Metals **2012**, *2*, 170-177; doi:10.3390/met2020170

OPEN ACCESS

metals

ISSN 2075-4701

www.mdpi.com/journal/metals/

Article

Mitigation of Blast Effects on Protective Structures by Aluminum Foam Panels

Changsu Shim [1,*], Nuri Yun [1], Robin Yu [2] and Doyeon Byun [2]

[1] Department of Civil and Environmental Engineering, Chung-Ang University, Seoul 156-769, Korea; E-Mail: nuri58@cau.ac.kr

[2] Manufacturing Development Team, Foamtech Co. Ltd., Seoul 137-869, Korea; E-Mails: ohmygirls@gmail.com (R.Y.); sky4546@gmail.com (D.B.)

* Author to whom correspondence should be addressed; E-Mail: csshim@cau.ac.kr; Tel.: +82-(0)2-820-5895; Fax: +82-(0)2-812-6397.

Received: 13 April 2012; in revised form: 16 May 2012 / Accepted: 1 June 2012 / Published: 11 June 2012

Abstract: Aluminum foams have low density and are attractive materials to mitigate high-speed pressure by blast loads due to high-energy absorption capabilities. In order to develop nonlinear material models for the aluminum foam with different density, mechanical properties of the foam and foam panels under compression, tension, shear and bending moment were obtained by numerous tests. Through the explicit analyses of the foam panels by LS-DYNA, the derived models were verified. Performance of the foam panels with different scaled distances was evaluated by blast tests. Thickness, density and skin plate properties of the panel are the most important parameters to estimate the transmitted pressure to protective structures. Because the pressure of close range blast loading is not uniform, the skin plays an important role in the behavior of the foam. Numerical simulations considering the parameters provided basic design guidelines for the protective structures with sacrificial foam panels. Properly designed panels for the required blast loads can control the transmitted pressure to the target structure under a certain pressure on the yield strength of the foam.

Keywords: aluminum foam; blast; mitigation; energy absorption

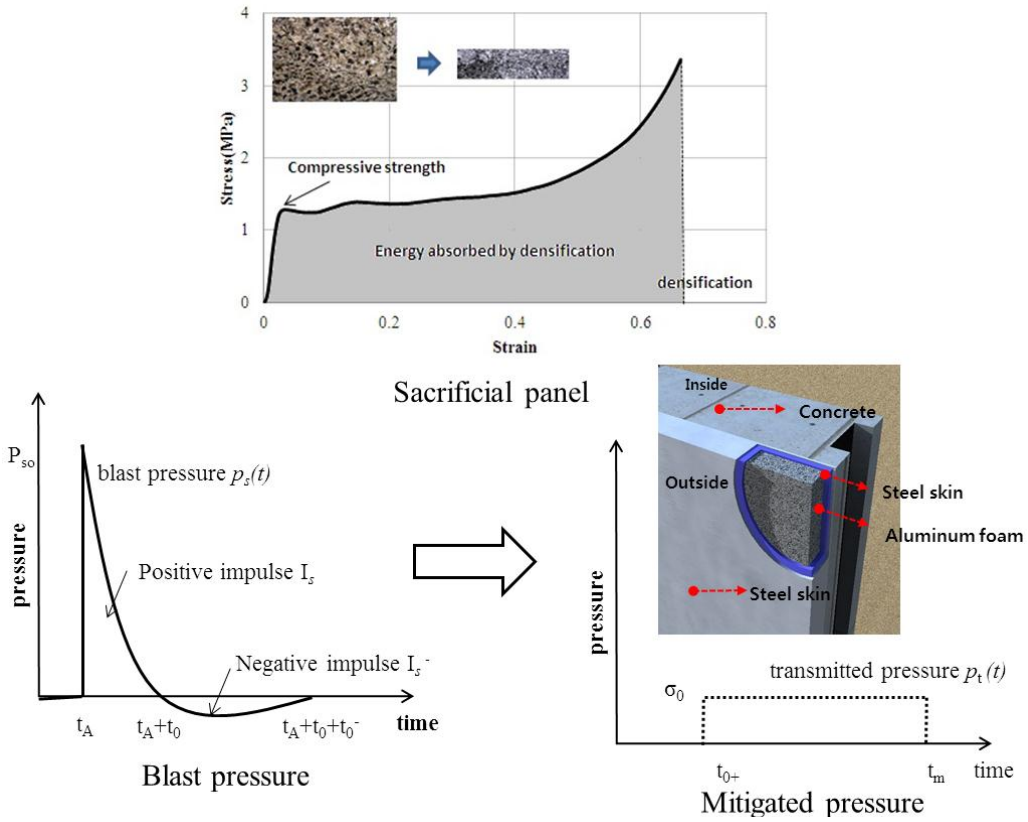
---

1. Introduction

Currently, extreme loads such as impacts and blasts, are taken into consideration for the design of important infrastructures. Hardening of existing structures has many limitations such as increase of thickness and wrapping. Concrete, which is brittle, is used in blast resistant construction either by modifying the matrix by inclusion of fibers or by ductile detailing. However, one of the disadvantages of concrete is the possibility of spalling and scabbing when it is subjected to blast loading. Loss of material caused by spalling and scabbing of concrete weakens the core and this could affect the integrity of the structure. An alternative but cost-effective way is to use composite structural forms which can improve blast resistance. Sacrificing claddings are commonly used for the protection of target structures.

Aluminum foams have low density and are attractive materials to mitigate high-speed pressure due to high-energy absorption capabilities. Energy absorbing material such as aluminum foams can be utilized to mitigate the blast pressure instead of strengthening target structures [1–7]. According to different basis of design (BOD), the aluminum foam panel can be designed to control the transmitted pressure lower than the maximum pressure which can be resisted by concrete structures, as presented in Figure 1. According to the density and thickness of a foam panel, the mitigated pressure can be adjusted to satisfy the required pressure level by the blast loads. In particular, the foam density is the key parameter to allow a certain level of pressure. Short duration of the blast load can be delayed to have long duration. A pressure-impulse diagram (PI diagram) is normally required for the design of protective structures. Therefore, designers need to have reliable material models to estimate the pressure mitigation.

Figure 1. Mitigation of blast pressure by aluminum foam panels.



In order to develop nonlinear material models for the aluminum foam with differing density, mechanical properties of the foam and foam panels under compression, tension, shear and bending moment were obtained by numerous tests. Several studies were carried out to investigate the constitutive response of aluminum foams during the past three decades. Various experimental facilities were used to load the foam at a range of strain and stress rates [1,5,6]. They reported that a closed-cell aluminum foam did not exhibit a strain rate effect. It was found that the initial elastic modulus is lower than that of fully dense alloys. Deformation in the cell walls led to stress concentration around the deformation zone, which resulted in a decrease of the modulus. The deformation of the foam under loads is not spatially uniform. Deformation first occurs in the weakest region and is propagated in this region until it is completely crushed or becomes fully densified.

Based on empirical data to generate a yield surface to reproduce the bulk properties of aluminum foams, a number of constitutive models such as a continuum model have been developed [6,8]. Some of these constitutive models have been implemented in commercial finite element programs and have been used in previous analytical studies [9,10].

In this paper, material tests were conducted to derive typical material models of aluminum foams. The derived models were verified through the explicit analyses of the foam panels by LS-DYNA [11]. Performance of the foam panels with different scaled distances was evaluated by blast tests. Numerical simulations considering the parameters provided basic design guidelines for the protective structures with sacrificial foam panels. Tests and simulations verified the proposed concept that properly designed panels for the required blast loads can control the transmitted pressure to the target structure under a certain pressure on the yield strength of the foam.

2. Material Models

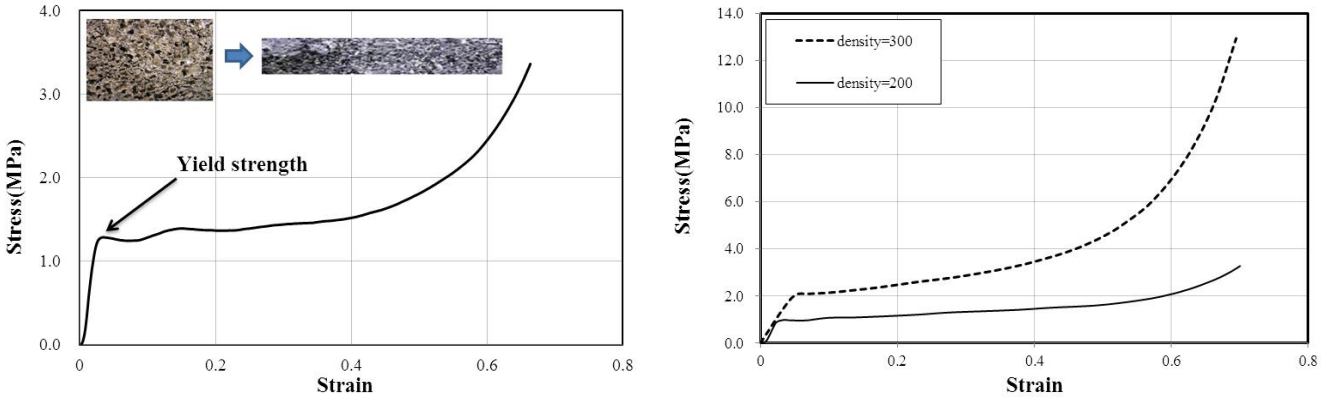
2.1. Mechanical Properties of Aluminum Foams

Compression tests according to ASTM (Standard Test Method for Compressive Strength of Metal Foams [12]) for the aluminum foam with different density were performed to derive material models. Dimension of the specimens were 100 mm × 100 mm × thickness. In order to build reliable material models considering a foam production process and variable properties, effects of loading direction and speed, density, thickness and thickening by layered bonding. The aluminum foam has an initial region of elastic deformation. There is an upper yield point, then a drop in stress, followed by a region of increase. The sharp increase in the hardening rate at the end of the curve corresponds to densification in the foam. The energy per unit volume of material that is absorbed by plastic deformation is the area under the stress-strain curve as shown in Figure 2 and Table 1. Although the foam material varies in material properties, the derived values can be used as characteristic values for the simulation to evaluate the mitigation effects. The accurate modeling of the material properties is essential to ensure validity in the results from the analyses that determine the dynamic responses of structures.

Fourty five tensile specimens were tested to investigate the behavior of the foam in tension. It was found that the variation of tensile strength is greater than compressive strength due to various distribution of pores in a foam. Tensile strength of the foam is increased as the density increases up to

300 kg/m^3. However, the increase was not observed when the density was more than 300 kg/m^3. Maximum tensile strength of the foam with density of 337 kg/m^3 was 2.0 MPa.

Figure 2. (**a**) Typical stress-strain curve; (**b**) stress-strain curves for material model.



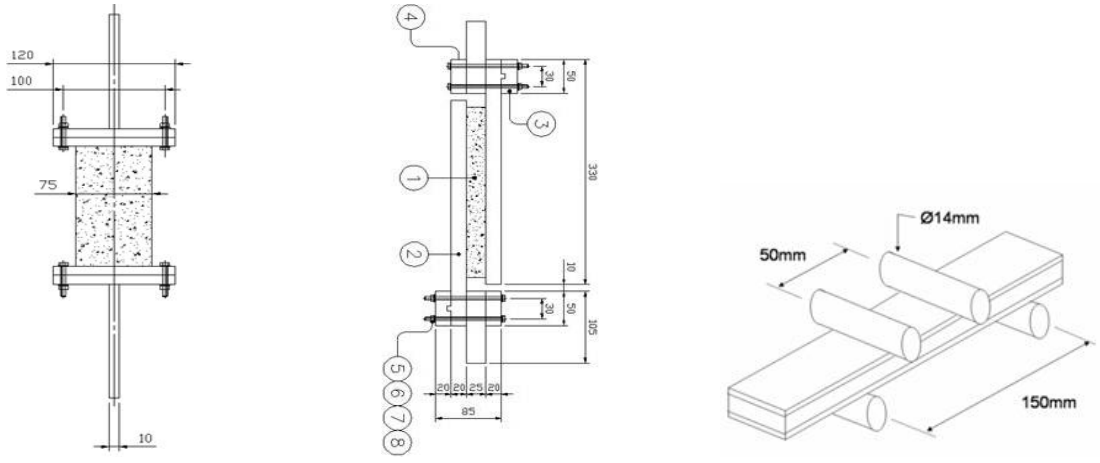
(**a**) (**b**)

Table 1. Typical material properties for analysis.

Density	Yield strength (Z)	Yield strength (X, Y)	densification strain	Energy absorption capacity (20% strain)	Energy absorption capacity (50% strain)
200 kg/m^3	0.8 MPa	0.9 MPa	70%	0.24 MJ/m^3	0.61 MJ/m^3
370 kg/m^3	1.9 MPa	2.2 MPa	65%	0.52 MJ/m^3	1.28 MJ/m^3

Fourty five specimens were tested to investigate the behavior of the foam in shear as shown in Figure 3. Increase of shear strength of the foam was clearly observed as the density increased. Typical shear strengths of the foam were 0.79 MPa, 1.09 MPa and 1.61 MPa for desnsity of 210 kg/m^3, 260 kg/m^3 and 320 kg/m^3, respectively.

Figure 3. (**a**) Direct tensile test; (**b**) shear test; (**c**) bending test.



(**a**) (**b**) (**c**)

Fourty five bending tests were performed for the foam without skins. Tensile strength was greater than that from the direct tensile tests. Typical tensile strengths of the foam from bending tests were 1.45 MPa, 1.90 MPa and 3.68 MPa for a desnsity of 230 kg/m^3, 270 kg/m^3 and 335 kg/m^3, respectively.

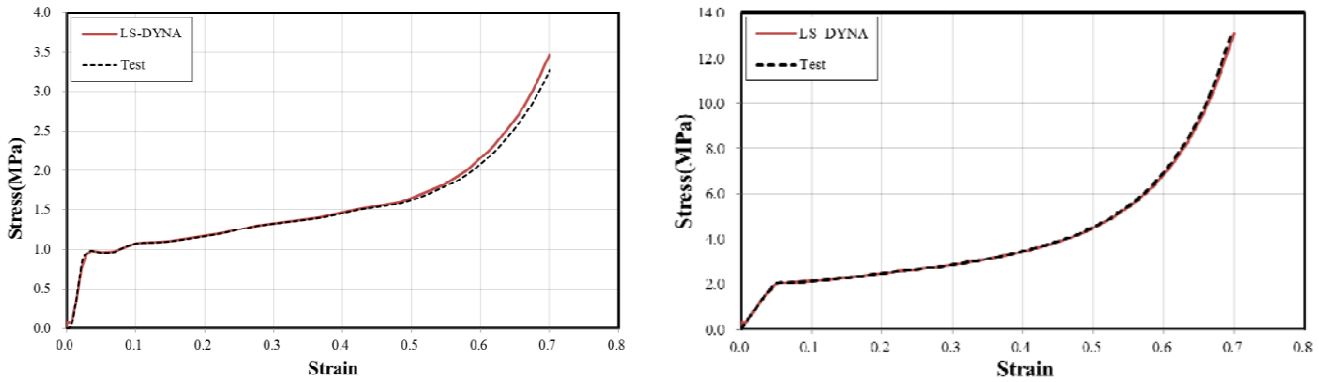
Stress-strain curves for aluminum foams under compression, tension and shear were used for the material models in finite element analyses to evaluate the inelastic behavior of the foam panels. For design purposes, typical stress-strain curves from material tests were selected according to different foam densities.

2.2. Material Models for Explicit Analysis

To model the real anisotropic behavior of the aluminum foam, a nonlinear elastoplastic material model can be used separately for all normal and shear stresses. The behavior before compaction is orthotropic where the components of the stress tensor are uncoupled, *i.e.*, a component of strain will generate resistance in the local x-direction with no coupling to the local y and z directions. For fully compacted material, it is assumed that the material behavior is elastic-plastic and the stress components adjust according to conventional elastic-plastic theory.

In order to build material models of the selected aluminum foams with different densities and thicknesses, static analyses using test results were performed by LS-DYNA [11]. Among material models in LS-DYNA, a modified-honeycomb model (*i.e.*, M126) was selected. As shown in Figure 4, the difference in energy absorption capacity was less than 5%. Therefore, these material input parameters are used for the blast simulation.

Figure 4. Verification of material models: (**a**) Foam density 200 kg/m^3; (**b**) Foam density 370 kg/m^3.



(**a**) (**b**)

The aluminum foam for blast pressure protection should be designed according to the basis of design (BOD). Main design parameters are foam density and required thickness to mitigate the blast pressure under a certain level. Target values of transmitted pressure can be defined by assessment of resistance of protected structures. Once the BOD is decided, incident blast pressure and the target transmitted pressure can be estimated. The derived material models can be utilized to assess the mitigation of the blast pressure to the target value by changing foam density and its thickness.

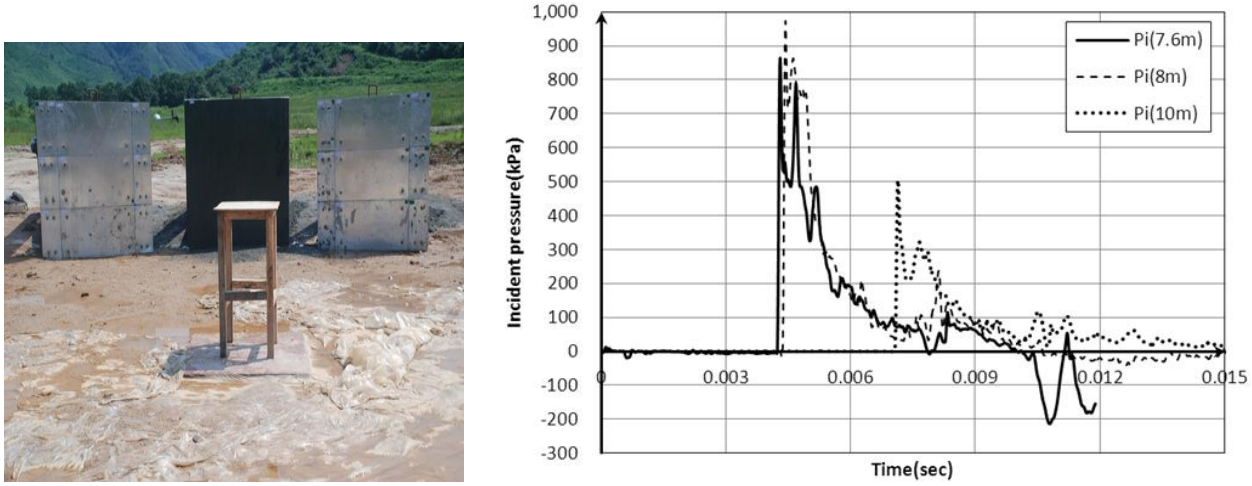
3. Blast Tests and Analyses

3.1. Test Setup and Specimens

In order to validate the material models and perform evaluation by analyses, a blast test was executed as shown in Figure 5. Three concrete wall specimens were fabricated to investigate the

pressure mitigation effects by aluminum foam panels. A concrete wall without foam panels is labeled C1AF0 and walls with foam panels are C1AF1 and C1AF2. Concrete walls had an average compressive strength of 20.0 MPa and thickness of 200 mm. The aluminum foam panels with 50 mm thick were attached at the front face of two walls. One specimen was installed without a sacrificial panel to evaluate the damage of a normal concrete wall.

Figure 5. (**a**) Test setup; (**b**) Blast pressure history.

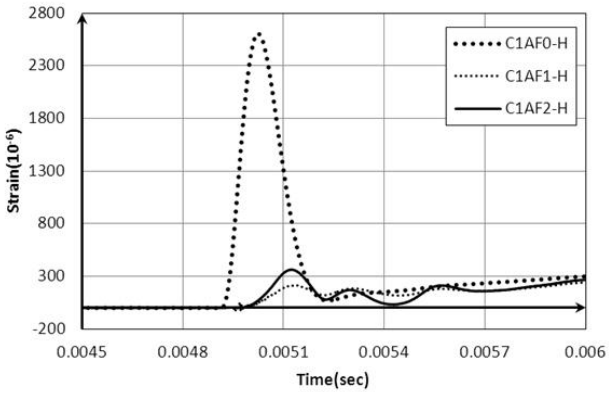


(a) **(b)**

A cylinder shape explosive of composition C-4 was used and a scaled distance Z was 1.014 (W = 92.5 kg, R = 5.0 m). Incident pressure at difference distances from the explosive was measured as shown in Figure 5. The center of the explosive was adjusted to apply the blast pressure on the wall center.

The concrete wall without foam panels (C1AF0) showed severe cracking at rear surface of the wall while walls with foam panels (C1AF1 and C1AF2) showed the effect of pressure mitigation by the plastic deformation of aluminum foam panels. Figure 6 presents a strain history of concrete at the center of rear wall surface. Deformation of the wall showed a significant reduction of blast pressure by the aluminum foam. Because the pressure of close range blast loading is not uniform, the skin plays an important role for the behavior of the foam. The test results provided a basis of design to use the proposed material models and ultimate strength calculation of concrete walls by yield line methods.

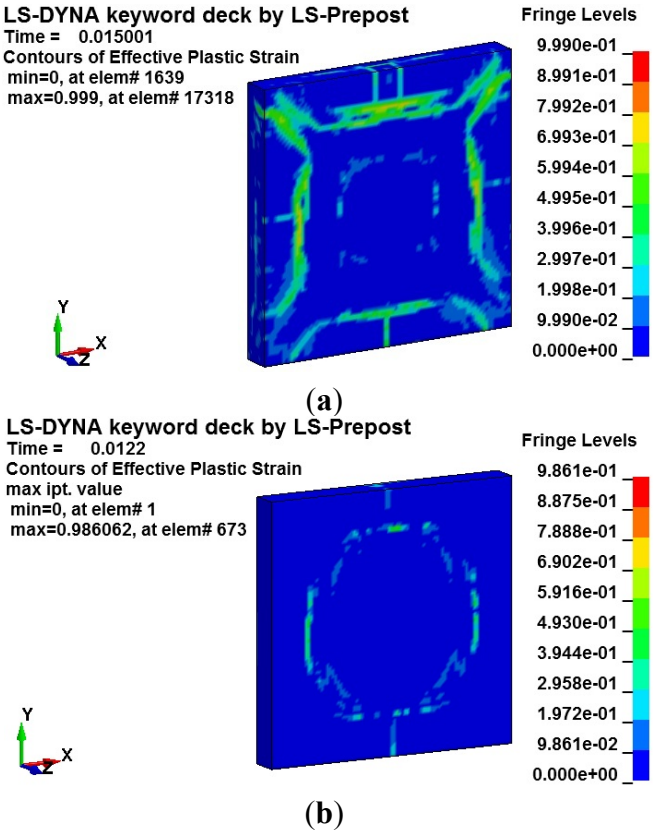
Figure 6. Measured strain history of concrete walls.



3.2. Explicit Finite Element Analyses

According to different scaled distances, the foam panel needs to be designed to mitigate the blast pressure under certain levels considering ultimate strength of concrete structures. Numerous analyses were performed to derive general design methods to decide adequate foam density and thickness. As shown in Figure 7, a normal concrete wall without protection showed a clear yield line pattern while the protected wall displayed minor damage for the same blast pressure.

Figure 7. Damage pattern by explicit analyses: (**a**) Normal concrete wall; (**b**) Protected concrete wall by foam panels.



4. Conclusions

In this study it has been shown that properly designed aluminum foam panels for the required blast loads, can control the transmitted pressure to the target structure under a certain pressure on the yield strength of the foam. Blast tests and analyses provided a generalized design approach for blast pressure mitigation.

Acknowledgments

The authors would like to acknowledge the support provided for this research by Foamtech Co., Ltd.

Conflict of Interest

The authors declare no conflict of interest.

References

1. Dannemann, K.A.; Lankford, J., Jr. High strain rate compression of closed-cell aluminum foams. *J. Mater. Sci. A* **2000**, *293*, 157–164.
2. Sadot, O.; Anteby, I.; Harush, S.; Levintant, O.; Nizri, E.; Ostraich, B.; Schenker, A.; Gal, E.; Kivity, Y.; Ben-Dor, G. Experimental investigation of dynamic properties of aluminum foams. *J. Struct. Eng.* **2005**, *131*, 1226–1232.
3. Shim, C.; Yun, N. Evaluation of close-range blast pressure mitigation using a sacrificial member. *J. Earthq. Eng. Soc. Korea* **2010**, *14*, 11–23.
4. Hanssen, A.G.; Enstock, L.; Langseth, M. Close range blast loading of aluminium foam panels. *Int. J. Impact Eng.* **2002**, *27*, 593–618.
5. Mukai, T.; Kanahashi, H.; Miyoshi, T.; Mabuchi, M.; Nieh, T.G.; Higashi, K. Experimental study of energy absorption in closed-cell aluminum foam under dynamic loading. *Scripta Met.* **1999**, *40*, 921.
6. Deshpande, V.S.; Fleck, N.A. Isotropic constitutive models for metallic foams. *J. Mech. Phys. Solids* **2000**, *48*, 1253–1283.
7. Langdon, G.S.; Karagiozova, D.; Theobald, M.D.; Nurick, G.N.; Lu, G.; Merrett, R.P. Fracture of aluminum foam core sacrificial cladding subjected to air-blast loading. *Int. J. Impact Eng.* **2010**, *37*, 638–651.
8. Hanssen, A.G.; Hopperstad, O.S.; Langseth, M.; Ilstad, H. Validation of constitutive models applicable to aluminium foams. *Int. J. Mech. Sci.* **2002**, *44*, 359–406.
9. Hanssen, A.G.; Girard, Y.; Olovsson, L.; Berstad, T.; Langseth, M. A numerical model for bird strike of aluminium foam-based sandwich panels. *Int. J. Impact Eng.* **2006**, *32*, 1127–1144.
10. Shahbeyk, S.; Petrinic, N.; Vafai, A. Numerical modelling of dynamically loaded metal foam-filled square columns. *Int. J. Impact Eng.* **2007**, *34*, 573–586.
11. *LS-DYNA Keyword User's Manual*; Livermore Software Technology Corporation: Livermore, CA, USA, 2006.
12. *Standard Test Method for Flatwise Compressive Properties of Sandwich Cores*; ASTM C365-03; American Society for Testing and Materials: West Conshohocken, PA, USA, 2003.