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Model Validation of a Structure Subjected to Internal Blast Loading

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ABSTRACT

In order to predict blast damage on structures, it is current industry practice to decouple shock calculations from computational structural dynamics calculations. Pressure-time histories from experimental tests were used to assess computational models developed using a shock physics code (CTH) and a structural dynamics code (PRONTO3D). CTH was shown to be able to reproduce three independent characteristics of a blast wave: arrival time, peak overpressure, and decay time. Excellent agreement was achieved for early times, where the rigid wall assumptions used in the model analysis were valid. A one-way coupling was performed for this blast-structure interaction problem by taking the pressure-time history from the shock physics simulation and applying it to the structure at the corresponding locations in the PRONTO3D simulation to capture the structural deformation. In general, the one-way coupling was shown to be a cost-effective means of predicting the structural response when the time duration of the load was less than the response time of the structure. Therefore, the computational models were successfully evaluated for the internal blast problems studied herein.

OVERVIEW

Blast-structure interaction problems involving an explosive charge at a standoff from a thin-walled steel structure pose significant challenges to accurate model predictions and often require expensive test series to elucidate the complex coupled structural and blast response. Additionally, validation studies can often strain experimental and computational budgets due to expensive test series or availability of compute resources to do possibly tens or hundreds of high-fidelity computations. This paper presents the tradeoff of the necessary through-thickness grid refinement versus computational physics resolution for an Eulerian treatment of a structure. Furthermore, results from a large-scale blast-structure interaction test series are provided, and these data are compared to complementary simulations using a shock physics code and a one-way coupling to a finite element code with a shell element formulation. This represents an engineering model assessment exercise where large scale test series and large scale computing often limit the scope of ideal model validation.

BLAST PHYSICS

Simulating blast events coupled with structural response is difficult. There is no one numerical method that can economically model the wide range of length scales typical of a blast against a thin-walled structure. The computational demands of predicting damage to thin, shell-like targets often exceed the computational resources available. This situation is true even when very large parallel computers are used in the simulations. Because the computational challenge is so great, most simulations will make assumptions that allow them to reduce the computational expense. The assumptions that work well in one regime may be inappropriate in another. Several different approaches are typically used depending on the charge location, charge size, and target geometry. Ideally one would like to model the effects of the explosive geometry, shock propagation, shock interaction,

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fragmentation, structural failure, and long-term structural response using one numerical simulation tool. Shock physics codes such as CTH [1, 2] with Adaptive Mesh Refinement (AMR) can generally model most of these effects; however, capturing the late-time structural response is most computationally efficiently solved with a FEM code with a shell element formulation such as PRONTO3D [3,4].

Depending upon the size of the problem (total number of computational cells and time steps), a shock physics code, or a Finite Element Method (FEM) code with a shell element formulation, or a coupled approach may be appropriate to capture the relevant problem physics. In Eulerian shock physics codes, the time step is explicitly controlled by the cell thickness and billions of cells can be required to capture the physics (air and explosive shocks, spall, debris tracking, fragmentation). These computations can be very costly, both in CPU time and memory required. With FEM codes that model thin features with shell elements, the through-thickness time step requirement is eliminated and larger time steps are possible, resulting in quicker run times. However, shocks, spallation, or fragment tracking cannot be captured with the shell element formulation.

The trade-offs between through-thickness cell resolution of an isotropic material and representative physics resolution for an Eulerian shock physics simulation are provided in Table 1. The qualitative descriptions *No*, *Some*, and *Yes* are experientially based and would need to be evaluated for a particular code or model. Note that these are only the necessary resolution conditions, but not sufficient conditions. Accurate models for each feature are required to capture the necessary physics.

Table 1. Representative physics feature as a function of cell resolution through an isotropic material.

Physics Feature	Resolution			
	Minimum (1 to 2 Cells)	Low (3 to 5 Cells)	Medium (5 to 7 Cells)	High (7 to 15 Cells)
Air Shock	Yes	Yes	Yes	Yes
Blast Impulse	Some	Yes	Yes	Yes
Through Thickness Shock	No	Some	Yes	Yes
Fragmentation	No	No	Some	Yes
Debris Tracking	No	No	Some	Yes
Spall	No	No	Some	Some
Ductile Tearing	No	No	No	Some
Bending Strength	No	No	Some	Yes
Welds	No	Some	Some	Yes
Internal Blast Pressures	Some	Some	Yes	Yes

Accordingly, for a shock physics simulation, incorporating a minimum of 1 to 2 cells resolution will enable capturing of the air shock (at impact surface), some blast impulse and some blast pressures inside of the structure. At this resolution, the structural response will be mostly hydrodynamic. Increasing to a low resolution of 3 to 5 cells through the thickness will enable better prediction of the blast impulse and some resolution of structural mechanics and through-thickness shock pressure. By increasing to a medium resolution of 5 to 7 cells through the thickness, through thickness shocks can be tracked as well as some wall bending, fragmentation, debris tracking, and spall. Provided the code has the necessary physics, a high resolution of 7 to 15 cells through the thickness can capture fragmentation, debris tracking, bending, and weld mechanics, while some ductile tearing and spallation can also be captured.

The relevant computational physics features needed to be captured in blast-structure interaction problems are strongly affected by charge standoff from the impact surface. These computational regimes, determined by standoff and structural response, are tabulated in Table 2. The *difficulty* of the simulation, as qualitatively described on a scale from 1 to 5, where 5 is the most computationally challenging, is based upon the computational expense in terms of number of cells, time step, CPU time, necessary physics features, code coupling procedures, etc.

Table 2. Representative physics per computational regime and numerical challenge.

Regime #	Computational Regimes	Difficulty
1	Small standoff—early time fragmentation	3
2	Small standoff—late time structural failure	4
3	Intermediate standoff—combination of fragmentation and structural failure with internal blast pressures	5
4	Large standoff—early structural failure before blast wave has passed	4
5	Large standoff—late structural failure	3

For blast-structure interaction problems, the most computationally efficient methods of solution for these computational regimes are shock physics code formulations, finite element formulations (with shells or higher order elements), one-way or two-way coupling methods (between a shock physics code and a finite element formulation with shells or higher order elements). An Eulerian shock physics code is the most appropriate choice to model *Regime 1*. For modeling *Regimes 2* and *4*, one-way coupling methods are generally the most computationally efficient; however, an Eulerian shock physics code could also be exclusively used for *Regime 4*. A finite element formulation (with shells or higher order elements) is the most appropriate choice to model *Regime 5*; however, blast pressures will be needed from another source.

A two-way coupling scheme is the most computationally efficient method to model *Regime 3*; however, such methodology can be problematic and clearly represents an active area of research. Since stress waves through the element thickness are eliminated in the shell formulation, errors in transmitting and reflecting strong shocks often occur and the magnitude of these tracking errors are strongly dependent upon the impedance imbalance between the Eulerian material and the shell. Limited success has been achieved in modeling structural failure using a two-way coupling with shell tearing. The best results for two-way coupling with shells are achieved when the Eulerian computational regions can be divided into an *inside* and *outside*. For these cases, each computational region is solved independently with the pressures from each computational region mapped onto the shell faces. The assumption for two-way coupling often breaks down when shell elements are used to model blast debris impacts or when the blast wave propagates through a failed structure.

Even with the highest resolution simulations currently possible, not all of the physics will be included in the simulations. A simulation should be viewed as a partial truth, fully exposed. Often, low fidelity simulations will provide insight that is not possible with full-scale testing. This insight is gained by advanced visualization of highly resolved (both space and time) data representing vector fields.

BLAST EXPERIMENTS

Blast testing was conducted at the Validation and Qualification Sciences Experimental Complex (VQSEC) at Sandia National Laboratories (SNL). These tests on simplified structures were used to economically assess the structural response and to provide data for engineering model assessment. The particular test item consisted of a welded steel box subjected to internal blast loading, as shown in Figure 1. The walls of the box were constructed from 3/16-in.-thick A36 steel plate. The individual plates were set with a ~0.10-in. gap and butt welded with the intent of 100% penetration. A continuous weld was created in two passes to avoid heat induced warping of the structure. The corners of the box were constructed using a steel angle with the plates overlapping on the inside of the angle and welded along the outside. The butt and lap welds were characterized from quasi-static pull tests on welded coupons. The strain was measured over a one-inch gauge length that included both the weld and some plate material. The weld quality was good and the failure strain was typically greater than 3%.

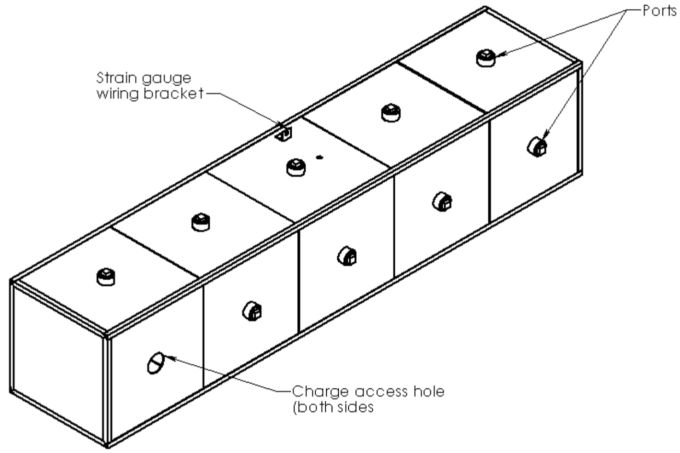

Figure 1. Schematic of the welded steel box used for blast experiments.

State-of-the-art data collection and photometric capabilities at SNL were used to interpret the experiments. The box was instrumented with four active pressure gauges, a noise-documenting pressure gauge, and two strain gauges. Endevco 8530B-500 and 8530A-1000 pressure gauges were used, which were piezoresistive MEMS type pressure transducers. The 8530B-500 transducers were modified by the manufacturer for explosive blast applications. These gauges used the "B" screen for greater particle-impingement protection and the diaphragms were coated in black grease to eliminate photosensitivity effects. Strain gauges were placed on the top and bottom measuring in the "hoop" direction, transverse to the long axis of the box. High-strain capable EP-08-125AC-350 strain gauges from Micro Measurements were installed with AE-15 epoxy cured at 150 ºF. This combination was specified for measuring strains of 10-15%. Micro Measurements MR1-350-130 precision resistor blocks were used to complete the bridge within inches of the gauge. Instrumentation data were collected with a mobile instrumentation unit (MIU) trailer. The pressure and strain gauges were sampled at 500 kHz with a 50-kHz anti-aliasing filter applied to the data prior to digitization. High-speed video coverage of the blast tests were recorded with five high-speed, Phantom digital cameras (3000 to 4800 fps) and two real-time video cameras (30 fps) split between two camera stations.

The box exhibited a late-time structural response to the internal blast loading, with the final shape of the box being nearly cylindrical, as the plates rounded due to the expansion of the explosive gases which vented from access ports. Although the box remained intact, very localized weld failure occurred at some junctions between the plate and angle irons, where insufficient weld penetration caused the welds to pull away from the plates. For the late-time structural response from the small explosive standoff, this problem is characterized according to computational *Regime 2* (from Table 2), where a one-way coupling scheme is the most computationally efficient solution method.

COMPUTATIONAL SETUP

A one-way coupling between CTH and PRONTO3D was used as a computationally efficient solution method. The internal blast physics were captured using CTH with AMR to resolve steep pressure gradients. Rigid wall boundaries were used, which provided an upper bound on reflected pressure prediction and facilitated hand off to PRONTO3D.

CTH Simulations

CTH is a shock physics code developed by SNL to model strong shock-wave propagation and material motion in multi-dimensions. Options for massively parallel computing and adaptive mesh refinement are available for resolving key areas of interest in the problem domain. Lagrangian forms of the conservation equations for mass, momentum, and energy are solved in conjunction with equation-of-state (EOS) and constitutive models. The deformed volumes are mapped onto the Eulerian grid in a remap step. These EOS and constitutive models, which are suitable for most conditions encountered in shock physics, are available for predicting material strength, fracture, porous materials, and high explosives. Interactive and post-processing options are available for displaying graphics. The thermodynamic behavior of the materials used in these simulations was described by a tabular SESAME EOS. The tabular form of the EOS allows for the representation of sophisticated phase transitions, and the look-up scheme is computationally efficient on parallel computers. Detonation of the high explosives is captured by the HEBURN model that propagates an ideal shock wave at the detonation velocity and pressure from a user-specified initiation point. All the CTH analyses reported here were compiled and run with dedicated nodes on the Feynman cluster at SNL. This machine presently includes more than 371 dual Intel Xeon nodes or 742 processors on a Red-Hat Linux operating system.

The problem definition for the CTH analyses consisted of a cylindrical charge placed at a location consistent with the experiment. Interior box dimensions were represented in the computational domain to facilitate hand off to PRONTO3D. Symmetry was used to reduce the computational expense. The CTH simulations contained over a million cells and were typically run on 100 compute nodes.

PRONTO3D Simulations
A finite element model was created for the structural analysis consisting of approximately 95,000 shell elements. A symmetry plane, consistent with the CTH model, was used to reduce computational expense. The plates and structural angles were included, and their material properties were based on handbook values [5]. The welds were modeled with one element wide strips. The elements in these strips were given material properties based on the weld tests. Thus, the effect of the welds was included without modeling the actual weld geometry. Furthermore, the mass of the actual box was represented by the finite element model. The container was divided into 420 sections that were roughly square, as shown in Figure 2. A unique pressure-time history, by averaging point data in CTH, was passed to the PRONTO3D model at each patch shown in Figure 2. The back wall appears to be divided into six long sections because the graphics package reuses the same six colors. However, it has the same number of pressure sections (32) along its length as the floor and ceiling.

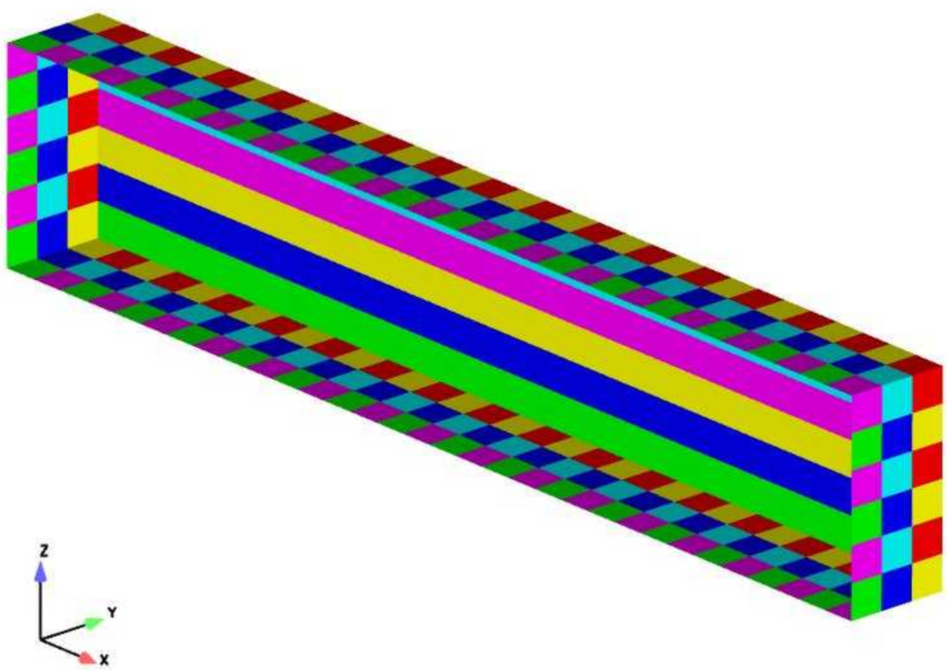

Figure 2: Pressure patches used for one-way coupling to PRONTO3D model.

RESULTS

The comparison between the experimental results and CTH predictions demonstrate remarkable agreement in peak overpressure, decay time, and arrival time, at early times, as shown in Figure 3. The repeatability in the pressure measurements is approximately ±15%. At later times, the pressure gauge attachments fail and the box vents. A comparison between the experimental structural deformation and the PRONTO3D predictions is shown in Figure 4. Strain gauge measurements were compared with the PRONTO3D simulations, as shown in Figure 5. Good agreement was achieved between model and experiment, confirming the qualitative agreement shown in Figure 4. This good agreement resulted from a combination of factors, such as using codes and physics models that were sufficiently verified and validated for this problem class, sampling the computed pressures using a similar sample rate as the experiment, and averaging the analysis pressure-time data over the square pressure patches that were representative of the pressure gauge surface area.

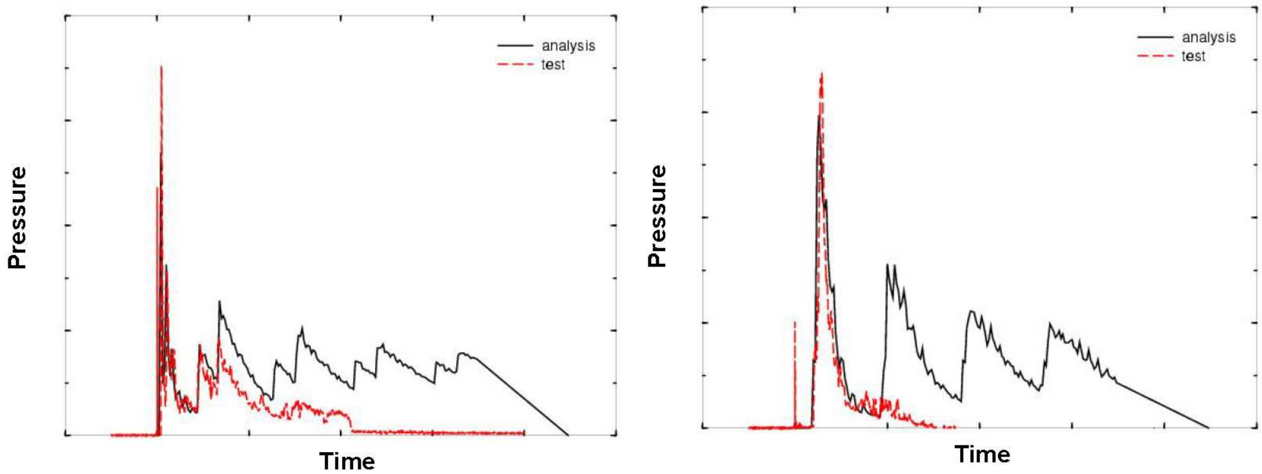

Figure 3. Comparison between test and CTH analysis at two gauge locations.

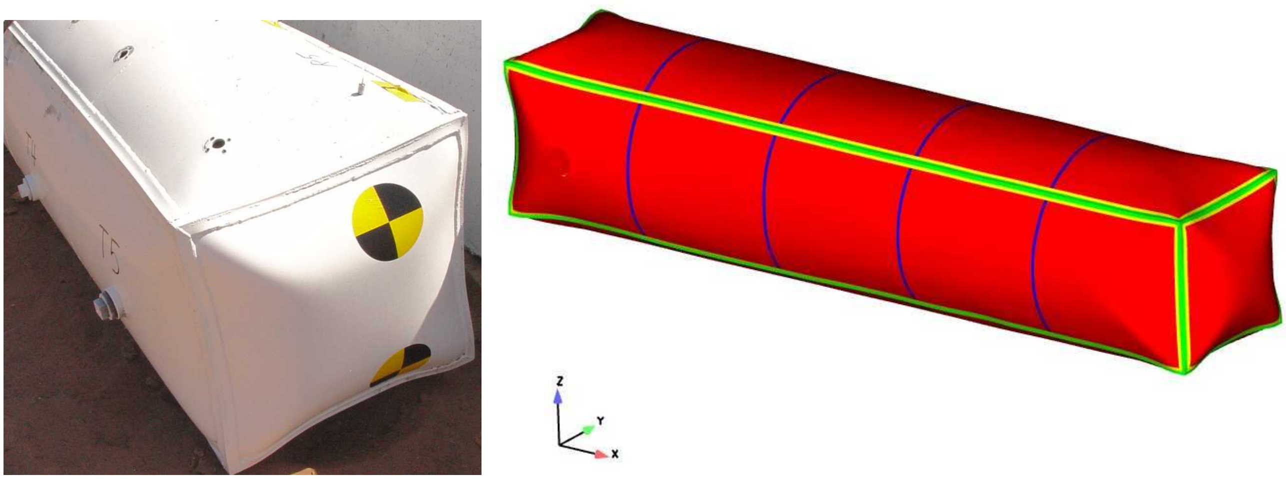

Figure 4. Experimental structural deformation and PRONTO3D structural dynamics prediction.

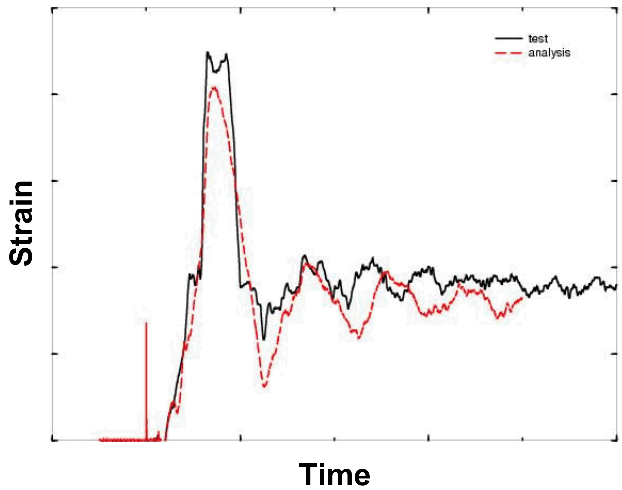

Figure 5. Comparison between test and PRONTO3D strains at one gauge location.

The test and analysis presented herein were used to make risk-informed decisions about structural design. Given the budget and time constraints of this project, a best estimate with nominal material properties was provided. The expense of the experiments and computations with a complex coupling between two computational models limited the feasibility of both repeated testing and computations. Ideally, more experiments and possibly tens or hundreds of computations with a separate dedicated budget for code verification and validation (V&V), and uncertainty quantification (UQ) would provide an ideal model validation according to Sandia's established V&V/UQ methodology. There are ongoing research efforts at Sandia to provide the right balance between ideal and realistic validation exercises that meet wide-ranging customer needs and address complex solution methodologies.

CONCLUSION

This paper illustrates the necessary blast physics and cell resolution, and identifies typical computational regimes that are needed to understand complex blast-structure interaction problems. For the particular problem investigated herein, where a small standoff and late structural response characterized this problem, a one-way coupling scheme was shown to be the most computationally efficient method of solution. Pressure-time histories from a representative box apparatus, constructed from welded sheet steel, were used to assess computational models developed using CTH and PRONTO3D. CTH was shown to be able to able to reproduce three independent characteristics of a blast wave: arrival time, peak overpressure, and decay time. Excellent agreement was achieved for early times, where the rigid wall assumptions used in the model analysis were valid. To determine the late-time structural response, a structural model was developed using PRONTO3D. A one-way coupling between CTH and PRONTO3D was established to apply blast pressures to the structural response model. Excellent agreement was achieved between the structural response and the experimental photometrics. Furthermore, the strain-gauge data was well predicted, confirming the qualitative structural data from the photometrics. In general, the one-way coupling was shown to be a cost-effective means of predicting the structural response when time duration of the applied load was less than the response time of the structure. This paper presents an example of where expensive explosive testing and high performance massively parallel computing can limit the scope of model validation. A well characterized high-fidelity model, with data from complementary experiments can be used to predict complex phenomena where repeated experiments are cost-prohibitive.

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