Blast Impact on Aluminum Foam Composite Sandwich Panels

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Abstract

*Sandwich aluminum foam structures are being considered for energy absorption applications, crashworthiness, protection of transformer housings, and structural safety. Blast loading is one such phenomenon that is a potential threat to such structures. This study examines LS-DYNA modeling for aluminum foam sandwich composites subjected to blast loads. The sandwich composite was designed using polymer composite facesheets and aluminum foam as core. The core was modeled using material model 126 (*MAT_MODIFIED_HONEYCOMB). The facesheets were modeled using material model 59 (*MAT_COMPOSITE_FAILURE_SOLID_MODEL) and material model 161 (*MAT_COMPOSITE_MSE). 1 point corotational solid element formulation was used for the core and constant stress solid element formulation was used for the facesheets. LS-DYNA implementation of CONWEP blast equations (*LOAD_BLAST) was used to apply the blast load. The box design was evaluated using simulation and iterated until similar performance was achieved. The results were used to predict the modes of failure and energy absorption phenomenon. The simulation was also performed for different dimensions of box having different curvatures. The paper discusses details of the LS-DYNA simulation work and the parametric studies for the aluminum foam sandwich constructions.*

Introduction

Blast loading is not just related to military structures but also to civilian structures. The design of energy-absorbing structures has become increasingly important in recent years. Aluminum foam structures are being considered for energy absorbing applications for events such as blast. Aluminum foams have high stiffness and yield strength at low density as mentioned by Asbhy (2000). They have high compressive strains at constant stress which impart high energy absorption capacity. An overview of thermomechanical properties of metal foams has been provided by Evans (1999). The overview examined the design implementation of metal foams for impact/blast amelioration. The porous nature of the foams helps in heat dissipation and provides acoustic damping.

The experimental verification on blast of aluminum foam was done by Hanssen (2002). The experimental results were compared with analytical and simulated model. The simulation was done using LS-DYNA. It was observed that the energy transfer increased by addition of a cover plate for low density foam compared to high density foam. The foam with a cover plate was found to be more effective for sustaining high blast loads. The cover plate concept is exploited in the design of sandwich composite for blast loading. Hutchinson (2003) compared the effect of blast loads on metal sandwich plates with those of solid plates of the same material. Three types of core geometries were analyzed: pyramidal truss, square honeycomb, and folded (or corrugated) plate. It was found that all three types of cores were able to sustain higher loads compared to a solid plate of equal mass.

The impact resistance and energy absorption property of aluminum foam sandwich composite with laminated facesheets was done by Vaidya (2003). It was found that energy absorption and failure strongly depended on the type and property of facesheets e.g. S2-glass, Kevlar, carbon and E-glass. The aluminum foam/laminated sandwich composites used in the analysis were produced by Vacuum Assisted Resin Transfer Molding (VARTM) process. In the present work an effort has been made to simulate the effect of blast on an aluminum foam sandwich composite structure. The blast load was applied using the *LOAD_BLAST card. The simulation was done on a sandwich composite plate model and on a box made of sandwich composite. This paper reports only results pertaining to the sandwich plate.

Blast Load

Blast is a condition of extraordinary dynamic load. The analytical modeling of blast has been done by Kingery (1984) and Beshara (1994). The incident portion of the blast wave is called the "shock front". When the shock wave of an air burst leaves the point of explosion, it travels as an incident wave until it strikes some object. Upon striking the object, a reflected wave is generated which travels back towards the point of explosion. At a point, some distance from the explosion centre, the reflected wave catches up with the incident wave, producing a single vertical wave front called "Mach Stem". Structures below the point of intersection of the reflected wave and the incident wave will experience a single shock whereas surfaces or objects above this point will experience a shock which is resultant of the incident and reflected waves. At a reasonable distance from the center of the explosion, blast waves from any explosive source, have the same behavior. The pressure time of blast wave is shown in Fig.1. The pressure jumps to a peak value of the overpressure (P_o). The pressure then decays to ambient in time (t_s), to a partial vacuum of very small amplitude and eventually returns to (P_o). The portion of the pressure-time history below zero is called the negative of the "suction phase" and the portion above zero is called the "positive phase". In most blast studies the negative phase of the blast wave is ignored, and only the parameters associated with the positive phase are considered.

In the positive phase the pressure at any time t is described in terms of the peak overpressure (P_s), dimensionless wave form parameter (α), and positive phase duration time (t_0). The relation is established as

$$t_o \geq t \geq 0 \qquad P(t) = \frac{t}{t_o} P_s \tag{1}$$

$$t \geq t_o \qquad P(t) = P_s \left(1 - \frac{t}{t_o}\right) e^{-\alpha \frac{t}{t_o}} \tag{2}$$

The equations used in the *LOAD_BLAST card are similar. The *LOAD_BLAST is based on the implementation of Randers-Pehrson and Bannister (1997). It is a convenient means of applying blast load to structures. The implementation fits the blast data obtained by Kingery (1984). The equation takes into consideration the angle of incidence of blast (θ), reflected pressure (P_{ref}), and the incident pressure (P_{in}).

$$P(t) = P_{ref} \times \cos^2\theta + P_{in} \times \left(1 + \cos^2\theta - 2\cos\theta\right) \tag{3}$$

The reflected pressure (P_{ref}) is expressed in terms of a decay coefficient (a) of reflected pressure and peak reflected overpressure (P_{ro}). The incident pressure (P_{in}) is expressed in terms of decay coefficient (b) of incident pressure and peak incident overpressure (P_{so}) exponential decay. The equations for positive phase duration time t_0 are given below.

$$P_{ref} = P_{ro}\left(1-\frac{t}{t_0}\right)e^{-a\frac{t}{t_o}} \qquad (4)$$

$$P_{in} = P_{so}\left(1-\frac{t}{t_0}\right)e^{-b\frac{t}{t_o}} \qquad (5)$$

The model uses the following inputs to calculate the pressure

- Weight: equivalent mass of Tri Nitro Toluene (TNT).
- Coordinates of the point of explosion.
- Delay time between when the LS-DYNA solution starts and the instant of explosion.

The model accounts for the angle of incidence (θ) of the blast wave, but it does not account for shadowing by the intervening objects or for the confinement effects.

Failure Modes in Sandwich Composite

Sandwich beams can fail by several modes: face yielding, face wrinkling, core yield, indentation and delamination. The sandwich panel design criteria and failure modes with aluminum foam cores have been analyzed by McCormack (2001) and Fleck (2000). The analysis was made under the assumption that there is perfect bonding between the facesheets and core. The analysis was verified with experimental results. According to the analysis, the facesheets carry the bending moment as longitudinal tensile and compressive stresses. The core carries the transverse shear force. The facesheets begin to yield when the maximum normal stress acting in them reaches the yield stress of the facesheet material. Facesheet wrinkles when the normal stress reaches the local elastic instability stress.

In the elastic regime of the core, the stress in the core is a superposition of constant shear stress τ_{core} and normal stress σ_{core}. If the shear stress is very large than the normal stress then the core can be considered to be in shear, otherwise the multiaxial stress in the core has to be considered. It was found by Ashby (2000) that there can be two different modes of failure for the core. The indentation in the foam occurs when the loading point crushes the foam and bending the facesheet to accommodate the foam deformation.

The facesheet is a laminated composite. The damage modes in a laminated composite are matrix tensile cracking, matrix compressive/shear failure, ply separation (delamination), and fiber breakage (tensile or compressive). Hashin (1980) developed the progressive layer failure criteria for unidirectional composite layer. The failure criterion of unidirectional composite layer was extended to a three-dimensional (3-D) composite layer and the effect of blast loading was analyzed by Yen (1998).

Blast Impact Simulation

The sandwich composite plate was fixed at all ends and was subjected to transverse loading. In the case of transverse loading, the angle of incidence of blast (θ) is 0^0 $(\cos\theta = 1)$ and the equation of the pressure reduces to the following equation.

$$P(t) = P_{ref} + P_{in} \qquad (6)$$

The preliminary model was generated using the preprocessor within LS-DYNA. The *LOAD_BLAST card was incorporated in the input LS-DYNA file using the text editor. Air blast was used in the simulation because the aim was to study the effect of incident and reflected wave. In the preliminary case, 1 kg of TNT blast was used to study the effect of the blast. 1 kg of TNT produces a pressure pulse of 5 MPa. It can be observed in the simulation that the maximum pressure produced at time $t = 0.53$ ms is 4.99 MPa.

Blast Impact on Foam Plate

The aluminum foam was modeled using material model 126 (MAT MODIFIED HONEYCOMB) with 1 point corotational solid element formulation (element formulation 9). The example in the CYMAT technical manual was used to study the effect of blast on the constituent aluminum foam. The material property of the aluminum foam used in the simulation is given in the Appendix A. The simulation was performed on a foam plate of dimension 1 m * 1 m * 0.015 m and a steel buffer plate of density (7877 kg/m^3) of dimension 1 m *1 m* 0.005 m. The foam plate of the above mentioned dimension is used to protect structures which can withstand a pressure of 0.3 MPa. The foam plate was modeled using 7500 brick elements and the steel plate was modeled using 2500 brick elements. The plate was restricted for all degrees of freedom in the corners. The front side is the side which is exposed to the blast load. It can be observed that the stress developed in the side which is exposed to the blast load is around 0.46 MPa (Fig. 2a), whereas on the back side of the foam plate the stress developed is 0.09 MPa (Fig. 2b). It can be seen that the stress acts at the middle of the plate, and then the spherical wave front moves outwards.

Blast Impact on Laminate Composite

The laminated composite was modeled using material model 161 (MAT COMPOSITE MSE) with constant stress solid element formulation (element formulation 1). The material used for the simulation was S2-glass/epoxy composite. The material property was obtained from the work of Yen (2003). The material property is listed in Appendix A. The simulation was performed on two laminate plates each of dimension 1 m* 1 m* 0.0015 m. Each plate was modeled using 1225 brick elements. ERODING_SINGLE_SURFACE contact interface was defined between the laminate plates. The plate was restricted for all degrees of freedom in the corners. When the plate was exposed to a blast load of 5 MPa, it was observed that the plate undergoes buckling (Fig. 3). The failure modes in the laminate composite were analyzed in the LS-POST post processor using the appropriate history variables. The tensile/shear and compression failure was observed in the fibers, and some matrix failure was also observed. When the buckling increased, the elements started to fail and erosion of elements was observed. After erosion of elements, delamination occurred between the matrix and fibers.

Blast Impact on Sandwich Composite Panel

The composite face sheets were modeled using material model 161 (MAT COMPOSITE MSE). 1 point corotational solid element formulation (element formulation 9) was used for the aluminum foam core and constant stress solid element formulation (element formulation 1) was used for the S2-glass/epoxy laminate facesheets. The core was simulated with two facesheets on each side. The dimension of the core was 0.25 m*0.25 m*0.015 m and the dimension of the facesheet was 0.25 m*0.25 m*0.0015 m. The sandwich plate was restricted for all degrees of freedom along the corners. The front side was exposed to the blast load. ERODING_SINGLE_SURFACE contact interface was used between the facesheets and ERODING_SURFACE_TO_SURFACE was used between the facesheet and the core. It was observed that the plate undergoes oscillations when subjected to high blast loads.

The sandwich plate with two facesheets failed because of core failure. The shear strain (γ_f) and tensile strain (ε_f) to failure of the aluminum foam used in the simulation was 0.002. These values were obtained from CYMAT technical manual. The core failure was catastrophic for a pressure of 5 MPa. The failure modes in the facesheets were analyzed using the LS-POST post processor. The matrix failure was observed in the facesheet. However when ε_f and γ_f was increased to 0.2, the sandwich plate was able to sustain a load of 10 MPa. But when the load was increased to around 13 MPa the core started to fail (Fig. 4). Figure 5 in the Appendix A provides the compression properties of the foam; it can be seen that foam has high densification strains (0.72) in compression.

The observed trend can be justified following the analysis of McCormack (2000) and Fleck (2000). According to them the core in the sandwich composite is subjected to transverse shear force in case of bending. So the core should have high shear strain to failure. As the shear strain is very low (0.002), the aluminum foam core fails. It has been observed that ε_f and γ_f is dependant on the relative density of the foam. In the present analysis 15% relative density foam was used which implies that foam has 15% aluminum and 85% air. However the present LS-DYNA model has to be verified with experimental and analytical results.

Material model 59 (MAT_COMPOSITE_FAILURE_SOLID_MODEL) was also used for the facesheet, but the failure modes cannot be predicted using the proper history (post processing) variables unlike material model 161. Material model 161 has the flexibility of defining layer in plane rotational angle (like whether the orientation of fibers in laminate composite is in the 0/90 direction). The direction of the fibers is not an input to the material model 59.

Summary

Blast loading on aluminum foam sandwich composite was simulated using *LOAD_BLAST card. The *LOAD_BLAST card is a convenient way for application of blast load. It considers the effect of incident pressure and reflected pressure in the blast loading condition. The similarity between the usual blast loading equation and the governing equation in the blast card has been illustrated. It was qualitatively illustrated that when the composite undergoes bending, the failure is dominated by shear strain. The failure in the composite with CYMAT aluminum foam sandwich composite is dominated by the core failure and the matrix failure which occurs in the laminate. Future studies will take into consideration blast effects on transformer box pads made of sandwich composites.

Acknowledgements

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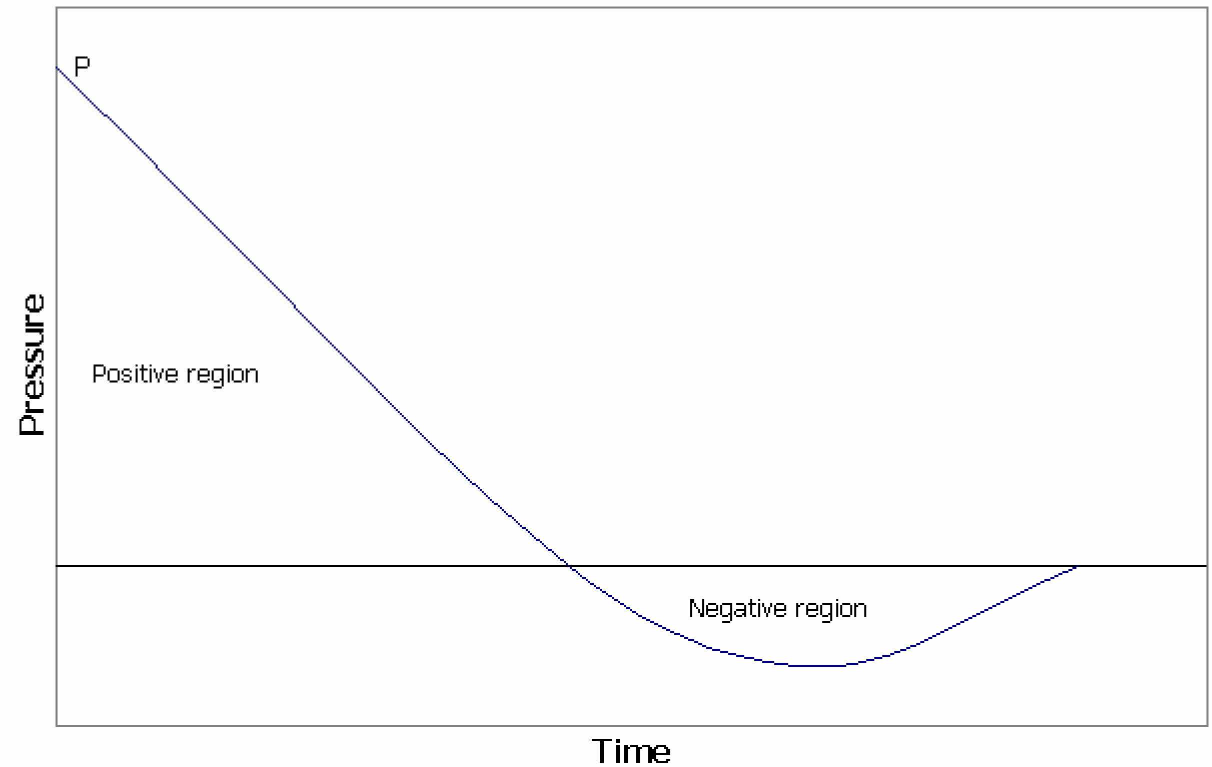

Figure 1. Pressure-time curve of a blast wave

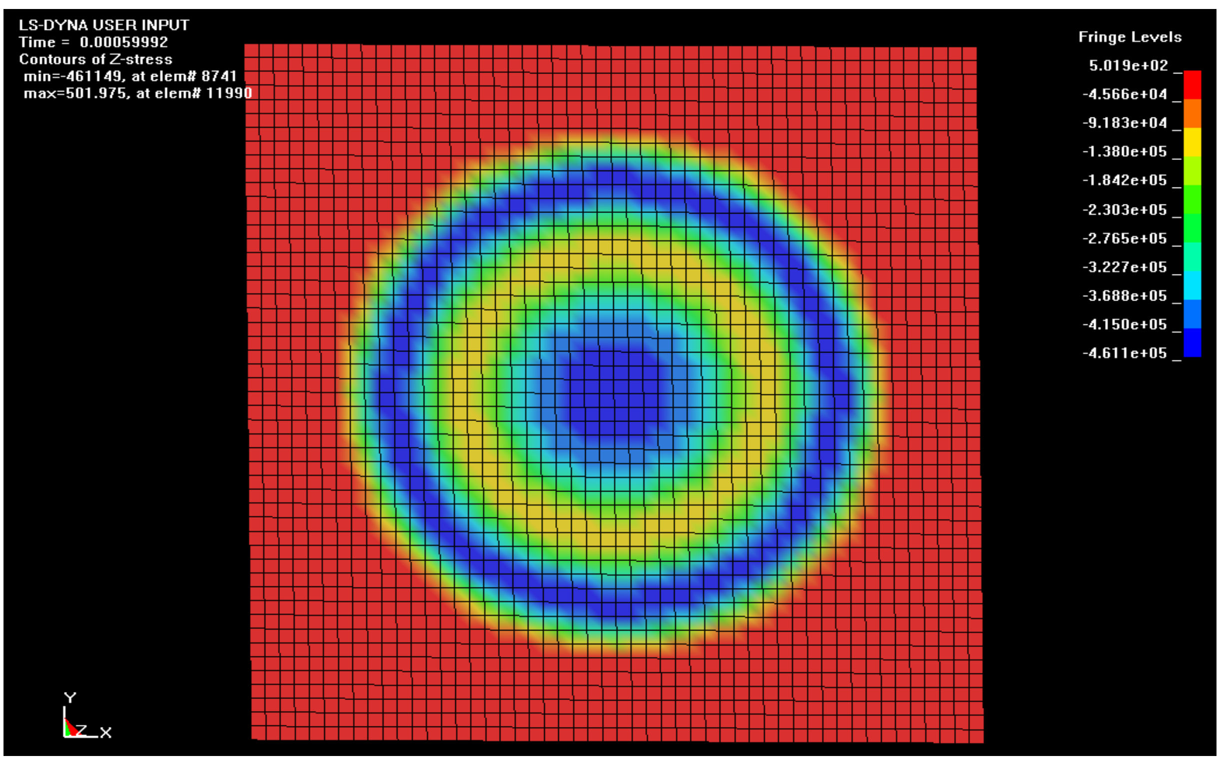

Figure 2a. Front side of the foam plate showing a maximum compressive stress of 0.46MPa

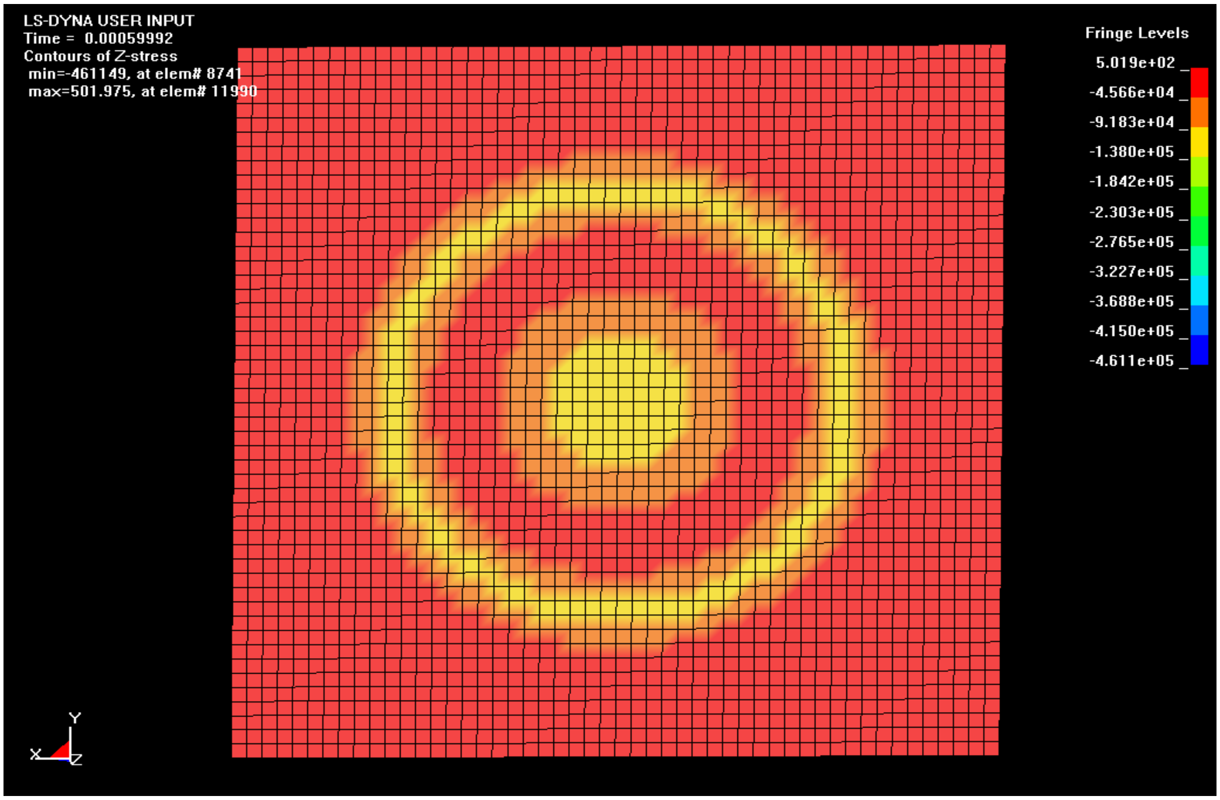

Figure 2b. Back side of the foam plate showing a compressive stress of 0.09 MPa

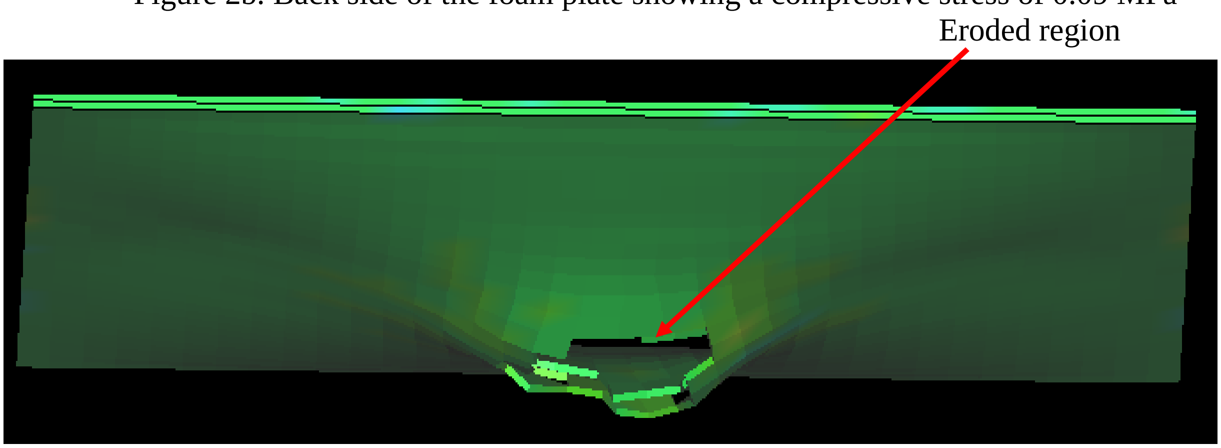

Figure 3. Laminated composite showing buckling under the blast load of 5 MPa

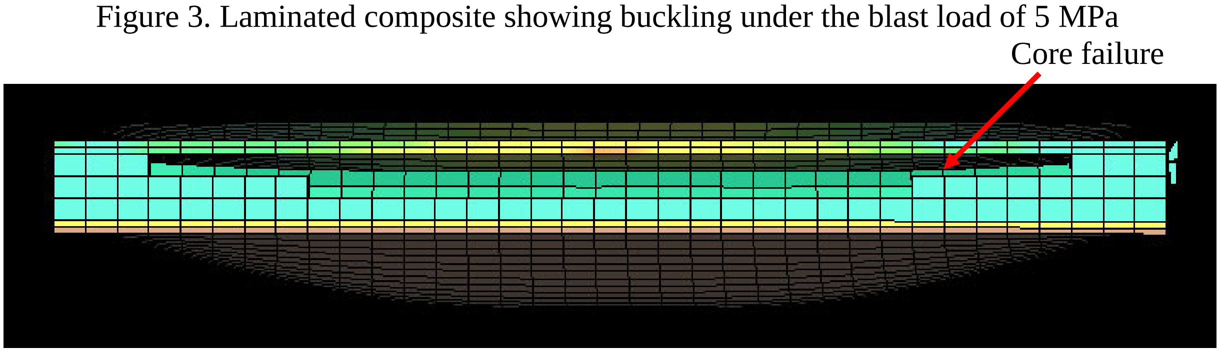

Figure 4. Sandwich composite showing buckling under the blast load of 13 MPa

Appendix A

Material property of Aluminum Foam

$\rho = 300 \ kg/m^3$ (15% relative density) $E = 72$ GPa

$\nu = 0.33$ $\sigma_y = 145$ MPa

$E_{xxu} = 300$ MPa $E_{yyu} = 460$ MPa

$E_{zzu} = 575$ MPa $G_{xyu} = G_{yzu} = G_{zxu} = 1000$ GPa

Stress-engineering strain is used as input for 1 point corotational element

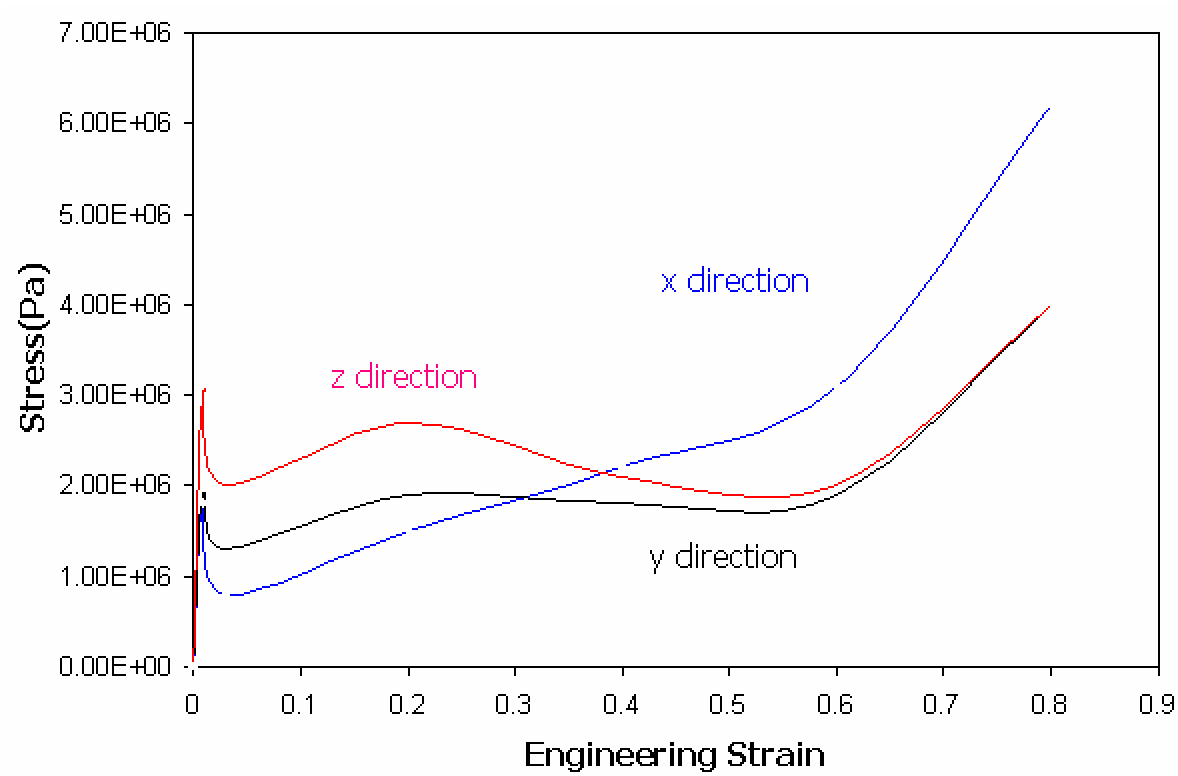

Figure 5.Compressive Stress-Engineering Strain of aluminum foam in three directions

Material property of S2-glass/epoxy

$\rho = 1783 \ kg/m^3$

$E_x = E_y = 24.1$ GPa $E_z = 10.4$ GPa

$\nu_{xy} = 0.12$ $\nu_{yz} = \nu_{zx} = 0.4$

$G_{xy} = G_{yz} = G_{zx} = 5.9$ GPa

$S_{xT} = S_{yT} = 0.59$ GPa $S_{xC} = S_{yC} = 0.35$ GPa

$S_{zT} = 69$ MPa $S_{FC} = 0.69$ GPa

$S_{FS} = 0.55$ GPa $S_{xCR} = S_{yCR} = 0.10$ GPa

$S_{xy} = S_{yz} = S_{zx} = 48.3$ MPa

$\varphi = 20^o$