Modeling Blast Damage of Composite Structures

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Abstract

Blast loading on monolithic materials, sandwich structures, and composite flat plates and cylinders are investigated using LS-DYNA® blast loading function and the progressive composite damage model MAT162. Energy dissipating damage mechanisms, momentum transfer, resistance forces, accelerations, and dynamic displacements are analyzed to understand the blast resistance behavior of the flat plates and the cylinders.

Introduction

Explosions due to terrorism have been a global issue for quite some time. These explosions affect a multitude of people and structures causing irreparable loss of life and damage to structures worth of millions. Blast is a challenge not only to structures, both civilian and military, but also to scientists who are trying to model it and come up with a series of viable blast resistant solutions. In order to minimize the effects of blast loading on structures we need to understand the way structures respond to blast loading. There are several factors one must consider to develop structures which can withstand blast, such as energy dissipated by the structure, different stresses acting on the structure, failure modes associated with blast loading, etc. as a function of blast parameters, e.g., standoff distance (SoD), charge mass, and pre-blast boundary conditions (air blast, surface blast, and buried blast).

Different types of materials have been used for blast or impact mitigation, such as, fiber-reinforced composites, magneto-rheological fluids, porous materials, sandwich or lattice systems, foams, etc have been discussed at length [1]. Foams and sandwich structures have attracted the attention of many researchers as they have light weight, some energy dissipation and load bearing capacity. A Sandwich structure consists of a core with face sheets either on top and bottom sides. The core can be either balsa wood, polymeric foam or metal foam. Metal foams are better suited for conditions where the temperatures are high; and moisture may be involved. The face sheets can be from paper, ply wood, metal plates, and composites. In order to test the effects of blast loading on sandwich structures, a test setup was devised [2], which consists of a foam panel with or without the exterior face sheet attached to the bob of the pendulum and an explosive charge was located at a given standoff distance. The test was conducted with different configurations, such as variable density of the aluminum foam, variable mass of the charge with or without exterior face sheet. The effect of these combinations was evaluated by measuring and comparing the maximum swing distance in each test, which was used to determine the energy and impulse transfer from the loading. One important observation

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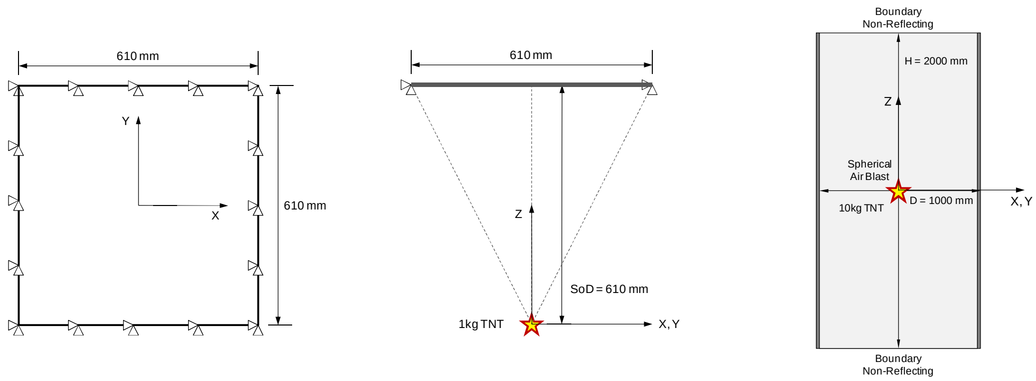
from the results are that an increase in the energy transfer by adding a cover plate was found higher for a low foam density than a high density foam. The important conclusions are that using foam for blast mitigation leads to local protection of the structure due to control of contact stresses. However, due to the conservation of momentum, the use of sacrificial layer doesn't affect the impulse transferred [2].

These results were similar to another research where the honeycomb strength showed a moderate effect on the pendulum system. The reduction of shear stresses with proper strength selection of honeycomb was confirmed [3]. There has been other experimental testing with aluminum alloy honeycomb core and mild steel face sheets where a disc of explosive is detonated very close to the surface of the sandwich structure. It was found that sandwich structures respond better to uniform loading than localized loading. The mode of failure depending on impulse magnitude, and were found to be micro-buckling, crushing and global bending of the core. At an impulse of 20 N-s, the displacement of the back plate was found to be less for foam core sandwich than an air core [4]. Finite element simulations with an aluminum foam core and mild steel face sheets showed that the load transfer to the back plate of the panel depends on the load intensity, core thickness and flexibility of the sandwich panels [5]. Some analytical treatment of the blast problem can also be found [6-9].

From literature, we find that a fixed mass explosion applies an impulse loading on the structure as a function of the SoD and the angle of incidence. The structure gains energy and momentum from the impulse loading. The blast resistance or the blast mitigation capacity of a structure can be quantified by the ability of the structure in dissipating energy and withstanding the momentum. An ideal blast resistant structure should maximize the energy dissipation without catastrophic failure. In this study, we will present the blast performance of different structures under similar blast loading and boundary conditions; such as energy dissipation capacities, momentum gained, maximum acceleration, displacement, and different forces.

Definition of Blast Problems

We will consider two problems, i.e., (i) the blast loading of flat plates from a standoff distance, and (ii) the blast loading inside a cylinder. The flat plate under blast loading consists of a square plate of dimension 610-mm x 610-mm with an aerial-density of 48.8 kg/m^2 (10psf) with fixed boundary conditions on all sides (Fig. 1a). The standoff distance of 1-kg TNT equivalent from the flat plate is 610-mm from the epicenter of the explosion to the bottom face of the plate (Fig. 1b). In order to eliminate the effect of boundary conditions, we will also study the blast loading inside an infinitely long cylinder (Fig. 1c). The diameter, and length of the cylinder geometry are taken as D = 1000-mm and H = 2000-mm, respectively, with non-reflecting boundary conditions at the cylinder edges. The areal-density of the cylinder is also taken as 48.8 kg/m^2 (10psf). The effect of material properties and sandwich architecture on blast performance is investigated.



(a) Plate with BCs (b) Blast and SoD (c) Blast Inside a Cylinder

Figure 1: Spherical Air Blast on Flat Plate and Cylinder.

Different flat plate architecture considered are: (i) a monolithic aluminum plate (Baseline, ID = Al Only, Thickness, h = 18.1-mm), (ii) an aluminum/al-foam/aluminum symmetric sandwich (ID = 2-2, h = 43.4-mm), (iii) two asymmetric aluminum/al-foam/aluminum sandwich (IDs = 1-3, & 3-1, h = 43.4-mm), (iv) two sandwich with only one face sheet (IDs = 0-4, & 4-0, h = 43.4-mm), (v) al-foam only (h = 68.8-mm) and (vi) monolithic composite (h = 26.4-mm). Densities of the aluminum, the al-foam, and the composites are taken as ρ_a = 2700 kg/m^2 and ρ_f = 710 kg/m^2, and ρ_c = 1850 kg/m^2, respectively. Thickness of each components are calculated from the areal-density, AD = ρh. Table 1 presents different plate architecture studied. Three different cylinder geometries (including the baseline monolithic aluminum) are investigated following a reduced test matrix, and is presented in Table 2.

Table 1: Flat Plate and Sandwich Architecture

			Areal Density, AD = 48.8 kg/m^2			
ID	**Description**	**Architecture**	**Top Face Sheet**	**Core**	**Bottom Face Sheet**	**Thickness, mm**
Al Only	Baseline Aluminum		-	-	-	18.1
2-2	Al/Al-Foam/Al		12.2	24.4	12.2	43.4
1-3	Al/Al-Foam/Al		6.1	24.4	18.3	43.4
3-1	Al/Al-Foam/Al		18.3	24.4	6.1	43.4
0-4	Al/Al-Foam/Al		0	24.4	24.4	43.4
4-0	Al/Al-Foam/Al		24.4	24.4	-	43.4
Foam Only	Al-Foam		-	48.8	-	68.8
Comp.	Composite		-	-	-	26.4

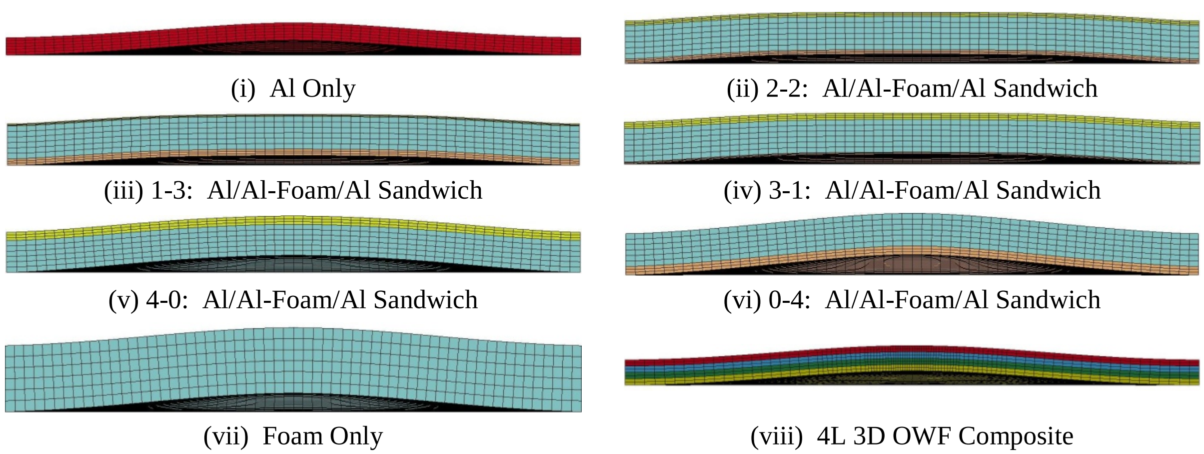
Table 2: Cylinder and Sandwich Cylinder Architecture

			Areal Density, AD = 48.8 kg/m^2			
ID	**Description**	**Architecture**	**Top Face Sheet**	**Core**	**Bottom Face Sheet**	**Thickness, mm**
Al Only	Baseline Aluminum		-	-	-	17.4
2-2	Al/Al-Foam/Al		12.2	24.4	12.2	40.8
Comp.	Composite		-	-	-	25.2

Finite Element Model and Blast Conditions

A finite element model (FEM) of the aluminum plate is developed using 60 x 60 x 6 = 21,600 solid elements, while the sandwich plates are modeled using 60 x 60 x (3+6+3) = 43,200 elements. The composite plate is modeled using four layers of 3D orthogonal weave fabric (OWF) composite with eight through-thickness and a total of 37,376 elements. Perfectly clamped boundary conditions are applied on the edge nodes. The interfaces between different layers of the flat plate/sandwich are considered perfectly bonded. A segment surface in the bottom face of the plate is defined to apply blast load using the CONWEP blast function, *LOAD_BLAST_ENHANCED. The cylinders are modeled using similar mesh densities, except non-reflecting boundary conditions are applied at the edges of the cylinders. Figure 1 shows the geometric axis and blast epicenters for both the flat plates and the cylinders.

Blast loading of 1-kg TNT at an SoD = 610-mm is applied on the flat plates and sandwich structures, while a blast load of 10-kg TNT is placed at the center of the cylinder. Figure 2 shows the mesh and maximum dynamic deformation of all flat plate and sandwich cases studied.



(i) Al Only

(ii) 2-2: Al/Al-Foam/Al Sandwich

(iii) 1-3: Al/Al-Foam/Al Sandwich

(iv) 3-1: Al/Al-Foam/Al Sandwich

(v) 4-0: Al/Al-Foam/Al Sandwich

(vi) 0-4: Al/Al-Foam/Al Sandwich

(vii) Foam Only

(viii) 4L 3D OWF Composite

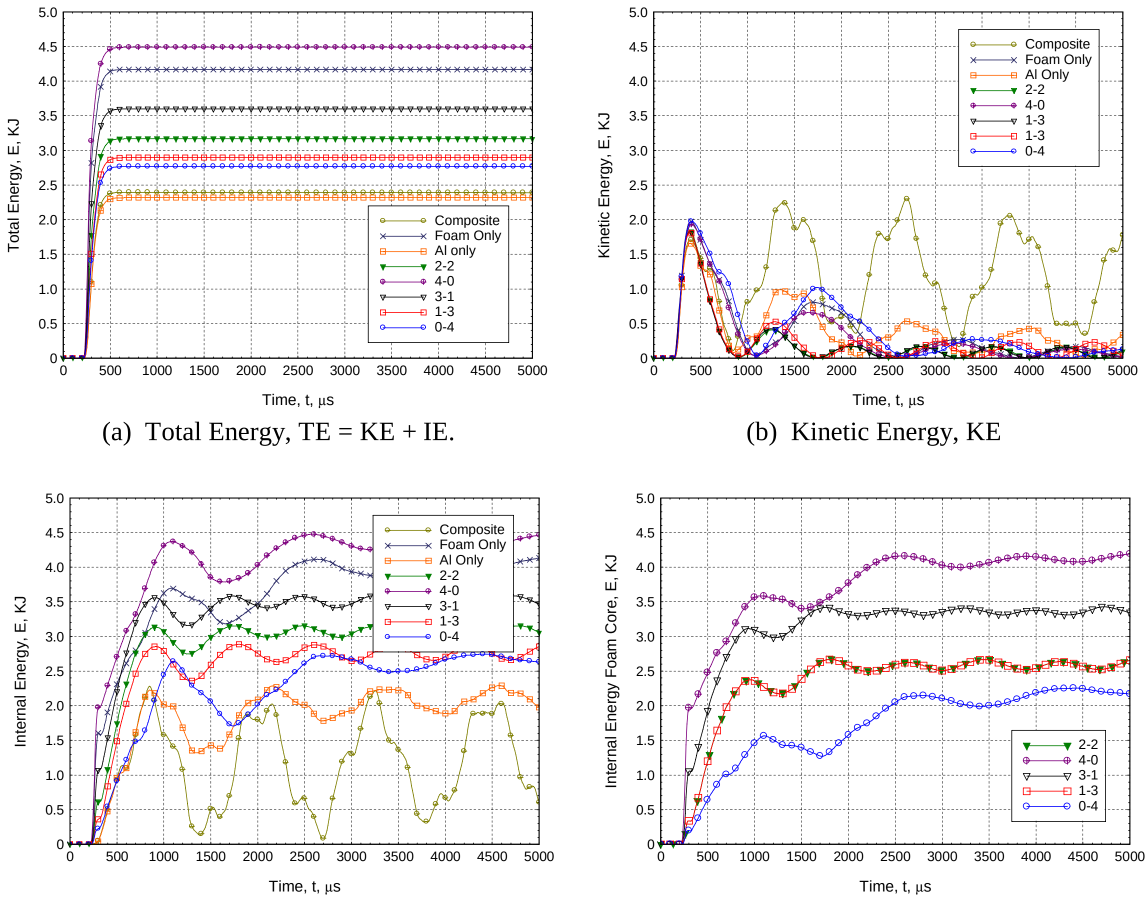
Figure 2: Maximum Dynamic Deflection of Different Geometric Architecture of Flat Plates.

The aluminum, the al-foam, and the composite materials are modeled with (i) elastic-plastic, (ii) honeycomb, and (iii) composite damage material models, respectively. The specific material properties are presented in Appendix A. LS-Dyna 971 is used for all computational simulations for a total duration of 5000 microseconds.

Results and Discussion

The global energies of the FEM have been checked for negligible hourglass energies, and is compared with the material energies. The global and material energy statistics are found to be consistent. The total energy of the system is found be the sum of kinetic and internal energies.

$$TE = KE + IE \tag{1}$$



(a) Total Energy, TE = KE + IE.

(b) Kinetic Energy, KE

(c) Internal Energy, IE

(d) IE of Foam Core

Figure 3: Energy Statistics for Blast Loading of Different Flat Plate/Sandwich Structures.

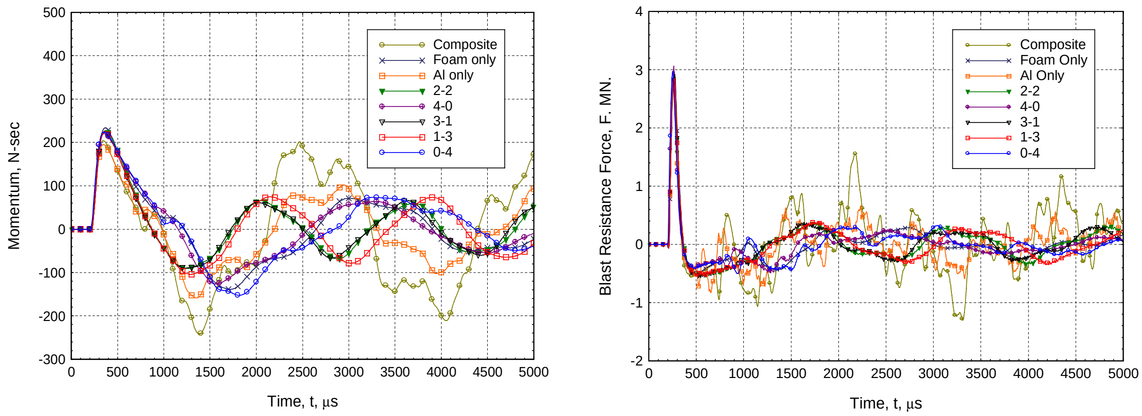
Figure 3(a-c) shows the total energies, kinetic energies, and internal energies of all flat plates studied, and Figure 3d shows the internal energies of the al-foam in the sandwich structures. It is interesting to note that the total energy transferred from the same blast loading to the Al/Al-Foam sandwiches is higher than that transferred to the Baseline Aluminum plate and composite plate. The time history of KE for all plates and sandwiches are more or less same except the composite plate. In fact, the energy transferred to the composites plate is stored in the plate as a sum of the elastic strain energy and kinetic energy with almost zero energy dissipation. On the other hand, huge amount of internal energy of the al-foam core is dissipated by plastic work.

These observations led to a general question, "How does energy dissipation by the materials relates with the blast resistance of the structure?"

The Z-momentum of each flat plate/sandwich configurations is presented in Fig. 4a. We know that time rate of change of momentum is force.

$$F = \frac{d(mv)}{dt} \tag{2}$$

The Z-momentum of Fig. 4a is differentiated with respect to time to calculate the Blast Resistance Force, and is presented in Fig. 4b. Figs. 4a and 4b show that both the Z-momentum and Forces on the flat plates/sandwiches are similar in the time range 0 to 500 microseconds, and is oscillatory after that due to the post-blast vibration of the structure.

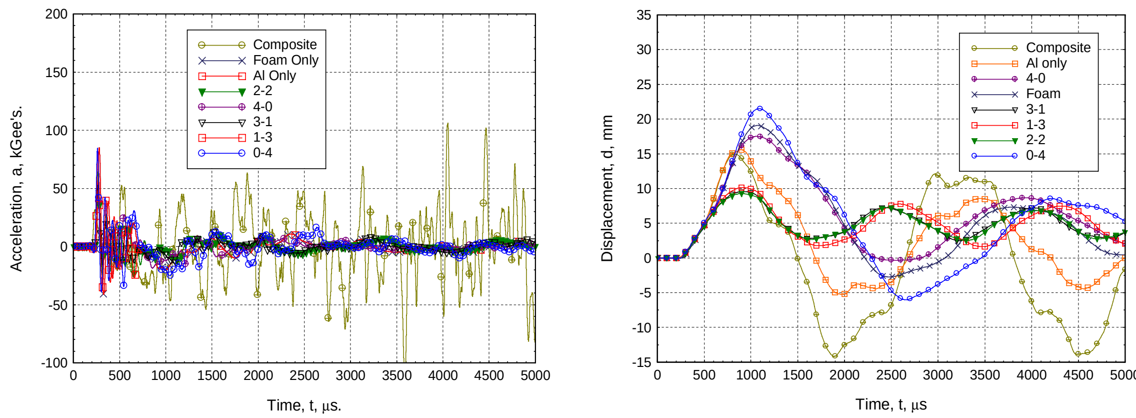


(a) Z-Momentum (b) Z-Blast Resistance Force

Figure 4: Momentum and Resistance Forces of Different Flat Plate/Sandwich Structures.

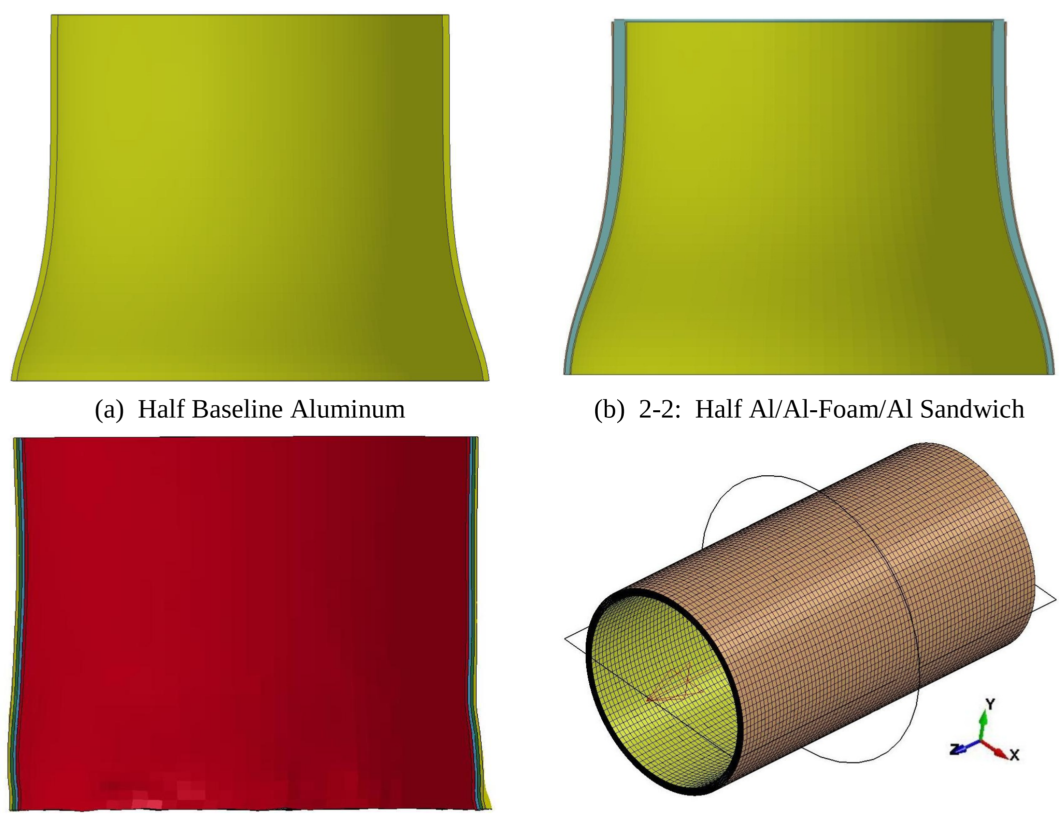
Thus for a fixed mass explosive, the early momentum transferred to a flat structure (plate and sandwich) and the resistance force on the structure are identical for different structural architectures, however, the energy dissipated is not. Furthermore, we present the acceleration and displacement at the center of the plate on the opposite side of the blast load in Fig. 5. For the 2-2 Al/Al-Foam/Al sandwich structure, both the acceleration and displacement were found to be minimum. Lower acceleration and dynamic deflection are good attributes for structures under blast, however, the mechanisms which can reduce the acceleration and dynamic deflection remains undetermined. Since the boundary conditions are fixed in case of the flat plates, it is also not obvious the role of the boundary conditions. The blast response of cylinders with non-reflecting boundary conditions are presented next.

Figs. 6(a-c) show the dynamic deformation of (i) the baseline aluminum cylinder, (ii) the Al/Al-Foam/Al sandwich cylinder , and (iii) the composite cylinder. Fig. 6c shows two section planes defined at Y = 0 (Radial), and at Z = 0 (Axial) to study the section forces.



(a) Acceleration (b) Displacement

Figure 5: Acceleration and Displacement at a Point of Different Flat Plate/Sandwich Structures.

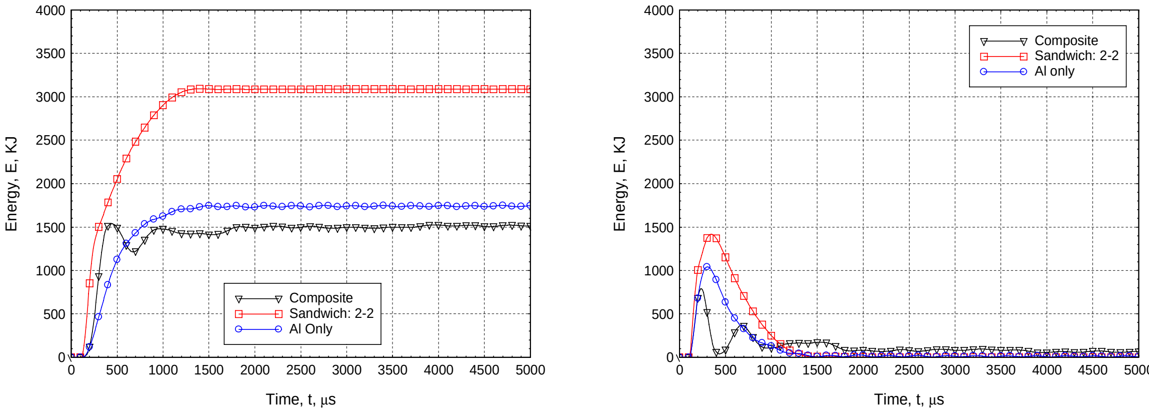


(a) Half Baseline Aluminum (b) 2-2: Half Al/Al-Foam/Al Sandwich

(c) Half Composite Cylinder (d) Full Cylinder with Section Planes

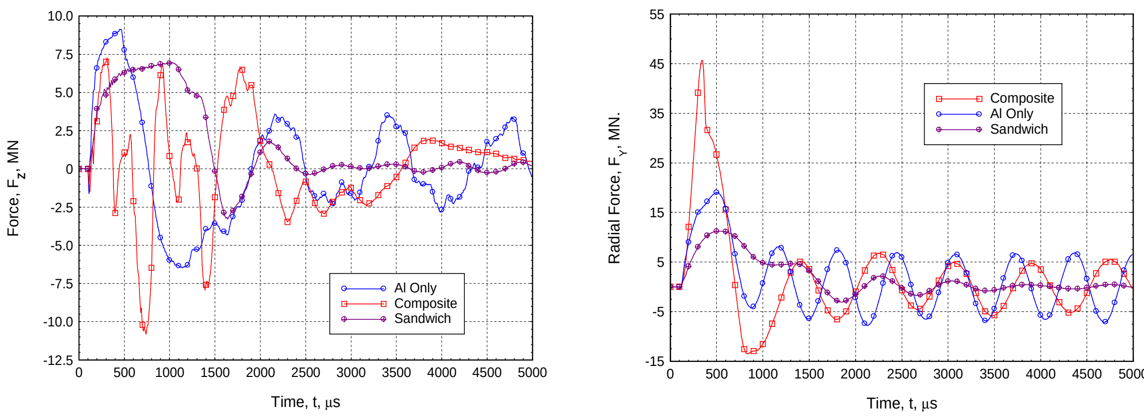
Figure 6: Dynamic Deformation of Different Cylinders and Section Planes.

The IE and KE of the cylinders are presented in Fig. 7. Results obtained for cylinders are similar to the flat plates/sandwich load cases. The cross section forces in the Axial and Radial directions are presented in Fig. 8. Further analyses of results will be discussed during presentation.



(a) Internal Energies (b) Kinetic Energies

Figure 7: Energy Statistics for Blast Loading of Different Cylinders.



(a) Axial Force, FZ. (b) Radial Force, FY.

Figure 8: Cross Sectional Forces of the Cylinder under Internal Blast.

Summary

Blast loading on flat plates and cylinder made from monolithic materials, sandwich, and composites are analyzed to study the energy dissipating damage modes, blast resistance forces, momentum, acceleration, and dynamic displacement. Energy dissipated by sandwich structures are found to be higher than the monolithic aluminum and composites. The research is in progress, and further results will be reported elsewhere.

References

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Appendix A

MATERIAL PROPERTIES: Unit System - gm-cm-microsec-1e7N-Mega Bar

Table A.1. Aluminum

```
$--------+---------+---------+---------+---------+---------+---------+---------+
*MAT_PLASTIC_KINEMATIC_TITLE
$--------+---------+---------+---------+---------+---------+---------+---------+
Aluminum
$--------+---------+---------+---------+---------+---------+---------+---------+
$#     mid        ro         e        pr      sigy      etan      beta
       100      2.70   0.69000     0.285   0.00265   0.00100       0.0
$#     src       srp        fs        vp
     0.000     0.000      4.00     0.000
$--------+---------+---------+---------+---------+---------+---------+---------+
```

Table A.2. Aluminum Foam

```
$---------+---------+---------+---------+---------+---------+---------+---------+
*MAT_HONEYCOMB_TITLE
$---------+---------+---------+---------+---------+---------+---------+---------+
Aluminum Foam
$---------+---------+---------+---------+---------+---------+---------+---------+
$#     mid        ro         e        pr      sigy        vf        mu      bulk
       400  0.710000  0.690000  0.285000  0.002650  0.263000
$#     lca       lcb       lcc       lcs      lcab      lcbc      lcca      lcsr
      5000      5000      5000      6000
$#    eaau      ebbu      eccu      gabu      gbcu      gcau      aopt      macf
   0.00200   0.00200   0.00200   0.00080   0.00080   0.00080     0.000         1
$#      xp        yp        zp        a1        a2        a3
     0.000     0.000     0.000     0.000     0.000     0.000
$#      d1        d2        d3      tsef      ssef
     0.000     0.000     0.000  0.800000  0.800000
$---------+---------+---------+---------+---------+---------+---------+---------+
*DEFINE_CURVE
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$     lcid      sidr       sfa       sfo      offa      offo    dattyp
      5000         0      1.00   0.00001
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$                   a1                  o1
                 -0.10               10.00
                  0.00               10.00
                  0.05               10.00
                  0.10               12.00
                  0.20               15.00
                  0.30               20.00
                  0.40               25.00
                  0.50               34.00
                  0.55               40.00
                  0.60               47.00
                  0.65               60.00
                  0.70               78.00
                  0.80              125.00
                  0.90              200.00
                  0.99              300.00
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
*DEFINE_CURVE
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$     lcid      sidr       sfa       sfo      offa      offo    dattyp
      6000         0      1.00  0.000005
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
$                   a1                  o1
                 -0.10               10.00
                  0.00               10.00
                  0.05               10.00
                  0.10               12.00
                  0.20               15.00
                  0.30               20.00
                  0.40               25.00
                  0.50               34.00
                  0.55               40.00
                  0.60               47.00
                  0.65               60.00
                  0.70               78.00
                  0.80              125.00
                  0.90              200.00
                  0.99              300.00
$---+----1----+----2----+----3----+----4----+----5----+----6----+----7----+----8
```

Table A.3. 3D OWF Composite

```
$---------+---------+---------+---------+---------+---------+---------+---------+
*MAT_COMPOSITE_DMG_MSC_TITLE
$---------+---------+---------+---------+---------+---------+---------+---------+
S-2 Glass/SC-15 0 Layer
$---------+---------+---------+---------+---------+---------+---------+---------+
$#     mid        ro        ea        eb        ec      prba      prca      prcb
       162      1.85     0.275     0.275     0.118     0.110     0.180     0.180
$#     gab       gbc       gca      aopt      macf
     0.029    0.0214    0.0214       2.0         0
$#      xp        yp        zp        a1        a2        a3
     0.000     0.000     0.000     1.000     0.000     0.000
$#      v1        v2        v3        d1        d2        d3      beta
     0.000     0.000     0.000     0.000     1.000     0.000     00.00
$#     sat       sac       sbt       sbc       sct       sfc       sfs       sab
   0.00604   0.00291   0.00604   0.00291   0.00058   0.00868   0.00300   0.00075
$#     sbc       sca      sffc    amodel      phic    e_limt    s_delm
   0.00058   0.00058     0.300       2.0      10.0     0.200      1.20
$#   omgmx     ecrsh     eexpn   cr1/sig   am1/fda
   0.99800     0.001     4.500     0.030      2.00
$# am2/fdb am3/sfc/s am4/mc/de cr2/ea/eb     cr3/g    cr4/ec
      2.00      0.50      0.30     0.000     0.030     0.030
$---------+---------+---------+---------+---------+---------+---------+---------+
```