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Modeling the Blast Load Simulator Airblast Environment Using First Principles Codes

Report 2: Blast Load Simulator Environment, Single Structures

Gregory C. Bessette, James L. O'Daniel, Stephen A. Akers,
Andrew T. Barnes, Gustavo Emmanuelli, Mark A. Hunt,
and Richard A. Weed

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Report 2: Blast Load Simulator Environment, Single Structures

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Abstract

The Blast Load Simulator (BLS) at the U.S. Army Engineer Research and Development Center (ERDC) has been utilized for applying simulated blast loads on structures for over a decade. An integrated experimental and computational program was undertaken to evaluate first principles codes (FPCs) for modeling airblast environments typical of those encountered in the BLS. The FPCs considered are CTH, DYSMAS, Loci/BLAST, and SHAMRC. The modeling is a multi-year effort and utilizes a number of BLS configurations for the code evaluation. The modeling discussed herein builds upon the first year, which examined the flow environment within an empty BLS and a case involving a single box-like structure. The current effort expands on the single-structure scenario by employing venting at the target end of the BLS to mitigate upstream reflections and ensure a more ideal loading pulse on the structure. Three structure configurations are considered for this effort. The first is a baseline case with the front face of the box oriented perpendicular to the incoming flow. The remaining two configurations consider a rotated box at 30- and 45-deg obliquity with respect to the incoming flow. Comparisons of modeling results and BLS measurements are discussed. Shortcomings in the modeling physics are identified, and areas for improvement are noted for future development.

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Preface

This study was conducted for the Defense Threat Reduction Agency (DTRA) under the Nuclear Airblast and Thermal Environment Test and Modeling project. The DTRA technical monitor was Dr. Culbert B. Laney.

The work was performed by the Structural Mechanics Branch (SMB) and the Geosciences and Structures Division (GSD) Research Group and the Impact and Explosive Effects Branch (IEEB) of the Engineering Systems and Materials Division (ESMD), U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory (ERDC-GSL). The ERDC manager for this program was Dr. James L. O'Daniel. The calculations discussed in this report were carried out on high-performance computing systems available at the Department of Defense Supercomputing Centers as well as at Mississippi State University.

At the time of publication, Mr. Bradford A. Steed was Chief, SMB; Mr. Jeffery G. Averett was Chief, IEEB; Mr. James L. Davis was Chief, GSD; Dr. Gordon W. McMahon was Chief, ESMD; and Ms. Pamela G. Kinnebrew was the Technical Director for Military Engineering. The Deputy Director of ERDC-GSL was Dr. William P. Grogan, and the Director was Mr. Bartley P. Durst.

COL Ivan P. Beckman was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
atmosphere (standard)	101.325	kilopascals
bars	100	kilopascals
feet	0.3048	meters
foot-pounds force	1.355818	joules
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per cubic inch	2.757990 E+04	kilograms per cubic meter
pounds (mass) per square foot	4.882428	kilograms per square meter
pounds (mass) per square yard	0.542492	kilograms per square meter
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

1 Introduction

1.1 Objective

The Blast Load Simulator (BLS) at the U.S. Army Engineer Research and Development Center (ERDC) has been utilized for applying simulated blast loads on structures for more than a decade. An integrated experimental and computational program has been undertaken for the Defense Threat Reduction Agency (DTRA) to evaluate several first-principles codes (FPCs) for modeling airblast environments typical of those encountered in the BLS. This integrated program will assess both computational accuracy and cost as well as identify any shortcomings in the physics modeling and areas for future improvement.

1.2 Purpose and scope

ERDC has been tasked by the DTRA to conduct an integrated experimental and computational program to evaluate a number of FPCs commonly used within the Department of Defense (DoD) community for modeling airblast. The modeling is a multi-year effort and utilizes a number of BLS configurations to scope out conditions for code evaluation. The modeling discussed herein builds on the first year of research, which examined the flow environment within an empty BLS as well as a case involving a single boxlike structure (Bessette et al. 2016, Dallriva et al. 2017, Mord 2015, O'Daniel et al. 2017). The current effort expands on the single-structure scenario by employing venting at the target end of the BLS to mitigate upstream reflections and ensure a more ideal loading pulse. Three structure configurations are considered for the modeling effort reported here. The first is a baseline case with the front face of the box structure oriented perpendicular to the incoming flow. The remaining two configurations considered a rotated box at 30- and 45-deg obliquity with respect to the incoming flow. These pose a more challenging environment for FPC evaluation. In all cases, the structure was instrumented on the exposed surfaces to provide data for the model comparisons.

The codes evaluated in this effort include the CTH code, developed by Sandia National Laboratories (McGlaun et al. 1990, Crawford et al. 2013); Dynamic System Mechanics Advanced Simulation (DYSMAS), developed by the U.S. Navy, Naval Surface Warfare Center, Indian Head (Harris et al.

2014); Loci/BLAST (Luke 1999, Luke and George 2005, Thompson et al. 2012), developed by the Mississippi State University (MSU) Center for Advanced Vehicular Systems; and the Second-Order Hydrodynamic Automatic Mesh Refinement Code (SHAMRC), developed by Applied Research Associates (Crepeau et al. 2012). All of these codes utilize Eulerian solvers of various types. CTH, DYSMAS, and SHAMRC utilize a structured mesh in their solution while Loci/BLAST utilizes an unstructured mesh. There are other codes capable of modeling airblast; however, the ones chosen are thought to have a relatively broad user base with ongoing support on DoD High Performance Computing (HPC) platforms.

The FPCs evaluated here utilize varied numerical approaches for solving the conservation equations. Thus, the model assessment extends beyond just matching experimental data to include the viability of a numerical solver to model this class of airblast problems. The longer-term goal is to simulate complex three-dimensional (3-D) environments, which include a number of obstacles in the flow field. It is important to understand the capabilities (both strengths and weaknesses) of each FPC in a simplified setting before tackling more complicated problems.

This report focuses on the computational effort. A summary of the experimental program is provided for background. Further details on the BLS and the overall experimental program can be found in Dallriva et al. (2017) and O'Daniel et al. (2017). The main body of this report deals with the model comparisons and assessments of FPC capability. One should recognize that each code (and solver) is unique. The analysts conducting the calculations were given the flexibility to model the BLS tests in their own way.

Much of the first year's effort was devoted to investigating how to model the BLS environment. This involved exploring various equations of state (EOSs), conducting mesh resolution studies, and investigating how best to model the BLS driver section. This earlier work is documented in Bessette et al. (2016). As with the earlier reporting, an appendix is devoted to each FPC considered to allow for a detailed discussion of the model setup, the reasoning behind choices made in the setup, and lessons learned during the course of the modeling. The main body of this report focuses on the bigger picture, looking for overall trends and areas for improvement needed in the physics modeling.

2 BLS Overview and Test Configurations

The BLS is located on the main campus of ERDC in Vicksburg, MS. It is housed in a tunnel structure for noise suppression and containment, as depicted in Figure 1. The BLS is composed of a series of modular sections that allow flexibility in prescribing the downstream airblast environment. The configuration utilized in the testing discussed in this report is depicted in Figure 2. This particular configuration is referred to as the 8-ft by 8-ft configuration with a 4-ft gap. It is composed of (1) a constant diameter driver section with a striker mechanism and diaphragm, (2) a continuously vented cone (CVC) section and conical expansion section, denoted as GSA C1, (3) a second non-vented conical expansion section, denoted as GSA C2, (4) two constant diameter transition (TR) sections, denoted as GSA TR1 and TR2, (5) a constant diameter, telescoping section, denoted as the GSA-Cascade, (6) a circle-to-square (C2SQ) transition, (7) a fixed-width square section (SQ1), and (8) the target vessel with mounted calibration plate. The sections depicted in Figure 2 are circular with the exception of the C2SQ, SQ1, and target vessel sections.

Figure 1. BLS residing within tunnel structure.

Figure 2. BLS 8-ft × 8-ft configuration with box structure and 4-ft gap.

The driver section is depicted in Figure 3. The driver diameter is fixed and has an inside diameter of 16 in. The length can be varied from 18 to 66 in. in 6-in. increments. This allows flexibility in controlling the loading pulse duration. During operations, a diaphragm is placed on the downstream end to enclose the pressure vessel. The driver is then pressurized to the desired test (burst) condition. A striker mechanism is placed outside of the diaphragm and subsequently is used to rupture it. Following rupture, the pressurized gas vents into the downstream BLS sections. The striker assembly (without the diaphragm) is depicted in Figure 4. The flange section of the assembly is bolted to the driver with the diaphragm on the inside to seal the pressure vessel during test operations. The BLS can accommodate mixed gases (e.g., helium and air); however, for the tests reported herein, the mixture was limited to 100% air to reduce uncertainty in the EOS modeling by the FPCs.

Figure 3. Driver section.

Figure 4. Striker assembly, striker, and flange.

The rupture of the diaphragm results in the generation of fragments that travel downstream. These fragments can adversely impact test structures placed within the BLS as well as damage other interior components and instrumentation. A grill is typically included in the test setup to trap fragments and to mitigate any damage to downstream components. The location of the grill in the BLS is shown in Figure 5. A photograph of the grill is provided in Figure 6. The outside diameter of the grill is 17-5/8 in. The horizontal and vertical bars in the grill are 1/8-in. thick with a depth of 1 in. The spacing between the horizontal and vertical bars is 1 in. and 4 in., respectively.

Figure 5. Grill placement in the BLS.

Figure 6. Photograph of grill.

The CVC cross section depicted in Figure 5 is composed of three cylindrical sections, referred to as CVC-1, -2, and -3. CVC-1 has a length and inner diameter of $31\frac{7}{8}$ in. and $16\frac{1}{16}$ in., respectively. CVC-2 has a length and inner diameter of $22\frac{1}{2}$ in. and 24 in., respectively. CVC-3 has a length and inner diameter of $22\frac{1}{2}$ in. and 32 in., respectively. The shell thickness for each section is $\frac{1}{2}$ in. The first and second sections overlap by $2\frac{15}{16}$ in. when the grill is attached to CVC-1. There are cylindrical vents at each overlap of the CVC sections. This provides a means for gas blowdown in the BLS and is particularly important when the tested configuration does not have a gap at the target vessel end.

The CVC connects to an expanding conical section that has a 20-deg cone angle. The length of the expansion section is $79\frac{13}{32}$ in. The inside diameter of this cone at the upstream and downstream sides is 40 in. and 68 in., respectively. The CVC and attached cone comprise the GSA C1 section. The shell thickness is $\frac{1}{2}$ in.

The GSA C2 is the next downstream section. It also has a 20-deg cone angle. The length of this section is $58\frac{1}{8}$ in. The inside diameter of the C2 cone at the upstream and downstream sides is 68 in. and $88\frac{1}{2}$ in., respectively. The shell thickness is $\frac{1}{2}$ in.

A series of constant diameter sections reside downstream of GSA C2. These are the two transition sections (TR1 and TR2) and the Cascade. The length and inner diameter of each of the transition sections is 46 in. and $88\frac{1}{2}$ in., respectively. The shell thickness for the transition sections is $\frac{1}{2}$ in. The Cascade is a telescoping section that allows for a variable length. The upstream Cascade section has a length and inner diameter of 58 in. and $88\frac{1}{2}$ in., respectively. The downstream Cascade section has a length and inner diameter of 52 in. and 91 in., respectively. The shell thickness for each is $\frac{1}{2}$ in. There is a slight radial gap between the Cascade sections to facilitate the telescopic movement.

The C2SQ transition section is attached to the Cascade, which in turn is attached to the SQ1 section. Dimensioned drawings for the C2SQ and SQ1 sections are provided in Figures 7 and 8, respectively. An interior view looking towards the target vessel is provided in Figure 9. Section C2SQ did not mate perfectly with the Cascade, resulting in an overlap at the radial extents. The largest overlap on the left-hand side was $1\frac{1}{4}$ in. (with respect to the view towards the target vessel depicted in Figure 9).

Similarly, the largest overlap on the right-hand side was 2-3/8 in. The view in Figure 9 does not include the box structure or the gap at the end; however, it does provide a good perspective of the overlap.

The target vessel at the far end of the BLS serves as a reaction mass. It has a flat wall (calibration plate) on one end that has reflected pressure gauges embedded within it. Reflected pressure data on the calibration plate were captured in all of the tests outlined in this report.

Figure 7. Circle-to-square transition section C2SQ.

Figure 8. Square section SQ1.

Figure 9. View towards target vessel.

The expansion and transition sections downstream of the CVC are designed to help facilitate the formation of a planar shock front. The amplitude and duration of the pulse are largely defined by the burst pressure and the driver length. An ideal waveform is one that has an initial peak followed by an exponential decay. In practice, the character of the pulse can differ from the ideal. When the computational effort was started, the BLS was undergoing a number of design iterations, with the waveforms differing slightly from the ideal. This is irrelevant for the modeling effort, as the FPCs should be able to capture the form and character of the measured waveform. For the tests reported herein, the burst pressure was 800 psig, or 800 psi above the ambient pressure, for all cases. This ensured that the initial conditions were consistent for the FPC comparisons.

Dallriva et al. (2017) provides a detailed description of the single-structure experiments, and only a summary is provided here. A box-like structure was placed on the floor of the BLS to represent a single structure that is impinged on by the flow field as it progresses down the BLS. The box structure was composed of a pedestal that was welded to the floor and a steel box that was bolted to the pedestal. The steel box had pressure gauges embedded at various locations on each of its exposed faces. The target vessel was moved approximately 4 ft downstream to create a large vent that could mitigate any reflections from propagating upstream and subsequently ensure a more ideal loading pulse on the structure. The gap between the SQ1 section and the calibration plate is shown in Figure 10. The location of the box within the BLS is depicted in the schematic of Figure 2.

Figure 10. BLS 8-ft ×8-ft configuration with 4.1-ft gap.

As mentioned earlier, three different structure configurations were considered for the FPC comparisons. The box was initially in an unrotated position (i.e., a face designated as the “front” was perpendicular to the incoming flow). This was designated as Problem Set 5 within the overall program. The additional cases, designated Problem Sets 7 and 8, had the structure rotated at 45- and 30-deg obliquity, respectively. The obliquity is defined as the angle between the direction of the incoming flow and the normal to the front face of the box. The 45-deg case represents the opposite extreme from zero degrees, while the 30-deg case provides an asymmetric scenario. For ease of reporting, the problem set terminology is omitted here, and the specific cases will be identified by the obliquity angle.

Figures 11 through 14 show the general setup of the structure, the dimensions of the box, a representative image of a rotated structure within the BLS (30-deg case shown), and the three configurations with respect to the direction of the incoming flow, respectively. Figures 15 and 16 provide additional views of the rotated structure as viewed looking toward the calibration plate. A pedestal was placed beneath the box to raise its overall height and to ensure the base resided within the GSA section perimeter. The position of the box is referenced to the centerline of the BLS in Figure 11.

Figure 11. BLS cross section showing the location of the box structure.

Figure 12. Box structure dimensions.

Figure 13. View of the box structure and calibration plate.

Figure 14. Plan view of structure at varied obliquity angles.

(a) 0-deg obliquity.

(b) 30-deg obliquity.

(c) 45-deg obliquity.

Figure 15. Structure rotated to 30-deg obliquity.

Figure 16. Structure rotated to 45-deg obliquity.

The layout of the pressure gauges on the calibration plate and the sidewall of the C2SQ/SQ1 sections are outlined in Figures 17 and 18, respectively. Prior testing from the first year did not include any sidewall measurements. These were added for the current effort to provide additional information about the pressure field near the gap.

Figure 17. Gauge layout on the calibration plate.

Figure 18. Gauge layout on the BLS sidewalls.

The gauge layout on the box structure is depicted in Figures 19 through 23. The naming convention is as follows: PBF refers to the front face; PBB refers to the back face; PBT refers to the top face; PBL refers to the left face; and PBR refers to the right face. For ease of reference, the figures depict the box in the unrotated configuration (i.e., at 0-deg obliquity).

Figure 19. Gauge layout on the front face of the structure.

Figure 20. Gauge layout on the back face of the structure.

Figure 21. Gauge layout on the top face of the structure (0-deg obliquity).

Figure 22. Gauge layout on the left face of the structure (0-deg obliquity).

Figure 23. Gauge layout on the right face of the structure (0-deg obliquity).

3 Modeling Approach and Comparisons

3.1 Overview

The FPCs chosen for this modeling effort were CTH, DYSMAS, Loci/BLAST, and SHAMRC. With the exception of Loci/BLAST, the codes listed are in common use within the DoD for modeling airblast applications. The DoD codes utilize Eulerian solvers of various types, all of which rely on a structured mesh. The Loci/BLAST code differs in that it utilizes an unstructured mesh. There are other codes capable of modeling airblast; however, the ones chosen are thought to have a relatively broad user base with ongoing support on a number of DoD HPC platforms.

The chosen codes represent an array of numerical approaches for modeling airblast applications. The overarching goal was to determine the strengths and weaknesses of each code for modeling this application of airblast propagation and interaction with structures and to identify shortfalls in the underlying physics models that needed to be addressed. The assessment also examined the computational cost and feasibility of a particular FPC for modeling a BLS event. The emphasis was on 3-D modeling as this provides a better indication of a code's performance for handling realistic applications. Thus, 3-D calculations were conducted for all cases discussed in this report; however, planes of symmetry were permitted across the center line axis of the BLS where applicable (i.e., for the 0- and 45-deg obliquity cases). The 30-deg obliquity case is asymmetric in nature and must be modeled as fully 3-D. The use of symmetry conditions was at the modeler's discretion.

The results from each FPC were compared against the experimental data to assess accuracy and trends. These comparisons are presented as generally qualitative in nature, as no in-depth uncertainty analysis was conducted. It should be noted that repeat experiments were performed for all of the cases modeled. In general, the experimental data were repeatable up to the tail end of the negative phase, after which there was considerable scatter. The comparisons focused on the time of arrival (TOA), pressure, and impulse. The emphasis was not only on capturing the peaks but also on considering the ability of the codes to capture the time-dependent nature of the wave form.

The calculations presented in this report were blind (i.e., the modelers did not have access to the measured data beforehand). This contrasts with the first-year effort where the modelers had access to the measured data a priori. The emphasis in the first year was on understanding how best to model the BLS environment in an efficient manner, which is most easily achieved in an open setting. This year's effort builds on that knowledge by testing the capabilities of both the code and the analyst in a blind setting. A major goal of the computational effort is to have an honest and open assessment of each code's capability. Regular teleconferences were conducted to foster communication among the analysts and to encourage openness. Without this openness, analysts could have gotten neither a clear assessment of the strengths and weaknesses of the individual codes nor a path forward for future model development.

Table 1 provides a brief description of the FPCs used in the BLS modeling. Further details on the numerical solver and features unique to each code are outlined in Bessette et al. (2016). An appendix is devoted to each FPC considered to allow for a detailed discussion of the model setup, the reasoning behind choices made in the setup, and lessons learned during the course of the modeling. The discussion for each code is in alphabetical order to avoid any perception of favoritism. Similarly, the order of the appendices follows this alphabetical listing. Thus, CTH is discussed in Appendix A, DYSMAS in Appendix B, etc.

Table 1. Brief description of FPCs used in BLS modeling.

FPC	Brief Description
CTH	Structured Eulerian code with two-step solution approach involving a Lagrangian step followed by a remap. Explicit finite volume approximation applied to conservation equations for Lagrangian step on a staggered mesh. Remap based on second-order-accurate van Leer scheme. Code supports wide range of EOS options and sophisticated material strength models.
DYSMAS	Coupled Euler/Lagrange code. Structure Eulerian code Gemini solves the Eulerian problem using a time-split, second order Godunov method based on a Monotonic Upstream Centered Scheme for the Conservations Laws (MUSCL). Lagrangian problem solved using the ParaDyn explicit Lagrangian finite element code. DYSMAS loosely couples the two solution domains.
Loci/BLAST	Unstructured, fully Eulerian, CFD code that uses a Harten-Lax-van Leer-Enfeldt (HLLC) approximate Riemann solver to compute fluxes at cell faces and least-squares reconstruction coupled with a nodal Baldwin-Barth limiter to provide second-order spatial accuracy. Explicit time integration performed using a two-stage second-order Total Variation Diminishing (TVD) Runge-Kutta scheme.
SHAMRC	Structured Eulerian code that uses a two-step approach involving a Lagrangian step followed by a remap. Conservation equations solved using a modified Lax-Wendroff finite difference approximation on a staggered mesh. Remap based on second-order accurate van Leer scheme with an alternating direction integration scheme.

The emphasis in this section is on the bigger picture, which involves overall comparisons of FPC performance. Performance entails an assessment of accuracy (i.e., ability to replicate the measured data) as well as computational cost in conducting 3-D analyses. The overarching goal is to assess the strengths and weaknesses of each of the FPCs and identify potential areas for improvement needed in the physics modeling.

As described in Bessette et al. (2016), the BLS setup posed modeling challenges. These challenges arise due to the disparate length and timescales that will be encountered in the modeling. The thin shell of the BLS structure (0.5 in.) drives much of the resolution requirement. In general, one needs several cells across the thickness of this thin structure to adequately capture it in the model, and the shell must be adequately resolved along the full length of the BLS (about 40 ft). Furthermore, additional complicated thin structures, such as the catch grill, require increased resolution when included in the model. The resolution requirement also affects the time-step, since the stable time-step is usually proportional to the minimum cell size. Thus, the mesh resolution affected the computational cost due to both the number of cells needed and the small time-steps involved to ensure stability.

The timescale is also an issue. In general, it takes 20 to 25 msec for the shock front to traverse the full length of the BLS. The time duration needed to fully capture the loading pulse on the structure is on the order of 60 to 70 msec. The addition of the gap between the SQ1 section and the calibration plate helped to mitigate most of the reflections that were propagated upstream in the first-year experiments. The net effect was the generation of a more idealized loading pulse on the structure, which included both positive and negative phase components. Time-steps in the calculations were on the microsecond timescale or less. Thus, a large number of computational cycles are needed to complete any given calculation. Therefore, one should expect that any BLS calculation will be highly resolved and long running. As stated previously, the differences in the computational cost of each code will be presented for all scenarios modeled.

3.2 Unrotated structure (0-deg obliquity)

A summary of the computational setup for each FPC is outlined in Table 2. The table summarizes parameters pertinent for ensuing code-to-code comparisons. These include the symmetry conditions, mesh resolution, EOS selected for the air, and approximate total cell count. Further details on

problem setup and assumptions can be found in the appendices. In most cases, the resolution was constant within the region of interest (i.e., the immediate region encompassing the BLS with a graded mesh used to model the exterior air space). The exception to this general rule was Loci/BLAST, which utilized an unstructured mesh composed of tetrahedral elements. Here, the nominal resolution (or range) is specified in the table. For all calculations, the burst pressure for the driver was specified as 800 psig. The ambient temperature was specified as 80°F with the ambient pressure assumed to be 14.7 psia (this was not directly measured during testing).

Table 2. Summary of FPC problem setup for unrotated structure case.

FPC	Model geometry	Mesh resolution (cm)	EOS for air	Approximate no. of cells (millions)
CTH	Half-symmetry	0.5	SESAME	474
DYMAS	Fully 3-D	1.0	Ideal gas	390
Loci/BLAST	Fully 3-D	1.3 – 12.7	Ideal gas	70
SHAMRC	Half-symmetry	1.0	Doan-nickel	377

Unless stated otherwise, the calculated results throughout this report have been time-shifted so that their arrival times coincide with the measured data. The measured data themselves have also been time-shifted to an average over the “valid” tests within each series. There was little scatter in the measured arrival times, so the degree of time-shifting was negligible. The data were time-shifted to focus comparisons on the form and character of the waveform and avoid any uncertainties in the measured arrival times. Select cases in this report show where comparisons are drawn against the unshifted data. This is done to assess overall trends in capturing the arrival time in the calculations.

Comparisons for the front face gauges are provided in Figure 24. The first thing to note in the measured data is the fairly ideal waveform, which is composed of a single positive phase pulse followed by a well-defined negative phase. The negative phase returns to ambient around 60 msec, after which there are lower amplitude reverberations within the BLS as the overall state draws down to ambient conditions. The measured data are highly repeatable up to the point where the minimum pressure is reached (minimum during the negative phase). Qualitatively, the codes capture the general character of the measured waveform out to the point of the minimum pressure. The initial peak is generally captured well by all of the

codes; however, there are disparities in the rate of decay from the initial peak, which leads to notable differences in the peak impulse. This is most obvious with DYSMAS, where the peak impulse is generally underpredicted by about 15 to 20 percent, depending on the particular gauge. The pressure history is similar for both CTH and Loci/BLAST, at least up until the time at which the peak impulse is reached. There is a clear departure between the two after this time, with CTH predicting a stronger negative phase than observed (both amplitude and duration). Both CTH and Loci/BLAST slightly underpredict the peak impulse on the order of 5 to 8 percent, depending on the gauge, but are well within reason. SHAMRC compares well with the measured data throughout the duration of the calculation.

Figure 24. Comparisons for front face gauges (0-deg obliquity).

Figure 24. (Continued)

(c) Gauge PBF3.

(d) Gauge PBF4.

(e) Gauge PBF5.

(f) Gauge PBF6.

Figure 24. (Concluded)

As an aside, it is interesting to compare the trends in the TOA data. The time shifts applied to gauge PBF3 are outlined in Table 3. The associated unshifted early-time pressure histories are plotted in Figure 25. The results noted at this gauge are representative of those at the other gauge locations. There is uncertainty associated with the measured data and the timing offset from the initial burst of the diaphragm. The degree of uncertainty has not been quantified, so one should focus attention on the trends rather than any precise differences between the calculated and the measured arrival times. Clearly, there is a tendency for the codes to lag the measured arrival time. There is no clear-cut reason for this latency, as there are a number of factors that affect the timing. These include the EOS, details on the FPC solver, and mesh resolution.

Comparisons for the top face gauges are provided in Figure 26. The differences between the calculated and the measured waveforms are more striking here. In general, the initial peak pressure is captured well by all of the codes; however, the differences between the measured and the calculated pressure histories grow over time. Qualitatively, both CTH and Loci/BLAST correlate reasonably well with the measured waveform for each of the gauges, with a tendency for underprediction of the peak impulse (< 15 percent). The differences for DYSMAS and SHAMRC are more notable, with both exhibiting significant underpredictions of the peak impulse (> 15 percent). There are noticeable drops in the post-peak pressure

profile, which result in a loss of accumulated impulse. The reason for these sharp drops is unclear and cannot be determined from the gauge data alone. As with the front face gauges, CTH exhibits a stronger negative phase than observed (in both amplitude and duration). One should also note the sharp spike in the pressure for gauge PBT1 around 50 msec. This is observed for the rotated configurations as well, and is thought to be an issue with the instrumentation rather than an indication of a physical event.

Table 3. Time-shifts applied to gauge PBF3 (0-deg obliquity).

FPC	Time-Shift (msec)
CTH	-3.635
DYSMAS	-1.500
Loci/BLAST	-2.900
SHAMRC	-2.925

Figure 25. Early-time comparison for gauge PBF3 without time-shifting (0-deg obliquity).

Figure 26. Comparisons for top face gauges (0-deg obliquity).

(a) Gauge PBT1.

(b) Gauge PBT2.

(c) Gauge PBT3.

(d) Gauge PBT4.

Figure 26. (Concluded).

(e) Gauge PBT5.

Comparisons for the remaining faces (back, right, and left) are provided in Figures 27 through 29. One should note that the gauges PBR3/PBR4 and PBL3/PBL4 on the right and left faces are not symmetric. Data at these gauges can be captured in a calculation with half-symmetry if tracers are placed appropriately. This was missed for the PBL3 and PBL4 gauges in the CTH calculation, so comparisons can be drawn only for the PBL1 and PLB2 gauges (symmetric with the right face). This is not an issue, as there are more than sufficient data to carry out the code evaluation.

Figure 27. Comparisons for back face gauges (0-deg obliquity).

(a) Gauge PBB1.

(b) Gauge PBB2.

(c) Gauge PBB3.

(d) Gauge PBB4.

Figure 28. Comparisons for right face gauges (0-deg obliquity).

(a) Gauge PBR1.

(b) Gauge PBR2.

(c) Gauge PBR3.

(d) Gauge PBR4.

Figure 29. Comparisons for left face gauges (0-deg obliquity).

The comparisons for the back face are mixed (see Figure 27). There is a general tendency for underprediction of the peak impulse, which ties back to the steeper rate of decay from the initial peak noted in most calculations. Similar observations apply to the gauges on the right and left faces; however, the degree of underprediction for the peak impulse is more severe. SHAMRC, in particular, severely underpredicts the peak impulse at all of the side face gauges.

Comparisons for the sidewall and calibration plate gauges are provided in Figure 30. Again, there is a tendency for underprediction of the peak impulse. The modeling of the venting at the aft end of the BLS has a direct effect on the predicted decay rate at these gauge stations. This affects the rarefaction traveling upstream, which in turn affects the pressure decay at the upstream gauges; however, the influence of modeling the venting will be most felt at the gauges nearest the gap (i.e., on the sidewall and calibration plates). The modeling of the venting process (or rate of gas blowdown) can be affected by mesh resolution, type of boundary condition (BC) applied at or near the gap, and, for structured meshes, the proximity of the mesh boundary to the rear gap. Another potential contributor is the EOS itself. The modeling of a gas in distension, especially in the negative phase, is problematic for almost any code. These are all factors that can be explored numerically via a sensitivity study.

Figure 30. Comparisons for sidewall and calibration plate gauges (0-deg obliquity).

Figure 30. (Continued).

(c) Gauge CP3.

(d) Gauge CP5.

(e) Gauge CP9.

3.3 Rotated structure (45-deg obliquity)

A summary of the computational setup for each FPC is outlined in Table 4. The table summarizes parameters pertinent for ensuing code-to-code comparisons. For all calculations, the burst pressure for the driver was specified as 800 psig. The ambient temperature was specified as 80°F, with the ambient pressure assumed to be 14.7 psia. Comparisons for the front face gauges are provided in Figure 31. As discussed previously, the

calculated results were time-shifted to match the measured arrival. The time-shifts applied to gauge PBF3 are outlined in Table 5. There is a tendency to lag the measured arrival for each of the codes. Comparisons for gauges on the other faces of the structure are provided in Figures 32 through 35 (top, back, right, and left faces, respectively). Comparisons for the sidewall and calibration plate gauges are provided in Figures 32 through 35. The overall comparisons are mixed, with correlation between the calculated and measured results being gauge dependent for each code. The only clear-cut trend is a tendency to underpredict the peak impulse. The rate of pressure decay following the initial peak is, in general, overpredicted by all of the codes. A likely contributor to the differences is the modeling of the venting at the rear gap, which in turn, affects any rarefaction propagating upstream. As mentioned previously, the ability to capture the venting process is influenced by the mesh resolution, BC type, and proximity of the mesh boundary to the rear gap. The EOS represents another potential contributor to the differences. All of these factors can be investigated via a sensitivity study to determine which one(s) have a first-order effect on the code predictions.

There are a number of gauges that exhibit erratic behavior later in time (after 50-60 msec). These spikes are thought to an issue with the instrumentation, rather than associated with a physical mechanism in the test. The erratic behavior is prominent for gauges PBF5, PBF8, PBB3, PBB4, PBT1, and PBR3.

Table 4. Summary of FPC problem setup for rotated box (45-deg obliquity).

FPC	Model geometry	Mesh resolution (cm)	EOS for air	Approximate no. of cells (millions)
CTH	Half-symmetry	0.5	SESAME	474
DYMAS	Fully 3D	1.0	Ideal Gas	390
Loci/BLAST	Fully 3D	1.3 - 12.7	Ideal Gas	16.3
SHAMRC	Half-symmetry	1.0	Doan-Nickel	377

Table 5. Time-shifts applied to gauge PBF3 (45-deg obliquity).

FPC	Time-shift (msec)
CTH	-3.640
DYMAS	-1.500
Loci/BLAST	-2.415
SHAMRC	-2.925

Figure 31. Comparisons for front face gauges (45-deg obliquity).

(a) Gauge PBF1.

(b) Gauge PBF2.

(c) Gauge PBF3.

(d) Gauge PBF4.

Figure 31. (Continued).

(e) Gauge PBF5.

(f) Gauge PBF6.

(g) Gauge PBF7.

(h) Gauge PBF8.

Figure 32. Comparisons for top face gauges (45-deg obliquity).

(a) Gauge PBT1.

(b) Gauge PBT2.

(c) Gauge PBT3.

(d) Gauge PBT4.

Figure 32. (Continued).

(e) Gauge PBT5.

Figure 33. Comparisons for back face gauges (45-deg obliquity).

(a) Gauge PBB1.

(b) Gauge PBB2.

(c) Gauge PBB3.

(d) Gauge PBB4.

Figure 34. Comparisons for right face gauges (45-deg obliquity).

(a) Gauge PBR1.

(b) Gauge PBR2.

(c) Gauge PBR3.

(d) Gauge PBR4.

Figure 35. Comparisons for left face gauges (45-deg obliquity).

(a) Gauge PBL1.

(b) Gauge PBL2.

(c) Gauge PBL3.

(d) Gauge PBL4.

Figure 36. Comparisons for sidewall and calibration plate gauges (45-deg obliquity).

(a) Gauge G1.

(b) Gauge G2.

(c) Gauge CP3.

(d) Gauge CP5.

Figure 36. (Continued).

(e) Gauge CP9.

3.4 Rotated structure (30-deg obliquity)

A summary of the computational setup for each FPC is outlined in Table 6. The table summarizes parameters pertinent for ensuing code-to-code comparisons. For all calculations, the burst pressure for the driver was specified as 800 psig. The ambient temperature was specified as 80°F with the ambient pressure assumed to be 14.7 psia. Comparisons for the front face gauges are provided in Figure 37. As discussed previously, the calculated results have been time-shifted to match the measured arrival. The time-shifts applied to gauge PBF3 are outlined in Table 7. There is a tendency to lag the measured arrival for each of the codes. Comparisons for gauges on the other faces of the structure are provided in Figures 38 through 41 (top, back, right, and left faces, respectively). Comparisons for the sidewall and calibration plate gauges are provided in Figure 42. The overall comparisons are mixed, with correlation between the calculated and measured results being gauge-dependent for each code. The only clear-cut trend is a tendency to underpredict the peak impulse. The potential contributors for the underpredictions in impulse have been previously discussed.

There are a number of gauges that exhibit erratic behavior later in time (after 50-60 msec). These spikes are thought to be an issue with the instrumentation, rather than associated with a physical mechanism in the test. The erratic behavior is prominent for gauges PBT1, PBB3, PBR3, and PBL2.

Table 6. Summary of FPC problem setup for rotated structure (30-deg obliquity).

FPC	Model geometry	Mesh resolution (cm)	EOS for air	Approximate no. of cells (millions)
CTH	Fully 3D	0.5	SESAME	947
DYSMAS	Fully 3D	1.0	Ideal gas	390
Loci/BLAST	Fully 3D	1.3 - 12.7	Ideal gas	15.8
SHAMRC	Fully 3D	1.0	Doan-nickel	753

Figure 37. Comparisons for front face gauges (30-deg obliquity).

Figure 37. (Continued).

(c) Gauge PBF3.

(d) Gauge PBF4.

(e) Gauge PBF5.

(f) Gauge PBF6.

Figure 37. (Continued).

(g) Gauge PBF7.

(h) Gauge PBF8.

Table 7. Time-shifts applied to gauge PBF3 (30-deg obliquity).

FPC	Time-shift (msec)
CTH	-3.640
DYSMAS	-1.500
Loci/BLAST	-2.385
SHAMRC	-2.925

Figure 38. Comparisons for top face gauges (30-deg obliquity).

(a) Gauge PBT1.

(b) Gauge PBT2.

(c) Gauge PBT3.

(d) Gauge PBT4.

Figure 38. (Continued).

(e) Gauge PBT5.

Figure 39. Comparisons for back face gauges (30-deg obliquity).

(a) Gauge PBB1.

(b) Gauge PBB2.

(c) Gauge PBB3.

(d) Gauge PBB4.

Figure 40. Comparisons for right face gauges (30-deg obliquity).

(a) Gauge PBR1.

(b) Gauge PBR2.

(c) Gauge PBR3.

(d) Gauge PBR4.

Figure 41. Comparisons for left face gauges (30-deg obliquity).

(a) Gauge PBL1.

(b) Gauge PBL2.

(c) Gauge PBL3.

(d) Gauge PBL4.

Figure 42. Comparisons for sidewall and calibration plate gauges (30-deg obliquity).

(a) Gauge G1.

(b) Gauge G2.

(c) Gauge CP3.

(d) Gauge CP5.

Figure 42. (Continued).

(e) Gauge CP9.

3.5 Data analysis and observations

Although the codes exhibit a tendency for underprediction of the peak impulse, it is useful to see whether their predictions are following expected trends in the measured data. This is best accomplished by examining the influence of obliquity on both the measured and the calculated results. Comparisons at select gauges are provided in Figures 43 through 45. The comparisons are drawn for gauges on roughly the mid-face of the front, top, and left sides. The plot bounds are identical for each gauge to help discern the influence of structure obliquity on both the measured and the calculated results. The naming of the individual tests has been dropped to improve clarity. Rather they are all collectively referred to as measured.

Figure 43. Influence of obliquity at gauge PBF3.

(a) 0-deg obliquity.

(b) 30-deg obliquity.

(c) 45-deg obliquity.

Figure 44. Influence of obliquity at gauge PBT2.

For the front face gauge PBF3, one notes a slight decrease in the measured peak pressure with increasing obliquity (see Figure 43). This is expected, as the amplitude of the normal component of the velocity vector for the incoming flow decreases with obliquity. The net effect is a decrease in the dynamic pressure contribution at the gauge location. The influence is more notable on the peak impulse, as it captures the accumulated effect over time. Although there are quantitative differences between the measured and the calculated values for the peak pressure and impulse, it appears that the codes are following the observed trends.

Figure 45. Influence of obliquity at gauge PBL1.

The trends for gauge PBT2 are not so clear-cut (see Figure 44). The gauge is stationary with respect to the longitudinal axis of the box, regardless of the obliquity. The measured peak pressure is consistent for each case (nominally 11 psi). The measured peak impulse is consistent at the obliquity angles of 30 and 45 deg (nominally 71 psi-msec); however, differences are noted for the unrotated configuration, where the impulse is nominally 62 psi-msec with significantly more scatter observed in the data

at the time where the peak occurs. Although the gauge is stationary with respect to the box center, the flow over the top surface changes due to the rotation of the leading edge. One should not expect identical results. In fact, the registered pressure will be dependent on the diffraction at the leading edge and the location where the shock contacts the top surface behind the vortex. The codes follow the trends in the measured data, albeit the impulse is generally underpredicted.

A different situation occurs at gauge PBL1 (Figure 45). As the box is rotated, the presented area of the face increases with respect to the incoming flow. Thus in the unrotated configuration, the flow travels parallel to the face with diffraction occurring at the leading edge. Here, the gauge measurement is highly affected by the location where the shock contacts the surface behind the vortex region. As the obliquity increases, the amplitude of the normal component of the velocity vector increases. The net effect is an increase in the dynamic pressure contribution. This trend is apparent in both the measured peak pressure and the impulse. The codes follow these trends in the measured data, albeit the predictions can be poor in some cases.

There is one other useful case to check. For the 45-deg obliquity case (Figure 46), the pressure-time-history should be symmetric with respect to gauges PBF2/ PBL1 and PBF4/PBL2. In practice, there will be differences in the measured data; however, one should expect good correlation in the calculated results. This is in fact the case, with only minor differences noted late in time for both DYSMAS and Loci/BLAST at gauges PBF4 and PBL2. The differences are negligible and likely due to slight variations in gauge location in the calculation setup.

Figure 46. Comparisons for symmetry with 45-deg obliquity case.

It is worth reviewing the findings from the previous year regarding mesh resolution and the implications for the current effort. The focus of the first year's code evaluation was to investigate how best to model the BLS problem as well as to define the resolution requirements. For the 8-ft $\times$ 8-ft C2SQ with box comparisons outlined in Bessette et al. (2016), it was found that a resolution of 0.5 cm was adequate for CTH; 1.0 cm for DYSMAS; 1.3 to 2.5 cm for Loci/BLAST; and 1.0 cm for SHAMRC. This particular test is comparable to the unrotated structure case discussed here, with the

exception that there was no gap between the SQ1 and the target vessel. Thus, the aft end of the BLS was essentially closed with venting occurring only in the gaps in the CVC section. Representative results from these comparisons are provided in Figure 47. These results are indicative of those observed at the other gauge locations on the structure. The comparison with the measured data was generally quite good for the codes listed. This contrasts with current comparisons, where there is an increased tendency for underprediction of the peak impulse.

Figure 47. Representative results from first-year modeling effort.

The major differences between the two sets of calculations for the unrotated structure are the venting at the aft end and the burst pressure (1298 psig in the first year). Of the two, it is believed that the modeling of the aft venting has the dominant effect on the calculations carried out this year. It is apparent from the comparisons for the sidewall and calibration plate gauges that the post-peak decay is not adequately captured in the current work. Clearly, the rarefaction from the edges is not captured well, and the modeling of this particular set of physics will be highly dependent on the mesh resolution, the implementation of the BCs, and the offset distance of the nearest mesh boundary to the BLS. The EOS modeling of the gas expansion also affects the results and likely contributes to the noted differences. These are all areas that should be explored further with additional parameter studies involving the simplest set of experimental data (0-deg obliquity case).

3.6 Computational cost

A cost comparison for each case is provided in Tables 8 through 10. The tables contain the nominal mesh resolution for reference, the approximate number of cells, the end time of the calculation, the HPC platform on which the calculation was run, the number of cores utilized, and the wall-clock hours (or central processing unit (CPU) time if reported). The total number of core hours is shown in the last column. This metric is the summation of the number of cores times the wall-clock time (or CPU if specified) overall restarts. The CPU times are preferred since they exclude the expense of reading and writing data; however, the wall-clock times were typically reported by the modelers.

Table 8. Computational costs for unrotated structure (0-deg obliquity).

FPC	Mesh resolution (cm)	Approximate no. of cells (millions)	Analysis end time (msec)	HPC platform	No. of cores	Wall clock time (hr)	Total core- hours
CTH	0.5	474	65	Topaz	1024	138	141,312
DYSMAS	1.0	390	75	Topaz	1016	22	22,352
Loci/BLAST	1.3-12.7	70	71	Shadow	200	237.5	47,500
SHAMRC	1.0	377	65	Spirit	64	11.3	723

Table 9. Computational costs for rotated structure (45-deg obliquity).

FPC	Mesh resolution (cm)	Approximate no. of cells (millions)	Analysis end time (msec)	HPC platform	No. of cores	Wall clock time (hr)	Total core- hours
CTH	0.5	474	65	Garnet	5120	95	486,400
DYSMAS	1.0	390	60	Topaz	1060	20	20,320
Loci/BLAST	1.3-12.7	16.3	70	Topaz	2048	123.6	253,133
SHAMRC	1.0	377	65	Spirit	64	11.75	752

Table 10. Computational costs for rotated structure (30-deg obliquity).

FPC	Mesh resolution (cm)	Approximate no. of cells (millions)	Analysis end time (msec)	HPC platform	No. of cores	Wall clock time (hr)	Total core- hours
CTH	0.5	947	65	Garnet	5120	132	675,840
DYSMAS	1.0	390	60	Topaz	1060	21.5	21,844
Loci/BLAST	1.3-12.7	15.8	74	Topaz	2048	121.6	249,037
SHAMRC	1.0	753	65	Spirit	128	12	1,536

The FPC calculations were conducted on different HPC platforms, each having different architectures. In particular, the number of cores available on a CPU, core speed, and memory capacity varied for each. The differences are summarized in Table 11. There can be no “apples-to-apples” comparisons due to the vastly differing architectures. Thus, care should be exercised in the assessment of computational costs. At best, the cost assessment can be made on an order-of-magnitude basis only. The reader should be able to recognize which FPCs provide a reasonable turn-around time for an analysis and which may result in intractable run times. Again, it is reiterated that the end goal is performing production computing involving more realistic applications.

Table 11. Comparison of HPC platform configurations.

HPC platform	Architecture	Core type	Cores/node	Core speed (GHz)	Accessible memory/node (GBytes)
Topaz (Small Memory)	SGI ICE X	Intel Xeon E5-2697v3 Haswell	36	2.3	117
Topaz (Large Memory)	SGI ICE X	Intel Xeon E5-4620v2 Ivy Bridge	32	2.6	1000
Garnet	Cray XE6	AMD Interlagos Opteron	32	2.5	60
Spirit	SGI ICE X	Intel Xeon Sandy Bridge	16	2.6	30
Shadow	Cray CS300-LC	Intel Xeon E5-2680	20	2.8	64

Both SHAMRC and DYSMAS provide high turn-around for an analysis (essentially overnight) with SHAMRC being exceedingly efficient. With today's HPC capabilities, it is not uncommon to get access to a few 1,000 cores in a standard queue. CTH exhibited the poorest performance in both computational resources needed and time to complete the analysis; however, one must keep in mind that the CTH calculations were carried out at the highest resolution (0.5 cm) and, in general, on the slowest platform (Garnet). The assessment of resource requirements for Loci/BLAST is mixed. Good performance was noted on the MSU platform Shadow; however, poor performance was noted on the ERDC platform Topaz. The number of cores specified increased by an order of magnitude, and it is likely that the on-processor memory was not well utilized, leading to excessive communication between cores. This can dramatically degrade performance. One cannot make any consistent comparisons for performance due to the disparate architectures utilized as well as computational resources requested. The reader should bear this in mind when reviewing the computational cost summaries.

4 Summary and Recommendations

An integrated experimental and computational program has been underway at the ERDC to evaluate several FPCs for modeling airblast environments typical of those encountered in the ERDC BLS. The modeling is a multi-year effort carried out for the DTRA and utilizes a number of BLS configurations to scope out conditions for code evaluation. The overarching goal of the integrated program is to assess the computational accuracy and cost of the FPCs evaluated, as well as to identify any shortcomings in the physics modeling and areas for future improvement. The modeling discussed in this report builds on the first year, which examined both the flow environment within an empty BLS and a case involving a single box-like structure. The current effort expanded on the single-structure scenario by employing venting at the target end of the BLS and considering rotated configurations for the box structure. The FPCs considered in this year's effort were CTH, DYSMAS, Loci/BLAST, and SHAMRC.

The first year's calculations were carried out in the open (i.e., the modelers had access to the experimental data beforehand), while the modeling conducted in the present study was carried out in the blind. The goal of the first year was to allow the modelers to gain experience with simulating the blast environment typical of the BLS. This year's effort built on that knowledge by testing the capabilities of both the code and the analyst in a blind setting. This turned out to be quite illuminating as the addition of the gap at the aft end of the BLS posed new challenges in the modeling, which were not investigated in the first year's effort.

In general, good correlation between the calculated and the measured data was achieved in the first year's effort, where the BLS was in a closed configuration. In contrast, comparisons were often poor in the present study. This poor performance appears to be directly related to modeling the venting and rarefaction process in the gap region. The disparities were most notable in the peak impulse and timing at which the peak occurred. There was a general tendency to underpredict the peak impulse. This was in large part due to an overprediction in the rate of decay from the initial peak, which resulted in less impulse accumulation over time. In turn, the calculated time at which the peak occurred was generally earlier than measured. It was not uncommon to have underpredictions of the impulse on the order of 30 to 40 percent. Of course, the degree of the disparity

between the calculated and the measured impulses differed for each code and gauge location.

Overall, both CTH and SHAMRC provided the best comparisons with the experimental data, with both Loci/BLAST and DYSMAS performing more poorly. This is a subjective statement based on a review of the pressure-history profiles for all data sets rather than comparisons based on peak pressure and impulse alone. None of the codes matched the measurements at every gauge location. Thus, it is difficult to quantify the accuracy of any of the codes.

It is recommended that additional parameter studies involving the simplest set of experimental data (unrotated case) be carried out to gain an understanding of the root cause for the poor comparisons with the measured data. This experimental data set offers a rare opportunity to directly compare results based on a BLS with and without the gap, as “apples-to-apples” a comparison as can be achieved in practice. The parameter study should focus on mesh resolution and modeling the BCs about the gap region. The EOS modeling could also be an issue; however, this is thought to be less of a factor given the gas pressure and temperature levels encountered in the BLS testing.

Mesh resolution has a first-order effect on any type of calculation, and in particular, it appears to play a more significant role in airblast calculations. The influence of mesh resolution was investigated in the first year’s effort for the BLS in a closed configuration; however, these studies did not address venting phenomena or ability to capture the negative phase in a blast calculation. Clearly, these are areas that need to be addressed. Unfortunately, there are no general rules of thumb for resolution. The definition of “adequate resolution” is nebulous and varies with both the class of problem being modeled and the individual code used in the modeling. In practice, the resolution chosen is the one that meets the time and schedule for the program. This is unsatisfying from a research perspective; however, it is a pragmatic choice. It may be necessary to recognize that adequate resolution cannot be achieved for production calculations and accept that quantities such as peak impulse will be underpredicted. What is important is to recognize the degree of underprediction that can be expected.

Boundary conditions (BC) pose another challenge. The manner in which BCs are imposed is code dependent. The DYSMAS and SHAMRC analysts both attempted to model the tunnel region surrounding the BLS. This approach best represents the surrounding environment. Even with a simplified box-like representation of the neighboring space, the analyst can still capture the timing and rate of venting as well as reflection off the tunnel sidewalls and their return to the gap region. Further, it avoids the need for the user to define a graded mesh outside the BLS or to impose transmissive BCs, which can be problematic for strong incoming shocks. The downside of this approach is cost. The computational mesh must extend into the tunnel, and the resolution should be consistent with that used in the interior of the BLS.

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Appendix A: CTH Modeling

CTH background

A comprehensive description of CTH, along with an initial study carried out during the first year of this program, can be found in Bessette et al. (2016). In this initial BLS study, several parameter studies were conducted. The relevant conclusions include the following: (1) CTH requires a 0.5-cm mesh resolution to well-match the experimental data in the BLS, and (2) thin rigid objects cause stability issues in CTH. The latter requires modeling the BLS and striker as deformable materials, thereby greatly reducing the time-step in the calculations. This was partly offset by using a Mie-Grüneisen EOS for lead and an enhanced von Mises yield strength for modeling the BLS walls and striker. The net result was a low wave speed in these materials, which improved the overall time-step. The modeling from the previous year considered both a SESAME and an ideal gas EOS for air. Both EOSs match the experimental data well, and neither EOS was found to reproduce the experimental results better than the other.

The approach used for these simulations was based on the approach used for the single-structure case outlined in Bessette et al. (2016). The center of the structure and the configuration of the BLS components in the cases presented herein are the same as the single-structure setup from the prior year, with the exception that for the current study the structure was rotated through several obliquities and the target vessel was moved 4 ft downstream from the end of the SQ1 section to delay and minimize the effect of the reflected shock on the on-structure gauge locations. This also changed the BLS from a nearly closed system to a vented system. All calculations presented herein used the SESAME EOS for air.

Analysis overview

The unrotated case CTH calculations were performed on the SGI ICE X located at the ERDC DoD Supercomputing Resource Center, commonly referred to as Topaz. The SGI ICE X has 3,456 compute nodes with 36 cores per node. Each standard memory compute node has a core speed of 2.3 GHz and 117 GB of accessible memory.

The calculations for the 30 deg and 45 deg obliquity cases were performed on the Cray XE6 located at the ERDC DoD Supercomputing Resource

Center, commonly referred to as Garnet. The Cray XE6 has 4,716 compute nodes with 32 cores per node. Each computer node has a core speed of 2.7 GHz and 64 GB of accessible memory.

Overview of the single structure calculations

In general, the 3-D CTH calculations of the BLS were conducted using half-symmetry, a nominal 0.5-cm cell size, the SESAME EOS for air, and deformable walls. The 30° obliquity case lacked a plane of symmetry; therefore, the model for that case contained the entirety of the BLS with no symmetry condition. As described in the main text, three configurations of a single box structure with varying obliquities of 0 deg (unrotated), 45 deg, and 30 deg in the C2SQ component were simulated. Each subsequent configuration added more complexity to the modeling effort.

For the unrotated and 45-deg cases, a reflective BC was applied to the plane of symmetry, and transmissive BCs were applied to the remaining boundaries of the computational domain. The boundaries on the left, right, top, and bottom of the BLS were 68 in. from the BLS centerline and used an expanding mesh from 48 in. away from the centerline to 68 in. away from the centerline. For the 30-deg case, the plane of symmetry was removed; and the extents of the computational domain on both sides of the removed plane of symmetry were identical to those of the 0- and 45-deg cases. The BC to the right side (as viewed from the driver) erroneously remained as reflective. The remaining BCs were all transmissive.

The BLS geometry was created in Cubit (a general preprocessing tool; Sandia National Laboratories 2015), and the major components output to individual Exodus files. CTH imports the Exodus files and extracts the volume of each component. It then simply superimposes the prescribed computational mesh on top of the volumes. Figure A1 shows images of the BLS configured with a 4-ft gap and an unrotated structure. The five colors represent the five volumes imported into CTH. Figure A2 depicts a close-up of the structure in the C2SQ section at the three obliquities tested. The 30-deg case shown in image (c) was not run in half symmetry; rather, the right-hand side of the BLS structure has been hidden for visibility. A close-up of the as-modeled striker geometry is shown in Figure A3.

Figure A1. CTH problem setup for BLS with 4-ft gap and unrotated structure.

(a) Image of half-symmetry model.

(b) Quarter-section image of model.

(c) Quarter-section image of driver section, striker, CVC-1, -2, and, -3.

Figure A2. Close-up views of box and C2SQ section at the three obliquities tested.

(a) Unrotated structure.

(b) Rotated structure, 45-deg obliquity.

(c) Rotated structure, 30-deg obliquity.

Figure A3. Three views of as-modeled striker geometry.

Before the results for each case are presented, the CTH pressure fields between 20 and 36 msec for the unrotated case are presented in Figure A4 to give the reader a sense of how the incident and reflected shocks transition with time. The units of pressure in the figure are dyne/cm². At 20 msec, the incident shock is entering the Cascade section of the BLS with a planar front and a relatively homogeneous mass of air at constant pressure behind it. A perturbed pressure field has engulfed the box at 24 msec with a reflected shock visible in front of it. The shock is just exiting the SQ1 section at 28 msec. At 32 msec, the shock front has reflected off the target vessel. At 36 msec, the reflected shock front has re-entered the SQ1 section. Compared to the reflected shock at 32 msec, the reflected shockwave has weakened considerably.

Figure A4. CTH pressure state plots for unrotated structure case.

(a) 20 msec.

(b) 24 msec.

(c) 28 msec.

(d) 32 msec.

(e) 36 msec.

Unrotated structure (0-deg obliquity)

The CTH calculation of the 0-deg obliquity case had 474 million cells and required 138 hr of wall-clock time using 1,024 cores on the Topaz system to run the simulation out to 65 msec. The primary objective was to calculate the time-histories for the pressure gauges located on the box structure. Since this calculation used half symmetry, gauges located on the opposing half of the box were mirrored about the plane of symmetry when possible.

The CTH-calculated pressure and impulse histories were compared against the measured data in Section 3.2 of the main body of this report. Comparisons were drawn for gauges on each face of the box as well as for gauges on the calibration plate and the sidewall. All of the CTH time-histories were shifted -3.76 msec to match the measured TOA at gauge PBF3. The comparisons are not repeated here for brevity, and the ensuing discussion will focus on general findings and lessons learned.

The ability of CTH to qualitatively match the measured data for gauges on the box varied from good to fair. In general, good agreement was observed between the CTH and the experimental traces up until the arrival of the second pressure peak (i.e., the arrival of the reflected shock from the end of the BLS). The results on the front face, which faced the incident shock, and the rear face, which faced the reflected shock, are generally better than the left and right faces, which were perpendicular to the incident shock. In almost all cases, the peak impulse was underpredicted. The underprediction of impulse tended to be greater for gauges on the structure sides (left and right faces) as compared to the other sides of the box.

After the arrival of the reflected shock, all of the CTH traces from the on-structure gauge locations and the sidewall gauges fell below the experimental results. In all cases, the amplitude of the negative phase pressure was overpredicted (i.e., too negative), and the pressure rise after the minimum was delayed in the simulations. This gave rise at multiple gauge locations to a negative impulse that had not been observed experimentally. In turn, this led to significant disparities between the measured and the calculated impulses after about 45 msec.

The pressure-time-histories for three gauges on the calibration plate (P3, CP5, and CP9) showed good agreement with the experimental results for the initial pressure, but then overpredicted the rate of pressure decay from the initial peak, resulting in an underprediction of the peak impulse.

Similar to the on-structure gauges, the calibration plate and the sidewall gauge traces deviate more strongly from the experimental results after about 40 msec; for the calibration plate, the secondary and tertiary pressure peaks are missed entirely, and CTH demonstrates a low negative pressure resulting in a decrease in the impulse after about 32 msec, whereas the experimental impulse continues to rise until about 70 msec. The overall trend in low pressures after the initial peak suggests venting from the computational domain via the transmissive BCs greater than that which occurred in the experiment.

The incident pressure fields in the vicinity of the box structure between 22.75 and 24.5 msec are shown in an elevation view 1.0 cm off the symmetry plane (Figure A5) and in a plan view at the gauge PBF6 elevation (Figure A6). The top of each image is downstream of the box. The units of pressure are dyne/cm² in both images. The unshifted TOA of the incident shock on the front corner of the box is 22.7 msec. At 22.75 msec, the reflected shock from the front face is visible in Figure A5 (a) and A6 (a). Towards the top of the structure at 24 msec (Figures A5 (c) and A6 (c)), the shock front has engulfed the top of the structure, and small low-pressure regions are visible at the corners just behind the leading edge of the structure on the top and side faces and near the top and sides of the rear face. At 24.5 msec (Figures A5 (d) and A6 (d)), the shock has fully engulfed the structure and reformed, and the low pressure regions remain just behind the corners of the structure.

Rotated structure (45-deg obliquity)

The CTH calculation of the 45° obliquity case had 474 million cells and required 95 hr of wall-clock time using 5,120 cores on the Garnet system to run the simulation out to 65 msec. The primary objective was to calculate the time-histories for the pressure gauges located on the box structure. Since this calculation used half symmetry, gauges located on the opposing half of the box were mirrored about the plane of symmetry when possible. The model setup was identical to the 0-deg case with the exception that the structure was rotated 45 deg about its center point. The tracer locations in the problem setup were updated accordingly.

The CTH-calculated pressure and impulse histories were compared to the measured data in Section 3.3 of the main body of this report. Comparisons were drawn for gauges on each face of the box, as well as for gauges on the calibration plate and the sidewall. All of the CTH time-histories were

shifted -3.67 msec to match the measured TOA at gauge PBF3. The comparisons are not repeated here for brevity, and the ensuing discussion will focus on general findings and lessons learned.

Figure A5. Plots of incident shock for the 0-deg obliquity case, side view.

Figure A6. Plots of incident shock for the 0-deg obliquity case, plan view.

The ability of CTH to qualitatively match the measured data for gauges on the box varied from good to fair. Similar to the unrotated case, generally good agreement was observed between the CTH and the experimental traces up to the arrival of the second pressure peak (i.e., the arrival of the reflected shock from the end of the BLS). The results on the front and left

faces, which faced the incident shock, and the top face, which was perpendicular to the shock, were generally better than the back and right faces, which faced away from the incident shock. Several gauge locations on the back and right faces contained additional features not observed experimentally, such as a sharp decrease and recovery in pressure around 27 msec for PBB2 in Figure 33. In almost all cases, the peak impulse was underpredicted.

Similar to the unrotated case and after the arrival of the reflected shock, all of the CTH traces on structure gauge locations and the sidewall gauges fell below the experimental results. In all cases, the amplitude of the negative phase pressure was overpredicted (i.e., too negative), and the pressure rise after the minimum was delayed in the simulation. This gave rise at multiple gauge locations to a negative impulse that was not observed experimentally. In turn, this led to significant disparities between the measured and the calculated impulses after about 45 msec.

Similar to the unrotated case, the pressure-time-histories for calibration plate gauges showed good agreement with the experimental results for the initial pressure, but then overpredicted the rate of pressure decay from the initial peak, resulting in an underprediction of the peak impulse. Similar to the on-structure gauges, the calibration plate and the sidewall gauge traces deviated more strongly from the experimental results after about 40 msec. For the calibration plate, the secondary and tertiary pressure peaks were missed entirely, and CTH demonstrated a low negative pressure, resulting in a decrease in the impulse after about 32 msec, whereas the experimental impulse continued to rise until about 70 msec. The overall trend in low pressures after the initial peaks suggests venting from the computational domain via the transmissive BCs greater than that which occurred in the experiment.

The incident pressure fields in the vicinity of the box structure between 22.75 and 24.5 msec are shown in an elevation view 1.0 cm off the symmetry plane (Figure A7) and in a plan view at the gauge PBF6 elevation (Figure A8). The units of pressure are dyne/cm². For the sake of visualization and comparison with the 30-deg images shown later, the elevation view images in Figure A8 are mirrored about the symmetry plane. The top of each image is downstream of the box. The unshifted TOA of the incident shock on the front corner of the box was 22.6 msec.

Figure A7. Plots of incident shock for the 45-deg obliquity case, side view.

Figure A8. Plots of incident shock for the 45-deg obliquity case, plan view.

At 22.75 msec, the reflected shock from the front and left faces is visible in Figure A7 (a) and A8 (a). Towards the top of the structure at 23.25 msec (Figures A7 [b] and A8 [b]), the shock front has progressed past the front and left faces and is beginning to diffract around the right and rear faces. At 24 msec, the shockwave has engulfed the top and the structure (Figures A7 (c) and A8 (c)), and the shock front is reforming. At 24.5 msec (Figures A7 (c) and A8 (c)), the shock wave has fully engulfed the structure.

To highlight the difference in the wraparound and the vortex shedding as a function of height on the structure, Figure A9 shows a close-in plan view of the structure at the PBL3 height in the left-hand column and at the PBL4 height in the right-hand column at equivalent times. At 22.75 msec in (a) and (b) and 23.25 msec in (c) and (d), the pressure contours are qualitatively similar. By 24 msec in (e), the diffracted shock front has started to reform near the top of the structure while lower on the structure (f) the diffracted shock fronts have not yet merged. In both (e) and (f), a low-pressure region has formed and is dwelling just behind the side corners of the structure. The morphologies of the low-pressure regions in

(e) and (f) are beginning to show differences. At 24.5 msec in (g) closer to the top of the structure, the shock front is more planar than in (h) closer to the bottom of the structure. The low-pressure regions in (g) and (h) are in similar locations to their respective previous time-steps and have grown in size. Additionally, the low-pressure region in (h) covers a larger area of the right and rear faces than in (g). At 25.5 msec in (j) at the lower height, the low-pressure region has been shed and is beginning to travel downstream while the low-pressure region at the higher location on the structure (i) is still growing but remains just behind the corner of the structure.

Figure A9. Plots of incident shock for the 45-deg obliquity case, plan view, zoomed in. Left-Upper, Right-Lower.

Rotated structure (30-deg obliquity)

The CTH calculation of the 30-deg obliquity case had 947 million cells and required 132 hr of wall-clock time using 5,120 cores on the Garnet system to run the simulation out to 65 msec. The primary objective was to calculate the time-histories for the pressure gauges located on the box structure. Unlike the unrotated and the 45-deg cases, this calculation did not have a plane of symmetry; therefore, no gauges were mirrored to the opposing side of the structure. All gauges in the simulation were at the same locations as in the experiments.

The CTH-calculated pressure and impulse histories were compared against the measured data in Section 3.4 of the main body of this report. Comparisons were drawn for gauges on each face of the box as well as for gauges on the calibration plate and the sidewall. All of the CTH time-histories were shifted -3.64 msec to match the measured TOA at gauge PBF3. The comparisons are not repeated here for brevity, and the ensuing discussion will focus on general findings and lessons learned.

The ability of CTH to qualitatively match the measured data for gauges on the box varied from good to fair. Similar to the other cases, generally good agreement was observed between the CTH and the experimental traces up to the arrival of the second pressure peak (i.e., the arrival of the reflected shock from the end of the BLS). The results on the front and left faces, which faced the incident shock, and the top face, which was perpendicular to the shock, were generally better than those on the back and right faces, which faced away from the incident shock. Several gauge locations on the back and right faces contained additional features not observed experimentally, such as a sharp decrease and recovery in pressure around 30 msec for PBR2 in Figure 40. In almost all cases, the peak impulse was underpredicted.

Similar to the other cases and after the arrival of the reflected shock, all of the CTH traces from on-structure and sidewall gauges fell below the experimental results. In all cases, the amplitude of the negative phase pressure was overpredicted, (i.e., too negative), and the pressure rise after the minimum was delayed in the simulation. This gave rise at multiple gauge locations to a negative impulse not observed experimentally. In turn, this led to significant disparities between the measured and the calculated impulses after about 45 msec.

As with the unrotated and 45-deg cases, generally good agreement with the measured initial peak pressure was noted for the calibration plate gauges. Following the peak, there was a consistent overprediction of the rate of pressure decay resulting in an underprediction of the peak impulse. Similar to the on-structure gauges, the calibration plate and the sidewall gauge traces deviated more strongly from the experimental results after about 40 msec; for the calibration plate, the secondary and tertiary pressure peaks were missed entirely. CTH also demonstrated a low negative pressure resulting in a decrease in the impulse after about 32 msec, whereas the experimental impulse continued to rise until about 70 msec. The overall trend in low pressures after the initial peaks for all gauges suggests venting from the computational domain via the transmissive BCs greater than that which occurred in the experiment.

The incident pressure fields in the vicinity of the box structure between 22.75 and 24.25 msec are shown in an elevation view 1.0 cm off the symmetry plane (Figure A10) and in a plan view at the gauge PBF6 elevation (Figure A11). The top of each image is downstream of the box. The units of pressure are dyne/cm² in both images. The unshifted TOA of the incident shock on the front corner of the box was 22.6 msec. At 22.75 msec, the reflected shock from the front and left faces is visible in Figures A10 (a) and A11 (a). Towards the top of the structure at 23.25 msec (Figures A10 (b) and A11 (b)), the shock front has progressed past the front face, is beginning to diffract around the right face, and has just arrived at the left-back corner. At 23.75 msec, the shock wave has nearly engulfed the top of the structure (Figures A10 (c) and A11 (c)), and low-pressure regions are visible just behind the corners of the structure. At 24.25 msec (Figures A10 (d) and A11 (d)), the shock has fully engulfed the structure and is reforming; the low-pressure regions remain just behind the corners of the structure.

Figure A10. Plots of incident shock for the 30-deg obliquity case, side view.

Figure A12 shows a close-in plan view of the structure at the PBF6 height demonstrating the diffraction of the shock front around this non-symmetric structure. At 22.75 msec in (a), the shock has just arrived at the leading edge of the structure. At 23.25 msec in (b), the shock is beginning to diffract around the front-right corner, forming a small low-pressure region just behind the corner. The shock at this time has just arrived at the left-rear corner. At 23.75 msec in (c), the shock has diffracted around both corners, leaving a small low-pressure region behind each corner. At 24.25 msec in (d), the shock has reformed on the downstream side of the structure. The low-pressure regions continue to dwell just behind the corners in (e) through (h) with time-varying morphologies. By 28 msec in (i), the low-pressure region on the left-rear corner disperses. By 29 msec in (j), the pressure around the structure is dropping, and the low-pressure regions are becoming less defined.

Figure A11. Plots of incident shock for the 30-deg obliquity case, plan view.

Lessons learned

The use of transmissive BCs 20 in. from the interior extents of the BLS in the SQ1 section caused the simulations to artificially vent a greater amount of air than was observed experimentally. The same BCs were used in the first-year modeling effort; however, the BLS configuration did not have a gap at the end of the BLS. For that nearly closed system considered here, the use of transmissive BCs kept the computational domain to a reasonable size without any observable effect on the structures of interest. The pressure traces produced in this set of computations, conducted in a blind manner, did not have any obvious discrepancies until comparisons were made with the experimental data, and thus the excessive (artificial) venting was not identified during the performance of this set of computations.

Figure A12. Plots of incident shock for the 30-deg obliquity case, plan view, zoomed in. Left-Upper, Right-Lower.

The modelers were provided with the experimental data for another problem set involving a column structure, which will be described in a future report. Additional calculations were conducted with the column structure to investigate the hypothesis that the excessive venting was caused by the use of transmissive BCs and their proximity to the BLS structure. The first calculation was run with transmissive BCs placed 68 in. from the BLS centerline and was comparable to the single-structure setup discussed throughout this report. The second calculation was run with reflective BCs placed 68 in. below the BLS and 107.4 in. above and to the side of the BLS. This setup was designed to represent the same cross-sectional area as the BLS tunnel, although not the same geometry.

Figure A13 depicts representative results from the unrotated box and column structure calculations. These are not direct comparisons but show that, at least qualitatively, the transmissive BCs caused the same discrepancies for the column results in (b) and (d) as for the unrotated box in (a) and (c). Furthermore, changing from the closer transmissive BC to the farther reflective BC eliminated these discrepancies. Particularly in (d), the modified BCs captured the secondary and tertiary peaks on the calibration plate that were entirely absent in calculations using the close-in transmissive BCs.

This comparison does not demonstrate that transmissive BCs in CTH are problematic in and of themselves. Instead, the combination of transmissive BCs and proximity to the BLS artificially induced excessive venting. Reflective BCs close to the BLS might have caused discrepancies as well, and the use of transmissive BCs farther from the BLS might have provided a similar improvement in the traces.

Figure A13. Investigation of CTH boundary condition options.

Summary

CTH was used to simulate the blast environment for three configurations of the ERDC BLS with a single box-shaped structure at varying obliquities. Qualitatively, CTH was able to capture the response on the structure and the BLS sidewall for each configuration. CTH did not match the shape of the waveforms after the arrival of the reflected shock at each gauge location. After the initial blind calculations, the discrepancy with the experimental data was investigated and found to be a result of the BCs chosen and their proximity to the BLS structure. CTH generally underpredicted the impulse for all gauges. It matched the initial shape of the calibration plate gauges well, but overpredicted the rate of pressure decay from the initial peak and between 35 to 60 msec underpredicted the

pressure. Similar to the discrepancy after the arrival of the reflected shock at the on-structure gauge locations, this behavior was due to the chosen BCs and their proximity to the BLS.

Transmissive BCs in CTH should be moved as far as reasonably possible from regions of complicated flow while still representing the problem and limiting the computational cost. Expanding meshes away from the area of interest are recommended for this purpose.

The combination of a large-length scale and thin BLS walls did not fit well into the strengths of CTH. The code would likely perform better for problems involving single or multiple structures in an open-air environment subjected to blast from an explosive source. CTH has a unique capability to handle material strength in its Eulerian solution approach. This capability is not available in typical CFD codes and would be necessary if any simulated structures exhibited elastic or inelastic deformations.

Appendix B: DYSMAS Modeling

DYSMAS background

The coupled code DYSMAS (Harris et al. 2014) was developed by the Naval Surface Warhead Center (NSWC)/ Indian Head to simulate underwater explosion (UNDEX) environments and the ensuing marine vessel response resulting from the fluid-structure interaction. The loosely coupled solution approach has three components: an Eulerian code Gemini (Wardlaw et al. 2003) that performs the fluid flow calculation, a Lagrangian code ParaDyn (DeGroot et al. 2013) that performs the structural response calculation, and a coupler that transfers information between Gemini and ParaDyn. This enables DYSMAS to execute calculations that include explicit shock fronts, bubble jets, structural failure, and fluid breakthrough. Included in Gemini are the capabilities to handle compressible and incompressible fluids. Gemini employs a time-split, second-order Godunov scheme to solve the Euler equations. ParaDyn is a 3-D explicit finite element program for analyzing the dynamic response of solids and structures.

DYSMAS is a fluid-structure interaction set of codes that was designed especially for weapon lethality studies, where the explosive charge is detonated in close proximity to the target structure. For such cases, there is strong interaction between the UNDEX loading and the target structure, where the motion of the structure significantly modifies the loading. The suite of codes can be applied to any fluid-structure interaction problem or to the individual portions used to simulate their regime alone (e.g., Gemini applied to a fluid problem). DYSMAS has been under continuous development as part of a U.S.-German Project Agreement entitled “Enhanced Undersea Weapons Effectiveness and Ship Survivability through the Application of Validated Computer Codes.”

The Gemini code is an Eulerian solver for the fluid equations of motion and was designed specifically to simulate explosions in water; however, it has been applied to other environments, including explosions in air and soil. The ParaDyn code is an explicit dynamics Lagrangian finite element code that solves the structural equations of motion. The existing interface routines allow Gemini and ParaDyn to exchange information in order for the fluid and structural integration to advance in time. This Eulerian-Lagrangian combination provides a powerful capability that has been

extensively validated for complex UNDEX phenomena, including explosive shock propagation, bubble formation and jetting, and fluid-structure interaction. Gemini uses a Cartesian structured mesh (i.e., fixed rectangular cells) and supports setups in varied dimensions (i.e., 1-D, 2-D, or 3-D).

ParaDyn is the parallel implementation of the finite element code DYNA3D (Whirley and Englemann 1993). DYNA3D is based on a finite element discretization of the three spatial dimensions and a finite difference discretization of time. The explicit central difference method is used to integrate the equations of motion in time. The central difference method is conditionally stable, and stability is governed by the Courant limit on the time-step. DYNA3D uses a lumped mass formulation for efficiency. This produces a diagonal mass matrix, which renders the solution of the momentum equation trivial at each step in that no simultaneous system of equations must be solved. The contribution of the element reaction forces and applied loads are accumulated into a nodal force vector, which is then divided by the lumped nodal mass to get the nodal acceleration. This is then integrated forward in time by using a central difference approximation to get the nodal velocity and displacement.

The ParaDyn code passes a list of “interface surfaces” to Gemini at the start of a coupled calculation that describes the location of the structure within the fluid domain (i.e., the wetted surface). Each discrete surface is defined solely by three or four nodes specified in the “interface element” section of the ParaDyn input deck. Loads are passed from Gemini to ParaDyn, inducing a response and potential motion of the structure. That new location and state of the structure are then passed back to Gemini for further loading. This coupled treatment occurs at every time-step in the calculation.

Modeling overview

All of the DYSMAS calculations were run on the ERDC HPC platform Topaz. Topaz has 3,460 compute nodes with 36 cores per node. Each compute node has a core speed of 2.3 GHz and 128 GB of accessible memory.

Full 3-D calculations were conducted for all cases considered in the BLS modeling effort. This effort built on the models constructed under the initial effort for this project (Bessette et al. 2016). The BLS structure and

the target structure within were modeled as Lagrangian constructs, which were then inserted into the Eulerian air domain. The structures were composed of shell elements with a nominal thickness of 0.5 in. The nodal displacements were fixed so that the structure would act in a completely nonresponding fashion. Coupled interfaces were set so that each shell element also was an interface element, and these interface elements acted as the transfer point for data between the Eulerian and Lagrangian codes. A typical model is shown in Figure B1. Transmitting BCs were applied to all mesh boundaries in the Gemini portion of the calculation. The Eulerian domain extended approximately 200 cm away from the sides and top of the BLS structure. A uniform cell size was specified throughout the Eulerian domain encompassed by the BLS. A graded mesh, increasing each cell size by 1 percent, was specified beyond the extents of the BLS. The driver gas was represented by a volume of high-pressure air that began to propagate at time zero (see Figure B2). The diaphragm and its failure were not modeled. An ideal gas EOS was used to model both the ambient air and the high-pressure air contained within the driver section. These were modeled as two separate Eulerian materials in the problem setup. The ambient air was assigned an initial pressure and temperature of 14.5 psia and 77°F, respectively. The driver air was assigned an initial pressure of 800 psig and an initial temperature of 77°F. The striker and grill (see Figures B3 and B4) were explicitly modeled within ParaDyn, using solid 8-noded finite elements (again nonresponding) that had coupled interface segments on all external element faces to interact with the Eulerian domain.

The closed end of the BLS was opened by moving the Target Vessel away from the end of the square section, creating a “gap” approximately 4 ft in length. This gap was explicitly modeled within DYSMAS by removing the layer of shells that capped the end of the BLS and setting that layer of shells 4 ft downstream (Figure B5). The opening can be clearly seen, including the target structure set within the BLS. After adding this gap into the model configuration, a representation of a portion of the tunnel was added (Figures B6 and B7) to allow pressure to reflect off the walls and potentially back into the BLS and affect the pressure gauges on the target box structure. The mesh was graded between the BLS structure and the tunnel representation, so there was probably some degradation of the blast wave as it propagated between the two parts of the model. This tunnel consisted of nonresponding shell elements set at the dimensions of the actual tunnel. The Eulerian domain extended beyond the extent of the

tunnel model and pressure was allowed to propagate out of the “open” end of the tunnel toward the upstream end of the BLS. It was decided that modeling a complete enclosed tunnel was not necessary during the time - frame under consideration.

Three configurations were modeled to reproduce those scenarios tested. These had the target structure rotated at 0-deg, 45-deg, and 30-deg obliquities with respect to the flow of the blast field down the BLS.

Figure B1. Typical DYSMAS model (8-ft × 8-ft C2SQ configuration with box shown).

Figure B2. Initial conditions/driver pressure.

Figure B3. Depiction of striker and grill models.

Figure B4. Close-up of striker and grill at the driver end.

Figure B5. View of the gap created at the end of the BLS.

Figure B6. Representation of the tunnel added to the model.

Figure B7. BLS constrained within the tunnel shell model.

Unrotated structure (0-deg obliquity)

This BLS configuration had the box structure at 0-deg obliquity, or unrotated, with respect to the direction of the flow field within the BLS. The box structure was inserted into the C2SQ section (see Figure B1). The BLS model included both the striker and the grill (see Figure B3).

A time sequence of the pressure propagation is shown for the pressure wrapping around the structure in Figures B8 and B9, which show views of the pressure inside and overhead, respectively. The velocity and density plots in Figure B10 illustrate that the contact surface (interface between the driver gas and the downstream air) extends only to the end of the Cascade. Thus, the pressure history for gauges residing on the box should be fairly clean and consistent. The lack of noise in the measured data bears this out. Previous experiments and simulations with the box/structure at an upstream location contained noisy data that varied from test to test. Moving the structure to its current location alleviated that variability in the measured pressure data.

A 1.0-cm uniform cell size was specified for the region within the BLS, with a graded Eulerian mesh utilized outside. The analysis end time was 150 msec. It took 22.08 hr of CPU time and 1,016 processors to run this calculation to 75 msec. In each calculation, 8 processors were allotted to ParaDyn and 1,008 to Gemini. There were approximately 390.7 million cells in the Gemini mesh. It took 14,112 time-steps in the Gemini portion of the coupled calculation to run the analysis to 75 msec.

Figure B8. Pressure state plots, elevation view (0-deg obliquity).

Figure B9. Pressure state plots, plan view (0-deg obliquity).

Figure B10. Velocity and density state plots at 50 msec.

(a) Flow velocity.

(b) Density.

Rotated structure (45-deg obliquity)

Rotating the box by 45 deg still produced symmetric conditions with respect to the flow field, but this was still modeled in DYSMAS without any symmetry planes (i.e., a full 3-D simulation). The various pressure gauge locations were tagged as locations to record the pressure within the simulation. Care was necessary so as not to place the recording location within an Eulerian cell that was turned off as part of the Lagrangian construct. Figure B11 shows the status of the cells around the Lagrangian structure. As is typical for an arbitrary structure shape, the surface of the structure body is not aligned with the fluid grid, and fluid cells will be intersected by this surface. Intersected cells are either included or excluded from the calculation in their entirety, depending on whether the cell center is inside or outside the body. This results in a stair-step approximation of the body surface. To represent the body with sufficient fidelity, surface velocity and orientation are accounted for by prescribing a flux through the cell edges that comprise the stair-step boundary. The non-blue cells in Figure B11 are those that are cut by the structure, and therefore, are turned off from the fluid calculation and used to compute the loads on the structure.

Figures B12 and B13 show the location within the BLS of the box structure oriented at 45-deg obliquity to the incoming flow. Several states of the flow field as it propagates around the structure are shown in Figure B14.

The analysis end time was 60 msec. It took 20.04 hr of CPU time and 1,016 processors to run this calculation to the 60-msec simulation time. In each calculation, 8 processors were allotted to ParaDyn and 1,008 to Gemini. There were approximately 390.7 million cells in the Gemini mesh. It took 12,244 time-steps in the Gemini portion of the coupled calculation to run the analysis to 60 msec.

Figure B11. Cell status surrounding the box structure.

Figure B12. Plan view of rotated box (45-deg obliquity).

Figure B13. Rotated box and flow field.

Figure B14. Flow field propagating past rotated box (45-deg obliquity).

Rotated structure (30-deg obliquity)

By moving to a 30-deg obliquity, symmetry was removed from the problem, and this was seen in the flow field surrounding the target structure. Figure B15 shows the orientation of the box structure within the BLS. The asymmetric flow field is shown in Figure B16.

The analysis end time was 60 msec. It took 21.47 hr of CPU time and 1,016 processors to run this calculation to 60 msec. In each calculation, 8 processors were allotted to ParaDyn and 1,008 to Gemini. There were approximately 390.7 million cells in the Gemini mesh. It took 12,866 time-steps in the Gemini portion of the coupled calculation to run the analysis to 60 msec.

Figure B15. Box rotated to 30-deg obliquity to incoming flow.

Figure 10 displays four finite element analysis (FEA) plots showing the stress distribution on the front and back of the knee joint. The plots are arranged in a 2x2 grid, comparing the 'No body' condition (left column) and the 'With body' condition (right column). The top row shows the front view, and the bottom row shows the back view. Each plot includes a color-coded stress scale from -14.00 to 14.00 MPa. The 'With body' plots show a significant reduction in stress concentration around the implant compared to the 'No body' plots.

Appendix C: LOCI-Blast Modeling

Introduction

The Loci/BLAST analysis of the three single-structure tests is documented in this appendix. This work is a continuation of the analysis previously performed by Clayton Mord for his master's thesis at the MSU (Mord 2015). The previous test setup was a single structure in the closed configuration of the BLS, as discussed in Bessette et al. (2016). The tests presented in this appendix have several key differences from those previously analyzed. The calibration plate is now farther downstream. An open gap area is included to better mimic the desired pressure signature in a real-world application. The inclusion of the open gap ensures that the air flow is not confined to the interior of the BLS sections and that it is allowed to exhaust to the exterior regions surrounding the BLS. In addition to the gap, the single-structure targets have different rotation geometries to generate data on the shock interactions for face-on and oblique configurations. These new features of the BLS configuration (the gap and rotated structures) have increased the complexity of the modeling tasks. However, the unstructured grid capability of Loci/BLAST simplifies the grid generation process somewhat because the quality of the meshes over complex geometry components and for the rotated targets can be controlled to a greater degree than codes with structured grid capabilities.

The second section of this appendix describes the computational setup for Loci/BLAST for each configuration modeled. This section outlines the mesh generation for each configuration, some of the issues with grid quality, initial conditions, and boundary conditions. The next section describes the computational performance of Loci/BLAST where issues with the grid quality are addressed. Additionally, the effect of the gap area on computational and test results is described. This is followed by a discussion of computational results that includes comparisons with experimental data. The final sections outline the advantages of using Loci/BLAST as well as general conclusions and recommendations for future work.

Loci/BLAST problem setup

Mesh generation

The Mississippi State University (MSU)-developed grid generation tool, SolidMesh, was used to define the surface geometries and meshes for the

unrotated structure case. The spacing around the structure, the gap region, and the various BLS sections was set to 0.5 in., while the rest of the grid had a maximum resolution of 1 in. There were no issues with generating the gap section, since the grid used unstructured tetrahedral cells. The total mesh size for this grid was approximately 70 million cells and had an overall “good” mesh quality, as identified by Loci/BLAST.

During the setup of the rotated structure cases, there was a change in the operating system at the MSU HPC center which disabled SolidMesh, and it was no longer available to support this effort. Consequently, it was necessary to find an alternative approach for mesh generation. Pointwise, a commercial grid generation tool (Pointwise 2016), was selected for the modeling due to its availability on both the MSU and the ERDC HPC systems. To create the meshes for the rotated cases, the SolidMesh definition of the BLS geometry was imported into Pointwise and subsequently used to generate a surface mesh. The defining surface mesh for the box structure was then rotated to the specified obliquity. The spacing for these cases was the same as that with the unrotated case; however, the Pointwise meshes had a much coarser and lower quality grid. Both generated grids had an overall quality of “marginal utility,” as identified by Loci/BLAST. The total mesh sizes for the 45-deg and 30-deg obliquity cases were approximately 16.3 and 15.8 million cells, respectively. The marginal quality of these meshes was due to a lack of experience with Pointwise and differences in the underlying volume mesh generation schemes between Pointwise and SolidMesh.

The Loci/BLAST results presented in the main body of this report are based on the lower quality meshes. These results were carried out blindly and provided in a timely manner to meet the program schedule. Later in the modeling effort, “good” quality grids were generated for the rotated cases. The updated mesh for the 45-deg obliquity case had approximately 70.1 million cells and an overall “good” grid quality. The updated mesh for the 30-deg obliquity case had approximately 68.8 million cells and an overall “good” grid quality. An investigation of the differences between the lower and higher quality grids revealed anomalies in the surface meshes generated for the catch grate and striker assemblies. It is felt that the mesh definition in these regions resulted in poorly formed cells that reduced the overall quality of the initial grids generated with Pointwise. The anomalies were discovered by using the EnSight (EnSight 2016) visualization program to inspect the mesh. One way to search for problem areas is to use outputs

from the grid generation process to assess the cell face angles in the entire mesh. EnSight can create contours of the cell face angle to easily view which areas have poor orientations. Figure C1 depicts the difference between the cell face angles of the initial (poor quality) and the updated (good quality) grid around the grate area for the 45-deg obliquity case. Figure C2 depicts a 2-D cross section of the area near the grate where the poor cell face angles could have negatively affected the cell density. Note the left side of the grate, where the cell face angle is large, has a greater cluster of cells than the right side of the grate has. The good quality grid shows great improvement in this area. This is just one example of where the lower quality grids could have played a role in poor computational performance for the initial modeling of the rotated structure cases. Other areas with possible poor cell quality were the striker area and an area found near the box structure. As will be discussed in a later section, this impacted the runtime performance of the Loci/BLAST simulations.

Figure C1. Grate cell face angle for 45-deg obliquity case (detail).

Figure C3 shows a 2-D section cut down the BLS centerline in the flow direction. These cross sections illustrate the variation in the mesh density for each case modeled. Since the mesh for the unrotated case was generated in SolidMesh and was known to have good quality, no effort was made to reconstruct a new grid in Pointwise. One notes obvious differences in the mesh quality for each case. The unrotated structure case appears to have a higher concentration of cells inside the BLS structure than that of the other cases. Further, the Pointwise-developed meshes have more cells outside of the BLS structure, which leads to a higher quality grid external to the BLS. This illustrates the difference between the grid generation process of SolidMesh and that of Pointwise. SolidMesh uses the Advancing-Front/Local-Reconnection (AFLR3) algorithm while Pointwise uses Delaunay Triangulation.

Figure C2. Grate cell density for 45-deg obliquity case.

Figure C4 depicts the cell density around the box structure. The unrotated case has a more uniform distribution of cells, whereas the rotated cases have a gradual decrease in cell density moving away from the structure. Figure C5 shows the cell density around the gap area. Similarly, the unrotated case has more cells in the center of the gap, with the mesh density gradually decreasing radially away from the center. However, the grids generated by Pointwise for the rotated cases in the gap section have fewer cells but a more even distribution for the entire gap.

Initial conditions

An initial absolute pressure of 814.7 psi (800 psig) was specified for the driver section. Driver and ambient temperatures were set to 80°F. Ambient pressure in all other regions of the mesh was set to 14.7 psi. Initial values of density were computed from the specified pressure and temperature using an ideal gas EOS.

Boundary conditions

The exterior boundary surfaces, along with the surfaces of the BLS, were given a reflecting BC. For the unrotated case, the boundary wall behind the calibration plate was placed at approximately 12 ft downstream of the calibration plate. For the rotated cases, this wall was placed 3.7 ft downstream of the calibration plate. The outer boundary wall parallel to the BLS was placed at 16.7 ft from the centerline for all BLS configurations.

As shown in Figure C6, the airflow seems to be coming back into the gap region once it is reflected off the outer boundary walls in both rotated cases. The images are a top view looking down on a 2-D section near the

height of the target (i.e., parallel to the top surface of the target). The wave front reaches the wall behind the calibration plate at 35 msec or later and is reflected back towards the gap region. It is believed that the reflection from the back wall affected the code predictions, which in turn, affected the correlation with the measured data late in the simulation (after approximately 50 msec).

As seen in the previous images, the outer computational boundaries were placed at similar locations as used in the previous closed BLS calculations in order to utilize as much as possible of the previous mesh geometry. However, anomalies in the results presented here suggest that this outer boundary location may not be appropriate for the open gap simulations due to potential boundary reflections, which travel back into the open gap region and interact with the BLS internal flow field. The unstructured mesh capability of Loci/BLAST enables an accurate modeling of the BLS roof geometry, which should be included in future simulations.

Figure C3. Comparisons of overall cell density.

(a) Unrotated structure case with good quality mesh.

(b) 45-deg case, initial poor quality grid.

(c) 45-deg case, updated good quality grid.

(d) 30-deg case, initial poor quality grid.

(e) 30-deg case, updated good quality grid.

Figure C4. Cell density near the box structure.

(a) Good quality grid for unrotated case.

(b) 45-deg case, initial poor quality grid.

(c) 45-deg case, updated good quality grid.

(d) 30-deg case, initial poor quality grid.

(e) 30-deg case, updated good quality grid.

Figure C5. Cell density in the gap region.

(a) Good quality grid for the unrotated case.

(b) 45-deg case, initial poor quality grid.

(c) 45-deg case, updated good quality grid.

(d) 30-deg case, initial poor quality grid.

(e) 30-deg case, updated good quality grid.

Figure C6. Pressure field in the gap region for the rotated cases.

Figure C6. (Continued).

Loci/BLAST computational performance

The effect of poor grid quality for the rotated target cases on computational performance is seen in Table C1. On equal size and quality meshes, the run times on the ERDC platform Topaz should have been on the order of one eighth to one tenth that of the runs on MSU's Shadow. However, after producing better quality grids, only the results for the 30-deg obliquity case showed any significant improvement in computational performance. This still could be a result of cell skewness that might have been missed in the mesh generation. It is important to note that despite the large total processor-hours for the improved grid for the 45-deg case, there is still an improvement in performance. The number of cells is nearly four times that of the lower-quality grid, but the total processor hours is just over double. The improved grid for the 30-deg case shows a more significant improvement with a speedup of about 2.5.

Table C1. Loci/BLAST computational performance.

Problem set	Approx. no. of cells (millions)	Analysis end time (msec)	HPC platform	No. of processors	Wall clock time (hours)	Total processor-hours
0°	70	71	Shadow	200	237.5	47,500
45° (Initial)	16.3	68	Topaz	2048	123.6	253,133
30° (Initial)	15.8	74	Topaz	2048	121.6	249,037
45° (Updated)	70.1	69	Topaz	2048	285.0	583,701
30° (Updated)	68.8	83	Topaz	2048	47.8	97,796

Loci/BLAST computes a rough estimate of parallel efficiency over the course of a simulation. On the MSU Shadow system, this number was usually around 80 percent. On the ERDC Topaz system, the parallel

efficiency dropped into the 60 percent to 70 percent range. Other potential causes of the wide variations in computational performance include differences in compilers used to build Loci/BLAST, the various libraries such as HDF5 and MPI that are linked to Loci/BLAST, and load balancing for the larger grids.

Computational results

The comparisons based on the poor-quality meshes for the rotated cases were presented in the main body of this report. These blind calculations were provided to the ERDC computational leader early-on to meet the schedule requirements for the overall program, with full knowledge that there were issues with the mesh quality. The computational grids were updated later with significant improvements noted in the mesh quality. A visual comparison was made of the pressure and impulse time-history results for the good- and poor-quality grids. The good-quality grids showed an improvement and overall better correlation with the measured data. Unless stated otherwise, the state plots in the remainder of this appendix are based on the updated (good quality) grids.

State plots of the pressure field about the box structure are provided in Figures C7 to C12. The figures depict the shock propagating downstream and its interaction with the structure at select times. It can be seen that the strength of the reflected shock wave appears to be weaker for the rotated structure than for the unrotated case. This agrees with the shock physics that the normal reflected shock is stronger in the unrotated case than in the oblique cases.

Figure C7. Pressure field around structure, side view, unrotated case.

(a) 22 msec.

(b) 23 msec.

(c) 24 msec.

Figure C8. Pressure field around structure, side view, 45-deg obliquity.

(a) 22 msec.

(b) 23 msec.

(c) 24 msec.

Figure C9. Pressure field around structure, side view, 30-deg obliquity.

(a) 22 msec.

(b) 23 msec.

(c) 24 msec.

Figure C10. Pressure field around structure, top view, unrotated case.

(a) 22 msec.

(b) 23 msec.

(c) 24 msec.

Figure C11. Pressure field around structure, top view, 45-deg obliquity.

(a) 22 msec.

(b) 23 msec.

(c) 24 msec.

Figure C12. Pressure field around structure, top view, 30-deg obliquity.

(a) 22 msec.

(b) 23 msec.

(c) 24 msec.

Comparisons between Loci/BLAST and the measured data for the unrotated case were provided in the main body of this report and will not be repeated here for brevity. The ensuing discussion focuses on the rotated structure, drawing comparisons based on the grid quality.

Comparisons between Loci/BLAST and the measured data for the rotated case are provided in Figures C13 to C24. Note that the experimental results from only a single test are presented in the figures. The measurements were repeatable, and the results from only a single test are shown to reduce clutter. The figures have two sets of results for Loci/BLAST. The plots labeled “BLAST – Poor” refer to those generated using the initial, poor-quality grids, while the plots labeled “BLAST – Good” refer to calculations using the updated, good-quality grids.

Overall, it appears that Loci/BLAST generally underpredicts the peak pressures for the calibration plate, the sidewall, and the back face of the structure, similar to the unrotated structure case. The peak pressures for the front, top, and side faces are slightly overpredicted. The expansion after peak is again steeper than that measured, causing the calculated impulse to be lower than the measured results for most gauge locations. The Loci/BLAST results mostly match the experimental data after the peak values with the exceptions of being slightly steeper and having random spikes and dips in the pressure valuations.

Of particular interest are the results for the PBT1 gauge (see Figures C15 and C21). The unrotated and 30-deg obliquity cases show a significant secondary shock at around 45 msec in the test data that is not captured by Loci/BLAST, which shows a continued expansion followed by a mild recompression. The 45-deg obliquity case shows a spike in the data around 50 msec. This is likely an issue with the instrumentation, rather than a physical mechanism as it is observed consistently with this particular gage for all configurations.

The updated grid did improve computational performance; however, there was only a marginal improvement in the comparisons to the measured data. This was a surprising result, and further investigation into the mesh quality is warranted. There is a learning curve associated with any mesh generation tool, and it is possible that local poor-quality cells could still remain in the Pointwise-generated grid. Further review is warranted.

Figure C13. Comparisons for calibration plate and sidewall (45-deg obliquity).

(a) Gauge CP5.

(b) Gauge CP9.

(c) Gauge G1.

(d) Gauge G2.

Figure C14. Comparisons for the front face gauges (45-deg obliquity).

Figure C14. (Continued).

Figure C15. Comparisons for the top face gauges (45-deg obliquity).

(a) Gauge PBT1.

(b) Gauge PBT2.

(c) Gauge PBT3.

(d) Gauge PBT4.

(e) Gauge PBT5.

Figure C16. Comparisons for the back face gauges (45-deg obliquity).

(a) Gauge PBB1.

(b) Gauge PBB2.

(c) Gauge PBB3.

(d) Gauge PBB4.

Figure C17. Comparisons for the right face gauges (45-deg obliquity).

(a) Gauge PBR1.

(b) Gauge PBR2.

(c) Gauge PBR3.

(d) Gauge PBR4.

Figure C18. Comparisons for the left face gauges (45-deg obliquity).

(a) Gauge PBL1.

(b) Gauge PBL2.

(c) Gauge PBL3.

(d) Gauge PBL4.

Figure C19. Comparisons for calibration plate and sidewall (30-deg obliquity).

Figure C20. Comparisons for the front face gauges (30-deg obliquity).

(a) Gauge PBF1.

(b) Gauge PBF2.

(c) Gauge PBF3.

(d) Gauge PBF4.

(e) Gauge PBF5.

(f) Gauge PBF6.

Figure C20. (Continued).

Figure C21. Comparisons for the top face gauges (30-deg obliquity).

(a) Gauge PBT1.

(b) Gauge PBT2.

(c) Gauge PBT3.

(d) Gauge PBT4.

(e) Gauge PBT5.

Figure C22. Comparisons for the back face gauges (30-deg obliquity).

Figure C23. Comparisons for the right face gauges (30-deg obliquity).

Figure C24. Comparisons for the left face gauges (30-deg obliquity).

Gap vs. no gap

The simulations from the prior year for the unrotated single structure without gap (see Bessette et al. 2016) displayed much better correlation with the experimental data. This is in contrast to the present simulations, which include a gap. There are a number of possible reasons for the differences. First, there is the change from SolidMesh to Pointwise as the mesh generator, which resulted in poor mesh quality in the initial analyses. Although improved grids were generated later on, it is unclear whether they met the same standards of quality generated by using SolidMesh. Much of this has to do with limited user experience with Pointwise. Also affecting quality are the inclusion of reflecting outer BCs outside the gap and the lack of detailed modeling in this outside region

(i.e., the load bars, floor, etc.). On the whole, the results of the simulations with the gap are disappointing when compared to the previous year's simulations of the BLS in a closed configuration. A more complete set of simulations that do a better job of modeling all aspects of the test geometry should be conducted to determine whether the discrepancies are due to inappropriate BCs or just poor mesh quality. Figures C25 to C27 illustrate the flow behavior in the gap region for the three cases considered here. As the shock enters the gap region, it diffracts around the sidewalls of the BLS and begins venting into the exterior region outside of the BLS. The forward propagating shock reflects off the calibration plate and re-enters the BLS structure. There is not much variation between each case except for the position of the exterior wall on the downstream side (see right-hand side of the figures). For the rotated cases, the wall appears to be positioned too close to the edge of the calibration plate, resulting in a much stronger reflection and an adverse effect on the modeling of the venting process.

Advantages of using Loci/BLAST

Loci/BLAST has demonstrated it possesses a wide range of capabilities for blast analyses. Unlike some other CFD codes, Loci/BLAST has the capability to use unstructured grid technology in simulations. Since the BLS configuration has complicated geometries, an unstructured grid greatly reduces the level of effort needed to create a good-quality grid for simulations. Loci/BLAST also has advantages when dealing with BCs. Loci/BLAST has the capability of enforcing a rigid surface BC where some other CFD codes may have only a responding material BC. Loci/BLAST's unstructured grid capability will be particularly important for future air blast simulations involving multiple buildings that represent a typical urban environment. Also, a recent revision of Loci/BLAST's parent code (Loci/CHEM) has merged all of the current stand-alone capabilities of Loci/BLAST into the Loci/CHEM code base. Therefore, the existing viscous simulation capabilities of Loci/CHEM as well as other Loci/CHEM capabilities, such as a Lagrangian particulate transport model, can now be used in blast simulations.

Figure C25. Pressure field in gap region, top view, unrotated case.

(a) 28 msec.

(b) 29 msec.

(c) 30 msec.

(d) 31 msec.

(e) 32 msec.

(f) 33 msec.

(g) 34 msec

(h) 35 msec.

Figure C26. Pressure field in the gap region, top view, 45-deg obliquity case.

(a) 28 msec.

(b) 29 msec.

(c) 30 msec.

(d) 31 msec.

(e) 32 msec.

(f) 33 msec.

(g) 34 msec.

(h) 35 msec.

Figure C27. Pressure field in the gap region, top view, 30-deg obliquity case.

Conclusions and recommendations

The MSU Loci/BLAST code was used to successfully simulate the 3-D flow fields in the ERDC BLS for three different experimental configurations. Comparisons were made with measured pressure-time-histories at a variety of gauge locations. In general, the quality of the comparisons ranged from good to very good when using the revised grids. In particular, the results for the peak pressures on the front face of the target for each case compared well with the experimental data. However, results for the other faces did not correlate as well. This is thought to be due to several issues, such as grid quality and the effect of the gap region on the flow fields around the targets. However, the overall quality is sufficient to indicate that Loci/ BLAST is an effective tool for this class of problems. In addition, the results indicate that Loci/BLAST is an excellent candidate for future BLS analyses and related airblast simulations.

Appendix D: SHAMRC Modeling

SHAMRC background

The Second-order Hydrodynamic Automatic Mesh Refinement Code, or SHAMRC, is a government-owned fluid dynamics suite of codes developed and maintained by Applied Research Associates (ARA). It is able to solve multidimensional problems using a finite-difference scheme and can be run either in serial or parallel processing environments. Applications for which the code is used include high-explosive detonations, nuclear-explosive detonations, structure loading, airblast, thermal effects, munitions blast and fragmentation, shock tube phenomenology, dust and debris dispersion, and atmospheric shock propagation. The code employs a structured Eulerian grid that can make use of adaptive mesh refinement (AMR) for dividing the computational domain into smaller grids at several levels of refinement to provide high-resolution results. Other capabilities of the code include multiple geometries, nonresponding and responding structures, two-phase flow with noninteractive and interactive drag-sensitive particles, several atmosphere models, multiple materials, a large material library, explosive detonations, a K- ϵ turbulence model, water and dust vaporization, and a predictive metal and gaseous afterburn model. SHAMRC is second-order accurate in space and time and is fully conservative of mass, momentum, and energy.

SHAMRC is best described as a suite of codes, as it is composed of multiple programs that are used for setting up, running, and post-processing each calculation (Crepeau et al. 2012, Happ et al. 2014). The main programs used for achieving these are listed and explained here. Prospective users of these codes must first call SHAMRC to generate the source code (referred to as “make”) and eventually execute it (simply called “run”). This makes sure that the code is tailored and optimized specifically for the problem at hand.

1. KEEL – generate initial computational grid
2. SHARC – solver that advances grid conditions in time
3. PULL – plot conditions in computational grid at various times
4. STASRT/STAPLT – process, plot, and extract station (gauge) data

This appendix covers all of the calculations that were performed for the three different BLS configurations using SHAMRC.

Model setup

The three cases considered in this effort were set up almost identically in SHAMRC. The main difference among the three cases was the angle of the front face of the instrumented structure with respect to the flow direction. Additionally, the unrotated and 45-deg obliquity cases made use of half symmetry, while the 30-deg obliquity was asymmetric and was run as fully 3-D.

Boundary conditions

Each of the six boundaries in the computational Cartesian grid of the three cases had a reflective condition. This condition was chosen to model the closed environment tunnel in which the BLS resided. Although the tunnel had a semicircular cross-section profile, the profile resulting from this BC assumption was rectangular.

For the unrotated and 45-deg cases, which used half symmetry, the left-most boundary was placed coinciding with the BLS centerline at the mid-width of the tunnel. This boundary was therefore a plane of symmetry as opposed to a tunnel wall. For the boundary opposite to the plane of symmetry, the reflective condition for simulating the tunnel wall was placed at a distance of 141.7 in. from the BLS centerline. This same distance was used to place the tunnel wall on the left-most boundary in the 30-deg case.

The ground plane or tunnel floor was placed 47.2 in. below the BLS centerline, while the roof of the tunnel was located 141.7 in. above the centerline. The wall on the driver end of the BLS and the one on the calibration plate end were located 118.1 in. away from the driver and the plate, respectively.

EOS, initial conditions, and materials

The EOS used for the ambient air was the Doan-Nickel version (Doan and Nickel 1963). It was selected because the magnitude of the pressure in the driver was greater than 300 psig. This EOS was paired with a constant density and pressure ambient atmosphere model, which required fixing the ambient internal energy and mass density.

In order to fix the ambient mass density, the measured test ambient temperature and relative humidity, along with an assumed standard pressure of 14.7 psia, were used to calculate the density of the moist air in

the tunnel. Although moist air was not explicitly modeled (i.e., dry air with water), the calculated density was used in the ambient air definition to account for the increase in density resulting from the presence of water.

For defining the internal energy, the ideal gas law shown in Equation D1 was employed as a starting point. The relations shown in Equations D2 to D5 were subsequently substituted into the ideal gas equation to come up with the modified version shown in Equation D6 for obtaining the internal energy. The density used in these equations corresponds to the moist air used to fix the ambient density. The ratio of specific heats remained unchanged at 1.402 for the different test conditions of the three BLS configurations considered. The pressure in the ideal gas equation was the assumed standard ambient pressure.

$$pV = mRT \quad (D1)$$

$$\rho = \frac{m}{V} \quad (D2)$$

$$C_v = \left(\frac{\partial u}{\partial T} \right)_v \quad (D3)$$

$$C_p(T) = C_v(T) + R \quad (D4)$$

$$\gamma = \frac{C_p(T)}{C_v(T)} \quad (D5)$$

$$u = \frac{p}{\rho(\gamma-1)} \quad (D6)$$

The variables included in these equations are defined as follows: p is pressure, V is volume, m is mass, R is the apparent gas constant for air, T is absolute temperature, ρ is density, C_v is specific heat capacity at constant volume, u is internal energy, C_p is specific heat capacity at constant pressure, and γ is the ratio of specific heats.

The initial conditions for the compressed air in the driver were defined in terms of pressure and density. The pressure corresponded to the driver pressure before the diaphragm ruptured, which was 814.74 psia for the three cases. In turn, the density required being fixed with two thermodynamic variables. The variables used were the driver pressure and the ambient test temperature. All values used for fixing the ambient and driver states for the three BLS cases are listed in Table D1 in both English and centigram-gram-second (CGS) units.

Table D1. Initial conditions of BLS tunnel and driver.

Obliquity (deg)	Tunnel temperature °F (K)	Tunnel relative humidity %	Tunnel air density lb/ft ³ (g/cm ³)	Tunnel internal energy ft-lbf (ergs)	Driver density lb/ft ³ (g/cm ³)
0	79.96 (299.794)	72.6	0.07285 (1.1669e-3)	159.31 (2.1600e9)	4.1140 (6.5900e-2)
30	80.20 (299.928)	78.6	0.07275 (1.1653e-3)	159.53 (2.1630e9)	4.1120 (6.5860e-2)
45	79.90 (299.760)	80.0	0.07279 (1.1660e-3)	159.44 (2.1616e9)	4.1140 (6.5910e-2)

Besides the air, the only other material in the problem was the one used for all the solid components of the BLS. These were specified in SHAMRC as “islands,” which are nonresponding structures that have no momentum or energy associated with them. All of these components were entirely rigid and were modeled by using a combination of the following 3-D simple geometries: cylinders, cones, rectangular cuboids, and tetrahedrons.

Mesh

The computational grid used for all cases was 3-D and orthogonal to the Cartesian axes. It was discretized into cells, having a size of 1.0 cm. Since the cells were essentially cubes, each cell had a volume of 1.0 cm³. All of the problems modeled had the same number of cells along the length of the tunnel and along the vertical direction of the BLS cross section: 480 and 2,180 cells, respectively. Due to the asymmetry of the 30-deg case, it was necessary to double the number of cells across the width of the BLS cross section to model the problem as fully 3-D. This resulted in 720 cells across the width for the 30-deg case and 360 cells for the other cases. In total, the unrotated and 45-deg cases had approximately 376.7 million cells each, while the 30-deg case had about 753.4 million cells.

For the unrotated case, all sides of the structure were either perpendicular or parallel to the flow direction as well as to the three orthogonal Cartesian planes in the computational grid. This, however, was not the case for the oblique configurations, as the box was turned with respect to the direction of the flow. Therefore, the sides of the structure were represented in a “stair-step” fashion. This is illustrated in Figure D1, which depicts a plan view of the rotated structure with overlaid grid.

Figure D1. Cross section of rotated structures with overlaid grid.

Stations (gauges)

Gauges/tracers are referred to as stations in SHAMRC. All of the stations used to record history data in the modeling of the three BLS configurations were fixed in space (i.e., Eulerian) and did not interact with the flow (i.e., massless). Moreover, the following default parameters were recorded as a function of time: overpressure, density, velocity components in the three spatial directions, specific internal energy, and material cell composition.

In total, there were 30 stations in each of the three experimental cases. Due to the use of symmetry in the modeling of the cases having the structure at 0-deg and 45-deg obliquities, stations located on one side of the symmetry plane, in the negative horizontal direction of the BLS cross section, would have been positioned outside of the computational domain. Therefore, these stations were mirrored about the plane of symmetry and placed onto the positive horizontal direction of the BLS cross section. For the 0-deg obliquity case, however, this meant that gauges PBR1 and PBL1, as well as PBR2 and PBL2, had equivalent coordinates, resulting in 28 stations actually being modeled instead of 30.

An iterative process was undertaken for placement of stations to avoid issues with their residing within partially-mixed cells. Stations were offset normal to the structure face at 1-mm increments. This iterative process was repeated until the code no longer printed warning messages about a “station being located inside of an island.” A significant advantage of station placement in SHAMRC is that the code warns the user during the KEEL step if a station is located inside a structure. Thus, the user can

correctly place stations during this preprocessing step and avoid the loss of the history data in the final SHARC step of the calculation.

Computational resources

All of the problems were run on the Air Force Research Laboratory (AFRL) HPC platform Spirit. Spirit has 4,590 compute nodes with 16 cores per nodes. Each compute node has a core speed of 2.6 GHz, and 32 GB of total memory, of which 29 are accessible.

All three problems were run up to a simulation time of 65 msec. Both symmetric cases (0-deg and 45-deg obliquity) used 64 processors, while the asymmetric case used 128 processors. Although each of the problems was submitted for a wall time of 16 hr, each problem required only about 12 hr for complete execution.

Results

Comparisons between the experimental and numerical results are discussed in the following paragraphs by structure face. The discussion focuses on data trends rather than a gauge-by-gauge comparison. These have already been presented in the main body of this report. Generally, the initial peak pressure and pressure-time curve shape were in agreement. However, SHAMRC tended to predict a faster decay rate near the conclusion of the positive pressure phase, which caused the impulse to be underpredicted in most cases. After 50 msec, the experimental scatter is significant, and it is not immediately clear whether the impulse is accurately predicted.

For the unrotated case, SHAMRC compares well with both the initial maximum pressure as well as the peak integrated impulse for the front face gauges. As the structure is rotated to 45 deg, an average underprediction of 9 percent to 10 percent is noticed in the impulse, although the peak pressure is matched well. This decrease in the integrated impulse is mainly due to a shorter positive phase duration as compared with the experimental data. A slight underprediction is noted in the impulse for the 30-deg case, although it tends to be less prominent than that observed for the 45-deg case.

For gauges on the top face of the structure, the comparisons between numerical and experimental results are mixed in terms of the accuracy. All

of the predictions at the top face gauges underperformed in terms of matching the impulse. As mentioned before, the underprediction is caused by a faster decay rate of the positive phase pressure, even though the peak pressure matched well. On average, higher impulses were recorded for the 30-deg case. For each of the three obliquity angles considered, gauge PBT3 provided the best comparison with the impulse, having underpredictions in the range of 6 percent to 14 percent with the 30-deg case outperforming the other ones. It should be noted that gauge PBT3 had the greatest distance from the driver for each of the three different angles of obliquity.

For the back face gauges, the calculation involving the unrotated structure provided the best match with the experimental data. Except for PBB3, all gauges recorded an average peak impulse that was below the experimental by about 9 percent. Gauge PBB3, however, produced an impulse that was less than the experimental value by about 26 percent. Besides the faster decay rate mentioned earlier, this lower impulse is caused by an underprediction of the pressure during the initial two pressure peaks in the data. For the 45-deg case, the results are completely opposite to those experienced with the unrotated case. That is, all gauges showed a significant underprediction of 17 percent to 27 percent in the impulse, except for gauge PBB3, which matched the experiment results almost exactly. For the 30-deg configuration, underprediction of the impulse was in the range of 12 percent to 19 percent. Gauge PBB4, which exhibited the most accurate impulse record, displayed a 25 percent pressure underprediction that plateaued for 5 msec during the second peak in the data.

The comparisons for the right face gauges for the unrotated structure were mixed. The impulse was underpredicted by an average of 44 percent due in part to a significant drop in pressure following the initial pressure peak at each gauge. Comparisons are much better for the 45-deg case, in which PBR1 matched the experimental data almost exactly. Moreover, gauges PBR2 and PBR4 exhibited an underprediction of 10 percent in the integrated impulse, while PBR3 showed an overprediction of 25 percent. Similar to what was experienced on the PBF face, results for the 30-deg case tended to be between what was seen for the 0-deg and 45-deg cases. In this case, the results for PBR4 matched the experimental data, while gauges PBR1 and PBR2 exhibited an impulse underprediction of 14 percent and 23 percent, respectively. Gauge PBR3 showed an overprediction close to 22 percent in the impulse.

The comparisons for the left face gauges followed trends similar to the right face gauges, except that no noticeable overpredictions occurred for the impulse. The 0-deg case showed the least accurate results among the three angles of obliquity tested, with underpredictions in the impulse in the order of 28 percent to 50 percent. Gauge PBL4 matched the data almost exactly for the 45-deg case. Gauges PBL1, PBL2, and PBL3 displayed impulse underpredictions of 14 percent, 8 percent, and 10 percent, respectively. Finally, the 30-deg case presented an average underprediction in the impulse of 15 percent.

These results show a trend for all of the lateral faces of the structure. First, the calculations tend to be more accurate for the front and back face in the 0-deg case. At this angle, both faces are perpendicular to the flow direction. As the structure is rotated, the numerical results for the gauges on these faces begin to underperform. This is evident, as the pressure and impulse compare very well for the 0-deg case but begin to deviate from the experimental data when the structure is at 30 deg. At the 45-deg angle, the difference between the numerical and the experimental data was the most significant.

Second, the trends observed for the right and left faces were opposite those of the front and back faces. That is, the pressure and impulse on these faces performed at their worst in the 0-deg case, improved slightly on the 30-deg case, and matched the experimental data almost exactly at 45-deg. It is worth noting that both of these faces were parallel to the flow direction when the structure was unrotated.

Figures D2 through D4 show a sequence of images of the incident shock wave as it approaches the structure for each of the different angles of obliquity considered. The units for the color-bar on the left of each figure are dyne per square centimeter, or baryes. As the wave wraps around the structure, regions of low pressure are formed around it, essentially creating vortices. It is conjectured that the presence of these vortices in the simulations is affecting the comparisons, as vortices are a feature of turbulence, and turbulence is not explicitly modeled in these SHAMRC simulations. Moreover, the inclusion of a turbulence model in these numerical calculations would require the use of significantly-fine cells, which would in turn increase the amount of computational resources needed. For a large-scale model such as this one, this would easily bring the total count of cells in the problem to a couple of billion cells, which would require several tens of thousands of processing cores for a reasonable turnaround.

Figure D2. Incident shock wave wrapping around structure, 0-deg obliquity. **Figure D3. Incident shock wave wrapping around structure, 45-deg obliquity.** **Figure D4. Incident shock wave wrapping around structure, 30-deg obliquity.**

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14. ABSTRACT The Blast Load Simulator (BLS) at the U.S. Army Engineer Research and Development Center (ERDC) has been utilized for applying simulated blast loads on structures for over a decade. An integrated experimental and computational program was undertaken to evaluate first principles codes (FPCs) for modeling airblast environments typical of those encountered in the BLS. The FPCs considered are CTH, DYSMAS, Loci/BLAST, and SHAMRC. The modeling is a multi-year effort and utilizes a number of BLS configurations for the code evaluation. The modeling discussed herein builds upon the first year, which examined the flow environment within an empty BLS and a case involving a single box-like structure. The current effort expands on the single-structure scenario by employing venting at the target end of the BLS to mitigate upstream reflections and ensure a more ideal loading pulse on the structure. Three structure configurations are considered for this effort. The first is a baseline case with the front face of the box oriented perpendicular to the incoming flow. The remaining two configurations consider a rotated box at 30- and 45-deg obliquity with respect to the incoming flow. Comparisons of modeling results and BLS measurements are discussed. Shortcomings in the modeling physics are identified, and areas for improvement are noted for future development.					
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