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MODELLING BLAST WAVE CLEARING USING LOAD_BLAST_CLEARING: PART 2 – OBLIQUE CLEARING AND TNT EQUIVALENCE

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1 Introduction

Part 1 of this work, Schwer *et al.* [9], provides a verification and validation study of the new keyword Load_Blast_Clearing (LBC); an additional keyword in LS-DYNA that modifies "standard" Load_Blast_Enhanced (LBE) predictions to account for pressure reduction due to blast wave clearing. LBC is based on an independent implementation of Hudson's [4] method and was validated against recent experimental results for both rigid and deformable finite-sized targets. The purpose of the present manuscript is to validate the new keyword Load_Blast_Clearing with some experiment results involving oblique Mach Stem reflections. Because PE4 was used as the explosive in the experiments, this necessitated using a TNT equivalent charge with Load_Blast_Enhanced and associated Load_Blast_Clearing. The question of TNT equivalence for incident, and normally reflected, blast waves is not a settled matter, e.g. several equivalence methods exist. TNT equivalence for reflected Mach Stems seems to be unexplored.

The manuscript has two main sections:

1. Clearing of Mach Stems on Oblique Targets – Validation;
2. TNT Equivalence for Mach Stem blast waves.

2 Oblique Mach Stem blast wave clearing – Validation

In the companion manuscript, Schwer *et al.* [9], Load_Blast_Clearing results for a target inclined at a 20° angle to the blast wave was compared to the results from a MM-ALE simulation. The loading scenario was a hemispherical surface burst that results in a spherically divergent blast wave. In this section, oblique blast waves are again the focus, here a Mach Stem blast wave is generated from a height-of-burst explosion and propagates as a cylindrically divergent shock, i.e. provides more momentum than a spherically divergent blast shock.

Rose *et al.* [8] conducted a series of height-of-burst explosive tests to assess clearing effects for a target surface subjected to oblique blast waves. The 37g spherical PE4 charge was placed a nominal 2 m from the target surface and elevated 350 mm above the ground surface, see Figure 1. This target and charge arrangement provided a nearly uniform Mach Stem loading of the target surface, i.e. the triple point height exceed the target height. Five target obliquities were tested, i.e. α = 15, 30, 45, 60 and 75 degrees, at two ranges of 2 and 4 meters. Each configuration was repeated twice. Unfortunately, no $\alpha = 0°$ result was reported.

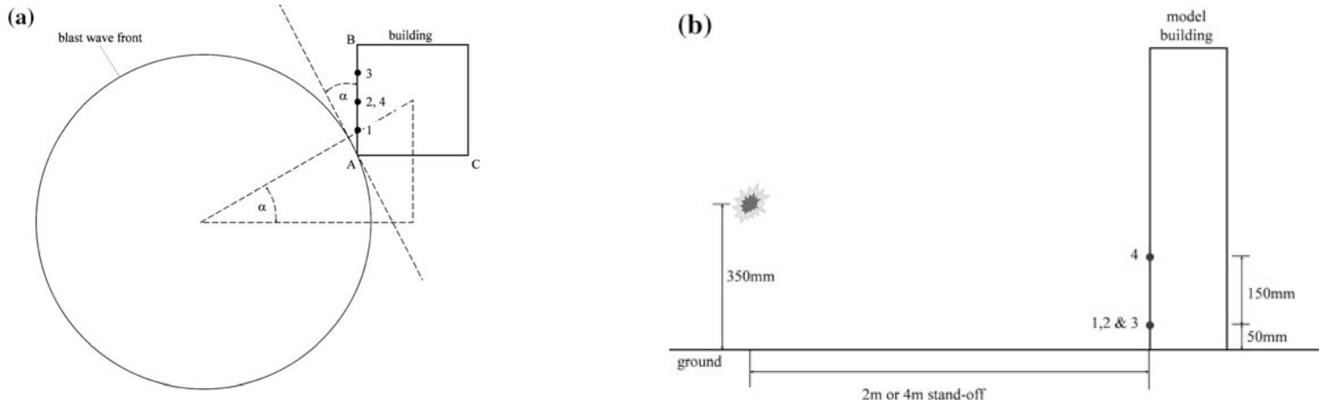

Figure 1 Schematic of experimental layout. a) Plan view and b) Elevation (Figure 2 in Rose *et al*. [8])

The rigid test structure had a square base of side length 200 mm and was 700 mm tall. Pressure gauges were located on one face: three gauges evenly spaced 50 mm apart and 50 mm above the ground surface, i.e. gauges 1-2-3 indicated in Figure 1; a fourth gauge was located 200 mm above the ground surface at the center of the face to assess the "planarity" of the Mach Stem. Rose *et al.* state:

"The different angles were achieved by rotating the model about its centre, which meant that the actual distance from the charge to the gauge locations varied slightly with the angle."

The experimental data was supplemented by numerical simulations using an adaptive mesh blast analysis code called FTT_AIR3D [7]. Only two comparisons of data and numerical results are presented, i.e. Figure 4 a & b in Rose *et al.*, with the authors noting:

"… numerical results are not perfectly resolved and that (sic) they do not match the experimental data exactly."

It appears the numerical results were only used to aid in determining the time of arrival (TOA) of the blast clearing waves at the gauges. The clearing TOA was sometimes evident in the data as a distinct change in slope of the pressure histories. In some cases, the slope change was not evident, and use was made of the derivative of the more smoothly varying numerical pressure histories. Figure 2 shows an example of the data and numerical simulation results for Gauge 2 of the 15° oblique target.

For the present purposes, the two things of note in this data are the initial blast wave time of arrival 3.48 ms and maximum pressure of ~100 kPa (ignoring the pressure spike). The numerical results used three mapping stages from 1D – 2D – 3D with multiple levels of adaptive mesh refinement in each stage; both of these CPU time saving techniques are sources of error in Eulerian calculations.

The application of Load_Blast_Clearing to this set of data requires an estimate of the TNT equivalence for PE4. TNT equivalencies are determined by comparing the pressure and impulse results from reliable experiments with numerical models or fast-running engineering models (e.g. in the work of Farrimond *et al.* [3]). The air blast literature provides adequate experimental data for several common explosives. However, these data are typically for spherical or hemispherical blasts. Experimental data for height-of-burst generated Mach Stems are more limited.

In the next section, an estimate of the TNT equivalence for the Mach Stem blast waves of the Rose *et al.* [8] experiments was determined to be 3.0, much larger than the ConWep [5] provided PE4 equivalence of 1.28 for spherically divergent free air and surface bursts.

As will be illustrated subsequently, there was a need for a time-shift of the numerical results for ease of comparison. Similar delayed TOA were observed for MM-ALE and CAB[1] simulations using C4 as the explosive. Figure 3 is a bar chart showing the required time shifts at all three gauges for all six angles of obliquity. Except for 30° obliquity, the pattern is consistent in that the gauge location closest to the explosive, i.e. Gauge 1, has the smallest time shift and the gauge location farthest from the explosive, i.e. Gauge 3, has the largest time shift. It is possible that about half of these time shifts could be due to shot-to-shot TOA variations, see Figure 3a in Rose *et al.* [8].

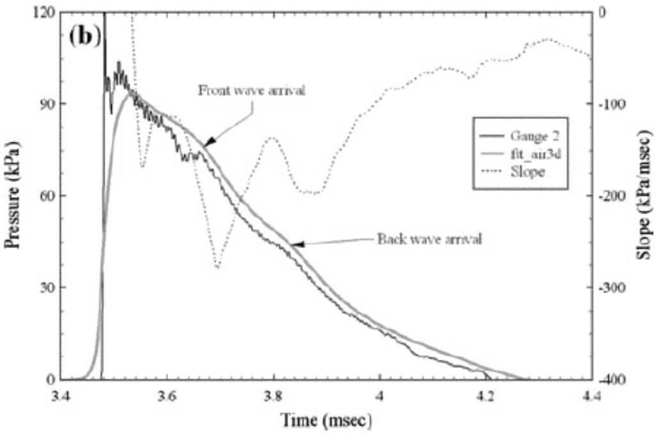

Figure 2 Comparison of measured (Gauge 2) and numerical (FFT_AIR3D) pressure histories for the 15° obliquity target and differentiation of numerical results (Figure 4b in Rose *et al.*)

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[1] CAB is discussed in the TNT equivalence section.

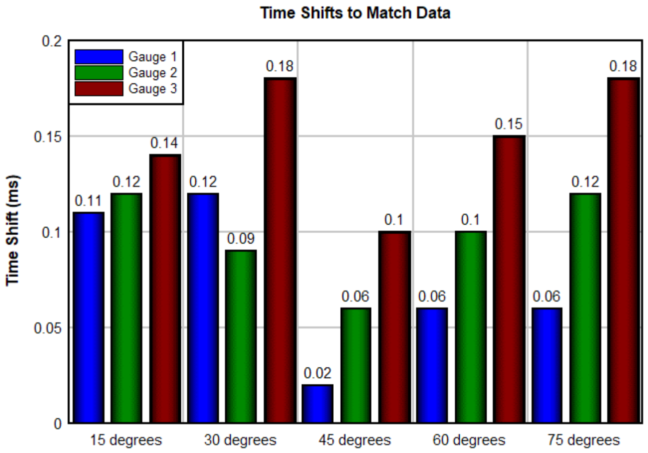


Figure 3 Initial blast time of arrival shifts for all three-gauge location and all six obliquities

Because the LBC pressure histories include edge clearing effects, the best comparison metric is maximum impulse, since maximum pressure is not affected by clearing. The following set of bar charts, Figure 4, show the maximum impulse at the three-gauge locations for all six angles of obliquity for both the Rose *et al.* data (top) and the time shifted LBC results (middle). An additional bar chart is presented depicting the relative error between the two sets of maximum impulse (bottom). In each maximum impulse chart, the trend is for the maximum impulse to decrease with increasing angle of obliquity; this trend is more obvious for the LBC simulation results. The other consistent trend in the LBC simulation results is for each group of three-gauge maximum impulses, the middle gauge, Gauge 2, always has the largest value. This is attributed to this gauge location being farthest from the clearing edges.

The relative error bar chart in Figure 4 shows a clear trend of the LBC maximum impulse relative error increasing with increasing obliquity. Other than experimental error – that was not quantified by Rose *et al.*, the LBC/LBE method has numerous sources of possible error:

- No change in clearing relief functions with angle of incidence;
- No accounting for interplay between Mach Stem and clearing relief functions;
- Possible inaccuracies in Mach Stem strength (LBE);
- Use of TNT equivalence as explosive source rather than C4 (nominally the same equivalence as PE4).

The subsequent sequence of figures at the various angle of obliquity provides the Rose *et al.* gauge data (digitized from the manuscript) as black lines. The corresponding LBC results are shown as thin colored lines and corresponding time shifted LBC results as thicker dashed lines. Corresponding impulse histories are also provided for the Rose *et al.* data and the time shifted LBC results.

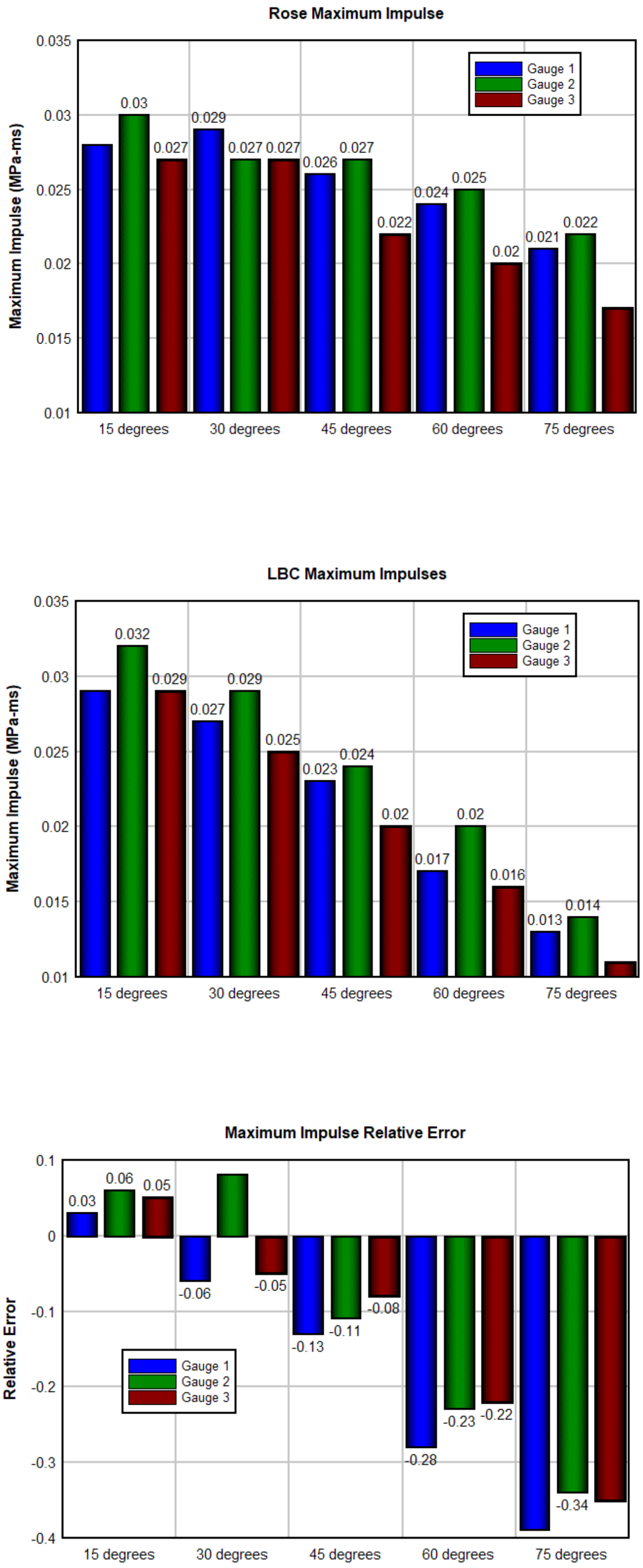


Figure 4 Maximum impulse from Rose data (top) and LBC simulations (middle) with comparison of relative errors (bottom)

2.1 Angle of Obliquity $\alpha = 15°$

Figure 5 shows a compilation of the pressure and impulse history results at three gauge locations for the Rose *et al.* experimental data and corresponding LBC results.

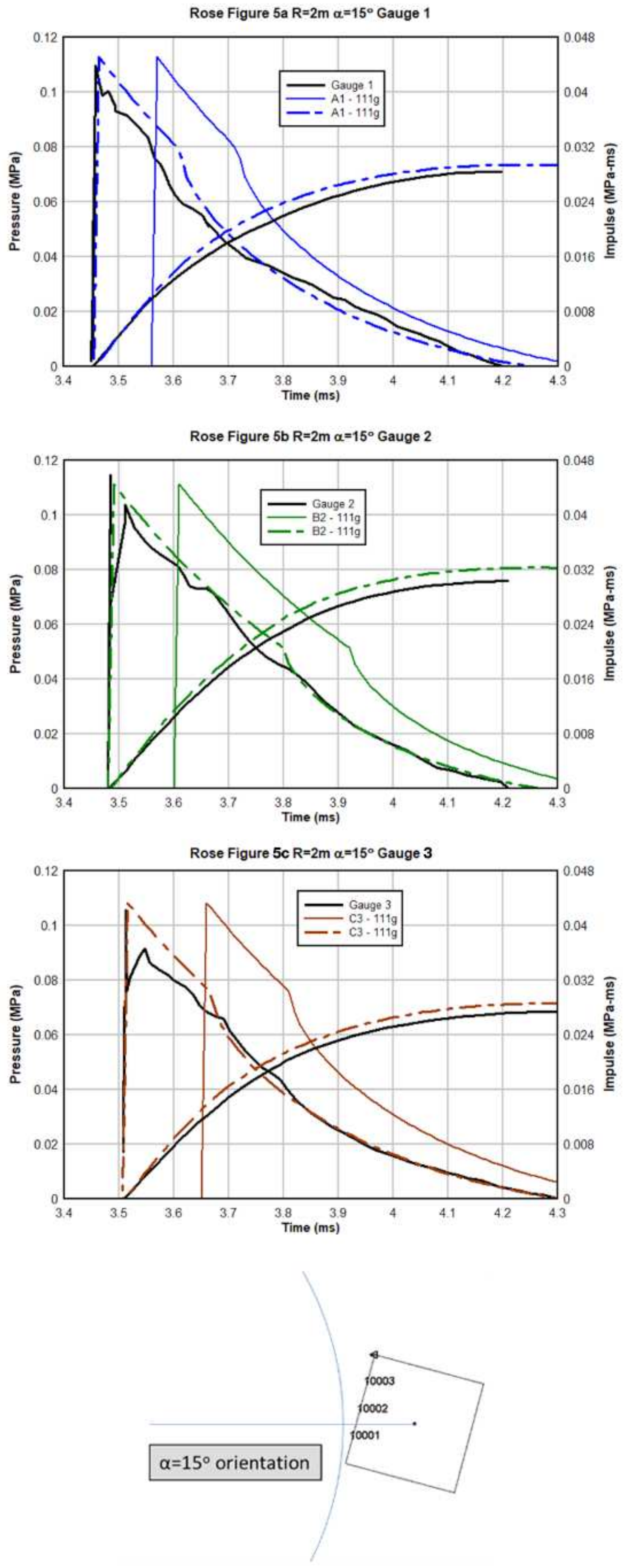


Figure 5 Pressure and impulse histories from Rose *et al*. and LBC simulation $\alpha = 15°$

2.2 Angle of Obliquity $\alpha = 30°$

Figure 6 shows a compilation of the pressure and impulse history results at three gauge locations for the Rose *et al.* experimental data and corresponding LBC results.

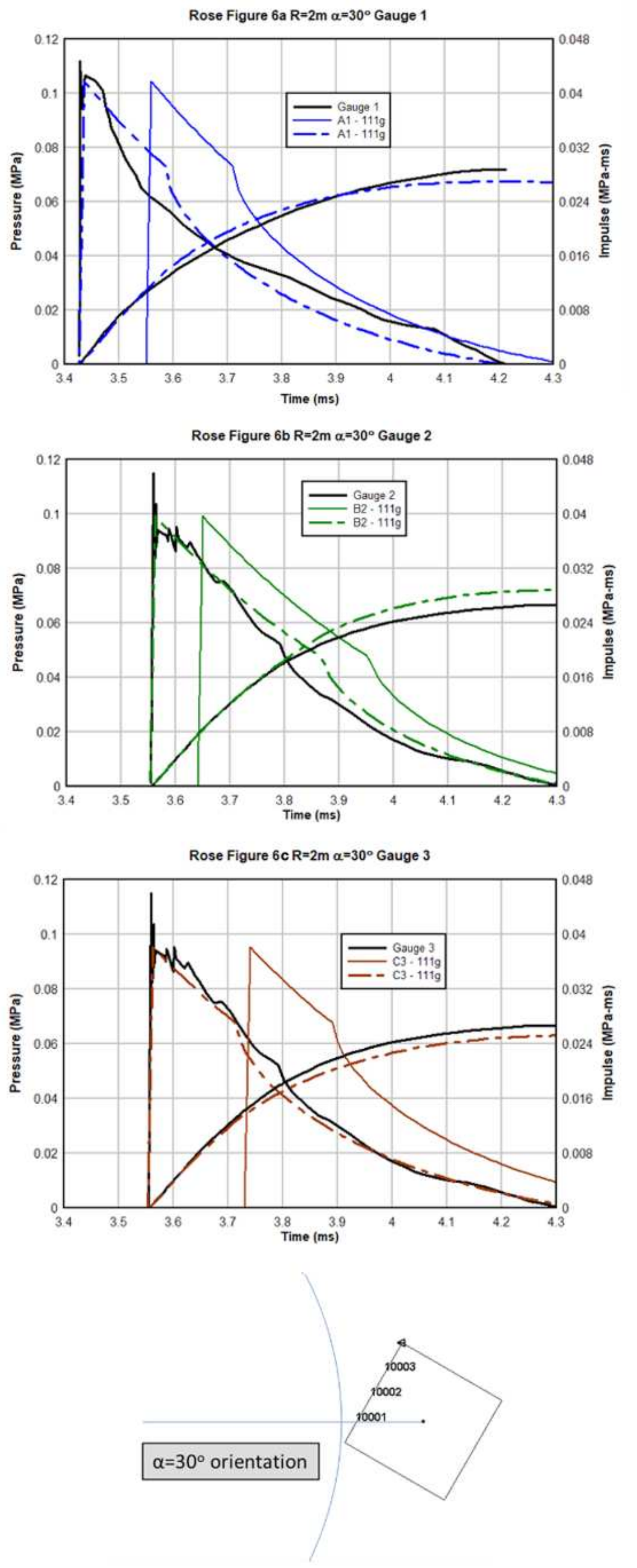
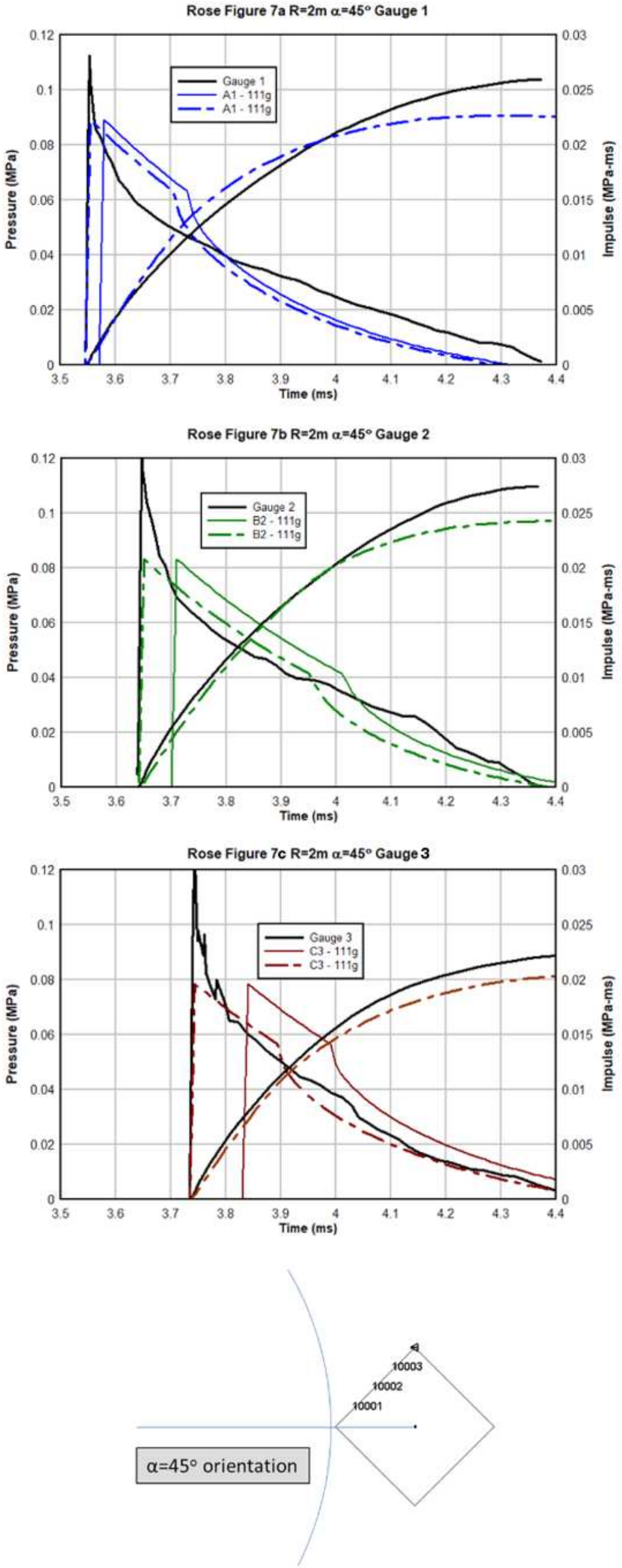


Figure 5 Pressure and impulse histories from Rose *et al*. and LBC simulation $\alpha = 30°$

2.3 Angle of Obliquity $\alpha = 45°$

Figure 7 shows a compilation of the pressure and impulse history results at three gauge locations for the Rose *et al.* experimental data and corresponding LBC results.


Rose Figure 7a R=2m α=45° Gauge 1

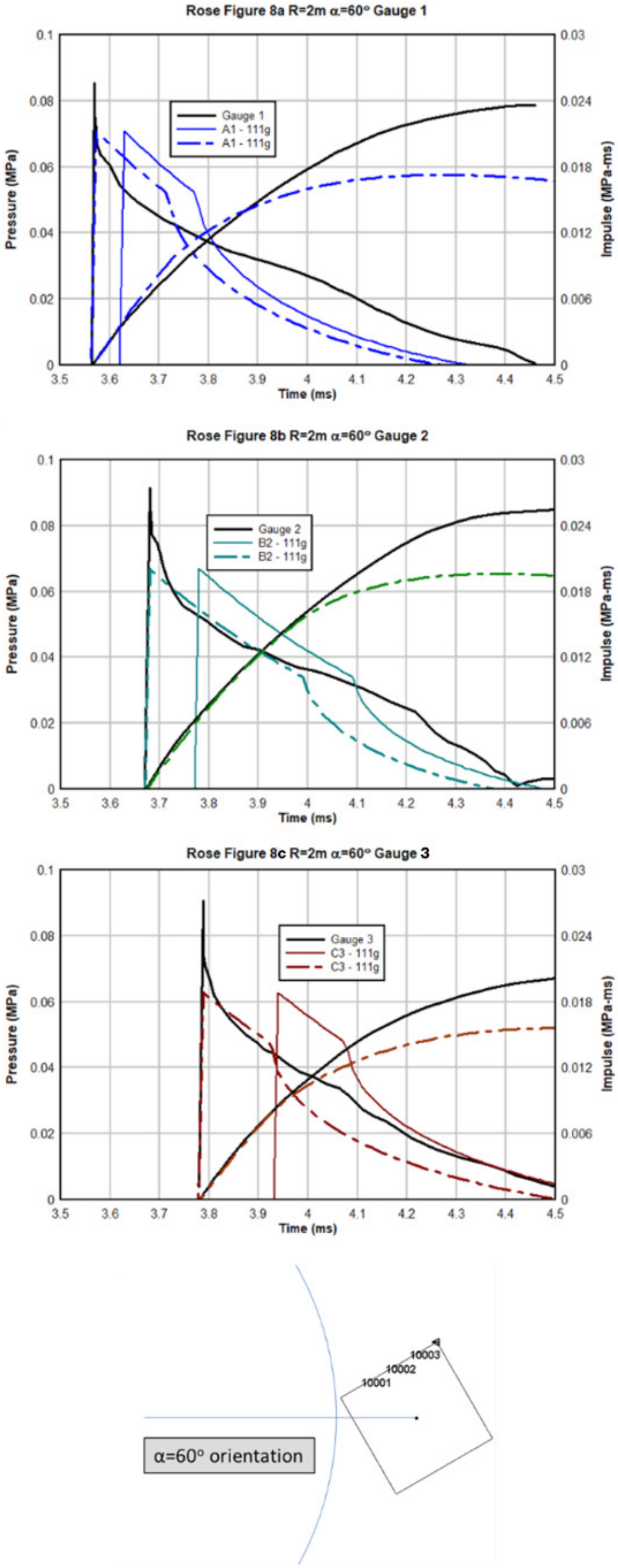
Rose Figure 7b R=2m α=45° Gauge 2

Rose Figure 7c R=2m α=45° Gauge 3

Figure 7 Pressure and impulse histories from Rose *et al.* and LBC simulation $\alpha = 45°$

2.4 Angle of Obliquity $\alpha = 60°$

Figure 8 shows a compilation of the pressure and impulse history results at three gauge locations for the Rose *et al.* experimental data and corresponding LBC results.


Rose Figure 8a R=2m α=60° Gauge 1

Rose Figure 8b R=2m α=60° Gauge 2

Rose Figure 8c R=2m α=60° Gauge 3

Figure 8 Pressure and impulse histories from Rose *et al.* and LBC simulation $\alpha = 60°$

2.5 Angle of Obliquity $\alpha = 75°$

Figure 9 shows a compilation of the pressure and impulse history results at three gauge locations for the Rose *et al.* experimental data and corresponding LBC results.

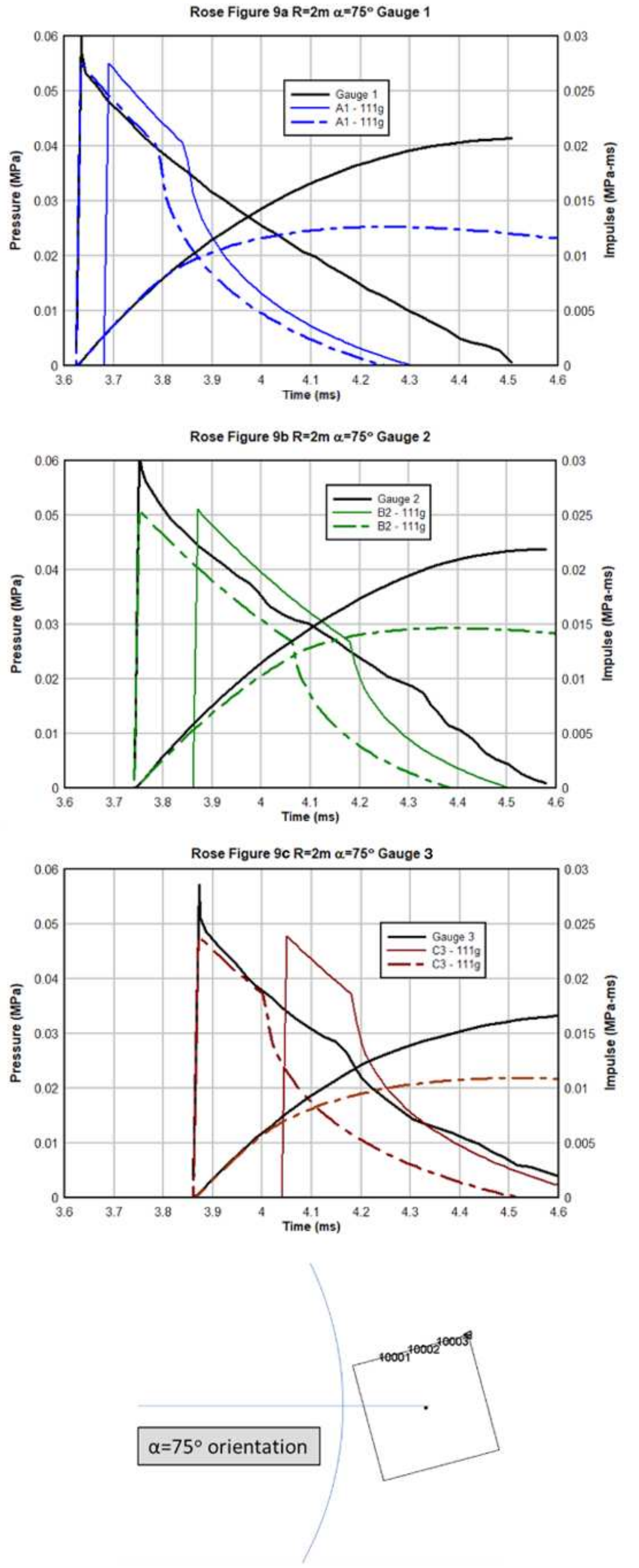


Figure 9 Pressure and impulse histories from Rose *et al.* and LBC simulation $\alpha = 75°$

3 TNT equivalence and Mach Stems

The need for TNT equivalence most often occurs when using engineering models of blast such as ConWep or its LS-DYNA implementation Load_Blast_Enhanced (LBE). TNT equivalence is commonly referenced to maximum pressure or maximum impulse. However, the value also depends on range, to a lesser extent charge size, charge shape and incident or reflected values of pressure and impulse. Applications like ConWep use the same TNT equivalence for both referents. For example, for the explosive C4, ConWep uses the average between the TNT equivalent for maximum pressure 1.37 and maximum impulse 1.19, or 1.28 as *the* equivalent regardless of range.

The most common scenarios for using engineering blast models are for assessing incident pressure histories or its simple (normal) reflection from a structure. The LS-DYNA engineering model LBE also includes an approximation, due to Randers-Pehrson and Banister (1997), of a blast wave's angle of incidence, i.e. angle between surface normal and a ray from the explosive charge to the structure. An additional Load_Blast_Enhanced capability approximates a Mach Stem blast wave. This wave typically forms when a charge is detonated above a surface (height of burst) and produces three air blast regions: (1) incident blast wave, (2) ground reflected blast wave and (3) a combination reinforcement of these two waves that grows vertically from the surface known as a Mach Stem; the Mach Stem has more impulse than either of the other two blast wave types.

TNT equivalencies are determined by comparing the pressure and impulse results from reliable experiments with numerical models, especially engineering models. The air blast literature provides adequate experimental data for several common explosives. However, these data are typically for spherical or hemispherical blasts. Experimental data for height-of-burst generated Mach Stems are more limited.

Having the Rose *et al.* [8] Mach Stem reflected pressure data provides an opportunity to assess the TNT equivalence for reflected Mach Stems. As mentioned above, Rose *et al.* did not report the results of a non-oblique (normal) blast impact test. Thus, use will be made of the 15° oblique data which is assumed to be *similar* in terms of maximum pressure and initial blast wave TOA to the non-oblique case.

4 TNT equivalence

Before comparing Load_Blast_Enhanced Mach Stem results with the oblique target results from Rose *et al.*, it is instructive to examine Mach Stem reflections for normal (non-oblique) reflections. The results from Load_Blast_Enhanced will be supplemented by MM-ALE results and another engineering blast model referred to as Close in Air Blast [1]. CAB allows for height-of-burst simulations and is based on interpolation of high-resolution Eulerian simulations. There is no need for the use of TNT equivalence as CAB includes a library of high explosive results.

As a starting point for the TNT equivalence of C4, Rose *et al.* state

"The charge was spherical with a TNT equivalent mass of 50 g (comprising 37 g PE4 explosive and an electric detonator)."

suggesting a TNT equivalence of 1.35, which is close to the 1.37 cited by ConWep for maximum pressure of C4.

4.1 MM-ALE model

All that is needed initially for TNT equivalence calibration is Mach Stem maximum pressure and corresponding TOA, so a simple axisymmetric model with a rigid outer circumference will suffice. A tracer particle (T1) located 50 mm above the ground surface at the outer constrained mesh boundary will provide the needed reflected pressure and TOA simulation data, see Figure 10.

The MM-ALE model was run in two explosive charge configurations: 37 g of C4 and 50 g of TNT (TNTeq=1.35). Note: C4 and PE4 are assumed to be essentially equivalent explosives.

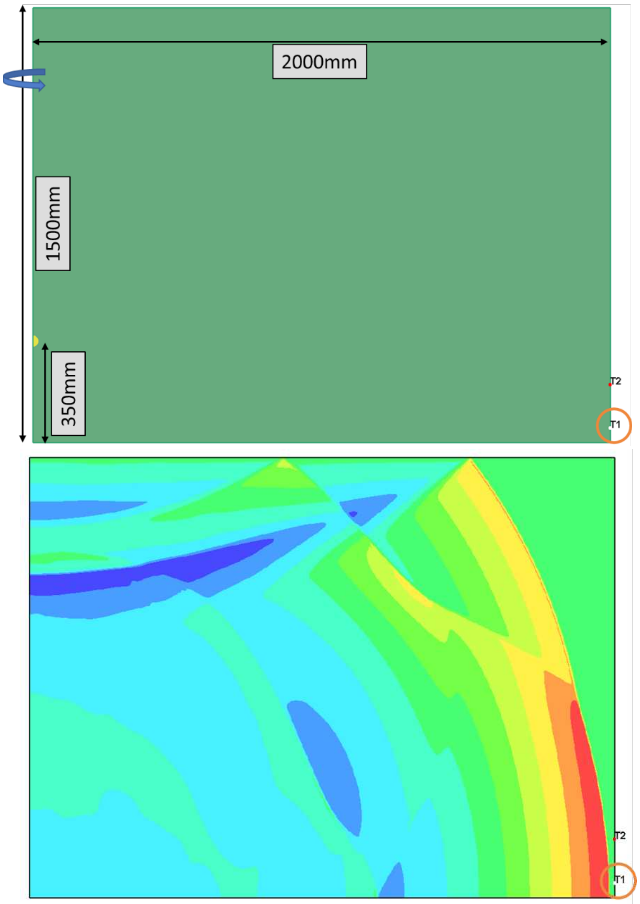


Figure 10 Illustration of the axisymmetric MM-ALE model for the HOB simulations (top) and Mach Stem at 3.5 ms just before wall impact (bottom)

Figure 11 compares the pressure history measured in the 15° oblique target with those from the MM-ALE simulation normal impact (non-oblique) for a TNT equivalence of 1.35 (50 g) and a 37 g C4 charge; the measured data is used as a relative point of reference for Mach Stem TOA and maximum pressure. The TNT equivalent charge has a TOA of 3.68 ms and the C4 charge has a TOA of 3.53 ms, the latter being closer to the Gauge 2 TOA of about 3.48. The TNT equivalent has a maximum pressure of 96 kPa while the C4 has a maximum pressure of 108 kPa – both basically bracket the data maximum pressure.

Just based on TOA for these MM-ALE Mach Stem simulations, using a 50 g of TNT (TNTeq=1.35) is not correct. A better approximation of the MM-ALE C4 pressure history is obtained with a 61 g TNT (TNTeq=1.65) charge as shown in Figure 12. This also highlights another TNT equivalence factor in that the amount of explosive affects the TOA.

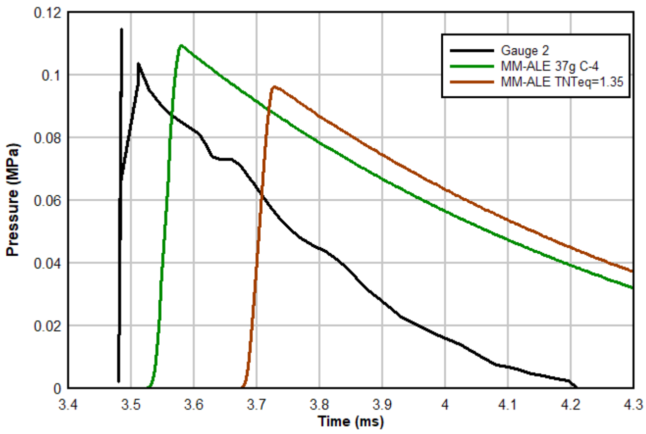


Figure 11 Comparison of pressure histories at Gauge 2 measured and with MM-ALE results for 37 g C4 and 50 g TNTeq=1.35

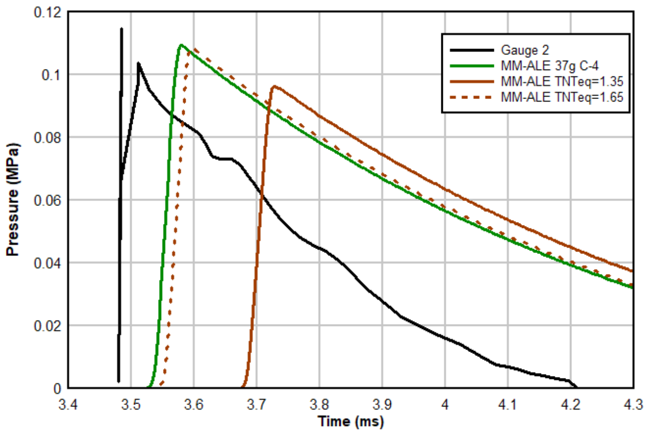


Figure 12 Comparison of pressure history at Gauge 2 with MM-ALE results for TNTeq=1.35 & 1.65 and 37 g C4

4.2 *Close-in Air Blast (CAB) model*

The CAB engineering model is from the US Army Engineering Research and Development Center (ERDC): CAB (Close-in Air Blast) has air blast simulation capabilities beyond those offered by ConWep (Conventional Weapons). CAB is based on Eulerian simulations, using the SAGE code. CAB uses these Eulerian results in the form of "tabular source models," i.e. interpolation of a database of Eulerian results.

Figure 13 shows the graphic interface used by CAB with the input parameters for the Rose *et al.* experiments at 2 m standoff. Separate options exist for defining what is termed a "Target Area" and "Reflecting Surface." The target area is optionally used to automatically generate a uniformly spaced array of target points that record pressure histories. The other option is to define target points via *xyz* coordinates on the target. The reflecting surface defines the edges of the target used to compute the clearing effects.

Figure 14 compares the pressure history at Gauge 2 with those shown previously in Figure 12, i.e. MM-ALE results for 37 g of C4 and 50 g of TNT (equivalent 1.35). The additional pressure history in Figure 14 is from the CAB simulation (blue color). The 37 g C4 MM-ALE and CAB results are similar with nearly identical maximum pressures and TOAs differing by only 0.08 ms.

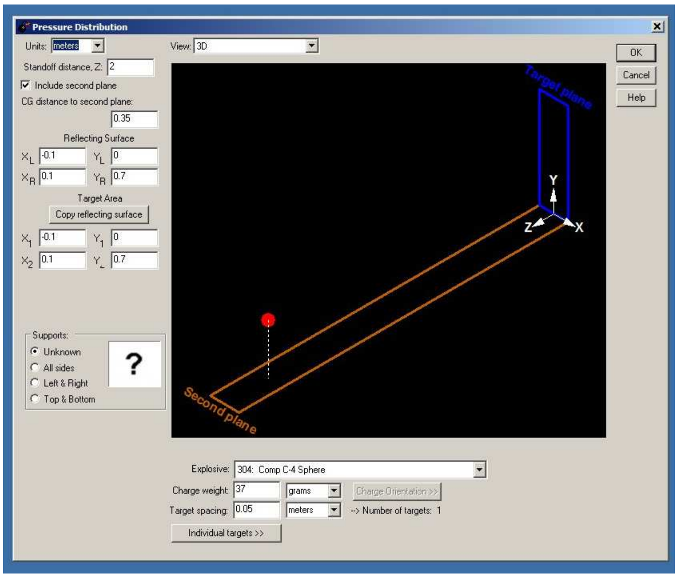
The CAB results using 37 g C4 verifies the MM-ALE results using 37 g of C4. Again, indicating that for the Mach Stem in this case the TNT equivalence of 1.35 is not appropriate.

4.3 *Load_Blast_Enhanced model*

Having demonstrated that a TNT equivalence of 1.35 is inadequate to model the Mach Stem reflected pressure for the PE4 charge used in the Rose *et al.* experiments, an investigation of what Load_Blast_Enhanced TNT equivalence best reproduces the MM-ALE and CAB maximum reflected pressure and TOA was undertaken.

The Load_Blast_Enhanced model consisted of a 200×700 mm target discretized by uniform 10 mm square shell elements. The shell segments associated with the four-gauge locations were the only segments to be loaded as the goal was to obtain the maximum reflected pressure and TOA for comparison with the CAB and MM-ALE results.

Figure 15 adds the pressure history from the LBE simulation at the Gauge 2 location for 50 g TNT (equivalence of 1.35) to the previously shown pressure histories in Figure 14. Comparing only the two 50 g TNT (equivalence of 1.35) results from MM-ALE and LBE it is evident that the algorithm used for the LBE Mach Stem results differs markedly from the MM-ALE solution. The LBE maximum pressure is 30% less than the MM-ALE maximum and the LBE TOA occurs 0.31 ms after the MM-ALE TOA.



Units: meters
View: 3D
Standoff distance, Z: 2
☑ Include second plane
CG distance to second plane: 0.35

Reflecting Surface
X_L -0.1 Y_L 0
X_R 0.1 Y_R 0.7

Target Area
Copy reflecting surface
X_1 -0.1 Y_1 0
X_2 0.1 Y 0.7

Supports:
● Unknown
○ All sides
○ Left & Right
○ Top & Bottom

Explosive: 304: Comp C-4 Sphere
Charge weight: 37 grams
Target spacing: 0.05 meters --> Number of targets: 1

Figure 13 Illustration of CAB graphical input for Rose *et al.* [8] experiments

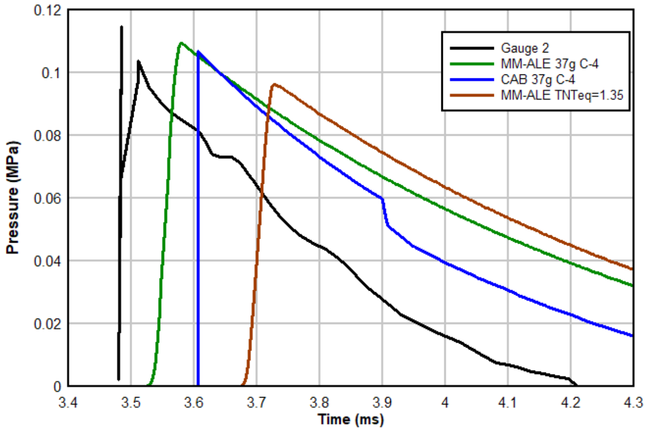


Figure 14 Comparison of pressure history at Gauge 2 with MM-ALE results for TNTeq=1.35 and MM-ALE and CAB results for 37 g C4

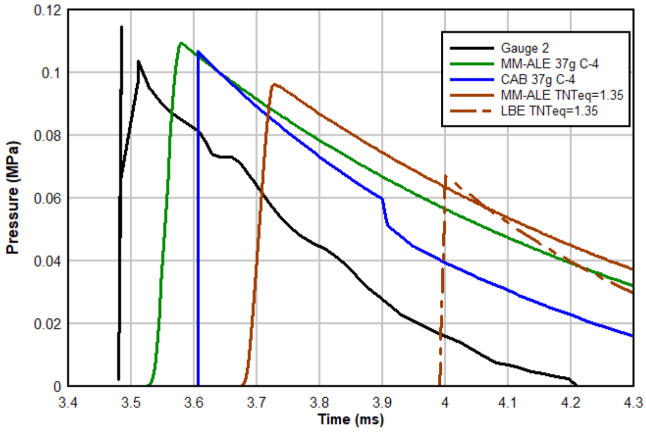


Figure 15 Comparison of pressure history at Gauge 2 with MM-ALE and LBE results for TNTeq=1.35 and MM-ALE and CAB results for 37 g C4

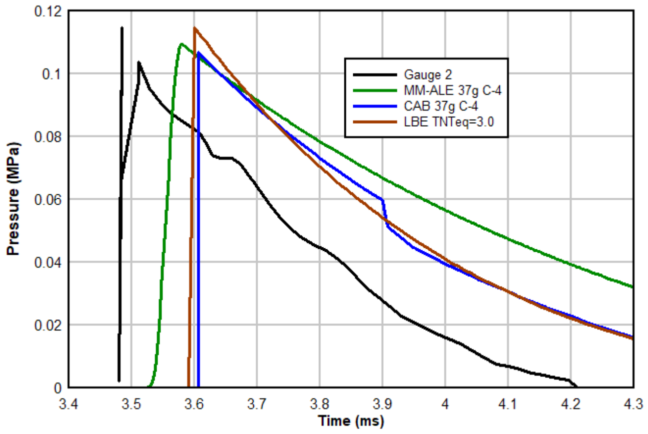


Figure 16 Comparison of pressure history at Gauge 2 with MM-ALE and CAB results for 37 g C4 and LBE results for a TNTeq=3.0

Figure 16 compares the Gauge 2 pressure histories from the 37 g C4 CAB and MM-ALE simulations with the LBE simulation using 111 g of TNT (equivalence of 3.0). All three numerical results have maximum pressures approximating the data. However, all three simulations have TOAs that occur well after the experimental TOA. There is some shot-to-shot TOA variation in the data, see Figure 3a in Rose *et al.*, but that is only about half the TOA difference shown here in Figure 16.

5 Conclusions

Load_Blast_Clearing is a useful addition to the blast loading engineering toolbox. In terms of validation for clearing of oblique reflected Mach Stem impulses, the clearing algorithm seems to do an adequate job for obliquity angles below 45 degrees. This is quite an achievement if you consider all the parameters that influence the development of impulse:

- **Clearing** – This is a useful feature that was verified and validated for normal impacts in a companion manuscript [9].
- **Oblique** – The angle of incidence pressure reduction is an engineering model unto itself, derived for spherically divergent blast waves and used here for cylindrically divergent Mach Stems.
- **Reflected** – Data on the reflection of Mach Stems is scarce. The Rose *et al.* data used in this manuscript is possibly all that is available in the open literature.
- **Mach Stem** – The engineering model for Mach Stem generation in Load_Blast_Enhanced makes all the other components of this validation effort possible.

Calibrating engineering blast models for TNT equivalence is a difficult task. In the present case of reflected Mach Stem at oblique angles, this situation is even more precarious. Using verified Eulerian simulation results, i.e. LS-DYNA MM-ALE and CAB, a degree of confidence was established for the use of a TNT equivalence of 3.0 in the present case – this is not to be taken as a general recommendation. Rather a method for estimating the TNT equivalence for Mach Stem reflections has been presented.

References

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