Mesh Sensitivity of Blast Wave Propagation

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Abstract

Calculation of blast propagation in air from a high explosive detonation is an often-used feature of LS-DYNA®'s Eulerian capabilities. To obtain credible results, a suitably fine mesh is needed, particularly in the vicinity of the explosive, to represent the nearly instantaneous rise of shock pressure and its gradual decay. In this paper, we aim to present a set of generally applicable guidelines for mesh refinement, using both 2-D axisymmetric and fully 3-D meshes. Models of a Composition B spherical detonation were exercised using various mesh sizes and for charges of varying mass. Simulations made use of the high explosive burn material model and initial detonation card within LS-DYNA. The results were evaluated based on the total impulse at various scaled standoff distances, and then characterized in terms of a scaled mesh dimension (scaled by the cube root of the charge mass). This relationship can be used in future studies to evaluate the trade-off between computational intensity and accuracy of results.

Introduction

To predict the response of a structure to blast loading, either due to accidental or intentional detonation of a high explosive (HE), the pressure wave resulting from this detonation must be determined. A variety of methods can be used to calculate the pressure history at various stand-off distances from the charge. The Kingery & Bulmash (K-B) curves, shown in Figure 1, are often used to calculate the pressure and impulse from a detonation by scaling the parameters by the cube root of the equivalent TNT charge mass [1]. These curves assume a spherical charge with a clear path to the measurement point and no reflections from the ground or other surfaces. And, while reliable at farther distances from the charge, they are not as accurate for very close standoff distances (< 0.4 m/kg$^{1/3}$). In LS-DYNA there is the option to use the keyword LOAD_BLAST_ENHANCED to make use of the K-B model with some enhancements (namely, adjusting for the angle of the surface with respect to the blast wave). Although convenient to use, this approach also loses accuracy at close standoff distances and does not account for shadowing or interior reflections from the target.

To address more complex problems, analysts turn to a 'first principles' physics-based method. This can be accomplished using LS-DYNA's multi-material arbitrary Lagrangian-Eulerian (MMALE) solver [2]. This approach allows investigation of different charge shapes, small standoff distances, and more complex target geometries that lead to phenomena such as reflection, diffraction, or clearing. A validation study of the LS-DYNA MMALE solver for blast waves yielded excellent correlation with experimental data [3]. However, the pressure and impulse predictions are sensitive to element size and can change significantly.

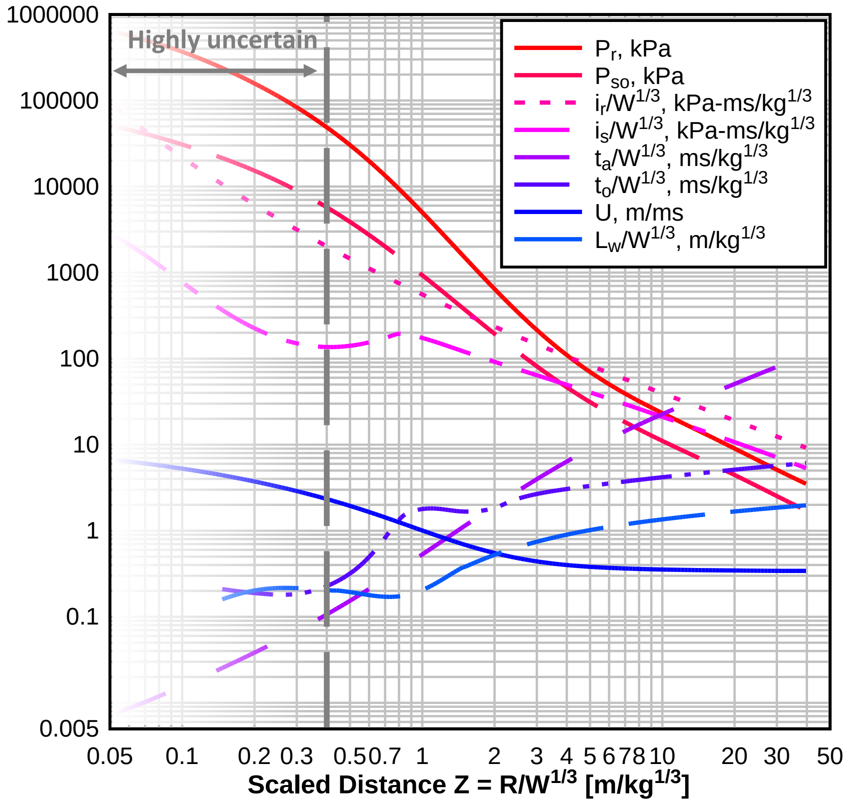

Figure 1: Kingery & Bulmash curves for positive phase shock wave parameters for a spherical TNT explosion.

Researchers modeling blast wave propagation have performed mesh refinement studies to determine the element size needed for measurements of peak pressure and total impulse to converge [3,4,5]. These studies produced recommended element sizes in absolute terms (e.g., millimeters) that are appropriate to the particular scenario being considered. However, repeating a mesh sensitivity study each time a different HE detonation scenario is simulated can be very time consuming. In the present study, the authors hypothesize that by scaling the element size by the cube root of the charge mass, similar to the scaling done by Kingery and Bulmash, general recommendations may be derived for guidance in determining mesh convergence for any charge mass used in future calculations. The following study will focus on the detonation, propagation of the shock through air, and reflection of the shock off a simple planar rigid surface. Additional mesh refinement needed due to complex target shapes will not be investigated in this study.

Approach

To investigate the mesh sensitivity of shock wave propagation from the detonation of HE, a spherical charge of Composition B was modeled, surrounded by air, and with a reflecting surface at the boundaries of the mesh, Figure 2. For cases where 2-D axisymmetric simulations were used, this surface was the inside of a hollow cylinder. For cases where 3-D simulations were used, the reflecting surface was the inside of a hollow box. The size of the surrounding structure was such that the shock wave was able to reach a given point on the surface (where the pressure history was recorded) and decay back to the ambient pressure prior to the arrival of reflections other surfaces in the model. To avoid unnecessary complexity, the mesh size in each simulation was kept uniform in all dimensions. In 2-D, all elements were square, and in 3-D all elements were cubic.

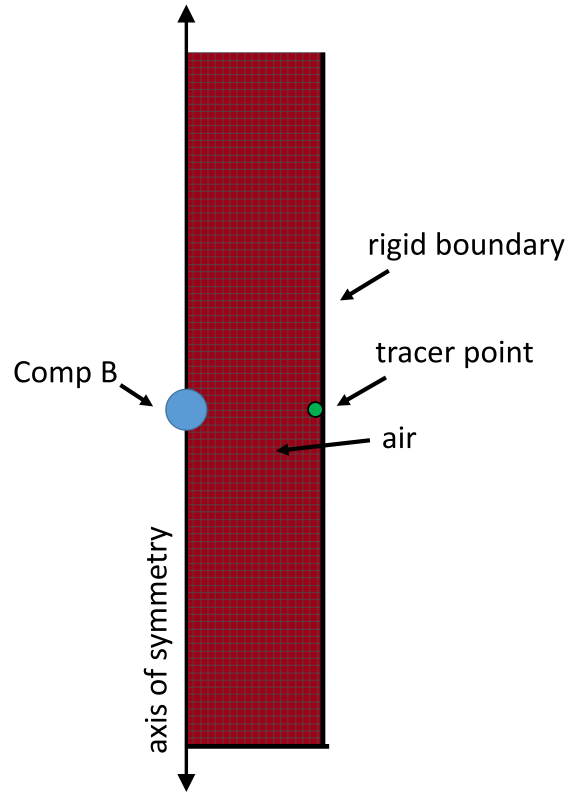

Figure 2: 2-D axisymmetric mesh for simulation of HE detonation

Simulations were run using LS-DYNA R10.0 on a 64-bit Windows machine, using 4-8 processors [6]. The simulation used LS-DYNA's Multi-Material ALE solver with the half-index-shift advection algorithm, conserving total energy over each advection step. MAT_HIGH_EXPLOSIVE_BURN and the EOS_JWL were used with the appropriate parameters for Composition B [7]. The air mass was modeled using MAT_NULL and EOS_LINEAR_POLYNOMIAL. The air had an ambient pressure of 1 atmosphere, thus allowing for the detonation to produce negative gauge pressures while the absolute pressure remained positive. The sphere of Composition B was inserted into the uniform air mesh using INITIAL_VOLUME_FRACTION_GEOMETRY.

2-D Results

The initial set of simulations examined a 12.2 kg sphere of Composition B using a 2-D axisymmetric mesh. The pressure histories were recorded with a tracer point at a distance of 0.762 meters from the charge, located on the surface of a reflecting wall. This corresponds to a scaled distance of 0.33 $m/kg^{1/3}$, which would typically be considered a close-in blast environment. Figure 3 compares the calculated pressure history from the LS-DYNA simulation to the K-B waveform. While the K-B waveform exhibits a simple, monotonic exponential decay, the LS-DYNA waveform includes a double spike. The first peak is from the arrival of the blast wave overpressure, while the second is due to impingement of the detonation products (a feature not represented in K-B). The two waveforms also differ in magnitude, duration, and arrival time. This illustrates some of the additional details the high fidelity model is able to capture and also demonstrates that the magnitudes of the pressure and impulse can differ significantly (e.g., total impulse is 47% higher in LS-DYNA than in K-B).

A series of simulations were run beginning with an element size of 40 mm squares and reducing the element size by a factor of 2 in each subsequent run. The pressure (gauge, not absolute) and impulse histories for each of these simulations is shown in Figure 4. Several trends can be seen. First, the larger elements produce gradual rise times with lower peaks, instead of a nearly-instantaneous shock wave with a higher peak. Second, the larger meshes fail to resolve the separate arrivals of the initial shock and the detonation products. Third, the impulse (shown by the dashed lines) is significantly lower in the larger element runs and increases as the element size is decreased. This is caused in part by the significantly lower peak pressure observed in the run with the larger elements. The peak pressure in the simulation with the 40 mm element size is approximately 40% of the peak pressure observed in the runs with the smallest element sizes. We also observe a slight delay in the time of arrival for the shock wave from the simulations with the larger elements, due to the reduced peak pressure affecting the wave speed as the shock propagates towards the measurement point.

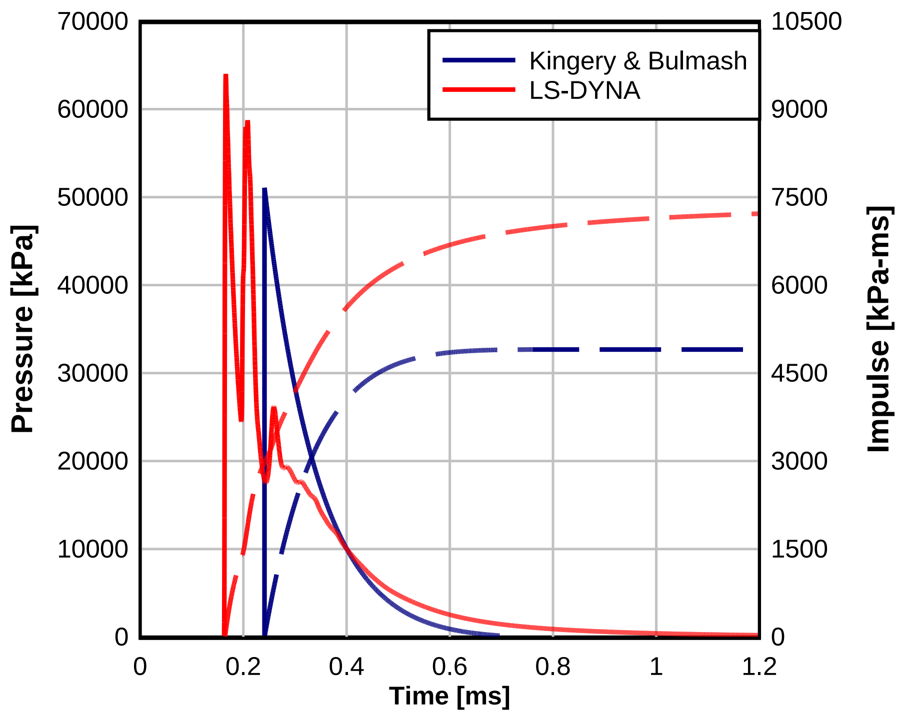

Figure 3: Comparison of waveforms from Kingrey & Bulmash with high fidelity LS-DYNA result.

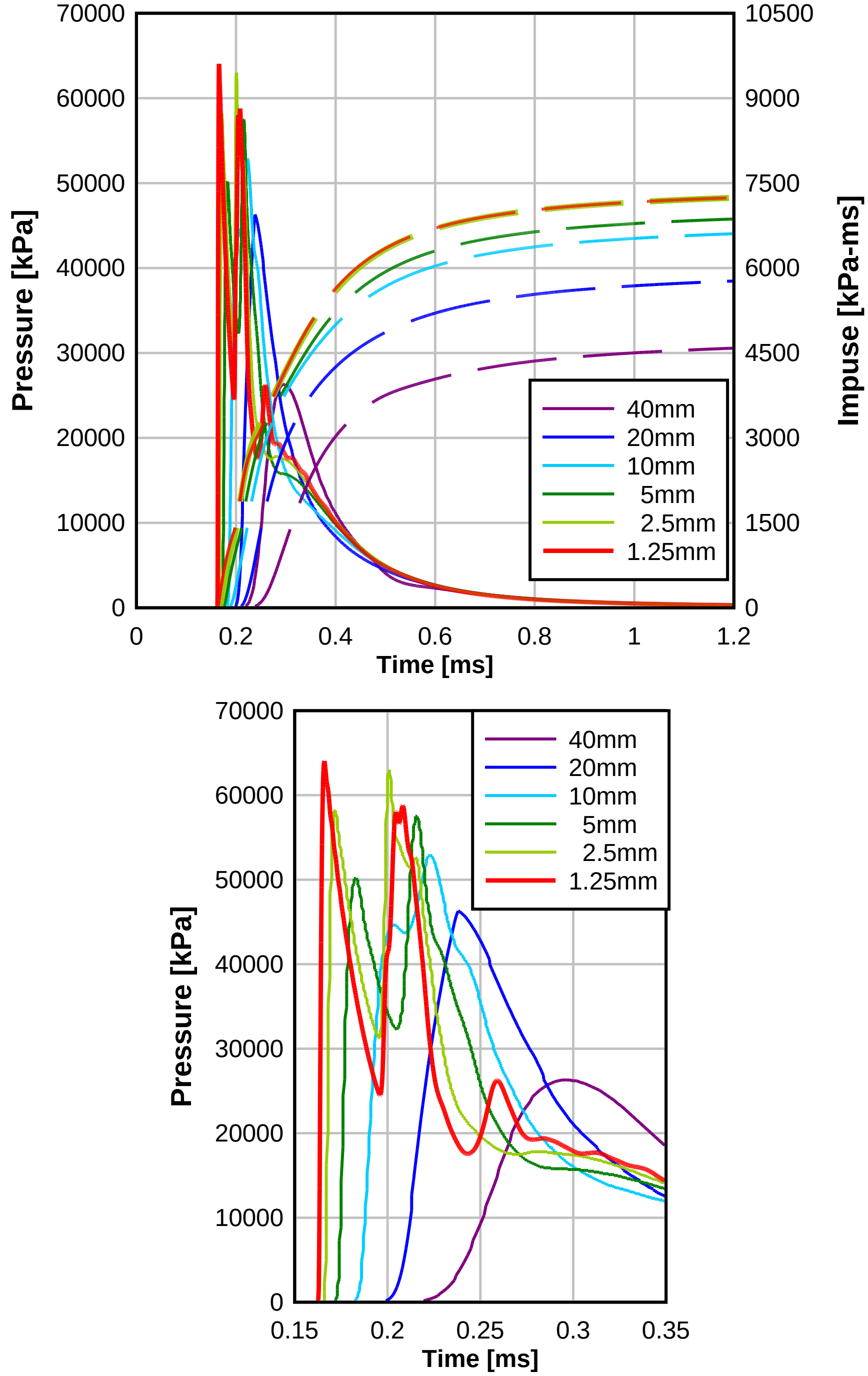

Figure 4: Pressure and impulse histories at a point opposite the charge on a reflecting wall (2-D axisymmetric).

The most common blast metrics to use for determining mesh convergence are either the peak pressure or the impulse of the shock wave at a given point. Figure 5 shows the peak pressure and impulse for each simulation normalized by the value from the simulation with the smallest (1.25 mm) element size, which we take to be as close to a theoretically "true" answer as available. The element size, on the x-axis, has been scaled by the cube root of the charge mass, just as with the standoff distance scaling used in the K-B curves. The peak pressure appears to exhibit a greater sensitivity to element size than does the impulse. The impulse is within 10% of the final value (red dashed line) once the element size is ~5 mm/kg$^{1/3}$ while the peak pressure is within 10% for an element size of ~2 mm/kg$^{1/3}$. By the time the element size is ~1 mm/kg$^{1/3}$, both the peak pressure and impulse are within 2% of the most accurate result. Since the total impulse (rather than peak pressure) is expected to control the response of most structural elements for a close-in loading such as this, the remaining mesh sensitivity analysis will use impulse as the sole metric by which to evaluate convergence. In addition, the calculation of peak pressure can be affected by the sampling frequency (an issue for both numerical models and experiments). However, this is not an issue if impulse is chosen as the metric.

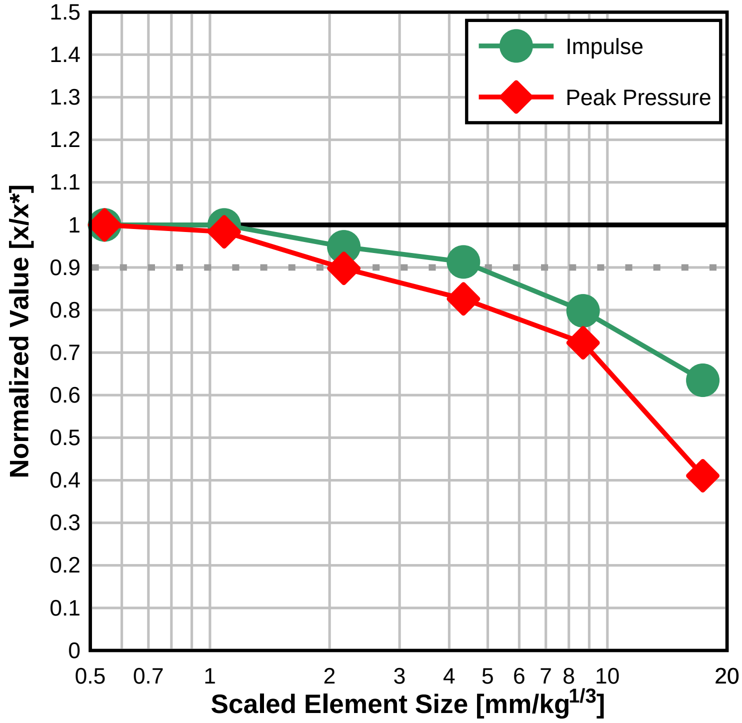

Figure 5: Normalized peak pressure and impulse vs scaled element size for 12.2 kg Comp B at a 0.762 m standoff.

The decision to consider convergence as a function of scaled element size is based on Hopkins-Cranz scaling, which in turn is based on geometric scaling. We would expect that mesh convergence behavior will yield consistent results when scaled properly. To this end, the simulations of the 12.2 kg sphere were repeated with the charge mass scaled up and down by a factor of 8. To retain the same scaled standoff, the location of the tracer point was scaled by a factor of 2 (cube root of 8). The distance of the charge from the other surfaces was also scaled accordingly to prevent reflections from interfering with the comparison. The results of that study are shown in Figure 6. The convergence behavior is essentially identical for each charge mass. Therefore we conclude that mesh convergence can be conveniently characterized in terms of a scaled element dimension with general application to any charge size. As a result, the rest of the convergence studies in this paper will focus on a single charge mass and present all results in terms of scaled element sizes.

So far only *reflected* pressure and impulse values have been examined. To explore mesh convergence for *incident* impulse, the previous simulations were rerun with the boundary moved to 1.524 meters, while the tracer point remained at its earlier location of 0.762 meters and was thus measuring the incident pressure and impulse. The comparison between the two simulations is shown in Figure 7. The incident impulse converges at a slightly larger element size than the reflected impulse. For example, using a 10% margin of error as before, the incident impulse requires a 6 mm/kg$^{1/3}$ mesh while the reflected requires 4 mm/kg$^{1/3}$.

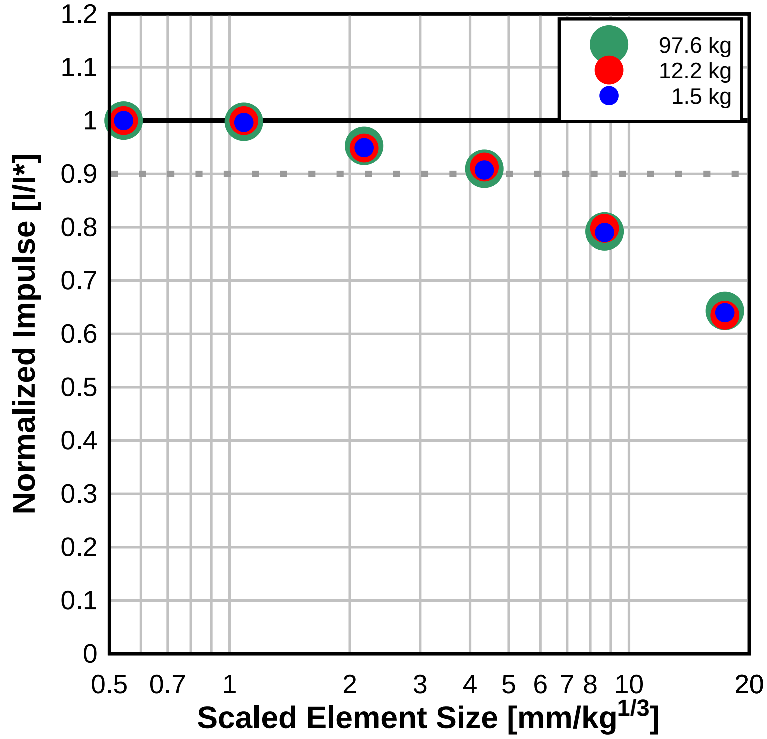

Figure 6: Normalized impulse versus scaled element size for each charge mass.

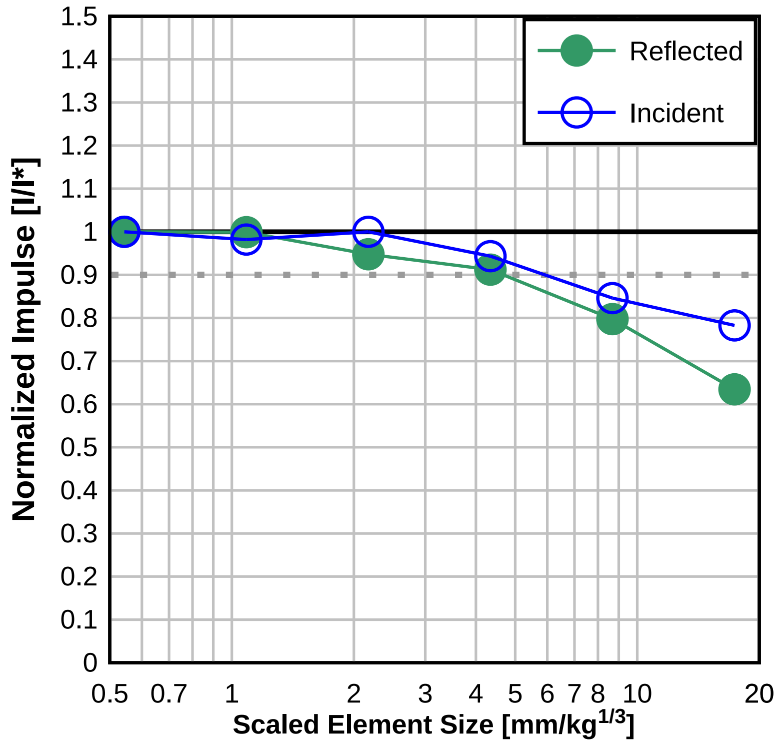

Figure 7: Normalized incident and reflected impulses taken at the same standoff.

Returning to an examination of reflected impulse data, Figure 8 examines how the scaled standoff between the charge and the target point affects mesh convergence. The earlier cases recorded the reflected impulse at a scaled standoff of 0.33 m/kg$^{1/3}$. Two additional scaled standoffs of 0.11 and 0.66 m/kg$^{1/3}$ were also investigated.

These results show that the closer the standoff of the target of interest, the smaller the mesh size required to produce an adequately converged result. If one uses 90% as the criterion of accuracy, at a standoff of 0.11 m/kg$^{1/3}$ the mesh needs to be 2 mm/kg$^{1/3}$; at 0.33 m/kg$^{1/3}$, that dimension increases to about 5 mm/kg$^{1/3}$; and at a standoff of 0.66 m/kg$^{1/3}$, the mesh can be 6 mm/kg$^{1/3}$.

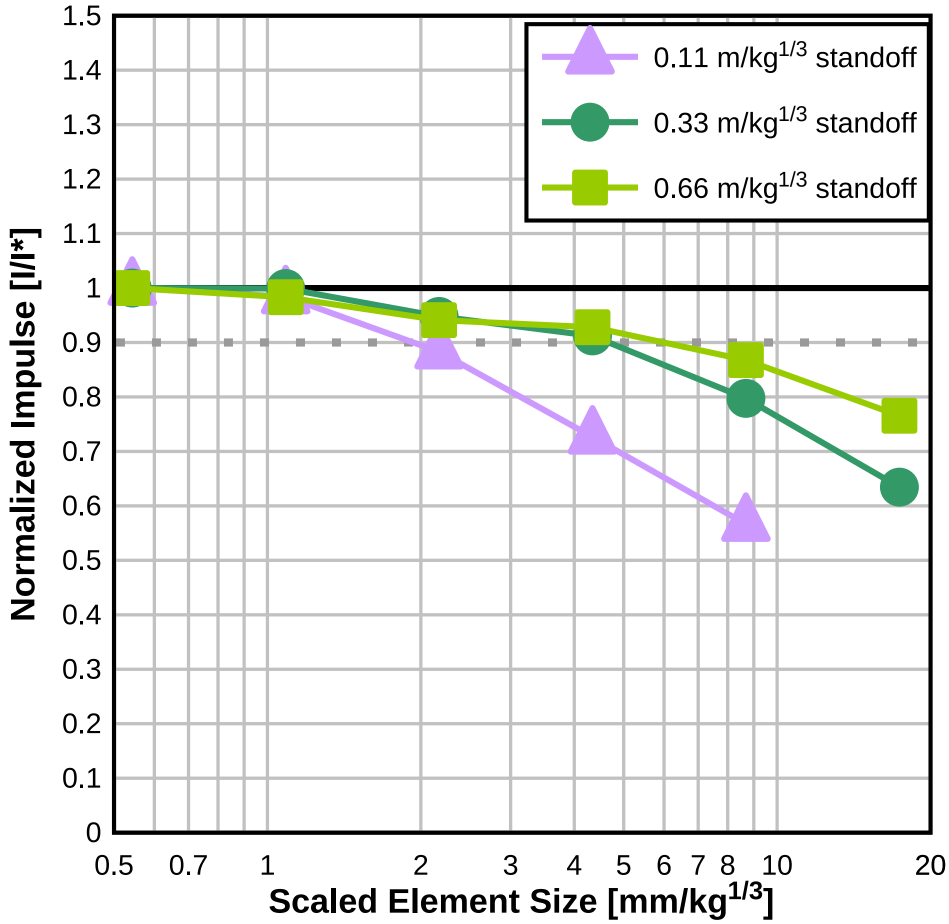

Figure 8: Normalized reflected impulse taken at different standoff distances from the charge.

To this point, the simulations have all looked at pressure and impulse values recorded along the element axis, where the blast wave is propagating orthogonal to the element face. In past work, we have observed anomalies in the predictions along radials 45° from the charge, corresponding to the wave propagating along the element diagonals. To evaluate this effect, a tracer point was placed at a 45° angle to the element axis, at a rigid boundary 0.33 m/kg$^{1/3}$ from the charge (Figure 9), and the convergence of the impulse was investigated. The results, presented in Figure 10, are somewhat surprising. While impulse along the 0° axis converges from below, impulse at the 45° location converges from above; it is also considerably less sensitive to mesh size, and reaches the ±10% criterion at a fairly large dimension (18 mm/kg$^{1/3}$). Thus, the need for accuracy along the 45° radial will not control mesh convergence, and moreover blast along those radials is seldom critical to structural response. However, it is important to note that the error introduced by large element sizes varies as a function of angle relative to the mesh axes.

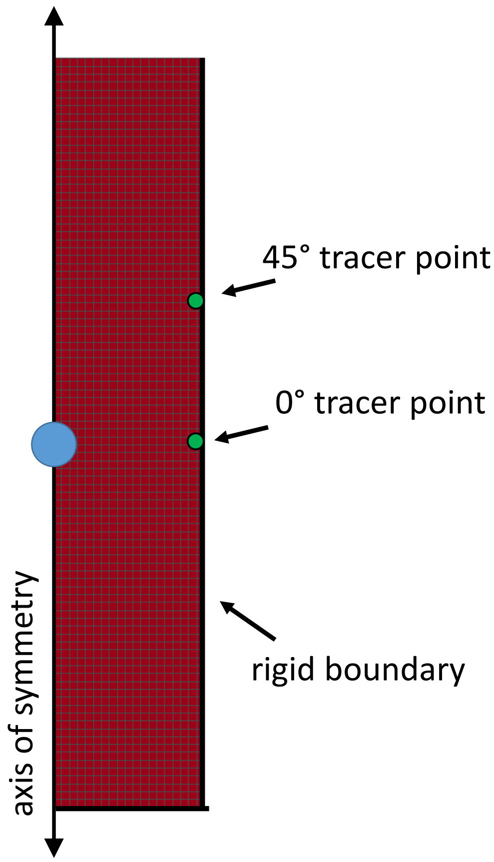

Figure 9: 2-D axisymmetric mesh showing the location where impulses were recorded.

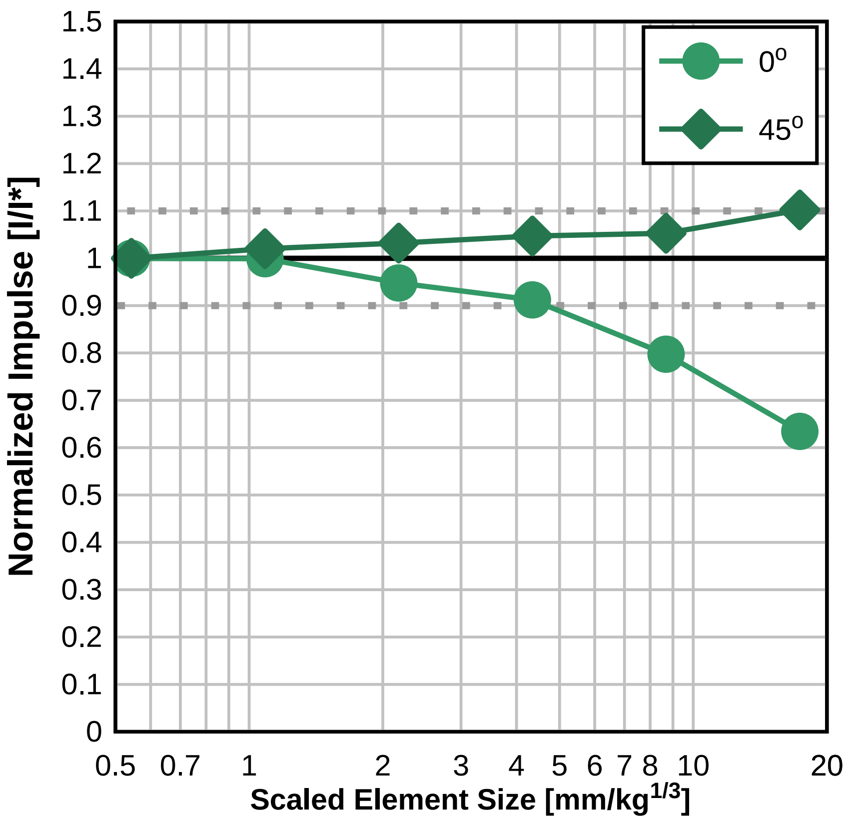

Figure 10: Comparison of normalized impulse along axis (0°) and diagonal (45°) of mesh.

3-D Results

The bulk of this study has dealt with 2-D axisymmetric problems. This was intentional as it allowed for simulations involving extremely fine meshes while still examining a reasonable range of scaled standoff distances. However, it is also prudent to examine convergence behavior in 3-D simulations. Due to the increased computational expense of brick elements, the overall size of the mesh was reduced. Whereas previously a scaled standoff of 0.33 and 0.66 m/kg$^{1/3}$ were considered, for the 3-D model a scaled standoff of 0.11 m/kg$^{1/3}$ was used. That, along with using axes of symmetry, allowed us to run simulations for the same scaled element sizes with our available computational resources. Since it was shown in Figure 8 that the convergence behavior was affected by scaled standoff, a series of 2-D simulations using the 0.11 m/kg$^{1/3}$ scaled standoff were also run for the purposes of comparison. The previous 2-D simulations examined the pressure along the curved surface of the cylindrical boundary. To remove as many differences between the 2-D and 3-D simulations as possible, this new set of 2-D simulations recorded the pressure and impulse on the flat ends of the cylindrical boundary to match the flat cubic boundary of the 3-D simulation (Figure 11).

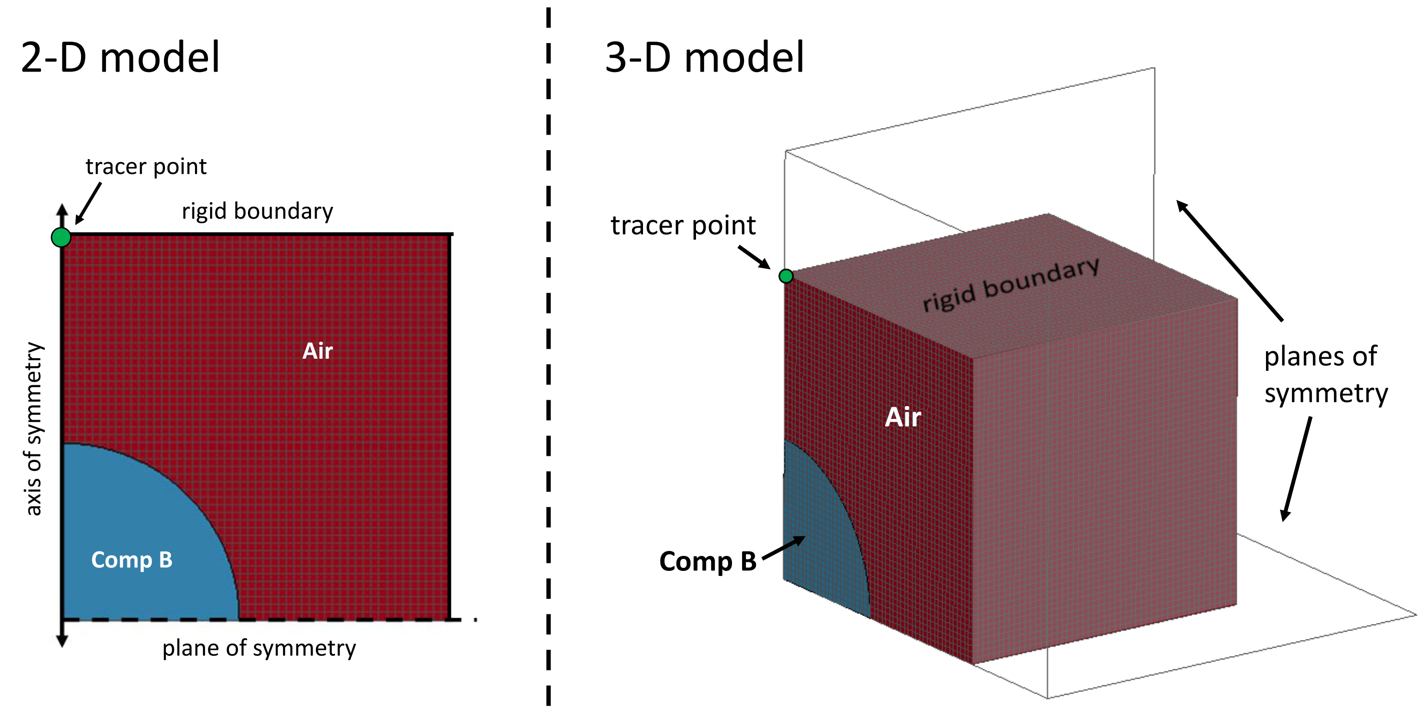

Figure 11: 2-D (left) and 3-D (right) models for comparison.

Figure 12 shows the impulse convergence of the 2-D and 3-D models. Though some small discrepancies are observed in the normalized impulse, the two have effectively identical mesh convergence behavior.

While 2-D axisymmetric models are typically preferred from the standpoint of computational expense and therefore the potential to use smaller elements than comparable 3-D models, most problems of interest do not have the cylindrical symmetry of the 2-D model. To take advantage of the computationally more efficient 2-D model, it is often more practical to begin with a 2-D axisymmetric model of the charge to model the detonation and initial shock wave expansion. Then, when the shock wave nears the structure or any surface that it will interact with, the 2-D pressure and velocities can be mapped into 3-D.

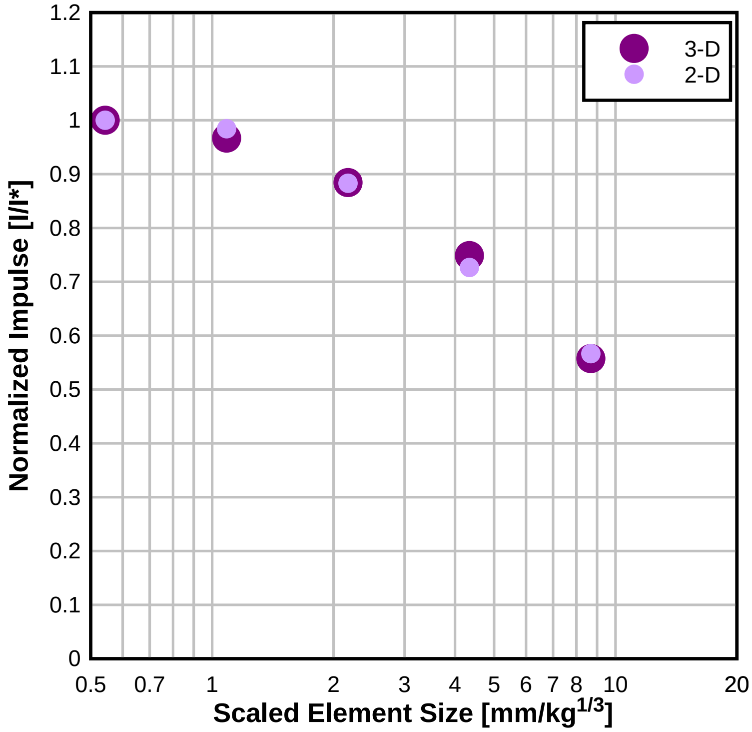

Figure 12: Comparison of mesh convergence for 2-D and 3-D simulations.

Several researchers have examined the effect the 2-D to 3-D has on mesh convergence for the case of buried charge. One study found that, given a sufficiently fine 2-D mesh, the results of the 2-D to 3-D mapped simulation appeared to be insensitive to the element size used in the 3-D mesh (within the range examined) [5]. Another study examining the mapping of blast found that a 3-D mesh with element size far greater than the 2-D map led to a reduction in peak pressure. To limit this reduction by 10%, a ratio of 3-D to 2-D element size must not exceed 10 [8]. However, when examining impulse, they found that the mesh ratio could be as high as 20 without affecting the impulse of the shock wave. However, both of these works involved blast propagation through soil. Further study is needed to quantify the effect of mapping from a finer mesh to a coarser mesh on mesh convergence for blast through air.

Conclusions

This work set out to determine a set of general guidelines for selecting the proper mesh size for the modeling of HE detonation and shock wave propagation. Based on our results, we reach the following conclusions:

- Scaling element size by the cube root of the charge mass leads to mesh convergence that is independent of charge mass (assuming standoff is similarly scaled).
- The required scaled element size is related to the scaled standoff, with smaller scaled standoffs requiring smaller elements to reach an answer within 90%.
- Recommended scaled element sizes, as a function of scaled standoff and desired accuracy, are provided in Table 1 for reflected impulse.
- Somewhat lower mesh densities are needed to predict *incident* impulse as opposed to *reflected* impulse with comparable accuracy.
- For rectangular meshes, error induced by increasing element sizes varies as a function of angle relative to the mesh axes, but the worst-case error is along the orthogonal axes.
- 2-D axisymmetric and 3-D models display effectively identical mesh convergence.

Error [%]	Scaled Element Size [mm/kg$^{1/3}$]		
	0.11 mm/kg$^{1/3}$	0.33 mm/kg$^{1/3}$	0.66 mm/kg$^{1/3}$
5	1.4	2.0	2.0
10	2.0	4.8	6.4
20	3.3	8.6	14.4

Table 1: Maximum scaled element size to attain a desired error based on scaled standoff (reflected impulse).

While problem specific features, such as surface geometry, may further affect the necessary element size for mesh convergence, this work provides a reasonable guideline for the initial selection of element size based on charge mass, standoff, and path of shock propagation relative to element axes for a given level of accuracy. By considering the mesh dimension scaled by the cube root of the charge mass, the LS-DYNA user can apply the generalized results of this study to a wide range of applications.

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