ELASTIC PROPERTIES OF OPEN CELL METALLIC FOAMS USING FINITE ELEMENT ANALYSIS AND HOMOGENIZATION TECHNIQUE

S. A. S. P. SATHURUSINGHE, K. R. B. HERATH, S. R. HERATH*

DEPARTMENT OF CIVIL ENGINEERING, UNIVERSITY OF PERADENIYA,

PERADENIYA, SRI LANKA

ABSTRACT

Metallic foams possess combinations of properties which very rarely occur in solid materials. Metal foams are composites of controlled-cell porosity made of a metal that contain a large proportion of air (generally from 70% to 95% of volume). These foams are known to have many interesting combinations of physical and thermal properties. These metal foams are produced as either closed cell or open cell foams. Closed cell metal foams replicate closely packed sphere like microstructures. Open cell metal foams have nodes connected with dog bone like struts, and they have larger porosity.

This study aims at estimating the elastic properties of open cell metal foams with varying porosity. A unit cell of a combination of a cube and a sphere was modeled using Finite element method and only one eighth of the cell was considered for symmetry. The model was analyzed using displacement loading method and the macroscopic properties were obtained using the homogenization technique. The results of this analysis were compared with previous experimental results as well as with analytical results for closed cell with three phase spherical model.

Keywords: Metallic Foams, Homogenization, FEM, Open Cell

1. INTRODUCTION

The foam materials are porous or cellular type materials which are made of isotropic materials. The pores in the material can be situated in a periodic or regular array or in a random manner. The constituent material can be a polymer, metal, carbon or a ceramic. Applications of different foam materials are limited only by ones imagination. The oldest manmade foam materials are the polymer foams and they have been used as packing, sound absorbers, energy absorbers and cushion materials.

The metal foams are a class of materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties which came into limelight in 1990's. During this period of time, there was a hunt for new materials which would effectively replace the then used conventional materials in order to make light weight strong and stiff structures in aerospace and automobile industry. Most of the pioneering research in the areas of composite materials, toughening and improving other properties of ceramic materials, metallic foams, tough polymers etc. was initiated with great interest around the globe during this time. In last two decades, many important applications emerged due to these research investments and today the industry has picked up manufacturing products using these novel materials. The metallic foams are used in lightweight structures due to their high strength and stiffness to weight ratios, for energy absorption, for thermal management, fluid flow control devices, filtration, porous electrodes etc. Some of these materials prove to be cost effective too.

A comprehensive design guide for metal foams (Ashby et al, 2000) gives a complete account of material properties, processing methods, testing methods, potential applications, production techniques and then potential suppliers of metallic foams in a broad context. Potential design techniques are also presented.

In producing metallic foams, various techniques can be adopted. It can be processed using molten metal, vapour phase deposition, or in solid state. Metallic foams are like sponge materials which contain voids and the associated solid parts are made of a metal. The metallic foam properties can be mastered by varying the pore size, density, shape and the solid material. The foam material can be considered as an isotropic material macroscopically if its voids (pores) are formed in a random manner. Most of the common metallic foam materials are manufactured in such a way that it will have isotropic macro scale behavior. For some applications, these materials are sandwiched to get desired properties. For such designs, the behavior must be studied with more complicated laminate theories.

Based on the cell morphology, the cellular foams can be divided into two major groups, namely, open cell foams and closed cell foams. The open cell type material consists of cells which possess open cell walls (Fig. 1a). The nodes are connected with solid material ligaments and it is possible to make very low density materials. The closed cell type material consists of cells with closed walls (Fig. 1b).

The closed cell foams are manufactured using melt air bubbling, gas releasing particle decomposition and gas releasing semi solid decomposition. The open cell foams are manufactured by casting using a polymer or wax precursor and also by metal deposition on cellular preforms.

The main objective of the present study is to establish a method to estimate the effective average elastic properties of an open cell metallic foam material in terms of its density. It is also very important to device a method to estimate properties of these materials in terms of cell geometry and suggest the manufacturer of the design of the foam internal structure. This provides us with a powerful tool to make cellular metallic foams with desired properties.

Several studies have been performed to predict the average effective properties of cellular materials. Gibson and Ashby considered unit cells and micromechanics with compressive loading for open cell as well as closed cell type cellular structures (Gibson, LJ. & Ashby, MF., 1982). The basic deformation mechanism considered was bending. (Grenestedt, JL., 1998) has used finite element analysis techniques to analyse unit cells along with experimental studies. (Christensen, RM., 1998) has used a continuum approach well known from Composite Mechanics with generalized self consistent method (GSCM) to closed cell materials. (Lu Z & Gao Z., 1998) used the Three Phase Model (TPM) as an extension to GSCM. (Schjodt-Thompsen J. & Pyrz R., 2001) modified the (Tanaka, K. & Mori, T, 1973) model to find effective properties of cellular materials and compared that with the self consistent models (DS1 and DS2) by (Dvorak, GJ. & Srinivas, MV., 1999). (Betts, C., 2012) has recently reviewed the benefits of metal foams and computational techniques.

The present study is focused on estimating the elastic properties of open cell metallic foams with various density values and the results are compared with previous experimental and analytical results.

2. MATERIAL AND METHOD

2.1 Material

The properties of Duocel® Aluminum Foam material manufactured by ERG AEROSPACE CORPORATION, Oakland, CA, USA is chosen because some samples of the product were available for observation. A micro-structural observation revealed that it had some irregular shapes which were more inclined towards forming a cube like open cell structure with a circular shape opening (Fig. 2a). The cross section of a strut was seen to be nearly triangular (Fig. 2b).

2.2 Elastic Properties of Aluminum

Young's Modulus (Em)	69 GPa
Poisson's Ratio (νm)	0.33

2.3 Methodology

In fact all materials are inhomogeneous at atomic scale. But for actual scale of its usage one can assume that the material is continuous and homogeneous with average apparent properties though at the atomic scale it consists of many atoms which are held together with inter-atomic attractive and repulsive forces.

The same concept could be valid for heterogeneous materials such as composites, concrete, porous and cellular materials. For any inhomogeneous material it can be assumed that there exists a length scale 'd' (d<<<D where D is the global length scale or the scale of the size of the body) at which the parameters like stress of the material can be averaged to give macroscopical properties. The average properties at this size scale are supposed to be independent of the position within the material. With this concept, the material can be considered macroscopically homogeneous. If we can find such a scale 'd', the effective properties of the material can be obtained. This process is called 'homogenization' and such a volume element of scale 'd' is called Representative Volume Element (RVE) or unit cell. For cellular foam structures there exists a periodicity and RVE is a unit cell of such structure.

Based on the microscopical observations on Al foam material considered, it was decided to use a unit cell of cubic shape with introduction of a spherical void within it so that the diameter of the sphere (2R) is larger than the length of the cube (2 a) as shown in Fig. 3 and used previously by Han et al (2005) to estimate the dynamic compressive behaviour of metal foams. This unit cell has capacity to model the cellular materials with large porosity with nearly triangular shape cross section struts. It is assumed that there is a periodic 3-D array of this unit cell within the metallic foam.

Estimation of the volume percentage of the material is done as follows.

Fig. 4 shows a spherical cap which is not included in the spherical shape void of the considered unit cell and must be therefore subtracted.

Volume of spherical cap

$$V = \int_a^R \pi (R^2 - y^2) dy \tag{1}$$

$$V = \pi \left[\frac{2R^3}{3} - R^2 a + \frac{a^3}{3} \right] \tag{2}$$

Volume of the void (V0) = Volume of the Sphere - 6 x V

V0 is found to be,

$$V_0 = \frac{\pi}{3}\left[-8R^3 + 18R^2 a - 6a^3\right] \tag{3}$$

$$\text{Porosity} = \frac{V_0}{\text{Volume of the cube}} \tag{4}$$

$$\text{Porosity} = \frac{\frac{\pi}{3}\left[-8R^3 + 18R^2 a - 6a^3\right]}{8a^3} \tag{5}$$

Hence the density of the foam is given by

$$\frac{\rho}{\rho_0} = 1 - \frac{\pi}{3}\left[-\frac{R^3}{a^3} + \frac{9}{4}\frac{R^2}{a^3} - \frac{3}{4}\right] \tag{6}$$

For a given density % there exist a ratio between cube dimension ‘a’ and void radius ‘R’. The spherical cap of Fig. 4 vanishes when ‘R’ approaches ‘a’ and thereby the unit cell become a closed cell when R is less than a.

2.4 Analysis

For the symmetry of the unit cell only one eighth of the cell was analysed using ABAQUS finite element package. The feature parts assembly is used to generate the model for various pore densities. 10-node solid tetrahedral elements were used with appropriate boundary conditions to represent cell symmetry and periodicity (Figs 5a and 5b). The displacement method was used with boundary conditions to impose all the strains are to be zero except the direct strain in x direction.

Since the periodic cubic cell considered was symmetric in 3-D space, the average properties of the foam materials are to be isotropic. Thus the stress strain relationships can be expressed using Generalized Hooke’s Law.

$$\varepsilon_{11} = \frac{\sigma_{11}}{E} - \frac{\nu}{E}\left(\sigma_{22} + \sigma_{33}\right) \tag{7}$$

$$\varepsilon_{22} = \frac{\sigma_{22}}{E} - \frac{\nu}{E}\left(\sigma_{33} + \sigma_{11}\right) \tag{8}$$

$$\varepsilon_{33} = \frac{\sigma_{33}}{E} - \frac{\nu}{E}\left(\sigma_{11} + \sigma_{22}\right) \tag{9}$$

where E and ν are the foam modulus and Poisson's ratio.

ε_{22} = ε_{33} =0 gives

$$\nu = \frac{\sigma_{22}}{\sigma_{11} + \sigma_{33}} \tag{10}$$

From equation (7)

$$E = \frac{\left(\sigma_{11} - \sigma_{22}\right)\left(\sigma_{11} + \sigma_{22} + \sigma_{33}\right)}{\varepsilon_{11}\left(\sigma_{11} + \sigma_{33}\right)} \tag{11}$$

3. RESULTS

The normalized average modulus of foam is plotted against the porosity along with the previous results from 3 phase model(TPM), DS1, DS2, MT, GSCM and unit cell method in Fig. 6. The open cell model vanishes when R= a (porosity 50%) and the results from present study is shown only for this range.

4. DISCUSSION

It can be seen that the results from this model agrees well with previous models in the range of 0.6-0.85 and the present model gives a lower stiffness value for higher volume fractions. This trend is reasonable as the open cell foams are to be less stiff than the closed cell foams and the TPM, GCSM and DS models are all closed cell foam models. The 'x' marks denote the data for the DIAB H Grade rigid polymer foam from Divinycell.

It is necessary to vary the structure of the unit cell and find out the dependence of effective modulus on the geometry of the internal structure of the foam material.

A further study will be based on the same unit cell for uniaxial stress boundary conditions. The analysis can also be extended to non-linear elasto-plastic deformation under various loading conditions.

5. CONCLUSION

Although the unit cell considered in this study was assumed to be repeating in the foam material it can be even seen with naked eye that the DUOCEL open cell Aluminum foam is having very much randomly distributed porosities with various sizes of cells which resemble the unit cell considered in this study. It is therefore of interest to consider a larger section of the material with multiplication of the same cell with a graded size distribution. It is also necessary to perform some experimental tests on the considered material to verify these models.

6. REFERENCES

Ashby MF, Evans AG, Fleck NA, Gibson LJ, Hutchinson JW, Wadley HNG. Metal Foams: A Design Guide. Burlington: Butterworth-Heinemann, 2000.

Veale JP. Investigation of the behaviour of open cell aluminum foam. Master's Thesis [serial online]. 2010. Available from: ScholarWorks@UMass Amherst.

Gibson LJ, Ashby MF. The Mechanics of Three-Dimensional Cellular Materials. Proceedings of Royal Society of London. 1982; 382(1782):43-59.

Grenestedt JL. Influence of wavy imperfections in cell walls on elastic stiffness of cellular solids. Journal of Mechanics of Physics and Solids. 1998; 46(1):29-50.

Christensen RM. Two theoretical elasticity micromechanics models. Journal of Elasticity. 1998;50(1):15-25.

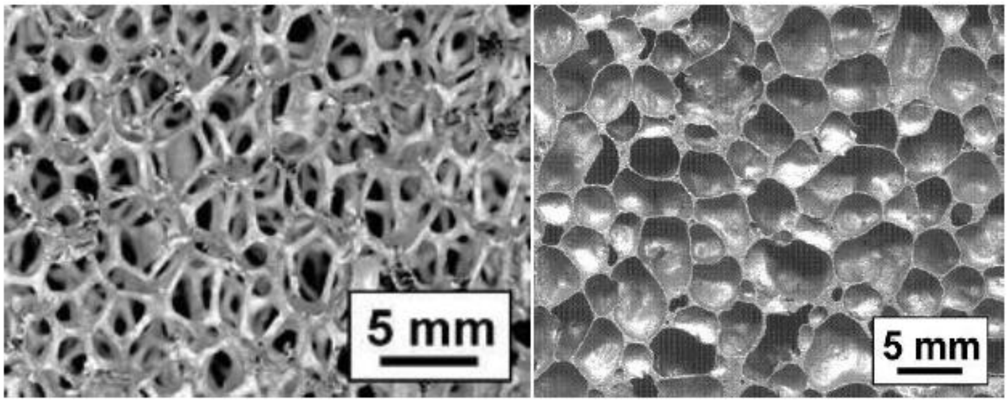
Lu Z, Gao Z. Theoretical Prediction for Young's Modulus and Yield Strength of High Density Foamed Plastics. Science in China Series E: Technological Sciences. 1998;41(3):271-279.

Schjodt-Thompsen J, Pyrz R. Effective Properties of Cellular Materials. Polymer Engineering and Science. 2001; 41(5):752-757.

Tanaka K, Mori T. Average Stress in Matrix and Average Elastic Energy of Materials with Misfitting Inclusions. Acta Metallurgica. 1973; 21:571-574.

Dvorak GJ, Srinivas MV. New estimates of overall properties of heterogeneous solids. Journal of the Mechanics and Physics of Solids.1999; 47(4):899-920.

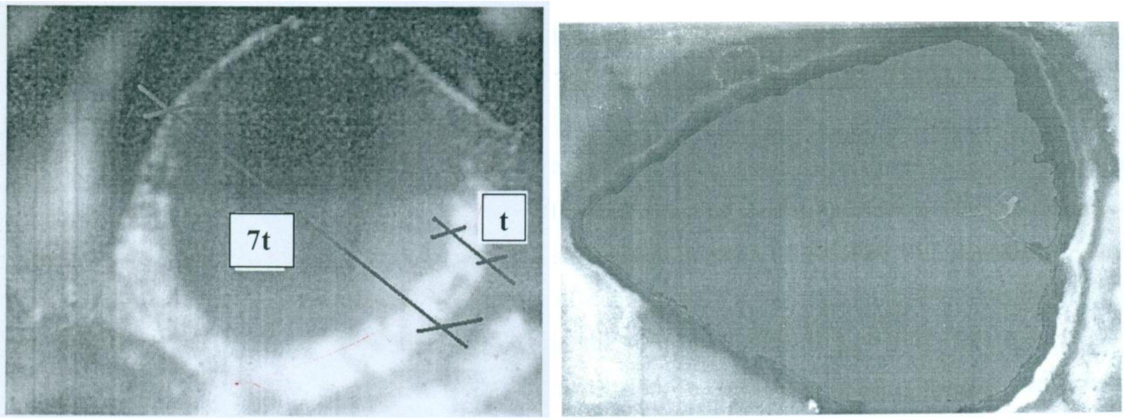
Betts C. Benefits of metal foams and developments in modelling techniques to assess their materials behaviour: a review. Materials Science and Technology. 2012; 28(2):129-143.



(a) (b)

Fig 1. (a) Open cell metal foam (b) Closed cell metal foam

(Patrick J Veale,[2] 2010)



(a) **(b)**

Fig 2. (a) Shape of an open cell wall (b) Cross section of a strut

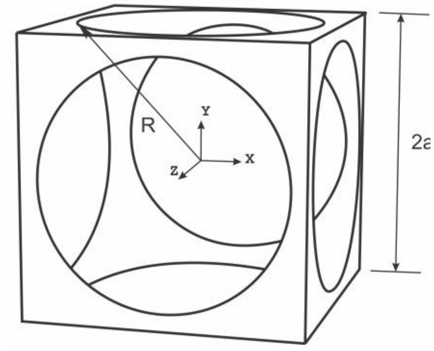


Fig 3. Unit cell of an Aluminum foam material

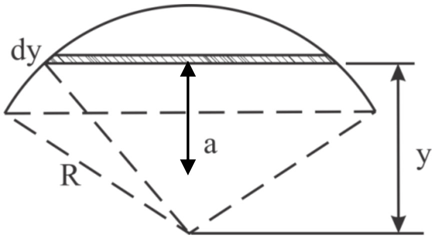
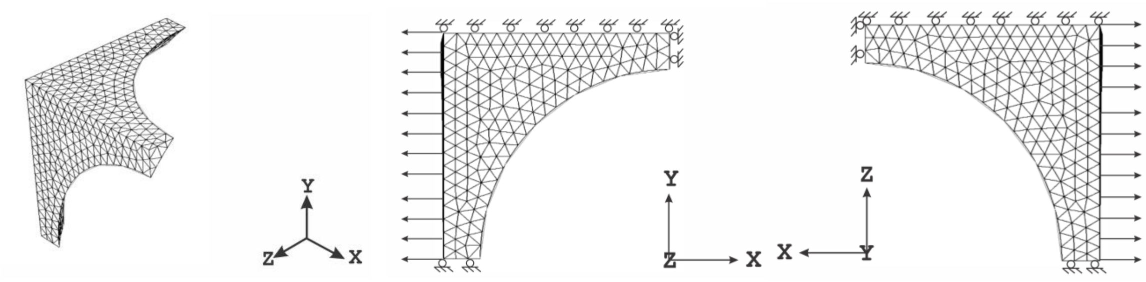


Fig 4. Configuration of a spherical cap



(a) (b)

Fig 5. (a) The Finite Element Mesh (b) Boundary Conditions and Loading

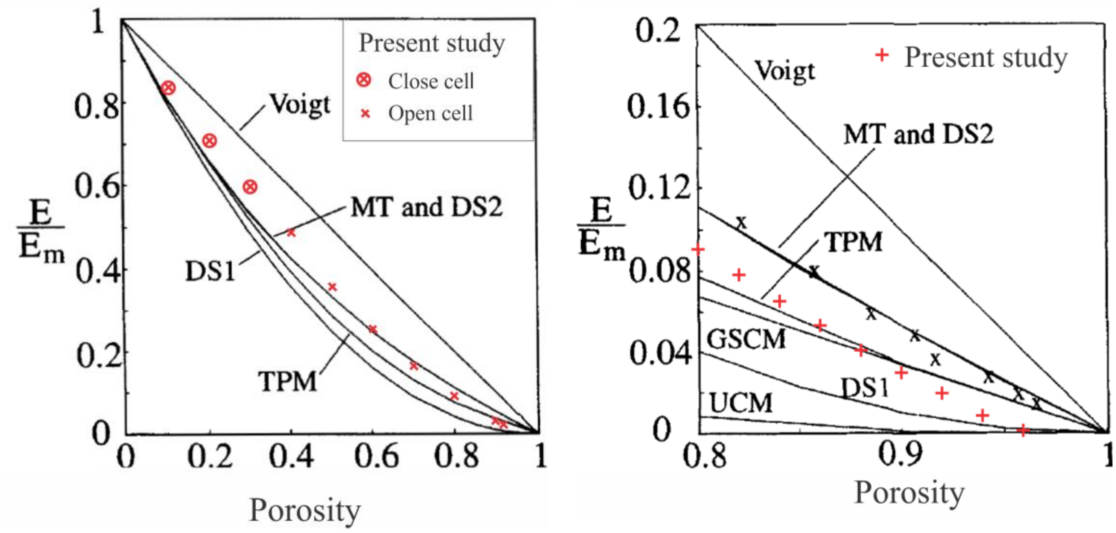


Fig 6. Variation of Young’s Modulus with Porosity