Stress Analysis of a Triple-nested Composite Blast Container

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Summary

The Indian Head Division, Naval Surface Warfare Center (IHDNSWC), was requested by the Naval Packaging, Handling, Storage and Transportation (PHST) Center at Naval Weapons Station Earle to perform an analysis of a blast containment concept shown on the left in Figure 1. The "three-orthogonal band" concept shown is a Honeywell proprietary design to be constructed of composite materials with a great percentage of the fibers oriented along the individual band directions. The high explosive (HE) is shown placed in the geometric center of the container. The intention is for the box to fully contain the blast pressure and fragments.

Simulations were performed to determine theoretically whether the container would withstand without rupture the blast pressure resulting from the detonation of one pound of C4 high explosive. No fragmentation effects were included in this study. The simulations were conducted using both uncoupled and fully coupled approaches.

Model Description

Figure 1 shows the finite element model generated using the *HyperMesh*[1] mesh generator. Three planes of symmetry exist for the box geometry and so were employed. The box contains 17,786 shell elements and contact surfaces to fully simulate the physical interactions of the three boxes. The model was exported into formats for use with both the *ABAQUS*[2] comprehensive general-purpose explicit and implicit finite element (Lagrangian) programs and the *Dyna_N(3D)*[3] Lagrangian finite element program. More detail of the model construction is given in Appendix A.

The Eulerian calculations were done with the *Gemini*[4] hydrocode to support both the uncoupled and fully coupled approaches. The uncoupled approach involved computing the internal shock pressure loading from the C4 high explosive (HE) using reflective boundary surfaces to represent the box walls and subsequently applying these loads in the *ABAQUS* finite element model via a user-written subroutine and *Gemini*-generated data files. Since *Gemini* is not currently coupled to *ABAQUS*, it was necessary and sufficient to decouple the problem by computing the shock loading on the inside surface of the container using the *Gemini* hydrocode and mapping this loading as a function of time and surface coordinates for input to the *ABAQUS* finite element model. More detail of the execution of the uncoupled procedure is provided in Appendix B.

The initial proposal only called for this uncoupled approach in order to take advantage of *ABAQUS*' superior contact capability. The reason why this uncoupled approach suffices

[1] http://www.altair.com/software/hw_hm.htm
[2] http://www.hks.com/
[3] Borrmann, M., Tewes, R., McKeown, R., "User's Manual, DYNA_N(3D), A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics," IABGmbH/TA40,NSWCIHD Code 420, May 2001. (HTML).
[4] Wardlaw, Jr., A. B., et al, "The Gemini Euler Solver for the Coupled Simulation of Underwater Explosions," IHTR 2500, 30 May 2003.

for this problem is two-fold: (1) The rise time (a fraction of a millisecond) in the loading is extremely rapid in comparison to the response time of the container, particularly with regard to the venting time which is on the order of seconds, and (2) there are no fluid-structure interaction effects since the fluid media inside and outside the container is air.

As the study progressed, we decided to include a fully coupled approach using the *DYSMAS*[5] code once we determined that the contact capability in *Dyna_N(3D)* was sufficient for these configurations. We also wanted to compare the two approaches and the different codes for corroboration of results. The two primary scenarios modeled with *DYSMAS* were (1) the case in which the box is filled with air, and (2) the case in which a number of four-inch diameter spheres were included within the box to investigate a shock mitigation methodology. For case (1), the Eulerian grid was comprised of approximately 9.1 million cells and, for case (2), approximately 4.5 million cells. Air was modeled with a gamma gas law equation of state (EOS); the C4 HE modeled with a JWL EOS; and the water spheres (case (2)) was modeled using the Tillotson EOS.

Figure 2 shows the directions of the shell normals as used in the two Lagrangian codes for reference in interpreting the locations of stresses reported. "Upper" and "Lower" surfaces are relative to the normal directions indicated by the arrows. Thus the upper and lower surfaces coincide with the outer and inner physical surfaces, respectively, for the *ABAQUS* stresses. (For the *Dyna_N(3D)* model, the outer box had to have its normals pointing toward the other boxes because of the contact surface definition requirements for that code.)

Material Properties

The triple-nested box is constructed of a laminated composite made from a cloth of Spectra® fiber and a rubber-like matrix. Spectra® fiber is made from ultra-high molecular weight polyethylene that is used in a patented gel-spinning process. The gel-spinning process and subsequent drawing steps allow Spectra® fiber to have a much higher melting temperature (150°C or 300°F) than standard polyethylene. The Spectra Shield® family of composite products technology lays parallel strands of synthetic fiber side by side and holds them in place with a resin system, creating a unidirectional tape. Two layers are then cross-plied at right angles (0º/90º) and fused into a composite structure under heat and pressure.

Honeywell, Inc. (HI), under a support contract,[6] provided the material properties used in the analyses. The properties provided are an approximation based on the unidirectional ply properties and the design stacking sequence (principally a 75/25 lay-up) and factoring in the high strain rate data of Figure 3. Table 1 summarizes the high strain rate material properties used in the analyses.

[5] McKeown, Reid M., et al, "Computer Codes for PredictingUnderwater Explosion Effects, Volume I: Executive Summary," Project Agreement RTP-US-GE-N-95-0002 Final Report, 17 January 2003.
[6] Contract No. N00174-03-M-0165 of 18 July 2003.

Table 1. High Strain Rate Material Properties of the Spectra Laminate.

Material Parameter	*ABAQUS* (English)	*Dyna_N(3D)* (cgs)
E1	15,000,000.	1.034E+12
E2	5,000,000.	3.477E+11
E3	50,000.	3.477E+09
<12	0.29	0.29*
<13	0.26	0.26*
<23	0.35	0.35*
G12	400,000.	2.758E+10
G13	80,000.	5.516E+09
G23	80,000.	5.516E+09
F_1^t	240,000.	-
F_2^t	80,000.	-
F_1^c	-22,500.	-
F_2^c	-7,500.	-
Thickness	0.3125	0.8166
Density	9.36E-05	1.0

* For *Dyna_N(3D)*, the actual input are the minor Poisson ratios: <21 = 0.097, <31 = 0.00087, <32 = 0.0035.

Upon review of the material properties of Kevlar-epoxy vs. the Spectra, it was deemed useless to merely substitute the Kevlar properties and repeat any of the analyses. This is because the Spectra high strain rate moduli and strengths were considerably higher than that of the Kevlar-epoxy. In comparison, an analysis with Kevlar data would not result in improved stresses.

Gemini-ABAQUS Results

Figures 4 and 5 give the in-plane principal stresses for the inner and outer surfaces, respectively, at 90 :s after detonation of the C4. The displaced shape is shown to scale and represents approximately the point of maximum displacement. The computed stresses are very high, particularly in the bend regions. We decided to repeat this analysis using the fully coupled DYSMAS code to compare results as well as to enable analyzing more complex Euler configurations not originally proposed.

Fully Coupled DYSMAS Results

Figures 6 through 10 give the results of one lb of C4 detonating inside the triple-nested box with air as the only media for shock propagation. Figure 6 shows the pressure loading at 63, 200, 400, and 600 :s. The pressure-time history at a cell near the middle of the inside surface of a wall is shown in Figure 7. The initial peak pressure is about 940 psi, peaking at about 65 :s, drops, and then sees a reflected peak shock pressure of about 4000 psi at about 93 :s. Subsequent reflections and shock interactions can be seen in the remaining time history in Figures 6 and 7.

Figure 8 shows the displacement at 1.0 and 1.9 ms. The maximum displacement occurs at about 1.0 ms and is about 3¼ inches. By 1.9 ms the displacement has dropped to about

1.6 inches. Figures 9 and 10 give the global xx and global normal stresses for the inner surface at 1.0 and 1.9 ms, respectively, (typical results). The normal stresses are the direct stress component of stress after subtracting out the bending stress components. That is, the normal stresses shown are due only to the in-plane tension or compression without showing the bending component. This is of interest because it gives an indication of the membrane loading condition of the walls under this pressure.

Note that the total stresses (i.e., including the bending stress components) greatly exceed the limits in tension and compression (F_i^t and F_i^c, respectively) shown in Table 1. Some of these results are a very conservative overstatement of expectations because none of the material models can simulate the progression of the compressive side of the bending stresses (e.g., outside half-thickness at the bend) to taking up a portion of the tensile load. That is, the laminated composite can only withstand, in compression, a small fraction of the stress that it can withstand in tension. When that level of compressive stress is reached (e.g., in bending at the corners), the stresses redistribute significantly and the corners open more while some of the thickness that was in compression picks up the loading in tension. Consequently, this can only happen if the deformation pattern is also changed to maintain equilibrium. This particular composite, which has a rubber-like matrix, can withstand a much greater degree of the inter-laminar shear strain in the matrix than a more conventional epoxy matrix, thus limiting the damage in this deformed transient state.[7] Unfortunately, the existing orthotropic material models do not allow a composite laminate to redistribute the loads when compressive stress limits are reached. Consequently, reliance on this redistribution of stresses is based on empirical evidence (HI tests).

Considering the above results, we decided to include spheres of water in the box in an attempt to simulate one method used by HI in mitigating the shock loading on the walls. Working with HI on the amount of water to include in the box (they used "baggies" of water), we added to the Eulerian domain 4-inch diameter water spheres distributed as shown in Figure 11. This is equivalent to 20 spheres in the total physical box volume (one at each of the eight corners and one at each of the 12 mid-edges). The total weight of the water (about 25 lb) was about 1/3 the weight of the triple-nested box (about 75 lb). (Note that the Eulerian domain shown in Figure 11 is larger than the box dimensions.)

[7] Igor Palley of HI provided the following elaboration: "The geometry of the 3-band box changes under the internal pressure (blast and shock). In general, a cube transforms for an instant into a shape close to a sphere. The cause of such noticeable transformation is that the flexural rigidity of the band walls is immeasurably smaller than their tensile rigidity. This is true for any thin wall structure, even more for a composite material of similar design (low shear rigidity). In the case of SpectraShield with the soft rubber matrix (that is several orders of magnitude lower than an epoxy matrix, for example, of a conventional structural composite), this effect is even more enhanced. The low compressive strength (actually, the low resistance to compressive force) helps this shape change and leads to a substantial stress redistribution. Actually, the band wall becomes loaded in almost pure tension and the bending factor disappears. The stress level can be estimated just taking into account the tensile component and ignoring the flex component as an artifact. One can make a quick estimate of stresses by considering a perfect sphere (with the perimeter equal to the band perimeter) loaded with the blast or the calculated pressure."

Figures 12 and 13 show the pressure loading and maximum displacement, respectively, resulting from this simulation. The outline of the water sphere that lies on the Eulerian plane plotted in Figure 12 can be seen. The shock propagation through, and reflection off, the water sphere can be seen, most notably at 100 and 200 :s.

Unfortunately, this simulation did not predict any reduction of stresses or displacement. The only hope was that work done in disbursing the water would help in this regard since the energy that goes into water phase change is not included in the calculations. No assessment was made on the effect this energy loss might have.

We briefly investigated potential EOSs for adequate mocking of shaving cream or other foams used for shock mitigation. A series of 1D spherical simulations was conducted in this regard. For reference, the pressure profiles are shown in Figure 14 for air and water as the shock media. One EOS that may have had some promise was the P-alpha EOS that was developed originally for sand. This could theoretically simulate the non-recoverable work done on crushing up the bubbles of foam. It became clear that this was becoming an academic exercise, as real test data were not available. Hence this effort was discontinued.

Pressure Equilibrium Condition

Recognizing that the triple-nested box must serve as a "pressure vessel" since it takes on the order of a few seconds to vent the C4 overpressure (according to those who witnessed such tests), then it follows that the box must withstand a quasi-static loading of internal pressure. Thus, assuming the box survives the initial shock loading, a relevant simulation is the application of a pressure load in a nonlinear static stress analysis. This would be the "gentlest" application of the pressure load, independent of any shock effects. That is, all questions of how the shock mitigation is handled in the simulation are moot.

The first item to determine is the equilibrium pressure. This was computed three different ways. Two methods are provided in Appendices C and D. Figure 15 is taken from Appendix C. In that method, the problem is bounded as described in the appendix and in the figure.

A 1D spherical *Gemini* calculation was done in which 1 lb of C4 was detonated and allowed to run until the pressure profile was nearly constant throughout the volume. The volume of the rigid sphere is the same as the initial internal volume of the box. Figure 16 shows the pressure profiles at 50, 260, and 270 :s (on the left of Figure 16) and at 90 milliseconds on the right.[8] The result is about 570 psi, which lies in between the results shown in Figure 15. The pressure computed in Appendix D also agrees with this result.

[8] The reason why the reflected pressure at 270 :s is so high on the left is because that is the center of a sphere (singularity) in the 1D model. This is the first reflection at the center. As time goes on, the numerical dissipation in the code dampens the peak pressures and, as seen on the right, equilibrium is nearly achieved by 90 ms.

The second item is to confirm our expectation that the blow down time is on the order of seconds. The Multi-Chamber BLowdown Model[9] (*MBLM*) was used to estimate the blow down times involved in this scenario. The venting area was estimated by post-processing the final shape of the corner region using the HyperMesh software and multiplying this area by 8. Figure 17 shows these results for a range of venting areas since the venting area reduces slowly with time and is therefore not known accurately. Nevertheless, the venting times over this range are on the order of the times witnessed in tests. (The picture included in Figure 17 is a close-up of the corner of the deformed model.)

The third item is the nonlinear static stress analysis. The *ABAQUS* Standard code was used and 550 psi internal pressure applied in the analysis. Figures 18 and 19 show the resulting displacements and stresses, respectively. The peak displacement (bulging of the sides at the middle) is just under 1.6 inches, slightly under the magnitude the displacements had relaxed to by 1.9 ms in the coupled analysis. The stresses are also very high, principally due to the bending component of stress.

Conclusions

1. Using available material properties, the triple-nested box reaches stresses in excess of failure limits, particularly in the bend regions. (A box with flat sides generally is not the way to design a pressure vessel.)
2. We do not have analytical proof that the box will survive.
3. The existing orthotropic material models do not allow a composite laminate to redistribute the loads when compressive stress limits are reached.
4. It is likely that substantial redistribution of stresses for this composite, which has a very compliant matrix, will redistribute the stresses at the bend regions to predominantly survivable tensile loads; however, no factor of safety can be assigned as a result of the above analyses.
5. Reliance on this redistribution of stresses is based on empirical evidence (HI tests).

Recommendations

1. Pursue testing of material properties of actual laminate at low-to-high strain rates.
2. Investigate development of an orthotropic material model that allows a composite laminate to redistribute the loads when compressive stress limits are reached.
3. Conduct tests of this triple-nested box configuration with strain gages in strategic positions (e.g., corners, mid-side) and high-speed photography.
4. Develop an EOS of choice shock mitigation media.
5. Consider alternate designs that do not include flat areas joined by relatively tight bends. E.g., composite high-pressure gas bottles are cylindrical with dome tops to avoid this very problem.

[9] Pierce, Todd, "MBLM Version 42c User's Reference Manual," Maxwell Technologies, Inc., DTR-96-15508, September 1996.

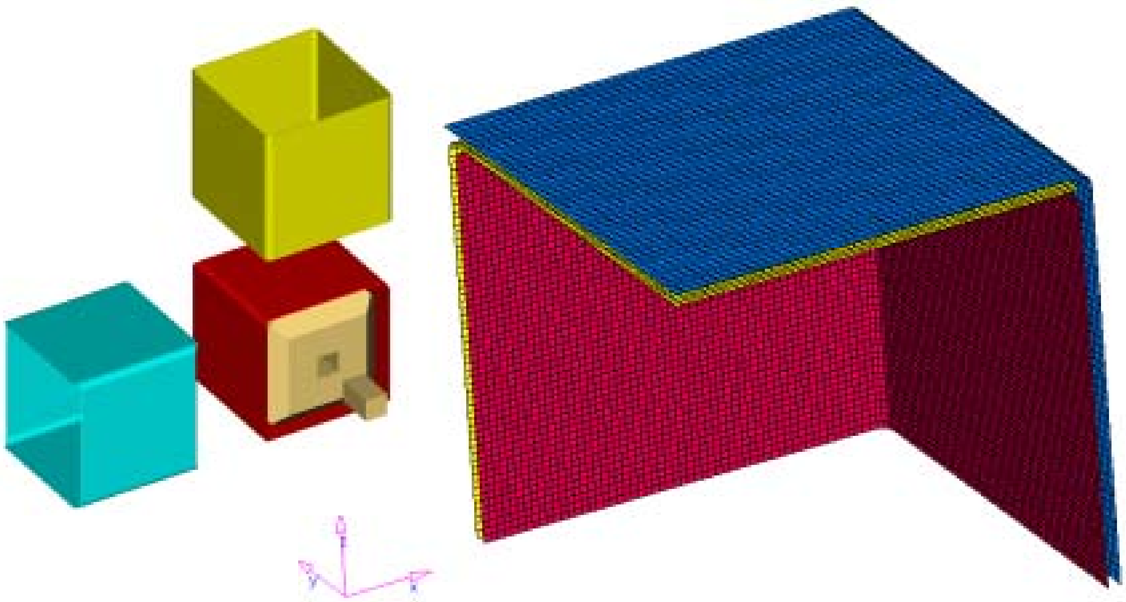


Figure 1. Triple-nested Box: Schematic and Finite Element Model

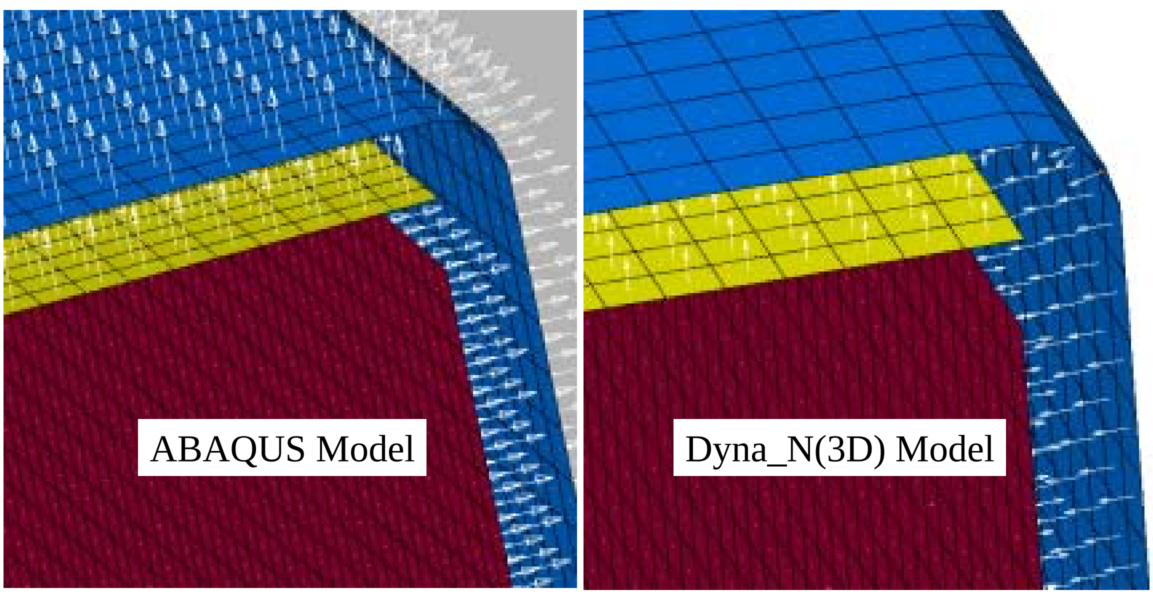


Figure 2. "Upper" and "Lower" surfaces are relative to normal directions.

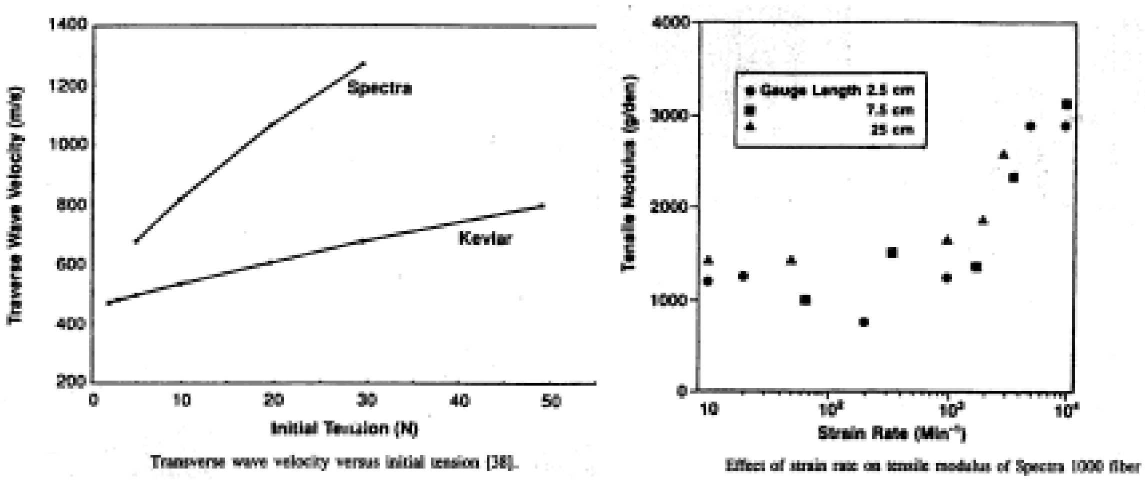


Figure 3. Spectra: The Latest High-Performance Fiber, data by D.C. Prevorsek.

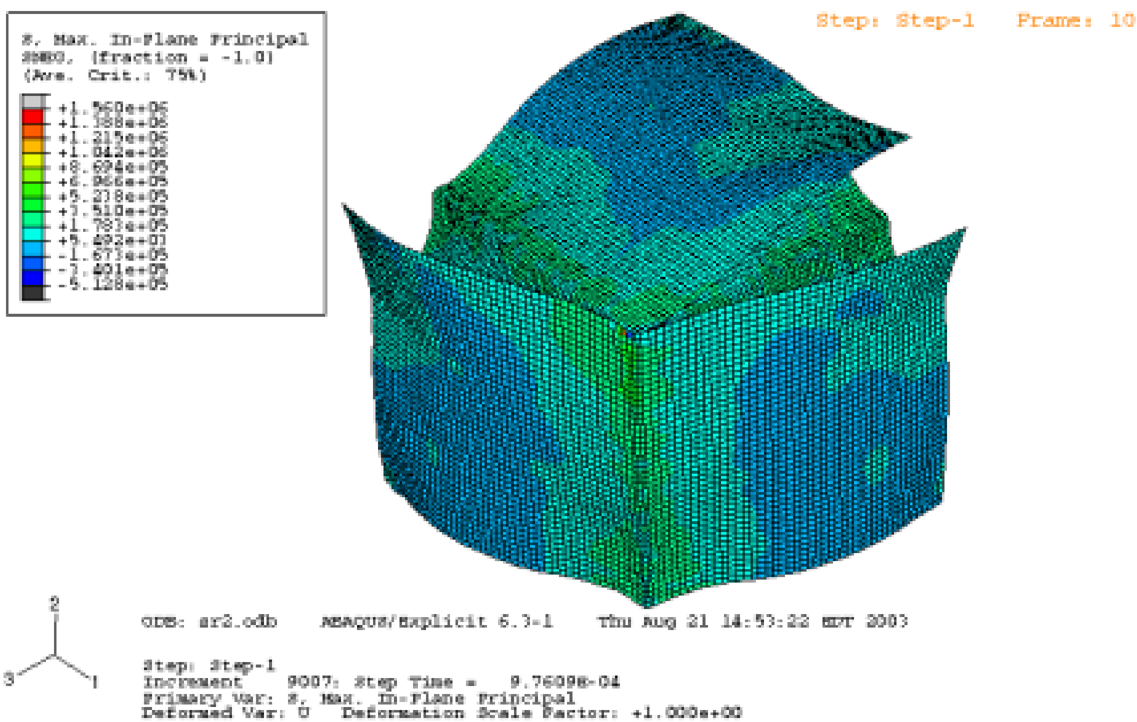


Figure 4. Uncoupled Gemini-ABAQUS Result:
In-plane principal stresses, inner surface.

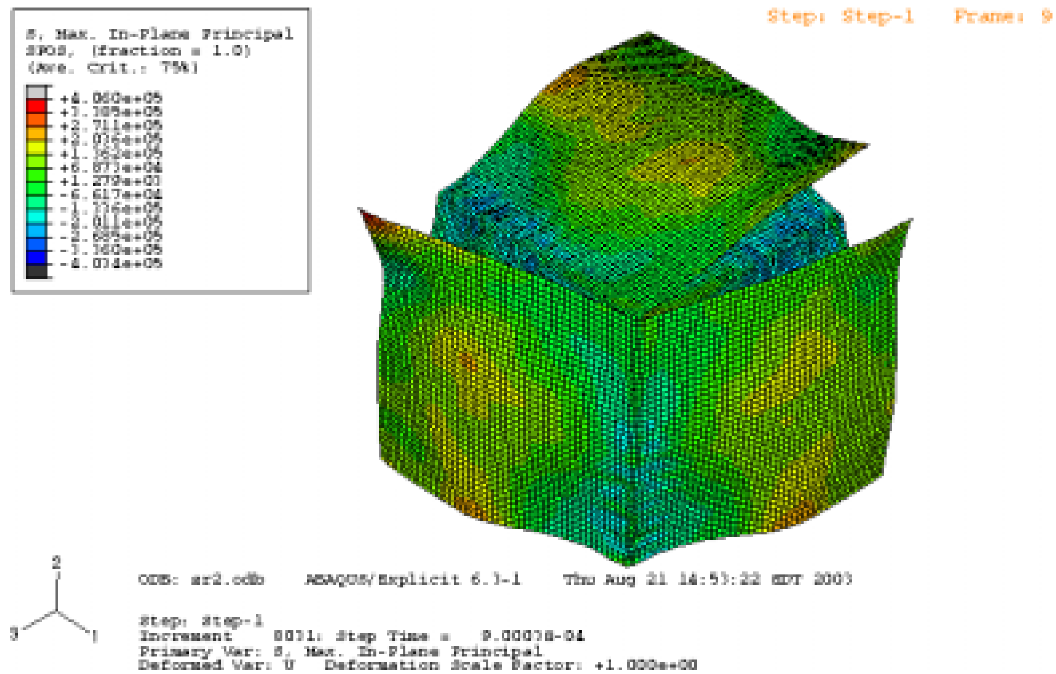


Figure 5. Uncoupled Gemini-ABAQUS Result:
In-plane principal stresses, outer surface.

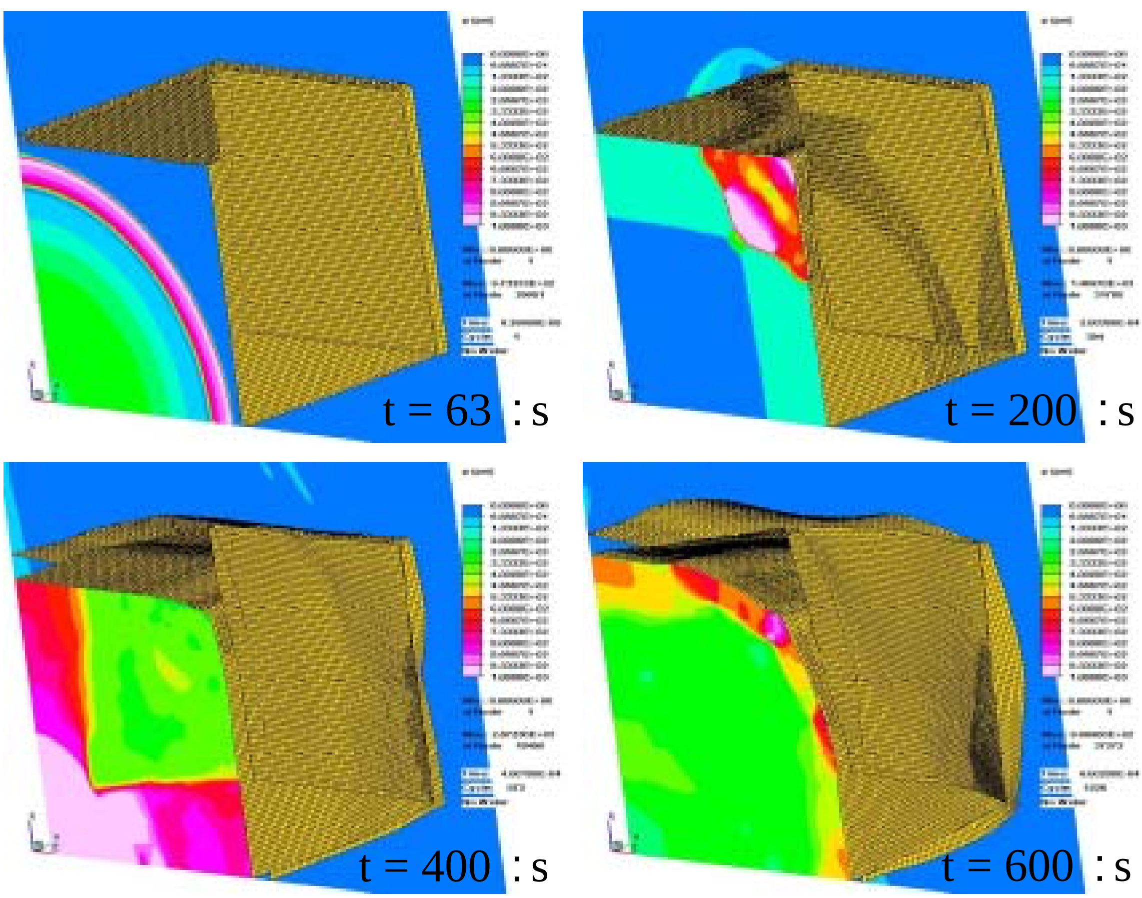


Figure 6. Fully Coupled DYSMAS Result: Internal Pressure Loading (no water).

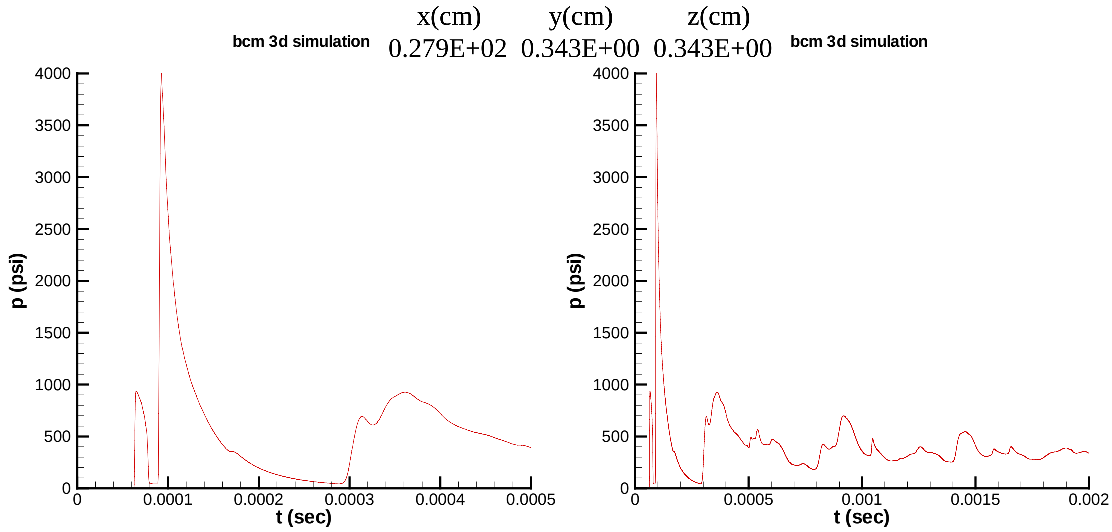


Figure 7. Fully Coupled DYSMAS Result: Pressure History (no water).

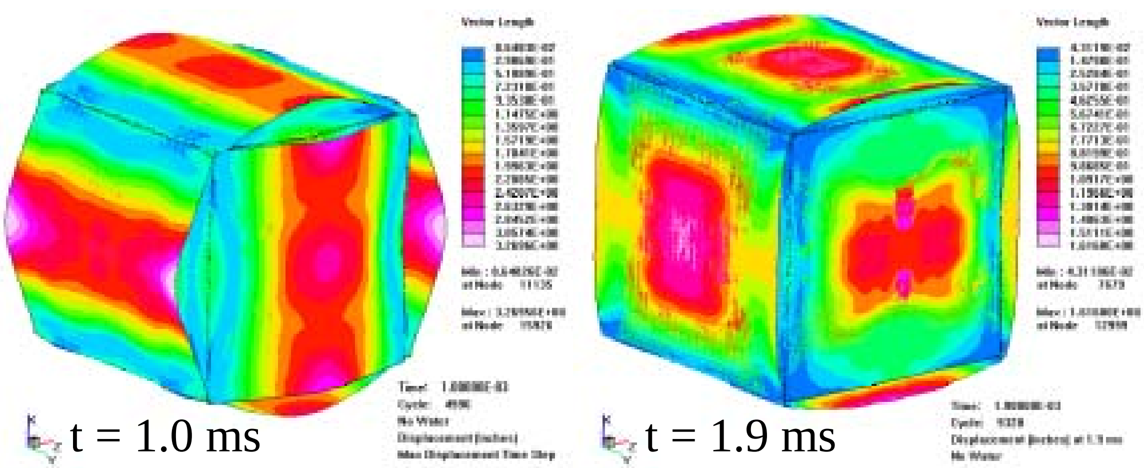


Figure 8. Fully Coupled DYSMAS Result: Displacement (no water).

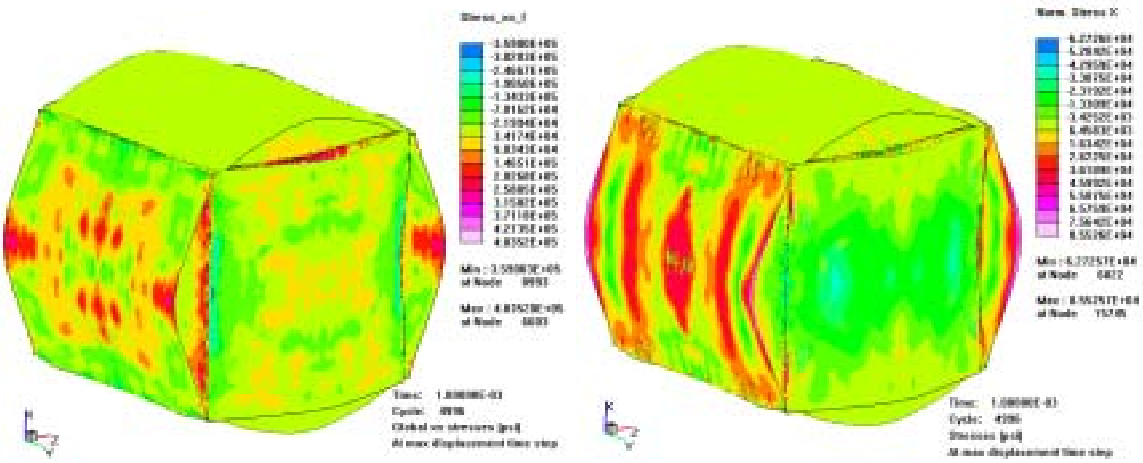


Figure 9. Fully Coupled DYSMAS Stress Results at 1.0 ms (no water): Total Global xx, "lower" surface (left); Global Normal x, no bending (right).

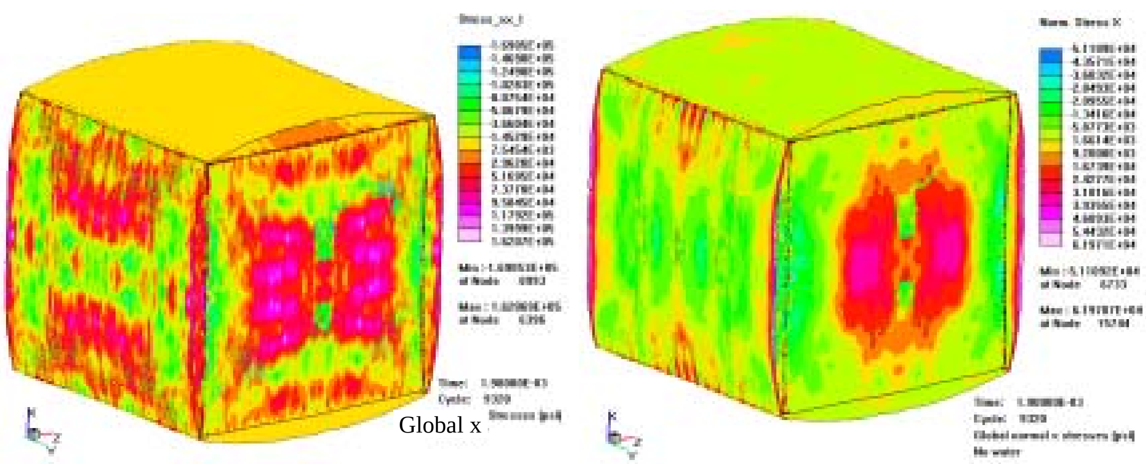


Figure 10. Fully Coupled DYSMAS Stress Results at 1.9 ms (no water): Total Global xx, "lower" surface (left); Global Normal x, no bending (right).

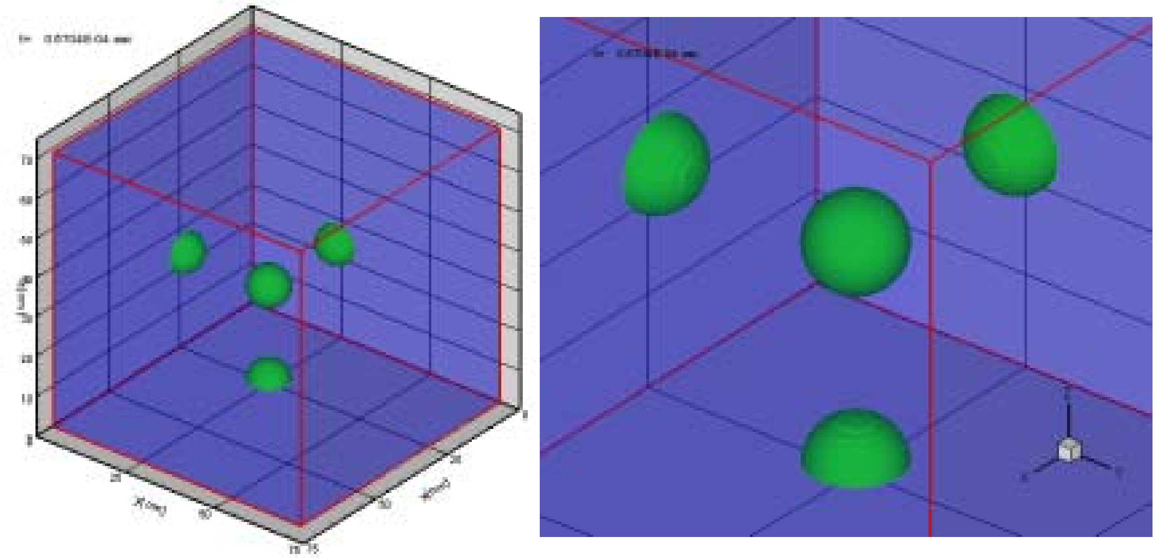


Figure 11. Water Spheres in Model Domain (3 Planes of Symmetry).

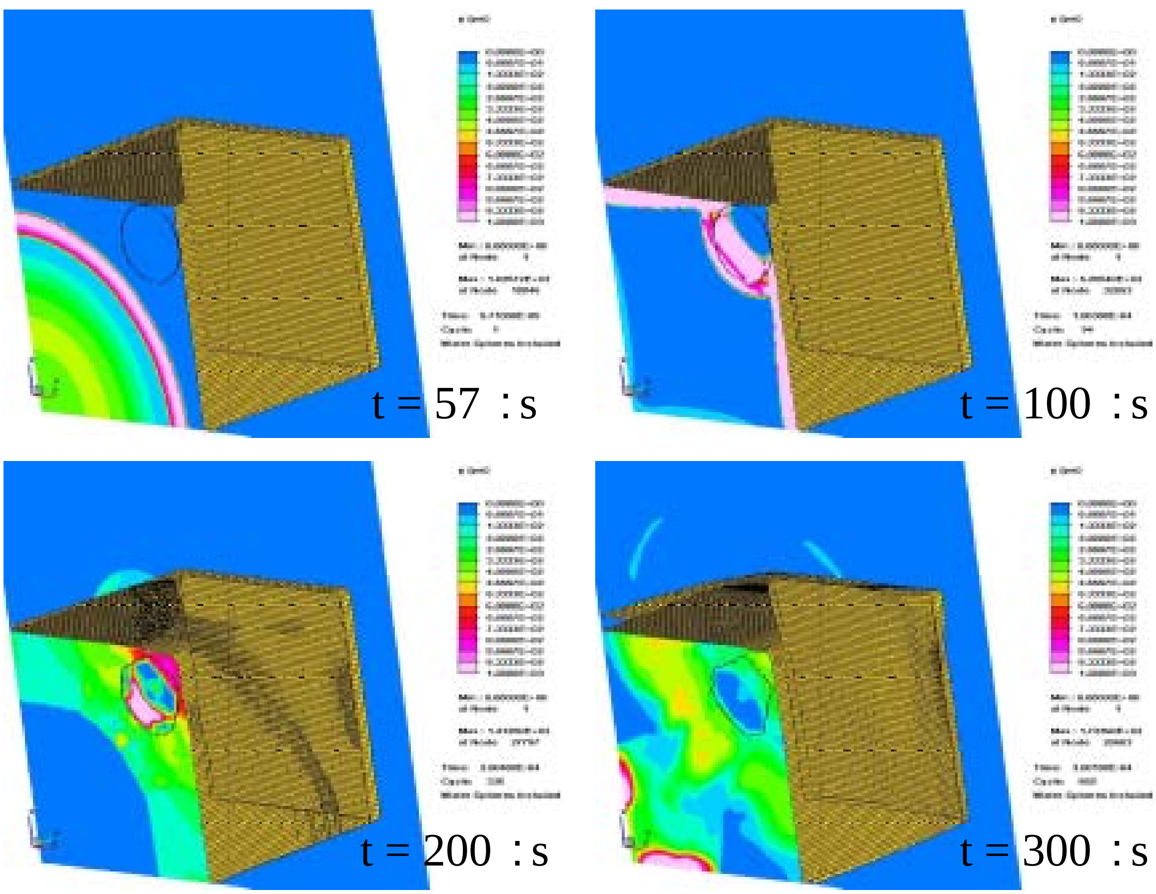


Figure 12. DYSMAS Result: Internal Pressure Loading (with water spheres).

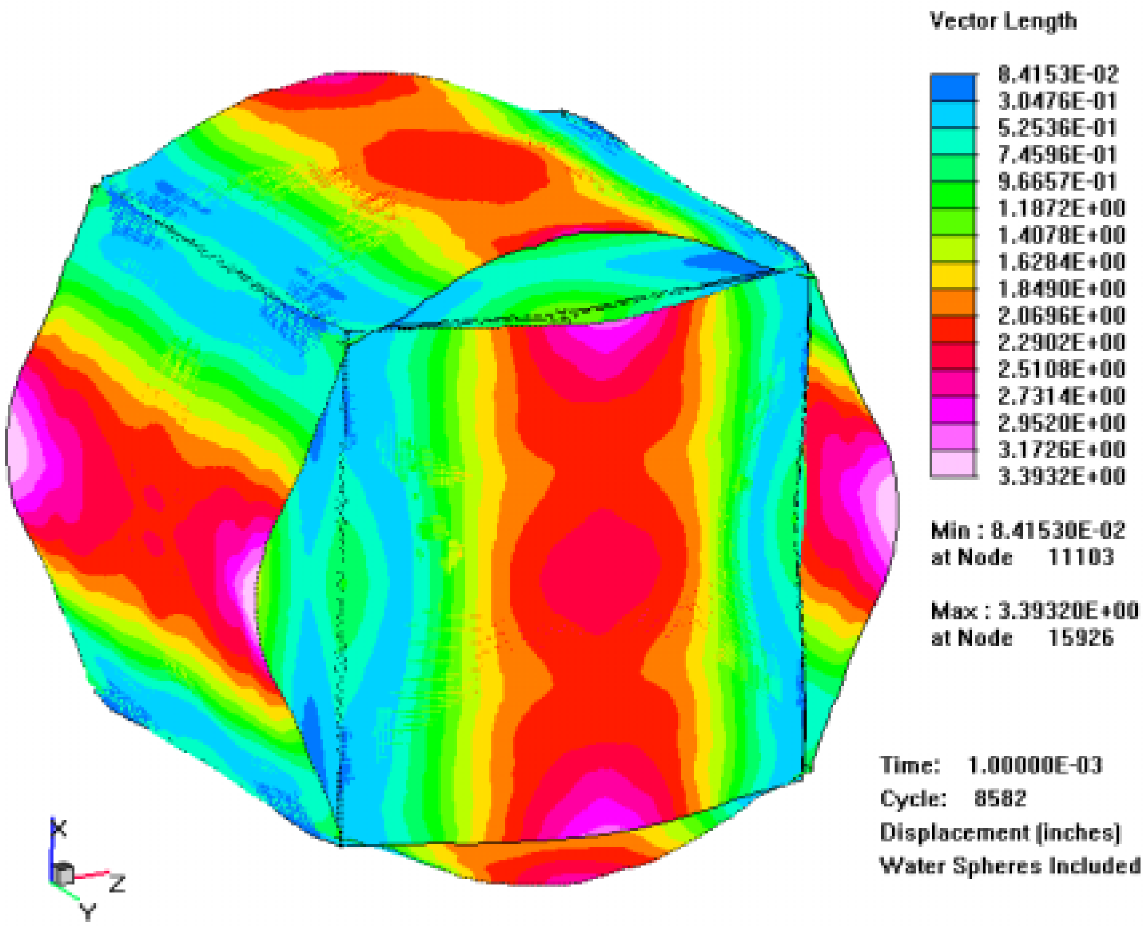


Figure 13. DYSMAS Result: Max Displacement (with water spheres).

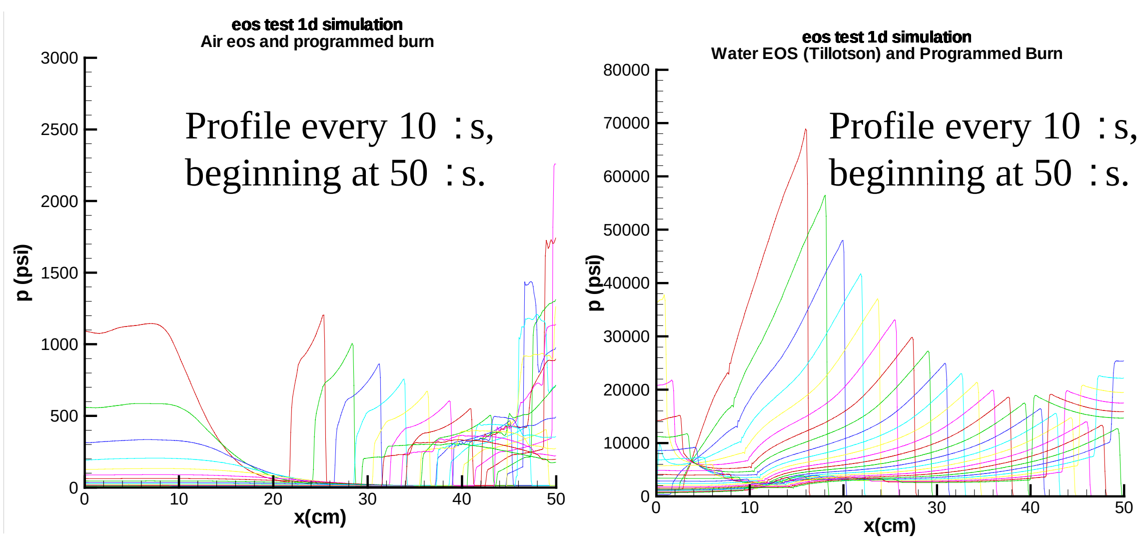
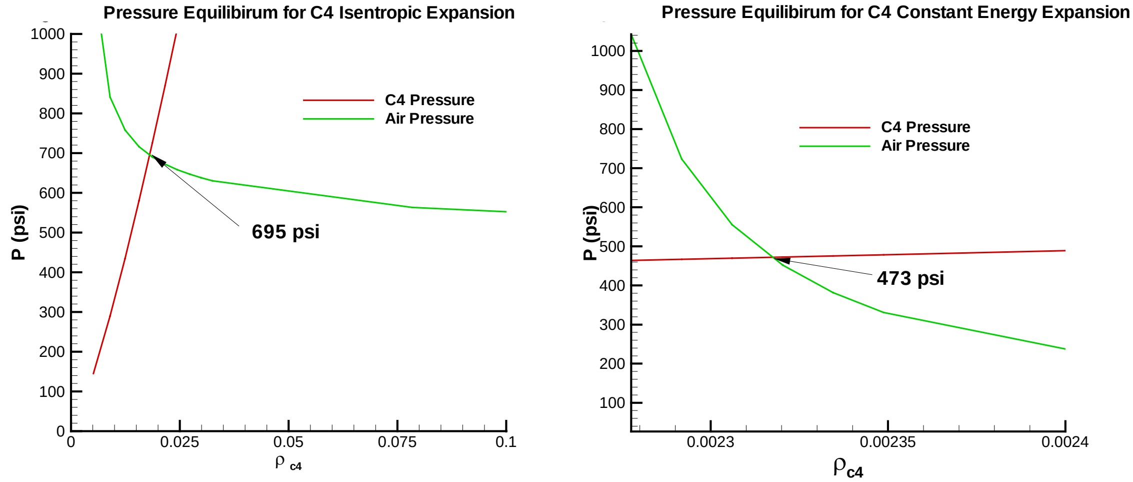


Figure 14. EOS 1D Benchmark Pressure Profiles in Air (left) and Water (right).



C4 material expands isentropically* and the kinetic energy that induced in the system is completely absorbed by the air. $* \; de = \frac{p}{\rho^2} d\rho$

C4 material expands at constant energy and thus absorbs all of the kinetic energy.

Figure 15. Bounding the Equilibrated Pressure in the Box Volume.

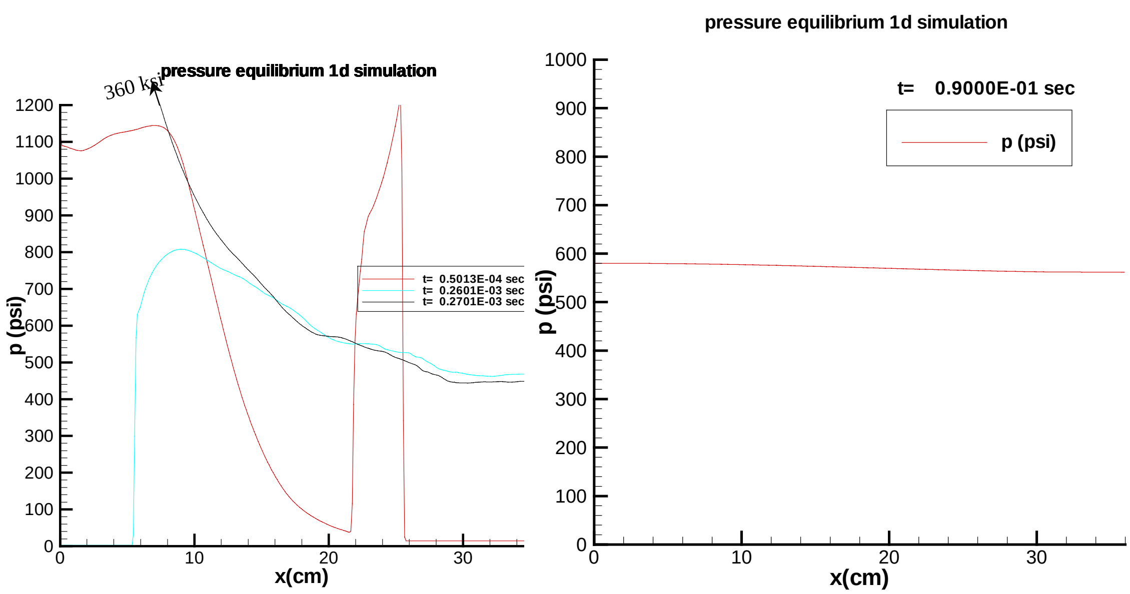


Figure 16. Gemini-computed Pressure Profiles in the Box Volume.

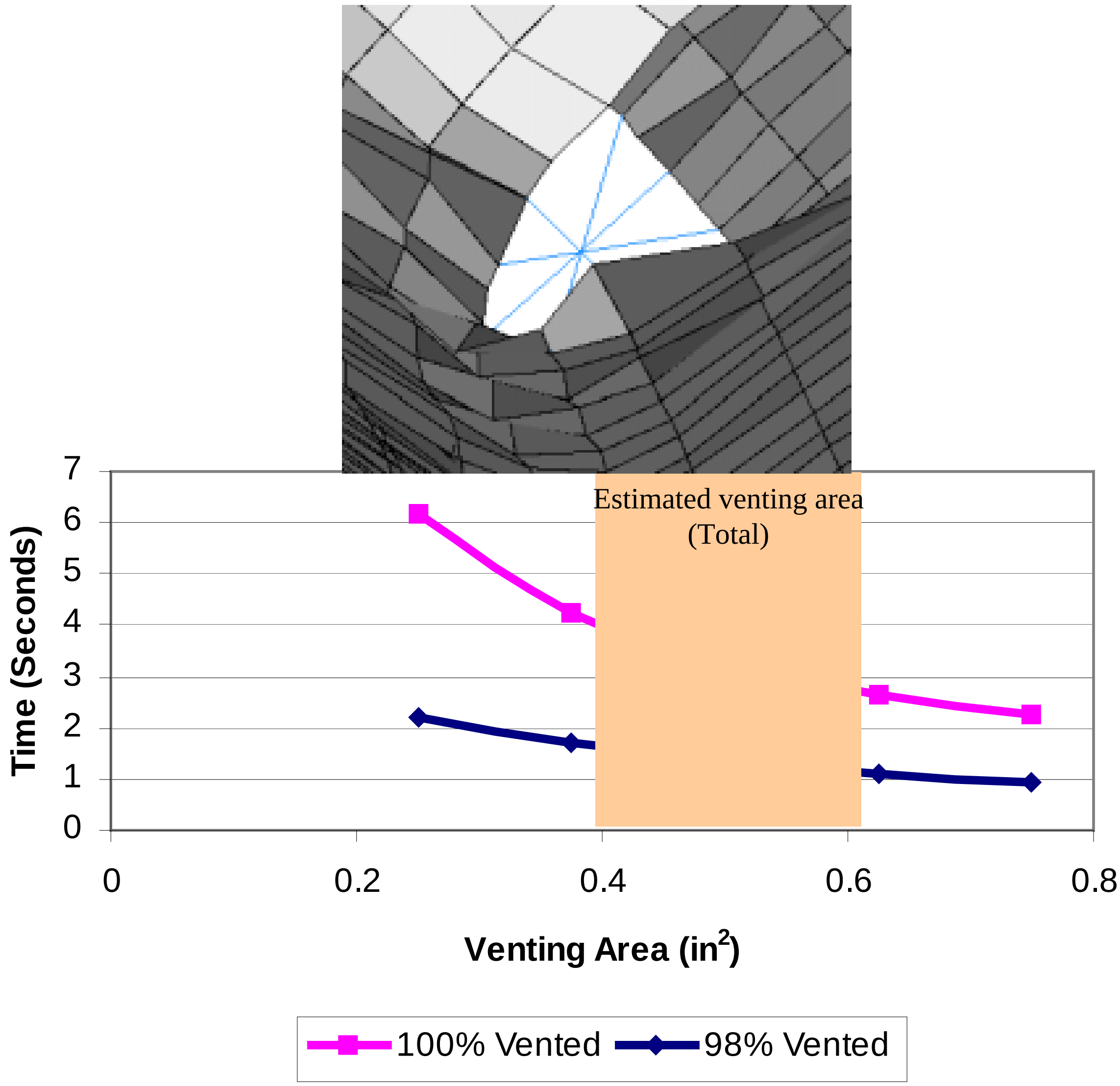


Figure 17. MBLM-computed Pressure Blow-down Conditions.

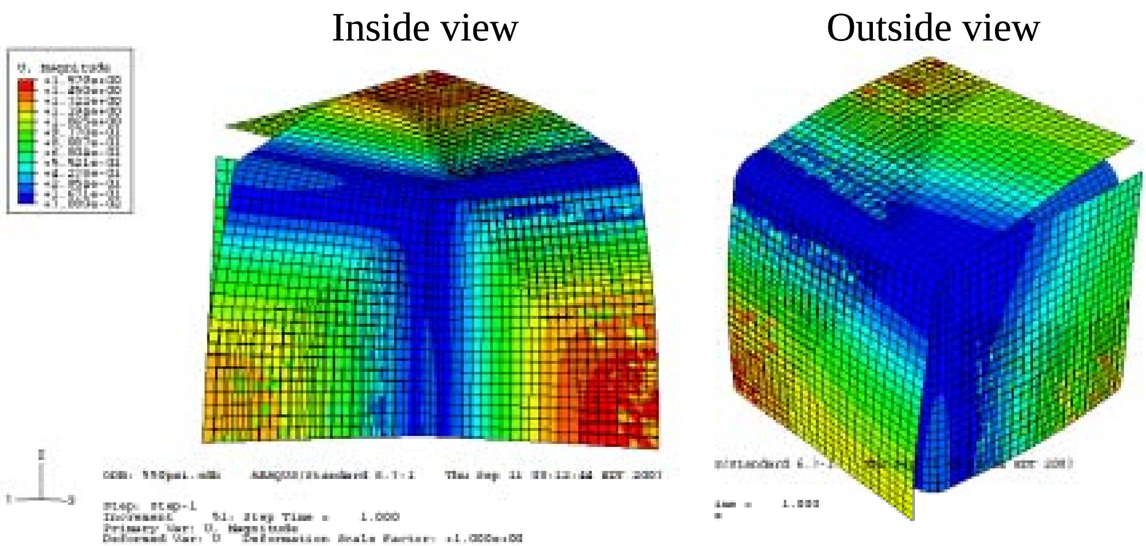


Figure 18. ABAQUS Nonlinear Static Result: Displacement from 550 psi.

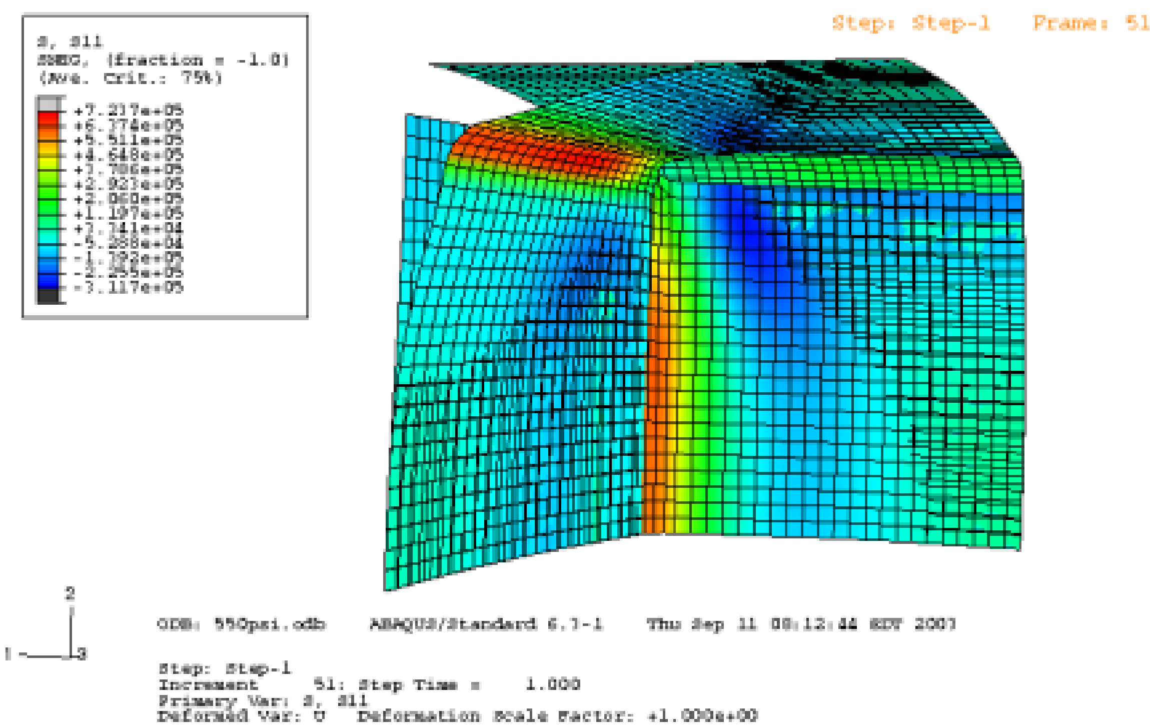


Figure 19. ABAQUS Nonlinear Static Result:
S11 Stresses, inner surface, from 550 psi.

Appendix A

Honeywell's "Box in a Box in a Box" Blast Containment Structural Model Description

Earle M. Sparks

System Description

The "box in a box in a box" blast containment concept is an effort to prove that a lightweight structural device of 70 pounds or less and 8 cubic feet in size is able to completely contain a blast equivalent to one pound of C4 explosive. Honeywell's "box in a box in box" blast containment concept consists of three boxes made of a composite material. Each box is constructed so that two opposite sides are missing. These boxes resemble a piece of square channel. The boxes are constructed by wrapping layers of a semi-unidirectional cloth around a square mandrel. Approximately 75% of the fibers in the cloth are oriented in the wrapping or hoop direction and the remaining fibers are orientated across the wrapping direction. There are no fibers orientated through the thickness of the box sides. A thin sheet of thermoplastic resin separates the layers of cloth. The sides of the box are fused together under pressure using a heated platen. The cloth is made of one of Honeywell's ultra high molecular weight polyethylene (UHMWPE) fibers. Honeywell's trademark name for this fiber is Spectra.

The three boxes are dimensioned so that the first box fits inside the second box. These two nested boxes are then placed inside the third box. The boxes are situated so that two box sides are between the inner and outer space of the nested boxes. A foam insert is placed in the first or inner box to center the explosive charge in the structure. The overall outer dimensions of the three box arrangement is 24" x 24" x 24". Wall thickness of each box is 0.3125". The wrapping mandrel is constructed so that an inner and outer radius is formed at the edges were the sides of the box come together.

Model Description

The geometry of the model was constructed using Altair's HyperMesh version 5.0 software. Due to geometric and loading symmetry only 1/8 of the structure was required to be modeled. This consisted of one corner of the structure and 1/4 of the two sides and 1/2 of the one edge of each box associated with that corner. The boxes were construct by drawing the outline of the box at the centerline of the box's wall thickness using a sketch provided by Honeywell. Projecting these outlines in proper direction to maintain relative orientation of the boxes created the geometry of the model. Surface elements were created on each side and edge of each box by using the meshing tool of HyperMesh. The surface elements were given the thickness of the box walls using the centerline of the wall thickness as the reference. Half of the wall thickness is projected to each side of the surface elements. Elements were put into several different groups or collectors so that loading conditions, contact surfaces, and material orientation could be more easily specified in the finite element code input deck.

ABAQUS Explicit finite element code is used to analyze the blast containment model. The *ABAQUS* code is selected because of its contact surface capability. Due to the dynamic nature of the problem the Explicit version of the code is selected over the *ABAQUS* Standard. An additional advantage to using Explicit is that in shell contact situations Explicit recognizes the shell thickness and orientation of the thickness with respect to the reference surface and adjusts the contact surfaces out to the thickness of the elements. In the Standard version *ABAQUS* recognizes the reference surface as the contact surface. The major disadvantage of using the *ABAQUS* explicit code over a dynamic finite element code named *Dyna_N(3D)* is *ABAQUS* is not coupled with the code used to determine the pressure load to be applied to the inner surface of the blast container. Using *ABAQUS* requires additional steps in order to apply the correct pressure load caused by the explosive detonation.

The three boxes are modeled using *ABAQUS* 4-node, 3D reduced integration shell elements. *ABAQUS* explicit code requires the use of the reduced integration option for all types of elements. The edges of the model that would connect to other portion of the structure that was excluded from the model due to symmetry are given symmetry constraints. These constraints simulate the effects that this excluded portion of the structure will have on the modeled portion of the structure.

When using shell elements in *ABAQUS* a positive and negative orientation is specified. This orientation is required so that loading can be applied to the desired side of the surface element. In this model all inner (towards the C4 blast) element surfaces were designated as negative and outer element surfaces were designated positive. Contact surfaces are created between the three different boxes. Determining sides of each box that contacts the other boxes and whether they are of a positive or negative orientation is how the surface contact pairs are designated. An example of this is the positive side of the shell elements of the inner box contact the negative side of the shell elements of the middle box. In *ABAQUS* contact loading, one surface must be designated a slave surface and the other surface designated a master surface. Since there is effectively no difference in element mesh density and material stiffness in the direction of contact, the surface that is designated master or slave makes no difference in this model. However in this model the elements whose negative surface was part of the contact pair was designated the master surface and the positive surface the slave surface.

C4 detonation pressure is applied to negative side of all elements that are not covered by an inner box. In other words, the entire inner box model, one side and the edge radius portion of the middle box model, and the middle row of elements along the length the edge radius portion of the outer box model are pressure loaded. These areas are divided into sectors for the purpose of applying time-pressure loading acquired from the *Gemini* detonation code. The output of this code is used in determining how to sector the pressure application region. The pressure-time data that is to be applied to the blast containment was determined by modeling the detonation of a one-pound sphere of C4. At the present date, the *Gemini* Code is not coupled with the *ABAQUS* Code. Therefore the pressure time data cannot be directly applied. Fortran user sub routines are created that reference data files that contain the detonation pressure-time data for each application sector. These data files are created from data acquired from the *Gemini* runs of the spherical C4 detonation.

The composite material that the blast containment is made of is modeled as an orthotropic material. Due to geometry of the model and the configuration of the composite material, nine different material orientations have to be specified to align the material properties of composite with the geometric configuration of the model. As stated above, 75% of the fibers in the cloth used to wrap the boxes are oriented in one direction and the other 25% of the fibers are in a perpendicular or cross direction. This configuration can be looked as a warp-weave configuration with 75% of the fibers in the warp direction and 25% of the fibers in the weave direction. These two directions are used as two of the principal material directions with third direction being through the thickness of the cloth and with no fibers orientated in that direction. Therefore there have to be three modulus of elasticity, three shear moduli, and three Poisson's ratios for each different way that the material is oriented with respect to the model's coordinate system. The way that this in done so that *ABAQUS* assigns the correctly oriented material properties to all portions of the model is to create additional coordinate systems with respect to the model's construction coordinate system. These new coordinate systems must correctly match the fiber directions and align the material properties in the proper direction. Six of these material property coordinate systems were created to align material properties with the sides of the box and were rectangular coordinate systems. The three coordinate systems created for material orientation for the curved box edges were cylindrical coordinate systems.

The following are the first cut material properties provided by Honeywell for insertion into the finite element model:

$E_1 = 7.5 \times 10^6$ psi
$E_2 = 2.5 \times 10^6$ psi
$E_3 = 1.0 \times 10^5$ psi
$\nu_{12} = 0.3$
$\nu_{13} = 0.3$
$\nu_{23} = 0.3$
$G_{12} = 2.0 \times 10^5$ psi
$G_{13} = 4.0 \times 10^4$ psi
$G_{23} = 4.0 \times 10^4$ psi
$\rho = 1.3$ g/cm^3.

E represents the elastic moduli, ν represents Poission's ratio, G represents shear moduli, and ρ represents density. The subscripts represent the material axis that the property is in respect to. The subscript 1 represents the axis direction that corresponds to the direction of 75% of fibers. Subscript 2 represents the 25% fiber direction and subscript 3 represents the through thickness of the box walls. These properties are checked for stability using the stability requirement found in the *ABAQUS* literature and were found to meet these stability requirements. The properties were updated by Igor Palley of Honeywell with the high strain rate properties reported in the main body of this report. All analysis results reported used the updated high strain rate properties.

Appendix B

Box Dimensional Checks and Uncoupled Load Calculations
Sean B. Tidwell

Dimensional Checks

The given band dimensions for the blast containment box did not satisfy the clearance specifications of 0.04 inches. In order to maintain an over all outer dimension of 24”x24”x24” and a band thickness of 5/16 inches the inner and middle band dimensions must be changed. The dimensions for the outer band will remain the same as shown in Figure B-1.

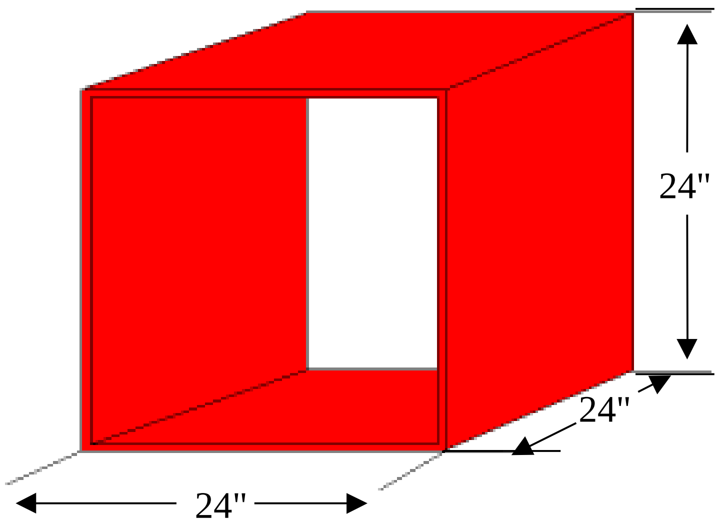


Figure B-1: Outer Band

Changing the middle band dimensions to those shown on the left in Figure B-2 will insure that the clearance requirements will be met. These values were calculated using equation (B-1), where BD_1 is the band dimension of an outer band, t is the band thickness, c is the clearance, and BD_2 is the band dimension of an inner band. Equation (B-1) will work for both the inner and middle band.

$$BD_1 - 2(t) - 2(c) = BD_2 \qquad \text{(B-1)}$$

Dimensions for the inner band are obtained using equation (B-1). A diagram of the inner band is also shown in Figure B-2. These new dimensions for the middle and inner band were used to model the structural geometry in *HyperMesh* for both the *ABAQUS* and *Dyna_N(3D)* runs. The *HyperMesh* model was made using mid-thickness dimensions for all three bands.

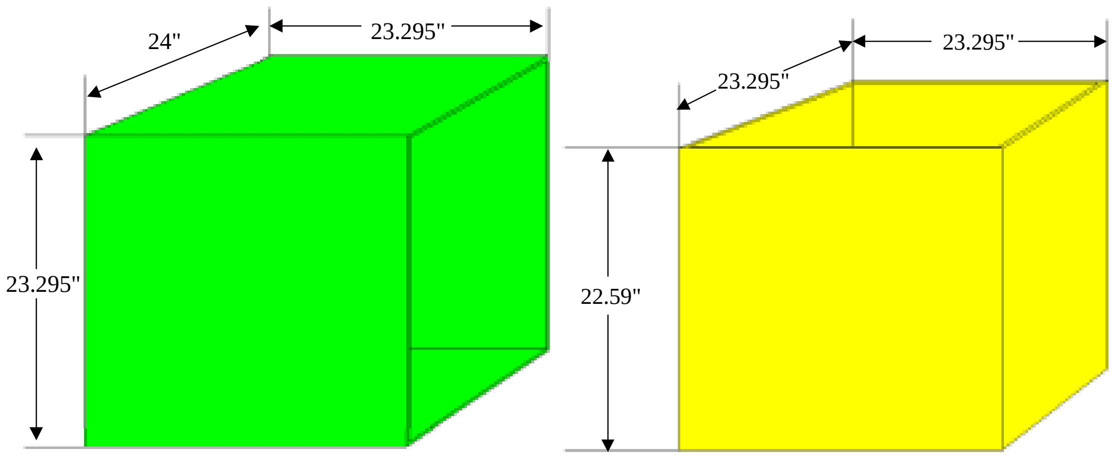


Figure B-2. Middle (left) and Inner (right) Bands.

Uncoupled Load Calculations

For the *ABAQUS* explicit run of the blast containment box a user-defined subroutine was needed to couple the *Gemini* code results. The *Gemini* hydro-code was first run separately to obtain pressure values to be passed into *ABAQUS*. Three planes of symmetry were used both in the *Gemini* and *ABAQUS* explicit runs. For the *Gemini* run a 1/8 pound cube of C4 was used as the explosive charge. The domain for the *Gemini* run consisted of 1/8 of the actual blast containment box utilizing the symmetry planes. Wall boundary conditions were used where the mid-plane of the blast box structure would be located. A 100x100x100 3D grid was used extending 29.18 cm in each direction, giving a grid cell size of 0.2918 cm. Each blast containment box surface was subdivided into 9 equal size areas. The edges where the surfaces join were subdivided into three equal size areas for each edge. The corner of the containment box was given its own area. An example for each type of are subdivision is shown below in Figures B-3 to B-5. Time history points were saved for the midpoint of each of these areas. Those history points stored the pressure versus time data that was passed to the *ABAQUS* run. The midpoint of the area was chosen because it corresponded to an approximately average pressure for the given area. In the *HyperMesh* model each area was divided using entity sets. These entity sets were named according to their location on the body. When the model was exported to an *ABAQUS* deck these entity sets were made into surfaces, with each surface having a name corresponding to a specific geometric location. The surface names were passed to the subroutine VDLOAD to apply a non-uniform, time dependent distributed pressure load for the structure.

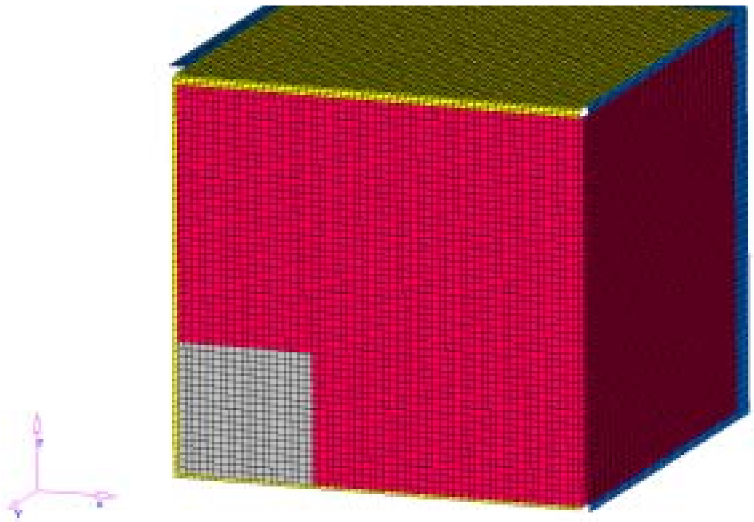


Figure B-3. An example of one area subdivision (XZAREA1 entity set).

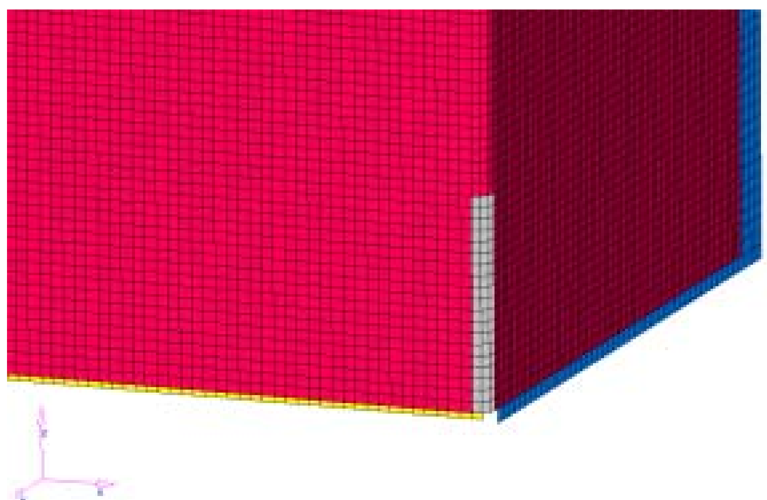


Figure B-4. An example of one edge subdivision (ZEDGE1 entity set).

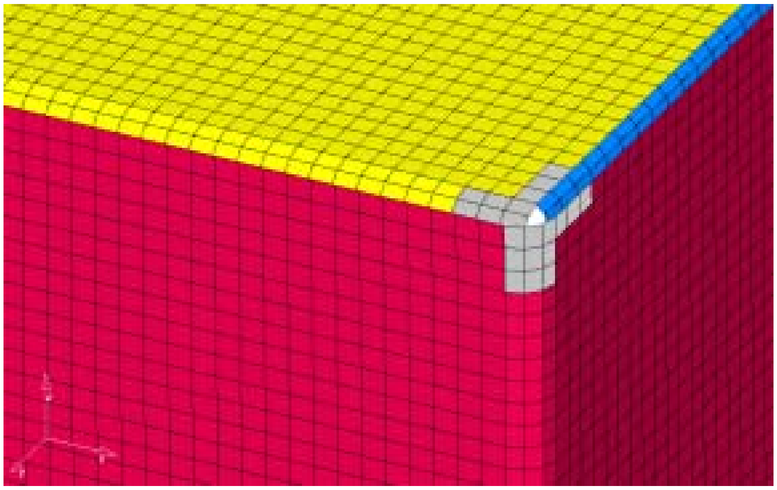


Figure B-5. Corner Subdivision (CORNERI & CORNERM entity sets).

VDLOAD is a user-defined subroutine, written in FORTRAN, for *ABAQUS*. For this model, VDLOAD allowed the application of a non-uniform, time dependent distributed pressure load to the blast containment structure. The key inputs for VDLOAD were total time and surface name that were passed in from the *ABAQUS* explicit run. The surface name was used to locate and open the appropriate data file. Once opened, the subroutine scanned the data file to find a time entry just before and just after the current time. When the appropriate data points were located a simple Lagrange formula (equation (B-2)) for linear interpolation was used to calculate the corresponding pressure value.

$$f(x) = \frac{(x - x_2)}{(x_1 - x_2)} f_1 + \frac{(x - x_1)}{(x_2 - x_1)} f_2 \tag{B-2}$$

Subroutine VDLOAD:

```
      subroutine vdload(
c Read only (unmodifiable)variable -
     1   nblock, ndim, stepTime, totalTime,
     1   amplitude, curCoords, velocity, dirCos, jltyp, sname,
c Write only (modifiable) variable -
     1   value )
c file = path(1:30)//filename(1:11)
      include 'vaba_param.inc'
      dimension curCoords(nblock,ndim), velocity(nblock,ndim)
      dimension dirCos(nblock,ndim,ndim), value(nblock)
      character*80 sname
      character*80 filename
      character*80 path, file
c Be sure to change the path name ro each run in abaqus
      path = '/lun10/jrenzi/blastcont/varp1/'
c Check for the right file name
      if (sname(1:7).EQ.'YZAREA1')then
      filename='yzarea1.dat'
      else if (sname(1:7).EQ.'YZAREA2')then
```

```
filename='yzarea2.dat'
else if (sname(1:7).EQ.'YZAREA3')then
filename='yzarea3.dat'
else if (sname(1:7).EQ.'YZAREA4')then
filename='yzarea4.dat'
else if (sname(1:7).EQ.'YZAREA5')then
filename='yzarea5.dat'
else if (sname(1:7).EQ.'YZAREA6')then
filename='yzarea6.dat'
else if (sname(1:7).EQ.'YZAREA7')then
filename='yzarea7.dat'
else if (sname(1:7).EQ.'YZAREA8')then
filename='yzarea8.dat'
else if (sname(1:7).EQ.'YZAREA9')then
filename='yzarea9.dat'
else if (sname(1:7).EQ.'XZAREA1')then
filename='xzarea1.dat'
else if (sname(1:7).EQ.'XZAREA2')then
filename='xzarea2.dat'
else if (sname(1:7).EQ.'XZAREA3')then
filename='xzarea3.dat'
else if (sname(1:7).EQ.'XZAREA4')then
filename='xzarea4.dat'
else if (sname(1:7).EQ.'XZAREA5')then
filename='xzarea5.dat'
else if (sname(1:7).EQ.'XZAREA6')then
filename='xzarea6.dat'
else if (sname(1:7).EQ.'XZAREA7')then
filename='xzarea7.dat'
else if (sname(1:7).EQ.'XZAREA8')then
filename='xzarea8.dat'
else if (sname(1:7).EQ.'XZAREA9')then
filename='xzarea9.dat'
else if (sname(1:6).EQ.'ZEDGE1')then
filename='zedge1.dat'
else if (sname(1:6).EQ.'ZEDGE2')then
filename='zedge2.dat'
else if (sname(1:6).EQ.'ZEDGE3')then
filename='zedge3.dat'
else if (sname(1:7).EQ.'XYAREA1')then
filename='xyarea1.dat'
else if (sname(1:7).EQ.'XYAREA2')then
filename='xyarea2.dat'
else if (sname(1:7).EQ.'XYAREA3')then
filename='xyarea3.dat'
else if (sname(1:7).EQ.'XYAREA4')then
filename='xyarea4.dat'
else if (sname(1:7).EQ.'XYAREA5')then
filename='xyarea5.dat'
else if (sname(1:7).EQ.'XYAREA6')then
filename='xyarea6.dat'
else if (sname(1:7).EQ.'XYAREA7')then
filename='xyarea7.dat'
else if (sname(1:7).EQ.'XYAREA8')then
filename='xyarea8.dat'
else if (sname(1:7).EQ.'XYAREA9')then
filename='xyarea9.dat'
```

```
      else if (sname(1:6).EQ.'XEDGE1')then
      filename='xedge1.dat'
      else if (sname(1:6).EQ.'XEDGE2')then
      filename='xedge2.dat'
      else if (sname(1:6).EQ.'XEDGE3')then
      filename='xedge3.dat'
      else if (sname(1:7).EQ.'YEDGE1I')then
      filename='yedge1.dat'
      else if (sname(1:7).EQ.'YEDGE2I')then
      filename='yedge2.dat'
      else if (sname(1:7).EQ.'YEDGE3I')then
      filename='yedge3.dat'
      else if (sname(1:7).EQ.'CORNERI')then
      filename='corner.dat'
      else if (sname(1:7).EQ.'YEDGE1M')then
      filename='yedge1.dat'
      else if (sname(1:7).EQ.'YEDGE2M')then
      filename='yedge2.dat'
      else if (sname(1:7).EQ.'YEDGE3M')then
      filename='yedge3.dat'
      else if (sname(1:7).EQ.'CORNERM')then
      filename='corner.dat'
      else
      write (6,*) "no file name"
      filename= 'garbage.out'
      end if
      file = path(1:30)//filename(1:11)
c open file
      do 100 km = 1, nblock
      open(115, FILE=file, status='old')
      read(115,*)t1, p1
      patm=p1
      ierror = 0
      do while (ierror.EQ.0)
      read(115,*)t2, p2
c convert from msec to sec
      time1=t1*0.001
      time2=t2*0.001
c convert from dyne/cm^2 to psi
      pres1=(p1-patm)*1.4503774E-5
      pres2=(p2-patm)*1.4503774E-5
      if((time1.LE.totalTime).and.(time2.GE.totalTime))then
c Linear Interpilation for time and pressure
      top=(totalTime-time2)*pres1+(time1-totalTime)*pres2
      bottom=time1-time2
      p=top/bottom
      ierror=1
      end if
      t1=t2
      p1=p2
      end do
      value(km)=p
      close(115)
  100 continue
      return
      end
```

Appendix C

Estimate of Equilibrium Pressure for a Confined Explosion

Andrew B. Wardlaw, Jr.

A spherical charge of C4 is detonated inside an air-filled, spherical container. Here we discuss a method of estimating the final equilibrium pressure calculated by the *Gemini* Euler solver.

We assume the C4 detonation occurs at time $t=0$ and is a constant volume event. Thus at the start of the problem 439 g of C4 and at the reference conditions (ρ_0 =1.61 g/cc and e_0 = 5.62E+10 ergs/cc) and 195 g of air at 1 pressure of 1 bar and density of 0.001 g/cc fill the chamber. To estimate the final equilibrium state at time t_e, we require that:

1. Energy be conserved: $E_{C4}(0) + E_A(0) = E_{C4}(t_e) + E_A(t_e)$

2. Mass of air and C4 be conserved: $M_{C4} = \rho_{C4} V_{C4} = const$ and $M_C = \rho_A V_A = const$

3. At equilibrium, air and C4 pressure must be equal: $p_{C4}(t_e) = p_A(t_e)$

To obtain a solution we must define how the initial energy is distributed. Since the calculation that we are simulating is inviscid the final state in the chamber will not be in temperature equilibrium. Here equilibrium occurs when the initial fluid motion induced by the pressure imbalance between C4 and air at $t=0$ is converted to internal energy via the numerical dissipative properties of the code. This yields a stationary fluid satisfying the above three conditions, but with an unknown energy distribution between the air and the C4. We will use two bracketing assumptions to bound the answer obtained by the numerical simulation:

1. C4 material expands isentropically and the kinetic energy that induced in the system is completely absorbed by the air.

2. C4 material expands at constant energy and thus absorbs all of the kinetic energy.

The resulting equilibrium pressure for assumptions 1 and 2 are 695 psi and 473 psi, respectively, and bracket the computational one of 570 psi. These were obtained graphically from Figures C-1 and C-2.

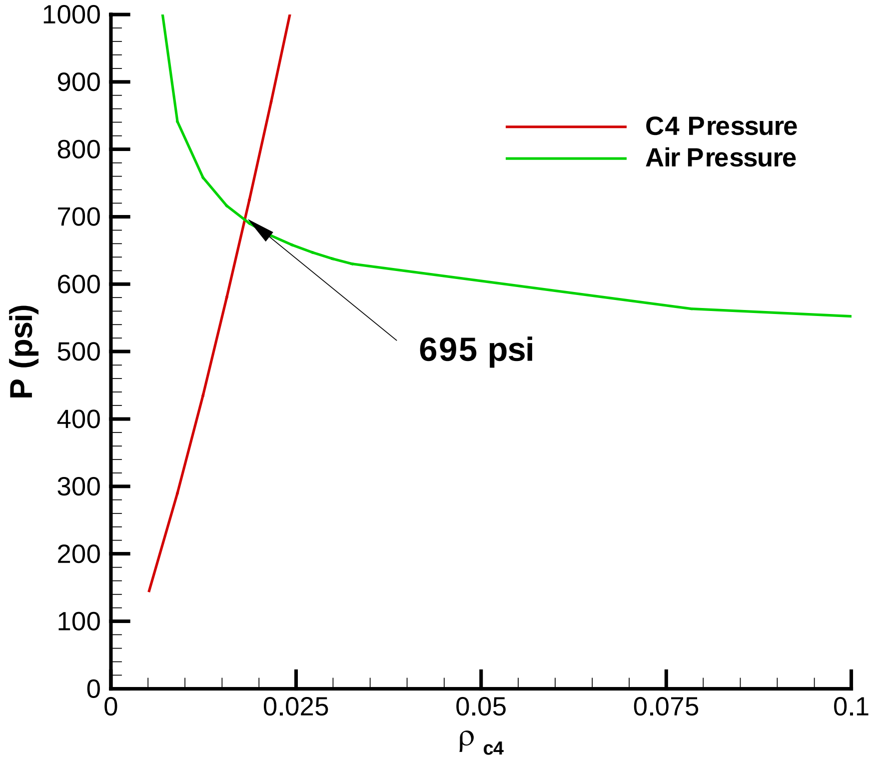


Figure C-1. Pressure Equilibrium for C4 Isentropic Expansion.

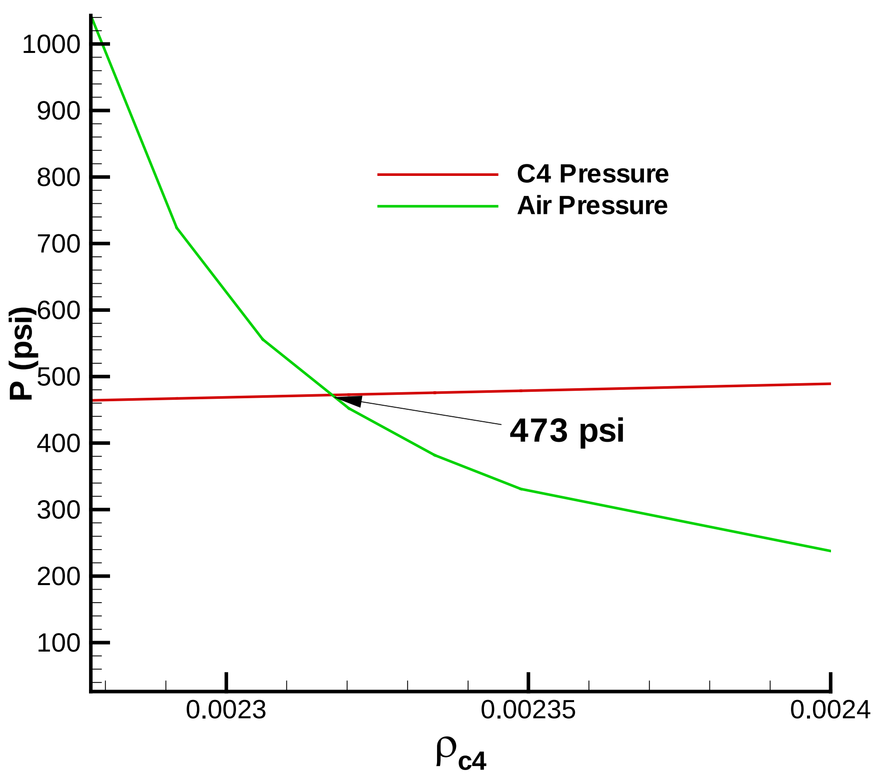


Figure C-2. Pressure Equilibrium for C4 Constant Energy Expansion.

Appendix D

Pressure Estimation for an Explosive Detonation within a Closed Volume

William B. Harvey

To make a relatively simple estimation of the final pressure within a closed volume from the detonation of an explosive inside that volume, some assumptions concerning the explosive must be made. The first assumption to make is that the equation of state for the detonation products can be described by a gas-law equation of state,

$$P = (\gamma - 1)\rho E \ . \qquad \text{(D-1)}$$

In equation (D-1), P is the pressure, ρ is the density and E is the specific internal energy of the detonation products. The parameter γ is a constant characteristic of the explosive. It will also be assumed that the equation of state for the air within the volume can be described by equation (D-1) but with different parameter values.

After the detonation has taken place it will be assumed that the air and detonation products will reach the same final pressure. This implies

$$(\gamma_H - 1)\rho_H E_H = (\gamma_A - 1)\rho_A E_A \ , \qquad \text{(D-2)}$$

where the subscript *H* refers to the detonation products of the explosive and the *A* subscript refers to the air.

The question now arises as to the procedure to calculate the final densities of the air and the detonation products as well as the final specific internal energies. If V_T is the volume of the enclosure and V_H is the final volume occupied by the explosive products then the final density of the detonation products is given by $\rho_H = m_H / V_H$ where m_H is the mass of the explosive. The air will occupy the remaining volume so the final density for the air is given by $\rho_A = m_A / (V_T - V_H)$ where m_A is the mass of the air. To calculate the final energies it will be assumed that the explosive-air system does not lose any energy to the enclosure. If E_O is the specific energy liberated with the detonation process then it must hold true under the assumptions made thus far that

$$m_H E_O = m_H E_H + m_A E_A \ . \qquad \text{(D-3)}$$

In equations (D-2) and (D-3), three unknown quantities can be identified, E_H, E_A, and V_H. To solve for these three unknowns a third equation must be invoked. The assumption is now made that the detonation products will release isentropically to the final pressure. It must be emphasized that it is explicitly not assumed that the air is compressed isentropically. Based on this last assumption then the final energy for the detonation products can be related to E_O by the equation

$$E_H = E_O \left\{ \frac{V_O}{V_H} \right\}^{\gamma_H - 1} . \tag{D-4}$$

Equations (D-2), (D-3), and (D-4) form a complete system of equations to solve for the final pressure. As an example consider a one-pound charge of C4 exploding in an enclosure of eight cubic feet. Explosive C4 has an approximate density of 1.6 g/cc, a detonation velocity of approximately 8.2 km/s and a detonation pressure of 280 kbars. When equation (D-1) is used to describe the detonation products it is found that γ_H is approximately 2.84 and E_O is 47.5 kbars-cc/g. Assuming that the air is initially at 1 bar with a density of 0.0013 g/cc the final pressure will be approximately 38.8 bars.