Comparative Analysis of Occupant Responses between LS-DYNA® Arbitrary LaGrange in Euler and (ALE) and Structured–ALE (S-ALE) Methods

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Abstract

The LS-DYNA ALE/FSI package can accurately model the dynamic response of the structure under blast loading. To simulate blast loading, High explosive, air and sometimes soil are modeled as different ALE materials which flow inside an ALE mesh that covers a spatial domain of our point of interest. If the spatial domain is of complex geometry, the ALE mesh is necessarily unstructured. But often times, the geometry is simply of a box shape so a structured (rectilinear) ALE mesh could be used.

In 2015, LSTC expanded its ALE solver by offering a structured ALE option. The Structured ALE (S-ALE) solver is dedicated to solve the subset of ALE problems where a structured mesh is appropriate. With theory and algorithms unchanged, S-ALE was implemented separately to utilize the regularity of mesh. This regularity led to simplifications in ALE algorithms and brought reductions in simulation time and memory usage.

*The new S-ALE solver generates ALE mesh automatically. Two new keywords are added, *ALE STRUCTURED MESH and *ALE STRUCTURED MESH CONTROL POINTS. The former is used to generate the mesh and invokes S-ALE solver. The latter is to provide mesh spacing information along each local direction. All other ALE keywords remain the same.*

TARDEC identified that this new S-ALE solver works well for structural analysis and when coupled with occupants S-ALE solver has difficulties. Venkatesh Babu of TARDEC Analytics and Dr. Hao Chen of LSTC worked continuously to root cause this issue and improved the S-ALE method further. In this proposed work, an improved S-ALE method and an equivalent ALE were analyzed in TARDEC developed generic hull structure with one occupant. Main objective of this research is to compare the structural and occupant responses between improvised S-ALE and ALE in an identical boundary conditions and initial energies.

*First S-ALE mesh geometry is developed and analyzed for structural response and occupant responses. *INITIAL VOLUME FRACTION GEMOTRY was used to identify the high explosive charge, soil, and air. Mesh generated by S-ALE is written as an output and this will be used as input background ALE mesh in ALE analysis. *INITIAL VOLUME FRACTIO GEOMETRY from S-ALE was used in this ALE analysis to make sure that everything is identical. Since the mesh boundaries are not large enough, non-reflecting boundaries are used in both S-ALE and ALE methods to eliminate the reflected pressure waves from the boundaries. Occupant responses are comparable between improvised S-ALE and ALE. S-ALE response tends to be slightly higher compared to ALE. Close observation of both the S-ALE and ALE internal energy responses shows that S-ALE does not show any leakage whereas ALE shows a small amount of leakage which results in slightly lower responses. Main takeaway is that computationally S-ALE is 29% faster than ALE in this analysis and is significantly easier to use. Figure 1 shows the comparative responses of left lower tibia loads between S-ALE and equivalent ALE. Complete summary of energy responses, structural and occupant responses will be presented in this study.*

Introduction

Full system end to end blast simulation of Improvised Explosive Devices (IED) with occupants inside the military vehicle is computationally expensive and challenging. Most widely used Arbitrary Lagrange in Euler commonly known as ALE requires very large domain and fine mesh to capture the blast effects on the vehicles and occupants accurately. This will be computationally expensive and also requires significant user interface in creating the ALE mesh. Simulating design changes using this approach may not be very effective due to large computational time. Supposedly one can use IMPULSE_MINE or LOAD_BLAST methods to counter the computational challenges, but this requires a compromise in accuracy and perhaps needs more to develop the right scale factors. Researchers and Engineers are always looking for newer and faster methods of capturing an end to end blast simulation capabilities. Smooth Particle Hydrodynamic (SPH), Discrete Element Methods (DEM) [1, 2] and the newer Structure ALE methods (S-ALE) are showing promises. In this paper S-ALE was chosen to compare to the ALE method. S-ALE is similar to ALE and it easier to use S-ALE methods is shown to be approximately 30% faster than the ALE methods in simple ALE only problems. In this paper both structural and occupant responses of ALE and S-ALE were compared.

Analysis Methods

ALE is widely used to simulate high energy blast simulation. In a typical blast simulation high explosive (HE) is buried at a certain Depth of Burial (DOB) below the soil with Lagrange structure in air above the soil. In this approach HE, soil and air are represented as Eulerian and assigned a MULTI_MATERIAL_GROUP id with highest density as the first material and vehicle structure and occupants are represented as Lagrange. Users need to generate the mesh using nodes and elements using one of the pre-processors. Due to large deformation and very high energy it is impossible to represent all the components as Lagrange. In eulerian method mesh will be fixed, whereas the materials flows through the fixed mesh as volume fraction of fluids. Vehicle structure and occupant is modeled as Lagrange. Interaction between ALE fluids and Lagrange is activated by using *CONSTRAINT LAGRANGE IN SOLID (CLIS) coupling. ALE can be computationally expensive depending on the mesh size and domain.

The newer method Structure-ALE (S-ALE) simplifies the mesh generation process. S-ALE generates the mesh automatically during the analysis phase. S-ALE mesh is created using only 2 keywords in the input deck.

*ALE_STRUCTURED_MESH – Purpose of this card is to provide mesh geometry.
*ALE_STRUCTURED_MESH_CONTROL_POINTS – Defines the mesh size in 3 local directions x, y, z using the space dimensions provided by the user. Details on how to use this S-ALE cards are well documented in LS-DYNA user's manual version 10 and above [3]

ALE only Simulation

In order to understand the benefit of S-ALE compared to that of ALE, a simple S-ALE model is created using S-ALE cards [4]. A 2 m x 2m x 2m cube is filled with equally spaced S-ALE generated mesh. Using INITIAL VOLUME FRACTION three ALE materials are created namely HE, SOIL and AIR. These three materials were assigned corresponding PART, SECTION, MATERIAL and Equation of State (EOS) ids to represent HE, soil and air. Figure 1, shows the S-ALE generated mesh. Since this is ALE only without any structure CLIS card is not necessary. Basic thought process of this analysis is to capture the internal and kinetic energies responses of soil and air when a buried HE detonates. Use the S-ALE generated mesh as a background mesh and material properties in ALE and compare the energy responses. In both ALE and S-ALE simulation non-reflecting boundaries is activated due to the small domain size to make sure that pressures at the boundaries are not reflected back in to the domain and increase the energies. In S-ALE first a segment set has to be created for the boundary elements using

```
$-----------------------------------------------------------------------------------------------------------------------
*SET_SEGMENT_GENERAL
$        SID
           1
$  OPTION    MSHID      E1      E2      E3      E4      E5      E6
  SALEFAC           1       1         1       1         1       1        1
$-----------------------------------------------------------------------------------------------------------------------
```

SALEFAC creates segments on the face of Structured ALE mesh. E1 here is the SALE mesh ID (MSHID). E2, E3, E4, E5, E6, E7 correspond to -X, +X, -Y, +Y, -Z, +Z faces. Assigning 1 to these 6 values would include all the surface segments at these faces in the segment set. This option is only to be used for Structured ALE mesh.

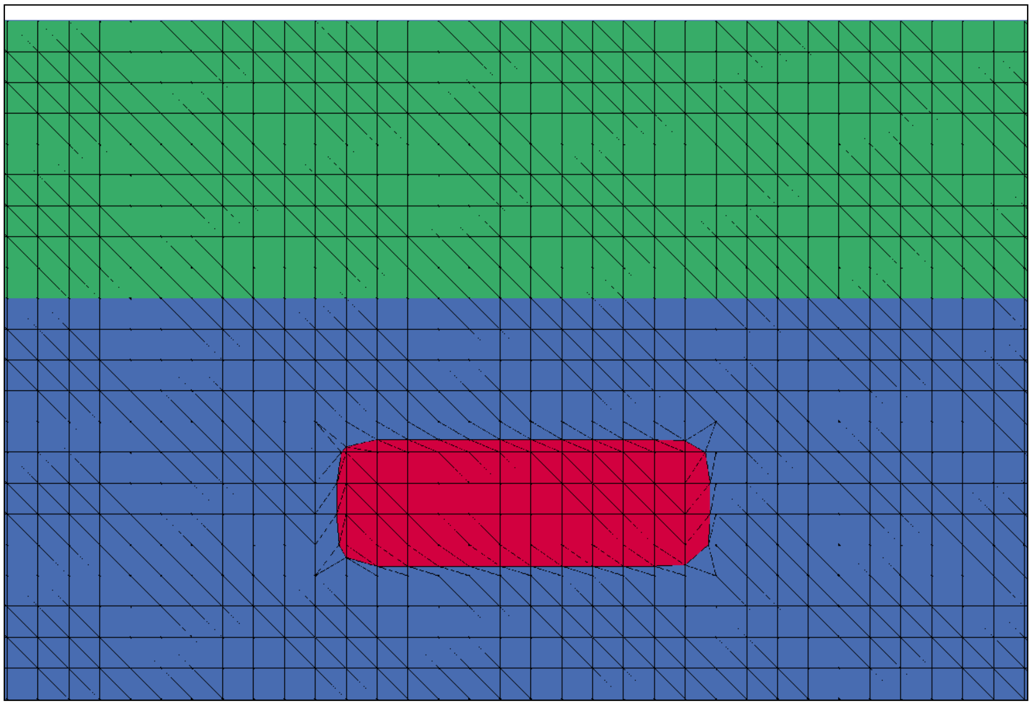

Figure 1: S-ALE generated mesh

S-ALE/ALE only Simulation Results

Results from the ALE only simulation is discussed in this section. Figure 2 shows the snap shots at different time steps. Pictures shown is from S-ALE simulation. ALE simulation responses are very similar.

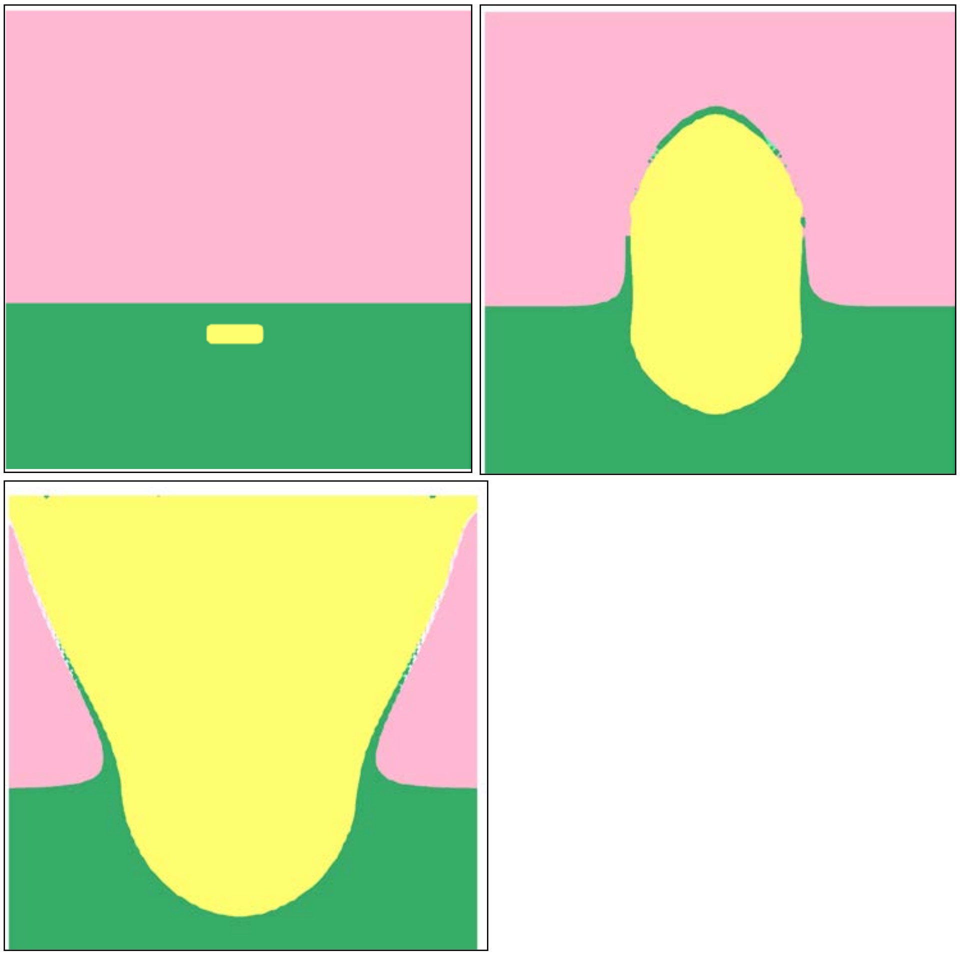

Figure 2: Snapshots of the animation at different time step

Following Figures 3-8 compares the internal energies and kinetic energies of HE, soil and air between S-ALE and ALE simulations.

Both internal energies and kinetic energies maps extremely well between S-ALE and ALE simulations. There is slight variation in soil internal energies otherwise it is comparable. Since there is no coupling involved with the Lagrange structure, energy dissipation appears very similar between S-ALE and ALE. Next step is to couple the vehicle structure and occupant to this S-ALE and ALE models and compare the responses.

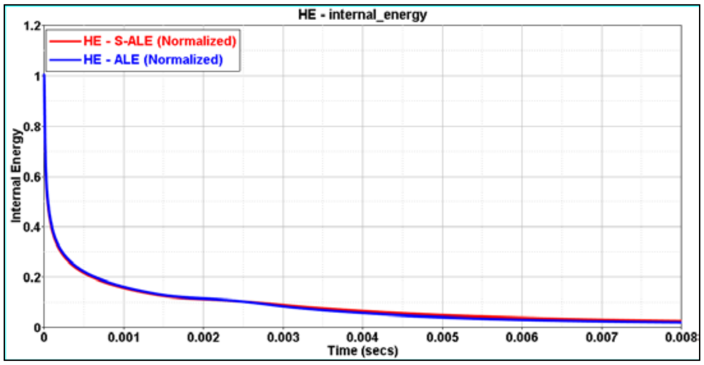

Figure 3: Internal Energies of HE

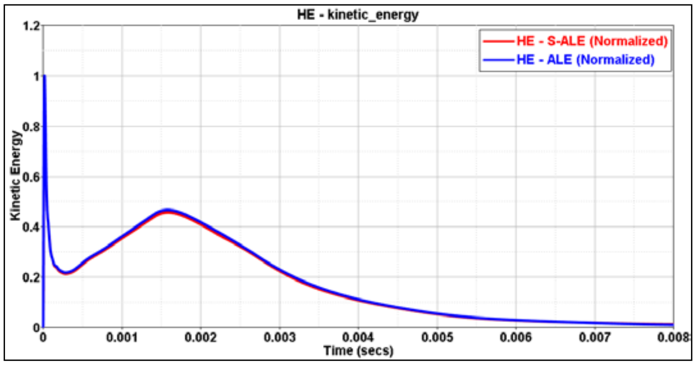

Figure 4: Kinetic Energies of HE

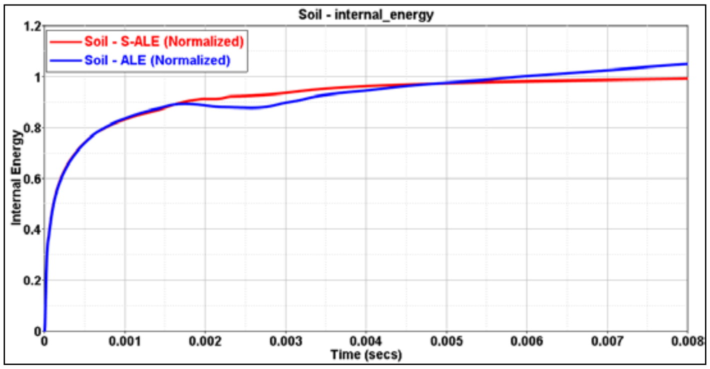

Figure 5: Internal Energies of Soil

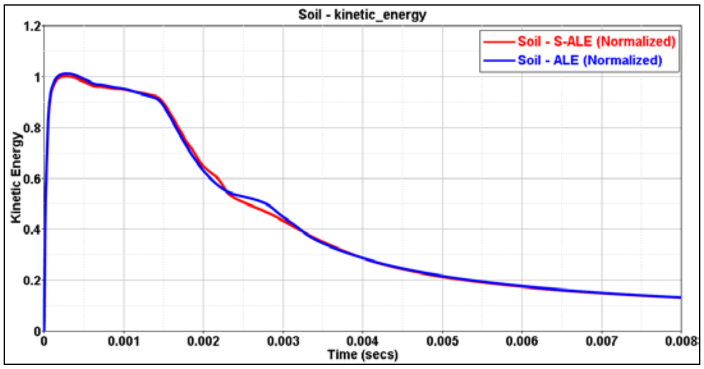

Figure 6: Kinetic Energies of Soil

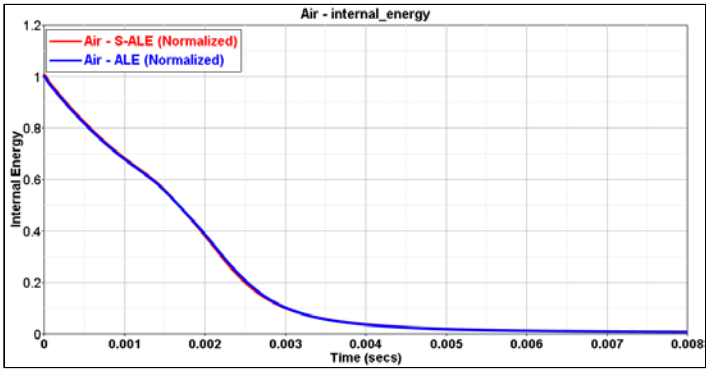

Figure 7: Internal Energies of Air

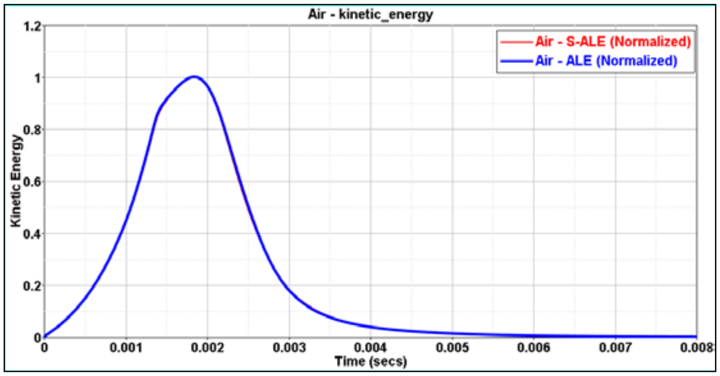

Figure 8: Kinetic Energies of Air

Vehicle Structure Model

In order to quantify the S-ALE method further, U.S. Army, TARDEC developed a Generic Hull (GH) structure model was used. GH model consists of 780,842 solid elements and weighs 16,000 lbs. as shown in Figure 9. Researchers and industry partners in the past performed many unclassified studies and developed technological solutions by utilizing fictitious vehicle geometry due to the unavailability of realistic information. Most of the blast work performed by the Department of Defense (DoD), and the data generated from testing military vehicles is usually classified in nature due to sensitivity making it difficult to share with public in general.

In order to enhance the knowledgebase from academia, researchers and industry partners, and studies performed by the wider scientific community, the US Army Tank Automotive Research, Development and Engineering Center (RDECOM-TARDEC) fabricated a generic vehicle hull, with the intent to share the geometry, test data and understand the blast mitigation technologies.

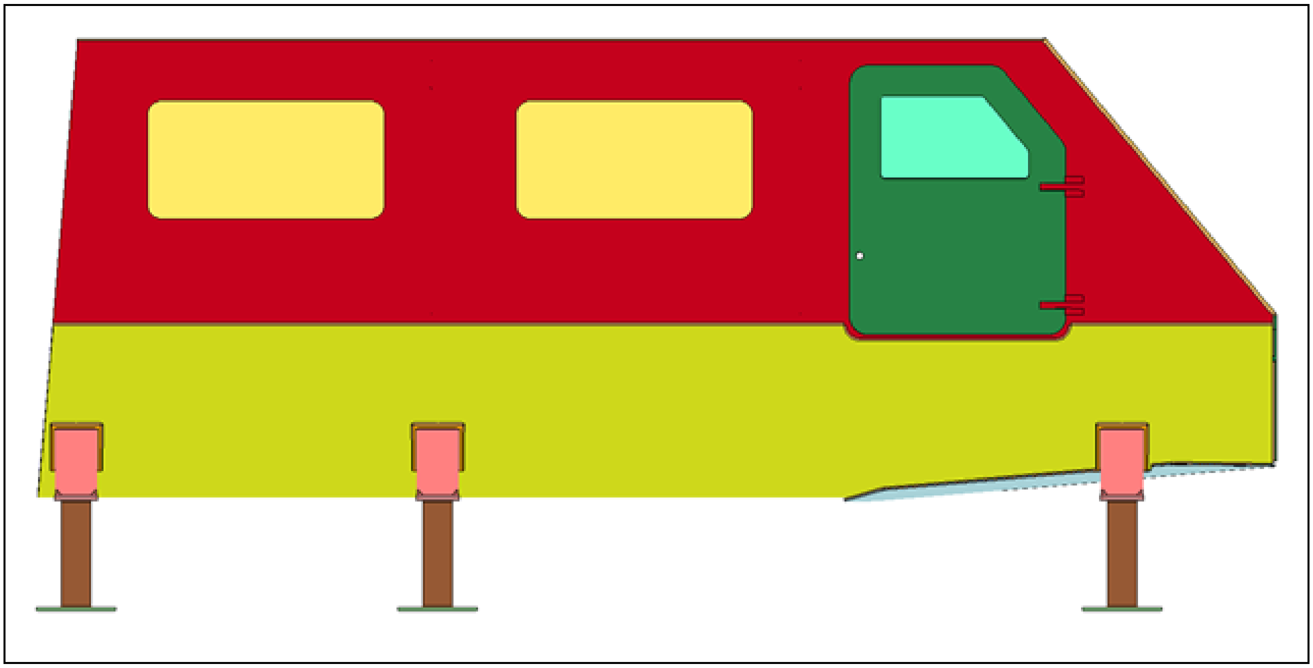

Figure 9. TARDEC Generic Hull Structure model

In one of my earlier studies performance of GH structure was evaluated without any occupants. [6]. In this study in addition to structural responses, occupant responses will be evaluated in S-ALE and compared to the responses from ALE. We have an extensive knowledge and experience in evaluating structural and occupant responses using ALE. Since S-ALE is showing significant improvement in computation time over ALE without structure and with structure, adding occupant and seat will complete the evaluation of the new executable. In order to establish high confidence level it is necessary to go through the step by step evaluation process. Moreover this way it is easy to identify opportunities for improvements rather than kitchen sink approach. For this purpose a single with stroking capabilities and a fully geared soldier is chosen in this study. There is a parallel effort is ongoing to assess the multiple seats and multiple soldiers using this S-ALE method. GH is modeled as a Lagrangian where both materials and nodes move together and coupled to the S-ALE and ALE fluids in which flows through fixed eulerian mesh using CLIS.

Seat & Hybrid III Dummy Model

Hybrid III dummy model from Humanetics was used to represent the soldier in a crew seating position. Occupant is positioned using LS-PrePost® to represent the Live Fire Test environment (LFTE). A generic stroking seat is employed in this study and the soldier is fully restrained with 5 point seat belt. Figures 12, 11 & 12 shows the stroking seat, soldier with gears and in a seated position.

After positioning the soldier in seated position, seat will be attached to the GH structure in one of the seat locations. GH model with seat and soldier is shown in figure 13.

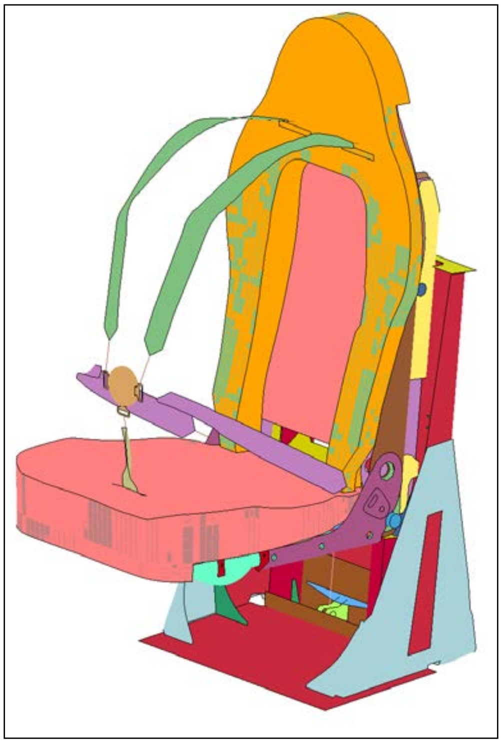

Figure 10: Seat Model

Figure 11: Soldier model

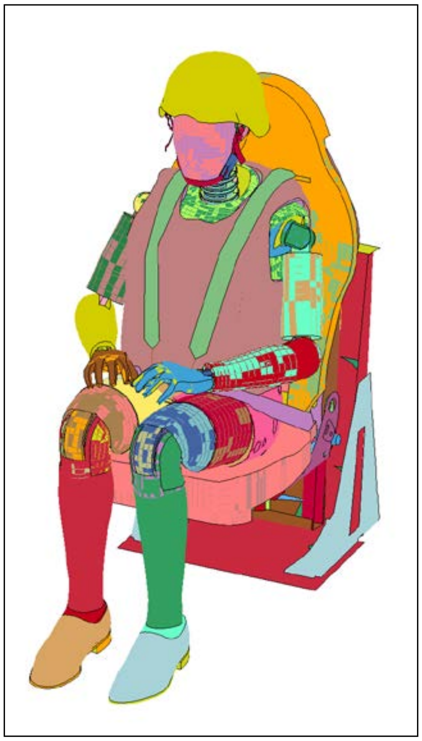

Figure 12: Soldier and seat assembly

Figure 13: GH model with soldier in seated position

Full System Analysis

Next step is to generate the S-ALE mesh using the two new control cards ALE_STRUCTURED_MESH and ALE_STRUCTURED_MESH_CONTROL_POINTS. This will generate a background mesh using the space dimensions from the later card. Using INITIAL VOLUME FRACTION background mesh will be filled with HE, soil and air with unique MULTI MATERIAL ID. HE in this study will be buried 50 mm from the top surface of the soil. Each of these materials will be assigned a material and equation of state models.

HE:

*MAT_HIGH_EXPLOSIVE_BURN, *EOS_JWL

SOIL:

*****MAT_ELASTIC_PLASTIC_HYDRO_SPALL, *EOS_TABULATED_COMPACTION

AIR:

*MAT_NULL, *EOS_LINEAR_POLYNOMIAL_TITLE

Figure 14 shows the full system blast simulation set up with HE, soil and charge location relative to GH and soldier

Figure 14: Full system blast model set up

S-ALE generated mesh was used as a background mesh in ALE and carried over all the material properties and volume fractions to establish one to one comparability. ALE full system will look exactly like the S-ALE full system.

Full System Results and Discussions

Energy responses from HE, soil and air are compared from full system S-ALE and ALE simulations. HE internal energies between S-ALE and ALE is compared in Figure 15. If we observe the HE internal energies from S-ALE/ALE full system analysis as shown in Figure 16, ALE simulation shows a faster dissipation/conversion compared to that of S-ALE during the onset of detonation. On a macro scale this may not significantly noticeable, but it is sufficient enough to skew the rest of the energy and other output responses which are shown in the later section. Both S-ALE and ALE simulation does not show any leakage during this time frame. Only difference between S-ALE and ALE is that, PFAC value is 0.06 in S-ALE to stop the leakage and ALE requires slightly higher PFAC values in this case it is set at 0.07. Don't know whether this may have affected the IE dissipation during the onset of detonation.

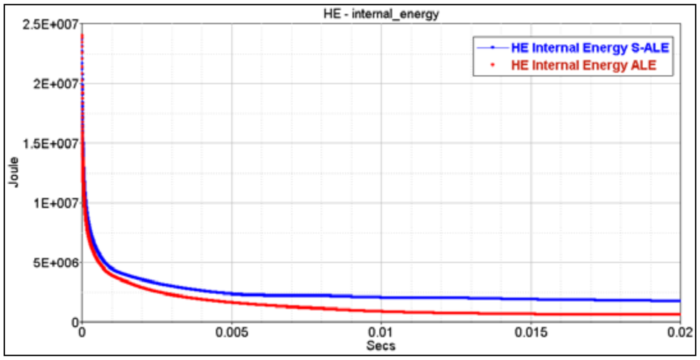

Figure 15: Internal energies of HE

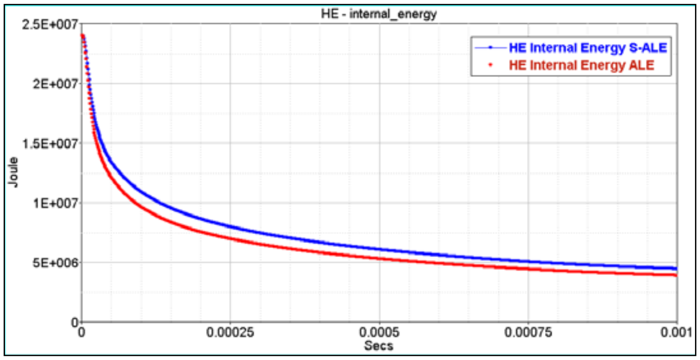

Figure 16: Internal energy of HE close-up

Internal energies of soil and air are shown in Figures 17 and 18. A much wider divergences are seen in soil and air internal energies between S-ALE and ALE. Further investigation is needed to understand the cause for the divergences. ALE only simulation did not show such a wide divergences in internal energies and kinetic energies. Only difference between ALE only and full system is that full system simulation has CLIS to couple the Lagrange structure.

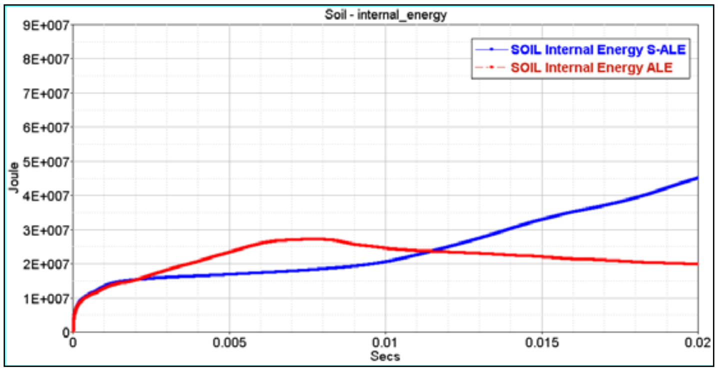

Figure 17: Internal energies of Soil

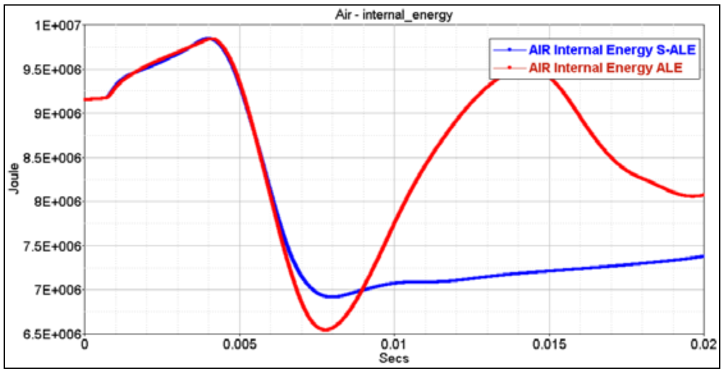

Figure 18: Internal energies of Air

Kinetic energies of HE, soil and air are shown in Figures 19, 20 and 21. Kinetic energy component seems to show less divergences, than the internal energies except the differences in peak values.

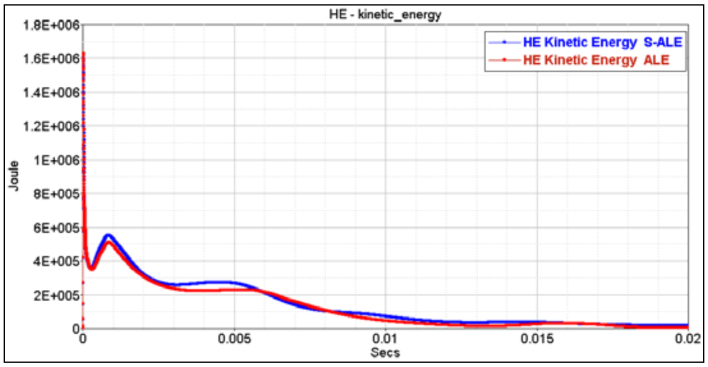

Figure 19: Kinetic energies of HE

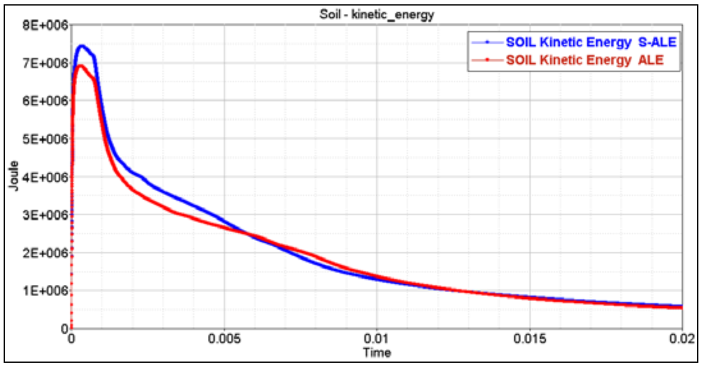

Figure 20: Kinetic energies of Soil

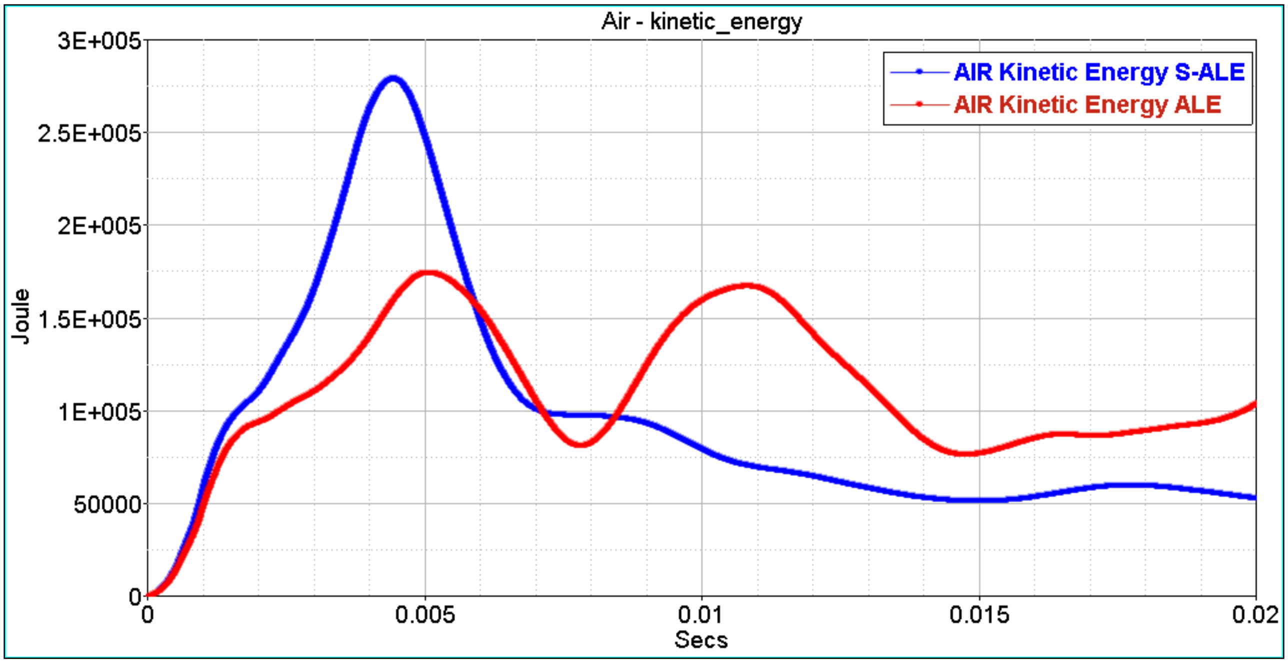

Figure 21: Kinetic energies of Air

Normalized occupant injury numbers are shown in Figures 22, 23 and 24. Overall both S-ALE and ALE responses are very similar.

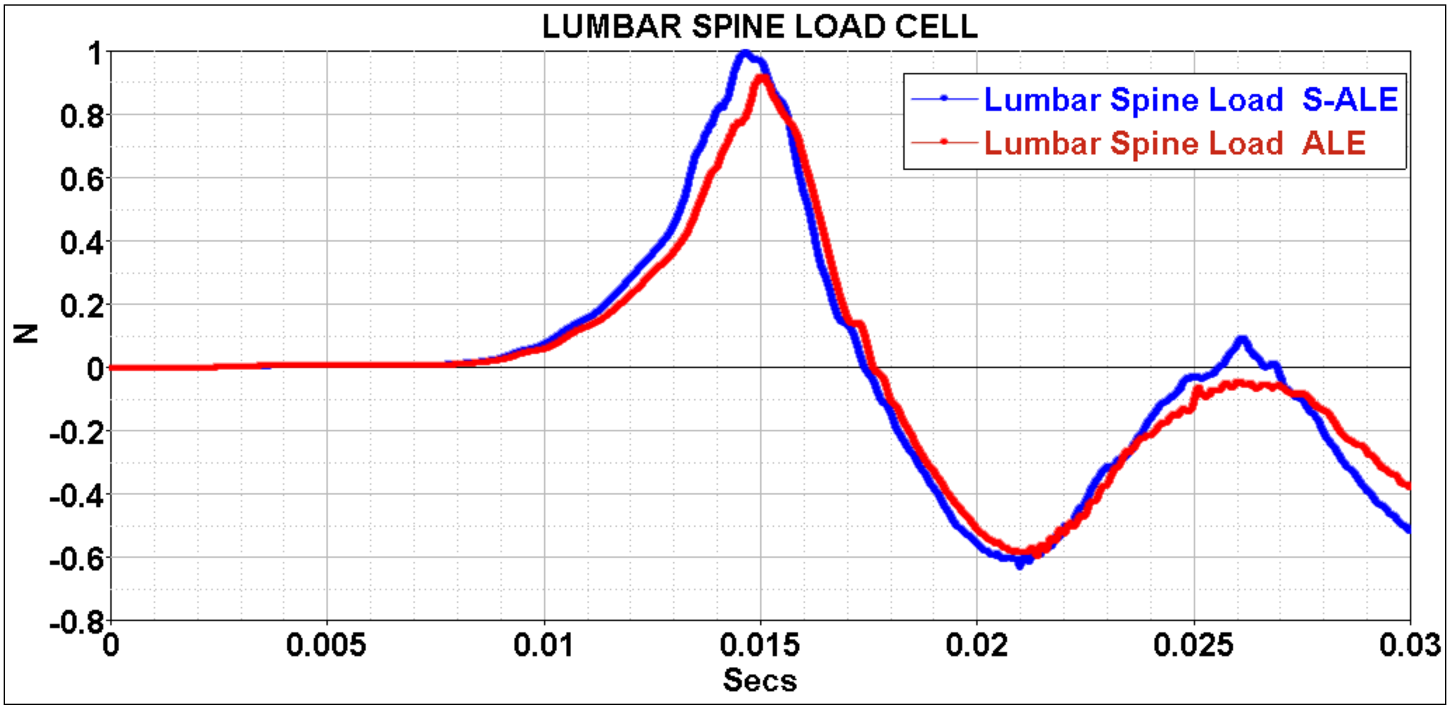

Figure 22: Lumbar spine load

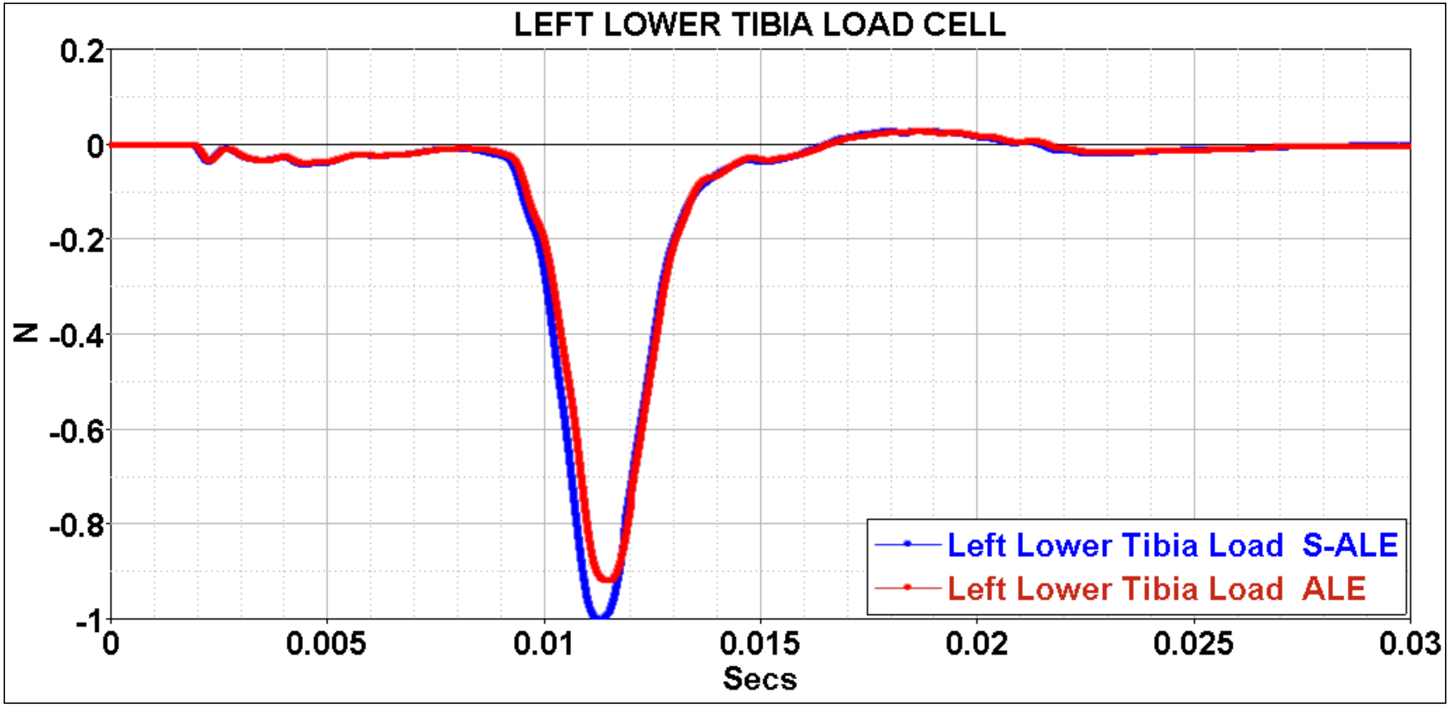

Figure 23: Left lower tibia load

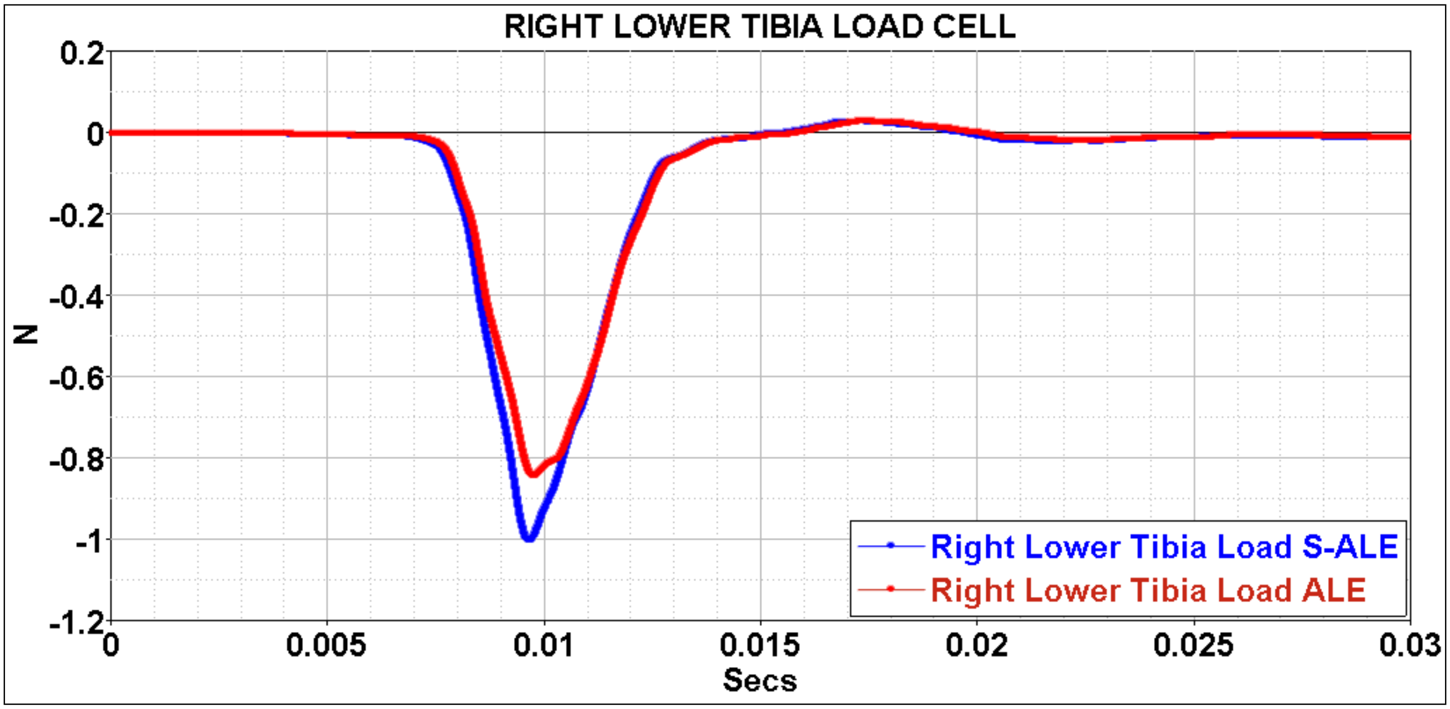

Figure 24: Right lower tibia load

Lower lumbar load, left and right lower tibia loads and pelvic accelerations profile looks very similar between S-ALE and ALE.

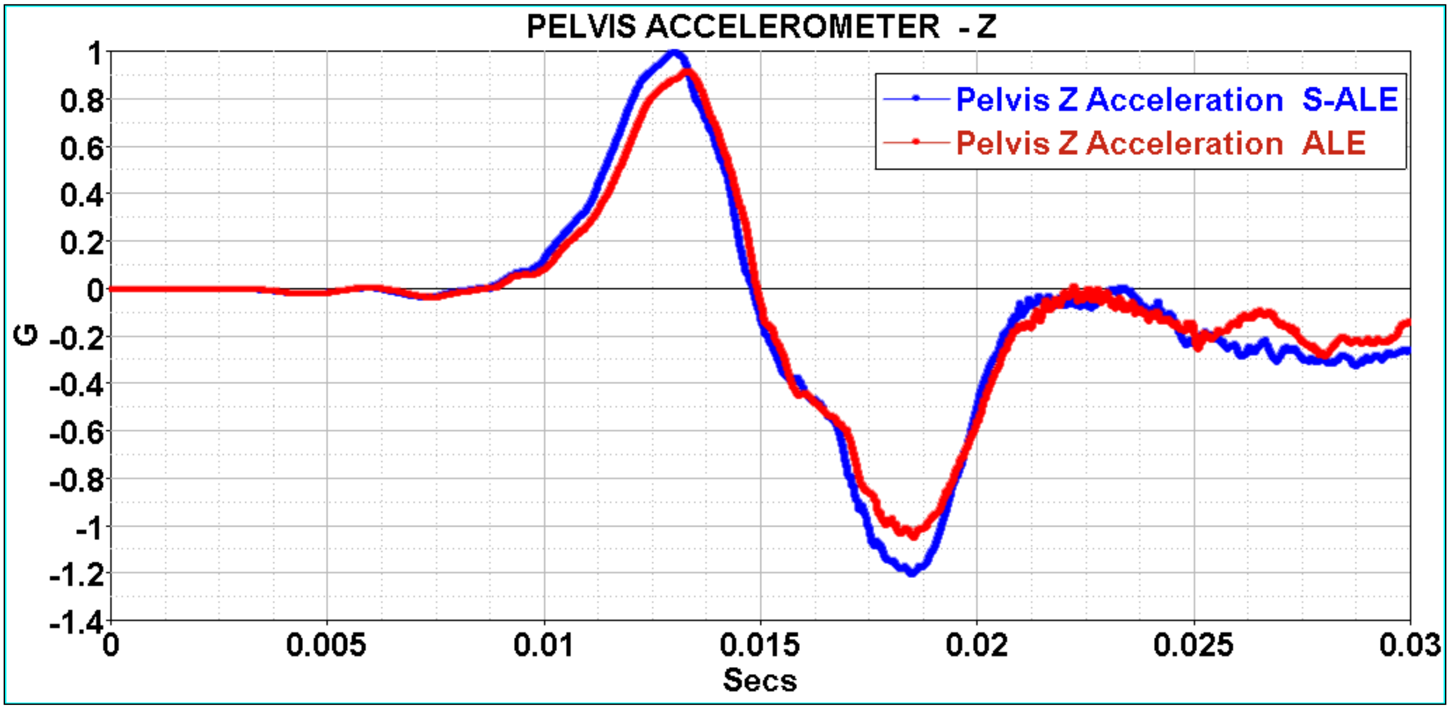

Figure 25: Pelvic vertical accelerations

Figure 26 shows the rigid body velocities of the structural response. Peak rigid body velocity values are higher for S-ALE, this could be due to higher internal energy of HE during the onset of detonation as shown in Figures 15 & 16.

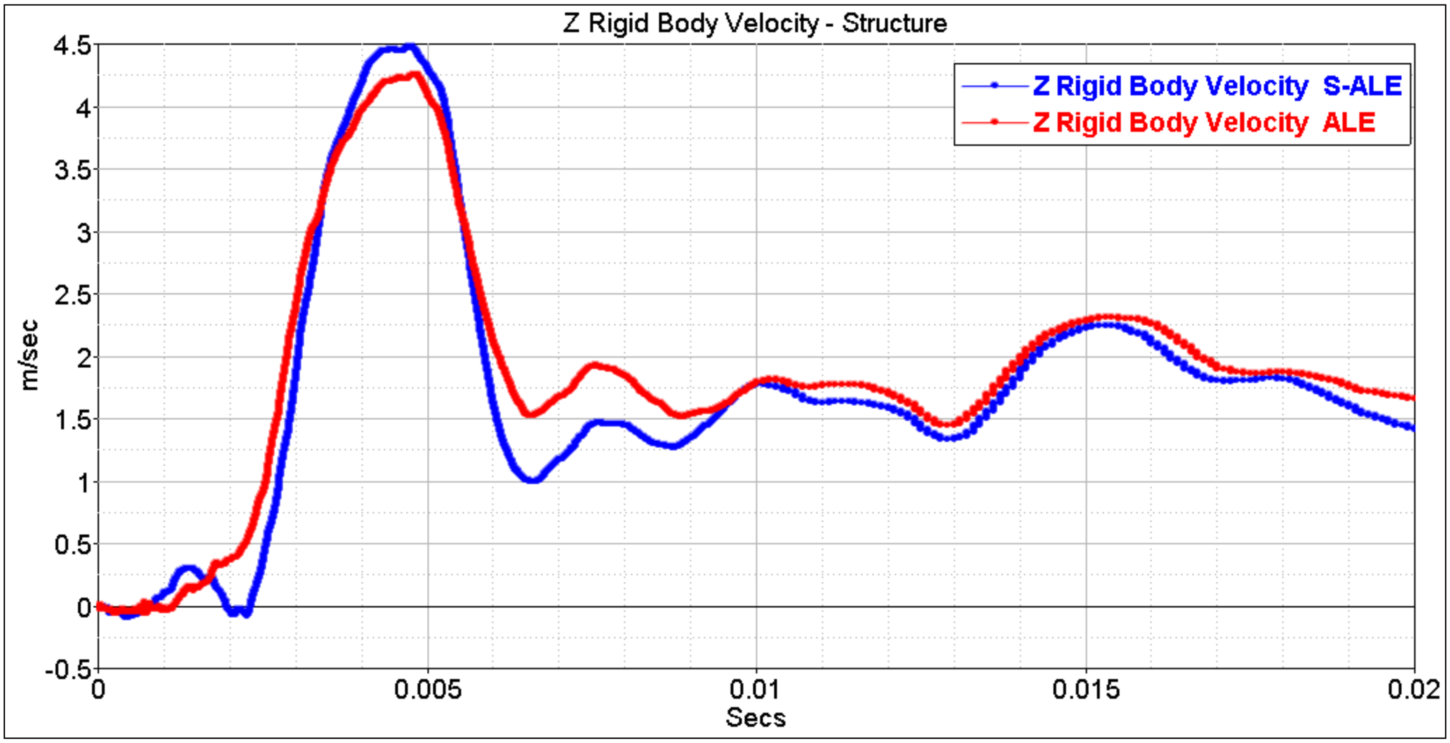

Figure 26: Global rigid body velocities of structure

Higher rigid body velocities of the structural response for S-ALE results in slightly higher peak occupant injury responses overall compared to that of ALE response.

ALE elapsed time 219130 seconds for 120000 cycles using 24 MPP procs (60 hours 52 minutes 10 seconds). S-ALE's elapsed time of 159750 seconds for 120000 cycles using same 24 MPP procs (44 hours 22 minutes 30 seconds) 28 percent faster than ALE. Animated snap shot of overall ALE-FSI is shown in Figures 27, 28, 29 & 30.

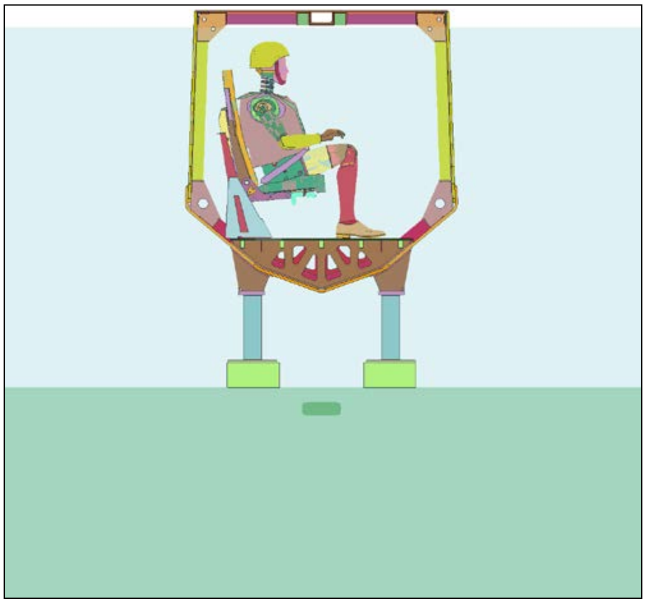

Figure 27: @ time = zero seconds

Figure 28: @ time = 0.008 seconds

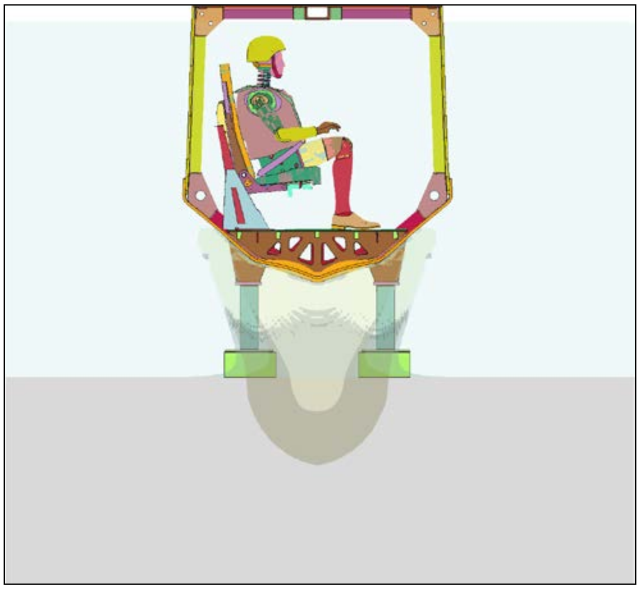

Figure 29: @ time = 0.002 seconds

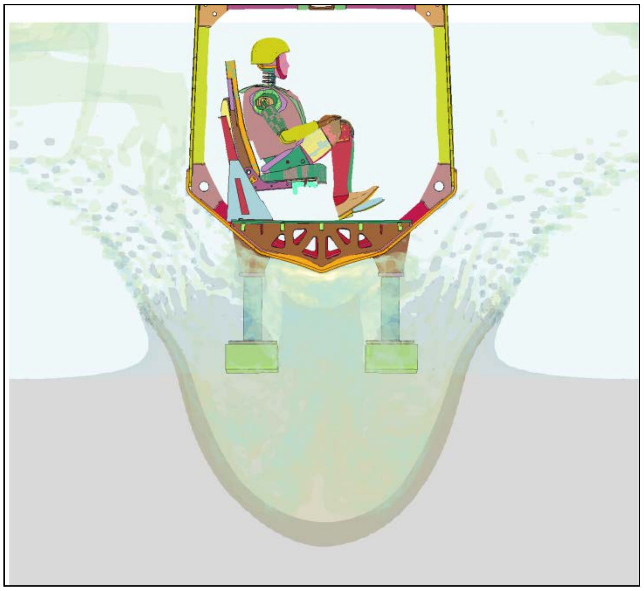

Figure 30: @ time = 0.025 seconds

Summary and Conclusions

The study presented in this paper compares the newer Structured ALE (S-ALE) method of blast system simulation to that of the traditional ALE method. S-ALE method has the computational advantage compared to the ALE and is promising in blast simulation where computational time is the significant cost and establish as a robust and reliable reduced order modelling (ROM) [6]. First ALE only simulation performed for generic HE charge and internal, kinetic energy responses of HE, soil and air are compared. Next, TARDEC generated generic hull with a single generic stroking seat and a hybrid III occupant with soldier gear in a crew seating position was coupled to the S-ALE and ALE models. Using the same generic HE charge a full system blast simulation was performed. Energy response, structure response and occupant injury responses are compared between S-ALE and ALE methods and presented.

S-ALE method responses compared very well to that of the traditional ALE method. HE energy dissipation in S-ALE is slightly higher than that of the ALE and results in an overall slightly higher response but well within the 95% of that of ALE. Main takeaway from this S-ALE/ALE comparative analysis is that S-ALE is 28% faster than the traditional ALE simulation. Generating S-ALE mesh is much simpler compared to the ALE with only 3 cards. Further evaluation of the S-ALE with multiple seats and multiple occupants is in progress to understand the S-ALE methods constraints, limitations and opportunities for large scale blast simulation modelling. S-ALE is faster, scalable, simpler and very stable.

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Acknowledgments

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Definitions/Abbreviations

ALE - Arbitrary-Lagrangian-Eulerian
CLIS - Constrained Lagrangian in Solid
DEM – Discrete Element Method
EOS - Equation of State
FSI - Fluid-Structure-Interface
GH – Generic Hull
HE - High Explosive
IED - Improvised Explosive Device
LS-DYNA - COTS structural dynamics software Lawrence Livermore Software Corporation, CA
LFTE – Live Fire Test & Evaluation
MPP – Multiple Parallel Processors
M&S - Modeling & Simulation
PFAC – Penalty Factor
ROM – Reduced Order Modeling
S-ALE - Structured Arbitrary Lagrangian Eulerian
SPH – Smooth Particle Hydrodynamics
TARDEC - Tank Automotive Research, Development and Engineering Center
RDECOM – Research Development and Engineering Command