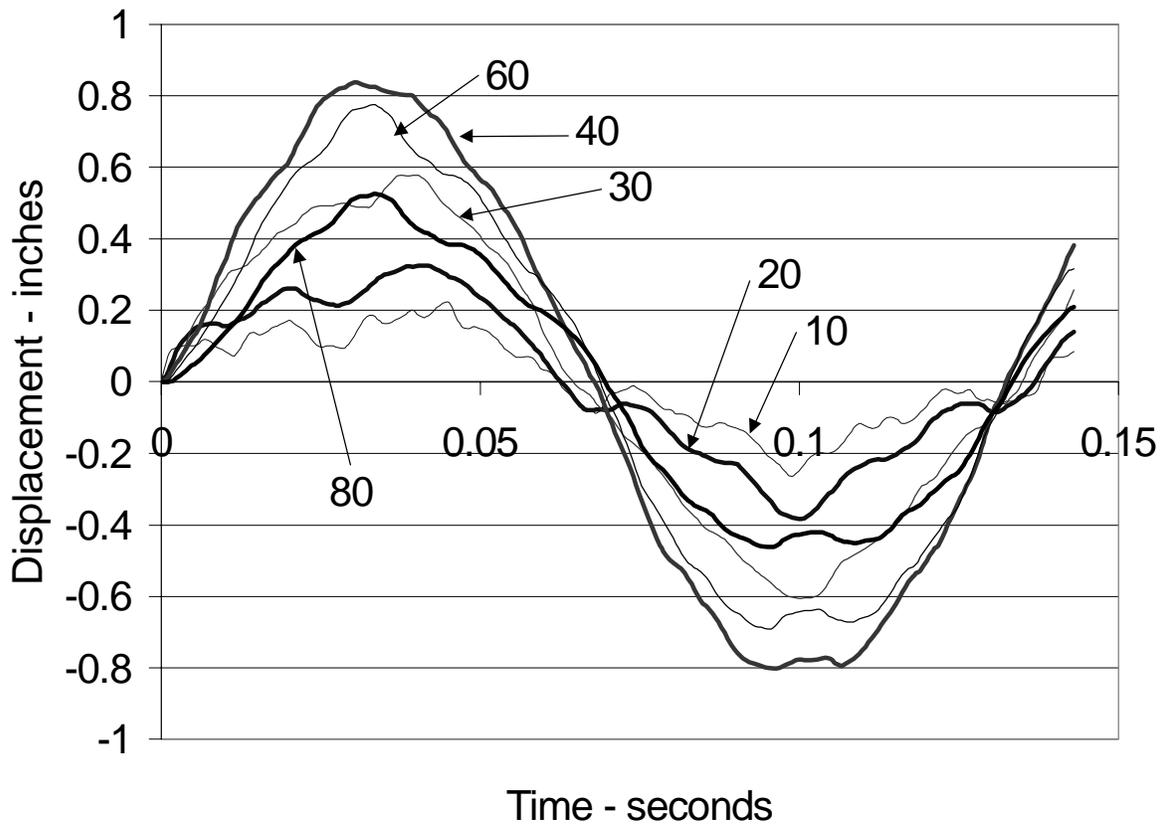


Figure 18. Plate response to Kingery & Bulmash calculated 5-lb mine blast at several blast distances.

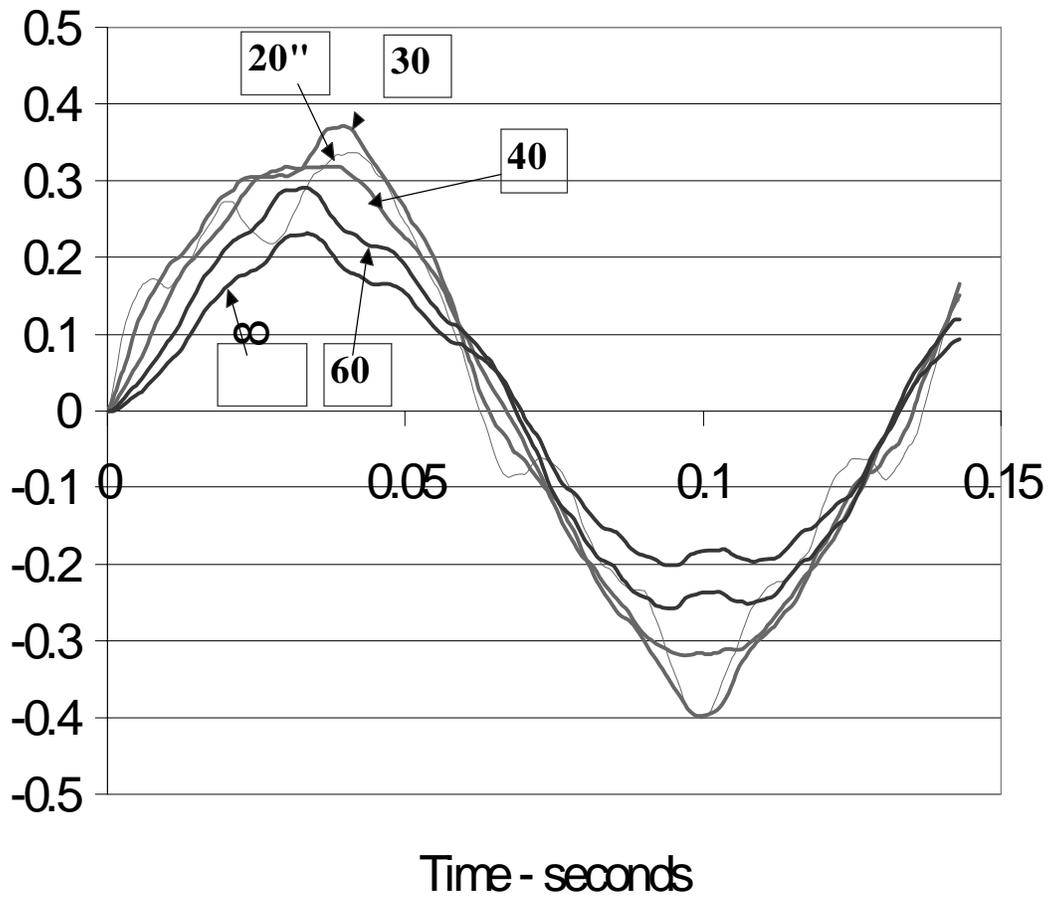


Figure 19. Plate response to EIA calculated 5-lb mine blast at several blast distances.

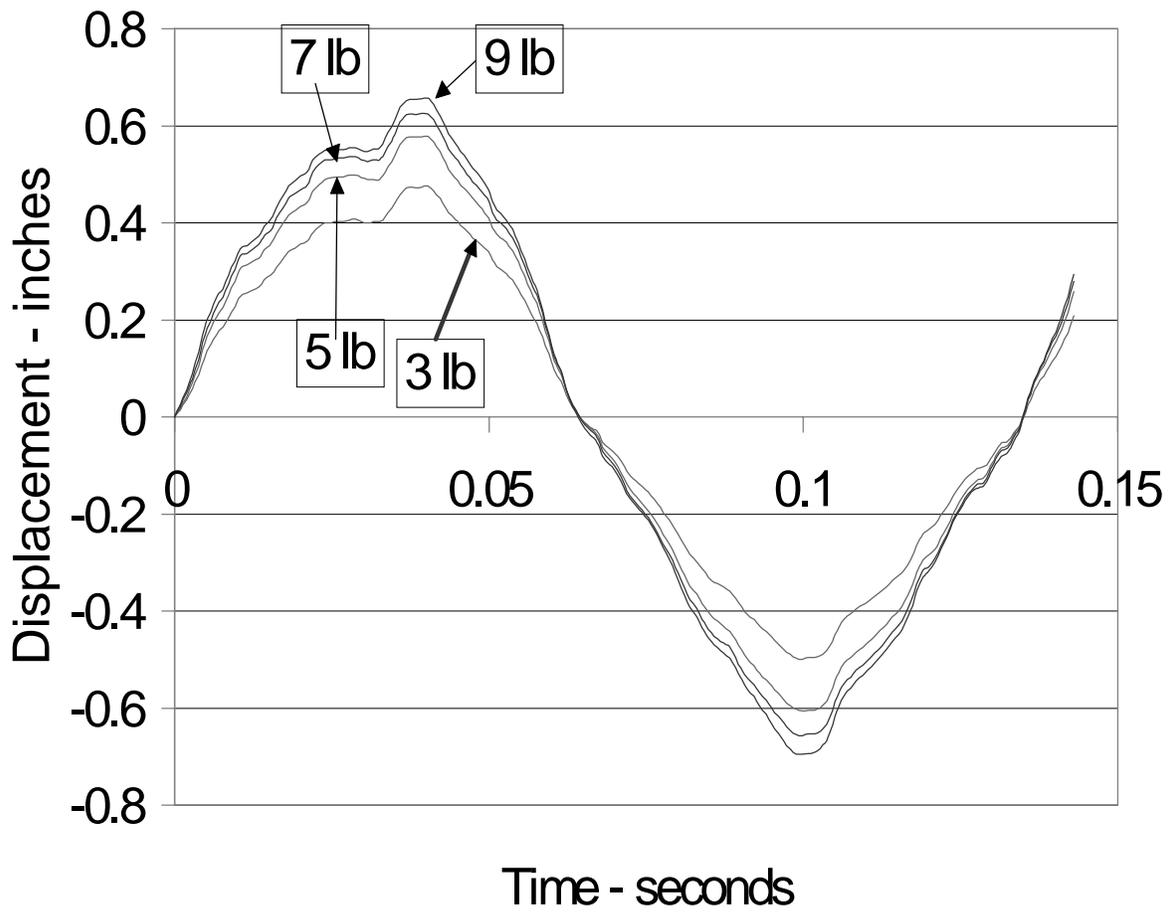


Figure 20. Plate response to Kingery & Bulmash mine blast at 30" for several charge weights.

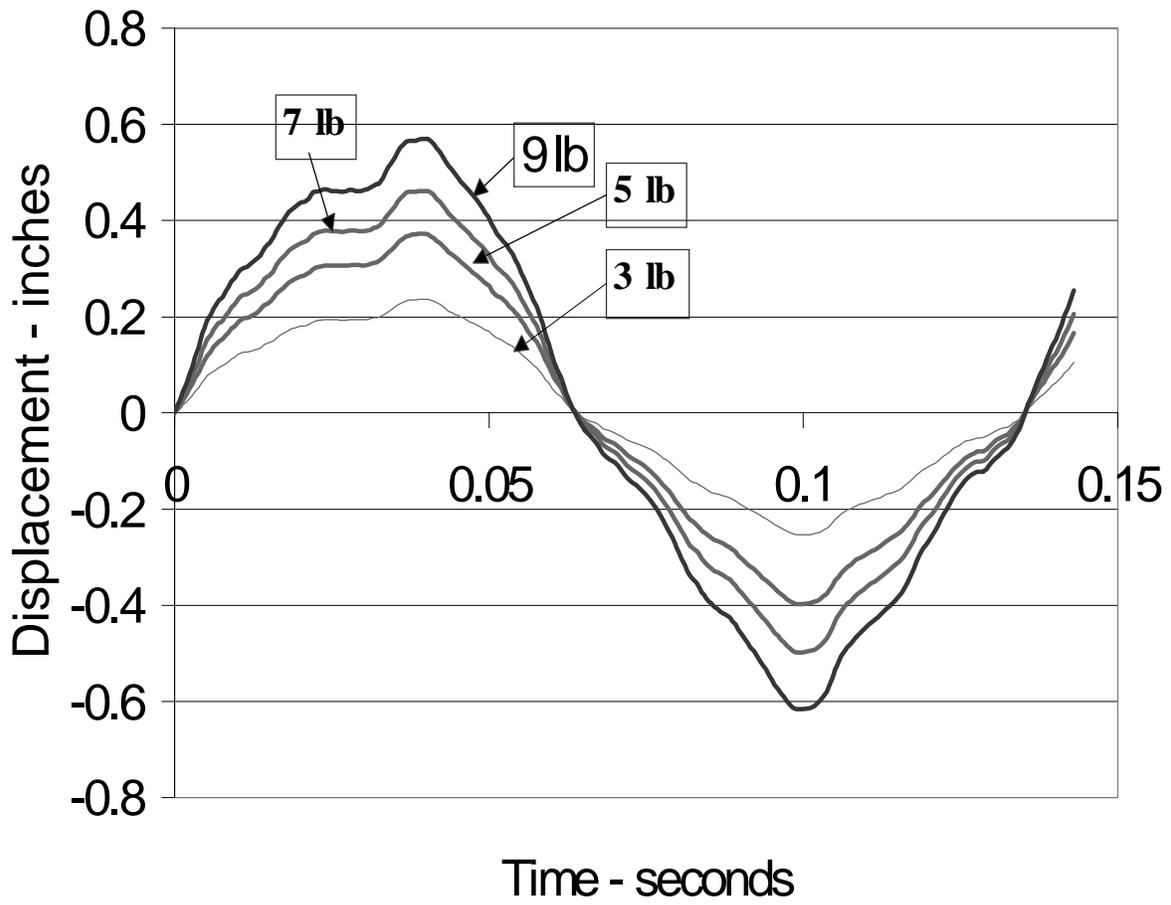


Figure 21. Plate response EIA calculated mine blast at 30' for several charge weights.

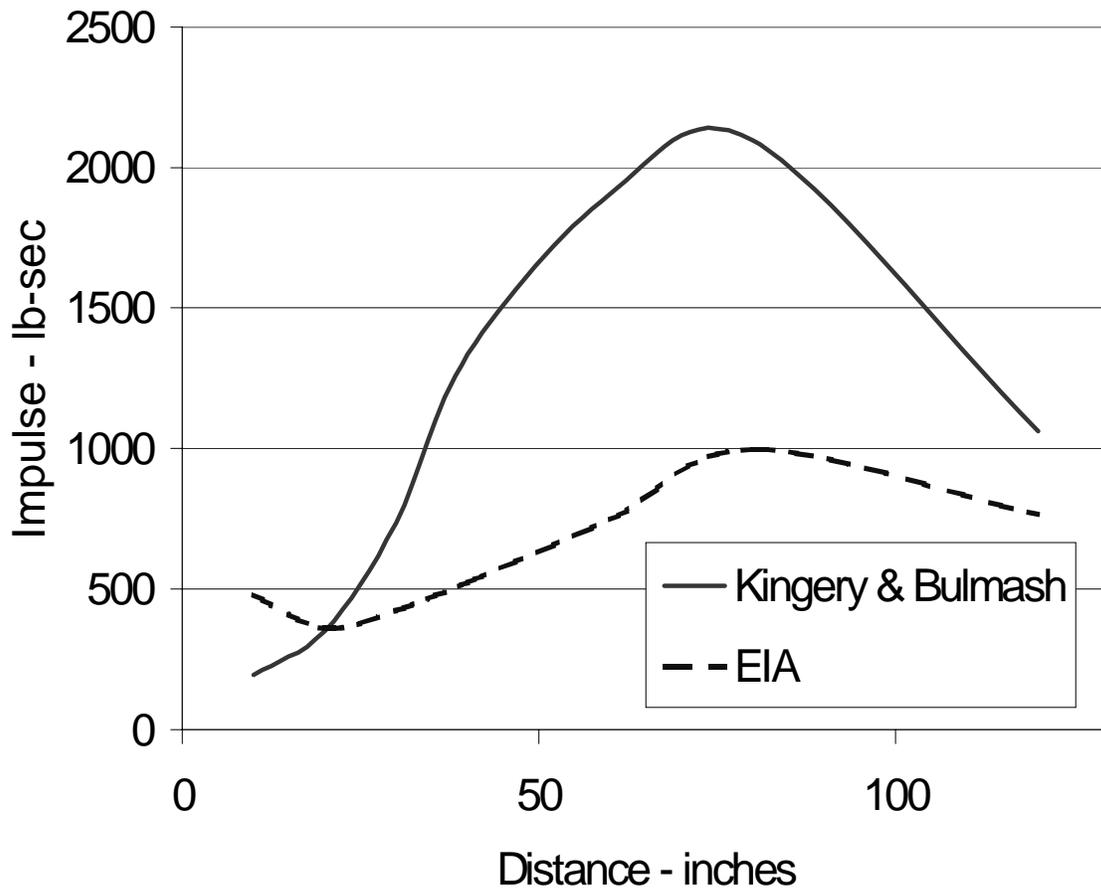


Figure 22. Total ideal impulse vs. blast distance for a 5-lb charge. A comparison of methods.

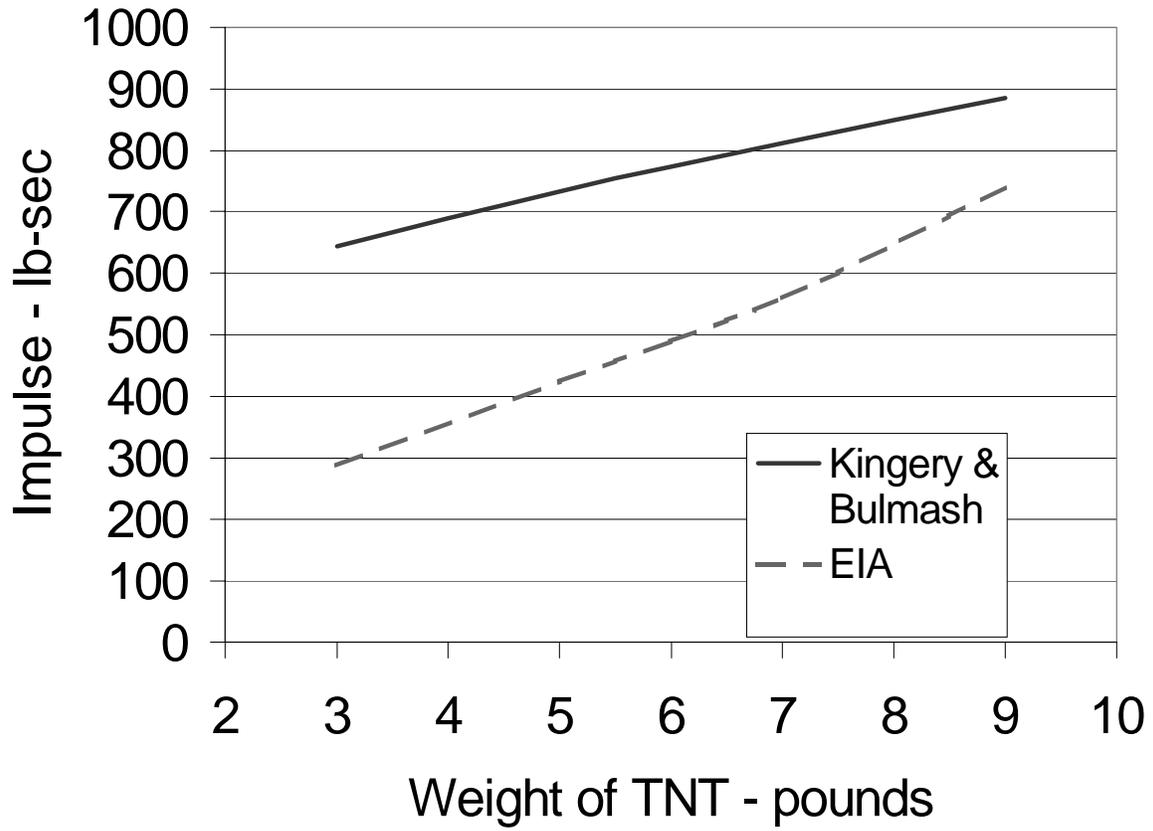


Figure 23. Total ideal impulse vs. charge weight for a mine blast at 30". A comparison of blast calculation methods.

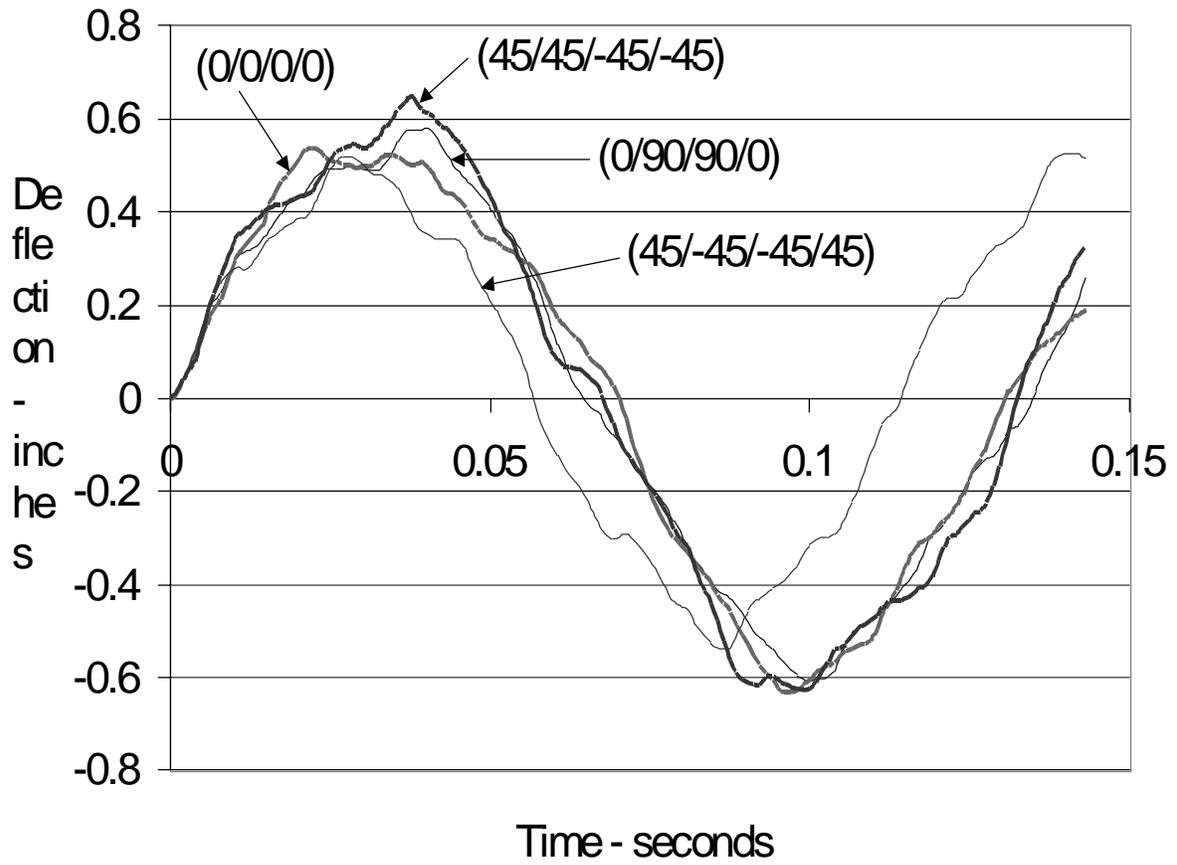


Figure 24. Various stacking sequences subject to 5-lb Kingery and Bulmash mine blast at 30”.

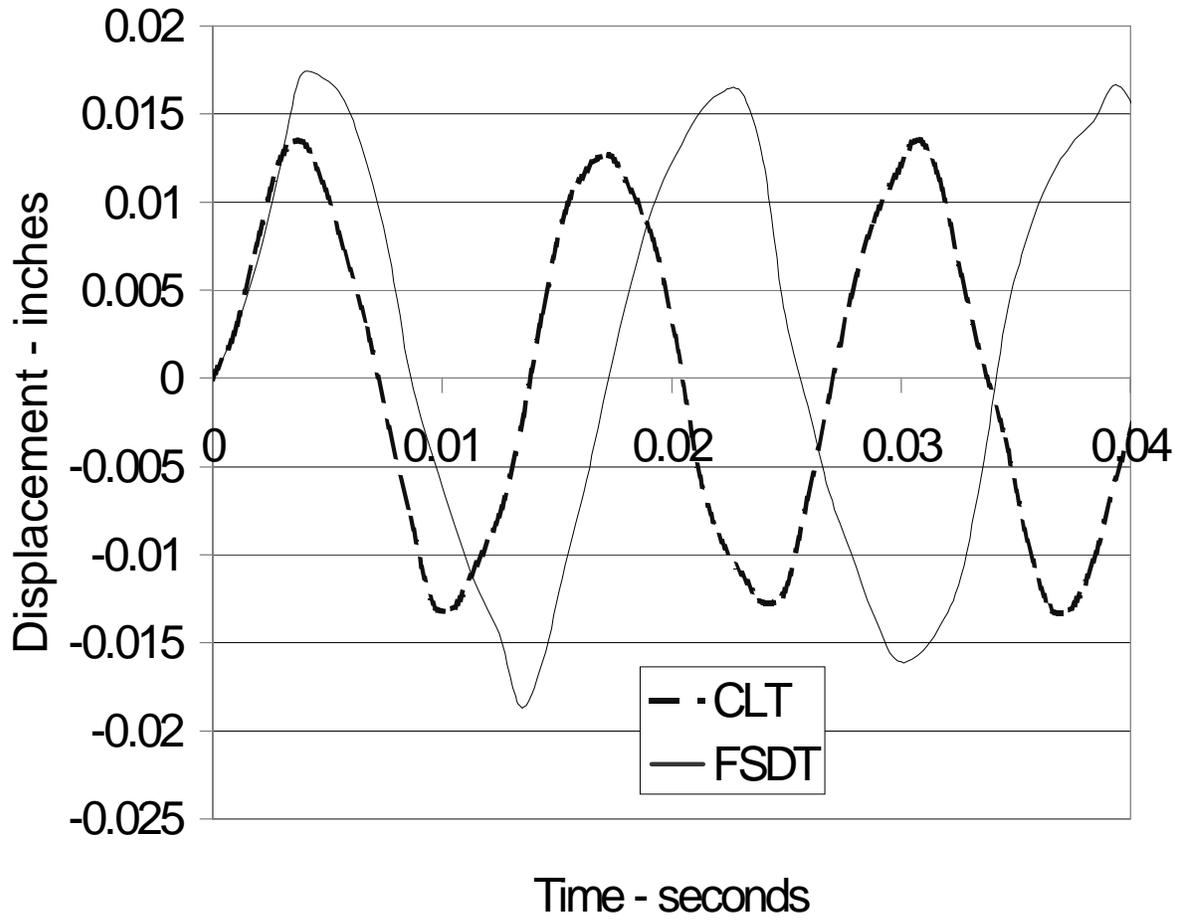


Figure 25. Comparison between CLT and FSDT for a 100" x 100" x 20" (45/45/-45/-45) laminate subject to a 20-lb Kingery and Bulmash mine blast at 30".

Chapter 8

Nonlinear Analysis of Contacting Plates Subject to A Mine Blast

In order to investigate the behavior of blast-loaded contacting plates, a model of two 100" x 100" x 1/4" plates was developed for a NASTRAN finite element solution. The two plates lie parallel to each other and are separated by some gap distance, which unless otherwise noted, was equal to the plate thickness of 1/4". Both plates were clamped at their boundary, and a blast load was applied to the center of the top plate in order to force contact between the plates. The 5-lb mine blast was applied at 16 inches normal distance from the center of the top plate. Due to the symmetry of the proposed analysis, only a quarter plate section (50" x 50" x 1/4") was modeled. This quarter plate model is shown in Figure 26.

Eight loading rings were used to discretize the blast load for these analyses. The 5-lb Kingery & Bulmash calculated mine blast at 16" imparted a total impulse of 262.63 lb-sec to the full plate. With only one quarter of this impulse applied to the quarter plate model, the error in the applied load was 1.1%.

The material properties used for both plates and for all the analyses were taken to be; modulus of elasticity $E = 10.9 \times 10^6$ psi, Poisson's ratio $\nu = .3$, mass density $\rho = .00026$ lbs-sec²/in⁴, and yield strength $\sigma_y = 58,000$ psi. The nonlinear material model utilized an elastic-perfectly plastic constitutive relation. Each quarter plate was meshed with 625, 2" x 2" square plate elements. The corresponding nodes of each plate were then connected with gap elements.

The following subsections investigate the effect of several parameters important to a contact analysis. The first analyses are performed to test for convergence of the integration time step. Once an appropriate time step is determined, the various gap parameters are investigated independently. These parameters include penetration depth, closed gap stiffness, and friction.

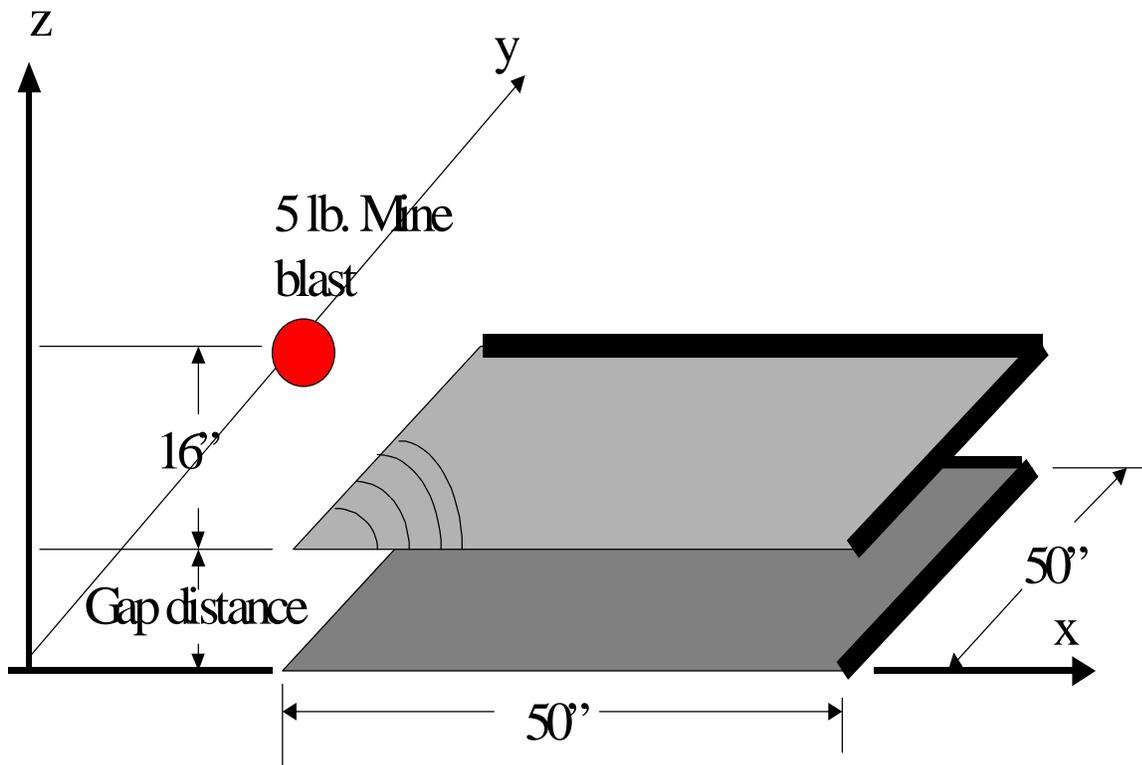


Figure 26. Illustration of the setup used for the contact analyses. The top plate is subject to a 5-lb. Mine blast at 16'.

8.1 Time Convergence

The first analyses were conducted in order to determine an appropriate value for the integration time step. For these analyses, the gap separation distance was set to the thickness of the plate (.25 in.), and the closed gap stiffness was set to $1/100^{\text{th}}$ the modulus of the plate, or 109,000 lbs/in. The global stiffness matrix was updated every two converged iterations based on the deformed geometry. The open gap stiffness was set to zero, and the effect of sliding friction was neglected. The maximum penetration depth was set to be $1/10^{\text{th}}$ the thickness of the plate, or .025 inches.

Figure 27 shows the center plate deflections of the top and bottom plates for various values of the integration time step. The blast pressure arrives on the top plate at approximately .0001 second after the explosion, endures for about 300 microseconds, and is completed by .0004 second. The deflection histories begin with the top plate already at its initial global z – coordinate of .25". Very shortly after the blast is completed, the center of the top plate collides with the bottom plate. This collision accelerates the previously static bottom plate in the negative z-direction. Simultaneously, the top plate recoils in the positive z-direction. All three analyses demonstrate this behavior, but only the two analyses with the finer time steps show a consistent result. The computer run times for these analyses were proportional to the number of integration steps used, and ranged from 1 hour 37 minutes to 37 minutes of actual CPU time. Judging from the results above, the finest integration time step of 5 microseconds will be used to perform further investigations.

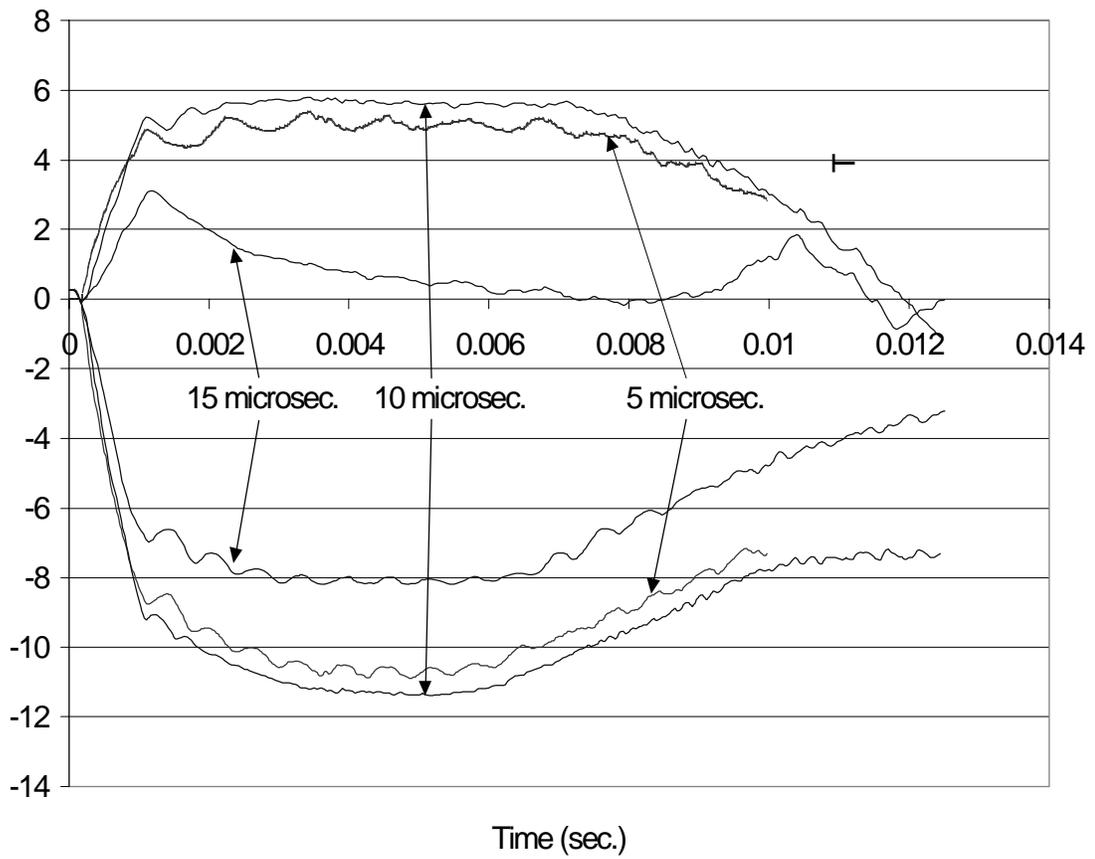


Figure 27. Deflection time histories for the center nodes of the two contacting plates. Three analyses are shown using integration time steps of 5, 10, and 15 microseconds.

8.2 Penetration Depth/Adaptive Gap Element

When a maximum allowable penetration depth is specified for the gap element, the closed gap stiffness is automatically increased as this maximum depth is approached. This is referred to as the adaptive gap element. Figures 28 and 29 depict identical analyses, except the analysis in Figure 8 utilizes the adaptive gap feature, while the analysis in Figure 7 maintains a constant gap stiffness. Both analyses utilized initial closed gap stiffness equal to $1/1000^{\text{th}}$ the modulus of the plate, and an integration time step of 5 microseconds. The adaptive gap analysis utilized a maximum allowable penetration depth of .025 inches, or $1/10^{\text{th}}$ the thickness of the plate. The two figures depict center plate deflections vs. time.

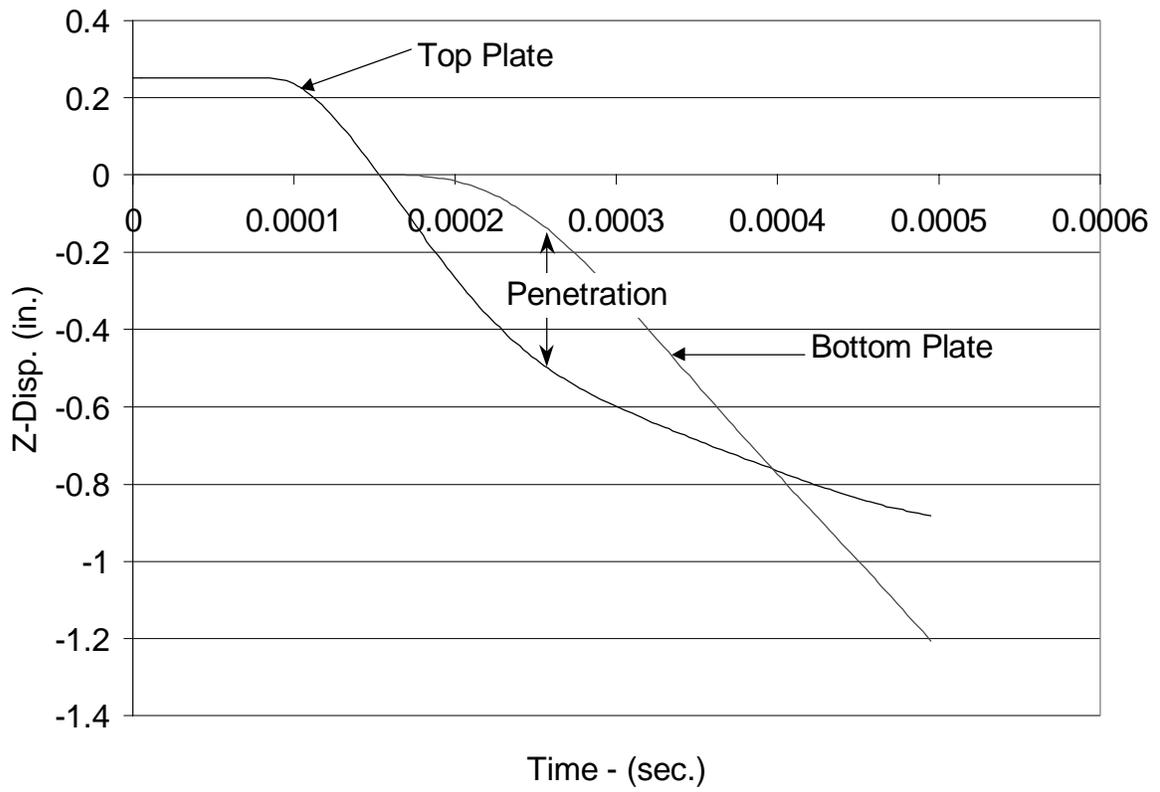


Figure 28. Top and bottom plate deflections for the analysis without the adaptive gap element.

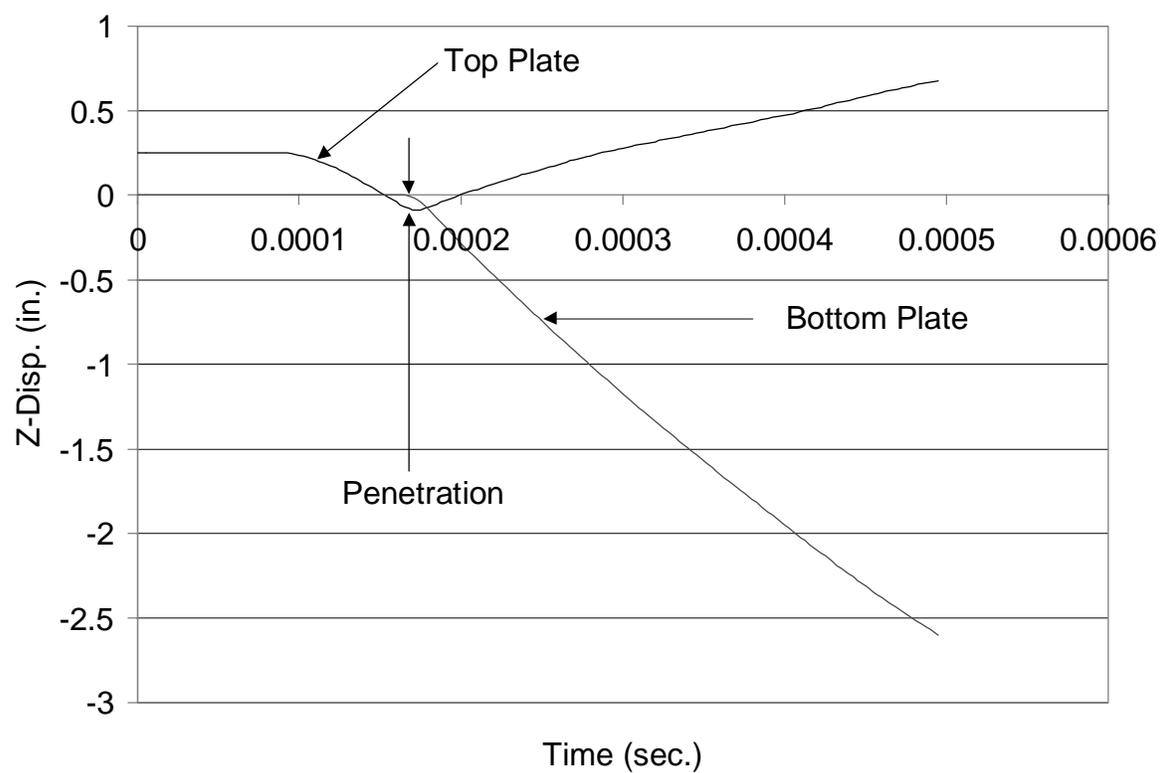


Figure 29. Top and bottom plate deflections for the analysis using the adaptive gap element. Maximum allowable penetration depth = .025 inches.

8.3 Closed Gap Stiffness

The effect of the closed gap stiffness on plate response is investigated with and without the adaptive gap element. All analyses were performed on the already described plate model, and used an integration time step of 5 microseconds. The analyses shown in Figures 30 through 34 show non-adaptive solutions for a range of closed gap stiffness. The values of closed gap stiffness were chosen to be fractions of the plate modulus E . The chosen range covers from $1/10000^{\text{th}}$ E up to $10 E$, in multiples of ten. Note that the $1/1000^{\text{th}}$ case for the non-adaptive gap element is already displayed in Figure 28.

Figures 35 through 37 show adaptive gap solutions for a range of initial closed gap stiffnesses. Recalling that the closed gap stiffness is modified as the maximum penetration depth is approached. The adaptive gap analysis utilized a maximum allowable penetration depth of 0.025 inches or $1/10^{\text{th}}$ the thickness of the plate. The chosen range covers from $1/1000^{\text{th}}$ E up to $1 E$, in multiples of ten. Note that the $1/1000^{\text{th}}$ case for the adaptive gap element is already displayed in Figure 28. These analyses were run for a longer duration than previous analyses in order to observe the accumulation of plastic strain as a result of the blast. Figures 38 and 39 show the center plate equivalent stress and plastic strain for the $1/10^{\text{th}}$ E case.

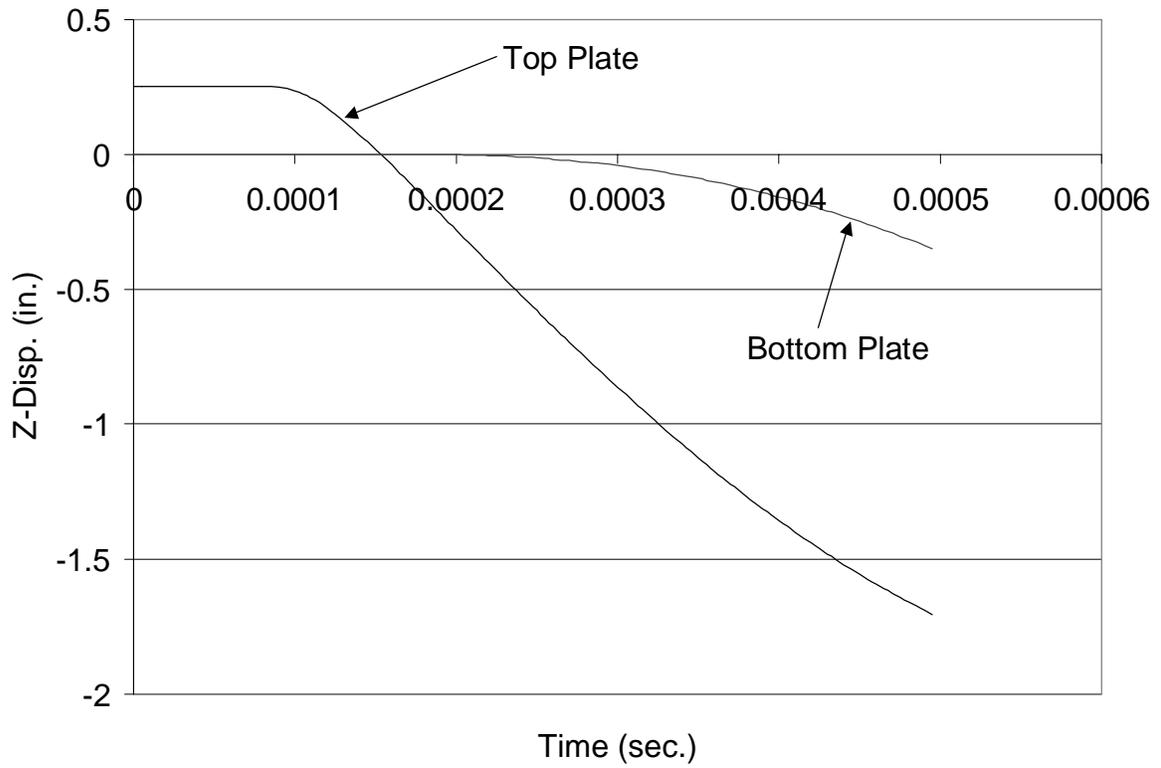


Figure 30. Center plate deflections vs. time for the two plates. Non-adaptive gap element, closed gap stiffness equal $1/10000^{\text{th}}$ E.

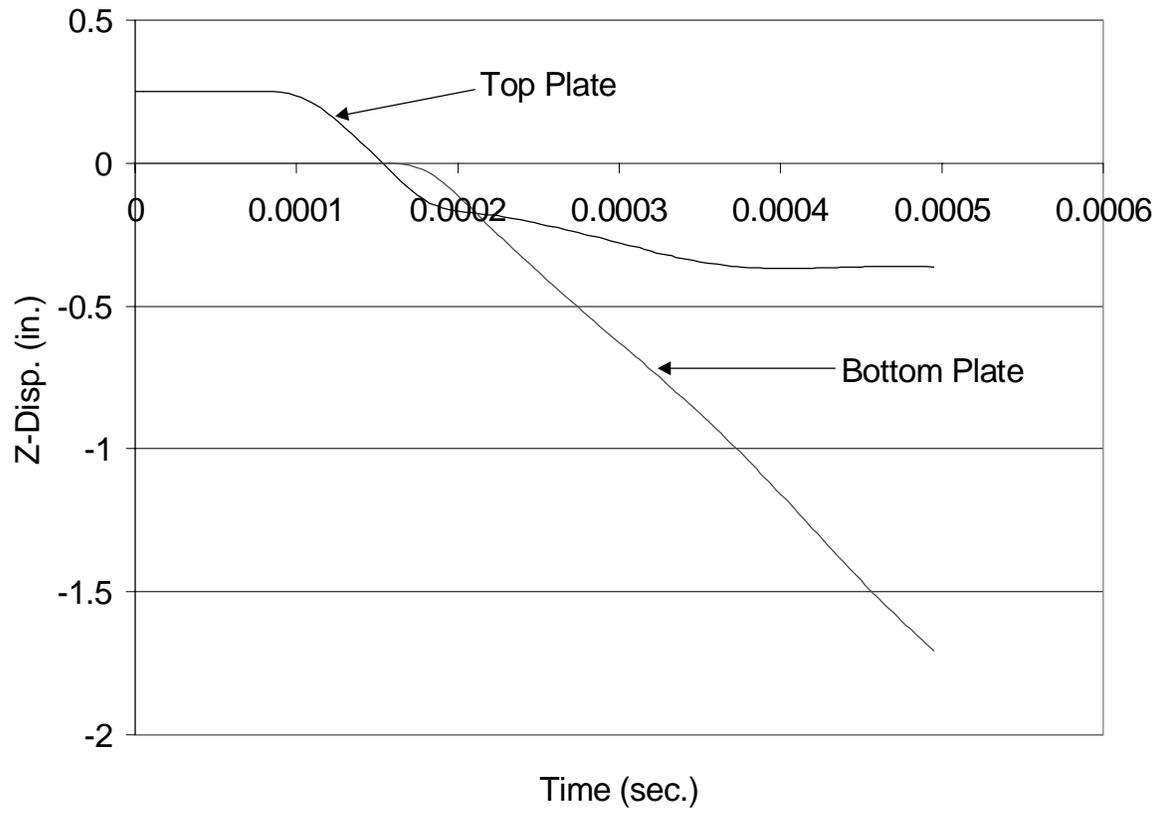


Figure 31. Center plate deflections vs. time for the two plates. Non-adaptive gap element, closed gap stiffness equal $1/100^{\text{th}}$ E.

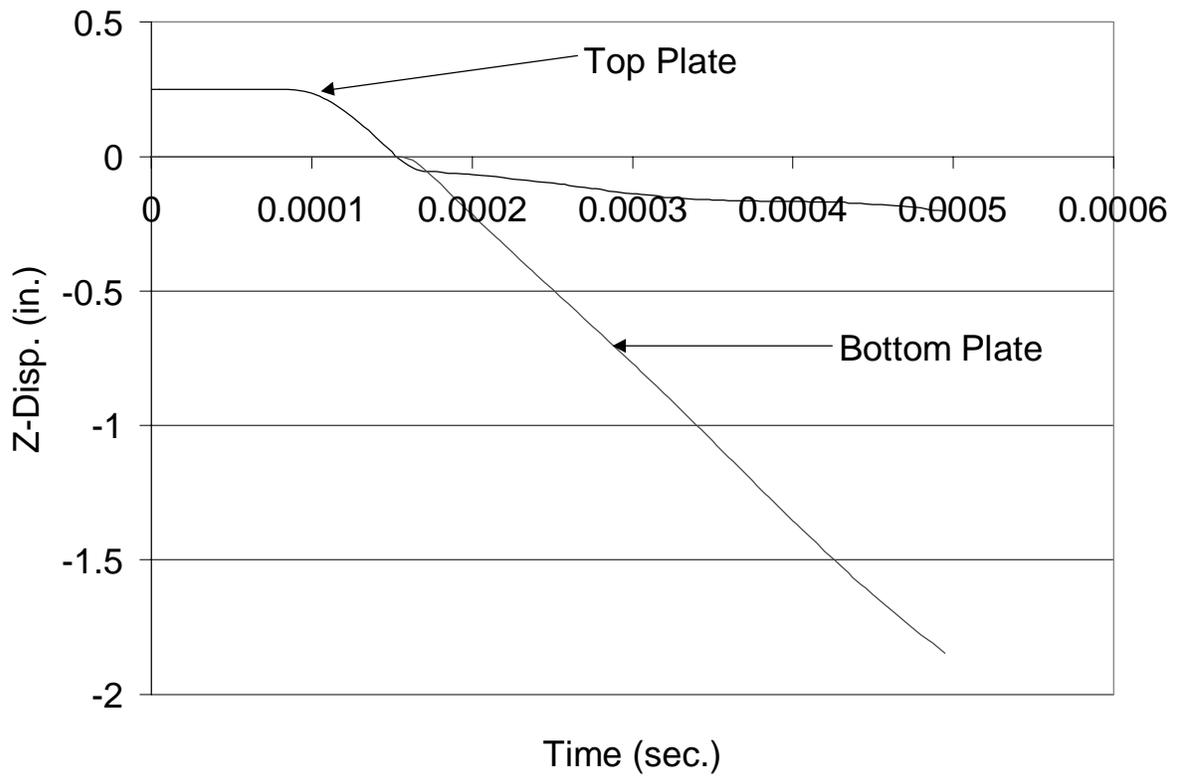


Figure 32. Center plate deflections vs. time for the two plates. Non-adaptive gap element, closed gap stiffness equal $1/10^{\text{th}}$ E.

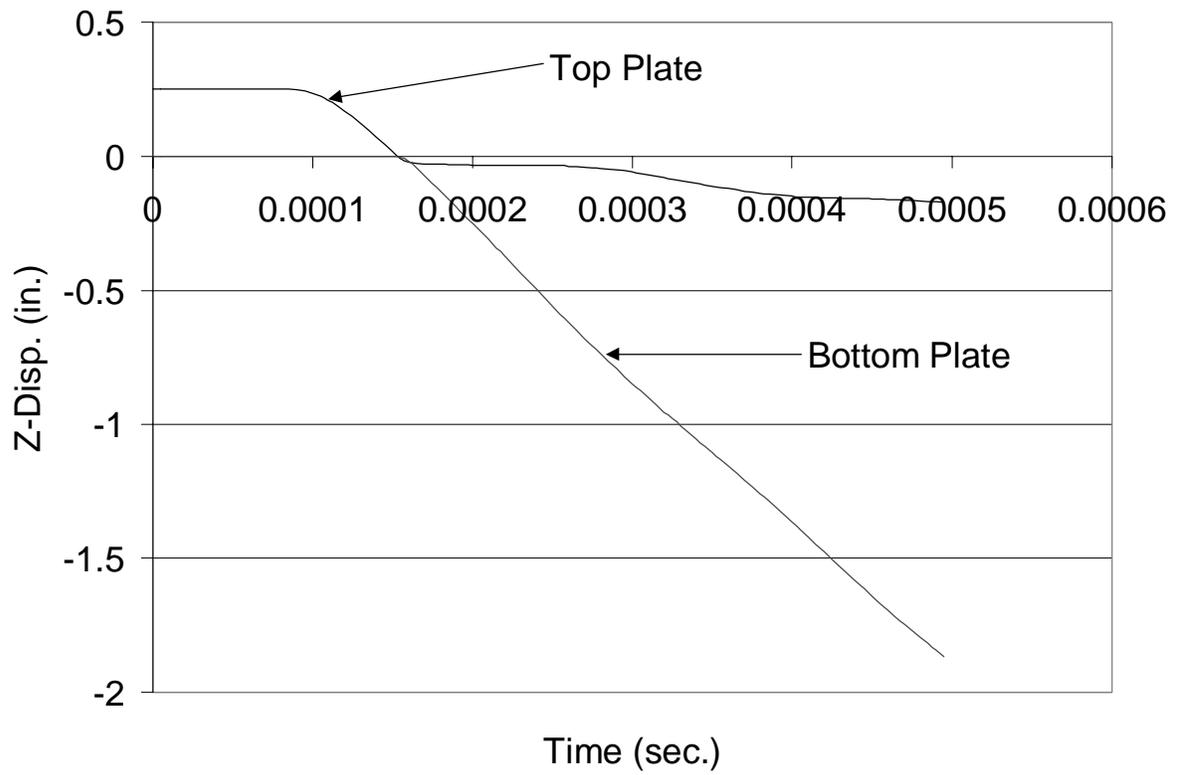


Figure 33. Center plate deflections vs. time for the two plates. Non-adaptive gap element, closed gap stiffness equal 1E.

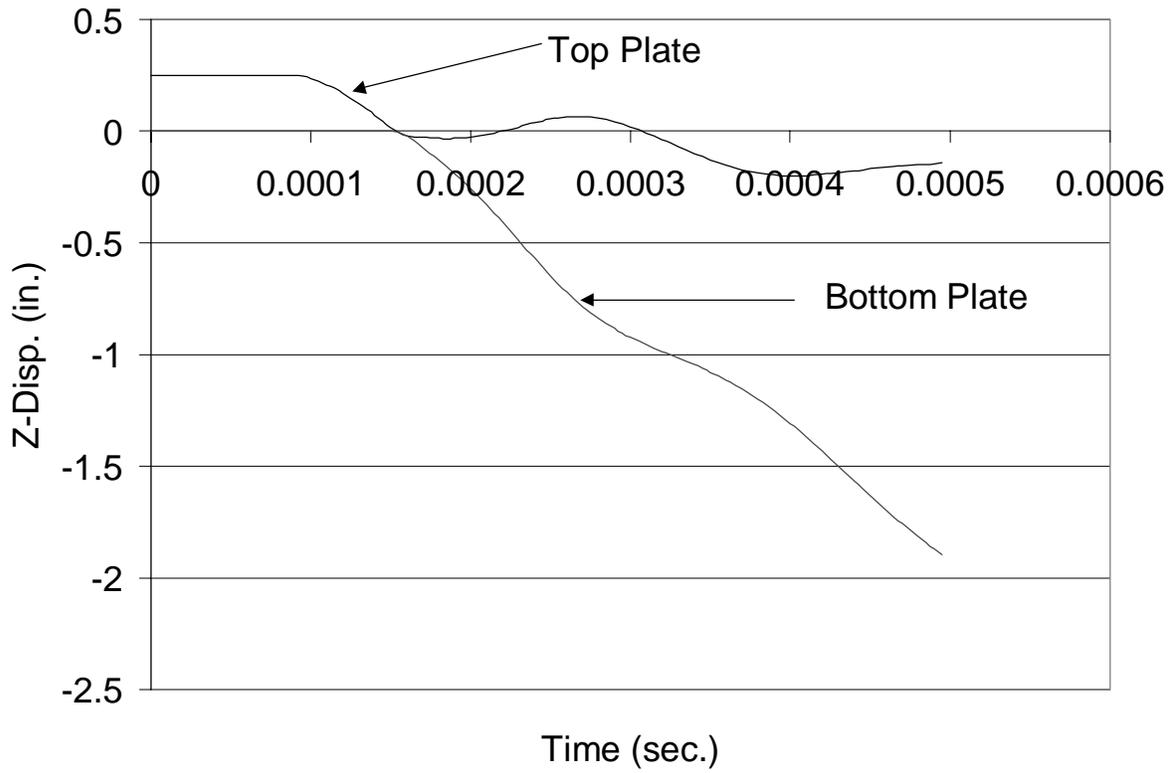


Figure 34. Center plate deflections vs. time for the two plates. Non-adaptive gap element, closed gap stiffness equal 10E.

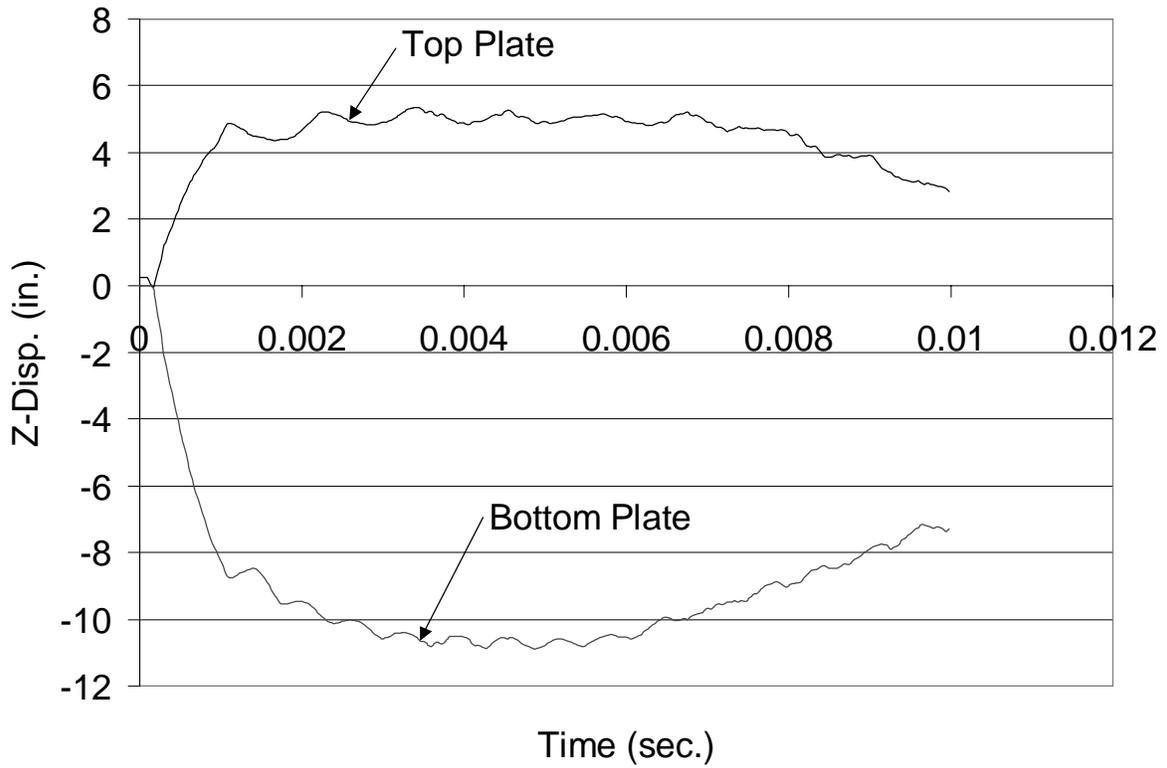


Figure 35. Center plate deflections vs. time for the two plates. Adaptive gap element, closed gap stiffness equal 1/100th E.

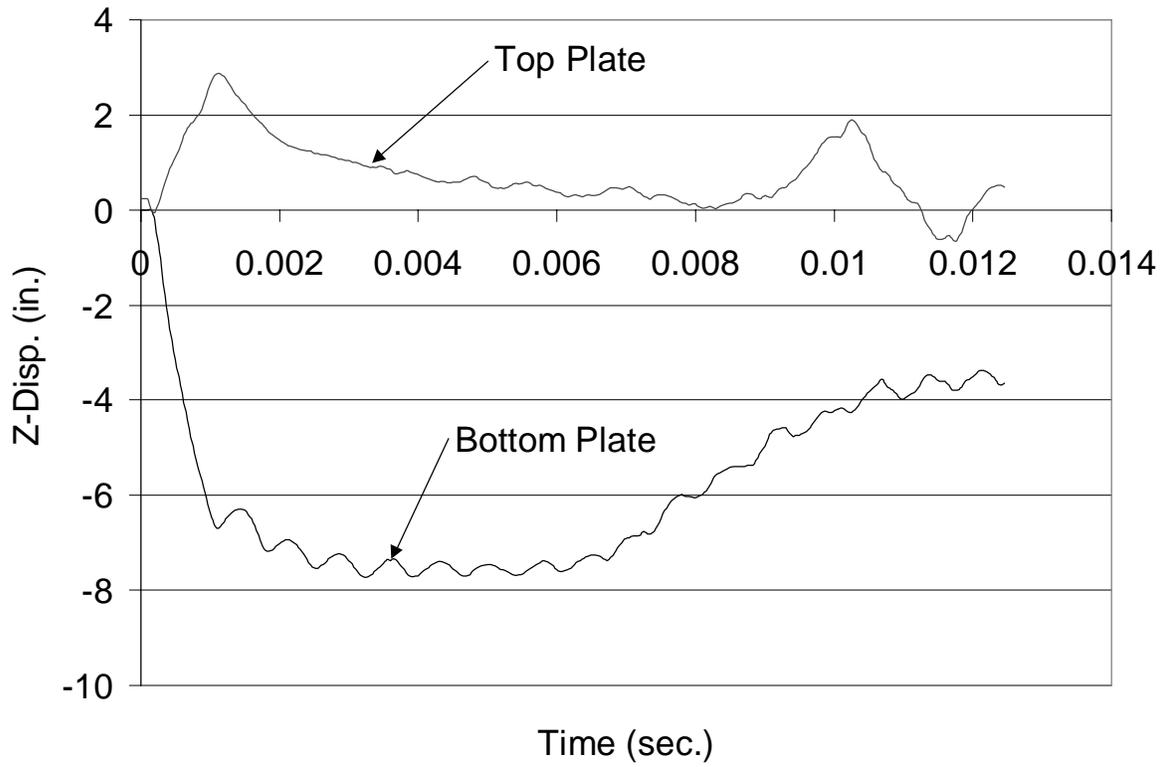


Figure 36. Center plate deflections vs. time for the two plates. Adaptive gap element, closed gap stiffness equal $1/10^{\text{th}}$ E.

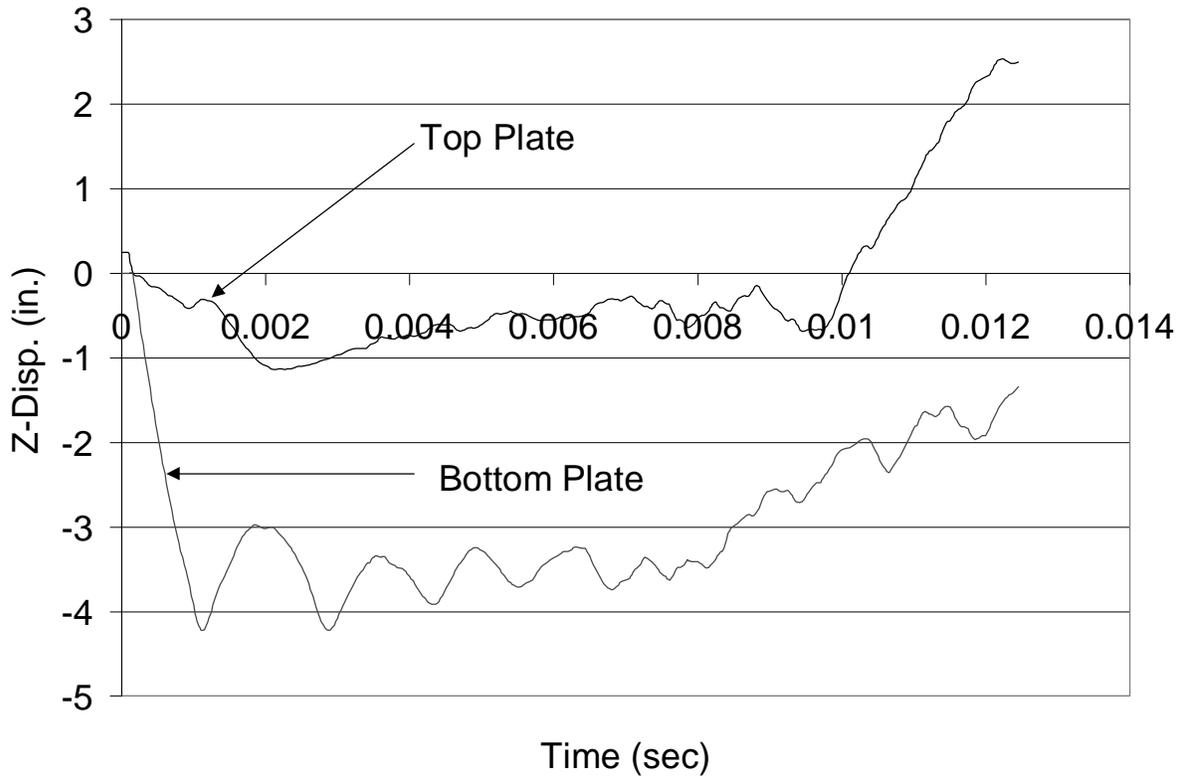


Figure 37. Center plate deflections vs. time for the two plates. Adaptive gap element, closed gap stiffness equal 1E.

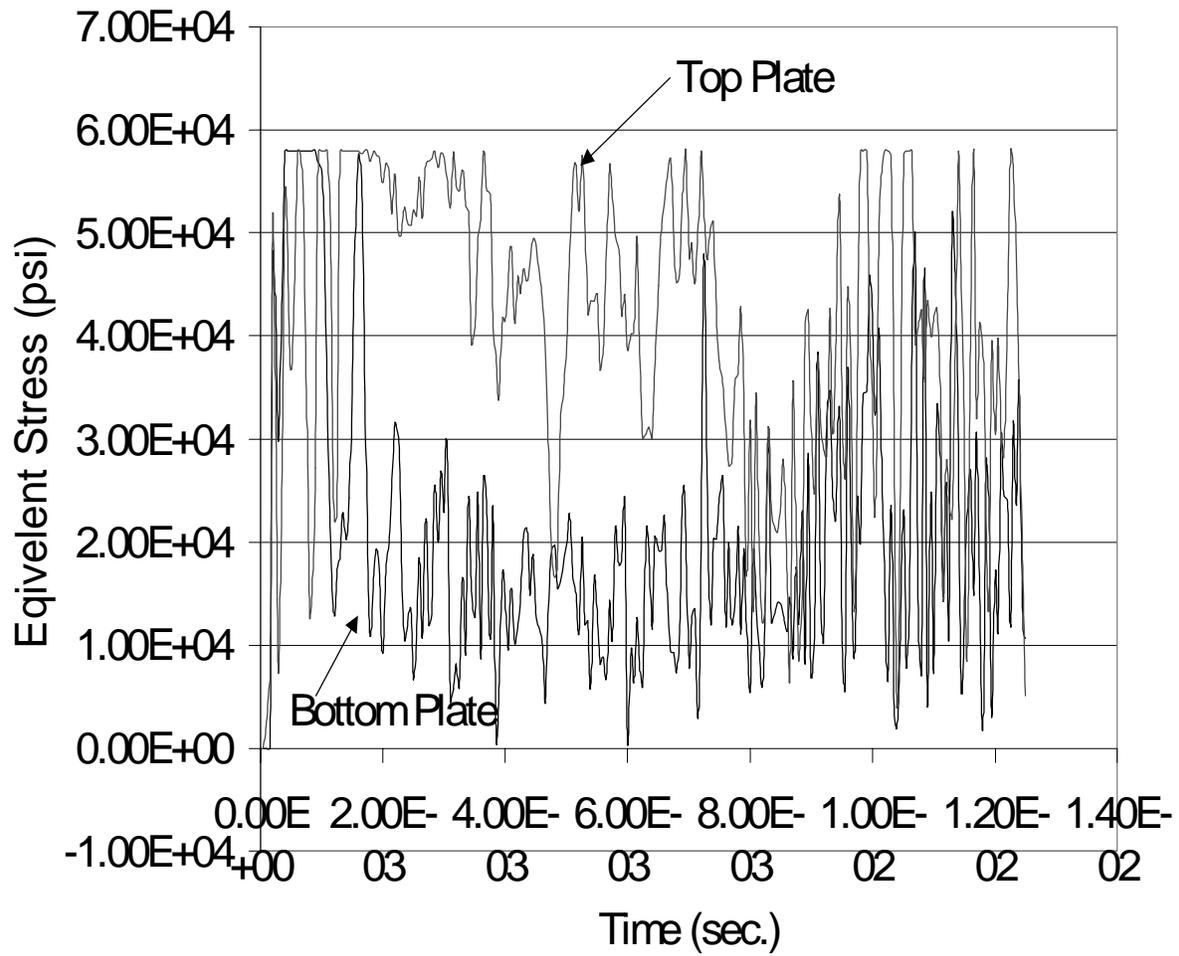


Figure 38. Time history of center plate equivalent stress for the top and bottom plates. Closed gap stiffness = $1/10^{\text{th}}$ E.

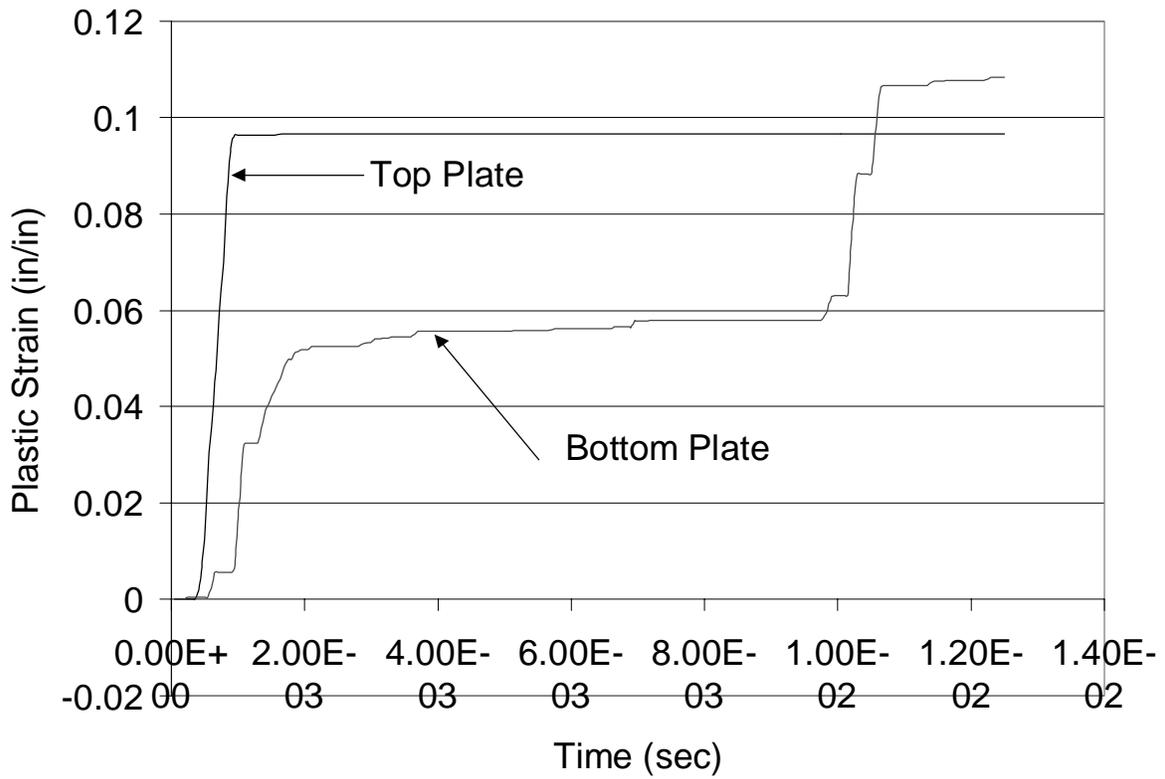


Figure 39. Time history of center plate plastic strain for the top and bottom plates. Closed gap stiffness = $1/10^{\text{th}}$ E.

8.4 Friction

The next contact analysis investigates the effect of including sliding friction in the analysis model. The analyses presented in Figure 40 are the same as the $1/100^{\text{th}}$ E case in Figure 35, except that now one of the analyses includes effects due to sliding friction between the two plates. For this case, the coefficient of static friction was set equal to .3, while the coefficient of kinetic friction was set equal to .28. These values represent typical coefficients for metal to metal contact. However, the actual value of these coefficients can be expected to vary by as much as 25 to 100 percent or more depending on the prevailing conditions of cleanliness, surface finish, pressure, lubrication, and velocity (Merriam, 1992).

The time step used was 5 microseconds, the maximum penetration depth was 0.025 inches, and the closed gap stiffness was $1/100^{\text{th}}$ E.

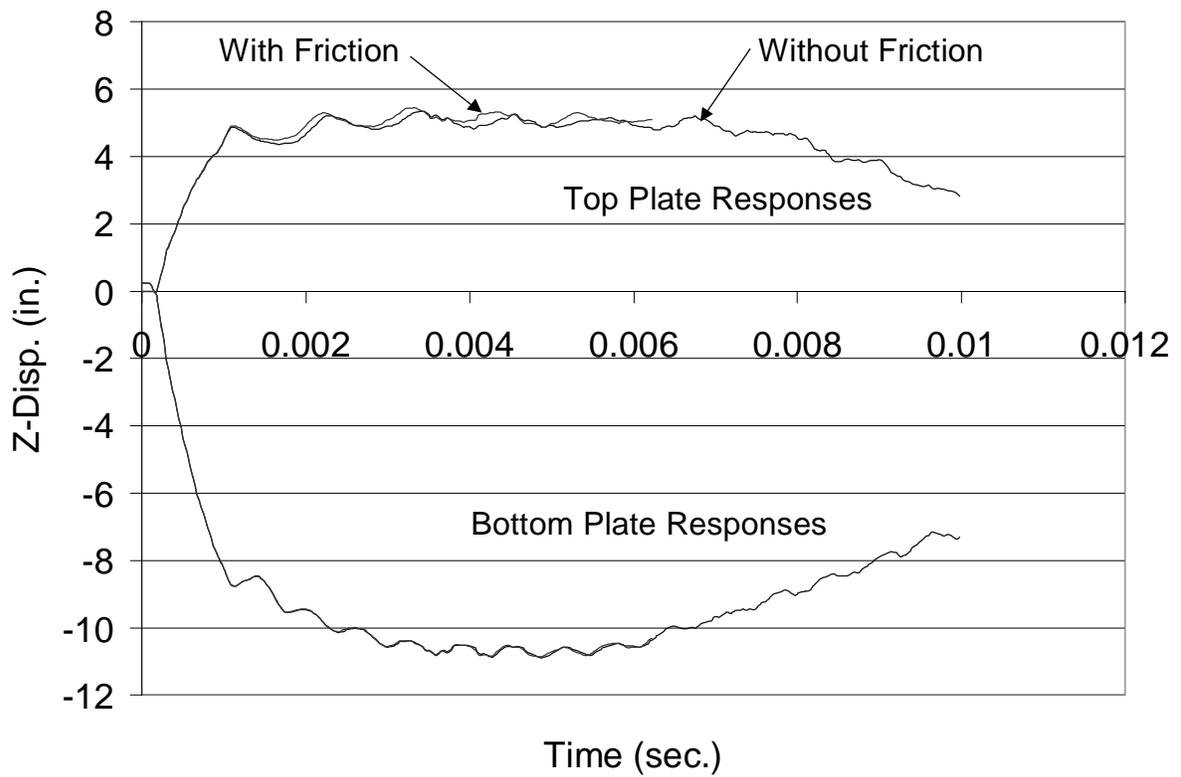


Figure 40. Comparison of center plate deflections for the top and bottom plates, with and without sliding friction.

8.5 Gap Separation Distance

These analyses investigate the effect of gap separation distance on the response of blast loaded plates. All gap parameters are held constant across the analyses depicted in Figures 41 through 44, excepting that the initial distance between the parallel plates is varied. All previous analyses were carried out with an initial gap distance equal to the plate thickness, or $\frac{1}{4}$ inch. Figures 41 through 44 depict analyses that utilize initial gap distances that are successively less than $\frac{1}{4}$ inch, particularly $\frac{1}{8}$ ", $\frac{1}{16}$ ", $\frac{1}{40}$ ", and $\frac{1}{400}$ ". The reader can refer back to Figure 35 for a comparable analysis that used the original gap distance of $\frac{1}{4}$ inch.

For the analyses shown in Figures 35, 41-44, the time step was 5 microseconds, the maximum penetration depth was .025 inches, and the closed gap stiffness was $1/100^{\text{th}}$ E. The specification of the penetration depth again indicates that the adaptive gap element will be used, and the closed gap stiffness will be increased as needed. For purposes of comparison, Figure 45 depicts the response of a single plate which has a thickness equal to the combined thickness of the top and bottom plates used in the previous analyses. All other dimensions, material properties, and relevant analysis parameters are equivalent. Figure 46 is a bar chart which shows the accumulated plastic strain at the center-plate as a function of gap distance.

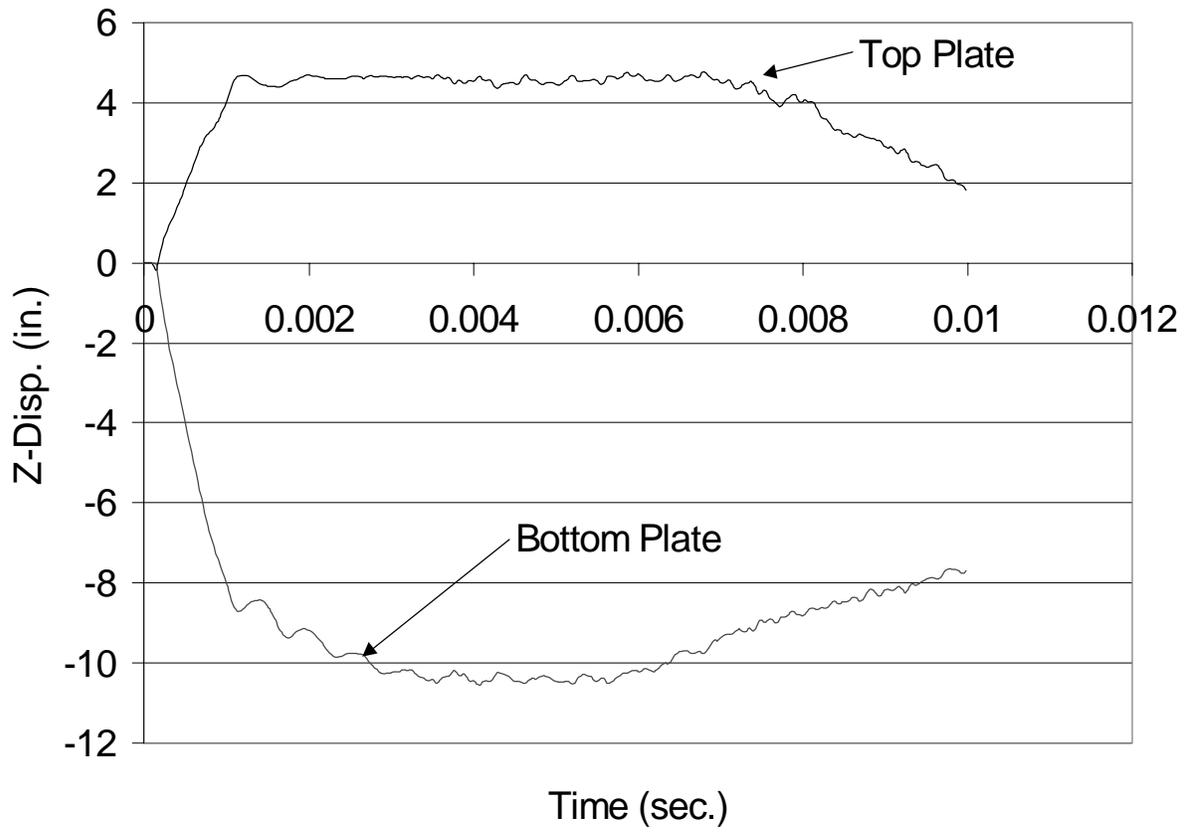


Figure 41. Center plate deflections vs. Time for the top and bottom plates. Initial gap distance equals 1/8th inch.

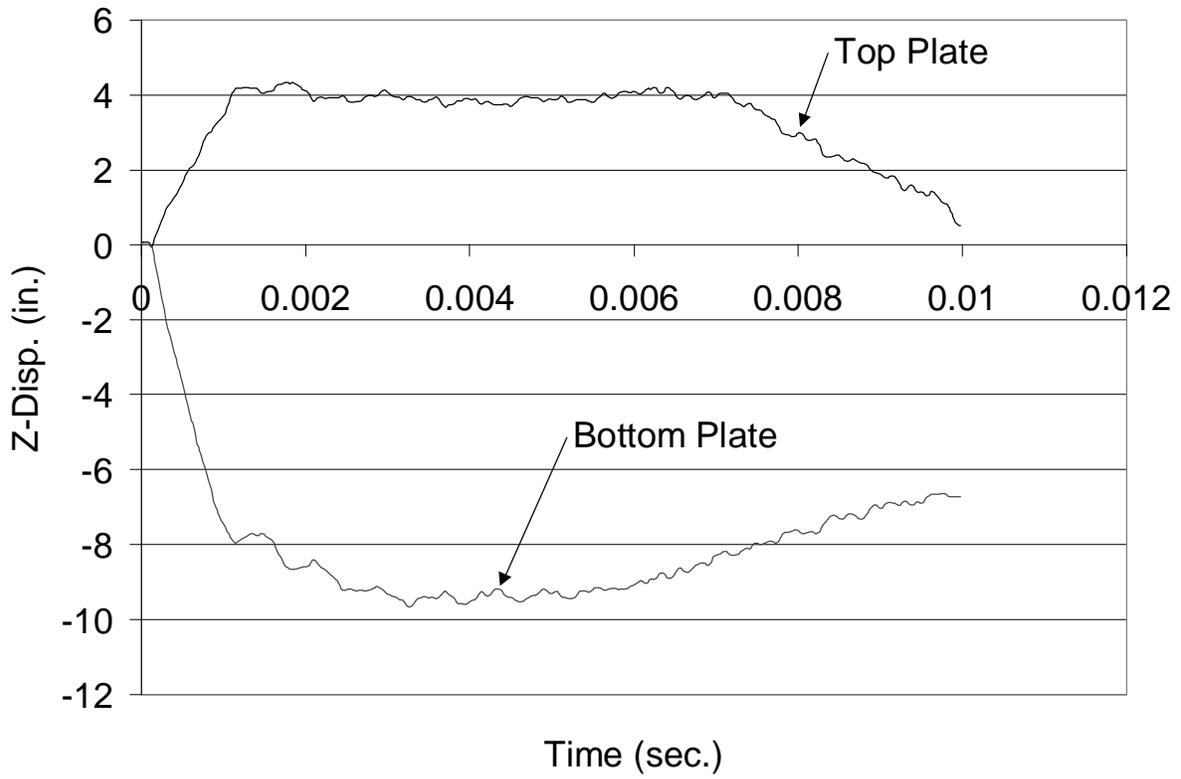


Figure 42. Center plate deflections vs. Time for the top and bottom plates. Initial gap distance equals 1/16th inch.

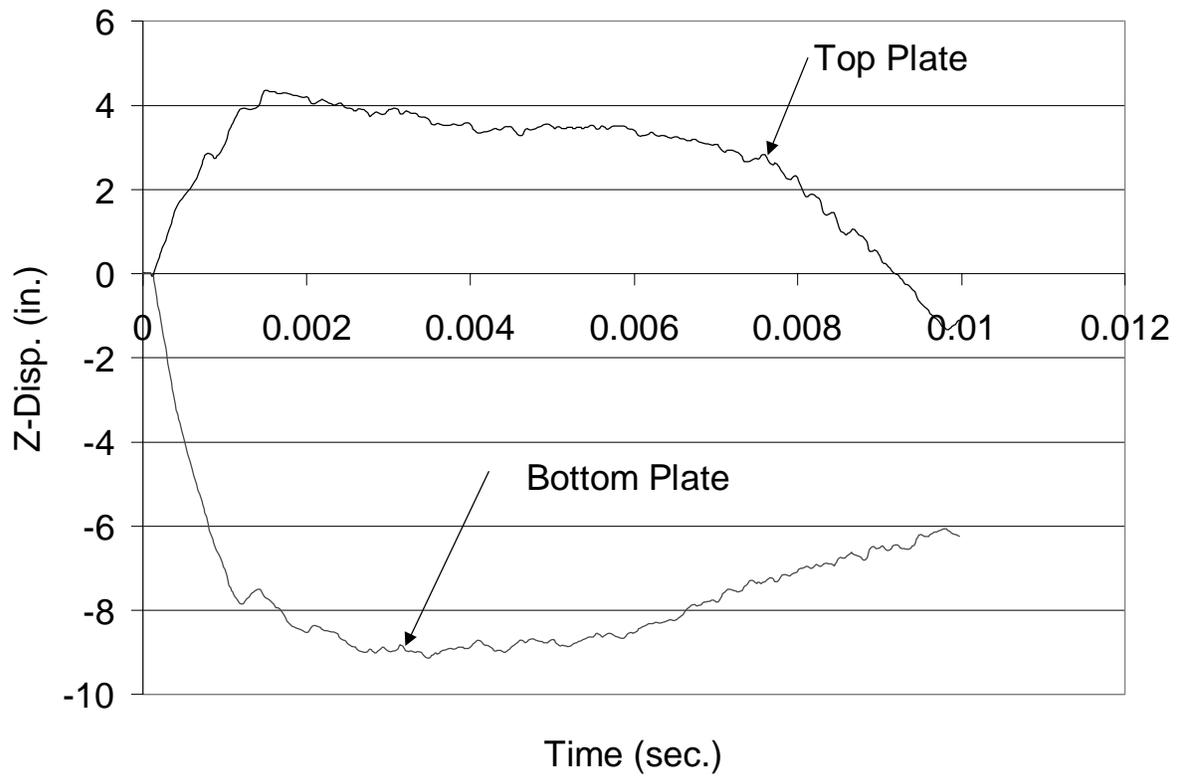


Figure 43. Center plate deflections vs. Time for the top and bottom plates. Initial gap distance equals 1/40th inch.

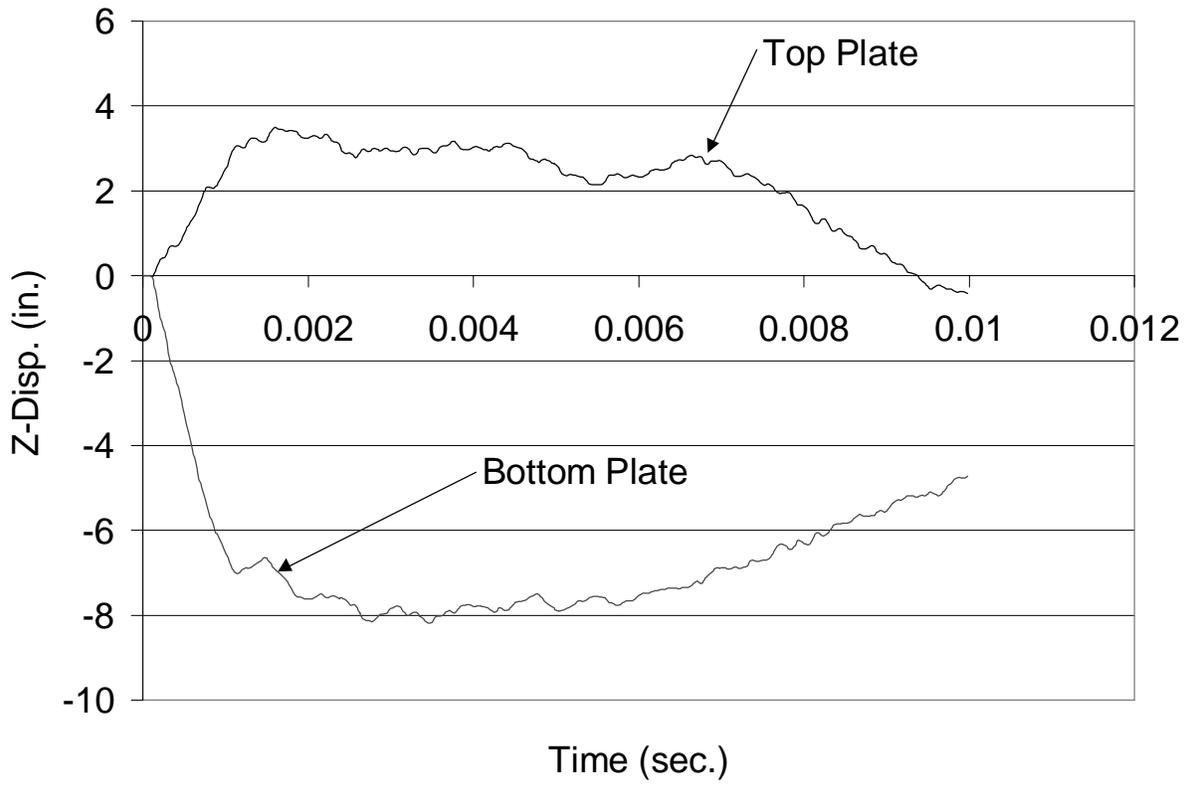


Figure 44. Center plate deflections vs. Time for the top and bottom plates. Initial gap distance equals 1/400th inch.

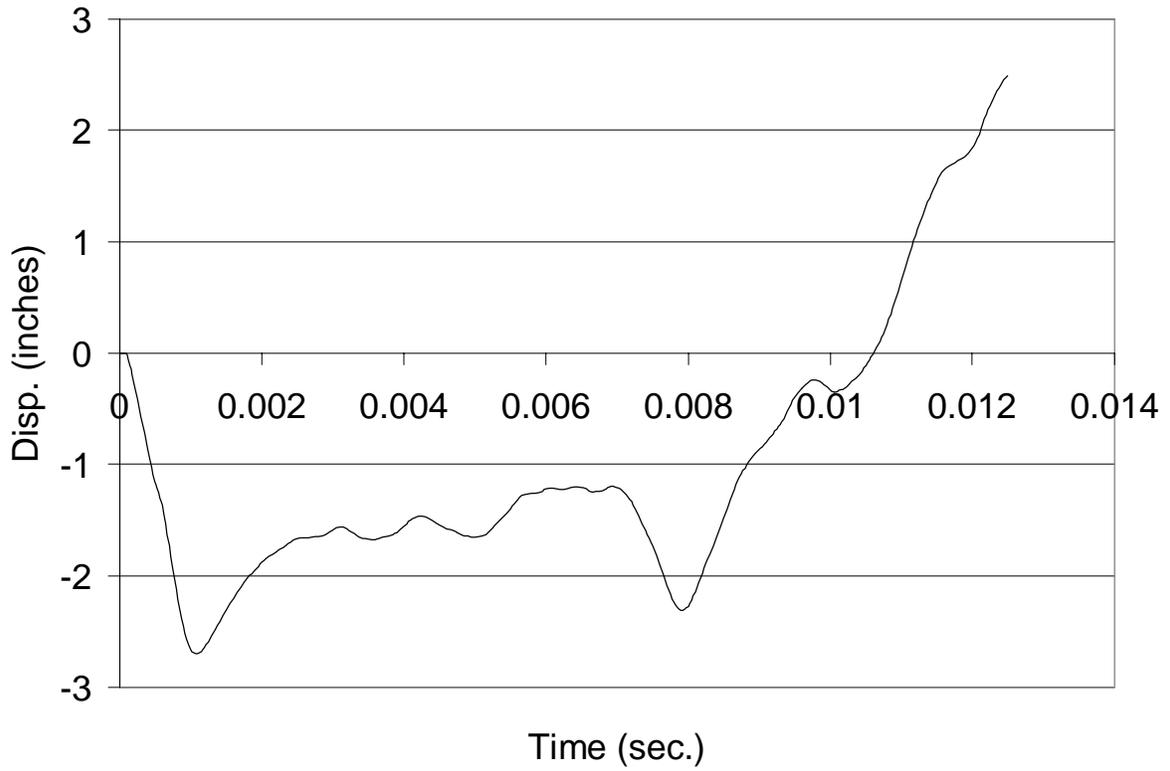


Figure 45. Center plate deflections vs. Time for a single plate of equal thickness to the combined thickness of the two plates used for gap analyses.

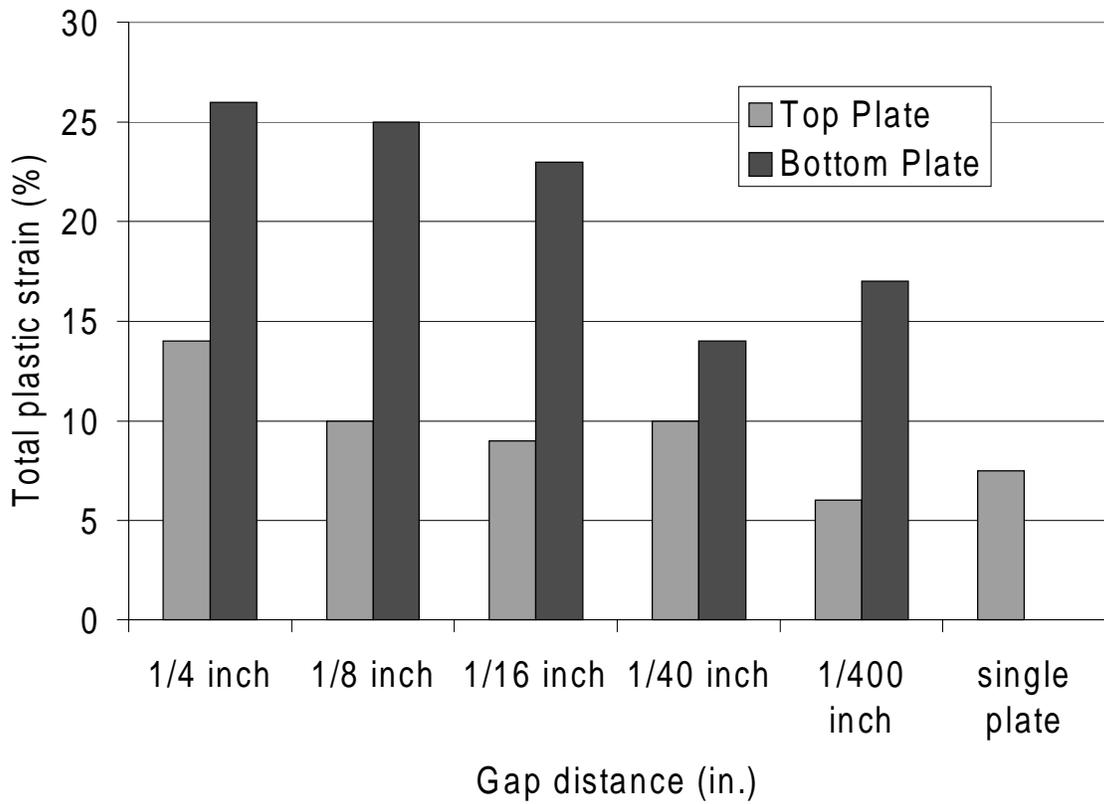


Figure 46. Bar chart depicting total plastic strain at the center of the top and bottom plates as a function of gap distance. A single plate of equivalent thickness is also shown.

8.6 Correlation of Contact Results

All the contact analyses performed here utilized a closed gap stiffness that was given in terms of the modulus of the plate, E. However, the MSC NASTRAN Quick Reference Guide specifies the recommended value in terms of the neighboring grid point stiffness. For purposes of comparison, it is necessary to ask the following question. What is the grid stiffness in the transverse z-direction for the plates studied here? The answer will likely vary from point to point on the plate, and will also be a function of the deformed geometry.

In order to get an estimate of the stiffness seen by the gap elements, the stiffness in the z-direction at the center node was examined. This was accomplished by performing the nonlinear static analysis of a single plate whose dimensions and properties were equivalent to the plates used for the previous contact analyses. A point force was applied at the center node, and the deflection in the z-direction was measured.

The load step history for a point force up to 500 lbs. is shown in Figure 47. The slope of this force-deflection curve is the center-plate grid stiffness as a function of displacement. Calculating the slope at the initial load step gives a grid stiffness of 198.6 lbs./in. A similar calculation at the final load step indicates a grid stiffness of 1131.2 lbs./in., corresponding to a center-plate deflection of approximately one-inch. These values correspond to a NASTRAN recommended closed gap stiffness of between 1.986×10^5 lbs./in. and 1.1312×10^6 lbs./in., or approximately $1/50^{\text{th}}$ to $1/10^{\text{th}}$ the modulus of the plate E.

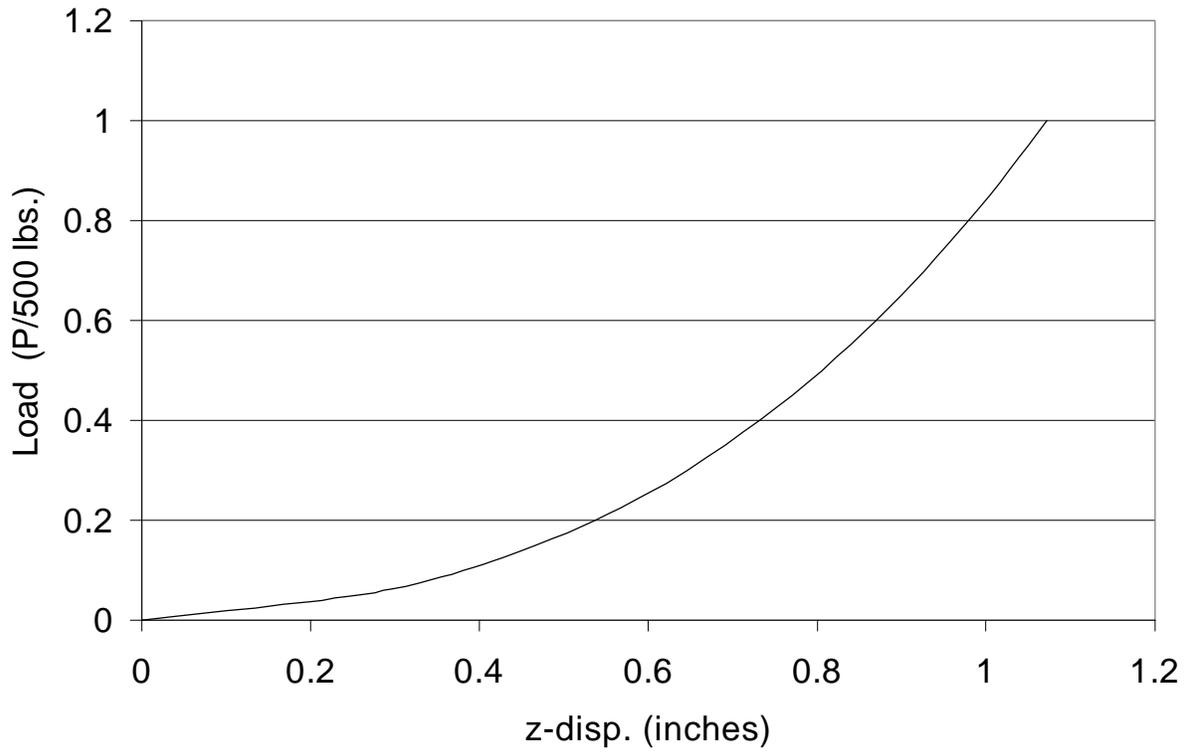


Figure 47. Force – deflection history for a point force in the transverse z-direction, applied to the center node of a single 100” x 100” x .25” plate.

Conclusions

A methodology for simulating plate response to close proximity blasts has been demonstrated. Preliminary elements of such a blast simulation were conducted and verified independently before these novel analyses were performed. The finite element program used for these blast studies was verified using a modal superposition solution described here. Mesh and time step convergence studies were conducted on plates subjected to a 5-pound mine blast. Two methods for calculating blast pressures from arbitrary blast parameters were used to conduct blast analyses. A FORTRAN program was described for automating the application of these spatially varying transient loads to a finite element mesh. All of these aspects were key preliminaries to the parametric studies conducted on blast loaded contacting plates.

The verification studies of Chapter 3 were a starting point for this research. Duplication of results from the literature provided confidence to move towards the more complex analyses. An attempt was made to demonstrate as many aspects of a mine-blast simulation as possible by reproducing similar examples in the literature. To this end, as many unknowns as possible were eliminated from further analyses. Key aspects of the solution such as, geometric nonlinearity, elastic-perfectly-plastic material behavior, transient loading, and contact stiffness were evaluated and found in good comparison to available results.

The convergence studies of Chapter 4 were the next step towards the goal of a close proximity blast simulation. These studies were conducted using a 5-lb blast load, and provided the information needed for appropriate selection of mesh size and integration time step. It was found that a plate element size of no more than 2.5"x2.5", and an integration time step of no more than 10 microseconds were adequate for such a blast simulation.

The blast load preprocessor developed in Chapters 5 and 6 automates the application of a blast load to a finite element mesh. Moreover, the FORTRAN program calculates the applied load based on various user-supplied blast parameters. This program replaced a manually intensive 4-6 hour task with a 10-minute turnkey solution, and was shown to accurately apply the blast load. Percent error in the total impulse applied to the plate was found to be less than 1% when an appropriate mesh size and spatial discretization of the blast load were used.

A comparison of solution procedures in Chapter 7 was a good validation of the commercial finite element code NASTRAN. The modal superposition solution developed for this purpose provided a quick method of solving for the linear plate response to spatially uniform transient loads. A good comparison between NASTRAN and modal superposition was found for the N-pulse, Friedlander blast, and step loads considered here.

A comparison of the two blast calculation procedures in Chapter 7 indicates a large discrepancy in plate response for a certain range of the blast parameters. The two calculation methods only give a similar plate response when the blast distance is on the order of 15-20 inches. At other distances, the method of Kingery & Bulmash results in a larger applied impulse, and therefore an increase in total plate response. The total impulse and plate response when using the method of Kingery & Bulmash can be as much as 2-3 times that predicted with the method of EIA. However, both methods exhibit the same general trends, and both indicate that for a given explosive charge, there exists a certain blast distance for which the plate response is a maximum. The peak of the impulse–distance plot in Fig. 22, indicates this nontrivial distance.

A comparison of different stacking sequences in Chapter 7 indicates that the symmetric cross-ply is more blast resistant than the anti-symmetric angle ply. However, the symmetric angle ply had the smallest maximum displacement. Analysis of a thick plate using CLT and FSDT displayed the well-known need to include shear flexibility in thick plate studies.

The contact analyses of Chapter 8 were by far the most complex and time-consuming analyses performed. The requirement for smaller integration time steps and more frequent stiffness updates was necessitated by the rapid and drastic changes in gap stiffness. These additional computational requirements meant that a contact analysis would take as much as 10 times as long as its single-plate equivalent.

Contact results were generated for a range of parameters important to the mine blast analysis of contacting plates. The time step convergence study of Figure 27 indicates that a value of 5 microseconds, or $1/60^{\text{th}}$ the blast duration (Figure 24) was required for good convergence.

The penetration depth comparison in Figures 28 and 29 indicate that the adaptive gap element successfully reduces kinematically unacceptable deformations of the plates. In other words, the adaptive gap element effectively prevents the top plate from passing through the bottom plate. The contact analyses shown in Figures 30-34 do not utilize the adaptive gap element. Therefore the closed gap stiffness is constant throughout the integration. It can be seen that the kinematically inadmissible deflections are reduced as the closed gap stiffness is increased. The stress plot in Figures 38 indicates that the equivalent stress does not surpass the specified yield stress of 58,000 psi, evidence of the elastic-perfectly-plastic material law. It can be correlated from figures 38 and 39 that an increase in plastic strain corresponds to the instants when the stress is at yield. The plastic strain history in Figure 39 indicates that the majority of yielding occurs during the very early stages of the simulation.

It can be seen in the friction analysis of figure 40 that this additional modeling complexity does very little to alter the deflection histories of the two plates. Only slight differences are visible in the response of the top plate.

The “initial gap distance” studies of Figures 41 through 45 indicate a slight decrease in maximum center-plate deflection as the gap distance decreases. The bar chart of Figure 45 shows that the accumulated plastic strain also decreases as the initial gap distance decreases. The bottom plate consistently shows more plastic strain than the top plate. However, the average of the top and bottom plate strains appears to approach the strain in the single plate as the gap distance is decreased. This is evidence that as the gap distance is decreased, the contacting plates approach the case of a single plate of equivalent thickness.

Many elements important to a contact analysis have been investigated. However, some physical effects not accounted for here may also be important to the behavior of blast loaded contacting plates. Of particular concern to the author is the effect of through the thickness deformation on the plate response. A full three-dimensional analysis might provide for important new behavior, and could provide a means to obtain appropriate values for the allowable penetration depth in a 2-D analysis.

Despite the all the efforts made herein to simulate plate response to blast loads, certain conclusions are still out of reach. One source of doubt is that the applied loads are not

experimentally verified, and that the two analytic methods for predicting these loads are in disagreement. Other sources of doubt lie in the solution procedure itself. A sincere attempt has been made to model a very dynamic and complex phenomenon, and many of the important physical mechanisms have been considered. However, without comparison to experiment, one cannot be certain that all the important mechanisms have been properly treated.

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Appendix A - Source Code for Blast Preprocessor

Main code for selecting and grouping loaded elements: MOTHERV.for

```
! PROGRAM USED TO APPLY A BLAST LOAD TO AN ARBITRARY SURFACE ON A
! FINITE ELEMENT MESH.
!
!-----
!
! USER INFORMATION:
! NASTRAN GEOMETRY FILE MUST END IN THE BULK DATA CLOSE COMMAND,IE.
! THE LAST LINE OF THE FILE MUST SAY ENDDATA.
!
! THERE SHOULD NOT BE ANY LOADING COMMANDS IN THE CASE CONTROL(CEND)
! OR BULK DATA(BEGIN BULK) SECTIONS OF THE NASTRAN GEOMETRY FILE.
!
! THE THREE POINTS USED TO SPECIFY THE PLANE SHOULD NOT BE CO-LINEAR.
!
! THE TOLERANCE USED IN SELECTING OTHER GRID POINTS IN THE PLANE
! SHOULD BE LESS THAN THE DISTANCE TO THE CLOSEST PLANE THAT IS
! PARALLEL TO THE PLANE OF LOAD APPLICATION. USUALLY, A TOLERANCE
! EQUAL TO ONE HALF THE THICKNESS OF THE PLATE IS A GOOD CHOICE.
!
! THE MAXIMUM NUMBER OF LOADING ZONES IS 23
!

CHARACTER(20) :: MESH,MET
CHARACTER(8)::GRIDQ,SKIP
CHARACTER(8)::ELEMQ
INTEGER::P1,P2,P3,GPNUM,NULL,C1,C2,C3,C4,ELEMNUM,GPCOMP,K,COUNT
REAL::GX,GY,GZ,XN,YN,ZN,PLANETOL,R,R1,R2,R3,R4,RAVG,CONVER
REAL::UPPER,LOWER,MIDDLE,TNTFACT,GREFLECT,LOAD,PLANEQN,SCALE
INTEGER::METHOD,EXPLOS,COORD,NPOINTS,PLOAD
INTEGER::UNITS,COUNTGRIDS,COUNTZONES(50),COUNTQUAD,COUNTTRI
CHARACTER(8)::SKIP1
CHARACTER(7)::LOADCASE
CHARACTER(80)::LINE
INTEGER::Z1
REAL(8)::DIST,LBSTNT,G1X,G1Y,G1Z,G2X,G2Y,G2Z,G3X,G3Y,G3Z,G4X,G4Y,G4Z
REAL::MIDDLEJ,DISTJ,AREA,AREA123,AREA134,FX,FY,FZ,MX,MY,MZ,HX,HY,HZ
PRINT*,'*****'
PRINT*,'*****'
PRINT*,'*****'
OPEN(UNIT=91,FILE="RESULTS",ACTION="WRITE",POSITION="REWIND")
WRITE(91,'(A65)')'*****'
WRITE(91,'(A65)')'*****'
WRITE(91,'(A65)')'***** INPUT QUANTITIES *****'
WRITE(91,'(A65)')'*****'
WRITE(91,'(A65)')'*****'
WRITE(*,'(1X,A)',ADVANCE="NO") &
"ENTER THE BLAST CALCULATION &
&METHOD, 1=KINGERY & BULMASH, 2=ETC, 3=GROUND REFLECTIVITY: "
READ*,METHOD
IF (METHOD==1)THEN
```

```

MET="KINGERY & BULMASH"
ELSEIF(METHOD==2)THEN
MET="ETC"
ELSEIF(METHOD==3)THEN
MET="GROUND REFLECTIVITY"
ENDIF
! METHOD = 3
WRITE(91,'(A20,A16)')MET,' METHOD SELECTED'
PRINT*,'*****'
PRINT*,'*****'
COUNTQUAD=0
COUNTTTRI=0
COUNTGRIDS=0
WRITE(*,'(1X,A)',ADVANCE="NO") &
"ENTER THE TYPE OF UNITS TO BE USED:      &
&1 = POUNDS & INCHES, 2 = POUNDS & FEET, &
&3 = NEWTONS & METERS, 4 = NEWTONS & MILLIMETERS: "
READ*,UNITS
WRITE(91,'(A9,I2,A9)')UNIT SET ',UNITS,' SELECTED'
PRINT*,'*****'
PRINT*,'*****'
WRITE(*,'(1X,A)',ADVANCE="YES") &
"ENTER THE DISTANCE(USING THE UNITS SELECTED)"
WRITE(*,'(1X,A)',ADVANCE="NO") &
"BETWEEN THE MINE AND THE CENTRAL GRID POINT: "
READ*,DIST
! DIST = 2.0
WRITE(91,'(A34,F10.4)')NORMAL BLAST DISTANCE SELECTED = ',DIST
PRINT*,'*****'
PRINT*,'*****'
WRITE(*,'(1X,A)',ADVANCE="NO") &
"ENTER THE SIZE OF THE &
&EXPLOSIVE IN POUNDS OF TNT: "
READ*,LBSTNT
PRINT*,'*****'
PRINT*,'*****'
WRITE(91,'(A37,F10.4)')NUMBER OF POUNDS OF T-N-T SELECTED = ',LBSTNT
! LBSTNT = 5.0
! WRITE(*,'(1X,A)',ADVANCE="NO") &
! "ENTER THE EQUIVALENT &
! &FACTOR OF POUNDS OF TNT: "
! READ*,TNTFACT
TNTFACT = 1.0
! WRITE(*,'(1X,A)',ADVANCE="NO") &
! "ENTER THE GROUND REFLECTION FACTOR: "
! READ*,GREFLECT
GREFLECT = 1.8
! COORDINATE SYSTEM TO BE USED - RADIAL
COORD = 1

```

```

!       WRITE(*,(1X,A),ADVANCE="NO") &
!           "ENTER THE TYPE OF &
!           &EXPLOSION, 1=MINEBLAST, 2=AIRBURST: "
! READ*,EXPLOS
!     EXPLOS = 1
!     WRITE(*,(1X,A),ADVANCE="YES") &
!         "ENTER THE NUMBER OF CONCENTRIC RINGS TO BE USED"
!     WRITE(*,(1X,A),ADVANCE="NO") &
!         " FOR SPATIAL DISCRETIZATION OF THE BLAST LOAD: "
! READ*,NPOINTS
!     WRITE(91,(A46,I2))'NUMBER OF SPATIAL DISCRETIZATION RING ZONES = ',NPOINTS
!     NPOINTS = 20
!     PRINT*, '*****'
!     PRINT*, '*****'
! REQUEST THE NASTRAN FILE CONTAINING FORMATTED GRID AND ELEMENT
!     WRITE(*,(1X,A),ADVANCE="NO") &
!         "ENTER THE NAME OF THE NASTRAN FILE: "
!     READ*,MESH
!     WRITE(91,(A41,A20))'THE NASTRAN INPUT DECK TO BE MODIFIED IS ',MESH
!     OPEN(UNIT=100,FILE="FILENAME.DAT",ACTION="WRITE")
!     WRITE(100,(A20))MESH
!     WRITE(100,(I1))UNITS
!     CLOSE(UNIT=100)
!     PRINT*, '*****'
!     PRINT*, '*****'
!     MESH = "smalltest.dat"
!     OPEN(UNIT=15,FILE=MESH,ACTION = "READ",POSITION="REWIND")
!     OPEN(UNIT=16,FILE="grids.dat",ACTION = "WRITE")

! REQUEST THREE POINTS IN THE PLANE AND THE TOLERANCE TO BE
! USED IN DETERMINING OTHER POINTS IN THE PLANE

!     WRITE(*,(1X,A),ADVANCE="NO") &
!         "ENTER THE GRID POINT &
!         &THAT SPECIFIES THE CENTER OF THE BLAST LOAD: "
!     READ*,P1
!     WRITE(91,(A46,I6))'GRID POINT SELECTED FOR BLAST CENTER LOCATION ',P1
!     PRINT*, '*****'
!     PRINT*, '*****'
!     P1 = 41
!     WRITE(*,(1X,A),ADVANCE="NO") &
!         "ENTER ANOTHER GRID POINT &
!         &IN THE SAME PLANE: "
!     READ*,P2
!     PRINT*, '*****'
!     PRINT*, '*****'
!     P2 = 1
!     WRITE(91,(A30,I6))'SECOND GRID POINT SELECTED ',P2
!     WRITE(*,(1X,A),ADVANCE="NO") &
!         "ENTER A THIRD NON-COLINEAR GRID POINT &
!         &IN THE SAME PLANE: "
!     READ*,P3
!     P3 = 73
!     WRITE(91,(A30,I6))'THIRD GRID POINT SELECTED ',P3
!     PRINT*, '*****'

```

```

PRINT*, '*****'

WRITE(*,(1X,A),ADVANCE="YES") &
      "ENTER A NUMBER SMALLER THAN THE DISTANCE TO THE"
WRITE(*,(1X,A),ADVANCE="YES") &
      " NEXT CLOSEST PLANE THAT IS PARALLEL TO THE SURFACE"
WRITE(*,(1X,A),ADVANCE="NO") &
      " OF LOAD APPLICATION(USE SELECTED UNITS): "
READ*,PLANETOL
PLANETOL = 2.0
WRITE(91,(A40,F8.4))'NEXT CLOSEST PLANE DISTANCE SELECTED = ',PLANETOL
PRINT*, '*****'
PRINT*, '*****'
PRINT*, '*****'
PRINT*, '*****'
! MESH,P1,P2,P3
! LBSTNT,DIST
! PRINT*, '*****'

```

```

! SEARCH FOR GRIDPOINTS IN THE PLANE OF INTEREST, WRITE THESE
! TO A FILE CALLED grids.dat
DO

```

```

      READ(15,(A8),ADVANCE="NO")GRIDQ
      IF (GRIDQ=="ENDDATA ")GOTO 10
      IF (GRIDQ=="GRID  ") THEN
        READ(15,(I8,A8,3F8.0),ADVANCE = "YES")GPNUM,SKIP,GX,GY,GZ
        WRITE(16,(A8,I8,3F10.4))GRIDQ,GPNUM,GX,GY,GZ

          IF (GPNUM==P1)THEN
            P1X=GX
            P1Y=GY
            P1Z=GZ
          ENDIF

          IF (GPNUM==P2)THEN
            P2X=GX
            P2Y=GY
            P2Z=GZ
          ENDIF

          IF (GPNUM==P3)THEN
            P3X=GX
            P3Y=GY
            P3Z=GZ
          ENDIF

        ELSE
          READ(15,(A8),ADVANCE="YES")SKIP
        ENDIF
      ENDDO
10  WRITE(16,(A8))GRIDQ
    CLOSE(UNIT=16)
    CLOSE(UNIT=15)

```

```

PRINT*, "
PRINT*, 'THE GRID POINTS YOU CHOSE WERE:'
PRINT*, "
PRINT*, '  GRID#' ,      X  ' ;  Y  ' ;  Z  '
PRINT*, P1, P1X, P1Y, P1Z
PRINT*, P2, P2X, P2Y, P2Z
PRINT*, P3, P3X, P3Y, P3Z
PRINT*, "
PRINT*, 'DONE MAKING A LIST OF ALL GRID POINTS - grids.dat'
PRINT*, "
! WRITE EQUATION OF THE PLANE USING THE POINTS P1, P1, P3
OPEN(UNIT=16, FILE="grids.dat", ACTION = "READ", POSITION="REWIND")
OPEN(UNIT=17, FILE="circle.dat", ACTION = "WRITE")

XN = (P2Y-P1Y)*(P3Z-P1Z) - (P3Y-P1Y)*(P2Z-P1Z)
YN = (P2X-P1X)*(P3Z-P1Z) - (P3X-P1X)*(P2Z-P1Z)
ZN = (P2X-P1X)*(P3Y-P1Y) - (P3X-P1X)*(P2Y-P1Y)
SCALE = SQRT(XN**2 + YN**2 + ZN**2)

! KEEP ONLY THOSE GRID POINTS THAT ARE IN THE PLANE AND WITHIN
! THE LOADED CIRCULAR AREA(45 DEGREE ANGLE OF ATTACK ASSUMPTION).
! WRITE THESE TO A FILE CALED circle.dat
DO

READ(16, '(A8)', ADVANCE = "NO") GRIDQ
IF (GRIDQ=="ENDDATA ") GOTO 20
READ(16, '(I8,3F10.0)', ADVANCE = "YES") GPNUM, GX, GY, GZ
PLANEQN = XN*(GX-P1X) - YN*(GY-P1Y) + ZN*(GZ-P1Z)
DISTANCE = SQRT((GX-P1X)**2 + (GY-P1Y)**2 + (GZ-P1Z)**2)
IF(ABS(PLANEQN)/SCALE <= PLANETOL .AND. DISTANCE <= DIST+DIST/(2.*NPOINTS)) THEN
WRITE(17, '(A8, I8, 3F10.4, F10.4)') GRIDQ, GPNUM, GX, GY, GZ, DISTANCE
COUNTGRIDS = COUNTGRIDS + 1
ENDIF

ENDDO

20 WRITE(17, '(A8)') GRIDQ
CLOSE(UNIT=16)
CLOSE(UNIT=17)
PRINT*, 'DONE MAKING A LIST OF THE RELEVANT GRID POINTS - circle.dat'
PRINT*, "
! READ THE NASTRAN INPUT DECK AGAIN TO EXTRACT THE PLATE ELEMENTS
! THAT HAVE ALL THEIR GRIDPOINTS IN THE LIST FORMED ABOVE(circle.dat).
! WRITE THESE TO A FILE CALLED elem.dat

OPEN(UNIT=15, FILE=MESH, ACTION = "READ", POSITION="REWIND")
OPEN(UNIT=21, FILE="elem.dat", ACTION = "WRITE")

! START MAIN DO LOOP: READ NASTRAN INPUT DECK AND EXTRACT LINES THAT
! CONTAIN THE WORD CQUAD4 OR CTRIA3(ELEMQ). THEN READ THE ELEMENT ID#(ELEMNUM)
! AND THE CORRESPONDING GRID POINTS THAT COMPRISE THIS TRIANGULAR(C1-C3) OR

```

! QUADRILATERAL(C1-C4) ELEMENT. THE CHARACTERS 'NULL' AND 'SKIP' ARE ONLY USED FOR
! INPUT FORMAT REASONS

```

DO 200
  AREA = 0.
  READ(15,'(A8)',ADVANCE="NO")ELEMQ
  IF (ELEMQ=="ENDDATA ") THEN
    GOTO 100

    ELSE IF (ELEMQ=="CQUAD4 ") THEN
      READ(15,'(6I8)',ADVANCE = "YES")ELEMNUM,NULL,C1,C2,C3,C4
    ELSE IF (ELEMQ=="CTRIA3 ")THEN
      READ(15,'(5I8)',ADVANCE = "YES")ELEMNUM,NULL,C1,C2,C3
      C4 = 0
    ELSE
      READ(15,'(A9)',ADVANCE = "YES")SKIP
      GOTO 200
  ENDF

```

! READ THE FILE CONTAINING THE LIST OF GRID POINTS WITHIN THE LOADED AREA.
! RETAIN ONLY THE QUADRILATERAL ELEMENTS HAVING ALL FOUR OF THEIR GRID
! POINTS WITHIN THE LOADED AREA.
! RETAIN ONLY THE TRIANGULAR ELEMENTS HAVING ALL THREE OF THEIR GRID
! POINTS WITHIN THE LOADED AREA

```

OPEN(UNIT=17,FILE="circle.dat",ACTION = "READ",POSITION="REWIND")
COUNT = 0
R1=0.
R2=0.
R3=0.
R4=0.
DO
  READ(17,'(A8)',ADVANCE = "NO")GRIDQ
  IF (GRIDQ=="ENDDATA ") GOTO 30
  READ(17,'(I8,3F10.0,F10.0)',ADVANCE = "YES")GPCOMP,GX,GY,GZ,R
  IF (GPCOMP==C1.OR.GPCOMP==C2.OR.GPCOMP==C3.OR.GPCOMP==C4) THEN
    COUNT = COUNT +1
    IF (COUNT==1) THEN
      R1 = R
    ELSE IF (COUNT==2) THEN
      R2 = R
    ELSE IF (COUNT==3) THEN
      R3 = R
    ELSE IF (COUNT==4) THEN
      R4 = R
    ENDF

```

ENDIF

! CALCULATE THE AREA OF EACH ELEMENT TO BE USED IN COMPUTATION OF THE
! IMPULSE ACTUALLY APPLIED TO TO THE MODEL(IE. WRITTEN TO ANALYSIS1.DAT).
! THIS ACTUAL IMPULSE IS THEN COMPARED TO AN IDEAL VALUE.
!

```

IF(GPCOMP==C1)THEN

```

```

G1X=GX
G1Y=GY
G1Z=GZ
ELSEIF(GPCOMP==C2)THEN
G2X=GX
G2Y=GY
G2Z=GZ
ELSEIF(GPCOMP==C3)THEN
G3X=GX
G3Y=GY
G3Z=GZ
ELSEIF(GPCOMP==C4)THEN
G4X=GX
G4Y=GY
G4Z=GZ
ENDIF
ENDDO
30  Rewind(17)
FX=G2X-G1X
FY=G2Y-G1Y
FZ=G2Z-G1Z
MX=G3X-G1X
MY=G3Y-G1Y
MZ=G3Z-G1Z
HX=G4X-G1X
HY=G4Y-G1Y
HZ=G4Z-G1Z
IF (ELEMQ=="CTRIA3 ".AND.COUNT==3) THEN
HX=0.
HY=0.
HZ=0.
ENDIF

AREA123 = .5*(SQRT((FY*MZ-FZ*MY)**2+(FX*MZ-FZ*MX)**2+(FX*MY-FY*MX)**2))
AREA134 = .5*(SQRT((MY*HZ-MZ*HY)**2+(MX*HZ-MZ*HX)**2+(MX*HY-
MY*HX)**2))
AREA=AREA123+AREA134

IF (ELEMQ=="CQUAD4 ".AND.COUNT==4) THEN
RAVG = (R1+R2+R3+R4)/4.0
WRITE(21,'(A8,5I8,F8.3,F10.5)')ELEMQ,ELEMNUM,C1,C2,C3,C4,RAVG,AREA
COUNTQUAD = COUNTQUAD + 1
ENDIF

IF (ELEMQ=="CTRIA3 ".AND.COUNT==3) THEN
RAVG = (R1+R2+R3+R4)/3.0
WRITE(21,'(A8,5I8,F8.3,F10.5)')ELEMQ,ELEMNUM,C1,C2,C3,C4,RAVG,AREA
COUNTTTRI = COUNTTTRI + 1
ENDIF

200 ENDDO

```

```

! WRITE ENDDATA ON LAST LINE OF ELEM FILE

100    WRITE(21,'(A8)')ELEMQ
      CLOSE(UNIT=15)
      CLOSE(UNIT=17)
      CLOSE(UNIT=21)
      PRINT*,'DONE MAKING A LIST OF ALL THE LOADED ELEMENTS - elem.dat'
      PRINT*,"
! END OF SEARCH FOR PLATE ELEMENTS WITHIN THE LOADED AREA

! GROUP ELEMENTS INTO "NPOINTS" LOAD SETS
! WRITE      ALL ITEMS REQUIRED BY THE BLAST CALCULATION CODE TO THE
! INPUT DECK "mineblst.inp"
! CALCULATION METHOD-"METHOD"
! BLAST NORMAL DISTANCE-"DIST"
! LBS. OF TNT-"LBSTNT"
! TNT EQUIVALENT FACTOR-"TNTFACT"
! GROUND REFLECTIVITY-"GREFLECT"
! TYPE OF EXPLOSION-"EXPLOS"
! RADIAL OR X-Y VALUES FOR LOAD CALCULATION POINTS-"COORD"
! NUMBER OF POINTS REQUESTED FOR BLAST CALCULATION-"NPOINTS"
! BLANK LINE
! 1ST POINT
! 2ND PONT
! .....
! LAST POINT = NPOINTS POINT
!
! CONVERSION KIT
  IF(UNITS==1) THEN
    CONVER = 1.0
  ELSEIF(UNITS==2) THEN
    CONVER = 12.0
  ELSEIF(UNITS==3) THEN
    CONVER = 39.37
  ELSEIF(UNITS==4) THEN
    CONVER = .03937
  ENDIF
!
  DISTJ=DIST*CONVER
  OPEN(UNIT=25,FILE="mineblst.inp",ACTION = "WRITE")
  OPEN(UNIT=22,FILE="zones.dat",ACTION = "WRITE")
  OPEN(UNIT=21,FILE="elem.dat",ACTION = "READ",POSITION="REWIND")

  WRITE(25,'(I3)')METHOD
  WRITE(25,'(F8.4)')DISTJ
  WRITE(25,'(F8.4)')LBSTNT
  WRITE(25,'(F8.4)')TNTFACT
  WRITE(25,'(F8.4)')GREFLECT
  WRITE(25,'(I3)')EXPLOS
  WRITE(25,'(I3)')COORD
  WRITE(25,'(I3)')NPOINTS
  WRITE(25,*)"
  WRITE(91,'(A65)')'*****'

```

```

WRITE(91,(A65))'*****'
WRITE(91,(A65))'***** OUTPUT QUANTITIES *****'
WRITE(91,(A65))'*****'
WRITE(91,(A65))'*****'
WRITE(91,(A45,I6))'NUMBER OF GRID POINTS IN THE LOADED REGION = ',COUNTGRIDS
WRITE(91,(A45,I6))'NUMBER OF LOADED QUADRILATERAL PLATE ELEMENTS =
',COUNTQUAD
WRITE(91,(A42,I6))'NUMBER OF LOADED TRIANGULAR PLATE ELEMENTS = ',COUNTTRI
DO 375 K=1,NPOINTS

LOWER = (K-1)*(DIST+DIST/NPOINTS)/NPOINTS
UPPER = (K)*(DIST+DIST/NPOINTS)/NPOINTS
MIDDLE = (LOWER+UPPER)/2.
MIDDLEJ=CONVER*MIDDLE
WRITE(25,(F8.4))MIDDLEJ
WRITE(22,(A8,I3))'ZONE # ',K
COUNTTRI = COUNTTRI + 1
COUNTZONES(K)=0

DO

READ(21,(A8),ADVANCE = "NO")ELEMQ
IF (ELEMQ=="ENDDATA ") GOTO 300
READ(21,(5I8,F8.0,F10.0),ADVANCE = "YES")ELEMNUM,C1,C2,C3,C4,RAVG,AREA
IF (RAVG>=LOWER.AND.RAVG<UPPER)THEN
WRITE(22,(A8,I8,F8.3,F10.5))'ELEM # ',ELEMNUM,RAVG,AREA
COUNTZONES(K)=COUNTZONES(K)+1
ENDIF

ENDDO
300 CONTINUE
REWIND(21)
WRITE(91,(I4,A32,F10.4))COUNTZONES(K),' ELEMENTS LOADED AT A RADIUS OF ',MIDDLE
375 ENDDO
WRITE(22,(A8))'ENDDATA '
CLOSE(UNIT=22)
CLOSE(UNIT=25)
PRINT*,'DONE MAKING THE FILE FOR EXPORT TO JEFF S CODE - mineblst.inp'
PRINT*,"
! CREATE A NASTRAN INPUT DECK TO BE USED FOR LOAD VISUALIZATION IN PATRAN,
! NOT A FUNCTIONAL NASTRAN INPUT DECK
!
! READ THE EXISTING NASTRAN GEOMETRY FILE(MESH) AND COPY IT TO A
! NEW FILE(patranvis.dat). SIMUTANEOUSLY INSERT THE LOAD
! INFORMATION INTO THE CASE CONTROL(CEND) AND BULK DATA(BEGIN BULK)
! SECTIONS OF THE NEW FILE(patranvis.dat).

OPEN(UNIT=15,FILE=MESH,ACTION = "READ",POSITION="REWIND")
OPEN(UNIT=30,FILE="patranvis.dat",ACTION = "WRITE",POSITION="REWIND")
OPEN(UNIT=22,FILE="zones.dat",ACTION = "READ",POSITION="REWIND")
LOADCASE='LOAD=25'

DO 399

```

```

READ(15,'(A8,A80)',ADVANCE = "YES")GRIDQ,LINE
IF (GRIDQ=="ENDDATA ") GOTO 400

! INSERT COMMANDS INTO THE CASE CONTROL SECTION
IF (GRIDQ=="CEND ") THEN
    WRITE(30,'(A8,A80)' )GRIDQ,LINE
    WRITE(30,'(A7)')'LOAD=25 '
    GOTO 399

! INSERT COMMANDS INTO THE BULK DATA SECTION
ELSE IF (GRIDQ=="BEGIN BU") THEN
    WRITE(30,'(A8,A80)' )GRIDQ,LINE

! READ THE FILE CONTAINING THE SPATIALLY DISCRETIZED ELEMENT SETS(zones.dat)
! AND ASSIGN A DIFFERENT PRESSURE LOAD TO EACH OF THESE SETS.
!
! A MAXIMUM LOAD OF 'NPOINTS' IS ASSIGNED TO THE CENTER-MOST LOAD ZONE(R1),
! A MINIMUM LOAD OF '1' IS ASSIGNED TO THE CENTER-MOST LOAD ZONE(R'NPOINTS').

DO
390   READ(22,'(A8)',ADVANCE="NO")SKIP1
      IF (SKIP1=="ENDDATA ")      GOTO 610

      IF (SKIP1=="ZONE # ") THEN
          READ(22,'(I3)',ADVANCE="YES")Z1
          PLOAD=10+Z1
          LOAD=NPOINTS-Z1+1.0
          GOTO 390
      ENDIF

      IF (SKIP1=="ELEM # ") THEN
          READ(22,'(I8)',ADVANCE="YES")ELEMNUM
          WRITE(30,'(A8,I8,I8,F8.3)' )PLOAD4 ',PLOAD,ELEMNUM,LOAD
      ENDIF
ENDDO
610  CONTINUE

      ELSE
          WRITE(30,'(A8,A80)' )GRIDQ,LINE

      ENDIF

399  ENDDO

400  WRITE(30,'(A8)' )GRIDQ
      PRINT*,'DONE MAKING PATRAN VISUALIZATION FILE - patranvis.dat'
      PRINT*,"
      PRINT*,'*****'

```

```

CLOSE(UNIT=15)
  CLOSE(UNIT=22)
  CLOSE(UNIT=30)
  CLOSE(UNIT=91)
END

```

Code for writing the NASTRAN input deck: NASTRAN2V.for

```

CHARACTER(20)::MESH
  CHARACTER(8)::GRIDQ,SKIP1,T(245),P(245)
  CHARACTER(7)::S,CONVERT
  CHARACTER(80)::LINE
  INTEGER::PLOAD,L,NPOINTS,LOADNUM,DAREA,TABLENUM,INC,COUNT,Z1,ELEMNUM
  INTEGER::NPAIRS,UNITS,Q,COUNTP,O
  REAL::LOAD,CONVER,AREATOT(50),INTEGRAL(50),AREAI,NULL1,IMPULSEA
  REAL::TI(245),PI(245),AREAIA,DIST,APPROX,IMPULSEI,CONVL

      OPEN(UNIT=91,FILE="RESULTS",STATUS="OLD",POSITION = "APPEND")
      OPEN(UNIT=31,FILE="analysis1.dat",ACTION = "WRITE")
      OPEN(UNIT=51,FILE="blast.out",ACTION = "READ",POSITION="REWIND")
      OPEN(UNIT=22,FILE="zones.dat",ACTION = "READ",POSITION="REWIND")
      OPEN(UNIT=23,FILE="mineblast.inp",ACTION = "READ",POSITION="REWIND")
      OPEN(UNIT=100,FILE="FILENAME.DAT",ACTION = "READ",POSITION="REWIND")
  READ(100,'(A20)',ADVANCE="YES")MESH
  READ(100,'(I1)')UNITS
  COUNTP=0

  PRINT*,'NASTRAN INPUT DECK IS ',MESH
      OPEN(UNIT=15,FILE=MESH,ACTION = "READ",POSITION="REWIND")

  DO 1 I=1,8
    IF (I==8) THEN
      READ(23,'(I8)')NPOINTS
    ELSEIF(I==2) THEN
      READ(23,'(F8.0)')DIST
    ELSE
      READ(23,'(A8)',ADVANCE="YES")S
    ENDIF
  1  ENDDO

  DO

      READ(15,'(A8,A80)',ADVANCE = "YES")GRIDQ,LINE
      IF (GRIDQ=="ENDDATA ") GOTO 1002

```

! INSERT COMMANDS INTO THE CASE CONTROL SECTION

```
IF (GRIDQ=="CEND ") THEN
  WRITE(31,'(A8,A80)')GRIDQ,LINE
  WRITE(31,'(A8)')DLOAD=25'
  WRITE(31,'(A10)')LOADSET=27'
  GOTO 1001
ENDIF
```

! INSERT COMMANDS INTO THE BULK DATA SECTION

```
IF (GRIDQ=="BEGIN BU") THEN
  WRITE(31,'(A8,A80)')GRIDQ,LINE
```

! READ THE FILE CONTAINING THE SPATIALLY DISCRETIZED ELEMENT SETS(zones.dat)

! AND ASSIGN A DIFFERENT PRESSURE LOAD TO EACH OF THESE SETS.

!

! A MAXIMUM LOAD OF 'NPOINTS' IS ASSIGNED TO THE CENTER-MOST LOAD ZONE(R1),

! A MINIMUM LOAD OF '1' IS ASSIGNED TO THE CENTER-MOST LOAD ZONE(R'NPOINTS').

```
DO
390  READ(22,'(A8)',ADVANCE="NO")SKIP1
    IF (SKIP1=="ENDDATA ") THEN
      GOTO 398
    ENDIF

    IF (SKIP1=="ZONE # ") THEN
      READ(22,'(I3)',ADVANCE="YES")Z1
      PLOAD=10+Z1
      LOAD=1.0
      GOTO 390
    ENDIF

    IF (SKIP1=="ELEM # ") THEN
      READ(22,'(I8,F8.0,F10.0)',ADVANCE="YES")ELEMNUM,NULL1,AREAI
      AREATOT(Z1)=AREATOT(Z1)+AREAI
      WRITE(31,'(A8,I8,I8,F8.3)')PLOAD4 ',PLOAD,ELEMNUM,LOAD
    ENDIF

  ENDDO
398  CONTINUE
    PRINT*,'DONE MAKING PLOAD'
```

! CREATE THE NASTRAN DLOAD COMMAND

```
IF (UNITS==1) THEN
  CONVL=1.0
  CONVER = 1.00000
  CONVERT = "1.00000"
ELSEIF (UNITS==2) THEN
  CONVL=1./12.0
  CONVER = 144.000
  CONVERT = "144.000"
ELSEIF (UNITS==3) THEN
  CONVL=.0254
  CONVER = 6895.00
  CONVERT = "6895.00"
```

```

ELSEIF(UNITS==4)THEN
    CONVL=25.4
    CONVER = .006895
        CONVERT = ".006895"
ENDIF
    PRINT*,UNITS

WRITE(31,'(A9,A7)',ADVANCE="NO")DLOAD,25,',CONVERT

DO Q=1,NPOINTS
    LOADNUM = Q+100
    PRINT*,Q
    IF (Q==NPOINTS) THEN
        WRITE(31,'(A5,I3)',ADVANCE="YES"),1.0,',LOADNUM
        GOTO 600
    ENDIF

    IF (Q==3.OR.Q==7.OR.Q==11.OR.Q==15.OR.Q==19.OR.Q==23) THEN
        WRITE(31,'(A5,I3,A1)',ADVANCE="YES"),1.0,',LOADNUM,',
    ELSE
        WRITE(31,'(A5,I3)',ADVANCE="NO"),1.0,',LOADNUM
    ENDIF

ENDDO

WRITE(31,'(A1)',ADVANCE="YES")'
600 CONTINUE
PRINT*,'DONE MAKING DLOAD'

! CREATE THE NASTRAN TLOAD1 COMMANDS

DO L=1,NPOINTS

    LOADNUM=100+L
    DAREA=60+L
    TABLENUM=150+L
    PLOAD=10+L
    WRITE(31,'(A8,I2,A1,I2)',ADVANCE="YES")LSEQ,27,',DAREA,',PLOAD

WRITE(31,'(A7,I3,A1,I2,A3,I3)',ADVANCE="YES")TLOAD1,',LOADNUM,',DAREA,',',TABLENUM

ENDDO

PRINT*,'DONE MAKING TLOAD'

! READ THE BLAST LOAD TIME HISTORIES OUTPUT FROM JEFF'S ROUTINE AND
! INSERT THEM INTO THE NASTRAN TABLED1 COMMANDS.

INC=0
601 CONTINUE
READ(51,'(1A7)',ADVANCE="YES")S

```

```

IF (S=="ZONE# =") THEN

  READ(51,'(I3)',ADVANCE="YES")NPAIRS
    INC=INC+1
    PRINT*,NPAIRS
    PRINT*,'ZONE# = ',INC
    TABLENUM=150+INC
    WRITE(31,'(A8,I8,2A8)',ADVANCE="YES")TABLED1',TABLENUM, &
    & 'LINEAR','LINEAR'
  OPEN(UNIT=93,FILE="INTEGRATE",ACTION = "WRITE")

    DO L=1,NPAIRS+1
      READ(51,'(2A8)',ADVANCE="YES")T(L),P(L)
      WRITE(93,'(2A8)',ADVANCE="YES")T(L),P(L)
    ENDDO

    CLOSE(UNIT=93)
    OPEN(UNIT=93,FILE="INTEGRATE",ACTION =
"READ",POSITION="REWIND")

    DO L=1,NPAIRS+1
      READ(93,'(2F8.0)',ADVANCE="YES")TI(L),PI(L)
    ENDDO
    CLOSE(UNIT=93)
! INTEGRATE EACH ZONE'S PARTICULAR PRESSURE VS. TIME HISTORY TO OBTAIN THE
! IMPULSE PER UNIT AREA FOR THAT ZONE. TRAPEZOIDAL RULE FOR INTEGRATION IS
APPLIED

    COUNTP=COUNTP+1
    DO L=2,NPAIRS+1
      INTEGRAL(COUNTP)=INTEGRAL(COUNTP) + (TI(L)-TI(L-
1))*((PI(L)+PI(L-1))/2.)
    ENDDO
    COUNT=0

    DO M=1,NPAIRS,4

WRITE(31,'(9A8)',ADVANCE="YES")',T(M),P(M),T(M+1),P(M+1),T(M+2),P(M+2),T(M+3),P(M+3)
!
! WRITE(31,'(A1,A2,A1,A2)',ADVANCE="NO")',,T(M),',',P(M)
! WRITE(31,'(A1,A2,A1,A2)',ADVANCE="NO")',,T(M+1),',',P(M+1)
! WRITE(31,'(A1,A2,A1,A2)',ADVANCE="NO")',,T(M+2),',',P(M+2)
!~ WRITE(31,'(A1,A2,A1,A2,A1)',ADVANCE="YES")',,T(M+3),',',P(M+3),','
ENDDO
WRITE(31,'(2A8)',ADVANCE="YES")', ' ENDT'
GOTO 601

    ELSEIF(S=="ENDDATA")THEN
      GOTO 1001
    ENDIF

ELSE

```

```

                WRITE(31,'(A8,A80)')GRIDQ,LINE
            ENDIF

1001 CONTINUE
    ENDDO

1002  WRITE(31,'(A8)')GRIDQ

        CLOSE(UNIT=15)
            CLOSE(UNIT=22)
            CLOSE(UNIT=31)
        CLOSE(UNIT=51)
            CLOSE(UNIT=23)
        CLOSE(UNIT=100)
! COMPUTE THE IDEAL AND ACTUALLY APLIED IMPULSES
        WRITE(91,'(A49,F10.3)',ADVANCE="YES")'ZONE #  IDEAL AREA  AREA OF LOADED
ELEMENTS'
        DO O = 1,NPOINTS
            AREAIA=3.14*((O*CONVL*DIST/NPOINTS)**2 - ((O-1)*(CONVL*DIST/NPOINTS))**2)
            PRINT*,INTEGRAL(O),' ',AREATOT(O),' ',AREAIA
            WRITE(91,'(I6,2F12.5)',ADVANCE="YES")O,AREAIA,AREATOT(O)
            IMPULSEA = IMPULSEA + INTEGRAL(O)*AREATOT(O)
            IMPULSEI = IMPULSEI + INTEGRAL(O)*AREAIA
        ENDDO

        PRINT*,TOTAL IMPULSE APPLIED TO THE NASTRAN MODEL = ',IMPULSEA
        PRINT*,TOTAL IDEAL IMPULSE = ',IMPULSEI
        APPROX = -((IMPULSEI-IMPULSEA)/IMPULSEI)*100.
        PRINT*,'BLAST LOADING IS IN ERR OF THE IDEAL BY ',APPROX,'% '
        WRITE(91,'(A16,F10.3)',ADVANCE="YES")'IDEAL IMPULSE = ',IMPULSEI
        WRITE(91,'(A18,F10.3)',ADVANCE="YES")'APPLIED IMPULSE = ',IMPULSEA
        WRITE(91,'(A24,F10.3,A2)',ADVANCE="YES")'ERROR IN APPLIED LOAD = ',APPROX,'% '
        CLOSE(UNIT=91)

        PRINT*,'Preprocessor is finished'
        END

```

Appendix B - Modal Superposition Example

Modal Superposition Method for the Transient Response of a Simply Supported Laminated Composite Plate Subject to a Square Patch Blast Load

Define the properties of the square laminate within the framework of Classical Laminated Plate Theory

```
<< "clt.m"

laminate = {0, 90, 90, 0}
{0, 90, 90, 0}

E1 = 1
E2 = E1 / 25
G12 = E2 / 2
nu12 = .25
rho = .5
h = 5
a = 25; b = 25

uvect = InvariantU[{E1, E2, G12, nu12}]
dmat = Dmatrix[laminate, uvect, h / 4]
```

Transverse and Rotatory Inertias are used to form the parameter "inert"

```
Inert = Io + I2 * ((m * Pi / a) ^ 2 + (n * Pi / b) ^ 2)
Io = rho * h
```

The frequency of the plate " ω ", is defined in terms of the bending stiffness matrix and the indices " m " and " n ".

$$\omega = \text{Sqrt}[(\pi^4 / (\text{Inert} * b^4)) * (\text{dmat}[[1, 1]] * (m^4) * (b/a)^4 + 2 * (\text{dmat}[[1, 2]] + 2 * \text{dmat}[[3, 3]]) * (m^2) * (n^2) * (b/a)^2 + \text{dmat}[[2, 2]] * n^4)]$$

$$\frac{1}{625} \pi^2 \sqrt{\frac{9.18964 m^4 + 1.04219 m^2 n^2 + 1.67084 n^4}{2.5 + I2 \left(\frac{m^2 \pi^2}{625} + \frac{n^2 \pi^2}{625} \right)}}$$

Define the parameters " α " and " β " to be used in expressing the mode shapes

$$\begin{aligned} \alpha &= m * \text{Pi} / a \\ \beta &= n * \text{Pi} / b \end{aligned}$$

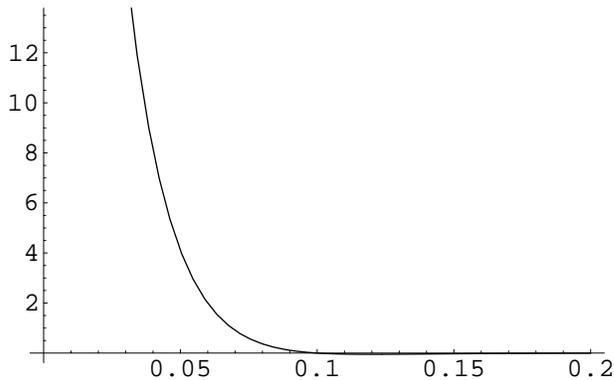
The mode shape for any integers " m " and " n " is given by the product for two sinusoidal functions.

$$\text{modes} = \text{Sin}[\alpha * x] * \text{Sin}[\beta * y]$$

$$\text{Sin}\left[\frac{m \pi x}{25}\right] \text{Sin}\left[\frac{n \pi y}{25}\right]$$

The variation of the blast load with time is expressed using Friedlander's exponential decay equation. The spatial variation is defined by a square patch whose center is located at a point $\{a_0, b_0\}$. The dimensions of the patch are given by "abar" and "bbar". The blast load is applied uniformly across the patch.

```
ftaublast = pm * (1 - tau / tp) * Exp[-50 * tau]
pm = 100
tp = .1
abar = a / 10
bbar = b / 10
ao = 2 * a / 3
bo = 2 * b / 3
pmn = (4 / (a * b * abar * bbar)) *
  Integrate[Integrate[modes, {x, ao - abar / 2, ao + abar / 2}], {y, bo - bbar / 2, bo + bbar / 2}]
Plot[ftaublast, {tau, 0, .2}]
```



- Graphics -

```
Qpatchblast = ftaublast * pmn
```

$$\frac{64}{625} E^{-50 \tau} (1 - 10. \tau) \left(-\frac{1}{2 m n \pi^2} \left(625 \left(-\text{Cos} \left[\frac{37 m \pi}{60} - \frac{37 n \pi}{60} \right] + \text{Cos} \left[\frac{43 m \pi}{60} - \frac{37 n \pi}{60} \right] - \text{Cos} \left[\frac{37 m \pi}{60} + \frac{37 n \pi}{60} \right] + \text{Cos} \left[\frac{43 m \pi}{60} + \frac{37 n \pi}{60} \right] \right) \right) + \frac{1}{2 m n \pi^2} \left(625 \left(-\text{Cos} \left[\frac{37 m \pi}{60} - \frac{43 n \pi}{60} \right] + \text{Cos} \left[\frac{43 m \pi}{60} - \frac{43 n \pi}{60} \right] - \text{Cos} \left[\frac{37 m \pi}{60} + \frac{43 n \pi}{60} \right] + \text{Cos} \left[\frac{43 m \pi}{60} + \frac{43 n \pi}{60} \right] \right) \right) \right)$$

```
ωs = ω / . I2 -> 0
```

```
m /: IntegerQ[m] = True
```

```
n /: IntegerQ[n] = True
```

```
True
```

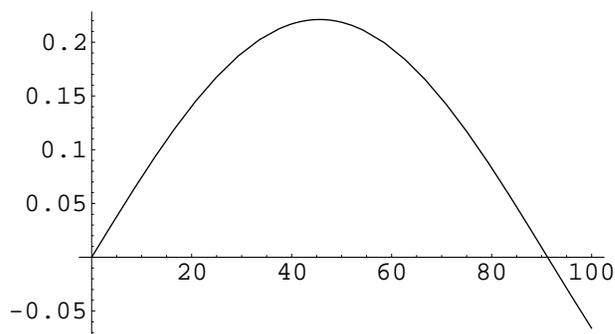
```
True
```

The particular solution for any "m" and "n" is given by

```
womn = (modes /  $\omega$ s) * Integrate[Qpatchblast * Sin[ $\omega$ s * (t - tau)], {tau, 0, t},
Assumptions -> {t > 0, m > 0, n > 0, x > 0, y > 0}]
```

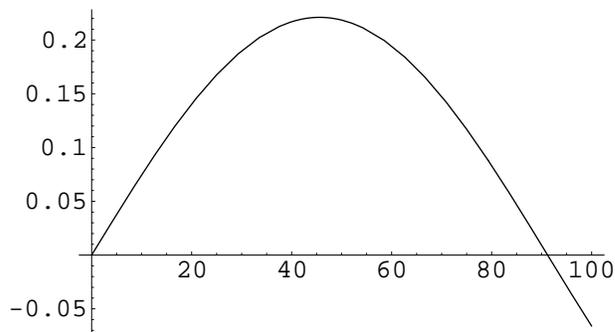
The total solution is given as the sum of all the modal responses for $m, n = 1 \rightarrow \infty$, Shown below are several solutions using values of m, n up to 15.

```
wosum = Sum[womn, {m, 1, 3}, {n, 1, 3}];
p3 = Plot[wosum /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

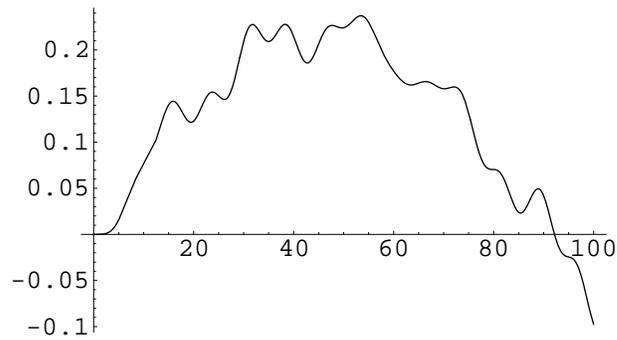
```
wosum4 = Sum[womn, {m, 1, 4}, {n, 1, 4}];
p4 = Plot[wosum4 /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

```
wosum5 = Sum[womn, {m, 1, 5}, {n, 1, 5}];
```

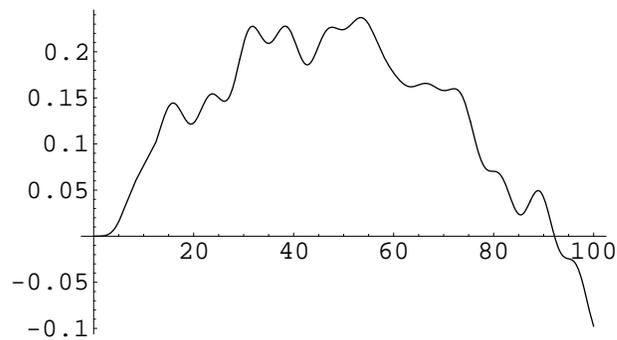
```
p5 = Plot[wosum5 /. {x -> a/2, y -> b/2}, {t, 0, 100}]
```



- Graphics -

```
wosum6 = Sum[womn, {m, 1, 6}, {n, 1, 6}];
```

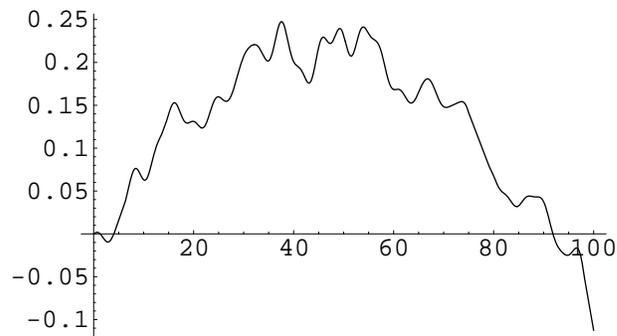
```
p6 = Plot[wosum6 /. {x -> a/2, y -> b/2}, {t, 0, 100}]
```



- Graphics -

```
wosum7 = Sum[womn, {m, 1, 7}, {n, 1, 7}];
```

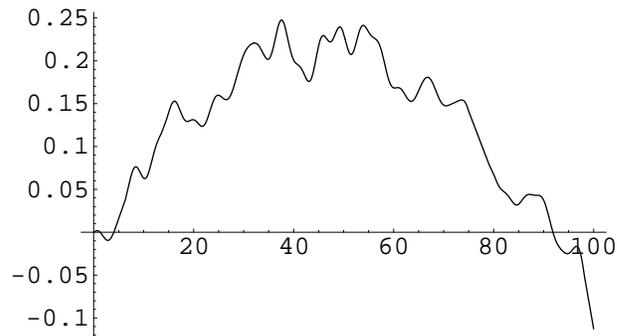
```
p7 = Plot[wosum7 /. {x -> a/2, y -> b/2}, {t, 0, 100}]
```



- Graphics -

```
wosum8 = Sum[womn, {m, 1, 8}, {n, 1, 8}];
```

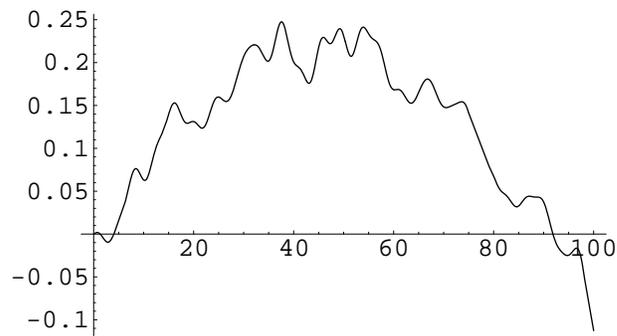
```
p8 = Plot[wosum8 /. {x -> a/2, y -> b/2}, {t, 0, 100}]
```



- Graphics -

```
wosum9 = Sum[womn, {m, 1, 9}, {n, 1, 9}];
```

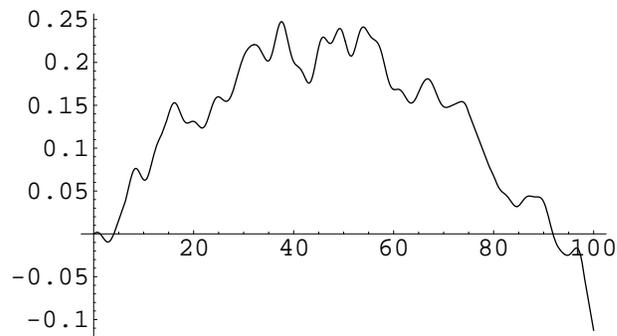
```
p9 = Plot[wosum9 /. {x -> a/2, y -> b/2}, {t, 0, 100}]
```



- Graphics -

```
wosum10 = Sum[womn, {m, 1, 10}, {n, 1, 10}];
```

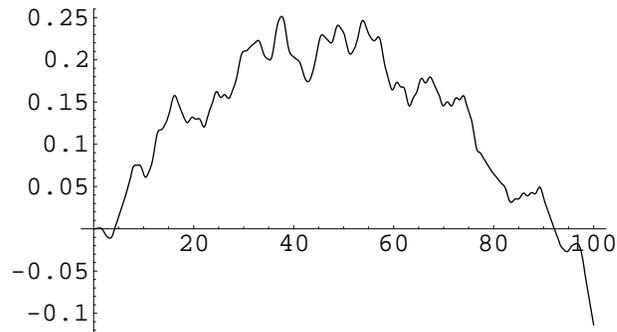
```
p10 = Plot[wosum10 /. {x -> a/2, y -> b/2}, {t, 0, 100}]
```



- Graphics -

```
wosum11 = Sum[womn, {m, 1, 11}, {n, 1, 11}];
```

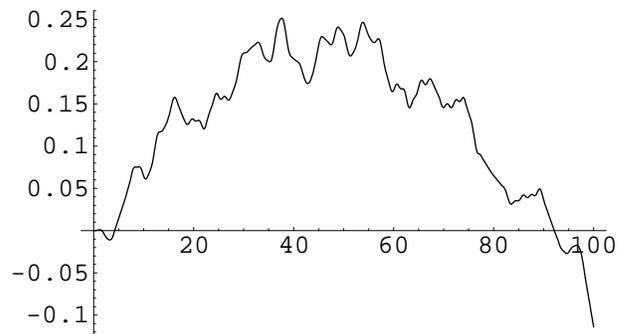
```
p11 = Plot[wosum11 /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

```
wosum12 = Sum[womn, {m, 1, 12}, {n, 1, 12}];
```

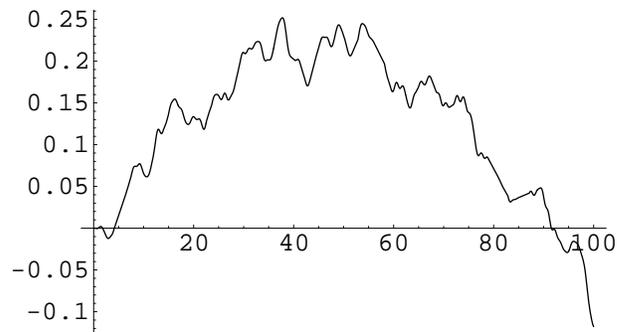
```
p12 = Plot[wosum12 /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

```
wosum13 = Sum[womn, {m, 1, 13}, {n, 1, 13}];
```

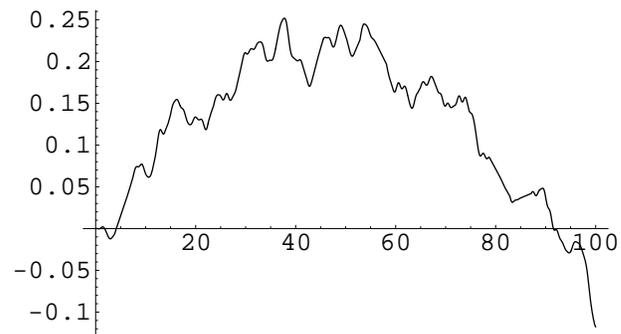
```
p13 = Plot[wosum13 /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

```
wosum14 = Sum[womn, {m, 1, 14}, {n, 1, 14}];
```

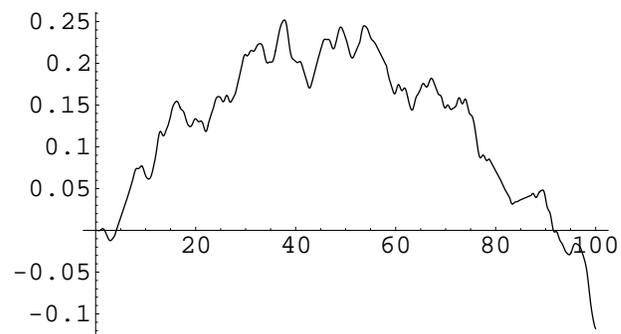
```
p14 = Plot[wosum14 /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

```
wosum15 = Sum[womn, {m, 1, 15}, {n, 1, 15}];
```

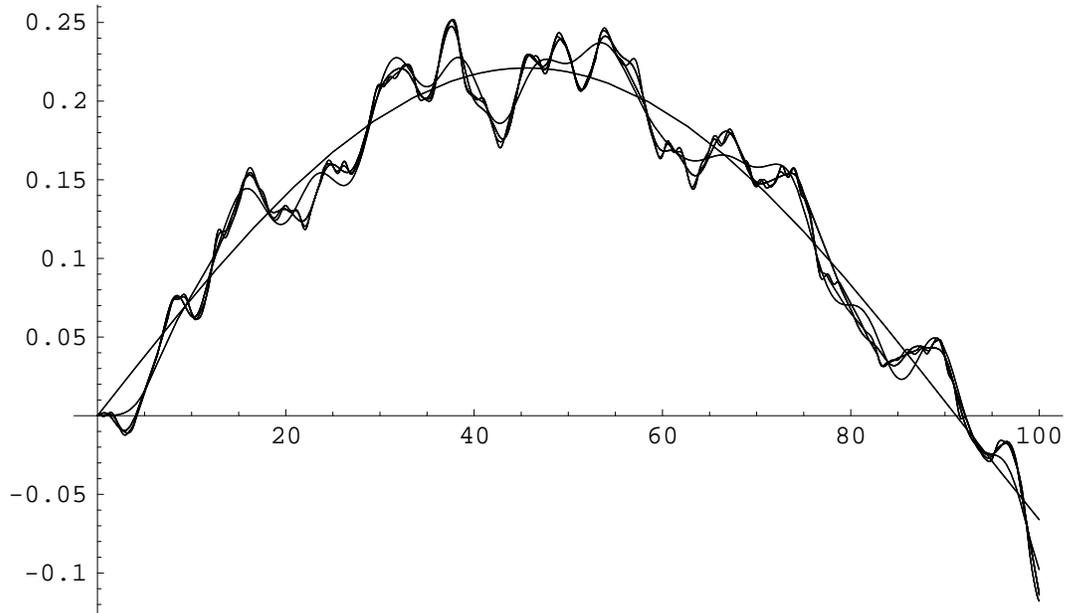
```
p15 = Plot[wosum15 /. {x -> a / 2, y -> b / 2}, {t, 0, 100}]
```



- Graphics -

All the solutions are shown below using values of m, n up to 15.

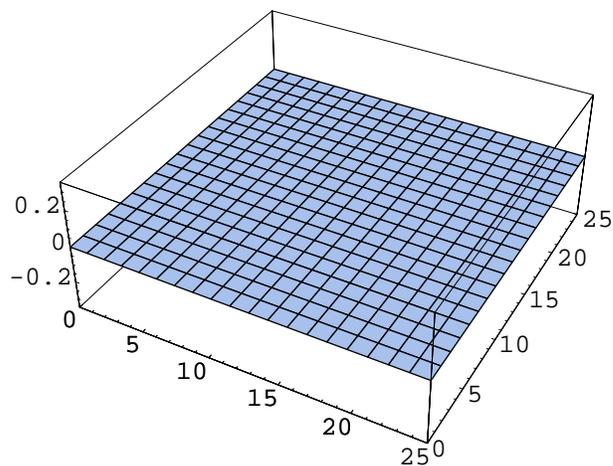
```
Show[p3, p4, p5, p6, p7, p8, p9, p10, p11, p12, p13, p14, p15]
```

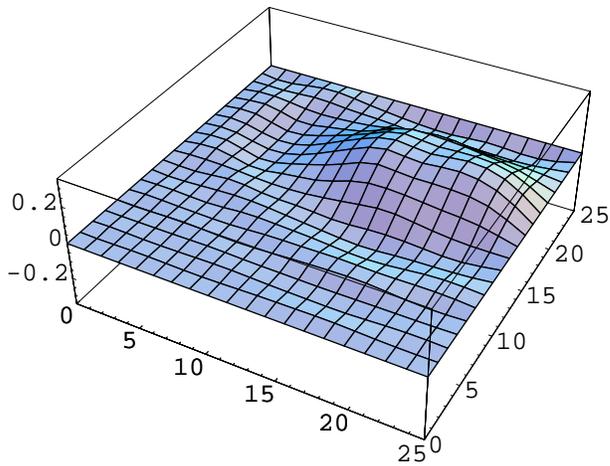
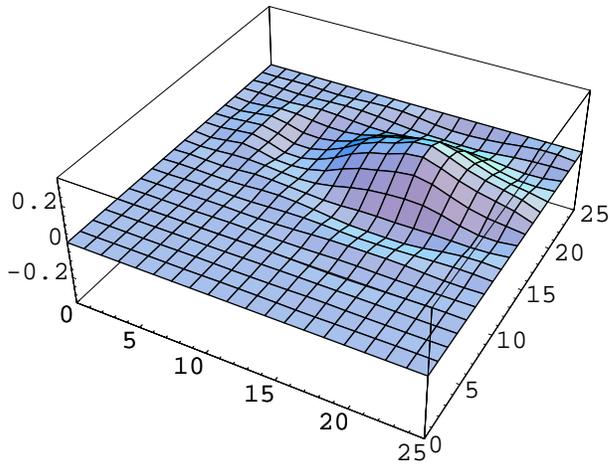
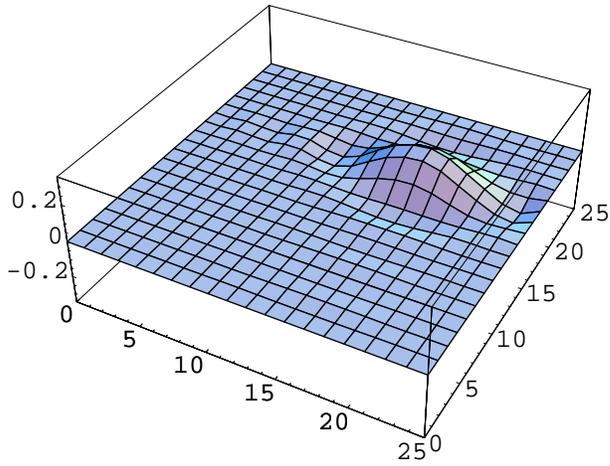


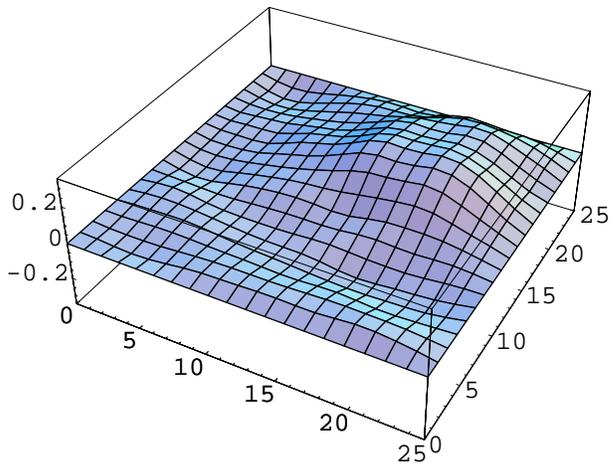
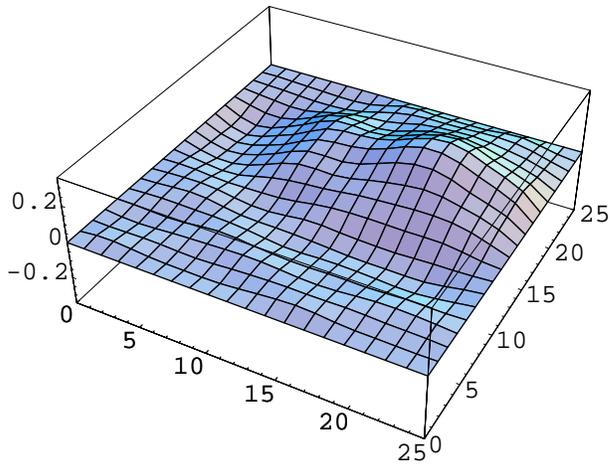
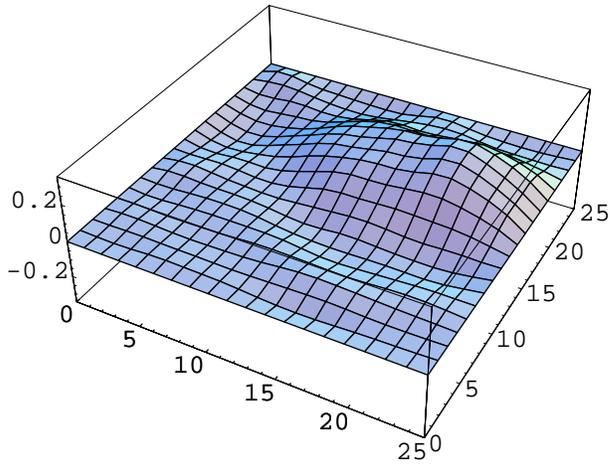
- Graphics -

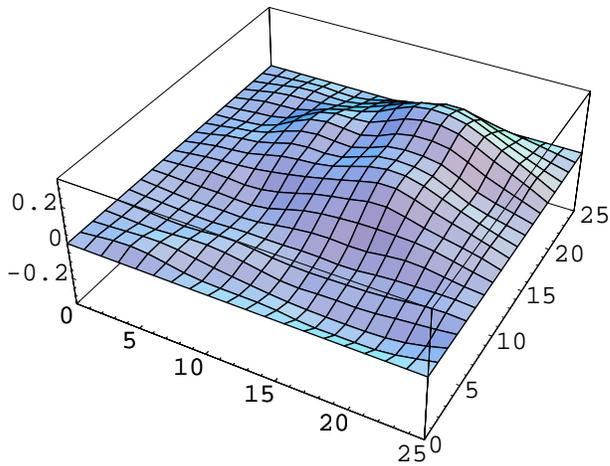
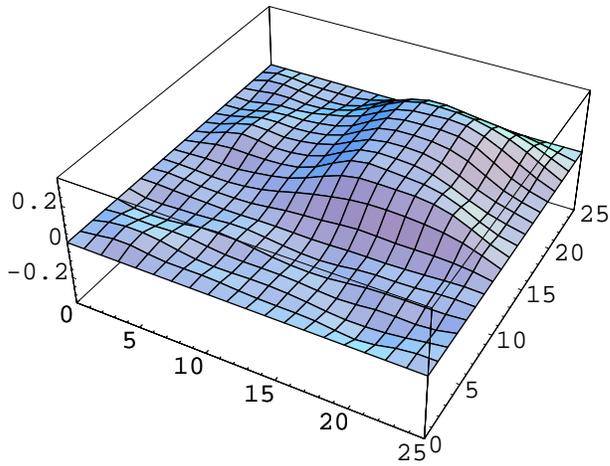
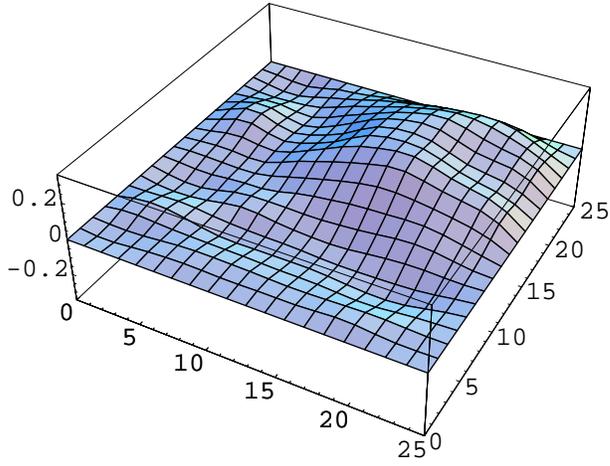
A 3-D Plot shows snapshots of the plate deflections due to the patch blast. Snapshots are at intervals of 2 seconds.

```
Do[Plot3D[N[Chop[wosum13]], {x, 0, a}, {y, 0, b},  
PlotPoints->20, PlotRange->{{0, a}, {0, b}, {-0.35, 0.35}}, {t, 0, 50, 2}]
```









Appendix C - NASTRAN Input Deck for Nonlinear Analysis of Blast Loaded Contacting Plates

```
$ Nonlinear Transient Response Analysis, Direct Formulation, Database
$CLAMPED-CLAMPED QUARTER PLATE MODEL OF TWO PARRALEL PLATES(SEPARATION = .25)
$ SUBJECT TO A BLAST LOAD - GEOMETRIC AND MATERIAL NONLINEAR ANALYSIS
INIT DBALL LOGICAL=(DBALL(9000MB))
INIT SCRATCH SCR300=(SCRA(9000MB))
INIT OBJSCR LOGICAL=(OBJSCR(9000MB))
ASSIGN SCRA='/kapania-disk/jcoggin/SCRbase'
ASSIGN SCRATCH='/kapania-disk/jcoggin/SCbase'
ASSIGN DBALL='/kapania-disk/jcoggin/DBALLbase'
ASSIGN OBJSCR='/kapania-disk/jcoggin/OBJSCRbase'
NASTRAN BUFFSIZE=8193
SOL 129
TIME 6000000
CEND
DLOAD=25
LOADSET=27
ECHO = NONE
MAXLINES = 999999999
SET 1=ALL
Set 2=ALL
SET 3=651,1327
Set 4=601,1600,2650
OLOAD=3
ACCELERATION=3
VELOCITY=3
SPCF=3
DISP=3
STRESS=4
TITLE=CASE A
SUBTITLE=NONLINEAR ANALYSIS
LABEL=DYNAMIC LATERAL PRESSURE LOAD (5lb mine blast)
SPC=1
ECHO=BOTH
TSTEPNL=888
BEGIN BULK
PLOAD4    11  1600  1.000
PLOAD4    12  1575  1.000
PLOAD4    12  1576  1.000
PLOAD4    12  1601  1.000
PLOAD4    13  1550  1.000
PLOAD4    13  1551  1.000
PLOAD4    13  1577  1.000
PLOAD4    13  1602  1.000
PLOAD4    14  1525  1.000
PLOAD4    14  1526  1.000
PLOAD4    14  1527  1.000
PLOAD4    14  1552  1.000
PLOAD4    14  1553  1.000
PLOAD4    14  1578  1.000
```

PLOAD4 14 1603 1.000
 PLOAD4 15 1475 1.000
 PLOAD4 15 1500 1.000
 PLOAD4 15 1501 1.000
 PLOAD4 15 1502 1.000
 PLOAD4 15 1528 1.000
 PLOAD4 15 1554 1.000
 PLOAD4 15 1579 1.000
 PLOAD4 15 1604 1.000
 PLOAD4 15 1605 1.000
 PLOAD4 16 1450 1.000
 PLOAD4 16 1451 1.000
 PLOAD4 16 1476 1.000
 PLOAD4 16 1477 1.000
 PLOAD4 16 1478 1.000
 PLOAD4 16 1503 1.000
 PLOAD4 16 1504 1.000
 PLOAD4 16 1529 1.000
 PLOAD4 16 1530 1.000
 PLOAD4 16 1555 1.000
 PLOAD4 16 1580 1.000
 PLOAD4 16 1581 1.000
 PLOAD4 16 1606 1.000
 PLOAD4 17 1425 1.000
 PLOAD4 17 1426 1.000
 PLOAD4 17 1452 1.000
 PLOAD4 17 1453 1.000
 PLOAD4 17 1479 1.000
 PLOAD4 17 1480 1.000
 PLOAD4 17 1505 1.000
 PLOAD4 17 1531 1.000
 PLOAD4 17 1556 1.000
 PLOAD4 17 1582 1.000
 PLOAD4 17 1607 1.000
 DLOAD,25,1.00000,1.0,101,1.0,102,1.0,103,
 ,1.0,104,1.0,105,1.0,106,1.0,107,
 ,1.0,108
 LSEQ,27,61,11
 TLOAD1,101,61,,,151
 LSEQ,27,62,12
 TLOAD1,102,62,,,152
 LSEQ,27,63,13
 TLOAD1,103,63,,,153
 LSEQ,27,64,14
 TLOAD1,104,64,,,154
 LSEQ,27,65,15
 TLOAD1,105,65,,,155
 LSEQ,27,66,16
 TLOAD1,106,66,,,156
 LSEQ,27,67,17
 TLOAD1,107,67,,,157
 LSEQ,27,68,18
 TLOAD1,108,68,,,158
 TABLED1 151 LINEAR LINEAR
 .0000000 .0.0000200 .0.0000400 .0.0000600 .0

.0000800	.0.0000867	.0.0000907	13308.3.0001000	9590.1
.0001200	4727.1.0001400	2316.6.0001600	1127.5.0001800	544.4
.0002000	260.3.0002200	123.0.0002400	57.2.0002600	26.1
.0002800	11.6.0003000	4.9.0003200	2.0.0003400	.7
.0003600	.2.0003800	.0.0004000	.0.0004200	.0
.0004400	.0.0004600	.0.0004800	.0.0005000	.0

ENDT

TABLED1 152 LINEAR LINEAR

.0000000	.0.0000200	.0.0000400	.0.0000600	.0
.0000800	.0.0000893	.0.0000933	12885.2.0001000	10201.2
.0001200	5063.0.0001400	2498.6.0001600	1224.9.0001800	595.7
.0002000	287.0.0002200	136.6.0002400	64.1.0002600	29.5
.0002800	13.2.0003000	5.7.0003200	2.3.0003400	.9
.0003600	.3.0003800	.0.0004000	.0.0004200	.0
.0004400	.0.0004600	.0.0004800	.0.0005000	.0
.0005200	.0.0005400	.0.0005600	.0.0005800	.0

ENDT

TABLED1 153 LINEAR LINEAR

.0000000	.0.0000200	.0.0000400	.0.0000600	.0
.0000800	.0.0000945	.0.0000985	12118.4.0001000	11500.6
.0001200	5790.8.0001400	2899.9.0001600	1442.9.0001800	712.6
.0002000	348.8.0002200	168.8.0002400	80.6.0002600	37.8
.0002800	17.3.0003000	7.7.0003200	3.2.0003400	1.3
.0003600	.4.0003800	.1.0004000	.0.0004200	.0
.0004400	.0.0004600	.0.0004800	.0.0005000	.0
.0005200	.0.0005400	.0.0005600	.0.0005800	.0

ENDT

TABLED1 154 LINEAR LINEAR

.0000000	.0.0000200	.0.0000400	.0.0000600	.0
.0000800	.0.0001000	.0.0001021	.0.0001061	11130.8
.0001200	7015.9.0001400	3595.1.0001600	1831.3.0001800	926.3
.0002000	464.7.0002200	230.8.0002400	113.2.0002600	54.7
.0002800	25.8.0003000	11.9.0003200	5.2.0003400	2.2
.0003600	.8.0003800	.2.0004000	.0.0004200	.0
.0004400	.0.0004600	.0.0004800	.0.0005000	.0

ENDT

TABLED1 155 LINEAR LINEAR

.0000000	.0.0000200	.0.0000400	.0.0000600	.0
.0000800	.0.0001000	.0.0001121	.0.0001161	10045.6
.0001200	8873.7.0001400	4692.4.0001600	2468.0.0001800	1290.0
.0002000	669.3.0002200	344.2.0002400	175.1.0002600	87.9
.0002800	43.4.0003000	20.9.0003200	9.8.0003400	4.4
.0003600	1.8.0003800	.6.0004000	.1.0004200	.0
.0004400	.0.0004600	.0.0004800	.0.0005000	.0
.0005200	.0.0005400	.0.0005600	.0.0005800	.0

ENDT

TABLED1 156 LINEAR LINEAR

.0000000	.0.0000200	.0.0000400	.0.0000600	.0
.0000800	.0.0001000	.0.0001200	.0.0001243	.0
.0001283	8957.8.0001400	6312.8.0001600	3454.6.0001800	1880.2
.0002000	1016.9.0002200	545.9.0002400	290.5.0002600	152.9
.0002800	79.4.0003000	40.5.0003200	20.2.0003400	9.7
.0003600	4.5.0003800	1.9.0004000	.7.0004200	.2
.0004400	.0.0004600	.0.0004800	.0.0005000	.0
.0005200	.0.0005400	.0.0005600	.0.0005800	.0

```

ENDT
TABLED1 157 LINEAR LINEAR
.0000000 .0.0000200 .0.0000400 .0.0000600 .0
.0000800 .0.0001000 .0.0001200 .0.0001387 .0
.0001400 .0.0001427 7926.9.0001600 4892.2.0001800 2788.9
.0002000 1581.6.0002200 891.5.0002400 498.9.0002600 276.9
.0002800 152.1.0003000 82.4.0003200 44.0.0003400 23.0
.0003600 11.6.0003800 5.7.0004000 2.6.0004200 1.0
.0004400 .3.0004600 .0.0004800 .0.0005000 .0
.0005200 .0.0005400 .0.0005600 .0.0005800 .0
.0006000 .0.0006200 .0.0006400 .0.0006600 .0
.0006800 .0.0007000 .0.0007200 .0.0007400 .0

```

```

ENDT
TABLED1 158 LINEAR LINEAR
.0000000 .0.0000200 .0.0000400 .0.0000600 .0
.0000800 .0.0001000 .0.0001200 .0.0001400 .0
.0001551 .0.0001591 6983.2.0001600 6832.7.0001800 4093.3
.0002000 2442.0.0002200 1449.9.0002400 856.2.0002600 502.3
.0002800 292.5.0003000 168.8.0003200 96.3.0003400 54.2
.0003600 30.0.0003800 16.2.0004000 8.4.0004200 4.2
.0004400 1.9.0004600 .7.0004800 .2.0005000 .0
.0005200 .0.0005400 .0.0005600 .0.0005800 .0
.0006000 .0.0006200 .0.0006400 .0.0006600 .0
.0006800 .0.0007000 .0.0007200 .0.0007400 .0

```

```

$
$
$ Elements and Element Properties for BOTTOM PLATE(Z=0)
PSHELL 3 105 .25 105 105
CQUAD4 1 3 1 27 28 2 0. 0.
CQUAD4 2 3 2 28 29 3 0. 0.
CQUAD4 3 3 3 29 30 4 0. 0.

```

```

$-----
$
$ Rest of Bottom Plate Elements In Here
$
$-----
CQUAD4 623 3 647 673 674 648 0. 0.
CQUAD4 624 3 648 674 675 649 0. 0.
CQUAD4 625 3 649 675 676 650 0. 0.

```

```

$
$
$ GAP Elements JOINING THE PLATES and GAP Element Property
PGAP,1,,.25,,10.9+4,,,,,
,.025
CGAP 2000 1 1 677 0. 1. .0
CGAP 2001 1 2 678 0. 1. .0
CGAP 2002 1 3 679 0. 1. .0

```

```

$-----
$
$ Rest of Gap Elements In Here
$
$-----
CGAP 2672 1 673 1349 0. 1. .0
CGAP 2673 1 674 1350 0. 1. .0

```

```

CGAP 2674 1 675 1351 0. 1. .0
CGAP 2675 1 676 1352 0. 1. .0
$ Elements and Element Properties for region : pshell.4
$ PROPERTIES FOR THE TOP PLATE (Z = .5)
PSHELL 4 105 .25 105 105
$ELEMENTS OF THE TOP PLATE
CQUAD4 1000 4 677 703 704 678 0. 0.
CQUAD4 1001 4 678 704 705 679 0. 0.
$-----
$
$ Rest of Top Plate Elements In Here
$
$-----
CQUAD4 1622 4 1323 1349 1350 1324 0. 0.
CQUAD4 1623 4 1324 1350 1351 1325 0. 0.
CQUAD4 1624 4 1325 1351 1352 1326 0. 0.
$ Nodes of the Entire Model
GRID 1 50. 0. 0.
GRID 2 50. 1.99998 0.
GRID 3 50. 3.99999 0.
$-----
$
$ Rest of Grid Points In Here
$
$-----
GRID 1349 0. 44.0000 .5
GRID 1350 0. 46.0000 .5
GRID 1351 0. 48.0000 .5
GRID 1352 0. 50. .5
$
$
$ QUARTER PLATE BC'S, TWO EDGES CLAMPED(123456), AND
$ TWO EDGES WITH SYMMETRY BC'S(246 OR 156)
SPC 1 1 123456 0.0
SPC 1 2 123456 0.0
SPC 1 3 123456 0.0
$-----
$
$ Rest of Boundary Conditions In Here
$
$-----
SPC 1 1350 156 0.0
SPC 1 1351 156 0.0
SPC 1 1352 123456 0.0
$
$
$
$
$ MATERIAL PROPERTIES FOR ALUMINUM - ELASTIC-PERFECTLY PLASTIC
MAT1,105,10.9+6,,0.3,.00026
,448.0E6
MATS1,105,,PLASTIC,0.0,1,2,58000.0
$
$
$ NONLINEAR TRANSIENT ITERATION CONTROL

```

```
TSTEPNL,888,2000,.000005,5,TSTEP,2,10000  
$  
$  
$OP2 REQUEST AND PARAM CARDS  
$PARAM POST -1  
PARAM LGDISP 1  
ENDDATA
```

Vita

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