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Numerical modeling of air blast effects on hybrid structures

Matthew J. Fox
West Virginia University

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NUMERICAL MODELING OF AIR BLAST EFFECTS ON HYBRID STRUCTURES

Matthew J. Fox

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College of Engineering and Mineral Resources
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in
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Ever Barbero, Ph.D., Chair
Julio Davalos, Ph.D.
Victor Mucino, Ph.D.

Department of Mechanical and Aerospace Engineering

Morgantown, West Virginia
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*Abstract***NUMERICAL MODELING OF AIR BLAST EFFECTS
ON HYBRID STRUCTURES**

Matthew J. Fox

Blast resistant structures are gaining increased need in today's society. This research addresses adding composite reinforcement to existing concrete structures to decrease blast damage. An upgraded material model for concrete is presented. This model, used in LS-DYNA3D, incorporates tensile damage, which allows the concrete to degrade as it is loaded. The concrete model is tested using existing unreinforced and reinforced concrete beam tests. Some beams were plain, others were externally reinforced with composites, bonded to the exterior of the beams. There is a very good correlation between the predicted and existing data. The concrete model was then used to predict the mean residual displacement of a plain and composite reinforced concrete wall subjected to a blast load.

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Nomenclature

α	=	Angle of incidence	t	=	Wall thickness
δD	=	Damage increment	T	=	Tension cutoff
$\delta \epsilon_v$	=	Strain increment	t_a	=	Arrival time
Θ	=	Decay coefficient	TDP	=	Tensile damage parameter
ω	=	Natural vibration frequency	t_o	=	Positive phase duration
ρ	=	Mass density	w	=	Material width
ν	=	Poisson's ratio			
ζ	=	Damping value			
a	=	Wall width			
A	=	Cross-sectional area			
b	=	Wall height			
c	=	Actual damping			
c_{cr}	=	Critical damping			
D_s	=	Overall system damping			
$[D]$	=	Bending stiffness matrix			
E	=	Modulus of elasticity			
G	=	Shear modulus			
I	=	Area moment of inertia			
K	=	Bulk modulus			
m	=	Mass of the system			
P	=	Applied load			
$P_s(t)$	=	Pressure at time t			
P_{so}	=	Peak incident pressure			
$[Q]$	=	Reduced stiffness matrix			
$[\bar{Q}]$	=	Transformed $[Q]$			
SJ1	=	Apparent engineering stress			
$\overline{SJ1}$	=	Effective stress			

CHAPTER 1

Introduction and Literature Review

1.1 Introduction:

The value of externally reinforcing existing structures with fiber reinforced composite materials is becoming increasingly important in today's society. For military applications, there are obviously many circumstances where added protection of structures is important, including protection against bombs, mortars, grenades and small caliber rounds. Applications in the civilian world are becoming more important following major bombings around the world, including two major ones recently in the United States, the World Trade Center Building in New York in February, 1993 and the Alfred P. Murrah Federal Building in Oklahoma City in April, 1995.

Blast loads from bomb explosions are unlike other types of loading, in that the maximum load occurs at the initial wave impact with the structure and the entire load is applied within milliseconds instead of seconds. This dynamic loading is very destructive compared to static loadings and therefore, added protection for existing structures is needed to ensure the survival of the structure and what it is housing during a blast.

A finite element model was developed for predicting the value of adding a composite material to an existing structure. There are many different finite element material models for the multitude of materials that exist. For example, there are models for elastic, orthotropic elastic, kinematic/isotropic plasticity, linear viscoelastic, etc. Also, within the many models there are variations, including whether or not there is failure. Some of these models

represent their prospective materials very well when compared to experimental data. However, others do not provide the acceptable values obtained in documented experimental procedures. Concrete is not a homogeneous material, therefore, it is very difficult to model, especially as the specimen accumulates damage (i.e. cracks). Concrete is the basic model developed in this research due to the many applications in military and civilian structures.

The efficiency of modeling concrete using a finite element program is apparent when considering the time and cost of full-scale tests. An acceptable material model is developed by comparing a finite element model with previously completed experimental work. This model can then be expanded to design and test full-scale structures without the need to physically build them.

One key problem encountered is that there are so many types of concrete that few people agree on any one model. Therefore, models that are developed are usually material and application specific and kept within the company using them.

To successfully model a concrete wall, a concrete model with damage must first be developed and tested using existing concrete data. This is accomplished using a variation of the two-invariant cap model, LS-DYNA3D material model 25. LS-DYNA3D is an explicit, nonlinear finite element modeling program developed by Livermore Software Technology Corporation [LSTC, 1996]. A damage model, UMAT43, was developed using this cap model and validated using the experimental work of Jerome [1996] and Faza, et al [1995].

Once the concrete material model was developed and successfully compared to other experimental work, a concrete wall was modeled and subjected to a blast load. The same wall was then covered with a layer of composite material and again subjected to the same blast load. The results were then compared.

1.2 Literature Review:

Blast mitigation is a subject of much consideration for research in today's society. Unfortunately, much of the data is considered proprietary by private companies, so many do not publish the results of their testing, be it experimental or theoretical. Few facilities have adequate setups to perform explosive testing. However, there are recurring conferences and technical sessions with pertinent information relating to this research. These include, but are not limited to, *Structures Under Shock and Impact* [Bulson, 1989], American Concrete Institute (ACI) *Short Duration Dynamic and Vibratory Load Effects* [Bounds, 1998] and American Society of Mechanical Engineers (ASME) *Pressure Vessels and Piping Conference* [Shin and Zukas, 1996].

The feasibility of retrofitting existing structures with advanced composite materials (ACM) for blast protection was studied by Barbero, et al. [1997]. They found an increase in strength and energy absorption under static loads and expected to have similar effects for blast loads. The U.S. Army Engineer Waterways Experimental Station (WES) also evaluated the use of ACM for use in field construction and retrofitting of existing structures [Cummins, et al., 1997]. They believe that ACM have potential in blast protection, but express the importance of future research to be able to adopt these materials effectively.

The military has studied the effects of blast loading for years. The task of transferring this information to the civilian world has been studied by the National Research Council [1995]. They found that several barriers exist that hinder the effective transfer of information to the civilian sector. These include the lack of proper education transfer to students for designing for blast effects, the military being slow to funnel the classified information to the

public, and the extra costs associated with designing and manufacturing structures that incorporate blast-hardening. Unclassified technical design manuals exist that can greatly help designers and engineers with blast protection of civilian structures, such as *Structures to Resist the Effects of Accidental Explosions Manual* [TM 5-1300, 1990]. This manual includes fundamental principles, analysis and design procedures for dynamic loading.

Experimental studies have been carried out by Ross, et al. [1997]. They used ammonium-nitrate-fuel-oil (ANFO) to subject concrete beams and slabs to blast loads. They tested both control specimens of internally reinforced concrete beams and slabs and the same specimens externally reinforced with carbon fiber reinforced plastic (CFRP). The results showed most of the damage to the CFRP specimens occurred due to the blast wave (Chapter 2) reflected from the test stand.

There are companies that have developed composite blast proofing systems to protect workers from industrial explosions and terrorist attacks. These systems are fundamental in protecting people from collapsing walls and shattering masonry, which often kill more people than the explosion. For instance, it has been estimated that at least 80 percent of the deaths at the Alfred P. Murrah Federal Building in Oklahoma City were caused by the structure falling on occupants, who might otherwise have survived the explosion [Prendergast, 1995]. DuPont™ is one of the companies that currently sell such a blastproofing system [Hranac, 2001].

Finite-element modeling of concrete by itself has been a focus of research for many. There are numerous forms of concrete and adding reinforcements only complicates the model. There has been experimental work with reinforcement arrangement [Taylor, et al., 1966] and efforts to generate efficient reinforcement modeling in finite-element concrete

structures [Barzegar and Maddipudi, 1994]. Miyamoto, et al. [1994] also pointed out that static based analysis is not acceptable for dynamic loading of concrete structures.

Many researchers that have worked on modeling the intricacies of concrete. Marzouk and Chen [1993] performed direct finite-element analysis of high-strength concrete slabs by varying the reinforcement ratios, width-to-thickness ratios, various concrete strengths and reinforcement yield strengths. In depth modeling of deformation and cracking of early-age concrete due to the curing process has been studied by de Borst and van den Boogaard [1994].

Beshara and Viridi [1992] developed their own finite-element linear and nonlinear dynamic analysis computer program to study the effects of impulsive and blast loading on two-dimensional reinforced concrete structures. The results obtained for the deflection at mid-span and along the beam were in good agreement with results published by experimental researchers.

Existing concrete models, specifically in LS-DYNA3D, have been calibrated to better represent experimentally observed material behavior [Malvar, et al., 1995 and 1997]. This was using material model 16, the pseudo tensor concrete/geological model. The two-invariant plasticity model was first enhanced to a three-invariant formulation in compression. The second enhancements also addressed the issues of the model in tension. This model was even used in blast load configurations [Crawford, et al., 1997]. They studied the effectiveness of jacketing columns of reinforced concrete with steel and composite and subjecting them to blast loads. They found that jacketing the columns prevented the ultimate failure of most of the beams and kept the reinforced concrete structure being supported from collapsing.

CHAPTER 2

Blast Loading of a Hybrid Wall

2.1 Blast Wave Phenomena

During typical pressure loading, a structure starts at an initial zero state and is incrementally loaded until the desired load is reached. This may be a specified maximum or until failure. Step loading is very helpful in understanding structural responses. Unfortunately, blast loads behave very differently.

Blast loads due to an explosion are very violent releases of energy. The shock wave travels radially from the center of the explosion as a hot gas sphere [Kornhauser, 1964]. The blast wave generated creates an almost instantaneous rise to the peak pressure from an ambient pressure (Fig. 2.1). The intensity of the peak incident pressure decreases with the distance from the initial blast and the application of the overpressure is dissipated in milliseconds.

Figure 2.1 – Idealized Pressure vs. Time Blast Wave

The overpressure versus time curve of Fig. 2.1 can be described as follows. At any location within the blast zone, there is an arrival time of the blast wave. For all practical purposes, this is considered the time the peak incident pressure occurs. The pressure then decreases during the positive phase duration until it reaches the original ambient pressure. From here, there is a reversal of the particle flow creating a negative overpressure. This is the negative phase duration, which lasts longer than the positive phase duration. The negative phase is not as important in the design of structures as the positive phase [TM 5-855-1, 1986]; therefore, it will be neglected in this research. Although these incident pressures can cause severe damage, the greatest pressures incurred are from the reflection of the shock wave (Fig 2.2).

Figure 2.2 – Incident vs. Reflected Pressures

If the wave encounters a surface as it moves away from the initial blast, that wave is reinforced and reflected. The magnitude of this reflected wave corresponds directly to the incident pressure and the angle of the surface. The peak reflected pressure is maximum at the point of initial shock wave contact. As the angle of incidence, α , of the surface increases, becomes more parallel with the blast wave, the magnitude of the reflected wave decreases (Fig. 2.3).

Figure 2.3 – Blast Wave Depiction

Except for the duration of the blast event, it is recommended for design purposes to use the reflected overpressure and corresponding parameters [Baker, 1973]. The duration used should be calculated with the incident values.

2.2 Determining Pressure Curves

To symbolize blast loads in LS-DYNA3D, pressure versus time curves must be developed and entered as load curves into the model. These load curves can then be associated with the location of the pressure acting on the wall. To determine the input pressure curves from an explosion, the US Army's Conventional Weapons Effects Program, CONWEP [1992], was used. The wall was modeled as an 8 x 12 feet target area on a 24 x 36 feet reflecting surface with a wall thickness of 6 inches (Fig. 2.4). These areas were chosen to represent the side of small building.

Figure 2.4 -- Wall as Modeled in CONWEP

To produce the desired blast strength, a general-purpose bomb was created using CONWEP. The bomb consisted of 37 pounds of trinitrotoluene (TNT) and was placed at a standoff distance of 30 feet from the wall (Table 2.1 and Fig. 2.5).

Table 2.1 -- General Purpose Bomb

Name	Matt Prototype 1
Total Weight, lb.	80
Charge Weight, lb.	37
Case Weight, lb.	43
Explosive Used	TNT
Assembled Length, in	24
Case Diameter, in	8.25
Caliber Radius Head	0 (flat ends)
Armor-Piercing?	No

Figure 2.5 -- Bomb Dimensions

The pressure versus time curves needed for LS-DYNA3D were calculated with a QuickBasic program, “T&P.BAS,” (Appendix A) using the time dependent pressure equation given by Kingery and Bulmash [1984].

$$P_s(t) = P_{so} * [1 - (t - t_a) / t_o] * \exp[-(t - t_a) / \Theta] \quad (2.1)$$

where: $P_s(t)$ = pressure at time t
 P_{so} = peak incident pressure
 t_o = positive phase duration
 t_a = arrival time
 Θ = decay coefficient

All of the unknowns in the equation, the peak incident pressures, the positive phase duration, the arrival times and the decay coefficient, were found using CONWEP. First, the decay coefficient and the positive phase duration were computed using the Hemispherical surface burst option, which is found under the Airblast and Aboveground detonation menus. For a 37 pound TNT bomb at a range of 30 feet, the reflected pressure decay coefficient was found to be 3.700 milliseconds and the duration of the blast was 8.222 milliseconds.

Next, the initial peak pressure distribution was found for the target area of the wall. This was accomplished by using the Loads on structures option found under the Airblast menu. After entering the wall dimensions, as shown in Fig. 2.4, the pressure distribution was displayed using contour lines. The peak pressures were then found using the read command at 81 nodes symmetrically located across the wall (Fig. 2.6).

Figure 2.6 -- Peak Pressure Distribution on the Target Surface

The time of arrival of the initial pressure for each of the 81 nodes was then found. This is accomplished by first finding the distance to each node from the 30 feet standoff distance. These values can then be entered, one at a time, into CONWEP under the Airblast, Aboveground detonation, Hemispherical surface burst options. The range to target is changed to the distance for each of the 81 nodes and CONWEP returns a value for the arrival time. It should be noted that the arrival times are symmetric about the vertical centerline of the wall. This procedure was simplified by deriving the above equations and adding them directly to the QuickBasic program, "T&P.BAS."

All of the variables of Eq. 2.1 were then known, so the pressure versus time curves for LS-DYNA3D were calculated using the QuickBasic program. The program then returns the pressure-time curves and the pressure/node locations needed for input into LS-DYNA3D as data files (Appendix B). These files are used in LS-INGRID [LSTC, 1995] to create the input geometry for use with LS-DYNA3D.

CHAPTER 3

Damping Calculations

3.1 Background:

All materials and structures exhibit a damping factor. Damping occurs as the vibration input into a system diminishes in amplitude with time. This energy is generally transformed to heat by friction.

LS-DYNA3D allows materials to have individual damping constants. These can be input as a constant value if only one material is being modeled. If more than one material is used, this damping constant can be applied as a load curve for each of the materials. Models using the critical damping constant are generally the best for convergence.

3.2 Plain Concrete Modeled as a Wall:

The concrete wall was modeled as a composite plate to determine the natural frequencies. An equation was derived to associate the natural frequency and the damping ratio to the overall system damping constant for LS-DYNA3D. The natural frequency of the system was calculated using the following equations, obtained from Reddy [1997].

$$\omega_{mn}^2 = \frac{\pi^4}{\tilde{I}_o b^4} \left[D_{11} m^4 \left(\frac{b}{a} \right)^4 + 2(D_{12} + 2D_{66}) m^2 n^2 \left(\frac{b}{a} \right)^2 + D_{22} n^4 \right] \quad (3.1)$$

$$\tilde{I}_o = I_o + I_2 \left[\left(\frac{m\pi}{a} \right)^2 + \left(\frac{n\pi}{b} \right)^2 \right] \quad (3.2)$$

$$I_o = \sum_{k=1}^L \rho_o^{(k)} (z_{k+1} - z_k) \quad I_2 = \frac{1}{3} \sum_{k=1}^L \rho_o^{(k)} (z_{k+1}^3 - z_k^3) \quad (3.3)$$

The wall dimensions are shown in Fig. 3.1 and the properties of the concrete wall are given in Table 3.1. This is assuming that the properties of the concrete are equivalent in all directions when modeled as a composite.

Figure 3.1 -- Wall Dimensions

Table 3.1 -- Concrete Wall Properties

Length (a) [in]	Height (b) [in]	Thickness (t) [in]	Modulus of Elasticity (E) [psi]	Density (ρ) [lbs·sec ² /in ⁴]	Shear Modulus (G) [psi]	Poisson's Ratio (ν)
144	96	6	3.00e6	1.77e-4	1.15e6	0.2

Using the properties of Table 3.1, the values of the reduced stiffness matrix [Q] were computed by applying the equations given in Barbero [1999].

$$[Q] = \begin{bmatrix} 3.13 & 0.625 & 0 \\ 0.625 & 3.13 & 0 \\ 0 & 0 & 1.15 \end{bmatrix} \times 10^6 \text{ psi}$$

Assuming that the fibers are oriented along the x-axis (0°), then the transformed reduced stiffness matrix $[\bar{Q}]$ equals the reduced stiffness matrix [Q]. Next, the bending stiffness matrix [D] was computed [Barbero, 1999].

$$[D] = \begin{bmatrix} 56.3 & 11.3 & 0 \\ 11.3 & 56.3 & 0 \\ 0 & 0 & 20.8 \end{bmatrix} \times 10^6 \text{ psi} \cdot \text{in}^3$$

The moments of inertia were calculated using Eq. 3.3 and then $\tilde{I}_o$ was found with Eq. 3.2. Two fundamental frequencies were examined to determine the minimum natural frequency. These were ω_{11} and ω_{21} , and were subsequently solved using Eq. 3.1. The results were

ω_{11} (rad/sec)	ω_{21} (rad/sec)
350.5	671.9

Finally, the overall damping constant for the entire system, to be used in the LS-DYNA3D input file, can be computed. The damping value, ζ , used for a concrete wall was 0.02 [Steidel, 1989]. The overall damping equation is derived from the following equations [Beards, 1983, Bachmann, 1987, Hallquist, 1993].

$$\left. \begin{aligned} \zeta &= \frac{c}{c_{cr}} \\ c_{cr} &= 2\omega_1 m \\ D_s &= \frac{c}{m} \end{aligned} \right\} (3.4)$$

Where c is the actual damping, c_{cr} is the critical damping and m is the mass of the system. The overall damping equation can then be derived.

$$D_s = 2\zeta\omega_1 \quad (3.5)$$

Since ω_{11} is the smallest frequency, it was used as the natural frequency, ω_1 . Therefore, the system damping constant was found using Eq. 3.5 to be 14.02.

3.3 Unreinforced Concrete Beam Model:

This model contains the actual dynamic loading of the system; therefore, the system damping constant should be that of the actual system. To find this value, the natural frequency of the beam must first be calculated [Nashif, et al., 1985].

$$\omega_n = \frac{\xi_n^2}{L^2} \sqrt{\frac{EI}{\rho H b}} \quad \xi_n = n\pi \quad (n = 1, 2, \dots) \quad (3.6)$$

Where L is the length, H is the height, b is the width of the beam, E is the modulus of elasticity, I is the area moment of inertia and ρ is the mass density. For a rectangle, the area moment of inertia can be calculated using Eq. 3.7.

$$I = \frac{1}{12} b H^3 \quad (3.7)$$

Finally, the overall damping constant for the entire system (to be used in LS-DYNA3D) can be computed. The damping value, ζ , used for concrete beams, was 0.007 [Bachmann and Ammann, 1987]. Since ω_1 is the smallest frequency, it was used as the natural frequency and solved using Eq. 3.5. Therefore, the system damping constant was found to be 18.6. For the unreinforced concrete beam with CFRP reinforcement, the system damping constant was found to be 46.4. The CFRP calculations were performed using a variation of the previous equations as explained in the next section.

3.4 Reinforced Concrete Beam Model:

During the actual test, the load was applied at a constant rate with brief stops every 2000 pounds for data collection. Because LS-DYNA3D is a dynamic program, modeling a quasistatic loading case is very time consuming and computationally expensive. At faster loading rates, the beam has a tendency to oscillate and take time to approach the real solution. This can be overcome by setting the overall damping constant of the system (D_s) equal to its critical value. To achieve this, the damping ratio (ζ), in Eq. 3.5, is set equal to one.

Finding the natural frequency (ω_1) of the reinforced concrete model is somewhat complicated. The problem occurs in finding the area moment of inertia because several different materials are used. Using the case of a steel plate on the bottom, tensile side, of the beam as an example, the Transformed Section Method [Barbero, 1999] is applied to find the area moment of inertia. For this problem, the value of ρHb in the denominator of Eq. 3.6 is transformed to $\rho_c(\Sigma A_c) + \rho_s(\Sigma A_s)$, where the subscripts c and s denote concrete and steel, respectively.

Figure 3.2(a) shows the original cross-section of the reinforced concrete beam with a steel plate on the bottom, tensile side. The steel plate has a width of 5.906 inches and a thickness of 0.177 inches. Next, the reinforcement bars are changed to equivalent steel rectangles, spanning the width of the concrete beam (Fig. 3.2(b)). After the reinforcement bars are adjusted, the concrete width has to be adjusted based upon the following ratio, assuming steel is the reference material.

$$\eta_c = \frac{E_c}{E_s} \quad (3.8)$$

Figure 3.2 – Transformed Section Method Used With the Reinforced Concrete Model

The new width of concrete, w_c' , can then be found.

$$w_c' = \eta_c w_c \quad (3.9)$$

Where w_c is the original width of the concrete, in this case 6 inches (Fig. 3.2(c)). To find the area moment of inertia, the neutral surface (NS) has to first be found using statics. After finding the neutral surface, the area moment of inertia can also be found using statics techniques. Finally, the values can be substituted into Eq. 3.6, using the reference modulus of elasticity (E_s in this case) to solve for the natural frequency. Assuming critical damping ($\zeta = 1$), Eq. 3.5 can be solved for the overall damping constant. For the case of the steel plate reinforced concrete, the value was found to be 1643. This example is solved step-by-step in Appendix C. The values for all of reinforced concrete beams can be found in Table C.4.

CHAPTER 4

Material Modeling

4.1 The Concrete Damage Model:

A large portion of this research was dedicated to developing a new concrete material model for LS-DYNA3D. The new designation is material type 43 or UMAT43. The input format for LS-DYNA3D, in structured format, can be found in Appendix D.

An inviscid, two-invariant geologic cap model (Fig. 4.1), was chosen as a basis to develop the damage model. This is LS-DYNA3D material type 25 [LSTC, 1996]. Surface F_e is the failure envelope (yield surface), F_c is the cap surface and the tension cutoff is the vertical line above T. The elements used were eight node, solid hexahedron elements, which were chosen for their efficiency in modeling simple rectangular structures. The existing code for the two-invariant cap model, obtained from Chen and Baladi [1985], was implemented into a Fortran program (Appendix E). A driver program (Appendix F) was also developed to simulate the results, so that LS-DYNA3D would not have to be compiled and executed each time a change was made. This saved time, because only basic information was needed while the program was being developed. After ensuring that the original cap model provided by Chen and Baladi performed the same as the original LS-DYNA3D cap model, the model was further developed to include damage.

Figure 4.1 – The Yield Surface of the Two-Invariant Cap Model in Pressure $\sqrt{J_{2D}} - J_1$ Space

The cap model works satisfactorily in compression. The existing code allows for movement of the cap, which allows for material hardening to occur. In tension, however, the strength of the concrete remains constant. Even after cracking and subsequent deterioration occurs, the tensile strength of the concrete remains at the user specified value of the tension cutoff. This value is not acceptable for a material that has cracking and must be adjusted to account for damage. Variations to the cap model are not uncommon. Others that have made modification to it are Simo, et al. [1988] and Schwer and Murray [1994].

To adjust the new cap model to include damage, the following equations had to be included in the program. First, the apparent engineering stress, $SJ1$, had to be computed using the load (P) and the original area (A_o).

$$SJ1 = \frac{P}{A_o} = \sigma_x + \sigma_y + \sigma_z \quad (4.1)$$

Next, the effective stress ($\overline{SJ1}$) had to be calculated for use internally in the UMAT43 program. This needed to include a damage parameter (D), which is initially set to zero (no damage).

$$\overline{SJ1} = \frac{SJ1}{1 - D} \quad (4.2)$$

Now, if the effective stress is less than the tension cutoff (T), damage has to be introduced. The reason the effective stress is less than the tension cutoff, instead of more, is that the cap model assumes that compression is positive and tension is negative. When it is less than the tension cutoff, it has migrated to the left of the tension cutoff surface. Once damage is introduced, the effective stress is reset to the current value of the tension cutoff and the apparent stress is recalculated.

$$SJ1 = \overline{SJ1} * (1 - D) \quad (4.3)$$

LS-DYNA3D then uses this value when making computations on the modeled structure.

Finally, the damage increment and total damage have to be calculated and implemented into the model. To calculate the damage increment, the modulus of elasticity (E) has to first be computed using the shear (G) and bulk (K) moduli [Aboudi, 1991].

$$E = \frac{9GK}{3K + G} \quad (4.4)$$

Next, the damage increment can be calculated using the tensile damage parameter (TDP), which is equal to the tension cutoff divided by four [Janson and Hult, 1977], and the current strain increment ($\delta\epsilon_v$).

$$\delta D = \frac{E * \delta\epsilon_v}{TDP} \quad (4.5)$$

This damage increment is then added to the previous damage parameter (initially zero) to compute the damage for the current increment of strain. This damage value is then used during the next strain increment iteration. The difference in modeling with and without damage can be seen in Fig. 4.2. The damage value never reaches a value of one, which could cause the model to crash. Instead, a limit of 0.95 is given to D , allowing the smallest value of the apparent stress to be equal to $0.05 * \overline{SJ1}$.

Figure 4.2 – Effect of Damage on Apparent Stress

To test the UMAT43 damage model, the value of TDP was set to 10^{12} . As can be seen in Eq. 4.5, this causes the damage increment to be zero for all practical purposes, therefore, no damage is ever introduced. This was used with the UC concrete model and compared to the original LS-DYNA3D cap model, material model 25, that did not incorporate tensile damage (Fig. 4.3).

Figure 4.3 – Comparison of UMAT43 with LS-DYNA3D Material Type 25

Three additional parameters were added to the UMAT43 damage model. These were the initial J_1 intersection of F_e and F_c , denoted as L_0 (Fig. 4.1), the tensile damage parameter (TDP), which is used in computing the damage accumulation, and $FCUT$ (Fig. 4.4), the imaginary intersection of J_1 and the F_e curve. Eq. 4.6 is used to calculate L_0 [Chen and Baladi, 1985].

$$\alpha - \gamma e^{-\beta L_0} - \frac{X_0 - L_0}{R} = 0 \quad (4.6)$$

This equation was solved for L_0 using a symbolic mathematical calculation program. The properties were then substituted and the resulting equation solved.

Figure 4.4 – Visualization of the Imaginary Intersection FCUT

The TDP and FCUT were calculated using the following equations.

$$TDP = \frac{T}{4} \quad (4.7)$$

$$FCUT = \frac{-1}{\beta} \ln\left(\frac{\alpha}{\gamma}\right) \quad (4.8)$$

4.2 The Unreinforced Concrete Beam Model:

The properties of the concrete used for material type 43 are found in Table 4.1 [Jerome, 1996].

Table 4.1 – Properties of Unreinforced Concrete Beam Model

K (psi)	1.928×10^6	X_θ (psi)	18000
G (psi)	1.446×10^6	L_θ (psi)	10440
ρ (lb-sec ² /in ⁴)	1.77×10^{-4}	W (unitless)	0.884
α (psi)	0.7×10^3	D (psi ⁻¹)	1.54×10^{-6}
θ (unitless)	0.1	T (psi)	-630
χ (psi)	0.2×10^3	TDP (psi)	-157.5
β (psi ⁻¹)	1.473×10^{-3}	$FCUT$ (psi)	-850.5
R	10.8		

The plain concrete beams used for the unreinforced concrete (UC) beam model (Fig. 4.5) have a total length of 30 inches, a width and height of three inches and are simply supported 1.5 inches from each end. These beams were modeled using solid hexahedron elements of length 1.5 inches, height one inch and width one inch. By using a symmetry plane through the center of the beam, only half of the beam had to be modeled. This reduces computation time without sacrificing the accuracy of the results.

Figure 4.5 – UC Beam Model

All of the UC beams were loaded in three-point bending, using a drop weight impact machine. The pressure versus time loading curve for the plain concrete beams is given in Table 4.2.

Table 4.2 -- Pressure vs. Time Curve Used in Beam Loading of the Plain UC Beam

Time (10^{-6} sec)	Pressure (ksi)	Time (10^{-6} sec)	Pressure (ksi)	Time (10^{-6} sec)	Pressure (ksi)	Time (10^{-6} sec)	Pressure (ksi)
0	0.000	300	0.903	600	2.457	900	0.893
50	0.024	350	1.202	650	2.530	950	0.540
100	0.067	400	1.568	700	2.385	1000	0.199
150	0.189	450	1.925	750	2.192	1050	0.000
200	0.397	500	2.173	800	1.537	1600	0.000
250	0.645	550	2.324	850	1.189		

The second set of beams that Jerome tested was externally reinforced with three layers of carbon fiber reinforced plastic (CFRP) with a total thickness of 0.0195 inches.

This layer of composite was added to the bottom, tensile side, of the beam. This material was also modeled using eight node, solid hexahedron elements, 1.5 inches long, one inch wide and 0.0195 inches thick. LS-DYNA3D material type 1 was used to model the CFRP (Table 4.3). This is a perfectly elastic model, but it is assumed that the concrete cracks before any significant damage occurs in the composite. The CFRP is assumed to be perfectly bonded to the concrete, which is a limitation of this finite element model. The pressure versus time loading curve for the CFRP reinforced concrete beams is given in Table 4.4.

Table 4.3 – CFRP Material Properties

0° Tensile Strength (psi)	320×10^3
0° Tensile Modulus (psi)	20×10^6
Poisson's Ratio (unitless)	0.3
Fiber Volume Fraction (%)	60

Table 4.4 -- Pressure vs. Time Curve Used in Beam Loading of the CFRP Reinforced Concrete Beam

Time (10-6 sec)	Pressure (ksi)	Time (10-6 sec)	Pressure (ksi)	Time (10-6 sec)	Pressure (ksi)	Time (10-6 sec)	Pressure (ksi)
0	0.000	250	6.950	500	6.090	750	0.205
50	0.669	300	7.430	550	3.955	800	0.062
100	2.178	350	7.763	600	2.027	850	0.000
150	4.168	400	7.970	650	0.892	1600	0.000
200	5.912	450	7.545	700	0.423		

This model contains the actual dynamic loading of the system; therefore, the system damping constant should be that of the actual system, as found in Section 3.3. Both input files for LS-DYNA3D, the plain beams and the reinforced beams, can found in Appendices G and H, respectively.

4.3 The Steel Reinforced Concrete Beam Model:

All of the reinforced concrete (RC) beams that Faza tested contained internal reinforcement, primarily steel reinforcement bars (rebars). The beam cross-section contains two #3 bars (3/8 inch diameter) in the upper section and two #6 bars (6/8 or 3/4 inch diameter) in the lower section (Fig. 4.6) [Faza, et al., 1995]. The rebars were modeled using material type 3, kinematic/isotropic elastic-plastic. Truss elements were chosen to model the beams due to compatibility with solid elements. The properties of the steel used in the material model are found in Table 4.5.

Figure 4.6 – Cross-Section of RC Beams

Table 4.5 – Properties of Steel Reinforcing Bars

Density (lb*sec ² /in ⁴)	7.34x10 ⁻⁴
Young's Modulus (psi)	29.0x10 ⁶
Poisson's Ratio (unitless)	0.29
Yield Stress (psi)	40.0x10 ³
Hardening Modulus (psi)	73.6x10 ³
Hardening Parameter (unitless)	1

The beam has a total length of 120 inches, with 108 inches between the supports. The beam is six inches wide and has a height of 12 inches. The beam was loaded in four-point

bending and is shown in Fig. 4.7 [Hota, et al., 1998]. Like the UC beams, a symmetry plane was placed through the center of the beam so only half had to be modeled, reducing computation time.

Figure 4.7 – RC Beam Model

The other types of reinforcement used on RC beams can be found in Fig. 4.8. It is noted that some of the composite wraps cover only eight inches of the beam height, while others cover the entire 12 inches.

Figure 4.8 -- Different Wrapping Configurations of RC Beam Model

The composite was made using a carbon fiber forca tow sheet with epoxy FR-E3P resin. The properties of the composite used in the RC beam models are found in Table 4.6.

Table 4.6 -- Properties of CFRP Used on RC Beams

Composite Wrap	
E_{1w} (psi)	4.88×10^6
E_{2w} (psi)	0.583×10^6
ρ_w (lbs*sec ² /in ⁴)	1.1992×10^{-4}

The RC beams contain multiple sliding interfaces. These include: between the steel reinforcement bar and the concrete, between the steel plate and the concrete, between the composite material and the concrete and between the differently oriented composite materials. Each of these interfaces make the model more complex and add significant CPU time to the process.

The initial properties of the RC concrete were chosen as the properties used by Logicon R & D Associates (RDA) [Murray and Lewis, 1995] and are shown in Table 4.7. Because the properties greatly differ for each type of concrete, these parameters had to be adjusted to match Faza's concrete data.

Table 4.7 – Initial RDA Concrete Properties

	Given (Metric)	Converted (English)		$1.6\text{e-}3 \text{ MPa}^{-1}$	$1.103\text{e-}5 \text{ psi}^{-1}$
K	14700 MPa	2.132e6 psi	R	1.2	1.2
G	11025 MPa	1.599e6 psi	X_0	210 MPa	30450 psi
ρ	2.28 gm/cm ³	2.13e-4 lb-sec ² /in ⁴	L_0	144.468 MPa	20953 psi
α	230 MPa	33350 psi	W	0.12	0.12
θ	0	0	D	$1.35\text{e-}4 \text{ MPa}^{-1}$	$9.31\text{e-}7 \text{ psi}^{-1}$
γ	221 MPa	32045 psi	T	-2.5 MPa	-362.6 psi

The first step was to match the slope of Faza's load vs. deflection diagram for plain concrete before any cracking occurred. To change the slope, the shear modulus, G , was

adjusted. By changing the shear modulus, the bulk modulus, K , also changed according to Eq. 4.10 [Barbero, 1999, Aboudi, 1991].

$$G = \frac{E}{2(1+\nu)} \quad (4.9)$$

$$K = \frac{2\nu G}{(1-2\nu)} + \frac{2G}{3} \quad (4.10)$$

After duplicating the initial slope, the concrete needed to exhibit cracking at approximately 4000 pounds. This was accomplished by changing the tension cutoff until cracking occurred at the desired load. At this point, the slope of the deflection versus load diagram decreases in magnitude.

Next, the hardening law exponent, D , was adjusted to match the isostatic compression (IC) test data. This test was modeled using a solid cube of concrete in LS-DYNA3D. A pressure, in the form of a velocity, was applied to three sides of the cube, while the sides opposite the velocities were restrained in the corresponding directions (Fig. 4.9).

Figure 4.9 – IC Test Diagram

The initial intersection of the cap with the J_1 axis, denoted as X_0 (Fig. 4.1), was changed to correspond to three times the pressure of the IC test. The parameters L_0 , TDP and FCUT were calculated for RC beams using Eqs. 4.6 – 4.8.

The remainder of the properties were obtained from Simo, et al [1988], using their Colorado concrete data. The final concrete properties of the RC model are shown in Table 4.8. The LS-DYNA3D input file for the RC beam can be found in Appendix I.

Table 4.8 –Final RC Concrete Properties

K (psi)	1.714×10^6	X_θ (psi)	16000
G (psi)	1.565×10^6	L_θ (psi)	1526
ρ (lb-sec ² /in ⁴)	1.77×10^{-4}	W (unitless)	0.42
α (psi)	3860	D (psi ⁻¹)	3.2×10^{-6}
θ (unitless)	0.11	T (psi)	-414.2
γ (psi)	1160	TDP (psi)	-103.6
β (psi ⁻¹)	4.4×10^{-4}	$FCUT$ (psi)	-2732
R	4.43		

4.4 The Concrete Wall:

The concrete wall was modeled as a 12 x 8 x 0.5 feet wall (Fig. 4.10). Only one quarter of the wall was modeled for computational speed. The wall was restrained across the entire six inch thickness on the outside edges. All displacements and rotations were restrained.

Figure 4.10 – Concrete Wall Model

The wall was meshed as three inch cubes, resulting in 24 elements in the x-direction, 16 in the y-direction and two in the z-direction. The values of the concrete were the same ones derived for the RC Beams (Table 4.8). The CFRP was modeled as elastic, material type 1 and the properties were those used in the UC model (Table 4.3). The CFRP was assumed to be perfectly bonded to the concrete wall, modeled as a tied interface. This allowed coincident nodes to be merged. The composite covered the entire span of the wall, was 0.072 inches thick and meshed into 3-inch elements in the x and y-directions. This produced 24 elements in the x-direction and 16 in the y-direction. The LS-DYNA3D input files for the plain and reinforced concrete walls are found in Appendices J and K, respectively.

CHAPTER 5

Results

5.1 The Unreinforced Concrete Beam

The LS-DYNA3D models of the UC beams, both plain and CFRP reinforced, showed excellent agreement with Jerome's experimental data (Figs. 5.1 & 5.2). This shows that the properties of the UMAT material type 43 were chosen effectively to simulate the behavior of Jerome's concrete beams.

Figure 5.1 – Comparison of the UC Beam

Figure 5.2 – Comparison of the CFRP Reinforced UC Beam

5.2 The Reinforced Concrete Beam

The data obtained from LS-DYNA3D is shown in Fig. 5.3 as compared to the experimental data obtained from Faza. This beam contained no external reinforcement. As can be seen from the figure, the initial slope of the UMAT43 curve closely matches the slope of Faza's data. At approximately 4000 pounds, cracking begins and the slopes change.

Figure 5.3 – Comparison of the RC Beam Containing No External Reinforcement

5.3 The Concrete Wall

All of the plots for the concrete walls are for the center element of the entire wall. This is the lower left corner on Fig. 5.4 and represented by element 2. To compare the results of the modeling, the residual deflection was chosen. This value is defined as the displacement of the wall after the blast load has subsided. This is a measurable value if future experimental tests are conducted for comparison.

Concrete Only (New Model)

time = 1.34996E-02
displacement vectors

min= 0.000E+00 at node 1275
max= 6.224E-04 at node 1

Figure 5.4 – Displacement Vectors at First Response

The Tensile Damage Parameter (TDP), used with UMAT 43, allows the concrete to be modeled without damage. This is accomplished by setting the value to a very large number, in this case, 10^{12} . When the damage increment, δD (Eq. 4.5), is calculated, the value is zero for all practical purposes. Fig. 5.5 shows a comparison of the plain concrete model with the undamaged concrete model ($TDP = 10^{12}$). It can be seen that the undamaged concrete has a residual deflection less than that of the UMAT 43 concrete model, as is expected.

Figure 5.5 – Comparison of Concrete Wall and Concrete Wall with Undamaged Concrete

The results of the concrete wall, reinforced with externally applied CFRP is shown in Fig. 5.6. This shows a greater residual deflection of the plain wall, but both deflections are relatively small. Increased airblast loads or decreased standoff distances may better show the benefits of external reinforcement.

Figure 5.6 – Comparison of Plain Concrete Wall and Concrete Wall with Composite on the Back

The mean values of residual deflection for all three concrete wall models are shown in Fig. 5.7. This shows that the CFRP reinforced concrete is better than concrete that does not sustain tensile damage.

Figure 5.7 – Mean Residual Deflection Value of All Three Concrete Wall Curves

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The UMAT43 damage model, developed from a two-invariant geologic cap model, was shown to correlate well to the available experimental data. Comparisons were made for three and four point bending tests of statically and dynamically loaded beams.

The concrete wall models show an increase in blast resistance when adding a layer of CFRP to the back of a plain wall. The strengthening effect was small because of a small bomb and large standoff distance. Therefore, it is also apparent from the research that increasing the standoff distance reduces the effects of the blast loads.

Many beams with external reinforcement have been tested experimentally under quasi-static load. All of these beams could be modeled using the proposed damage model. These models will require large amounts of CPU time due to the complexity of the geometry and the number of sliding interfaces. More simplistic representations of the model need to be developed to allow for solving in a realistic amount of time.

6.2 Recommendations:

Time and budget restraints of this study limited the amount of models that could be investigated. Areas that could be explored further.

- Modeling of remaining five beams tested by Faza
 - With a steel plate bonded to the bottom
 - Wrapped in CFRP in four configurations
- Study the effect of placing the composite on the front (outside) of wall
- Effects of different composite layups on walls subject to airblast loads
- Larger amounts of TNT for larger airblast loads
- Change standoff distances to change airblast loads
- Modeling of adhesive layer between concrete and composite

CHAPTER 7

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Appendix A: T&P.BAS Program

```

*****
'* This program calculates the angles and distances to the nodes *
'* on a user defined wall. Inputs include wall width, height, *
'* the number of columns and rows to break the wall into and the *
'* offset distance. This program assumes that the explosion *
'* occurs at the LOWER LEFT hand corner (The center of a four *
'* panel wall where only a quarter of the wall is needed for *
'* modeling). Node numbers are counted from left to right, *
'* bottom to top. *
'* *
'* Programmed by Matt Fox for standoff calculations for use with *
'* CONWEP, the Army's Conventional Weapons program. *
'* *
'* Programmed: July 08, 1997 *
*****

```

```

DIM angl(1 TO 1000) AS SINGLE
DIM side(1 TO 1000) AS SINGLE
DIM dist(1 TO 1000) AS SINGLE
DIM pressure(1 TO 1000) AS SINGLE
DIM arrival(1 TO 1000) AS SINGLE
DIM duration(1 TO 1000) AS SINGLE
DIM decay(1 TO 1000) AS SINGLE

```

```

OPEN "c:\t&p_out.Dat" FOR OUTPUT AS #1
OPEN "c:\pr_out.Dat" FOR OUTPUT AS #2

```

```

***INPUT***

```

```

'Enter the width of the wall (ft):
w = 6
'Enter the height of the wall (ft):
h = 4
'Enter the number of rows to be used:
m = 16
'Enter the number of columns to be used:
n = 24
'Enter the offset distance (ft):
offset = 30

```

```

CONST pi = 3.141592654#

```

```

CLS
PRINT
PRINT
PRINT DATES$
PRINT

```

```
PRINT "node distance(ft) pressure(psi) arrival(msec) duration(msec) decay"
```

```
z = (m + 2) * (n + 2)
```

```
h1 = h / m
```

```
w1 = w / n
```

```
o = 1
```

```
r = n + 2
```

```
t = 0
```

```
WHILE r <= z
```

```
  FOR i = o TO r
```

```
    IF i = o THEN
```

```
      j = o
```

```
    ELSEIF i = r THEN
```

```
      j = r - 1
```

```
    ELSE
```

```
      j = i - .5
```

```
    END IF
```

```
    side(i) = SQR(((j - o) * w1) ^ 2 + (t * h1) ^ 2)
```

```
    angl(i) = ATN(side(i) / offset) * 180 / pi
```

```
    dist(i) = SQR((side(i) ^ 2) + (offset ^ 2))
```

```
    'Only valid for standoff distances of 30-31 feet
```

```
    pressure(i) = -1.48 * dist(i) + 64.95
```

```
    arrival(i) = .75 * dist(i) - 8.85
```

```
    duration(i) = .106 * dist(i) + 4.308
```

```
    decay(i) = .277 * dist(i) - 4.348
```

```
    PRINT i; dist(i); pressure(i); arrival(i); duration(i); decay(i)
```

```
  NEXT i
```

```
  o = o + (n + 2)
```

```
  r = r + (n + 2)
```

```
  IF t = 0 THEN
```

```
    t = .5
```

```
  ELSEIF t = m - .5 THEN
```

```
    t = t + .5
```

```
  ELSE
```

```
    t = t + 1
```

```
  END IF
```

```
WEND
```

```
LOCATE 25, 2
```

```
PRINT "Press any key when you are ready to continue."
```

```
SLEEP
```

```

*****
'* This section of the program calculates the pressures at various times      *
'* to obtain the time/pressure data for LS-DYNA3D.                          *
'*                                     *
'* Programmed by: Matt Fox                                                    *
'* Date:      July 08, 1997                                                  *
*****

```

```

CLS
LOCATE 10, 35
PRINT "PLEASE WAIT"

```

```

l1 = 1
FOR l = 1 TO z
  IF l < 28 OR l > 441 OR l = 52 OR l = 53 OR l = 78 OR l = 79 THEN
    GOTO 10
  ELSEIF l = 104 OR l = 105 OR l = 130 OR l = 131 OR l = 156 OR l = 157 THEN
    GOTO 10
  ELSEIF l = 182 OR l = 183 OR l = 208 OR l = 209 OR l = 234 OR l = 235 THEN
    GOTO 10
  ELSEIF l = 260 OR l = 261 OR l = 286 OR l = 287 OR l = 312 OR l = 313 THEN
    GOTO 10
  ELSEIF l = 338 OR l = 339 OR l = 364 OR l = 365 OR l = 390 OR l = 391 THEN
    GOTO 10
  ELSEIF l = 416 OR l = 417 THEN
    GOTO 10
  END IF

```

```

  dist(l1) = dist(l)
  pressure(l1) = pressure(l)
  arrival(l1) = arrival(l)
  duration(l1) = duration(l)
  decay(l1) = decay(l)
  l1 = l1 + 1
10 NEXT l

```

```

z1 = z - 2 * (n + 2) - 2 * m

```

```

FOR m1 = 1 TO z1
  IF arrival(m1) < 13 THEN
    WRITE #1, "lcd", m1, 12
    WRITE #1, .012, "", 0
    WRITE #1, arrival(m1) * .001, "", pressure(m1)
    FOR n1 = 13 TO 21
      p = pressure(m1) * (1 - (n1 - arrival(m1)) / duration(m1)) * EXP(-(n1 - arrival(m1)) /
      decay(m1))
    
```

```

        WRITE #1, n1 * .001, "", p
    NEXT n1
    WRITE #1, .022, "", 0
ELSEIF arrival(m1) > 13 AND arrival(m1) < 14 THEN
    WRITE #1, "lcd", m1, 11
    WRITE #1, .013, "", 0
    WRITE #1, arrival(m1) * .001, "", pressure(m1)
    FOR n1 = 14 TO 21
        p = pressure(m1) * (1 - (n1 - arrival(m1)) / duration(m1)) * EXP(-(n1 - arrival(m1)) /
decay(m1))
        WRITE #1, n1 * .001, "", p
    NEXT n1
    WRITE #1, .022, "", 0
ELSE
    WRITE #1, "lcd", m1, 10
    WRITE #1, .014, "", 0
    WRITE #1, arrival(m1) * .001, "", pressure(m1)
    FOR n1 = 15 TO 21
        p = pressure(m1) * (1 - (n1 - arrival(m1)) / duration(m1)) * EXP(-(n1 - arrival(m1)) /
decay(m1))
        WRITE #1, n1 * .001, "", p
    NEXT n1
    WRITE #1, .022, "", 0
END IF
    WRITE #1, ""
NEXT m1

CLOSE #1

```

```

*****
'* This program calculates the pressure load commands for the *
'* above data for input into LS-DYNA3D. *
'* *
'* Programmed by: Matt Fox *
'* Date: July 14, 1997 *
*****

```

```

z2 = 1
h = 1

```

```

FOR j = 1 TO m
    FOR i = 1 TO n
        x1 = i
        x2 = i + 1
        y1 = j
    
```

```
y2 = j + 1
WRITE #2, "pr", x1, y1, z2, "", x2, y2, z2, "", h, "1.0 0 0 -1"
h = h + 1
NEXT i
NEXT j

CLOSE #2

CLS
LOCATE 9, 35
PRINT "|-----|"
LOCATE 10, 35
PRINT "| SUCCESS |"
LOCATE 11, 35
PRINT "|-----|"
LOCATE 15, 26
PRINT "The output files were saved as:"
LOCATE 17, 23
PRINT "c:\t&p_out.dat"
LOCATE 18, 40
PRINT "&"
LOCATE 19, 24
PRINT "c:\pr_out.dat"
```

Appendix B:

T&P.BAS Output Files

Input load curves for the blast loading of the concrete wall.

lcd 1 11	.014 18.06375	.017 5.084029	.02 .7868857	lcd 22 10
.013 0	.015 12.08244	.018 3.023638	.021 .1597122	.014 0
1.365039E-02 20.54922	.016 7.869045	.019 1.626567	.022 0	1.400847E-02 19.84261
.014 17.93532	.017 4.932854	.02 .7000523	lcd 17 11	.015 13.52645
.015 11.98265	.018 2.914008	.021 .104181	.013 0	.016 8.976992
.016 7.79319	.019 1.549581	.022 0	1.386189E-02 20.13186	.017 5.764073
.017 4.876517	.02 .648248	lcd 12 11	.014 19.09793	.018 3.522077
.018 2.873268	.021 7.143895E-02	.013 0	.015 12.89013	.019 1.981083
.019 1.521069	.022 0	1.375328E-02 20.34619	.016 8.486432	.02 .9425589
.02 .6291468	lcd 7 11	.014 18.50014	.017 5.394141	.021 .2610986
.021 5.944407E-02	.013 0	.015 12.42234	.018 3.249889	.022 0
.022 0	1.368318E-02 20.48452	.016 8.128133	.019 1.786604	lcd 23 10
lcd 2 11	.014 18.11512	.017 5.125839	.02 .8087563	.014 0
.013 0	.015 12.12238	.018 3.054036	.021 .1738194	1.404228E-02 19.77589
1.365195E-02 20.54614	.016 7.899437	.019 1.647979	.022 0	.015 13.67393
.014 17.94388	.017 4.955446	.02 .7145186	lcd 18 11	.016 9.091207
.015 11.9893	.018 2.930363	.021 .1133773	.013 0	.017 5.850622
.016 7.798241	.019 1.561042	.022 0	1.388819E-02 20.07996	.018 3.586106
.017 4.880266	.02 .6559395	lcd 13 11	.014 19.24285	.019 2.027125
.018 2.875977	.021 7.628096E-02	.013 0	.015 13.00391	.02 .9744919
.019 1.522963	.022 0	1.377194E-02 20.30938	.016 8.57388	.021 .2821607
.02 .6304144	lcd 8 11	.014 18.60272	.017 5.459869	.022 0
.021 6.023879E-02	.013 0	.015 12.50244	.018 3.298071	lcd 24 10
.022 0	.016941 20.46298	.016 8.189341	.019 1.82088	.014 0
lcd 3 11	.014 18.17504	.017 5.171557	.02 .8322067	1.407758E-02 19.70624
.013 0	.015 12.16899	.018 3.087313	.021 .1889971	.015 13.82813
1.365508E-02 20.53998	.016 7.934918	.019 1.671453	.022 0	.016 9.210825
.014 17.96101	.017 4.981837	.02 .7304056	lcd 19 11	.017 5.941433
.015 12.0026	.018 2.949481	.021 .1235027	.013 0	.018 3.653425
.016 7.808347	.019 1.57445	.022 0	.013916 20.02508	.019 2.07565
.017 4.887768	.02 .6649468	lcd 14 11	.014 19.39614	.02 1.008248
.018 2.881399	.021 8.195993E-02	.013 0	.015 13.12442	.021 .3045171
.019 1.526755	.022 0	1.379213E-02 20.26953	.016 8.666631	.022 0
.02 .6329525	lcd 9 11	.014 18.71381	.017 5.529686	lcd 25 11
.021 6.183044E-02	.013 0	.015 12.58927	.018 3.349336	.013 0
.022 0	1.370657E-02 20.43837	.016 8.255757	.019 1.857421	1.365195E-02 20.54614
lcd 4 11	.014 18.24351	.017 5.22122	.02 .8572704	.014 17.94388
.013 0	.015 12.22229	.018 3.123507	.021 .2052766	.015 11.9893
1.365976E-02 20.53073	.016 7.975517	.019 1.697021	.022 0	.016 7.798241
.014 17.9867	.017 5.012055	.02 .7477434	lcd 20 11	.017 4.880266
.015 12.02255	.018 2.971388	.021 .1345831	.013 0	.018 2.875977
.016 7.823513	.019 1.589828	.022 0	1.394533E-02 19.96722	.019 1.522963
.017 4.899029	.02 .6752895	lcd 15 11	.014 19.55782	.02 .6304144
.018 2.88954	.021 8.849228E-02	.013 0	.015 13.25169	.021 6.023879E-02
.019 1.53245	.022 0	1.381386E-02 20.22665	.016 8.764729	.022 0
.02 .636766	lcd 10 11	.014 18.83339	.017 5.603644	lcd 26 11
.021 .0642235	.013 0	.015 12.68281	.018 3.403738	.013 0
.022 0	1.372059E-02 20.41069	.016 8.327393	.019 1.896277	1.365352E-02 20.54306
lcd 5 11	.014 18.32052	.017 5.274849	.02 .8839925	.014 17.95244
.013 0	.015 12.28227	.018 3.162643	.021 .2226968	.015 11.99595
1.366601E-02 20.5184	.016 8.021238	.019 1.724712	.022 0	.016 7.803293
.014 18.02095	.017 5.046111	.02 .7665591	lcd 21 11	.017 4.884017
.015 12.04917	.018 2.996099	.021 .1466432	.013 0	.018 2.878688
.016 7.843744	.019 1.607193	.022 0	1.397615E-02 19.90639	.019 1.524858
.017 4.914054	.02 .6869845	lcd 16 11	.014 19.7278	.02 .631683
.018 2.900406	.021 9.589331E-02	.013 0	.015 13.38571	.021 6.103424E-02
.019 1.540056	.022 0	1.383711E-02 20.18076	.016 8.868177	.022 0
.02 .6418617	lcd 11 11	.014 18.96143	.017 5.681762	lcd 27 11
.021 6.742378E-02	.013 0	.015 12.7831	.018 3.461305	.013 0
.022 0	1.373616E-02 20.37997	.016 8.404279	.019 1.937484	1.365664E-02 20.5369
lcd 6 11	.014 18.40606	.017 5.332479	.02 .9124082	.014 17.96957
.013 0	.015 12.34895	.018 3.204759	.021 .2412915	.015 12.00925
1.367382E-02 20.503	.016 8.072101	.019 1.754561	.022 0	

.016 7.813401	.021 8.277393E-02	1.379368E-02 20.26646	.018 3.352194	1.365508E-02 20.53998
.017 4.891521	.022 0	.014 18.72236	.019 1.859459	.014 17.96101
.018 2.884112		.015 12.59595	.02 .8586707	.015 12.0026
.019 1.528652	lcd 33 11	.016 8.26087	.021 .2061877	.016 7.808347
.02 .6342227	.013 0	.017 5.225045	.022 0	.017 4.887768
.021 6.262738E-02	1.370813E-02 20.43529	.018 3.126297		.018 2.881399
.022 0	.014 18.25206	.019 1.698993	lcd 44 11	.019 1.526755
	.015 12.22895	.02 .7490823	.013 0	.02 .6329525
lcd 28 11	.016 7.98059	.021 .1354401	1.394687E-02 19.96417	.021 6.183044E-02
.013 0	.017 5.015832	.022 0	.014 19.56631	.022 0
1.366133E-02 20.52765	.018 2.974128		.015 13.25839	
.014 17.99526	.019 1.591753	lcd 39 11	.016 8.769894	lcd 50 11
.015 12.02921	.02 .6765849	.013 0	.017 5.607541	.013 0
.016 7.828571	.021 8.931133E-02	1.381541E-02 20.22359	.018 3.406607	1.365664E-02 20.5369
.017 4.902785	.022 0	.014 18.84192	.019 1.898329	.014 17.96957
.018 2.892256		.015 12.6895	.02 .8854055	.015 12.00925
.019 1.534351	lcd 34 11	.016 8.332513	.021 .2236197	.016 7.813401
.02 .638039	.013 0	.017 5.278685	.022 0	.017 4.891521
.021 6.502267E-02	1.372215E-02 20.40762	.018 3.165444		.018 2.884112
.022 0	.014 18.32907	.019 1.726695	lcd 45 11	.019 1.528652
	.015 12.28894	.02 .7679085	.013 0	.02 .6342227
lcd 29 11	.016 8.026319	.021 .1475096	1.397769E-02 19.90335	.021 6.262738E-02
.013 0	.017 5.049897	.022 0	.014 19.73629	.022 0
1.366757E-02 20.51532	.018 2.998847		.015 13.39241	
.014 18.0295	.019 1.609125	lcd 40 11	.016 8.873352	lcd 51 11
.015 12.05581	.02 .6882868	.013 0	.017 5.685673	.013 0
.016 7.8488	.021 9.671837E-02	1.383866E-02 20.1777	.018 3.46419	1.365976E-02 20.53073
.017 4.91781	.022 0	.014 18.96996	.019 1.939551	.014 17.9867
.018 2.903123		.015 12.78979	.02 .9138359	.015 12.02255
.019 1.541958	lcd 35 11	.016 8.409406	.021 .2422276	.016 7.823513
.02 .6431366	.013 0	.017 5.336326	.022 0	.017 4.899029
.021 6.822488E-02	1.373772E-02 20.3769	.018 3.207572		.018 2.88954
.022 0	.014 18.41461	.019 1.756557	lcd 46 10	.019 1.53245
	.015 12.35562	.02 .7882463	.014 0	.02 .636766
lcd 30 11	.016 8.07719	.021 .1605883	1.401001E-02 19.83957	.021 .0642235
.013 0	.017 5.087825	.022 0	.015 13.53316	.022 0
1.367538E-02 20.49992	.018 3.026397		.016 8.982184	
.014 18.07231	.019 1.628509	lcd 41 11	.017 5.768004	lcd 52 11
.015 12.08909	.02 .7013633	.013 0	.018 3.524983	.013 0
.016 7.874107	.021 .1050134	1.386344E-02 20.12881	.019 1.98317	1.366445E-02 20.52148
.017 4.936615	.022 0	.014 19.10645	.02 .9440043	.014 18.01238
.018 2.916731		.015 12.89682	.021 .2620501	.015 12.04251
.019 1.551488	lcd 36 11	.016 8.491571	.022 0	.016 7.838683
.02 .6495275	.013 0	.017 5.398002		.017 4.910295
.021 7.224395E-02	1.375483E-02 20.34312	.018 3.252716	lcd 47 10	.018 2.897687
.022 0	.014 18.50868	.019 1.788614	.014 0	.019 1.538152
	.015 12.42901	.02 .8101297	1.404382E-02 19.77286	.02 .6405861
lcd 31 11	.016 8.133226	.021 .1747068	.015 13.68063	.021 6.662238E-02
.013 0	.017 5.129642	.022 0	.016 9.096398	.022 0
1.368474E-02 20.48145	.018 3.056803		.017 5.85456	
.014 18.12368	.019 1.64993	lcd 42 11	.018 3.589022	lcd 53 11
.015 12.12903	.02 .7158376	.013 0	.019 2.029225	.013 0
.016 7.904501	.021 .114217	1.388974E-02 20.07691	.02 .9759506	1.367069E-02 20.50916
.017 4.959212	.022 0	.014 19.25136	.021 .2831249	.014 18.04663
.018 2.933091		.015 13.0106	.022 0	.015 12.06913
.019 1.562954	lcd 37 11	.016 8.579025		.016 7.858924
.02 .6572233	.013 0	.017 5.463739	lcd 48 10	.017 4.925332
.021 7.708977E-02	1.377349E-02 20.30631	.018 3.30091	.014 0	.018 2.908565
.022 0	.014 18.61127	.019 1.822901	1.407911E-02 19.70322	.019 1.545768
	.015 12.50912	.02 .8335918	.015 13.83483	.02 .6456914
lcd 32 11	.016 8.194447	.021 .1898952	.016 9.216028	.021 6.983096E-02
.013 0	.017 5.175373	.022 0	.017 5.945387	.022 0
1.369566E-02 20.4599	.018 3.090093		.018 3.65636	
.014 18.1836	.019 1.673415	lcd 43 11	.019 2.077769	lcd 54 11
.015 12.17565	.02 .7317348	.013 0	.02 1.009724	.013 0
.016 7.93999	.021 .124351	1.391755E-02 20.02203	.021 .3054966	.0136785 20.49376
.017 4.985611	.022 0	.014 19.40466	.022 0	.014 18.08944
.018 2.952216		.015 13.13112		.015 12.10241
.019 1.576369	lcd 38 11	.016 8.671791	lcd 49 11	.016 7.884238
.02 .6662366	.013 0	.017 5.533574	.013 0	.017 4.944146

.018 2.922182		.015 12.9102	.021 .2639529	.015 12.06247
.019 1.555308	lcd 60 11	.016 8.501853	.022 0	.016 7.853862
.02 .6520901	.013 0	.017 5.405725		.017 4.921572
.021 7.385682E-02	1.375794E-02 20.33699	.018 3.258374	lcd 71 10	.018 2.905844
.022 0	.014 18.52578	.019 1.792636	.014 0	.019 1.543863
	.015 12.44236	.02 .8128787	1.404689E-02 19.7668	.02 .6444139
lcd 55 11	.016 8.143422	.021 .1764837	.015 13.69404	.021 6.902776E-02
.013 0	.017 5.137255	.022 0	.016 9.106795	.022 0
1.368786E-02 20.47529	.018 3.062341		.017 5.862447	
.014 18.1408	.019 1.653835	lcd 66 11	.018 3.594864	lcd 77 11
.015 12.14235	.02 .7184789	.013 0	.019 2.033431	.013 0
.016 7.914639	.021 .1158988	1.389283E-02 20.07081	.02 .9788729	1.367538E-02 20.49992
.017 4.966751	.022 0	.014 19.2684	.021 .2850569	.014 18.07231
.018 2.938551		.015 13.02399	.022 0	.015 12.08909
.019 1.566783	lcd 61 11	.016 8.589324		.016 7.874107
.02 .6597948	.013 0	.017 5.471487	lcd 72 10	.017 4.936615
.021 7.871049E-02	.0137766 20.30018	.018 3.306596	.014 0	.018 2.916731
.022 0	.014 18.62836	.019 1.826951	1.408218E-02 19.69717	.019 1.551488
	.015 12.52247	.02 .8363666	.015 13.84824	.02 .6495275
lcd 56 11	.016 8.204659	.021 .191695	.016 9.226443	.021 7.224395E-02
.013 0	.017 5.183007	.022 0	.017 5.953302	.022 0
1.369878E-02 20.45375	.018 3.095654		.018 3.662235	
.014 18.20071	.019 1.677341	lcd 67 11	.019 2.082009	lcd 78 11
.015 12.18897	.02 .7343953	.013 0	.02 1.012679	.013 0
.016 7.950136	.021 .1260497	1.392064E-02 20.01594	.021 .3074585	1.368318E-02 20.48452
.017 4.993161	.022 0	.014 19.42168	.022 0	.014 18.11512
.018 2.957689		.015 13.14452		.015 12.12238
.019 1.58021	lcd 62 11	.016 8.682112	lcd 73 11	.016 7.899437
.02 .668819	.013 0	.017 5.54135	.013 0	.017 4.955446
.021 8.440416E-02	1.379679E-02 20.26034	.018 3.357909	1.365976E-02 20.53073	.018 2.930363
.022 0	.014 18.73943	.019 1.863538	.014 17.9867	.019 1.561042
	.015 12.6093	.02 .861473	.015 12.02255	.02 .6559395
lcd 57 11	.016 8.271092	.021 .2080119	.016 7.823513	.021 7.628096E-02
.013 0	.017 5.232695	.022 0	.017 4.899029	.022 0
1.371124E-02 20.42914	.018 3.131876		.018 2.88954	
.014 18.26918	.019 1.702939	lcd 68 11	.019 1.53245	lcd 79 11
.015 12.24228	.02 .7517613	.013 0	.02 .636766	.013 0
.016 7.99075	.021 .1371554	1.394995E-02 19.95809	.021 .0642235	1.369254E-02 20.46605
.017 5.023398	.022 0	.014 19.58332	.022 0	.014 18.16648
.018 2.979616		.015 13.27179		.015 12.16233
.019 1.595608	lcd 63 11	.016 8.780231	lcd 74 11	.016 7.929847
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	.015 12.70287	.02 .8882353	.015 12.02921	.02 .6636575
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.018 3.004352		.015 13.40581		.015 12.20896
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.018 3.031917		.016 8.992559		.015 12.26228
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.014 18.654	.019 1.83303	1.408678E-02 19.68809	.019 1.559129	lcd 107 11
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	.018 2.930363		.015 12.56254	.02 .8377544
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.015 13.48623		.015 12.30894	.02 .7584761	.013 0

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.014 19.57482			.015 12.26894	.02 .7370585	.013 0
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.02 .8868206	.016 7.934918		.021 9.424365E-02	1.379679E-02 20.26034	.018 3.32937
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	.017 5.004496	.022 0	.014 19.07234	.019 1.954053	
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	.017 5.034753	.022 0	.014 19.14056	.02 .9353516
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.017 5.961219		.015 12.52247	.02 .8156303	1.403153E-02 19.79711
.018 3.668112	lcd 197 11	.016 8.204659	.021 .1782629	.015 13.62701
.019 2.086252	.013 0	.017 5.183007	.022 0	.016 9.054844
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	.016 8.026319	.021 .1260497	1.389283E-02 20.07081	.02 .9642935
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.017 6.052425	.022 0	.014 18.71381	.019 1.826951	1.406377E-02 19.73348
.018 3.735895		.015 12.58927	.02 .8363666	.015 13.7678
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	.015 12.32227	.02 .7477434	.013 0	.02 .9949952
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.014 18.24351	.019 1.618806	lcd 204 11	.016 8.671791	lcd 215 10
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.018 2.971388		.015 12.66276	.02 .8586707	.016 9.278524
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	.015 12.36229	.02 .7625146	.013 0	.021 .3173045
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.018 2.974128		.015 12.74298	.02 .8825789	.017 6.084225
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lcd 195 11	.016 8.117937	.021 .1544659	1.397153E-02 19.91551	
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.018 2.998847		.015 12.80316	.02 .8953215	.017 6.12004
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.018 3.004352		.015 12.89013	.02 .9209887	.017 5.084029
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	.015 12.58258	.02 .828052	1.404536E-02 19.76983	.022 0
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	.015 12.78979	.02 .8854055	.017 6.068318	
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.017 5.163929	.022 0	.014 19.7108	lcd 264 10	.017 5.163929
.018 3.081759		.015 13.3723	.014 0	.018 3.081759
.019 1.667532	lcd 253 11	.016 8.857819	1.416176E-02 19.54013	.019 1.667532
.02 .72775	.013 0	.017 5.673934	.015 14.19681	.02 .72775
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	.015 12.87006	.02 .9095521	.018 3.815942	
lcd 248 11	.016 8.471017	.021 .2394193	.019 2.193276	lcd 270 11
.013 0	.017 5.382565	.022 0	.02 1.090492	.013 0
.0137797 20.29405	.018 3.24141	lcd 259 10	.021 .3593629	.0137766 20.30018
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.015 12.53583	.02 .8046405	.015 13.49294		.015 12.52247
.016 8.214873	.021 .171161	.016 8.951068	lcd 265 11	.016 8.204659
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.018 3.101217		.018 3.507579	1.375328E-02 20.34619	.018 3.095654
.019 1.68127	lcd 254 11	.019 1.970672	.014 18.50014	.019 1.677341
.02 .7370585	.013 0	.02 .9353516	.015 12.42234	.02 .7343953
.021 .1277508	1.387737E-02 20.10133	.021 .2563567	.016 8.128133	.021 .1260497
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	.015 12.95705		.018 3.054036	
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.016 8.255757	.021 .1827238	.016 9.049648	lcd 266 11	.016 8.235309
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.018 3.123507		.018 3.56278	1.375483E-02 20.34312	.018 3.112354
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	.015 13.05076		.018 3.056803	
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.0138061 20.24196	.018 3.317975	.014 0	.021 .114217	1.379679E-02 20.26034
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.018 3.148647		.018 3.621179	1.375794E-02 20.33699	.018 3.131876
.019 1.714803	lcd 256 11	.019 2.052392	.014 18.52578	.019 1.702939

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.018 3.154243		.017 5.862447	1.377349E-02 20.30631	.018 3.145849
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.018 3.207572		.019 2.120302	1.378126E-02 20.29098	.018 3.187889
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	.017 5.834861	.014 18.71381	.019 1.726695	lcd 324 11
lcd 302 11	.018 3.574436	.015 12.58927	.02 .7679085	.013 0
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	.018 3.629966	.014 18.72236	.019 1.738619	lcd 325 11
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.019 1.881928	.015 13.90858		.015 12.77641	.02 .8544738
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	.019 2.101124	.014 18.73943	.019 1.752566	lcd 326 11
lcd 304 11	.02 1.02601	.015 12.6093	.02 .7855253	.013 0
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.014 19.62582		.018 3.131876		.015 13.1981
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.019 1.912719	.016 9.382804		.015 12.82992	.02 .8727091
.02 .8953215	.017 6.072292	lcd 316 11	.016 8.440201	.021 .2153331
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	.02 1.057339	.014 18.76506	.019 1.768554	lcd 327 11
lcd 305 11	.021 .3371912	.015 12.62935	.02 .7964298	.013 0
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.022 0	.019 2.128843	.014 18.85901	.019 1.78058	lcd 350 11
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.017 5.685673	.015 14.13649	.021 .1492452	1.386963E-02 20.11659	.018 3.420974
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.022 0	.02 1.076888	.014 18.88462	.018 3.264035	lcd 351 11
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.018 3.510477	.016 9.565622	.021 .1518528	1.388355E-02 20.08912	.018 3.461305
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.016 9.044459	1.421669E-02 19.43172	.017 5.31325	lcd 347 11	.015 13.48623
.017 5.815179	.015 14.43799	.018 3.190699	.013 0	.016 8.945881
.018 3.55987	.016 9.685966	.019 1.74459	1.389901E-02 20.05861	.017 5.740525
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.022 0	.02 1.145464	lcd 342 11	.017 5.48699	.021 .2554098
lcd 331 10	.021 .3963062	.013 0	.018 3.317975	.022 0
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.017 5.961219	1.381541E-02 20.22359	.016 8.435064	.022 0	.016 9.117195
.018 3.668112	.014 18.84192	.017 5.355577	lcd 349 11	.017 5.870337
.019 2.086252	.015 12.6895	.018 3.221655	.013 0	.018 3.600709
.02 1.015637	.016 8.332513	.019 1.766551	1.393453E-02 19.98853	.019 2.037641
.021 .3094226	.017 5.278685	.02 .7950634	.014 19.49827	.02 .9817988
.022 0	.018 3.165444	.021 .1649815	.015 13.2048	.021 .286992
lcd 333 10	.019 1.726695	.022 0	.016 8.728565	.022 0
.014 0	.02 .7679085	lcd 344 11	.017 5.576365	lcd 355 10
1.411588E-02 19.63066	.021 .1475096	.013 0	.018 3.383661	.014 0
	.022 0	1.385725E-02 20.14103	.019 1.881928	1.407758E-02 19.70624
		.014 19.07234		

.015 13.82813	.013 0	.017 5.390282	.022 0	.016 9.106795
.016 9.210825	1.383711E-02 20.18076	.018 3.247062		.017 5.862447
.017 5.941433	.014 18.96143	.019 1.784596	lcd 372 11	.018 3.594864
.018 3.653425	.015 12.7831	.02 .8073837	.013 0	.019 2.033431
.019 2.07565	.016 8.404279	.021 .1729327	1.393916E-02 19.97939	.02 .9788729
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.021 .3045171	.018 3.204759		.015 13.2249	.022 0
.022 0	.019 1.754561	lcd 367 11	.016 8.744061	
	.02 .7868857	.013 0	.017 5.588052	lcd 378 10
lcd 356 10	.021 .1597122	1.386963E-02 20.11659	.018 3.392261	.014 0
.014 0	.022 0	.014 19.14056	.019 1.888073	1.407298E-02 19.71532
1.410669E-02 19.64879	lcd 362 11	.015 12.92359	.02 .8783444	.015 13.80802
.015 13.95551	.013 0	.016 8.512135	.021 .2190094	.016 9.195211
.016 9.309797	1.383866E-02 20.1777	.017 5.41345	.022 0	.017 5.92957
.017 6.016698	.014 18.96996	.018 3.264035		.018 3.644623
.018 3.709327	.015 12.78979	.019 1.79666	lcd 373 11	.019 2.069299
.019 2.116035	.016 8.409406	.02 .8156303	.013 0	.02 1.003824
.02 1.036419	.017 5.336326	.021 .1782629	1.395766E-02 19.94288	.021 .3015817
.021 .3232441	.018 3.207572	.022 0	.014 19.62582	.022 0
.022 0	.019 1.756557	lcd 368 11	.015 13.30529	
	.02 .7882463	.013 0	.016 8.806078	lcd 379 10
lcd 357 10	.021 .1605883	1.388046E-02 20.09522	.017 5.634853	.014 0
.014 0	.022 0	.014 19.20022	.018 3.426723	1.410057E-02 19.66088
.0141373 19.58839		.015 12.97043	.019 1.912719	.015 13.92869
.015 14.08957	lcd 363 11	.016 8.548137	.02 .8953215	.016 9.288949
.016 9.414116	.013 0	.017 5.44051	.021 .2301017	.017 6.000835
.017 6.096155	1.384176E-02 20.17159	.018 3.283872	.022 0	.018 3.697536
.018 3.768444	.014 18.98703	.019 1.810772		.019 2.10751
.019 2.158829	.015 12.80316	.02 .8252852	lcd 374 11	.02 1.030467
.02 1.066347	.016 8.41967	.021 .1845119	.013 0	.021 .3192822
.021 .3432072	.017 5.344026	.022 0	1.397769E-02 19.90335	.022 0
.022 0	.018 3.213204		.014 19.73629	
	.019 1.760553	lcd 369 11	.015 13.39241	lcd 380 10
lcd 358 10	.02 .7909716	.013 0	.016 8.873352	.014 0
.014 0	.021 .1623441	1.389283E-02 20.07081	.017 5.685673	1.412965E-02 19.60348
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.015 14.23031		.015 13.02399	.019 1.939551	.016 9.388024
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lcd 359 10	.019 1.766551	lcd 370 11	.015 13.48623	.014 0
.014 0	.02 .7950634	.013 0	.016 8.945881	1.416023E-02 19.54314
1.420297E-02 19.4588	.021 .1649815	1.390674E-02 20.04337	.017 5.740525	.015 14.19011
.015 14.37771	.022 0	.014 19.34506	.018 3.504679	.016 9.492451
.016 9.638856		.015 13.08425	.019 1.968591	.017 6.155903
.017 6.267764	lcd 365 11	.016 8.635697	.02 .9339115	.018 3.812968
.018 3.896483	.013 0	.017 5.506389	.021 .2554098	.019 2.191118
.019 2.251817	.0138526 20.15019	.018 3.33222	.022 0	.02 1.088978
.02 1.131637	.014 19.04675	.019 1.845212		.021 .3583484
.021 .3869932	.015 12.84999	.02 .8488894	lcd 376 10	.022 0
.022 0	.016 8.455606	.021 .1998264	.014 0	
	.017 5.370995	.022 0	1.402231E-02 19.8153	lcd 382 10
lcd 360 10	.018 3.23294		.015 13.58679	.014 0
.014 0	.019 1.774563	lcd 371 11	.016 9.023694	1.419229E-02 19.47987
1.423802E-02 19.38964	.02 .8005317	.013 0	.017 5.799444	.015 14.33082
.015 14.53174	.021 .1685087	1.392218E-02 20.01289	.018 3.548229	.016 9.602231
.016 9.759289	.022 0	.014 19.4302	.019 1.999875	.017 6.239757
.017 6.359966		.015 13.15122	.02 .9555808	.018 3.875554
.018 3.965476	lcd 366 11	.016 8.687272	.021 .2696771	.019 2.23659
.019 2.302091	.013 0	.017 5.545238	.022 0	.02 1.120922
.02 1.167082	1.386035E-02 20.13491	.018 3.360768		.021 .3797853
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.022 0	.015 12.88344	.02 .8628749	.014 0	
	.016 8.481294	.021 .2089247	1.404689E-02 19.7668	lcd 383 10
lcd 361 11			.015 13.69404	.014 0

1.422584E-02 19.41368
.015 14.47818
.016 9.717388
.017 6.327868
.018 3.941442
.019 2.284564
.02 1.154714
.021 .4025437
.022 0

lcd 384 10
.014 0
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.015 14.63215
.016 9.837912
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.02 1.190391
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.022 0

Input pressure loads for surfaces for the blast loading of the concrete wall.

pr 1 1 1 2 2 1 1 1.000 -1	pr 6 3 1 7 4 1 54 1.000 -1	pr 11 5 1 12 6 1 107 1.000 -1
pr 2 1 1 3 2 1 2 1.000 -1	pr 7 3 1 8 4 1 55 1.000 -1	pr 12 5 1 13 6 1 108 1.000 -1
pr 3 1 1 4 2 1 3 1.000 -1	pr 8 3 1 9 4 1 56 1.000 -1	pr 13 5 1 14 6 1 109 1.000 -1
pr 4 1 1 5 2 1 4 1.000 -1	pr 9 3 1 10 4 1 57 1.000 -1	pr 14 5 1 15 6 1 110 1.000 -1
pr 5 1 1 6 2 1 5 1.000 -1	pr 10 3 1 11 4 1 58 1.000 -1	pr 15 5 1 16 6 1 111 1.000 -1
pr 6 1 1 7 2 1 6 1.000 -1	pr 11 3 1 12 4 1 59 1.000 -1	pr 16 5 1 17 6 1 112 1.000 -1
pr 7 1 1 8 2 1 7 1.000 -1	pr 12 3 1 13 4 1 60 1.000 -1	pr 17 5 1 18 6 1 113 1.000 -1
pr 8 1 1 9 2 1 8 1.000 -1	pr 13 3 1 14 4 1 61 1.000 -1	pr 18 5 1 19 6 1 114 1.000 -1
pr 9 1 1 10 2 1 9 1.000 -1	pr 14 3 1 15 4 1 62 1.000 -1	pr 19 5 1 20 6 1 115 1.000 -1
pr 10 1 1 11 2 1 10 1.000 -1	pr 15 3 1 16 4 1 63 1.000 -1	pr 20 5 1 21 6 1 116 1.000 -1
pr 11 1 1 12 2 1 11 1.000 -1	pr 16 3 1 17 4 1 64 1.000 -1	pr 21 5 1 22 6 1 117 1.000 -1
pr 12 1 1 13 2 1 12 1.000 -1	pr 17 3 1 18 4 1 65 1.000 -1	pr 22 5 1 23 6 1 118 1.000 -1
pr 13 1 1 14 2 1 13 1.000 -1	pr 18 3 1 19 4 1 66 1.000 -1	pr 23 5 1 24 6 1 119 1.000 -1
pr 14 1 1 15 2 1 14 1.000 -1	pr 19 3 1 20 4 1 67 1.000 -1	pr 24 5 1 25 6 1 120 1.000 -1
pr 15 1 1 16 2 1 15 1.000 -1	pr 20 3 1 21 4 1 68 1.000 -1	pr 1 6 1 2 7 1 121 1.000 -1
pr 16 1 1 17 2 1 16 1.000 -1	pr 21 3 1 22 4 1 69 1.000 -1	pr 2 6 1 3 7 1 122 1.000 -1
pr 17 1 1 18 2 1 17 1.000 -1	pr 22 3 1 23 4 1 70 1.000 -1	pr 3 6 1 4 7 1 123 1.000 -1
pr 18 1 1 19 2 1 18 1.000 -1	pr 23 3 1 24 4 1 71 1.000 -1	pr 4 6 1 5 7 1 124 1.000 -1
pr 19 1 1 20 2 1 19 1.000 -1	pr 24 3 1 25 4 1 72 1.000 -1	pr 5 6 1 6 7 1 125 1.000 -1
pr 20 1 1 21 2 1 20 1.000 -1	pr 1 4 1 2 5 1 73 1.000 -1	pr 6 6 1 7 7 1 126 1.000 -1
pr 21 1 1 22 2 1 21 1.000 -1	pr 2 4 1 3 5 1 74 1.000 -1	pr 7 6 1 8 7 1 127 1.000 -1
pr 22 1 1 23 2 1 22 1.000 -1	pr 3 4 1 4 5 1 75 1.000 -1	pr 8 6 1 9 7 1 128 1.000 -1
pr 23 1 1 24 2 1 23 1.000 -1	pr 4 4 1 5 5 1 76 1.000 -1	pr 9 6 1 10 7 1 129 1.000 -1
pr 24 1 1 25 2 1 24 1.000 -1	pr 5 4 1 6 5 1 77 1.000 -1	pr 10 6 1 11 7 1 130 1.000 -1
pr 1 2 1 2 3 1 25 1.000 -1	pr 6 4 1 7 5 1 78 1.000 -1	pr 11 6 1 12 7 1 131 1.000 -1
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pr 3 2 1 4 3 1 27 1.000 -1	pr 8 4 1 9 5 1 80 1.000 -1	pr 13 6 1 14 7 1 133 1.000 -1
pr 4 2 1 5 3 1 28 1.000 -1	pr 9 4 1 10 5 1 81 1.000 -1	pr 14 6 1 15 7 1 134 1.000 -1
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pr 9 2 1 10 3 1 33 1.000 -1	pr 14 4 1 15 5 1 86 1.000 -1	pr 19 6 1 20 7 1 139 1.000 -1
pr 10 2 1 11 3 1 34 1.000 -1	pr 15 4 1 16 5 1 87 1.000 -1	pr 20 6 1 21 7 1 140 1.000 -1
pr 11 2 1 12 3 1 35 1.000 -1	pr 16 4 1 17 5 1 88 1.000 -1	pr 21 6 1 22 7 1 141 1.000 -1
pr 12 2 1 13 3 1 36 1.000 -1	pr 17 4 1 18 5 1 89 1.000 -1	pr 22 6 1 23 7 1 142 1.000 -1
pr 13 2 1 14 3 1 37 1.000 -1	pr 18 4 1 19 5 1 90 1.000 -1	pr 23 6 1 24 7 1 143 1.000 -1
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pr 17 2 1 18 3 1 41 1.000 -1	pr 22 4 1 23 5 1 94 1.000 -1	pr 3 7 1 4 8 1 147 1.000 -1
pr 18 2 1 19 3 1 42 1.000 -1	pr 23 4 1 24 5 1 95 1.000 -1	pr 4 7 1 5 8 1 148 1.000 -1
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pr 22 2 1 23 3 1 46 1.000 -1	pr 3 5 1 4 6 1 99 1.000 -1	pr 8 7 1 9 8 1 152 1.000 -1
pr 23 2 1 24 3 1 47 1.000 -1	pr 4 5 1 5 6 1 100 1.000 -1	pr 9 7 1 10 8 1 153 1.000 -1
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pr 1 3 1 2 4 1 49 1.000 -1	pr 6 5 1 7 6 1 102 1.000 -1	pr 11 7 1 12 8 1 155 1.000 -1
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pr 16 7 1 17 8 1 160 1.0 0 0 -1	pr 24 9 1 25 10 1 216 1.0 0 0 -1	pr 8 12 1 9 13 1 272 1.0 0 0 -1
pr 17 7 1 18 8 1 161 1.0 0 0 -1	pr 1 10 1 2 11 1 217 1.0 0 0 -1	pr 9 12 1 10 13 1 273 1.0 0 0 -1
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pr 20 7 1 21 8 1 164 1.0 0 0 -1	pr 4 10 1 5 11 1 220 1.0 0 0 -1	pr 12 12 1 13 13 1 276 1.0 0 0 -1
pr 21 7 1 22 8 1 165 1.0 0 0 -1	pr 5 10 1 6 11 1 221 1.0 0 0 -1	pr 13 12 1 14 13 1 277 1.0 0 0 -1
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pr 11 9 1 12 10 1 203 1.0 0 0 -1	pr 19 11 1 20 12 1 259 1.0 0 0 -1	pr 3 14 1 4 15 1 315 1.0 0 0 -1
pr 12 9 1 13 10 1 204 1.0 0 0 -1	pr 20 11 1 21 12 1 260 1.0 0 0 -1	pr 4 14 1 5 15 1 316 1.0 0 0 -1
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pr 17 9 1 18 10 1 209 1.0 0 0 -1	pr 1 12 1 2 13 1 265 1.0 0 0 -1	pr 9 14 1 10 15 1 321 1.0 0 0 -1
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pr 20 14 1 21 15 1 332 1.000 -1	pr 15 15 1 16 16 1 351 1.000 -1	pr 10 16 1 11 17 1 370 1.000 -1
pr 21 14 1 22 15 1 333 1.000 -1	pr 16 15 1 17 16 1 352 1.000 -1	pr 11 16 1 12 17 1 371 1.000 -1
pr 22 14 1 23 15 1 334 1.000 -1	pr 17 15 1 18 16 1 353 1.000 -1	pr 12 16 1 13 17 1 372 1.000 -1
pr 23 14 1 24 15 1 335 1.000 -1	pr 18 15 1 19 16 1 354 1.000 -1	pr 13 16 1 14 17 1 373 1.000 -1
pr 24 14 1 25 15 1 336 1.000 -1	pr 19 15 1 20 16 1 355 1.000 -1	pr 14 16 1 15 17 1 374 1.000 -1
pr 1 15 1 2 16 1 337 1.000 -1	pr 20 15 1 21 16 1 356 1.000 -1	pr 15 16 1 16 17 1 375 1.000 -1
pr 2 15 1 3 16 1 338 1.000 -1	pr 21 15 1 22 16 1 357 1.000 -1	pr 16 16 1 17 17 1 376 1.000 -1
pr 3 15 1 4 16 1 339 1.000 -1	pr 22 15 1 23 16 1 358 1.000 -1	pr 17 16 1 18 17 1 377 1.000 -1
pr 4 15 1 5 16 1 340 1.000 -1	pr 23 15 1 24 16 1 359 1.000 -1	pr 18 16 1 19 17 1 378 1.000 -1
pr 5 15 1 6 16 1 341 1.000 -1	pr 24 15 1 25 16 1 360 1.000 -1	pr 19 16 1 20 17 1 379 1.000 -1
pr 6 15 1 7 16 1 342 1.000 -1	pr 1 16 1 2 17 1 361 1.000 -1	pr 20 16 1 21 17 1 380 1.000 -1
pr 7 15 1 8 16 1 343 1.000 -1	pr 2 16 1 3 17 1 362 1.000 -1	pr 21 16 1 22 17 1 381 1.000 -1
pr 8 15 1 9 16 1 344 1.000 -1	pr 3 16 1 4 17 1 363 1.000 -1	pr 22 16 1 23 17 1 382 1.000 -1
pr 9 15 1 10 16 1 345 1.000 -1	pr 4 16 1 5 17 1 364 1.000 -1	pr 23 16 1 24 17 1 383 1.000 -1
pr 10 15 1 11 16 1 346 1.000 -1	pr 5 16 1 6 17 1 365 1.000 -1	pr 24 16 1 25 17 1 384 1.000 -1

Appendix C:

RC Damping Example

The following is a step-by-step example of how to use the Transformed Section Method. The beam is Faza's Case #2, which is steel reinforced concrete, with a steel plate bonded to the bottom of the beam (Fig. C.1).

Figure C.1 – The Original Concrete Beam With a Steel Plate on the Bottom

Find the area of the two small reinforcing bars, diameter of 3/8 in, shown in Fig. C.1.

$$A_{SR} = 2 \left[\pi \frac{d^2}{4} \right] = \frac{\pi}{2} (0.375 \text{ in})^2 = 0.221 \text{ in}^2$$

Find the new thickness of the small reinforcing bars combined. This uses a width of 6 in, the original width of the beam to make a new rectangular shape.

$$t_{SR} = \frac{A}{w} = \frac{0.221 \text{ in}^2}{6 \text{ in}} = 0.037 \text{ in}$$

Find the area of the two large reinforcing bars, diameter of 3/4 in, shown in Fig. C.1.

$$A_{LR} = 2 \left[\pi \frac{d^2}{4} \right] = \frac{\pi}{2} (0.75 \text{ in})^2 = 0.884 \text{ in}^2$$

Find the new thickness of the large reinforcing bars combined. This uses a width of 6 in., the original width of the beam to make a new rectangular shape.

$$t_{LR} = \frac{A}{w} = \frac{0.884 \text{ in}^2}{6 \text{ in}} = 0.147 \text{ in}$$

Fig. C.2 shows the first transformation of the beam.

Figure C.2 – Beam after Transforming the Steel

Table C.1 shows the values of modulus of elasticity and density for the materials used.

Table C.1 – Modulus of Elasticity and Density		
	E (psi)	ρ (lb*sec²/in⁴)
Steel	29.0×10^6	7.34×10^{-4}
Concrete	3.47×10^6	1.77×10^{-4}

By finding the relation between the modulus of steel and the modulus of concrete, a new width for the concrete can be calculated.

$$\eta = \frac{E_{concrete}}{E_{steel}} = \frac{3.47 \text{ psi}}{29.0 \text{ psi}} = 0.120$$

The transformed width of the concrete can now be calculated.

$$w'_{concrete} = \eta w_{concrete} = (0.120)(6 \text{ in}) = 0.718 \text{ in}$$

The final transformed beam is shown in Fig. C.3.

Figure C.3 – Completely Transformed Beam

The next step is to find the neutral surface of the beam, denoted NS in Fig. C.3. Calculation values are found in Table C.2. The area is denoted by A and the distance from the very bottom of the beam (the steel plate) to the center of each segment by $\tilde{y}$.

Table C.2 – Neutral Surface Calculations

Segment	A (in ²)	$\tilde{y}$ (in)	$\tilde{y}A$ (in ³)
1	1.046	0.089	0.093
2	0.934	0.828	0.773
3	0.884	1.552	1.371
4	6.575	6.205	40.795
5	0.221	10.990	2.428
6	0.839	11.593	9.730
	$\sum A=10.499$		$\sum \tilde{y}A=55.190$

The zero y-axis is chosen through the center of the beam, so the distance to the x neutral surface, $\bar{x}$, is zero. The distance to the neutral surface in the y direction is calculated.

$$\bar{y} = \frac{\sum \tilde{y}A}{\sum A} = \frac{55.190 \text{ in}^3}{10.499 \text{ in}^2} = 5.257 \text{ in}$$

The area moment of inertia, I_x , must be found for the transformed section. This is accomplished by finding I_x for each segment first. Needed are d_y , the distance from NS to the center of each segment, and the area moment of inertia for each rectangle as if it were by itself, I'_x . Because all of the segments are rectangles, I'_x can be found by

$$I'_x = \frac{1}{12}bh^3$$

Table C.3 contains the calculated values.

Table C.3 – Area Moments of Inertia

Segment	A (in ²)	d_y (in)	$A*d_y$ (in ³)	I'_x (in ⁴)	I_x (in ⁴)
1	1.046	-5.168	27.944	0.003	27.947
2	0.934	-4.429	18.325	0.132	18.457
3	0.884	-3.704	12.125	0.002	12.127
4	6.575	0.948	5.910	45.951	51.862
5	0.221	5.733	7.260	0.000	7.260
6	0.839	6.336	33.694	0.096	33.790
					$\sum I_x=151.443$

The natural frequency can now be calculated using Eq. 3.5.

$$\omega_n = \frac{\xi_n^2}{L^2} \sqrt{\frac{EI}{\rho H b}}$$

where,

$$\xi_n = n\pi$$

$$L = 120 \text{ in}$$

$$EI = E_{steel} * \sum I_x$$

$$\rho H b = \rho_1 A_1 + \rho_2 A_2 + \rho_3 A_3 + \rho_4 A_4 + \rho_5 A_5 + \rho_6 A_6 = \rho_s (A_1 + A_3 + A_5) + \rho_c (A_2 + A_4 + A_6)$$

Substituting these values yields

$$\omega_n = n^2 (821.6)$$

With $n = 1$, $\omega_1 = 821.6$

The system damping is finally calculated, assuming the system is critically damped ($\zeta = 1$).

$$D_s = 2\zeta\omega_1 = 1643$$

The values for system damping for all of Faza's beams can be found in Table C.4.

Table C.4 – System Damping for Faza's Beams

Case #	ybar (in)	ω_1	D_s
1	5.651	846.7	1693.3
2	5.257	821.6	1643.3
3	5.507	835.4	1670.7
4	5.658	848.0	1695.9
5	5.661	848.3	1696.6
6	5.665	848.4	1696.8

Appendix D:

Input Format for LS-DYNA3D

Material Type 43 (Kinematic Hardening Cap Model with Tensile Damage)

Columns		Quantity	Format
1-10	Card 3	Initial bulk modulus, K	E10.0
11-20		Non-linear bulk modulus, K1	E10.0
21-30		Non-linear bulk modulus, K2	E10.0
31-40		Initial shear modulus, G	E10.0
41-50		Non-linear shear modulus, G1	E10.0
51-60		Non-linear shear modulus, G2	E10.0
61-70		Failure envelope parameter, α	E10.0
71-80		Failure envelope exponential coefficient, γ	E10.0
1-10	Card 4	Failure envelope exponent, β	E10.0
11-20		Failure envelope linear coefficient, θ	E10.0
21-30		Hardening law coefficient (porosity), W	E10.0
31-40		Hardening law exponent, D	E10.0
41-50		Hardening law parameter, X_0	E10.0
51-60		Cap, surface axis ratio, R	E10.0
61-70		Tension cutoff, T<0 (positive in compression)	E10.0
71-80		Tensile damage parameter, TDP (=T/4)	E10.0
1-10	Card 5	Formulation flag, LTYPE (ITYPE) EQ.1.0 compacting (soil or concrete, cap my contract) EQ.2.0 dilative material (rock, cap doesn't contract) EQ.3.0 damage (must be used for this model)	E10.0
1-10	Card 6	Plot database flag, IPLOT EQ.1.0 hardening variable κ , in units of J1 EQ.2.0 cap – J1 intercept, X(κ) EQ.3.0 volumetric plastic strain, ϵ^p_v EQ.4.0 first stress invariant, J1 EQ.5.0 second stress invariant, sqrt(J2D) EQ.6.0 not used EQ.7.0 not used EQ.8.0 response mode number EQ.9.0 number of iterations	E10.0
61-70	Card 8	Intersection of yield and J1, FCUT	E10.0
71-80		Initial J1 of intersection of F_e and F_c , L_0	E10.0

Figure D.1 – The Yield surface of the Two-Invariant Cap Model in Pressure $\sqrt{J_{2D}} - J_1$ Space

Surface F_e is the failure envelope (yield surface), F_c is the cap surface and the tension cutoff is the vertical line above T.

Figure D.2 – Representation of the Parameter FCUT

Solve the Tensile Damage Parameter using

$$TDP = \frac{TCUT}{4} \quad (D.1)$$

Solve the variable FCUT using

$$FCUT = \frac{-1}{\beta} \ln\left(\frac{\alpha}{\gamma}\right) \quad (D.2)$$

Solve the value L_0 using MAPLE V and

$$\alpha - \gamma e^{-\beta L_0} - \frac{X_0 - L_0}{R} = 0 \quad (D.3)$$

Appendix E:

UMAT43 Damage Model Fortran Program

```

subroutine umat43 (cm,eps,sig,hisv,dt1,AKAPP,etype,time)
c*****
c| Matthew J. Fox, Dr. Ever J. Barbero, West Virginia University      |
c| -----|
c| copyright 1998 Dr. Ever J. Barbero, WVU|
c| all rights reserved|
c*****
c
c  concrete model
c  yield surface SJ2Y
c  cap SJ2C
c  tension cutoff with damage
c
c  eps(1)=local x  strain increment
c  eps(2)=local y  strain
c  eps(3)=local z  strain
c  eps(4)=local xy strain
c  eps(5)=local yz strain
c  eps(6)=local zx strain
c
c  sig(1)=local x  stress accumulated
c  sig(2)=local y  stress
c  sig(3)=local z  stress
c  sig(4)=local xy stress
c  sig(5)=local yz stress
c  sig(6)=local zx stress
c
c  dt1=current time step size
c  capa=reduction factor for transverse shear
c  etype:
c    eq."brick" for solid elements
c    eq."shell" for all shell elements
c    eq."beam"  for all beam elements
c
c  time=current problem time.
c
c  All transformations into the element local system are
c  performed prior to entering this subroutine. Transformations
c  back to the global system are performed after exiting this
c  routine.
c
c  All history variables are initialized to zero in the input
c  phase. Initialization of history variables to nonzero values
c  may be done during the first call to this subroutine for each
c  element.
c

```

```

c      Energy calculations for the dyna3d energy balance are done
c      outside this subroutine.
c
C
C      MATERIAL MODEL
C
C      COMMON/STRESS/ SIGX,SIGY,SIGZ,SIGXZ,SIGYZ,SIGXY
C      COMMON/STRAIN/ EPSX,EPSY,EPSZ,EPSXZ,EPSYZ,EPSXY
C      COMMON/STRINC/ DEPSX,DEPSY,DEPSZ,DEPSXZ,DEPSYZ,DEPSXY
C      COMMON/DUMMY / MTYPE,LTYPE,TCUT,FCUT,GEOP,NOCON,ISTAT
C      COMMON/PROPER/ AKI,AK1,AK2,AGI,AG1,AG2,AA,AB,AC
C      COMMON/PREPRO/ CR0,CR1,CR2,AW,AD,AKAPP,AL0,LAYER
c
c      implicit real*8 (a-h,o-z)
c      character*(*) etype
c      dimension cm(*),eps(*),sig(*),hisv(*)
c
C      External definitions
C
c      external dmin1(x,y)=amin1(x,y)
c      external dmax1(x,y)=amax1(x,y)
C
C      THE POTENTIAL FUNCTIONS OF THE MODEL
C
C      FAILURE ENVELOPE FUNCTION FOR SJ2
C
C      F(SJ1) = AA-AC*EXP(-AB*SJ1)
c*ejb F(SJ1) = AA-AC*EXP(-AB*SJ1)+AT*SJ1
C
C      HARDENING STATEMENT FUNCTIONS
C
C      BIGL(AKAPP) = AMAX1(AL0,AKAPP)
C      R(CAPL) = CR0*(1.-CR1*EXP(-CR2*BIGL(AKAPP)))/(1.-CR1)
c      X(AKAPP) = AMAX1(zero,EP+R(BIGL(EP))*F(EP))
C      EVP(XL) = AW*(1.0-EXP(-AD*XL))
C EJB
C      BIGL(AKAPP) = AMAX1(AL0,AKAPP)
c*ejb R(CAPL) = CR0*(1.-CR1*EXP(-CR2*CAPL))/(1.-CR1)
c*ejb R(CAPL) = CR0*(1.-CR1*EXP(-CR2*BIGL(AKAPP)))/(1.-CR1)
c*ejb X(CAPL) = AMAX1(zero,CAPL+R(CAPL)*F(CAPL))
c*ejb X(AKAPP) = AMAX1(zero,AKAPP+R(BIGL(AKAPP))*F(AKAPP))
c*ejb EVP(XL) = AW*(1.0-EXP(-AD*(XL-X0)))
c*ejb EVP(XL) = AW*(1.0-EXP(-AD*XL))
c*ejb SJ2C(SJ1,XL,CAPL) = SQRT(ABS((XL-CAPL)**2-
*      (SJ1-CAPL)**2))/R(CAPL)
C

```

```

C      ELASTIC BULK MODULUS
C
      BMOD(SJ1) = AKI*(1.0-AK1*EXP(-AK2*SJ1))/(1.-AK1)
C
C      ELASTIC SHEAR MODULUS
C
      SMOD(SJ2) = AGI*(1.0-AG1*EXP(-AG2*SJ2))/(1.0-AG1)
C
c      initialize
      data cr1,cr2/0.0,0.0/
      DATA CONV,NIT/0.001,60/
      parameter zero=0.0
c
c HISTORY VARIABLES
c
c      cm(1)=bulk modulus
c      cm(4)=shear modulus
c      cm(2-3)= AK1,AK2 : nonlinear bulk modulus
c      cm(5-6)= AG1,AG2 : nonlinear shear modulus
c
c      yield surface
c
c      cm(7)= AA (alpha)
c      cm(8)= AC (gamma)
c      cm(9)= AB (beta)
c      cm(10)= AT (theta)
c
c      hardening rule
c
c      cm(11)= AW (porosity)
c      cm(12)= AD (exponent)
c      cm(13)= X0 (elastic range of I1 during IC test)
c
c cap
c      cm(14)= CR0 (elipticity ratio)
c
c      cm(48)= AL0 (initial I1 of intersection of Fe and Fc)
c
c cutoff
c
c      cm(15)= TCUT: tension cutoff value for I1
c      cm(16)= TDP : tensile damage parameter
c
c      cm(17)= LTYPE : 1=compacting, 2=dilative material, 3=damage
c
c      recover material parameters

```

```

c
    AKI = CM(1)
    AK1 = CM(2)
    AK2 = CM(3)
    AGI = CM(4)
    AG1 = CM(5)
    AG2 = CM(6)
    AA = CM(7)
    AC = CM(8)
    AB = CM(9)
    AT = CM(10)
    AW = CM(11)
    AD = CM(12)
    X0 = CM(13)
    CR0 = CM(14)
    TCUT = cm(15)
    TDP = cm(16)
    LTYPE = cm(17)

c
c    recover history variables
c
c    hisv(1) : printed as plastic-strain in taurus
c    same as material 25
c    if
c        cm(25)=1 : hardening parameter k in units of I1
c        cm(25)=2 : cap J1 intercept X(k)
c        cm(25)=3 : volumetric plastic strain
c        cm(25)=4 : first stress invariant I1
c        cm(25)=5 : second stress invariant sqrt(J2)
c        cm(25)=6 :
c        cm(25)=7 :
c        cm(25)=8 : response mode number
c        cm(25)=9 : number of iterations
c
c    hisv(2)=AKAPP : kappa (value of I1 at the last yield/cap/cutoff point)
c    hisv(3)=omega : damage parameter
c
    AKAPP = hisv(2)
    OMEGA = hisv(3)

c
c    =====
c    ASSUMING eps(i) are increments & sig(i) are accumulated values from dyna
c    =====
c
c    recover stress from dyna array
c    (-)sign for soil-mech. convention

```

```

c
    SIGX = -sig(1)
    SIGY = -sig(2)
    SIGZ = -sig(3)
    SIGXZ = -sig(6)
    SIGYZ = -sig(5)
    SIGXY = -sig(4)

c
c    recover strain increment
c    (-)sign for soil-mech. convention
c
    DEPSX = -eps(1)
    DEPSY = -eps(2)
    DEPSZ = -eps(3)
    DEPSXZ = -eps(6)
    DEPSYZ = -eps(5)
    DEPSXY = -eps(4)

c
c    compute intersection of yield with tensile I1 axis
c    I1 (+) in compression; TCUT is (-)
c
c    if(AB.eq.0.or.AC.eq.0.or.AA.eq.0) then
c        write(*,*)' The yield surface does not intecepts the I1 axis'
c        stop 1
c    else
c        FCUT = -1.0/AB*ALOG(AA/AC)
c    endif
c    FCUT = CM(47)

c
c    compute initial position I1 of the intersection between Fe and FC
c
    AL0 = CM(48)

c
c    The initial I1 at intersection of cap and I1 axis is X0, or
c    XI = AL0 + R(AL0)*F(AL0)
c
C    COMPUTE VOLUMETRIC STRAIN INCREMENT
C    AND STRAIN DEVIATION INCREMENT TENSOR
C
    DEV = DEPSX + DEPSY + DEPSZ

c
    DEVO3 = DEV/3.0
    DEXX = DEPSX - DEVO3
    DEYY = DEPSY - DEVO3

C
C    COMPUTE INITIAL MEAN NORMAL STRESS,

```



```

C      STRESS DEVIATION TENSOR, AND STRESS INVARIANTS
C      NOTE THAT SZZ = -(SXX+SYX)
C
C      PRESS = (SIGX + SIGY + SIGZ)/3.0
c
C      SXX = SIGX - PRESS
C      SYX = SIGY - PRESS
C      SXZ = SIGXZ
C      SYZ = SIGYZ
C      SXY = SIGXY
C
C      SJ1I= 3.*PRESS
c
C      SJ2I=
C      SQR(XXX*XXX+SYX*SYX+SXX*SYX+SZX*SZX+SYZ*SYZ+SXY*SXY)
C      CAPL= BIGL(AKAPP)
C EJB
c      XL = X(AKAPP)
C      XL = X(CAPL)
c
C      EVPI= EVP(XL)
C
C      ELASTIC MATERIAL PROPERTIES
C
C      THREEK = 3.0*BMOD(SJ1I)
C      TWOG = 2.0*SMOD(SJ2I)
C
C      ELASTIC TRIAL
C
C      SJ1 = THREEK*DEV+SJ1I
c
C      SXX = SXX + TWOG*DEXX
C      SYX = SYX + TWOG*DEYY
C      SXZ = SXZ + TWOG*DEPSXZ
C      SYZ = SYZ + TWOG*DEPSYZ
C      SXY = SXY + TWOG*DEPSXY
C      RATIO = 1.0
C      MTYPE = 1
c MJF Added for damage material
C      SJ1BAR = SJ1/(1.0-OMEGA)
C
C      TENSILE CODING
C
C      EJB changed amax1 for amin1 (because it is negative)
C      TENCUT = AMAX1(FCUT,TCUT)
c      TENCUT = AMIN1(FCUT,TCUT)

```

```

c      IF(SJ1BAR.GT.TENCUT) GO TO 10
      SJ1BAR = TENCUT
c MJF Calculate E (AEI), the modulus of elasticity
      AEI = 9.0*AGI*AKI/(3.0*AKI+AGI)
      DOMECA = (1.0/TDP)*AEI*DEV
      DOMECA = AMAX1(zero,DOMECA)
      OMEGA = OMEGA + DOMECA
      IF(OMEGA.GT.0.95) OMEGA=0.95
      SJ1 = SJ1BAR*(1-OMEGA)
      MTYPE = 0
      IF(LTYPE.EQ.2 .OR. LTYPE.EQ.3 .OR. AKAPP.LE.AL0) GO TO 200

C
C      TENSION DILATANCY CODING
C
      ELL = AMAX1(AL0,AKAPP+CONV*F(AKAPP))
      XLL = X(ELL)
      DENOM = EVP(XLL)-EVPI
      IF(DENOM.GT.zero) GO TO 5
      AKAPP = AL0
      GO TO 200
5      DEVP = DEV-(SJ1-SJ1I)/THREEK
      AKAPP = AKAPP+DEVP*(ELL-AKAPP)/DENOM
      AKAPP = AMIN1(AL0,AKAPP)
      GO TO 200

C
C      CHECK FAILURE ENVELOPE
C
10     CONTINUE
      SJ2 =
      SQRT(SXX*SXX+SYI*SYI+SXX*SYI+SZI*SZI+SYI*SZI+SXI*SXI)
      IF(SJ1.GT.CAPL) GO TO 30
      TMISES = SJ2C(CAPL,XL,CAPL)
      FJ1 = F(SJ1)
      FF = SJ2 - AMIN1(FJ1,TMISES)
      IF(FF.LE.zero) GO TO 200

C
C      YIELD SURFACE CALCULATION
C
      MTYPE = 2
      DFDJ1 = zero
      IF(FJ1.LT.TMISES) DFDJ1 = (F(SJ1+CONV*SJ2)-FJ1)/(CONV*SJ2)
      DLAMD = FF/(3.*THREEK*DFDJ1**2+0.5*TWOG)
      DEVP = -3.*DFDJ1*DLAMD
      SJ1E = SJ1
      SJ1 = SJ1 - THREEK*DEVP

```

```

C
C      DILATANCY AND CORNER CODING
C
      IF(LTYPE.EQ.1 .AND. AKAPP.GT.AL0) GO TO 60
      SJ1 = AMIN1(SJ1,CAPL)
      GO TO 70
60     CONTINUE
      ELL = AMIN1(SJ1E,AKAPP+CONV*SJ2)
      XLL = X(ELL)
      DENOM = EVP(XLL)-EVPI
      IF(DENOM.GT.zero) GO TO 65
      SJ1 = SJ1E
      AKAPP = AMAX1(AL0,SJ1)
      GO TO 70
65     DILAT = (ELL-AKAPP)/DENOM
      ELINT = AKAPP
      AKAPP = AMAX1(AL0,ELINT+DEVPI*DILAT)
      IF(SJ1.LE.BIGL(AKAPP)) GO TO 70
      SJ1 = (DILAT*SJ1E+THREEK*ELINT)/(DILAT+THREEK)
      AKAPP = AMAX1(AL0,SJ1)
70     CONTINUE
      FJ1 = F(SJ1)
      RATIO = AMIN1(FJ1,TMISES)/SJ2
      GO TO 200

C
C      HARDENING CALCULATION
C
30     CONTINUE
      IF(SJ1.GT.XL) GO TO 40
      IF(SJ2.LE.SJ2C(SJ1,XL,CAPL)) GO TO 200
40     CONTINUE
      SJ1E = SJ1
      SJ2E = SJ2
      ELL = AKAPP
      ELR = SJ1E
      IF(SJ1E.GE.XL) FL=(AKAPP-SJ1E)/(AKAPP-XL)
      IF(SJ1E.LT.XL) FL=2.0*SJ2E/(SJ2E+SJ2C(SJ1E,XL,CAPL)) - 1.0
      XR = X(ELR)
      SJ1R = SJ1E-THREEK*(EVP(XR)-EVPI)
      FR = (XR-SJ1R)/(ELR-XR)
      COMP = CONV*F((FL*XR-FR*XL)/(FL-FR))
      IF(ABS(SJ1)+SJ2.LT.COMP) GO TO 200
      MTYPE = 3
      FOLD = zero
      DO 190 IT = 1,NIT
      AKAPP = (FL*ELR-FR*ELL)/(FL-FR)

```

```

C EJB XL = X(AKAPP)
      XL = X(BIGL(AKAPP))
c
      DEVP = EVP(XL) - EVPI
      SJ1 = SJ1E - THREEK*DEVP
      CAPL = BIGL(AKAPP)
      IF(SJ1.GE.XL) FC=(AKAPP-SJ1)/(AKAPP-XL)
      IF(SJ1.LE.CAPL) FC=(XL-SJ1)/(CAPL-XL)
      IF(SJ1.GE.XL .OR. SJ1.LE.CAPL) GO TO 300
      SJ2 = SJ2C(SJ1,XL,CAPL)
      DELJ1 = CONV*(XL-SJ1)
      DESP = zero
C
C EJB modified for single precision, no computational cost increase.
C      IF(DELJ1) 205,206,205
C205  DESP=(DEVP/6.0)*(DELJ1/(SJ2-SJ2C(SJ1+DELJ1,XL,CAPL)))
      delj2 = SJ2-SJ2C(SJ1+DELJ1,XL,CAPL)
      IF(delj2/XL) 205,206,205
205  DESP=(DEVP/6.0)*(DELJ1/delj2)
c
206  CONTINUE
      SJ2TRY = SJ2 + TWOG*DESP
      FC = (SJ2E-SJ2TRY)/(SJ2E + SJ2TRY)
      IF(ABS(SJ2E-SJ2TRY).LE.COMP) GO TO 195
      IF(FC.GT.zero .AND. (SJ1-CAPL).LE.DELJ1) GO TO 195
300  IF(FC.GT.zero) GO TO 320
      ELR = AKAPP
      FR = FC
      IF(FOLD.LT.zero) FL = 0.5*FL
      GO TO 190
320  CONTINUE
      ELL = AKAPP
      FL = FC
      IF(FOLD.GT.zero) FR = 0.5*FR
190  FOLD = FC
      NOCON = 1
      SJ1 = AMIN1(SJ1,XL)
      IF(SJ1.LT.BIGL(ELR)) SJ1 = CAPL
      SJ2 = AMIN1(SJ2E,SJ2C(SJ1,XL,CAPL))
195  RATIO = zero
      IF(SJ2E/XL) 201,200,201
201  RATIO=SJ2/SJ2E
200  CONTINUE
      SXX = SXX*RATIO
      SYX = SYX*RATIO
      SXZ = SXZ*RATIO

```

```

      SYZ = SYZ*RATIO
      SXY = SXY*RATIO
      PRESS = SJ1/3.
C
      SIGX = SXX + PRESS
      SIGY = SYY + PRESS
      SIGZ = PRESS - SXX - SYY
      SIGXZ = SXZ
      SIGYZ = SYZ
      SIGXY = SXY
c
c      return stress to dyna
c      (-)sign for soil-mech. convention
c
      sig(1) = -SIGX
      sig(2) = -SIGY
      sig(3) = -SIGZ
      sig(6) = -SIGXZ
      sig(5) = -SIGYZ
      sig(4) = -SIGXY
c
c      update history
c
      hisv(2) = AKAPP
      hisv(3) = OMEGA
c
c      output to taurus as "plastic strain"
      i=cm(25)
      select case (i)
      case (1)
         hisv(1) = AKAPP
      case(2)
         hisv(1) = X(BIGL(AKAPP))
      case(3)
         hisv(1) = EVP(X(BIGL(AKAPP)))
      case(4)
         hisv(1) = sig(1)+sig(2)+sig(3)
      case(5)
         hisv(1) =
*
      SQRT(SXX*SXX+SYY*SYY+SXX*SYY+SXZ*SXZ+SYZ*SYZ+SXY*SXY)
      case(8)
         hisv(1) = MTYPE
      case(9)
         hisv(1) = IT - 1
      case default

```

```
        hisv(1) = EVP(X(BIGL(AKAPP)))
    end select
c
c    open(2,file="driver.out",status="unknown")
c    itime=100.0*time
c    ttime=itime/100.0
c    if (ttime.ne.omega) then
c        hisv(2) = ttime
c        write(2,1000) time,MTYPE,SJ1,CAPL,XL,SJ2,sj2c(sj1,xl,capl),
c    *                               sj2c(capl,xl,capl),F(SJ1)
c1000    format(f10.3,i5,9(g10.3))
c    endif
c    return
c    end
```

Appendix F:

UMAT43 Driver Program

```

c *****
c * Driver program for UMAT43                *
c * Matthew J. Fox / Dr. Ever J. Barbero      *
c *****
c
c      dimension cm(48),hisv(4),eps(6),sig(6)
c      character*8 etype
c
c      write(*,1001)
1001  format(" driver for umat43 "/50("="))
c
c  mjf
c      open(2,file="driver.out",status="unknown")
c      write(2,1001)
c
c      etype="brick"
c      do i=1,48
c          cm(i)=0.0
c      enddo
c      open(1,file="ingrido",status="old")
c      do i=1,60
c          read(1,*)
c      enddo
c      read(1,"(8G10.3)") ((cm((j-1)*8+i),i=1,8),j=1,6)
c      write(*,"(8(E10.3,1x))") ((cm((j-1)*8+i),i=1,8),j=1,6)
c      write(*,1000) ((cm((j-1)*8+i),i=1,8),j=1,2),cm(17),cm(47)
c      *,cm(48),cm(25)
c  mjf
c      write(2,1000) ((cm((j-1)*8+i),i=1,8),j=1,2),cm(17),cm(47)
c      *,cm(48),cm(25)
c
c      do i=1,6
c          sig(i)=0.0
c          eps(i)=0.0
c      enddo
c      hisv(1)=0.0
c      hisv(2)=0.0
c      hisv(3)=0.0
c      hisv(4)=0.0
c
c      itime = 0.0
c      ttime = 0.0
c
c      strainrate1 = 0.
c      strainrate2 = 0.
c

```



```

c      IC test
      strainrate1 = -0.001E-0
c
c      with -90/30 hits the yield, then the cap
c      pressure = -90
c      strainrate1 = pressure/3/cm(1)
c      shear = 30
c      strainrate2 = shear/cm(4)
c
c      tension cutoff
c      pressure = 1
c      strainrate1 = pressure/3/cm(1)
c      strainrate2 = strainrate1 * 11.25
c
      write(*,*)" strain rates ",strainrate1,strainrate2
c mjf
      write(2,*)" strain rates ",strainrate1,strainrate2
c
c mjf
      dt1=0.001E-0
c      dt1=3.7E-6
c mjf removed next 5 lines from loop
c      compute strain increment eps(i)
      do i=1,3
        eps(i+3)=strainrate2*dt1
        eps(i) =strainrate1*dt1
      enddo

c      loop over time
      time=0.0
      N1=0
      N2=20/dt1
      do it = N1,N2
        time=time+dt1
c      update stress
        call umat43 (cm,eps,sig,hisv,dt1,capa,etype,time)
c
        itime=10*time
        ttime=itime/10
        if(ttime.ne.hisv(4)) then
          write(*,*) ttime,hisv(1)
c mjf
          write(2,*) ttime,hisv(1)
c
          hisv(4) = ttime
        endif
      enddo

```

```
        enddo
        write(*,*) time,hisv(1)
c mjf
        write(2,*) time,hisv(1)
c
1000 format(" K   ",E10.3," K1   ",E10.3," K2   ",E10.3/
*         " G   ",E10.3," G1   ",E10.3," G2   ",E10.3/
*         " alpha ",E10.3," lambda",E10.3," beta  ",E10.3/
*         " theta ",E10.3," W    ",E10.3," D    ",E10.3/
*         " X0    ",E10.3," R    ",E10.3," TCUT ",E10.3/
*         " damage",E10.3," LTYPE ",E10.3," FCUT ",E10.3/
*         " L0    ",E10.3," NPLOT ",E10.3,"      ",E10.3/)
        end
```

Appendix G:

UC Model – Plain Concrete

Jerome Model Plain (UMAT43) 93 large

* CARD 1: Model Size-General
1 176 90 0 0 0 1 0 0

* CARD 2: Model Size-Boundary Conditions
0 0 0 0 0 0 0 0

* CARD 3: Model Size-Loading
2 4 0 0 0 0 0 0

* CARD 4: Model Size-Constraints and Contact
0 0 0 0 0 0 0 0 0 0 0 0

* CARD 5: Model Size-Rigid Body Parameters
0 0 0 0 0 0 0

* CARD 6: Model Size-Seat Belts
0 0 0 0 0 0 0 0 0 0 0 0

* CARD 7: Model Size-Output Options
0 0 0 0

* CARD 8: Computation Options-Termination
1.60000-3 0 0.0000000 0

* CARD 9: Computation Options-Time Step Size Control
0.0000000 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 10: Computation Options-Body Forces
0 0 0 0 0 0 0

* CARD 11: Computation Options-Input Control
0 0 0e20.0 0 0

* CARD 12: Computation Options-Beams and Shells
0.0000000 0 0 0 0 0 0 0 0 0 0 0

* CARD 13: Computation Options-Material Related Input
0 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 14: Computation Options-Damping/Dynamic Relaxation
2 000000000 0 0 0.0000000 0.0000000 0.0000000 0.0000000 0 0.0000000

* CARD 15: Computation Options-Contact
0.0000000 0.0000000 0 0 0 0 0 0 0 0 0 0.0000000 00

* CARD 16: Computation Options-Parallel and Subcycling
1 0 0

* CARD 17: Computation Options-Coupling Control
0.0000000 0.0000000 0.0000000 0 00 0.0000000 0 0 0

* CARD 18: Computation Options-Output Control
0 0 0 0 0 0 0 0 0 0.0000000

* CARD 19: Computation Options-Output Energy
1 2 1 1

* CARD 20: Computation Options-TAURUS Database Control I
5.00000-5 0.0000000 0.0000000 0 0 0 0 0 0

* CARD 21: Computation Options-TAURUS Database Control II
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

* CARD 22: Computation Options-ASCII Output Control I
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000

* CARD 23: Computation Options-ASCII Output Control II

```

0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 24: Computation Options-ASCII Output Control III
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 25: ALE Options-Control I
    0    0    0 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 26: ALE Options-Control II
0.0000000 0.0000000 0.0000000  0 0.0000000 0.0000000  0
* CARD 27: User Subroutine control card
  43 48  3  0  1  4  0  0
*
*----- MATERIAL CARDS -----*
*** MATERIAL: 43 (cap/yield/tcut)
  1 43 1.77000-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  2
material type # 43
1.92800+6 0.0000000 0.0000000 1.44600+6 0.0000000 0.0000000 0.70000+3 0.20000+3
1.47300-3 0.1000000 0.8840000 1.54000-6 18000.000 10.800000-630.00000-157.50000
3.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
4.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000-850.48402 10440.000
*
*----- NODAL POINT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- BRICK ELEMENT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- LOAD CURVE DEFINITIONS -----*
*
  1 23  0    0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000
5.00000-5 24.000000
1.00000-4 67.000000
1.50000-4 189.00000
2.00000-4 397.00000
2.50000-4 645.00000
3.00000-4 903.00000
3.50000-4 1202.0000
4.00000-4 1568.0000
4.50000-4 1925.0000
5.00000-4 2173.0000
5.50000-4 2324.0000
6.00000-4 2457.0000
6.50000-4 2530.0000

```

```

7.00000-4 2385.0000
7.50000-4 2192.0000
8.00000-4 1537.0000
8.50000-4 1189.0000
9.00000-4 893.00000
9.50000-4 540.00000
1.00000-3 199.00000
1.05000-3 0.0000000
1.60000-3 0.0000000
  2  2  0      0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 18.616300
1.60000-3 18.616300

```

*

----- CONCENTRATED NODAL LOADS AND FOLLOWER FORCES -----

*

```

173  2  1-0.1250000
174  2  1-0.1250000
175  2  1-0.1250000
176  2  1-0.1250000

```

Appendix H:

UC Model – CFRP Reinforced

Jerome Model CFRP (UMAT43)

93 large

* CARD 1: Model Size-General

2 264 120 0 0 0 1 0 0

* CARD 2: Model Size-Boundary Conditions

0 0 0 0 0 0 0 0

* CARD 3: Model Size-Loading

2 4 0 0 0 0 0 0

* CARD 4: Model Size-Constraints and Contact

0 1 0 0 0 0 0 0 0 0 0 0 0 0 0

* CARD 5: Model Size-Rigid Body Parameters

0 0 0 0 0 0 0

* CARD 6: Model Size-Seat Belts

0 0 0 0 0 0 0 0 0 0 0 0

* CARD 7: Model Size-Output Options

0 0 0 0

* CARD 8: Computation Options-Termination

1.60000-3 0 0.000000 0

* CARD 9: Computation Options-Time Step Size Control

0.0000000 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 10: Computation Options-Body Forces

0 0 0 0 0 0 0

* CARD 11: Computation Options-Input Control

0 0 0e20.0 0 0

* CARD 12: Computation Options-Beams and Shells

0.0000000 0 0 0 0 0 0 0 0 0 0 0

* CARD 13: Computation Options-Material Related Input

0 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 14: Computation Options-Damping/Dynamic Relaxation

2 0.0000000 0 0 0.0000000 0.0000000 0.0000000 0.0000000 0 0.0000000

* CARD 15: Computation Options-Contact

0.0000000 0.0000000 0 0 0 0 0 0 0 0 0 0.0000000 00

* CARD 16: Computation Options-Parallel and Subcycling

1 0 0

* CARD 17: Computation Options-Coupling Control

0.0000000 0.0000000 0.0000000 0 00 0.0000000 0 0 0

* CARD 18: Computation Options-Output Control

0 0 0 0 0 0 0 0 0 0.0000000

* CARD 19: Computation Options-Output Energy

1 2 1 1

* CARD 20: Computation Options-TAURUS Database Control I

5.00000-5 0.0000000 0.0000000 0 0 0 0 0 0

* CARD 21: Computation Options-TAURUS Database Control II

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

* CARD 22: Computation Options-ASCII Output Control I

0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000

* CARD 23: Computation Options-ASCII Output Control II


```

0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 24: Computation Options-ASCII Output Control III
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 25: ALE Options-Control I
    0    0    0 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 26: ALE Options-Control II
0.0000000 0.0000000 0.0000000  0 0.0000000 0.0000000  0
* CARD 27: User Subroutine control card
  43 48  3  0  1  4  0  0
*
*----- MATERIAL CARDS -----*
*** MATERIAL: 43 (cap/yield/tcut)
  1 43 1.77000-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  2
material type # 43
1.92800+6 0.0000000 0.0000000 1.44600+6 0.0000000 0.0000000 0.70000+3 0.20000+3
1.47300-3 0.1000000 0.8840000 1.54000-6 18000.000 10.800000-630.00000-157.50000
3.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
4.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000-850.48402 10440.000
*** MATERIAL: 2
  2 1 1.47500-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  0
material type # 1 (elastic)
2.00000+7 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.3000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
*
*----- NODAL POINT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- BRICK ELEMENT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- LOAD CURVE DEFINITIONS -----*
*
  1 19  0    0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000
5.00000-5 669.00000
1.00000-4 2178.0000
1.50000-4 4168.0000
2.00000-4 5912.0000

```

```

2.50000-4 6950.0000
3.00000-4 7430.0000
3.50000-4 7763.0000
4.00000-4 7970.0000
4.50000-4 7545.0000
5.00000-4 6090.0000
5.50000-4 3955.0000
6.00000-4 2027.0000
6.50000-4 892.00000
7.00000-4 423.00000
7.50000-4 205.00000
8.00000-4 62.000000
8.50000-4 0.0000000
1.60000-3 0.0000000
  2  2  0      0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 46.364000
1.60000-3 46.364000

```

*

----- CONCENTRATED NODAL LOADS AND FOLLOWER FORCES -----

*

```

173  2  1-0.1250000
174  2  1-0.1250000
175  2  1-0.1250000
176  2  1-0.1250000

```

*

----- SLIDING INTERFACE DEFINITIONS -----

*

** INTERFACE NAME: 1 . Type: Tied

*

REMOVED FOR SPACE

Appendix I:

RC Model – Internally Reinforced Concrete

Faza Fail Case 1 (UMAT43) 93 large

* CARD 1: Model Size-General
3 508 240 80 0 0 1 0 0

* CARD 2: Model Size-Boundary Conditions
0 0 0 0 0 0 0 0

* CARD 3: Model Size-Loading
2 4 0 0 0 0 0 0

* CARD 4: Model Size-Constraints and Contact
0 0 0 0 0 0 0 0 4 0 0 0 0 0

* CARD 5: Model Size-Rigid Body Parameters
0 0 0 0 0 0 0

* CARD 6: Model Size-Seat Belts
0 0 0 0 0 0 0 0 0 0 0 0

* CARD 7: Model Size-Output Options
0 0 0 0

* CARD 8: Computation Options-Termination
1.0000000 0 0.0000000 0

* CARD 9: Computation Options-Time Step Size Control
0.0000000 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 10: Computation Options-Body Forces
0 0 0 0 0 0 0

* CARD 11: Computation Options-Input Control
0 0 0e20.0 0 0

* CARD 12: Computation Options-Beams and Shells
0.0000000 0 0 0 0 0 0 0 0 0 0 0

* CARD 13: Computation Options-Material Related Input
0 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 14: Computation Options-Damping/Dynamic Relaxation
2 0.0000000 0 0 0.0000000 0.0000000 0.0000000 0.0000000 0 0.0000000

* CARD 15: Computation Options-Contact
0.0000000 0.0000000 0 0 0 0 0 0 0 0 0 0.0000000 00

* CARD 16: Computation Options-Parallel and Subcycling
1 0 0

* CARD 17: Computation Options-Coupling Control
0.0000000 0.0000000 0.0000000 0 000 0.0000000 0 0 0

* CARD 18: Computation Options-Output Control
0 0 0 0 0 0 0 0 0.0000000

* CARD 19: Computation Options-Output Energy
1 2 1 1

* CARD 20: Computation Options-TAURUS Database Control I
1.00000-2 0.0000000 0.0000000 0 0 0 0 0 0

* CARD 21: Computation Options-TAURUS Database Control II
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

* CARD 22: Computation Options-ASCII Output Control I
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000

* CARD 23: Computation Options-ASCII Output Control II

```

0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 24: Computation Options-ASCII Output Control III
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 25: ALE Options-Control I
    0    0    0 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 26: ALE Options-Control II
0.0000000 0.0000000 0.0000000  0 0.0000000 0.0000000  0
* CARD 27: User Subroutine control card
  43 48  3  0  1  4  0  0
*
*----- MATERIAL CARDS -----*
*** MATERIAL: 43 (cap/yield/tcut)
  1 43 1.77000-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  2
material type # 43
1.71429+6 0.0000000 0.0000000 1.56522+6 0.0000000 0.0000000 3.86000+3 1.16000+3
0.44000-3 0.1100000 0.4200000 3.20000-6 16000.000 4.4300000-414.20000-103.55000
3.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
4.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000-2732.3800 1525.9927
*** MATERIAL: 2
  2 3 7.33860-4  0  0 0.0000000  0 0.0000000 0.0000000  1  0  3
material type # 3 (elastic-plastic)
2.90000+7 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.2900000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
40000.000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
7.36380+4 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
1.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
section properties
0.0000000  1    0    0
0.4417865 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
*** MATERIAL: 3
  3 3 7.33860-4  0  0 0.0000000  0 0.0000000 0.0000000  1  0  3
material type # 3 (elastic-plastic)
2.90000+7 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.2900000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
40000.000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
7.36380+4 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
1.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
section properties
0.0000000  1    0    0
0.1104466 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
*
*----- NODAL POINT CARDS -----*

```

```

*
***REMOVED FOR SPACE***
*
*----- BRICK ELEMENT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- ELEMENT CARDS FOR BEAM ELEMENTS -----*
*
***REMOVED FOR SPACE***
*
*----- LOAD CURVE DEFINITIONS -----*
*
  1  8  0      0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000
1.00000-1 5000.0000
2.00000-1 10000.000
3.00000-1 15000.000
4.00000-1 20000.000
5.00000-1 25000.000
6.00000-1 30000.000
1.0000000 50000.000
*
*----- CONCENTRATED NODAL LOADS AND FOLLOWER FORCES -----*
*
  385  2  1-0.1250000
  386  2  1-0.1250000
  387  2  1-0.1250000
  388  2  1-0.1250000
*
*----- 1-D Slide Lines -----*
*
***REMOVED FOR SPACE***

```

Appendix J:

Concrete Wall Model

```

Concrete Wall Plain (UMAT43)                                     93 large
* CARD 1: Model Size-General
  1  1275  768  0  0  0  1  0  0
* CARD 2: Model Size-Boundary Conditions
  0  0  0  0  0  0  0  0  0
* CARD 3: Model Size-Loading
  385  0  384  0  0  0  0  0
* CARD 4: Model Size-Constraints and Contact
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
* CARD 5: Model Size-Rigid Body Parameters
  0  0  0  0  0  0  0
* CARD 6: Model Size-Seat Belts
  0  0  0  0  0  0  0  0  0  0  0  0
* CARD 7: Model Size-Output Options
  0  0  0  0
* CARD 8: Computation Options-Termination
  0.5000000  0 0.0000000  0
* CARD 9: Computation Options-Time Step Size Control
  0.0000000 0.0000000  0 0.0000000 0.0000000  0 0  0
* CARD 10: Computation Options-Body Forces
  0  0  0  0  0  0  0
* CARD 11: Computation Options-Input Control
  0  0  0e20.0  0  0
* CARD 12: Computation Options-Beams and Shells
  0.0000000  0  0  0  0  0  0  0  0  0  0  0
* CARD 13: Computation Options-Material Related Input
  0 0.0000000  0 0.0000000 0.0000000  0 0  0
* CARD 14: Computation Options-Damping/Dynamic Relaxation
  385 0.0000000  0  0 0.0000000 0.0000000 0.0000000 0.0000000  0 0.0000000
* CARD 15: Computation Options-Contact
  0.0000000 0.0000000 0 0  0  0  0  0  0  0  0 0.0000000  00
* CARD 16: Computation Options-Parallel and Subcycling
  0  0  0
* CARD 17: Computation Options-Coupling Control
  0.0000000 0.0000000 0.0000000  0 000 0.0000000  0  0  0
* CARD 18: Computation Options-Output Control
  0  0  0  0  0  0  0  0  0 0.0000000
* CARD 19: Computation Options-Output Energy
  1  2  1  1
* CARD 20: Computation Options-TAURUS Database Control I
  5.00000-4 0.0000000 0.0000000  0  0  0  0  0  0
* CARD 21: Computation Options-TAURUS Database Control II
  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0  0
* CARD 22: Computation Options-ASCII Output Control I
  0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 23: Computation Options-ASCII Output Control II

```



```

0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 24: Computation Options-ASCII Output Control III
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 25: ALE Options-Control I
    0    0    0 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 26: ALE Options-Control II
0.0000000 0.0000000 0.0000000  0 0.0000000 0.0000000  0
* CARD 27: User Subroutine control card
  43 48  3  0  1  4  0  0
*
*----- MATERIAL CARDS -----*
*
*** MATERIAL: 43 (cap/yield/tcut)
  1 43 1.77000-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  2
material type # 43
1.71429+6 0.0000000 0.0000000 1.56522+6 0.0000000 0.0000000 3.86000+3 1.16000+3
0.44000-3 0.1100000 0.4200000 3.20000-6 16000.000 4.4300000-414.20000-103.55000
3.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
4.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000-2732.3800 1525.9927
*
*----- NODAL POINT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- BRICK ELEMENT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- LOAD CURVE DEFINITIONS -----*
*
#1-#384***REMOVED FOR SPACE***
  385  2  0    0.0000000 0.0000000 0.0000000 0.0000000  0
0.0000000 14.020000
0.5000000 14.020000
*
*----- PRESSURE BOUNDARY CONDITION CARDS -----*
*
***REMOVED FOR SPACE***

```

Appendix K:

CFRP Reinforced Concrete Wall Model

Concrete Wall with CFRP on Back (UMAT43) 93 large

* CARD 1: Model Size-General
2 2125 1152 0 0 0 1 0 0

* CARD 2: Model Size-Boundary Conditions
0 0 0 0 0 0 0 0

* CARD 3: Model Size-Loading
385 0 384 0 0 0 0 0

* CARD 4: Model Size-Constraints and Contact
0 1 0 0 0 0 0 0 0 0 0 0 0 0 0

* CARD 5: Model Size-Rigid Body Parameters
0 0 0 0 0 0 0

* CARD 6: Model Size-Seat Belts
0 0 0 0 0 0 0 0 0 0 0 0

* CARD 7: Model Size-Output Options
0 0 0 0

* CARD 8: Computation Options-Termination
0.5000000 0 0.0000000 0

* CARD 9: Computation Options-Time Step Size Control
0.0000000 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 10: Computation Options-Body Forces
0 0 0 0 0 0 0

* CARD 11: Computation Options-Input Control
0 0 0e20.0 0 0

* CARD 12: Computation Options-Beams and Shells
0.0000000 0 0 0 0 0 0 0 0 0 0 0

* CARD 13: Computation Options-Material Related Input
0 0.0000000 0 0.0000000 0.0000000 0 0 0

* CARD 14: Computation Options-Damping/Dynamic Relaxation
385 0.0000000 0 0 0.0000000 0.0000000 0.0000000 0.0000000 0 0.0000000

* CARD 15: Computation Options-Contact
0.0000000 0.0000000 0 0 0 0 0 0 0 0 0 0 0.0000000 00

* CARD 16: Computation Options-Parallel and Subcycling
2 0 0

* CARD 17: Computation Options-Coupling Control
0.0000000 0.0000000 0.0000000 0 00 0.0000000 0 0 0

* CARD 18: Computation Options-Output Control
0 0 0 0 0 0 0 0 0 0.0000000

* CARD 19: Computation Options-Output Energy
1 2 1 1

* CARD 20: Computation Options-TAURUS Database Control I
5.00000-4 0.0000000 0.0000000 0 0 0 0 0 0

* CARD 21: Computation Options-TAURUS Database Control II
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

* CARD 22: Computation Options-ASCII Output Control I
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000

* CARD 23: Computation Options-ASCII Output Control II

```

0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 24: Computation Options-ASCII Output Control III
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 25: ALE Options-Control I
    0    0    0 0.0000000 0.0000000 0.0000000 0.0000000
* CARD 26: ALE Options-Control II
0.0000000 0.0000000 0.0000000  0 0.0000000 0.0000000  0
* CARD 27: User Subroutine control card
  43 48  3  0  1  4  0  0
*
*----- MATERIAL CARDS -----*
*
*** MATERIAL:  43 (cap/yield/tcut)
  1 43 1.77000-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  2
material type # 43
1.71429+6 0.0000000 0.0000000 1.56522+6 0.0000000 0.0000000 3.86000+3 1.16000+3
0.44000-3 0.1100000 0.4200000 3.20000-6 16000.000 4.4300000-414.20000-103.55000
3.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
4.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000-2732.3800 1525.9927
*** MATERIAL:  2
  2 1 1.47500-4  0  0 0.0000000  0 0.0000000 0.0000000  0  0  0
material type # 1 (elastic)
2.00000+7 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.3000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000 0.0000000
*
*----- NODAL POINT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- BRICK ELEMENT CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- LOAD CURVE DEFINITIONS -----*
*
#1-#384***REMOVED FOR SPACE***
  385  2  0    0.0000000 0.0000000 0.0000000 0.0000000  0
0.0000000 14.020000
0.5000000 14.020000
*
```

```
*----- PRESSURE BOUNDARY CONDITION CARDS -----*
*
***REMOVED FOR SPACE***
*
*----- SLIDING INTERFACE DEFINITIONS -----*
*
** INTERFACE NAME: 1      . Type: Tied surf to surf
   384   384 0 2 0.0000000 0.0000000 0.0000000   0   0   00.000000.00000
*
*** Slave segments, surface: 1
*
***REMOVED FOR SPACE***
*
*** Master segments, surface: 1
*
***REMOVED FOR SPACE***
```