Simulation of Energy Absorbing Materials in Blast Loaded Structures

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Abstract

Energy absorbing materials such as foam or honeycomb are of interest in blast protection because of their ability to absorb energy through plastic deformation. After reaching their yield stress, these materials exhibit a region of constant stress for increasing strain until the material is completely compacted. The energy needed to crush the material is proportional to the area under the stress-strain curve. Because foams and honeycombs have this "plateau" region, they absorb a considerable amount of energy relative to their low density. These materials are investigated to determine if their energy absorbing abilities can be used to mitigate the load and shock transferred to a vehicle structure subject to blast loading.

Ballistic pendulum experiments show that energy absorbing materials increase the imparted impulse from a blast. This behavior was contrary to expected results so computational models were created in LS-DYNA to understand the phenomenon that causes an increase in imparted impulse. ConWep and Arbitrary-Lagrangian-Eulerian (ALE) techniques were used in simulations to demonstrate their efficiency and accuracy. An additional ConWep aluminum foam model was created to directly compare simulations against ballistic pendulum experiments found in the literature.

1. Introduction

As the military industry moves forward into the 21st century, strong lightweight materials are changing their status from exotic to commonplace. Vehicles are being reevaluated to create a safer, more efficient, and more lethal vehicle with significant weight savings. Survivability from mine blast is of particular concern: as weight is reduced, the accelerations of the vehicle when subjected to mine blast aluminum increases. A sacrificial layer of material that can absorb some or all of the blast energy is one possibility for light vehicle survivability. Metal foams and honeycombs are materials that absorb a considerable amount of energy relative to their low density.

A simple device to measure impulse imparted to a structure from a blast is a ballistic pendulum (Figure 1). With a charge detonated in front of the pendulum, the face is subjected to a pressure wave, which causes the pendulum to rotate a measurable amount. Knowing the rotation of the center of mass (cm in Figure 1) and the distance from the rotation center, the imparted impulse from the blast can be calculated. Panels of various shapes and materials can be placed on the face of the pendulum to investigate their abilities to reduce the imparted impulse. With the material absorbing some of the energy, the resulting rotation of the structure was expected to be reduced. Ballistic pendulum experiments show opposite results; energy absorbing materials placed on the front of the panel caused an increase in rotation [1][2].

Hanssen et al. [1] performed ballistic pendulum tests on Al foam panels as early as 1998. Hannsen showed an increase in imparted impulse to Al foam panels subjected to close range blast. This increase was attributed to collapse of the foam under the blast (dishing), which allowed confinement of the blast. Hanssen used numerical models to show that although an increase in impulse was observed, the transmitted force through the Al foam panels was decreased.

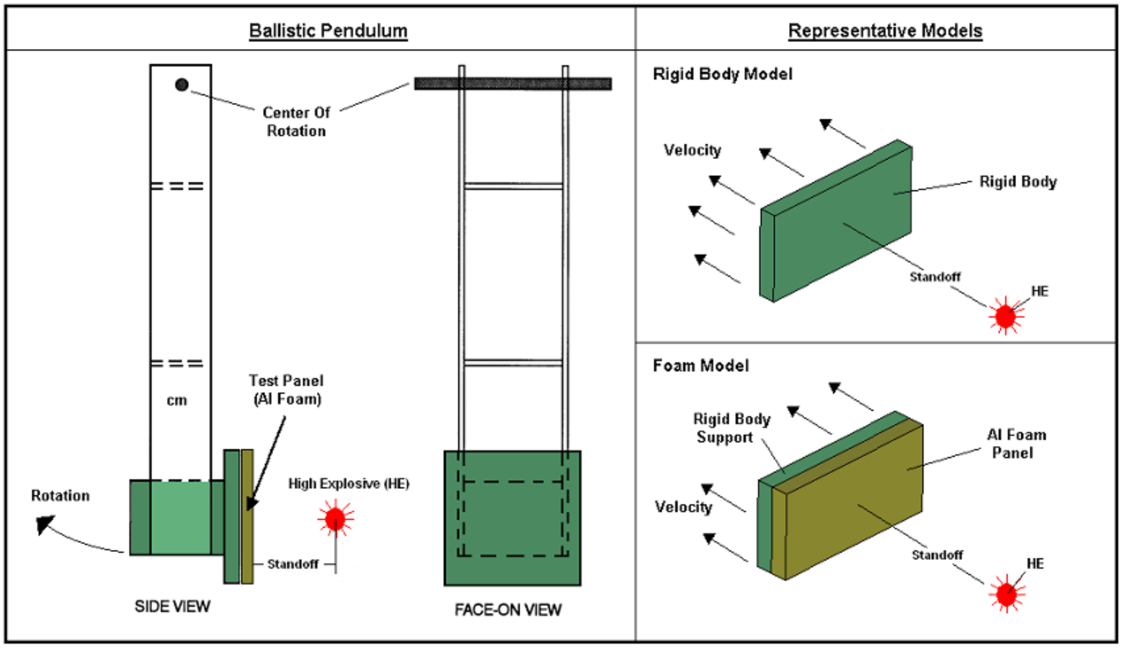

Figure 1: Ballistic Pendulum and Representative Models Diagram.

This paper compares two loading methods available in LS-DYNA: one using a Lagrangian model and the ConWep air blast function and the other using Arbitrary Lagrangian-Eulerian (ALE) coupling including the explosive material as part of the model. Although these models use the same standoff, equivalent charge mass and material properties, they are not representative of any physical experiment. A separate ConWep model is presented that compares ConWep's capabilities against experimental values for simulating blast loading of Al foam panels.

2. Blast Loading Using LS-DYNA

Both ConWep and ALE techniques have been validated for simulating mine blast [3],[4],[5]. Randers-Pehrson [3] describes the ConWep air blast function and concluded the function as adequate for use in mine blast applications. Similarly, Wang [4] benchmarked material properties used in ALE modeling of detonating landmines. Williams [5] compared ConWep to a commercially unavailable mine blast algorithm and concluded ConWep as apt if a scale factor is determined for the soils being used. The ballistic pendulum, which is what the models presented here simulate, is more appropriately simulated with an air blast. The effect of soil is not an issue, so standard practice values [3],[4],[5],[6] are used for the representative models.

In order to reduce the computational expense of modeling the maximum displacement of a pendulum (with a period of over 2.5 seconds) with a time step appropriate for capturing ballistic phenomena, simpler models were devised (Figure 1). These simpler models consist of a sled of known mass subjected to the same blast load the pendulum counterpart would be exposed to. The sled has the same area exposed to the blast as the pendulum bob as well as the same mass. When the sled is subjected to the impulse of the blast, it will undergo acceleration until the sled reaches a maximum velocity (upon completion of the impulse). The resulting kinetic energy, which is calculated using the maximum velocity of the sled, is comparable to the potential energy calculated from the maximum height of the pendulum swing.

The following two subsections describe the models made to compare the different loading methods of ConWep and ALE. Both methods have a rigid body model and an Al foam model. For the foam models, the foam panel is attached to the front of a rigid body support using a contact card. The exposed surface of the foam model has the same standoff as the exposed surface of the rigid body model (Figure 1).

2.1 Lagrangian Models with ConWep Blast Function

LS-DYNA's ConWep air blast function has inputs of TNT equivalent mass, type of blast (surface or air), location in space of detonation, and surface identification for which the pressure will be applied. From this information, ConWep calculates the appropriate pressure to be applied to the designated surface. This method is computationally less expensive than the ALE method at the cost of accuracy: ConWep is unable to account for confinement (focusing of the blast due to geometry) or shadowing (when an object is blocking a surface from direct loading)[3].

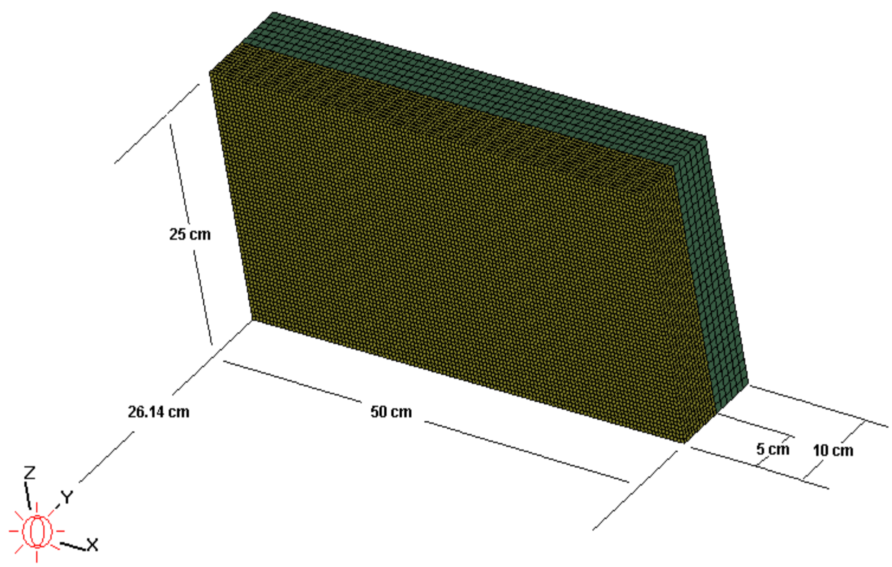

Figure 2: Discretization of Lagrangian panels. Foam elements (numbering 86,400) are shown in yellow, rigid body elements (numbering 10,800) are displayed in green.

The rigid body model has dimensions (in x, y, z) of (50cm, 5cm, 25cm), consists of 10,800 elements, and is positioned 26.14 cm away from the source of the blast. The foam model (Figure 2) adds a panel of foam elements of the same dimensions as the rigid body and splitting each solid element into 8 equally sized smaller elements. All the Lagrangian elements use a single integration point element formulation and have a 1:1:1 aspect ratio. Quarter symmetry was used to reduce the number of elements in the model; all nodes on the planes of symmetry were constrained to stay on the planes of symmetry. *Contact_tied_surface_to_surface_offset was used to tie the rigid body to the foam plate. The "offset" option is necessary when tying a deformable part to a rigid body. The rigid body was chosen as the master and the foam as the slave for the contact algorithm.

One pound of C-4 was chosen for the blast load simulations to be similar to ballistic pendulum experiments performed by Skaggs [2]. The ConWep air blast function requires an input for equivalent mass of TNT. C-4 explosives release more energy per pound than TNT by a factor of 1.14 [5], [6]. Using that factor and converting from lb to gm, the equivalent mass of the TNT used in these studies is 517.1gm.

2.1.1 Material Properties

Material properties for the ConWep and ALE models are listed in Table 1. Some of the material properties required in these material cards are not easily described, so the values are displayed according to what is required for the LS-DYNA material cards. Wang [4] used a similar table structure and it is felt that this format displays the data in a format most useful to the end user.

Table 1: Material Properties Used For ConWep And ALE Models.

Model	Material	LS-DYNA Cards (Units = cm, gm, microseconds)								
		*MAT_RIGID								
ConWep	Rigid Body	RO	E	PR	N	COUPLE	M	CON1	CON2	
		0.01	2	0.3	0	0	0	6	7	
		*MAT_HONEYCOMB								
	Al Foam [8]	RO	E	PR	SIGY	VF	MU	BULK	AOPT	
		0.15	0.7	0.285	0.0024	0.137	0.05	0	0	
		EAAU	EBBU	ECCU	GABU	GBCU	GCAU			
		2.48E-03	2.48E-03	2.48E-03	9.65E-04	9.65E-04	9.65E-04			
		*DEFINE_CURVE (STRESS VS. VOLUME STRAIN)								
		(STRAIN)	0.00E+00	8.63E-01	8.66E-01					
		(STRESS)	1.00E-05	1.00E-05	2.40E-03					
		*DEFINE_CURVE (SHEAR STRESS VS. VOLUME STRAIN)								
		(STRAIN)	0.00E+00	8.63E-01	8.66E-01					
		(STRESS)	4.00E-06	4.00E-06	9.34E-04					
		*MAT_HIGH_EXPLOSIVE_BURN								
ALE	C4 [4]	RO	D	PCJ	BETA					
		1.601	0.8193	0.28	0					
		*EOS_JWL								
		A	B	R1	R2	OMEG	EO	VO		
		6.0977	0.1295	4.5	1.4	0.25	0.09	1		
		*MAT_NULL								
	Air [4]	RO	PC	MU	TEROD	CEROD				
		1.29E-03	0	0	0	0				
		*EOS_LINEAR_POLYNOMIAL								
		CO	C1	C2	C3	C4	C5	C6	EO	VO
		-1.00E-06	0	0	0	0.4	0.4	0	2.50E-06	1

*MAT_RIGID (material 20) was used for the rigid body model. Material properties for steel were used with the exception of density. For all models, the overall mass of the sled was 4 kg; with a volume of 25000cm^3 the density of the rigid body in the rigid body model was set to 0.16 gm/cc. The foam model has a rigid body support panel and a foam panel each with a volume of 25000 cm^3. With the Al foam density at 0.15gm/cc, the rigid body's density was set at 0.01gm/cc to keep the overall mass of the sled the same.

*MAT_HONEYCOMB (material 26) was chosen for the Al foam material model. Material 26 offers uncoupled orthotropic behavior as seen in foams. Nonlinear elastoplastic material behavior can be defined separately (for each direction) for all normal and shear stresses. These curves can be used to define elastic-perfectly-plastic-rigid material behavior as seen in the majority of papers modeling foams subjected to high strain rates [1], [7],[8]. The values used for the foam material model were gathered from a couple of sources [1],[8].

2.2 ALE Models

Using ALE in LS-DYNA involves modeling the charge and surrounding fluid with an Eulerian mesh, which is then coupled with a Lagrangian mesh (used for the foam and rigid body panel). Equations of State (EOS) are used for the High Explosives (HE) and air. The ALE method models the explosion and calculates the pressure profile throughout the Eulerian mesh. ALE is computationally more expensive than ConWep, and is only appropriate for small standoff distances: with the small Eulerian mesh needed to appropriately capture the pressure wave front, large amounts of elements are needed.

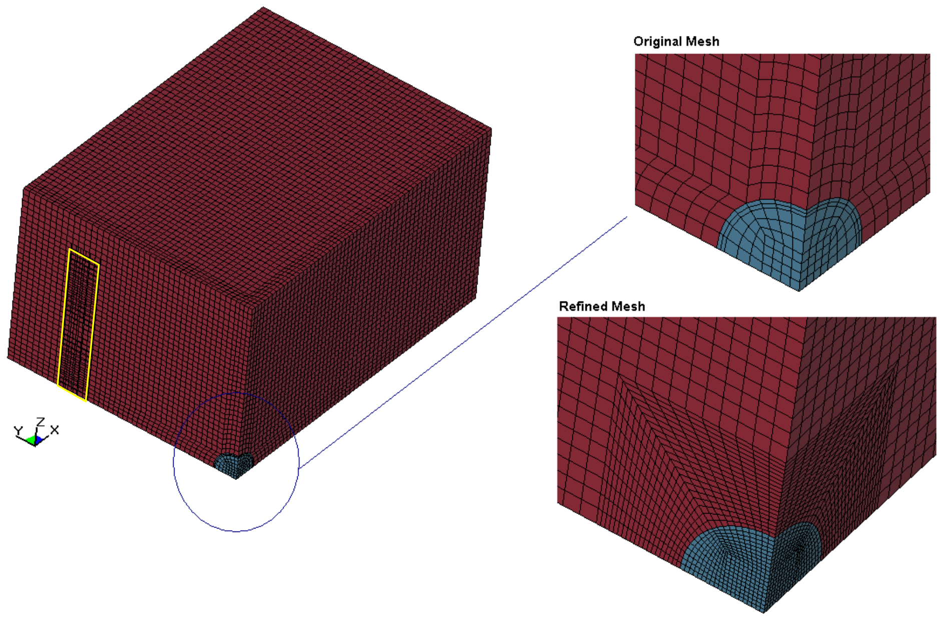

Figure 3: Discretization of the ALE Eulerian mesh. There are 88,200 air elements and 304 HE elements in the original mesh; 128,284 and 4,000 elements in the refined mesh respectively.

Several ALE models were constructed to improve the accuracy and efficiency of the models. The list includes an eighth symmetry rigid body model, a fourth symmetry rigid body model, a rigid body model with a refined Eulerian mesh, a rigid body model with an increased number of quadrature points, a foam model, and a foam model with a refined Eulerian mesh. The same amounts of Lagrangian elements (10,800 rigid and 86,400 foam) were used in the ALE models as were the ConWep models. In the eighth symmetry rigid body model (Figure 3), the number of Eulerian elements used to model the HE and air were 304 and 88,200 respectively. The mesh seen in (Figure 3) labeled "Original" was created by Powers [9] in a previous ALE parametric study. In the figure the red mesh shows the discretization of the air Eulerian elements, the blue mesh shows the High Explosive (HE) discretization. The darker area (highlighted) shows the Lagrangian part overlapping the Eulerian mesh, which explains why the mesh looks different in that region. The overall dimensions used in the x, y, and z directions are 55 cm, 40 cm, and 30 cm respectively. A 1:1:1 ratio was not achievable with the Eulerian mesh because of the spherical nature of the charge, but all elements are hexahedral. Boundary conditions disallowing motion normal to the planes were placed on the XY, XZ, and YZ planes (the three planes intersect at the center of the spherical explosive).

A quarter symmetry model was constructed to address a boundary condition concern inherent with the eighth symmetry model: the constraints on the XZ plane of the eighth symmetry (Figure 3) model simulate another plate mirrored across the XZ plane. It was necessary to model quarter symmetry conditions to see if the affect, if any, the reflected blast wave from the mirrored plate had on the solution. A total of 18,598 (304 HE, 18,294 air) elements were mirrored about the XZ plane allowing for quarter symmetry conditions while keeping the number of elements down (Figure 4). This addition of elements allowed the blast wave to reflect off of itself about the XZ plane while not calculating a full model (nor simulating another plate on the other side). Nodes along the YZ and the XY planes were constrained to stay on their respective planes. The darker region in Figure 4 (highlighted) is where the rigid body and air mesh overlap.

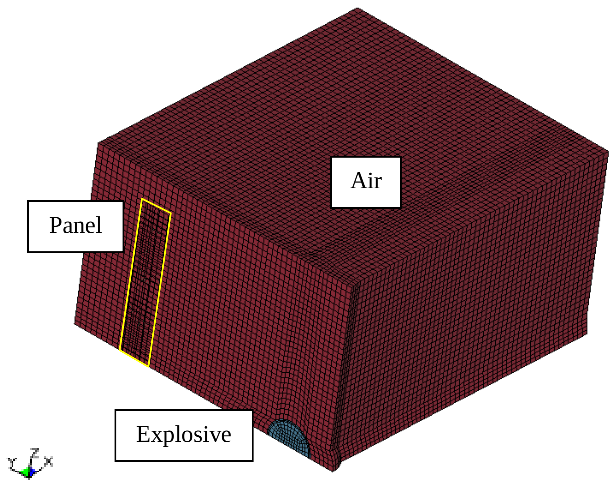

Figure 4: Quarter symmetry model: 106,190 Air (red) elements, 608 HE (blue) elements, 10,800 Rigid body (within air mesh) elements.

As reported by Wang [4], the mesh density significantly influences the peak pressure in the Eulerian mesh. A new mesh was constructed (Figure 3) with 43,780 more Eulerian elements, to understand mesh effects for this set of models. Maximum velocity of the sled with the refined mesh was within 8% of the original mesh.

2.2.1 Material Properties

The rigid body and Al foam material properties are the same as those found in the ConWep section and are listed in Table 1. Air and HE material properties and equation of state (EOS) parameters were obtained from [4] and are also listed in Table 1.

2.2.2 Arbitrary-Lagrangian-Eulerian Coupling

For accurate solutions, two Eulerian elements must fit across one Lagrangian element when coupling the two meshes [9]. This sizing promotes appropriate advection from Eulerian to Lagrangian elements. Increasing the number of quadrature points, which are used to couple the Lagrangian and Eulerian elements, can be used in place of mesh refinement for fluid-structure contact issues. If the number of quadrature points is not enough, the solution will underpredict the energy transferred from the blast. Increasing the number of quadrature points significantly increases the computational expense. Considering the mesh densities used in these models, four quadrature points are used for the rigid body model and two are used for the Al foam model.

To couple the foam and the rigid body support panels to the fluid, a part set containing both panels was used as the slave id on the in the *CONSTRAINED_LAGRANGE_IN_SOLID (*CLS) card. Using a part set allowed both parts to be coupled with the Eulerian fluid. One concern using this method is the number of quadrature points needed: the meshes of the rigid body and foam are different so a careful number is needed to keep costs down while not allowing penetration of the coarser mesh. It was decided to keep the number of quadrature points based on the foam mesh reasoning that the rigid body's interaction with the fluid was not as significant:

the rigid body is only exposed to the overpressure of the blast after it travels around the foam panel.

Also on the *CLS card, the penalty factor was set to 0.2 and the coupling type (CTYPE) chosen allows for erosion of the Lagrangian elements. Examining the model after the part set was implemented showed all parts coupling appropriately without penetration. The time scale factor had to be reduced significantly for the ALE models: a value of 0.10 was needed for the foam models to run to completion.

3. Results: ConWep vs. ALE

3.1 Maximum Velocity/Kinetic Energy

More ALE models were created than ConWep models because there are a lot more variables to consider using ALE. The sled velocity curves for all six ALE models are shown in Figure 5a, while tabulated results are located in Table 2. The kinetic energy was within 1% for the ALE eighth symmetry rigid body model, fourth symmetry rigid body model, and the rigid body model with 5 quadrature points. The refined Eulerian mesh model showed an increase of 7% in sled kinetic energy over the original mesh in the rigid body models and a decrease of 3% in the foam models.

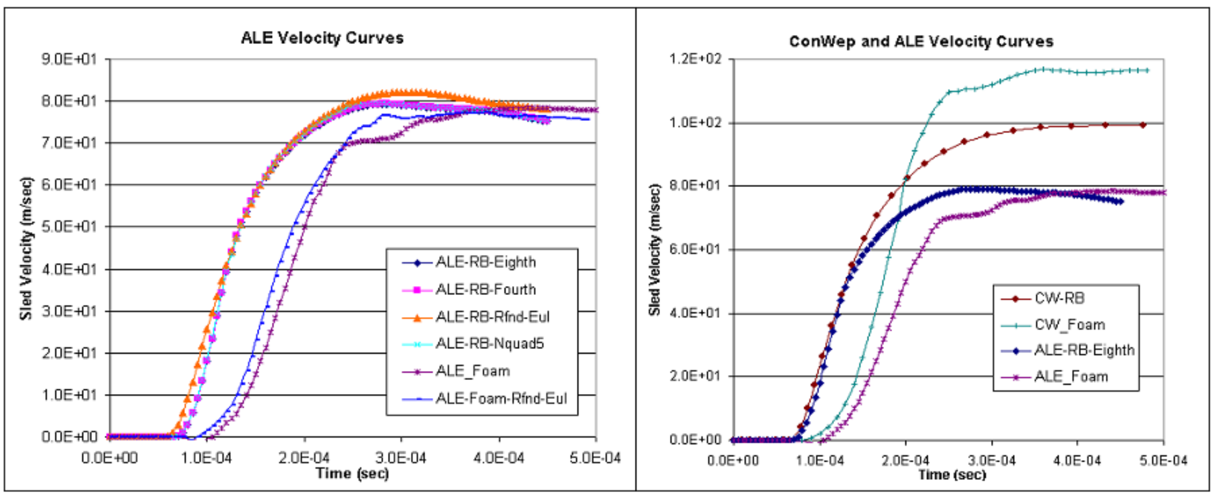

Figure 5: A) All ALE Models Sled Velocity vs. Time B) ConWep and ALE Sled Velocity Curves.

As shown in Figure 5b and Table 2, using benchmarked parameters found in the literature [3], ConWep increases the KE of the sleds over ALE: 58% higher in the rigid body models, and over 115% higher in the foam model. The ConWep models show an increase in energy transferred to the foam models by 37% over the rigid body models; this behavior is seen in the experiments [1],[2]. ALE foam models show a slight decrease in energy transferred to the rigid body sled velocity, contrary to what has been shown in experiments.

Table 2: ConWep and ALE Results.

Model	Max Velocity (m/sec)	Mass (Kg)	KE (J)	% Diff (from ALE eighth)	Time to Run (hours)
ALE-RB-Eighth	7.92E+01	4.00E+00	1.26E+04	0.00	2.1083
ALE-RB-Fourth	7.94E+01	4.00E+00	1.26E+04	0.38	2.6700
ALE-RB-Refind-Eul	8.22E+01	4.00E+00	1.35E+04	7.57	5.6000
ALE-RB-Nquad5	7.94E+01	4.00E+00	1.26E+04	0.39	30.5800
ALE-Foam	7.86E+01	4.00E+00	1.23E+04	-1.68	24.2333
ALE-Foam-Refined-Eul	7.73E+01	4.00E+00	1.20E+04	-4.74	47.7667
CW-RB	9.95E+01	4.00E+00	1.98E+04	57.76	0.0025
CW-Foam	1.17E+02	4.00E+00	2.72E+04	116.94	1.2300

3.2 Computation Time

The length of time to run the ALE models is significant: especially when coupled with a deformable material or when the number of quadrature points or elements is increased. The ALE rigid body eighth symmetry model took over 840x as much time as its ConWep counterpart. The ALE Foam model took as much as 38x as much time as the ConWep foam model, depending on the level of Eulerian mesh refinement.

3.3 Foam Behavior

Figure 6 shows the Y-displacement contours of the 3 foam models at an elapsed time of 4.5E-4 seconds (when the foam is done deforming). Hanssen [1] showed similar foam panel deformation as seen in the ConWep model. The panels tested by Skaggs [2], which had a much larger cube root scaling [11], were completely destroyed by the explosive. The behavior seen in the ALE foam panels is unlike any physical experiments, and is dependent on the discretization of the Eulerian mesh.

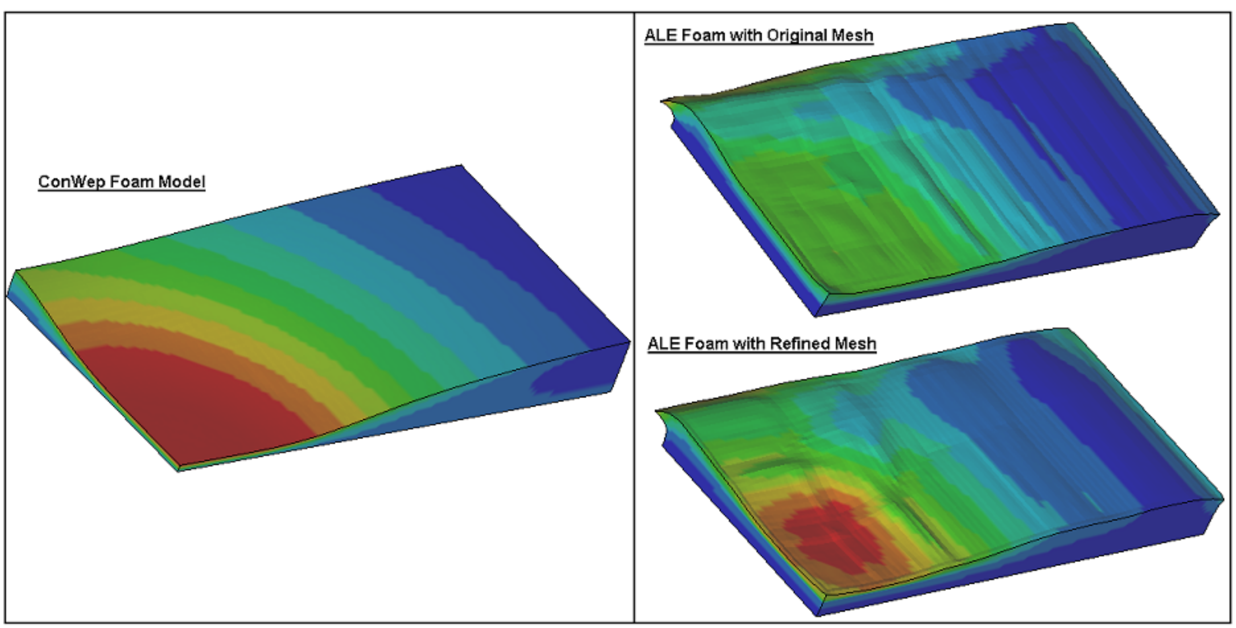

Figure 6: Y-Displacement Contours Of The Foam Panels At Maximum Deformation.

4. Comparing Models to Experiments

4.1 Modeling the Norwegian Ballistic Pendulum Experiment

It was desirable to compare the numerical simulations with a ballistic pendulum experiment. Hanssen's work [1] provided most of the details needed from his experiments to build a representative finite element model. Additional aluminum foam material properties not listed in Hannsen's work were supplemented from [8]. With ConWep as the blast loading method of choice, sleds were constructed in the same manner as described in section 2.1. The dimensions of the foam panel match those of Hanssen's. The rigid body support plate (red elements in Figure 7) is representative of the bare pendulum: the face area matches Hanssen's and the dimension in the y direction was chosen so that the density of the rigid body could be set to a value in the range of steel. Quarter symmetry conditions were utilized to reduce the size of the model.

Table 3: Material Properties Used To Match Experiments Performed By Hanssen [6].

Model	Material	LS-DYNA Cards (Units = cm, gm, microseconds)							
Norwegian BP		*MAT_RIGID							
	Rigid Body	RO	E	PR	N	COUPLE	M	CON1	CON2
		8.13666	2	0.3	0	0	0	6	7
		*MAT_HONEYCOMB							
	Al Foam [1,8]	RO	E	PR	SIGY	VF	MU	BULK	AOPT
		0.36	0.7	0.285	0.0024	0.3	0.05	0	0
		EAAU	EBBU	ECCU	GABU	GBCU	GCAU		
		2.48E-03	2.48E-03	2.48E-03	9.65E-04	9.65E-04	9.65E-04		
		*DEFINE_CURVE (STRESS VS. VOLUME STRAIN)							
		(STRAIN)	0.00E+00	7.00E-01	7.03E-01				
		(STRESS)	5.00E-05	5.00E-05	2.40E-03				
		*DEFINE_CURVE (SHEAR STRESS VS. VOLUME STRAIN)							
		(STRAIN)	0.00E+00	7.00E-01	7.03E-01				
		(STRESS)	1.90E-05	1.90E-05	9.34E-04				

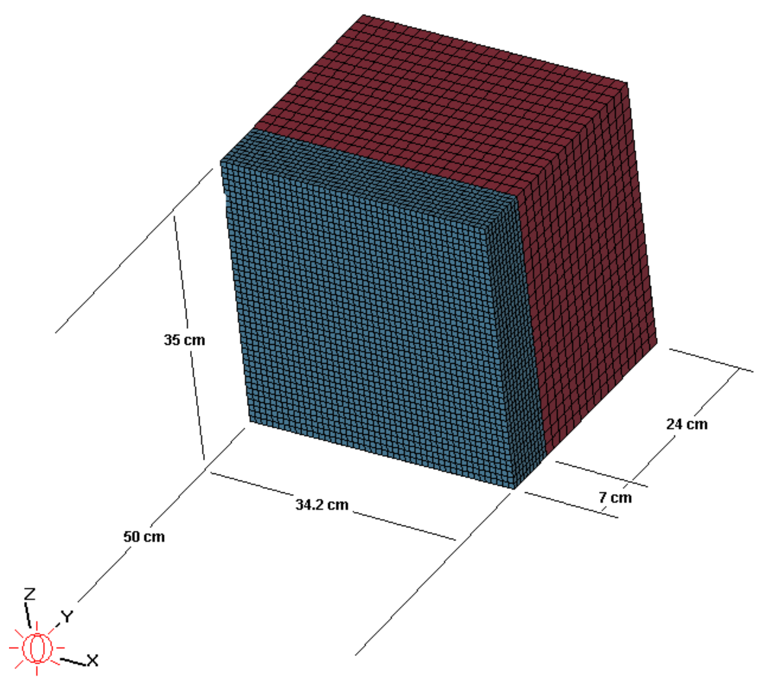

Figure 7: Discretization of Norwegian Foam Model NF-21160 Used To Compare Against Experiments. Foam elements (numbering 21,160) are shown in blue, rigid body elements (numbering 8,464) are displayed in red.

4.2 Comparison With Experiment

The rigid body model was originally run with no scale factor on the *LOAD_SEGMENT card. The model showed a 19% higher kinetic energy (KE) than the experiment, so the load curve was scaled down by a factor of 0.914 to match the experimentally measured KE. This factor was also used in the foam model. With the scaling factor, the rigid body model KE matches, but the foam model value is lower from the experimental foam model by about 25%.

The mesh of the foam model was refined until the maximum velocity was within 3% of the last refinement. The velocity curves of the Norwegian Rigid Body model (NRB) and Norwegian Foam Models (NF-#) can be seen in Figure 8. Here the number after "NF" is the number of foam elements used in the model. All elements in foam models NF-21160 and NF-169280 have 1:1:1 aspect ratios. Foam elements in NF-169280 were split in the y-direction to build model NF-338560 (2:1:2 aspect ratio).

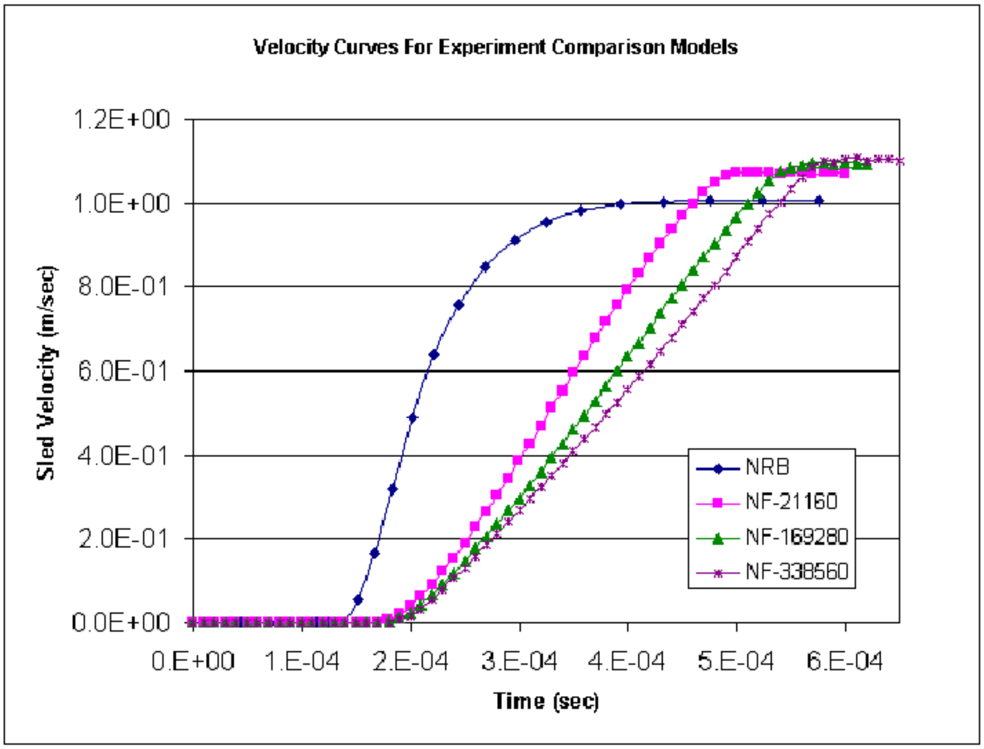

Figure 8: Velocity Curves For Experiment Comparison Models.

Table 4: Experiment And Model Results.

Model	Max Velocity (m/sec)	Mass (Kg)	KE (J)	% Diff (from Exp J [6])	Dishing (mm)	Time to Run (hours)
NRB	1.01E+00	9.35E+02	4.75E+02	0.12	N/A	0.0008
NF-21160	1.08E+00	9.47E+02	5.47E+02	15.46	29.54	0.0750
NF-169280	1.10E+00	9.47E+02	5.72E+02	20.70	36.18	0.8833
NF-338560	1.11E+00	9.47E+02	5.81E+02	22.48	33.03	2.1167
Experiment J [1]	N/A	9.35E+02	4.74E+02	0.00	N/A	N/A
Experiment G [1]	N/A	~9.47E+02	6.70E+02	41.35	13.50	N/A

Hanssen [1] reported a double curvature deformation pattern in the Al foam panels from the ballistic pendulum tests. Although the model predicts a higher amount of dishing than the experiments, the deformation pattern matches the double curvature behavior seen in the experiments (Figure 9). This pattern was not seen in the ALE results of the previous section.

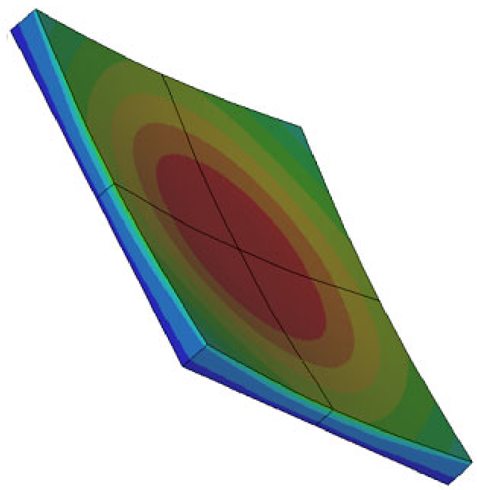

Figure 9: Y-Displacement Contours Of The Norwegian Ballistic Pendulum Model Under Maximum Deformation (Image Was Reflected About The Planes Of Symmetry).

5. Discussion

Although the maximum sled velocity is close between the original and refined Eulerian mesh models, the patterns in the foam deformation vary. Additionally, the foam in the ALE models deformed much differently from the ConWep models. The ALE deformation patterns imply that the results are highly dependent on the Eulerian mesh. A spherical Eulerian mesh may improve the deformation of the foam, because it will allow the pressure wave to propagate outward normal to the solid element faces in all directions. The foam mesh refinement on the Norwegian foam model was not performed on the models used in ConWep/ALE comparison section. Further refinement of these models may bring out more discrepancies between the blast loading methods.

The coupling between the Lagrangian and Eulerian meshes is problem specific. The LS-DYNA guidelines suggest two Eulerian elements to one Lagrangian element, which proved effective in these models. If that ratio is not possible, the number of quadrature points can be adjusted to improve the contact. The propagation of the pressure wave is more mesh dependent than the coupling between the Lagrangian and Eulerian elements.

The ConWep air blast function is a lot simpler than the ALE models, and produces results seen in physical experiments. Hanssen [1] attributed the increase in impulse transferred to the Al foam ballistic pendulum tests as a factor of the foam deformation. He theorized that the dishing seen in the foam panels caused a focusing or confinement of the blast. Originally it was felt that this would not be demonstrated with ConWep models because ConWep does not account for confinement. In the ConWep algorithm [3], LS-DYNA looks up tables of information to determine pressure for a given cube root scaling value (not time). The algorithm implements Friedlander's equation to find the rate of decay for the pressure. Friedlander's equation uses the current model time, time to arrival, and duration time along with a decay coefficient to calculate the drop in pressure over time. A possible explanation for the increase in KE seen in the ConWep foam models without accounting for confinement is that as the elements collapse, the orientation of the elements changes such that the angle of incidence is decreased (the faces become more normal to the blast). As the angle of incidence decreases, the reflected pressure on the element increases, resulting in an overall increase in impulse.

The foam in the Norwegian models show more dishing then the results from the experiments. This increase in dishing may be transferring more of the blast energy to internal energy (IE) instead of kinetic energy (KE). The loss of KE to IE helps explain the difference between model and experiment. The experiment cannot produce a value for how much energy was converted to internal energy from foam deformation. Additionally, the foam material properties were gathered from a couple of sources because a complete set of values was not provided by Hanssen. Hourglass control had to be implemented in NF-338560, which helps explain why NF-338560 dished more than NF-169280.

The conversion factor used to convert PE4 (used in the Norwegian ballistic pendulum experiments) to TNT was 1.043. Barker [12] explains in his results that the conversion of PE4 to a TNT equivalent is slightly on the conservative side. Barker's statement compliments the 0.914 scaling factor on the ConWep load curve needed to equate the KE of the Norwegian rigid body model to the experiment.

Kinetic energy was used to compare the results between models and experiments, but it is not the best factor for determining the Al foam's effectiveness of mitigating blast damage. Although the Norwegian foam models reached a higher maximum velocity than the rigid body models, the slope of the velocity curves (acceleration) of the sleds was reduced. This could be crucial to vehicle occupants whom are limited to certain amounts of acceleration for survivability. Additionally, the foam undergoes constant stress from yielding until the densification strain is reached. With the level of stress limited to the collapse strength of the foam until densification, if the foam panel is thick enough not to completely densify through the thickness, the structure behind it (at a higher yield strength) could be saved.

6. Conclusion

This paper compared two loading methods available in LS-DYNA: one using a Lagrangian model and the ConWep air blast function and the other using Arbitrary Lagrangian-Eulerian (ALE) coupling including the explosive material as part of the model. Additionally, a separate model using the ConWep air blast function compared simulation against ballistic pendulum experiments. Results showed ALE models as mesh dependent when coupled with deformable materials. ConWep models showed similar deformation patterns compared to experiments. With a scaling factor used to match the kinetic energy of the baseline models, the kinetic energy of the Norwegian foam model underpredicted and the dishing overpredicted the experiments. These discrepancies were related to more blast energy being converted to internal energy in the models than the experiments. From these results using common practice material properties, it is apparent that scaling factors will have to be determined for each experiment.

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