Shock Wave Effect on Aluminium Foam

M. Vesenjak[1], M. Borovinšek[1], Z. Ren[1], S. Irie[2] and S. Itoh[3]

[1] University of Maribor, Faculty of Mechanical Engineering, Slovenia

2 Kumamoto University, Shock Wave and Condensed Matter Research Center, Japan

3 Okinawa National College of Technology, Japan

1 Abstract

The behaviour of aluminium foam under impact loading conditions and especially the shock wave propagation are still not well understood. The shock wave propagation through the cellular material structure under impact loading conditions has a significant effect on its deformation mechanism and therefore it is imperative to understand its effects thoroughly. The goal of this research was to investigate and examine the effects of shock wave propagation on aluminium foam. Additionally, the material and structural properties of pore-filled aluminium foam under impact loading conditions with particular interest in shock wave propagation and its effects on cellular material deformation have been studied. For this purpose experimental tests and explicit computational simulations of aluminium foam specimens inside a water tank subjected to explosive charge have been performed. Comparison of the results shows a good correlation between the experimental and simulation results.

2 Introduction

Metal foams have become very popular engineering materials in recent years due to their high applicability and various advantageous mechanical and thermal properties [1-4]. Metal foam is made of interconnected network of solid struts or plates which form the edges and faces of cells (Fig. 1). The advantages of metal foams in general are low density (light-weight structures), high acoustic isolation and damping, high energy absorption capabilities, durability at dynamic loadings and fatigue, recyclability [1]. Their micro- and macroscopic properties make them perfect for use in automotive, rail, naval, aerospace and armour industry as heat exchangers, filters, bearings, acoustic dampers, bio-medical implants, blast protectors and especially as elements for crash energy absorption [1, 2, 5].

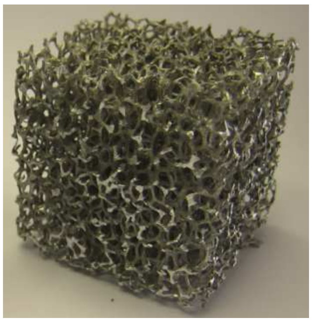


Figure 1. Open-cell metal foam

Mechanical behaviour of cellular materials mainly depends on their relative density and on their base material. The other important parameters of the cellular structures are morphology (open or closed cell), the geometry and topology (regular or irregular structure) and possible filler type. Cellular materials have a characteristic stress-strain relationship in compression, which can be divided into four main areas: (i) quasi-linear elastic response, (ii) transition zone, (iii) stress plateau and (iv) densification.

Although these materials have been subjected to several researches through past years, there is still a lack of their mechanical characterization. The behaviour of metal foams under impact loading conditions and especially the shock wave propagation are still not well understood and are subject of several ongoing investigations. The shock wave propagation through the cellular material structure under impact loading conditions has a significant effect on its deformation mechanism and is therefore imperative to understand its effects thoroughly.

The paper describes the shock wave propagation effect on aluminium foam. For this purpose experimental tests and explicit computational simulations of aluminium foam specimens inside a water tank subjected to explosive charge have been performed.

3 Experimental setup

The experimental tests of the aluminium foams samples have been performed at the Shock Wave and Condensed Matter Research Center, Kumamoto University, Japan. In order to observe and visualize the propagation of the shock wave the aluminium specimens were submerged in a water tank. The container with clear PMMA walls with following dimension: 200 mm x 200 mm x 135 mm, was filled with water. Aluminium foam with the following dimension: 40 mm x 40 mm x 40 mm, was placed at the bottom of the water container. The SEP explosive set (mass: 50 g, detonation velocity: 7000 m/s, density: 1310 kg/m^3) in the PVC pipe was positioned 110 mm above the foam specimen at the water surface. It was used as booster explosive for shock wave generation and was initiated by an electric detonator. The experimental setup is shown in Fig. 2.

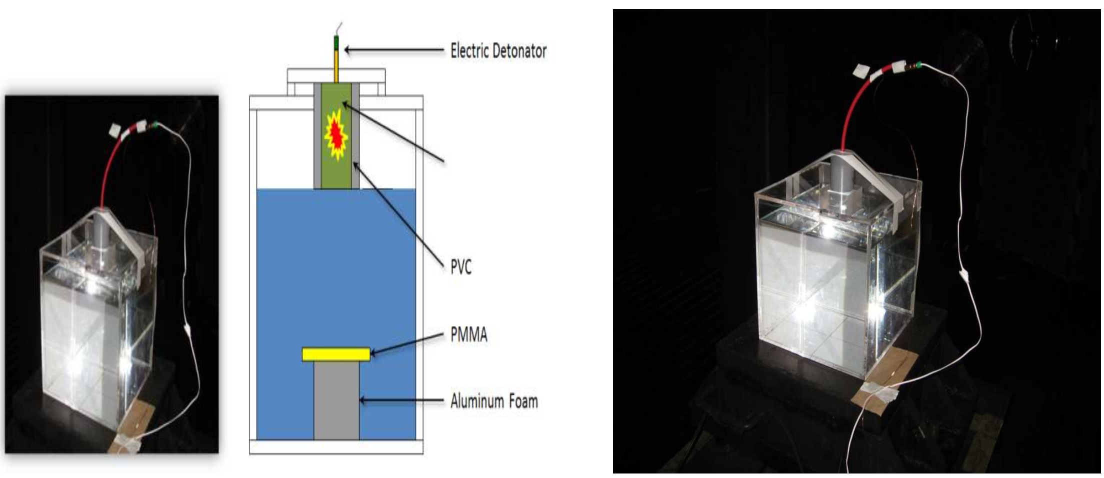


Figure 2. Experimental setup

The shadowgraph method was used to observe the generation of shock wave and its influence on the aluminium foam. This method is used to observe and project the shadow of the light by density change on a screen or the film of a camera, and it is also called the direct projective technique (Fig. 3).

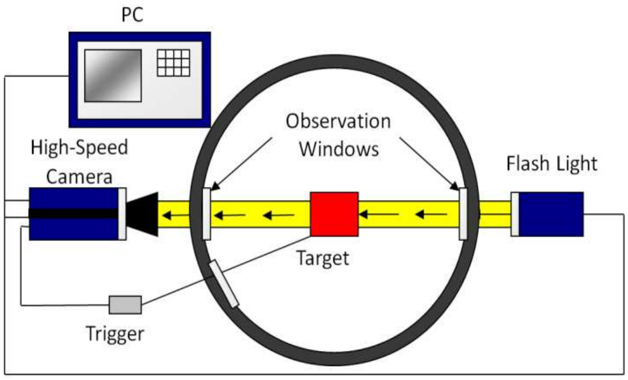
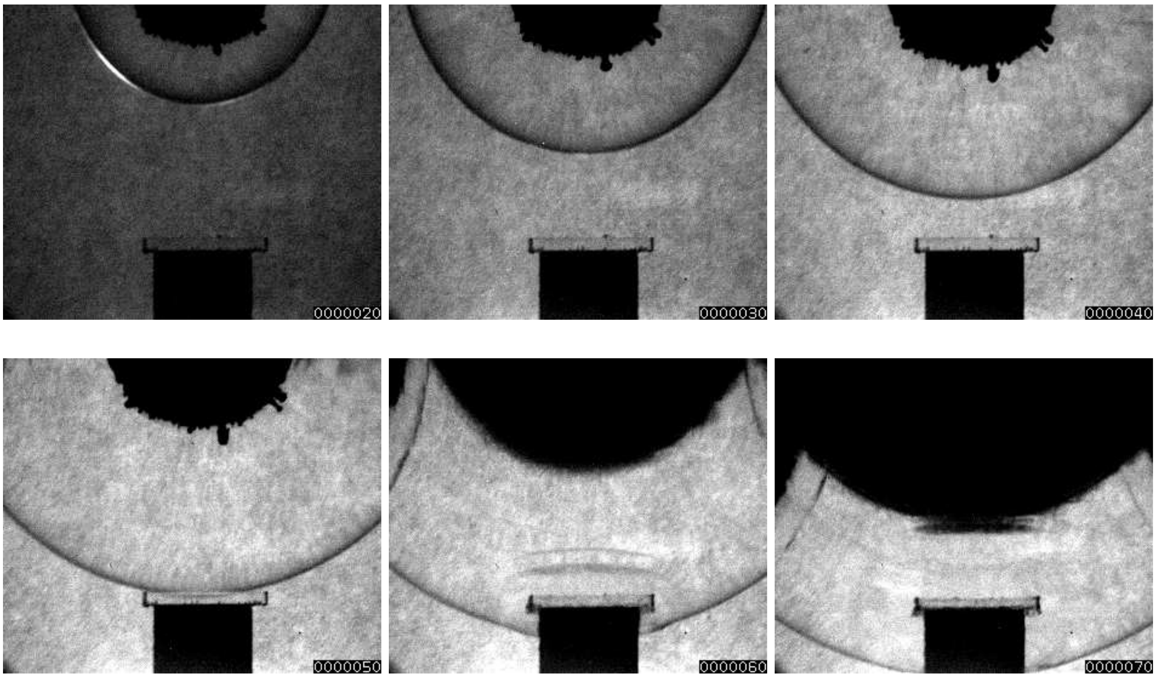


Figure 3. Shadowgraph method

For this purpose the high speed video camera HPV-1 (Shimadzu Corporation) with a frame rate of 500.000 FPS and an image resolution of 320 x 260 pixels was used that allowed the visualization of the shock wave propagation during the experiment (Fig. 4).



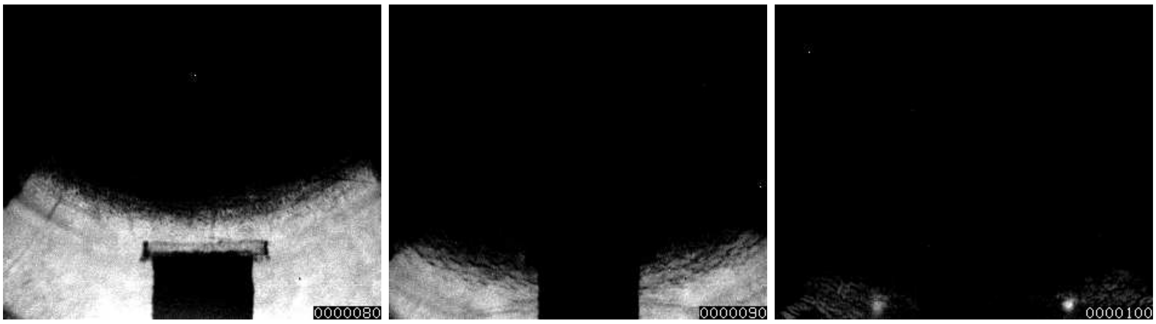


Figure 4. Shock wave propagation (from 20 to 100 µs after detonation)

The speed of the shock wave (Fig. 5) was determined by analysing the images taken during the experiment (Fig. 4). The maximum value of the shock wave speed equalled to approximately 2700 m/s. The accuracy was limited by the pixel size and was approximately ± 250 m/s.

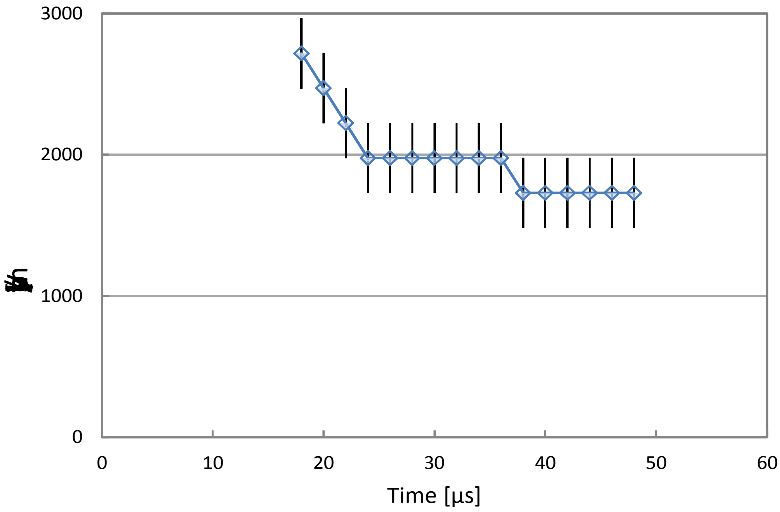


Figure 5. Shock wave propagation speed during the experiment

4 Computational simulation

In order to further investigate the behaviour of open-cell aluminium foams under shock wave loading conditions computational simulations using LS-DYNA were performed.

4.1 Shock wave speed

First a simulation of the shock wave propagation through water without a foam model was done (the size of the Eulerian mesh was 1 mm). Due to the double symmetry only a quarter of the volume was modelled [6]. The computational model (Fig. 6) consisted of parts modelled with an Eulerian mesh (explosive SEP using the Jones-Wilkins-Lee (JWL) equation of state, water using the Mie Gruneisen equation of state, air using the linear polynomial equation of state) and Lagrangian mesh (PVC using the piecewise-linear plasticity constitutive model with failure). The fluid-structure interaction interface was used on the boundaries of the PVC mesh.

The shock wave speed in the computer simulation was determined from the position of the pressure measurement points by observing their maximum pressure (Fig. 6). The accuracy of this calculation was limited by the time sampling interval which equalled to 0.15 µs but was much higher than by the experiment.

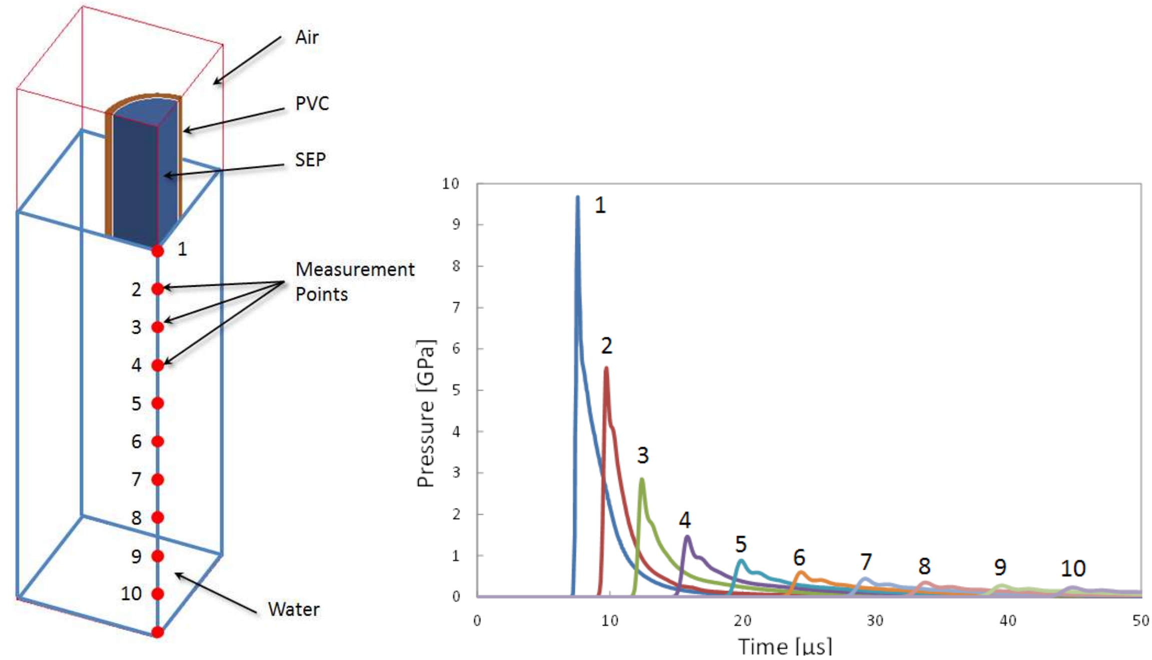


Figure 6. Computational model (left) and pressure history at selected points (right)

In order to measure the pressure values a series of 10 measurement points was defined every 10 mm from the water surface to the bottom (Fig. 6). Comparison of the results in Fig. 7 shows a good correlation between the experimental and simulation results considering the measurement error.

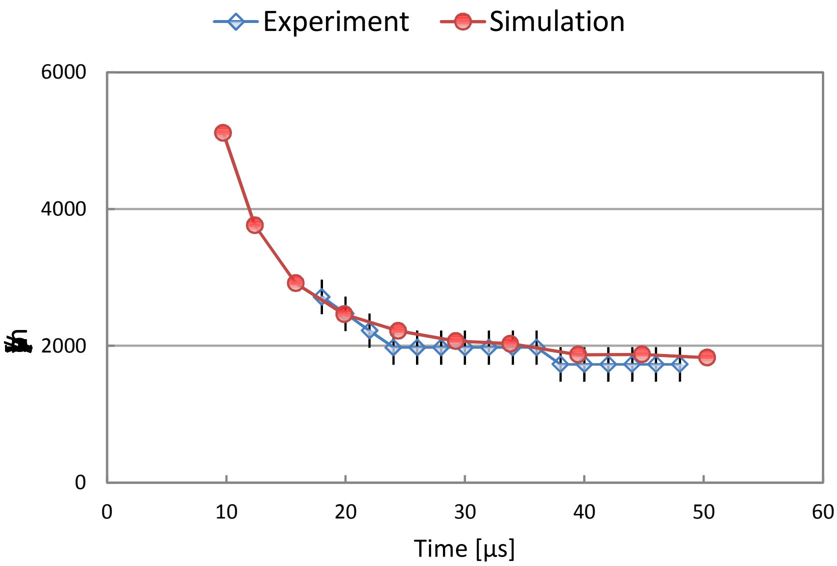


Figure 7. Shock wave speed comparison of the experimental and computational results

4.2 Homogenized model of the aluminium foam

In order to simulate the explosion effects on the deformation behaviour of the open-cell aluminium foam, a homogenized foam model was added to the simulation. Three different modelling approaches were taken into account:

- Model 1: The foam was modelled using a Lagrangian mesh with a piecewise-linear plasticity constitutive model. A water domain was modelled inside the foam;
- Model 2: The foam was modelled using a Lagrangian mesh with a piecewise-linear plasticity constitutive model. An air domain was modelled inside the foam;
- Model 3: The foam was modelled using an Eulerian mesh with a piecewise-linear plasticity constitutive model.

Deformation behaviour of the three differently modelled homogenized foam models is shown in Fig. 8. From the figure it can be observed that the deformation of the foam increases with the model number.

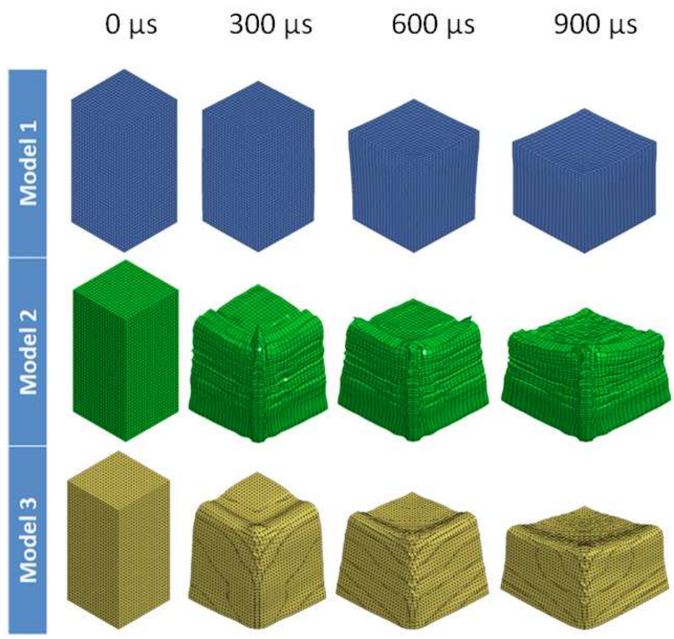


Figure 8. Deformation of the homogenized foam model

The plot in Fig. 9 shows the average displacement of the top surface of the aluminium foam. By the Lagrangian models (1 and 2) the average of all nodes on the top surface was taken into account and by the Eulerian model only 4 positions on the top surface were followed. The model 3 (Eulerian foam model) exhibited the lowest stiffness while the highest stiffness was observed for model 1 (Lagrangian mesh filled with water).

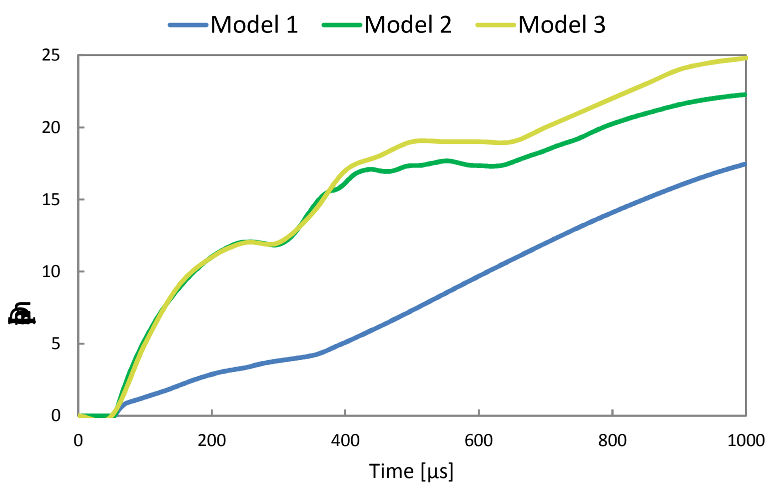


Figure 9. Average vertical displacement of the top surface of the aluminium foam

4.3 Lattice model of the aluminium foam

In the following simulations the aluminium foam was modelled with a lattice model to represent the irregularity of the structure. The foam cell edges were modelled with beam finite

elements and their topology was created using a developed algorithm based on Voronoi 3D regions [7]. Since the lattice foam model is not symmetric the whole simulation domain had to be modelled. In order to transfer the pressure forces on to the foam model a PVC plate was included as by the experiment (fluid structure interaction with beam finite elements does not work in LS-DYNA). The PVC plate was modelled using an Eulerian mesh with a piecewise-linear plasticity constitutive model. A fluid structure interaction interface was used to transfer the pressures between the plate and water. Three different relative densities of the aluminium foam were considered: 5, 10 and 15 %.
The deformation of the lattice model is represented in Fig. 10. It can be observed, that due to the high velocity loading of the PVC plate, the foam material primarily deforms at the upper part where the blast wave impacts the PVC plate.

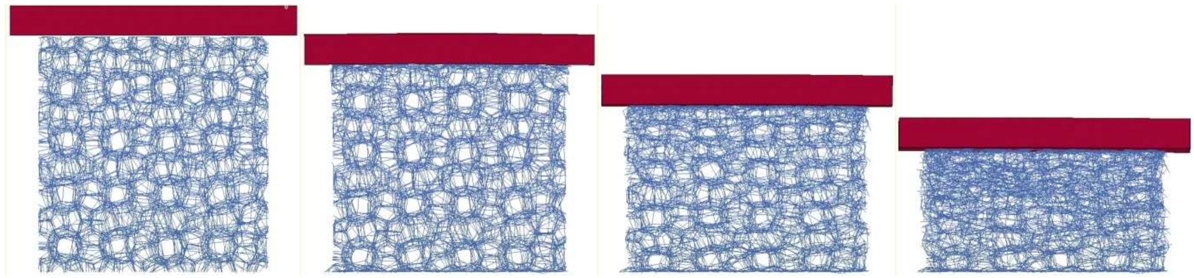


Figure 10. Deformation of the lattice foam model

The diagram in Fig. 11 shows the average displacement of the top surface of the aluminium foams with different relative densities. The blue curve in the diagram represents the model without the aluminium foam, where only the plate was taken into account. As expected, the foam with the lowest relative density experiences the highest displacements (deformations). Increasing the relative density of the foam also increases the macroscopic stiffness of the foam and at the same time decreases the displacements (deformations).

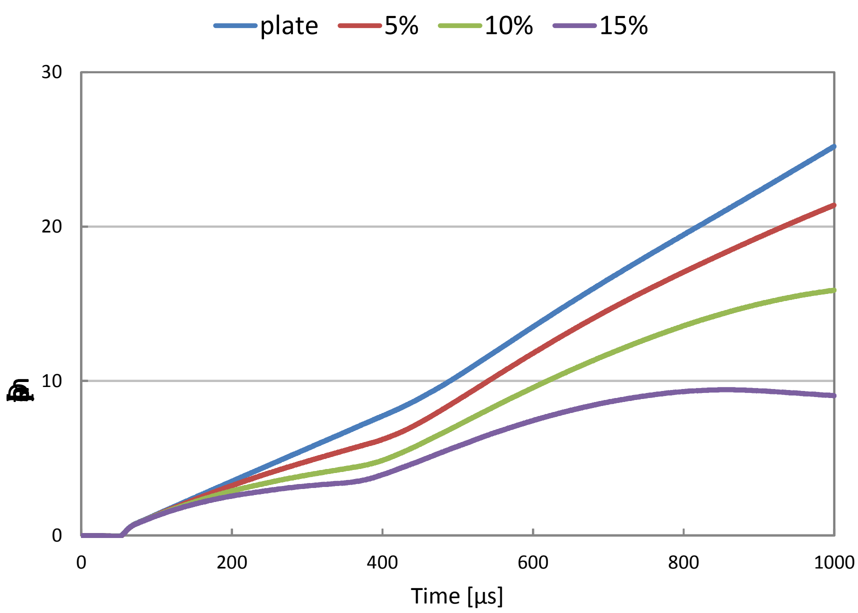


Figure 11. Comparison of displacements for aluminium foams with different relative densities

5 Conclusions

The paper presents the shock wave propagation effect on aluminium foam. For this purpose experimental tests and explicit computational simulations of aluminium foam specimens inside a water tank subjected to explosive charge have been performed. With the shadowgraph method the shock wave propagation and its speed were determined. Later the computational models were validated according to the experimental results, comparing different ALE modelling approaches and foam models. Comparison of the results shows a good correlation between the experimental and simulation results.

6 References

[1] J. Banhart, "Manufacture, characterisation and application of cellular metals and metal foams," *Progress in Materials Science,* vol. 46, pp. 559-632, 2001.

[2] L. J. Gibson and M. F. Ashby, *Cellular solids: structure and properties* vol. Second edition. Cambridge: Cambridge University Press, 1997.

[3] S. T. Hong, *et al.*, "Quasi-static crush behavior of aluminum honeycomb specimens under compression dominant combined loads," *International Journal of Plasticity,* vol. 22, pp. 73-109, 2006.

[4] M. Vesenjak, *et al.*, "Experimental Study of Open-Cell Cellular Structures with Elastic Filler Material," *Experimental Mechanics,* vol. 49, pp. 501-509, 2009.

[5] J. L. Yu, *et al.*, "Strain-rate effect and micro-structural optimization of cellular metals," *Mechanics of Materials,* vol. 38, pp. 160-170, 2006.

[6] S. Irie, *et al.*, "Dynamic Property of Aluminum Foam," *The International Journal of Multiphysics,* vol. 4, pp. 103-111, 2010.

[7] M. Borovinšek, *et al.*, "Structure of real metal foam," in *Kuhljevi dnevi 2008,* Cerklje na Gorenjskem, 2008.