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ADVANCED M&S TECHNIQUES TO REDUCE COMPUTATIONAL TIME FOR UNDERBODY BLAST SCEANRIOS

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ABSTRACT

Modeling and Simulation (M&S) of underbody blast to vehicles can take a significant amount of time, often days to months, to run. This significant run time is due to the need for coupled Eulerian-Lagrangian computational algorithms to be used in order to accurately represent the effect of an underbody blast to a vehicle and its occupants. Several techniques exist which can significantly reduce the time it takes to complete such a simulation without affecting its accuracy, two of which will be emphasized here. These techniques are 2-D to 3-D mapping of the Eulerian domains and Early-Deletion of the Eulerian elements. For detailed vehicle simulations, simulation rates have been demonstrated to be 4-6 times faster along with a theoretical increase in accuracy and a decrease in troubleshooting time.

1. INTRODUCTION

Coupled Eulerian-Lagrangian simulations representing shockwave-related scenarios take a significant amount of time to run. For underbody blast to vehicles, such simulations often take several days and if there is interest in vehicle return-to-ground then they could take months. Several techniques exist within LS-DYNA which are not routinely used by organizations conducting shockwave-related simulations, particularly for Underbody Blast (UBB) simulations. These approaches to Modeling and Simulation (M&S) in Finite Element Analysis (FEA) have great potential to save both time and computational resources while still producing accurate results. Since such simulations can take days to months to run, being able to reduce the computational time without sacrificing predicted accuracy is a much needed and valuable commodity. The two advanced M&S techniques discussed here will be 2-D to 3-D mapping of the Eulerian fluid domains and early-deletion of the Eulerian fluid domains in a simulation. While not each of these advanced techniques can or should be used in every shockwave-related situation, these features should be investigated for their respective purposes and implemented where applicable. This work began while supporting the Army Research Laboratory (ARL) and has continued on into work within the Ground Vehicle Survivability Center (GVSC).

2. BACKGROUND

2.1. 2-D to 3-D Mapping

LS-DYNA has the ability to start a simulation in 1-D, 2-D, or 3-D and then expand upon the same scenario in 2-D or 3-D. This method of

DISTRIBUTION A. Approved for public release; distribution is unlimited OPSEC #2471 transformation is termed 'Mapping'. The benefit of beginning a calculation (particularly one which contains Eulerian fluid domains) in 1-D or 2-D and then converting over to a 2-D or 3-D simulation is the ability to have a very fine resolution of elements but yet still have a very quick run time (on the order of seconds to minutes in 1-D or 2-D as opposed to hours or days in 3-D). The benefit of starting in 3-D and converting to another 3-D simulation is the ability to employ the use of symmetry in the first calculation and then map it over to a 3-D domain, which may not require the use symmetry. Additionally, the first calculation never needs to be re-done because a mapping file is outputted from the first portion and only that is used as the input for future cases.

Figure 1 displays the basic components of an UnderBody Blast (UBB) simulation common within a LS-DYNA Arbitrary Lagrangian Eulerian (ALE) simulation (air portion is not on display but present in the calculation). The target, in this case a flat plate, consists of Lagrangian (solid) elements. If Lagrangian elements were the only ones in a calculation (with loading applied directly to the specific nodes) the simulation time would be relatively quick and not as much of an issue. However, because the loading to the target is applied via Eulerian (fluid) elements, the simulation requires a greater amount of time as well as computational power. The Eulerian elements represent the High Explosive (HE), soil, and air. The inclusion of these fluid parts is necessary to provide what is presently considered to be the most accurate form of loading to a target within an UBB simulation. What is important here is to realize that the fluid elements must encompass the entire area of where the simulation will take place and ensure the boundaries will not create any type of non-realistic effects to the target of interest (e.g. pressure wave reflections). This means the number of Eulerian elements can be very large and therefore produce a simulation which takes a large amount of time (hours, days, weeks) to complete or may not even be able to be done at all due to computational restrictions.

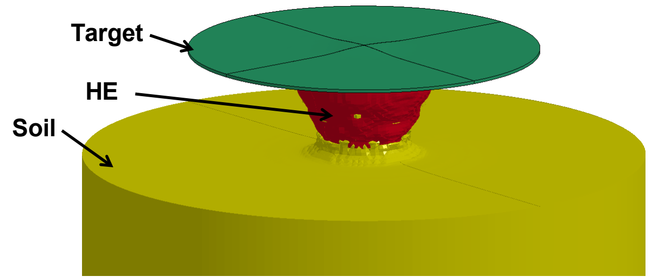

Figure 1: Components of an UBB Simulation

What a user must realize is that the number of cells (a term synonymous with element or mesh size) within a simulation is directly related to the length of time a simulation will take. If the number of elements can be reduced by ½, the simulation will be completed twice as fast. Therefore every effort must be taken to reduce the total number of elements in order to complete it as quickly as possible without sacrificing accuracy. As far as knowing how to initially mesh these solid and fluid parts, the following are general guidelines for the number of elements needed to accurately represent parts of a simulation:

1. *Lagrangian and Eulerian parts should have a minimum of 4-10 elements through its thickness (a.k.a. the smallest section length).*
2. *A minimum of 10-20 elements are needed across the smallest length of the HE in order to accurately simulate the energy released.*
3. *Lagrangian and Eulerian element sizes should ideally be equal.*

An exception to the first rule is when using Lagrangian shell elements where the stresses or strains through the thickness are not of concern. These guidelines should be viewed as a starting point for the meshing of solid and fluid parts and does not guarantee that a finer resolution will not be required in the future. Now let's say an UBB simulation contains an explosive with 15 elements through its thickness but only two elements through the layer of soil above it. In this case the soil layer would drive the element size and the mesh would need to become finer in order to get the minimum of 4-10 elements through the soil thickness. Most times the mesh size is determined by the target and its required number of cells through the thickness of a component, though there are still times when the HE would drive the cell size.

Now let us examine an UBB scenario using the same mesh sizes. Figure 2 displays the HE (red), soil (brown), and air (blue) for the 30 mm and 2.5 mm square mesh sizes. Same as before the 30 mm mesh contains 4-6 elements through the HE thickness and the 2.5 mm mesh has 58 elements through the HE thickness. In this scenario the point of detonation was located at the bottom left-center of the explosive. With the inclusion of the soil and a two inch Depth of Burial (DOB) for the HE, the 30 mm mesh only has 1-2 elements through the soil thickness while the 2.5 mm mesh has 20 elements through the soil on top of the explosive.

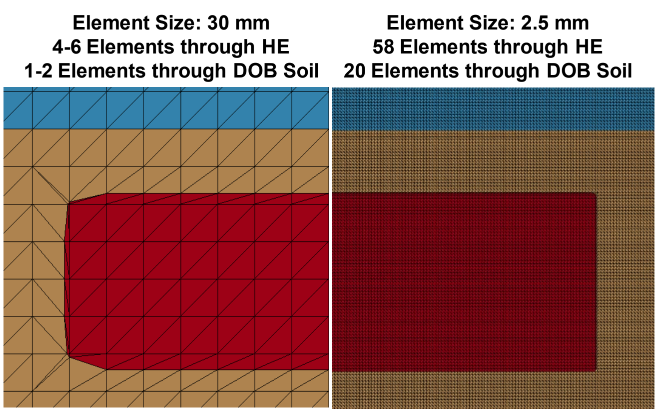

Figure 2: 2-D UBB Scenario - Mesh Size Comparison

The meshing guidelines state to use 4-10 elements through the thickness of a part of interest. Considering the fact that the HE is meant to be buried within two inches of soil it is safe to say the soil must be characterized properly to accurately depict the effect of the soil DOB on the HE. However, in the 30 mm mesh simulation, the soil only has 1-2 elements through its thickness and not meeting this rule. This inadequate meshing of the soil appears to have a strange effect on UBB calculations, at times simply allowing the HE to break through the soil with ease and imparting a larger impulse to a target than it actually should. Figure 3 depicts the velocity contour of the UBB for the five mesh sizes at a time of 0.3 ms (approximately the time before it would reach the under-body of a vehicle). Notice how the soil and HE have visually separate velocities within the 2.5 and 1 mm square meshes. This is just one of several reasons why a finer mesh is more desirable than a coarser one. Figure 4 shows the velocity histories at 0.2 m (Loc. A) and 0.4 m (Loc. B) centered above the ground plane. The peak magnitudes are greater and occur earlier for the finer mesh size.

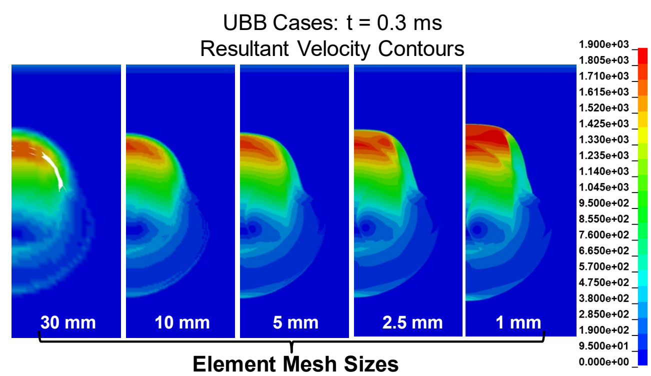

Figure 3: 2-D UBB Mesh Study - Velocity Contours at 0.3 ms

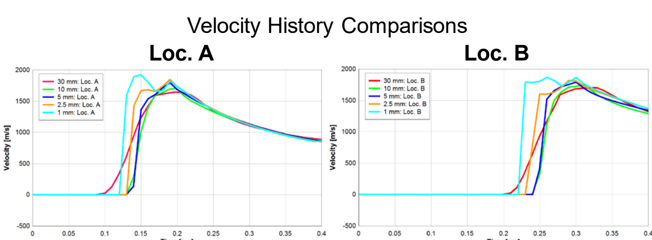

Figure 4: 2-D UBB Mesh Study - Velocity Histories at 0.2 m (Loc. A) and 0.4 m (Loc. B) Centered Vertically Above the Ground Plane

2.2. Early ALE Removal

Figure 5 once again displays the basic setup for an UBB calculation. The HE (red), soil (yellow), and air (blue) make up the ALE parts, while the Sandbox model (green) is the Lagrangian structural part. Once the HE and soil have imparted their loading to the target, they do not provide any further value but yet make the simulation take very long to complete. It should be noted that normally the air portion is not thought to provide loading in itself and that it is set up to be large enough so that when the shockwave moves past the target, shockwaves will not reflect back and interact with the target. Thus, the idea here is to carry out the simulation as one normally would with the ALE and Lagrangian components, stop and remove the ALE once the forces from the HE and soil to the structure have become minimal, and then restart the calculation with only the Lagrangian structure. While this method is simple to implement, it is knowing what time to remove the ALE that is the issue. With the goal to run the simulation as fast as possible without any loss of predicted accuracy, knowing the earliest one can remove the ALE is a question with an answer that is dependent on the situation.

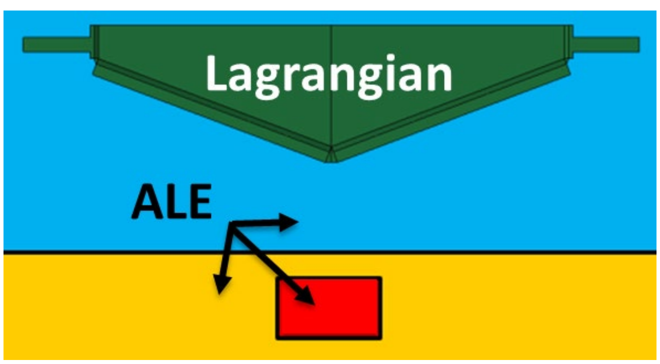

Figure 5: ALE and Lagrangian Parts Setup for an UBB

While it may be tempting to remove the ALE parts at a time based only on the images of the simulation, LS-DYNA has a very useful feature for helping to determine an optimal time to remove the ALE parts. The LS-DYNA card *DATABASE_FSI, something that needs to be invoked prior to starting the calculation, communicates the loading from the ALE parts to the Lagrangian surfaces specified in the *CONTRAINED_LAGRANGE_IN_SOLID card. The output is called the 'dbfsi' (database fluid structure interaction) file. Note that this card can only be associated with penalty method coupling. While the dbfsi card provides a good starting point of when to remove the ALE, simulations with more realistic vehicles containing occupants have been shown to require a longer period with ALE components present.

3. Results/Discussion

3.1. 2-D to 3-D Mapping

The mapping function within LS-DYNA is a very powerful tool which can save significant computational time depending upon its application. For a majority of scenarios the beginning of a simulation would take place in 2-D allowing the HE to have a fine mesh size and the pressure wave emanating from it to be as refined as possible. Generally speaking the finer the mesh the more accurate one can simulate a shock wave. Once the shock wave is close to encountering the target, which is presumably a 3-D target (otherwise the entire simulation would be in 2-D), the 2-D portion of the simulation would be finished and a 'mapping' file would be produced. The same simulation would be able to continue on in 3-D by including the mapping file alongside the rest of the 3-D input. Figure 6 displays an example of the sequence of events for an UBB case. The first simulation would be using a 2-D axisymmetric setup and just before the blast wave was to affect the target (in this case at 0.8 ms) the 2-D simulation would be stopped and a mapping file created. A 3-D quarter-symmetric setup (shown at 1.3 ms but restarted at 0.8 ms) then continued on the simulation beginning where the 2-D simulation ended.

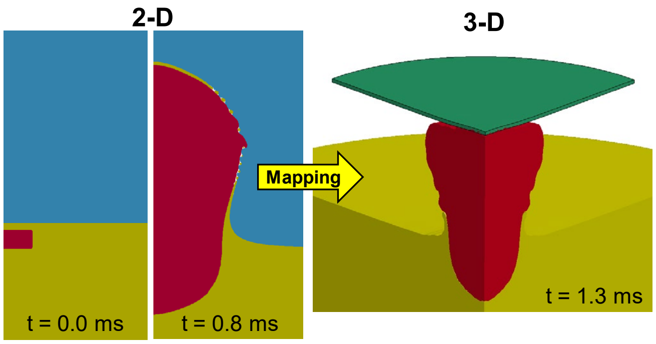

Figure 6: Mapping Function - UBB Example

One of the most interesting things about performing a blast simulation in this way is the fact that the target is not even included in the 2-D simulation. Because of this the target does not determine the cell size of the 2-D calculation. Considering that for an UBB case the standoff distance is relatively small and often the HE and soil reach the target in less than 1 ms, the amount of CPU time savings is not as significant as its ability to accurately define the HE and the thin layer of soil above it.

Take the UBB simulation in Figure 7 as an example. The target is a circular plate with a standoff of 1.5 meters (a larger standoff compared to most UBB cases) with the HE having a DOB of two inches. Figure 8 provides a zoomed in view of the HE, soil, and air Eulerian mesh sizes for the two different simulations: the left side being a calculation done all in 3-D (30 mm mesh size) and the right side a calculation starting in 2-D (10 mm mesh size).

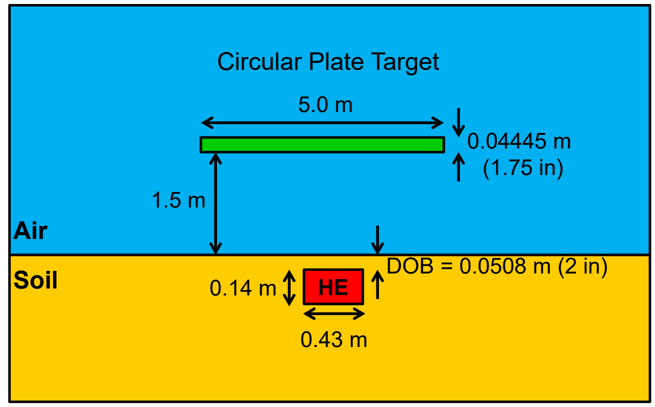

Figure 7: UBB Circular Plate Example

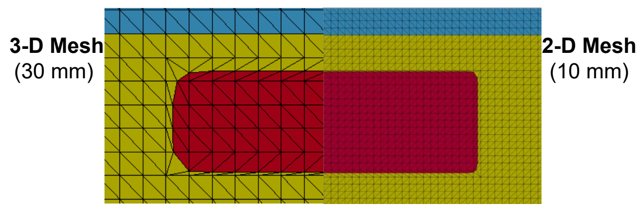

Figure 8: Zoomed In View of HE, Soil, and Air Eulerian Mesh Sizes. The 3-D Mesh (left) has a 30 mm Mesh Size and the 2-D Mesh (right) has a 10 mm Mesh Size

As can be seen from Figure 8 for the 3-D mesh of 30 mm elements, there are about 4 elements through the shortest length of the explosive and 1-2 elements through the layer of soil above the explosive. However the 2-D mesh composed of 10 mm elements has 14 elements through the thickness of the explosive and 5 through the soil layer above it. Recall that the guidelines for FEA demands 10-20 elements through the thickness of the HE and at least 4 elements to adequately describe practically anything else. The 3-D 30 mm mesh fails both of these criteria for the HE and soil while the 2-D 10 mm mesh meets the criteria. Also the 3-D 30 mm mesh takes about 40 minutes to reach 0.8 ms (the time before the HE/soil reach the circular target) whereas the 2-D 10 mm mesh takes only 8 minutes. Figure 9 displays a comparison of the 3-D and 2-D material and velocity contours at 0.8 ms which is just before the HE and soil reach the target. It is apparent from looking at the material contours that the 3-D 30 mm mesh does not adequately contain the HE within the soil unlike the 2-D 10 mm mesh. The velocity contours also speak to how much more refined and concentrated the shock wave appears to be in the 2-D compared to the 3-D case.

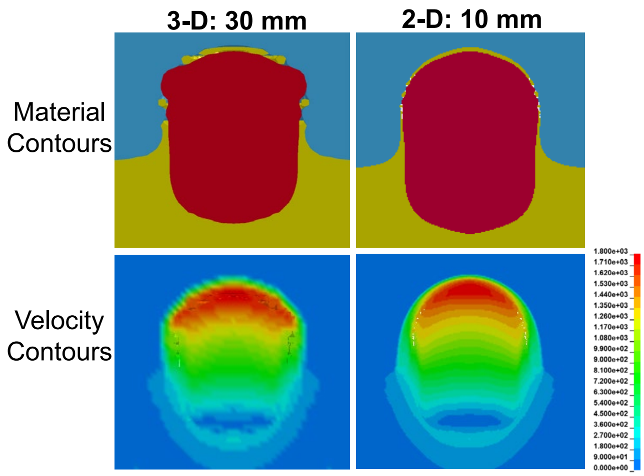

Figure 9: Material and Velocity Contours for the 3-D (30 mm Mesh) and 2-D (10 mm Mesh) Before Reaching the Target

A summary of the results for the Standard and Mapping/Symmetry approaches can be seen in Table 1. The takeaway from this comparison should be that the Mapping/Symmetry approach results in a more realistic target response, particularly related to the difference in impulse experienced by the target, and is much faster than the Standard method. If using quarter-symmetry, which would be applicable for simpler targets such as a flat plate or V-Hull, this new modeling method would be 5.4 times faster than the standard method or 2.7 times faster if using half symmetry, which could be useful for other types of simple targets.

Table 1: Comparison Summary of the Standard and Mapping/Symmetry Approaches

Metric	Standard Procedure	Mapping & Qtr. Symmetry	Mapping & Half Symmetry
Peak Impulse	136.7 kN·s	126.5 kN·s	
		7% Lower	
Peak Average Pressure	4.8 MPa	4.9 MPa	
		2% Higher	
CPU Clock Time	27 hours	5 hours	10 hours
		5.4 Times Faster	**2.7 Times Faster**

To further demonstrate the usefulness of beginning a calculation in 2-D (with a fine mesh) rather than in 3-D (with a coarser mesh) is that depending upon the size of the HE inputted into the INITIAL_VOLUME_FRACTION_GEOMETRY card in LS-DYNA, erratic HE sizes can result. Figure 10 displays how a smaller HE (DOB = 2 in.) is formulated in a coarse 3-D mesh and a fine 2-D mesh. The important factor here is the coarseness of the 30 mm mesh and its affect upon a small HE size, not the fact that it is in 3-D and not 2-D. What may be even more surprising is that by simply changing the burial depth to 4 in. (Figure 11), the HE is more accurately formed in the 3-D 30 mm mesh. This tells us one very important fact that when placing an explosive using the INITIAL_VOLUME_FRACTION_GEOMETRY card (which is common) in a coarse mesh, the resulting size and therefore mass of the explosive can be very different than expected. However, this is not an issue for finer meshes which is all the more reason to start a calculation in 2-D with a fine mesh and then use the mapping function to convert to a coarser (faster-running) 3-D Eulerian mesh.

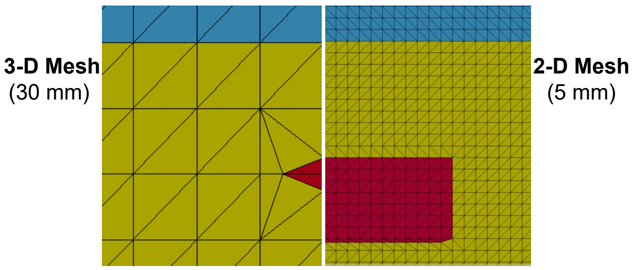

Figure 10: Zoomed in View of Smaller HE Scenario (DOB = 2 in.) for a 3-D (30 mm) and 2-D (5 mm) Eulerian Mesh

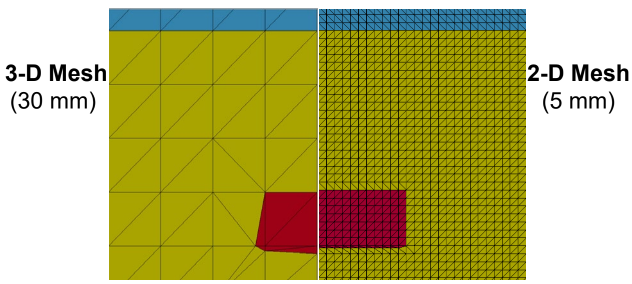

Figure 11: Zoomed in View of Smaller HE Scenario (DOB = 4 in.) for a 3-D (30 mm) and 2-D (5 mm) Eulerian Mesh

This conversion of 2-D to 3-D Eulerian domains of course comes with a couple of questions associated with it. Do the 2-D simulations produce the same results as in 3-D? Is there any loss of accuracy when transforming from the 2-D to 3-D domains? To answer these questions, UBB simulations were done with one completely in 3-D using a 30 mm mesh and the other starting in 2-D with a 30 mm mesh and then mapping over to 3-D also using a 30 mm mesh. Both of the previous questions can be answered with this comparison. Figure 12 displays velocity contours for the 3-D no mapping case (left) and the 3-D with mapping (right) at 0.5 ms. The 2-D to 3-D mapping occurred at 0.4 ms. It can be seen that there appears to be essentially no difference between the simulations and that the mapping function performs as one would hope.

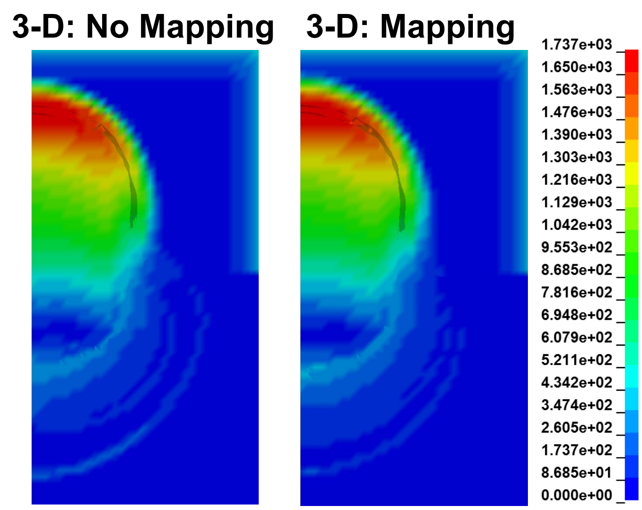

Figure 12: Velocity Contours for the 3-D (No Mapping) and 3-D (Mapping) UBB

Providing further validation that there is little to no effect from the mapping function, Figure 13 provides a velocity history plot for two separate tracer points within the calculations. The red and green solid lines depict two history points within the simulation done entirely in 3-D, whereas the blue and orange solid lines are the histories for the 2-D simulation followed by the same colored dashed lines in 3-D (after the mapping function was used). While the 2-D calculation does appear to begin to ramp up 0.01 ms earlier than in 3-D, it can be seen that the same velocity peaks are reached and decrease at nearly the exact same rate. To state it succinctly, the results from a 2-D Eulerian domain are the same as that from a 3-D domain and the effect of the mapping function is minimal to non-existent within LS-DYNA.

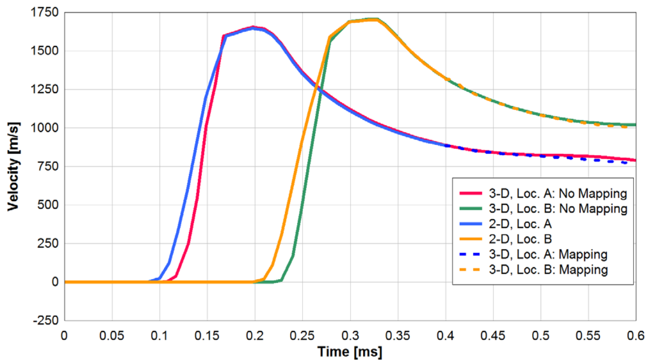

Figure 13: Velocity Histories Comparison: Effect of the Mapping Function

Another logical question is the effect of the 2-D mesh size once the mapping function has been put into place using the same 3-D mesh size. Figure 14 depicts two simulations which have both been mapped to a 3-D 30 mm mesh but the left calculation began in 2-D with a 30 mm mesh while the right calculation used a 2.5 mm mesh. It can be seen that there are several differences between the two cases: the amount of soil present above the expanded HE, the general shape of the HE, and even the height of the HE expansion. Of course, if there is a minimal CPU time and computational cost with using a finer mesh, there is no reason not to use one. The only guideline with regards to a situation such as this is that it is recommended to not use a factor greater than 10 between the mesh sizes when mapping (i.e. if the 3-D mesh size to be used is 20 mm then one should not go below a 2 mm mesh size in 2-D).

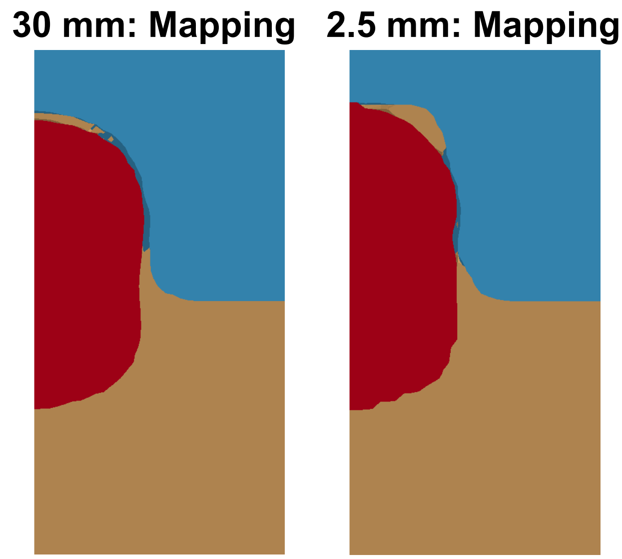

Figure 14: Effect of 2-D Mesh Size after Mapping into a 3-D 30 mm Mesh Domain

3.2. Early ALE Removal

Figure 15 displays the setup for the Generic Hull UBB. It is a centerline shot, so half-symmetry can be applied. Several nodes labeled 'NSO' will be analyzed for internal metrics.

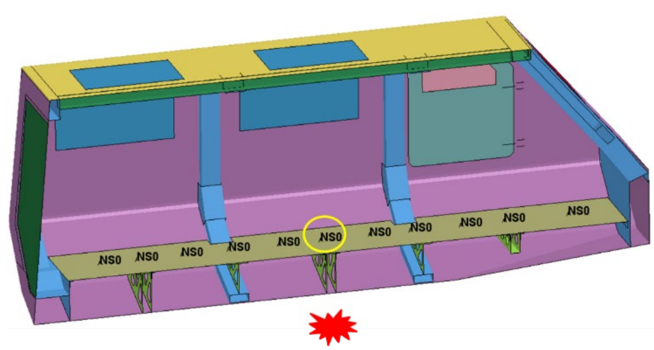

Figure 15: Half-Symmetry Generic Hull UBB Setup

In order to emphasize how the dbfsi curves can differ significantly for different HE configurations, Figure 16 shows the vertical force curves for two different UBB scenarios:

1. Mass 1 with a 4.0 in. DOB
2. Mass 2 (half that of Mass 1) with a 2.0 in. DOB

Based on the results of Figure 11, the Mass 1/4.0 in. DOB case had the ALE removed at a simulation time of 12 ms. This was considered a conservative choice as the vertical force appears to taper down to nearly zero by this time. The Mass 2/2.0 in. DOB case had the ALE removed at 3 ms. This could be considered a non-conservative choice of time for ALE removal. It should be noted that 2.5% of the maximum loading occurs at ≈ 8 ms for the Mass 1/DOB = 4 in. case, and ≈ 3 ms for the Mass 2/DOB 2 in. case. Once again, the optimal ALE removal time is dependent on the soil properties (which remain constant here), HE size, HE location, DOB, and target geometry.

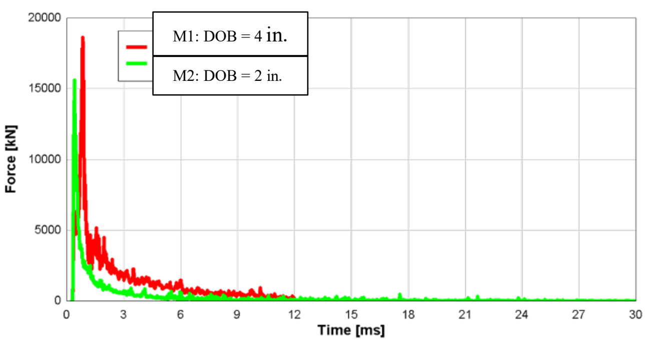

Figure 16: Vertical Forces from the ALE (HE/Soil) Interaction with the Generic Hull for Two Different UBB Scenarios

Figure 17 presents the difference in the predicted vertical vehicle impulse when removing the ALE parts at the times specified prior for the two cases. The red lines represent the full ALE calculation, and the green lines represent the simulations when the ALE is removed. For the Mass 1/DOB = 4 in case, the early removal of the ALE at 12 ms resulted in an ≈ 10% reduction in the predicted vehicle impulse. For the Mass 2/DOB = 2 in. case, an ≈ 30% difference in vehicle impulse is shown. While global impulse of the vehicle does provide a metric to compare against with actual testing, there is no occupant injury metric associated with it.

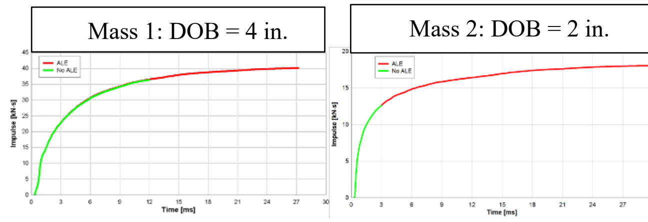

Figure 17: Impulse Comparisons of ALE vs. No ALE for the Generic Hull

Figure 18, Figure 19, and Figure 20 display the results for the vehicle interior pressures, velocities, and displacements, respectively. For the Mass 1/DOB = 4 in. case which removed the ALE at 12 ms, there is excellent correlation between the two simulations' metrics. Only towards the end of the simulation is there ≈ 6% difference in the displacement. For the Mass 2/DOB = 2 in. case which removed the ALE at 3 ms, there is still good correlation between the two simulations' metrics, with a larger disparity of displacement (25% difference at the end of the simulation). However, note that without the ATDs being in the actual simulation, the metric which is used most often to predict injury would be velocity and those injury predictions would be nearly identical for both of these cases with and without the ALE removed at their stated times.

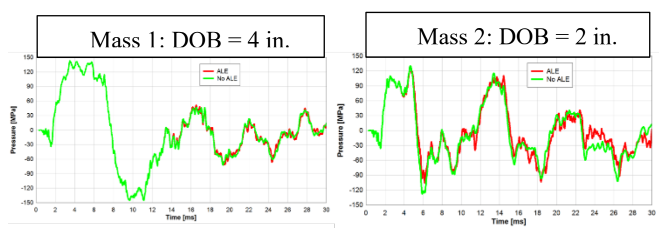

Figure 18: Pressure History Comparisons of ALE vs. No ALE for the Generic Hull

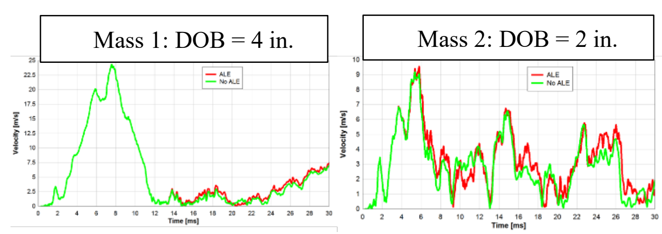

Figure 19: Velocity History Comparisons of ALE vs. No ALE for the Generic Hull

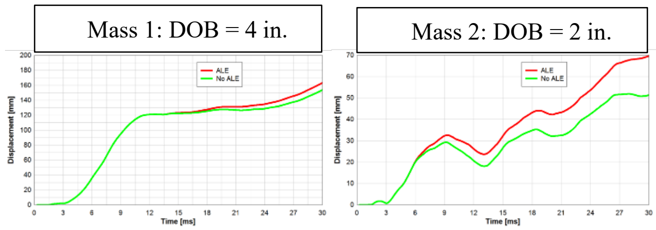

Figure 20: Displacement History Comparisons of ALE vs. No ALE for the Generic Hull

Table 2 highlights the differences in the metrics of interest for the Mass 1/DOB = 4 in. case. An additional simulation is also added which removed the ALE at 6 ms (a non-conservative choice) to further highlight how such a change could affect the results. While the peak vehicle impulses and internal peak displacements are noticeably different when removing the ALE at 6 and 12 ms, the peak pressures and velocities are nearly identical for both scenarios. By removing the ALE at 12 ms the simulation runs 2.2 times faster and removing the ALE at 6 ms allows the simulation to run 3.6 times faster, all without changing the accuracy of the predicted injury metric (velocity in this case).

Table 3 highlights the differences in the metrics of interest for the Mass 2/DOB = 4 in. case. The peak vehicle impulse and internal peak displacement are noticeably different when removing the ALE at 3 ms, while the peak pressure and velocity are nearly identical for both scenarios. By removing the ALE at 3 ms the simulation runs 5.4 times faster, all without changing the accuracy of the predicted injury metric (velocity in this case).

Table 2: Removing ALE Study – Mass 1, DOB = 4 in. Generic Hull Setup

Metric	ALE	No ALE after 12 ms	No ALE after 6 ms
Peak Impulse	42.7 kN·s	38.5 kN·s	32.2 kN·s
		10% Lower	**25% Lower**
Peak Pressure	143.2 MPa	143.2 MPa	143.2 MPa
		No Difference	**No Difference**
Peak Velocity	24.3 m/s	24.3 m/s	24.1 m/s
		No Difference	**1% Lower**
Peak Displacement	162.9 mm	153.4 mm	135.0 mm
		6% Lower	**17% Lower**
Total CPU Time	38.7 Hours	17.7 Hours	10.7 Hours
		2.2 Times Faster	**3.6 Times Faster**

Table 3: Removing ALE Study – Mass 2, DOB = 2 in. Generic Hull Setup

Metric	ALE	No ALE after 3 ms
Peak Impulse	18.0 kN·s	12.6 kN·s
		30% Lower
Peak Pressure	128.5 MPa	129.8 MPa
		1% Higher
Peak Velocity	9.5 m/s	9.2 m/s
		3% Lower
Peak Displacement	69.6 mm	51.9 mm
		25% Lower
Total CPU Time	37.2 Hours	6.9 Hours
		5.4 Times Faster

As with the Sandbox model simulation, the Generic Hull underbody blast simulation runs significantly faster once the ALE is removed. The following shows the simulation rate with and without ALE for this setup:

- ALE CPU time/simulation time ratio ≈ 1.29 hr/ms
- No ALE CPU time/simulation time ratio ≈ 0.125 hr/ms

By deleting the ALE parts, the simulation rate is now 10 times faster. To put that into perspective, the Mass 2/2 in. DOB case took 3.7 hours to run its first 3 ms with the ALE. Once the ALE was removed, the rest of the 27 ms simulation time took 3.2 hours to run. Of course, if the simulation needed to run longer than 30 ms, the overall simulation would run much faster without the ALE. Table 4 and Table 5 show how much faster the simulations could be if the simulations were to be run out to 50, 100, or 200 ms. While there may be little need to run the simulation longer than 30 ms for this underbody blast scenario with the Generic Hull, there often is interest in doing so for a detailed vehicle underbody blast simulation. Note that only two CPU processors are being used to demonstrate this time savings and thus increasing the number of processors would change these values. As mentioned prior, these case studies are meant to showcase how to efficiently conduct M&S, regardless of the computing resources available.

Table 4: Mass 1, DOB = 4 in. Generic Hull CPU Time Savings Based on Simulation Time

Simulation Time	30 ms	50 ms	100 ms	200 ms
ALE CPU Time	38.7 Hours	64.5 Hours	129 Hours (5.4 Days)	258 Hours (10.8 Days)
No ALE after 12 ms CPU Time*	17.7 Hours	20.2 Hours	26.5 Hours	39.0 Hours
Times Faster	**2.2**	**3.2**	**4.9**	**6.6**
No ALE after 6 ms CPU Time*	10.7 Hours	13.2 Hours	19.5 Hours	32.0 Hours
Times Faster	**3.6**	**4.9**	**6.6**	**8.1**

Table 5: Mass 2, DOB = 2 in. Generic Hull CPU Time Savings Based on Simulation Time

Simulation Time	30 ms	50 ms	100 ms	200 ms
ALE CPU Time	37.2 Hours	62.0 Hours	124 Hours (5.2 Days)	248 Hours (10.3 Days)
No ALE after 3 ms CPU Time	6.9 Hours	9.4 Hours	15.7 Hours	28.2 Hours
Times Faster	**5.4**	**6.6**	**7.9**	**8.8**

The Combat Vehicle Prototype (CVP), meant to feed into the Next Generation Combat Vehicle (NGCV), is designed to withstand a significant underbody blast and hold multiple occupants. The Survivability and Protection M&S (SPMS) group within GVSC have successfully modeled the CVP and exposed it to a variety of UBB cases. The sensitive nature of this vehicle does not permit showcasing the details of the simulation; however, removing the Eulerian elements affects the simulation will be described. The cutoff time for this simulation was 25 ms with the rest of the simulation running out to 60 ms. An additional case where there was interest in the return-to-ground of the vehicle also had the ALE cutoff time at 20 ms while the remaining simulation ran out to 900 ms. This simulation did contain multiple ATDs and the changes in their predicted injury metrics are what will be specified here.

Table 6 shows how much faster the simulation is by removing the ALE after 25 ms for the simulation run out to 60 and 900 ms. For the 60 ms simulation, removing the ALE early reduces the computational time by a factor of approximately 4 and saving nine days of M&S time. For the return-to-ground case running the simulation ran out to 900 ms, removing the ALE early reduces the computational time by approximately a factor of 5 and saving 48 days of M&S time. Along with these significant time savings, the predicted ATD injuries were practically the same when removing the ALE. Shorter ALE cutoffs were attempted but found that it did affect the predicted injuries so the 25 ms cutoff time was chosen.

Table 6: CVP - CPU Time Savings Based on Simulation Time

Simulation Time	60 ms	900 ms
ALE CPU Time	2 Weeks	2 Months
No ALE after 25 ms CPU Time	3 Days	12 Days
Times Faster	**4**	**5**

Combining these advanced techniques are also applicable to other types of shockwave analysis where there is interest in the effects of a shockwave onto a structure. These methods are also not exclusive to LS-DYNA and thus can be used in other modeling software. One example would be simulating a blast wave impacting a human head. The author's previous work (Jacques Goeller A. W., 2012; Jacques Goeller A. W., 2017) used a shock tube to develop a blast wave and placed a head surrogate at the end of the tube (see Figure 21) modeled using DYSMAS. The shock tube and the initiation of the blast wave was modeled in 2-D axisymmetry, allowing the simulation to be done with a higher resolution of elements and completed in a much shorter time than if modeled in 3-D. The other benefit of modeling in this manner is that this portion of the simulation only needs to be done once as an output file comes from the 2-D simulation and is used as input for the following 3-D simulation.

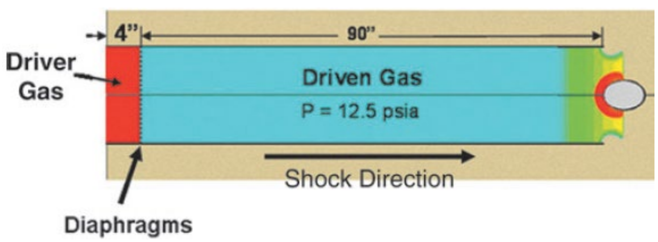

Figure 21: Shock Tube Modeled Using 2-D Axisymmetry

Once the blast wave was close to the end of the tube and near the head surrogate (Figure 21 does not represent stopping the blast wave and was fully done in 2-D), the Eulerian domain was converted into 3-D and run for the appropriate amount of time to see the effects the blast wave placed upon the target. Figure 22 displays the simulation once it has been converted into the 3-D domain with the blast wave moving across the head surrogate. The 3-D portion of this simulation consisted of ≈24 million Eulerian elements and took 3-4 days to run. At the time, the author did not conceive of the idea that the Eulerian domain outside of the surrogate head could have been deleted and reduced the computational time significantly.

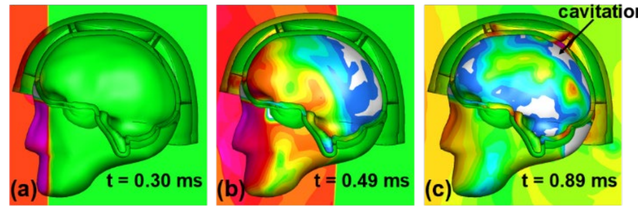

Figure 22: Blast Wave Impacting Human Head Surrogate

4. Conclusions

The advanced techniques presented here are applicable for nearly any type of computer simulation one may perform but in particular cases which involve shockwaves. The objective for most cases of M&S is to produce the most accurate simulation possible while still using the least amount of time and/or computational resources. Though a more accurate calculation requires a greater number of elements which equates to a greater computational cost, there are methods to maximize the number of elements and keep costs to a minimum.

The mapping function allows the user to begin a simulation in 2-D and then at a time just before the shock wave (in the case of UBB: the HE and soil) were to reach the 3-D target, then the 2-D domain can be mapped onto a 3-D domain and the calculation can continue. The benefits from such a process is that the calculation runs faster in 2-D (a calculation in 3-D which takes hours to days will only take seconds to minutes in 2-D) and allows for a finer resolution of the areas of interest, such as an explosive or the soil layer above the explosive. While the time savings is minimal for an UBB simulation due to the relatively short standoff from the ground, the increased accuracy of the HE and soil above it more than makes up for the effort to use the mapping function. Additionally if mapping is used the 3-D mesh used for a majority of the calculation does not need to have a fine region centered at where the explosive is located and instead could be focused upon the target. Having a larger element size in the 3-D domain because the HE is not detonated there can save significant computational time during the course of the 3-D calculation.

Early removal of the ALE can make a substantial difference in how fast the overall simulation can take to run without affecting the accuracy of the end results. While it is easy to remove and restart the calculation, the most difficult aspect of this process is defining the optimal time to remove the ALE. Since removing the ALE early leads to a greater reduction of the time it takes to run the simulation, it is ideal to do so as soon as one can without affecting the accuracy of the desired results. While the dbfsi file does provide an idea of when the vertical loading from the ALE to the Lagrangian structure is mostly complete, it only seems to provide a good time to remove the ALE for simpler targets and not detailed vehicles.

Removing the ALE makes a significant difference because coupled Eulerian-Lagrangian shockwave-related simulations take a significant amount of time to run. Since the ALE portion is a principle reason the simulation takes so long, removing it has shown simulations to run 5-17 times faster with just the Lagrangian target. The overall simulation time translates to running 4-6 times faster. These computational time savings are associated with nearly identical predicted injury metrics, which injury prediction often being the primary reason to conduct such simulations. Note that both of these advanced techniques can be used together to optimize a simulation's run time and level of accuracy.

4. REFERENCES

[1]Jacques Goeller, A. W. (2012). Investigation of Cavitation as a Possible Damage Mechanism in Blast-Induced Traumatic Brain Injury. *Journal of Neurotrauma*.

[2]Jacques Goeller, A. W. (2017). Establishing Cavitation as a Damage Mechanism for Traumatic Brain Injury (TBI) from an Improvised Explosive Device (IED) Blast. *Journal of Neurotrauma*.