FINITE ELEMENT ANALYSIS OF CLOSED CELL METAL FOAM

A DISSERTATION

Submitted in partial fulfilment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

In

METALLURGICAL AND MATERIALS ENGINEERING

(With Specialization in Industrial Metallurgy)

By

SURENDER

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING

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CANDIDATE DECLARATION

I hereby declare that the work carried out in this dissertation, entitled "**FINITE ELEMENT ANALYSIS OF CLOSED-CELL METAL FOAM**" is presented on behalf of partial fulfilment of the requirement for the reward of degree of "**Master of Technology**" in Metallurgical & Materials Engineering with specialization in "**INDUSTRIAL METALLURGY**" submitted to the Department of Metallurgical & Materials Engineering, Indian Institute of Technology, Roorkee under the supervision of **Dr. B.S.S Daniel**, Professor, Department of Metallurgical & Materials Engineering.

I have not submitted the record embodied in this report for the award of any other degree or diploma.

Date: ____ ____ ______ SURENDER

Place: Roorkee, India

CERTIFICATE

This is to certify that the above statement made by candidate is correct to the best of my knowledge and belief.

Dr. B.S.S Daniel

Professor

Department of Metallurgical & Materials Engineering

Indian Institute of Technology Roorkee

Roorkee-247667

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Date: (**SURENDER)**

Place: INDUSTRIAL METALLURGY

Enroll. No. 14544019

ABSTRACT

The numerical simulation of crushing under compressive load is employed to predict deformation pattern of closed cell aluminium foam. To represent closed cell aluminium foam, tetrakaidecahedral structure is used due the fact that is it has minimum surface are per unit volume, which is also characteristic of real aluminium foam. It was observed that simple phenomenological model consider average behaviour of foam material under quasi static condition and generate yield surface based upon this data for representing dynamic response of metal foam. Though it give reasonable result, still it lack to relate with real foam topography. So unit cell based approach employed in this study can help in tailor design of foam, so that it is acceptable in aerospace, automobile industries as a main structural material.

Simulation of crushing analysis of a standard specimen made up of tetrakaidecahedral aluminium foam carried out using ANSYS16.2 finite element code. In this study, solid material distribution is more along face edges, which results in low peak to valley region. It was seen that cell wall starts collapsing on face rather than near edges due to more material along edges. Stress- Strain curve of foam crushing has been plotted by using Displacement-Reaction force data from ANSYS post solution results.

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LIST OF ABBREVIATIONS AND SYMBOLS

FE	Finite Element
Al	Aluminium
G&A	Lorna Gibson and Michael Farries Ashby
SS&TW	Sigit Santosa and Tomasz wierzbicki
σ_f	Crushing Resistance (MPa)
ε_d	Densification strain
t	Cell wall thickness in mm
ρ^*	Foam density (kg/m^3)
ρ_s	Parent material density (kg/m^3)
E^*	Foam Elastic Modulus
l	Cell edge’s length
E_s	Parent material Elastic Modulus
ε	Strain
σ_{pl}	Plastic collapse strength of metal foam (MPa)
σ_{ys}	Base material yield strength (MPa)
φ	Solid material fraction in cell edges

For Cubic pyramidal & cubic spherical foam model

b	cube width in mm
c	half diameter of pyramid in mm
W	Cube section width in mm
D	Spherical section diameter in mm

CHAPTER 1: INTRODUCTION

Competition in the field of automotive, aerospace and defence industries and strict pollution emission control norms pushed manufacture to look on extra light materials with high specific strength associated with impact energy absorbing capability to safeguard occupants. With continuously increase in fuel prices in international market and certainty of their exhaustion it become necessary for car maker to focus on fuel efficiency to cut fuel consumption by employing light weight material in automotive main frame. Moreover, with increase in demands for high performance vehicle, high speed travel increase the risk of fatal injuries in crash situation (Renault 2008). So metal foam of high specific strength can be better choice for designing crash management system.

Metallic foam possess very unique class of physical, thermal and mechanical properties that make it a potential candidate in diverse field of engineering applications. These feature of metallic foam such as high specific stiffness, very light weight (which otherwise not possible by any other way) make it suitable to use for light weight structures. Metallic foam aren't a new type of materials, foam are very common in nature, bones of animal gives rigidity it require to move body and it has cellular structure inside. In-fact acoustic properties of bone enable to sense their surrounding as it travels through animal's body. For solid material porosity is taken as defect which are not desirable have advantage in case of foams. Wood is an another cellular material which once was main structure material due to light weight and better mechanical properties, but manufacturing is not possible as other materials, also it not stable at high temperature operating condition. Some of other common natural cellular materials are cork, sponge, coral, bone etc. To increase heat transfer rate between solid and fluid, effective heat transfer area should be large as possible, that why porous materials take advantage of increased area.

1.1 Defining Metal Foam

The definition of foam is not well defined, it can be understand from Fig.1 by Banhart which show possible phase dispersion in each of three matter state viz. solid, liquid and gases. On the basis of this classification foam is dispersion of gasses phase in either liquid or solid. More specifically foam are dispersion of gasses in solid. Solid material is present along cell's columns and boundary between adjacent pores. Material along cell edges and face depends upon the application of the foam. Metal and ceramics are used where thermal condition are main concern, owing to high brittleness of ceramics it's not suitable for crushing application, though it may be prefer over metals in case of high temperature application area. Polymer are used as solid phase material for foam where large elastic deformation is utilized such as cushion, sofa pads.

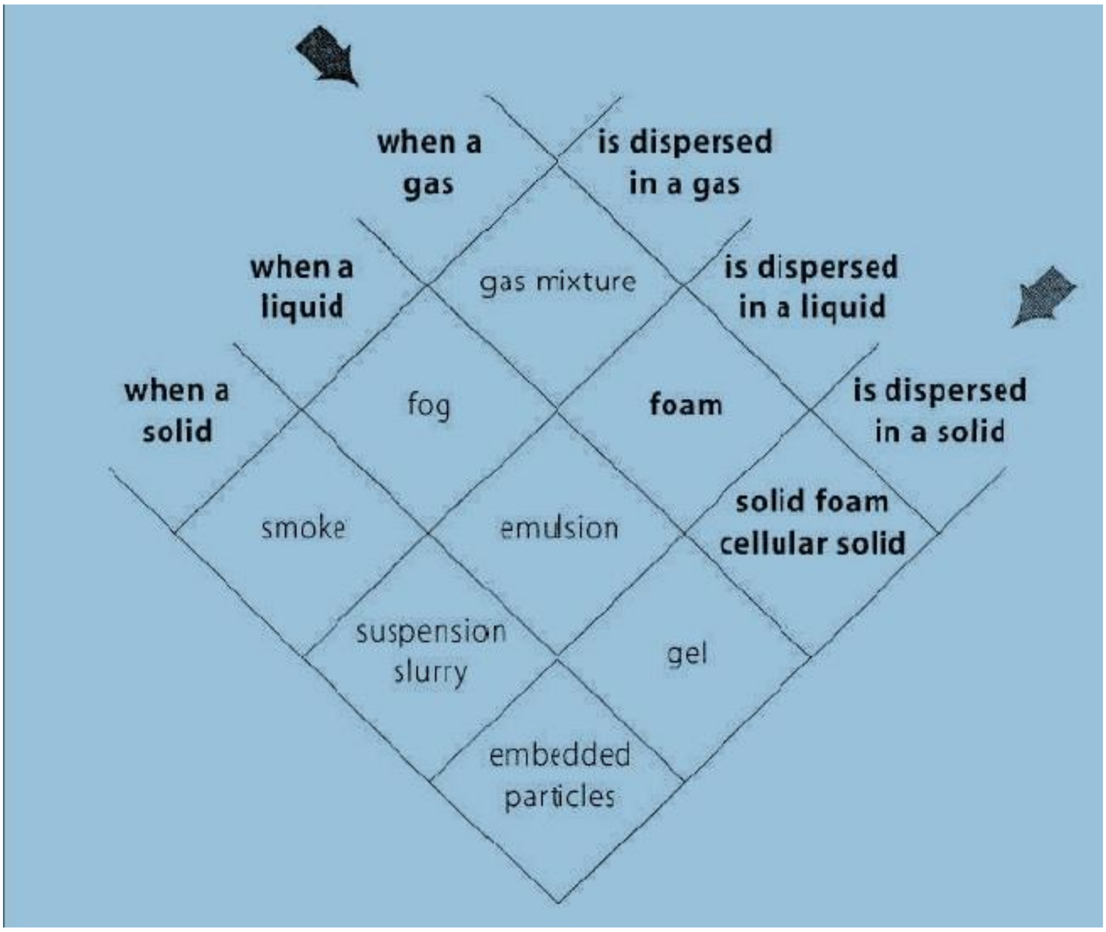


Fig. 1. Different phases dispersion defining cellular materials

As foam constitute solid phase of material with gases, so when it is no longer able to serve its purpose it can easily recycled back to base material of which it was made, leaving gases to surrounding, thus it is 100% recyclable material. There is no solid waste hence no pollution to environment.

1.2 Why Metal Foam ?

How well a material is suitable to use for a particular component can be known only by its different geometrical & mechanical properties analysis. For applications requiring light weight designs, strenght and stiffness relative to density should be high. That means if we know which have higher strength for same weight, is become easy to select material for that application.

Michael Farries Ashby in 2005 prepared diagram constituting density vs stiffness and density vs strength as shown in Fig. 2 & Fig.3 simply called Ashby’s maps on specific properties. These maps are very useful to select a material based on its application requirement. It gives merit index to different materials based its relative position on Ashby’s map. By using high stiffness and low density material is easy to make very light weight, though stiff structures and materials. It is clearly visible on ashby map for elastic stiffness vs density that material with highest “specific stiffness” fall on upper left hand corner Fig.3. Maps shows that materials like CFRP, titanium matrix composite and light metals shows stiffness closed to theroitical value at low density.

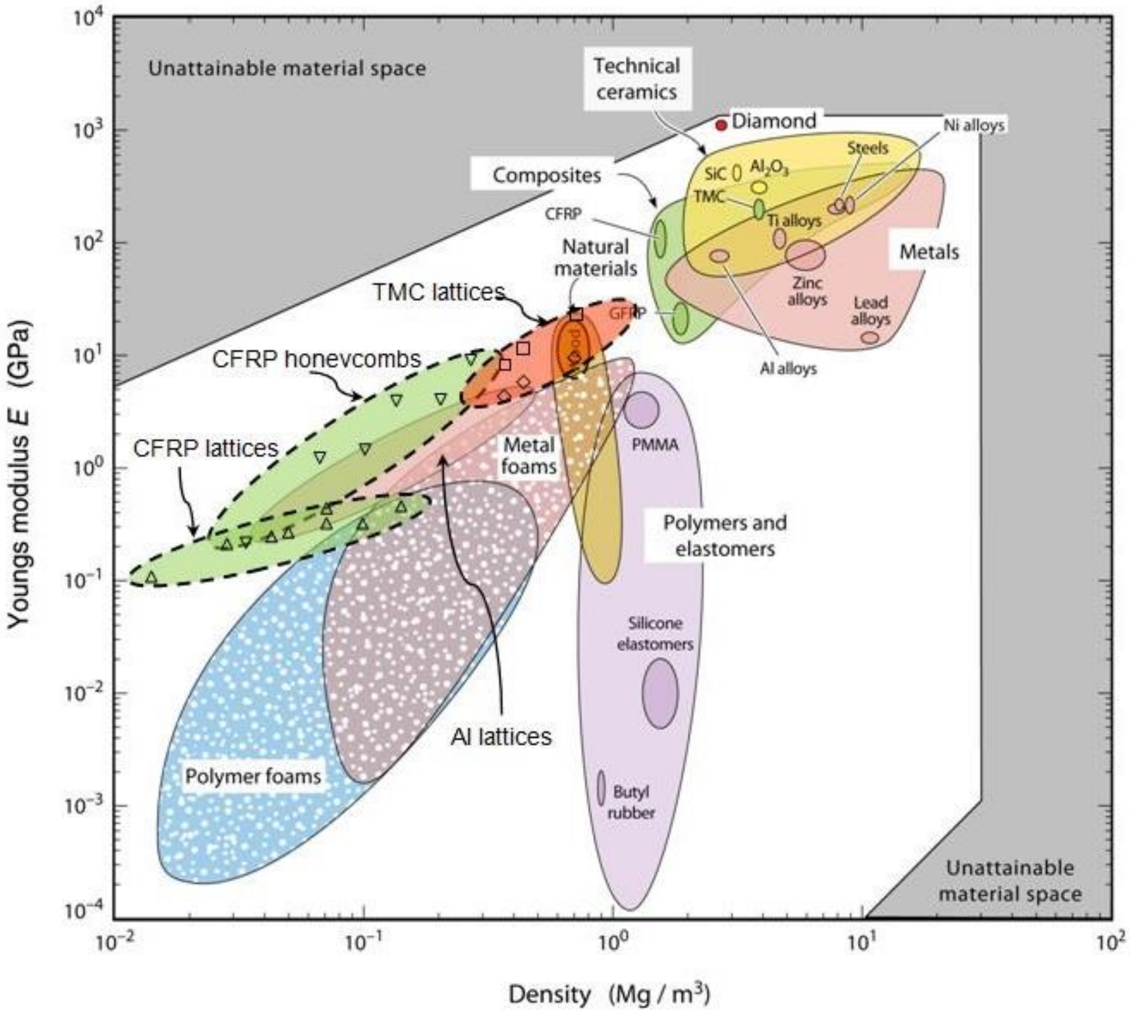


Fig. 2. Specific stiffness of various materials, showing metal foams in left side

Stiffer cellular tailoring needs the use of structure and materials that can extends range failure mode such as plastic yielding, buckling of faces and edges, plastic buckling etc. Cellular material like metal foam have strength much higher than conventional materials like wood.

Closed-cell aluminium alloy foams have high specific strength along with low relative density. Under compression, foams can absorb high energy through progressive collapse of their cellular structure, they display a low increase in instantaneous stress levels over a large range of strain. Also, aluminium foam can attenuate stress-waves. Hence, their usage is becoming greater in crashworthiness.

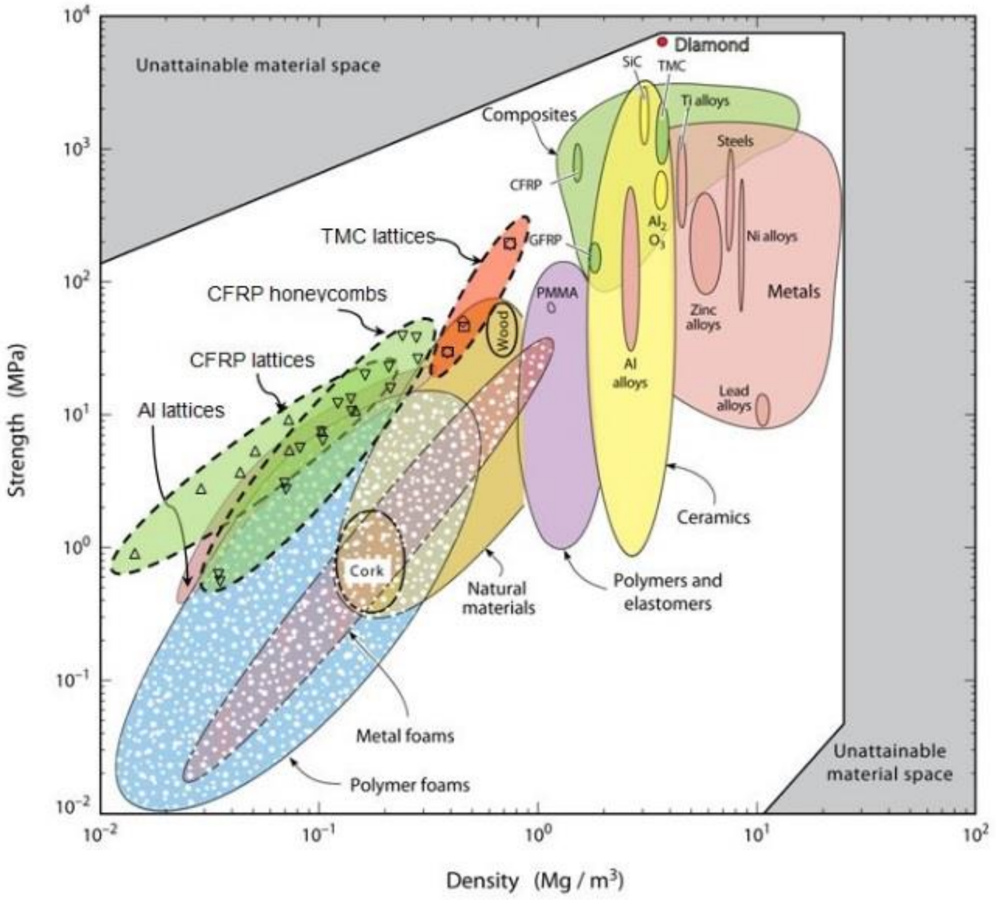


Fig. 3. Comparison of relative strength of various engineering materials

Density of materials depends upon the atomic weight of element or ion of which they made and nature of atomic packing, whereas stiffness of a material dependent upon its bond and how dense is the bonding between material’s atoms. For example those materials which have covalent bonding in their structure show higher stiffness in comparison to those having Vander wall bonds between their elements. Stiffness of aluminium foam varies from 0.15 GPa to 2

GPa, which is a very small fraction of solid aluminium Young's Modulus (69GPa) and foam density is in range of 200 to 1000 Kg/m^3, which less than 30% of solid material density (2700 Kg/m^3)

Strength has different definition for different types of materials, for example for a brittle material modulus of rupture is assume its strength, whereas yield strength is taken as strength for polymer and metals. Same way for metallic foams plateau stress (characterised by extended constant stress region after elastic limit) is consider as strength. This constant stress region also determine amount of impact energy that can be absorb by material upto densification.

In general the word strength means material's lattice resistance to the plastic shear. A recent investigation by Edwin & Daniel shows for a density range of 200 to1000 kg/m^3 there is change in strength (crushing resistance) from 2 to 25 MPa. Which fall in a region far away from metal, to be exact it overlaps with conventional materials like polymer, wood etc. in Ashby's map for strength vs density. This unusual extended feature in this domain shows metal foam potential for replacement of natural material once its reliability and cost effectiveness is proved in automobile, transport, aerospace industries.

This abrupt change in mechanical properties after foaming a material enable metals foam for two important engineering application. First rewards for its high specific strength, metal foam is sandwiched between any metal plates to form sandwiched panel, it is very stiff at the same time very less weight which can of great importance in many structural application. Second aspect is due to its ability to deform at large strain at almost constant stress before densification, which not present in any other material. This feature is of great importance when we want to give protection against shock and impact loading. Due to this feature it is able to attenuate high frequency sound wave effectively as sound wave travel through metal foam it subjected to change of medium from one cell to another thus losing most of its energy. Now a day, it is being used in auditorium for good sound reception to avoid eco.

In this century it has been seen that man has achieve imaginable speed by using high performance in machine like formula one racing cars. Power comes at cost of increase in overall weight of moving machine, to cut increased weight conventional material like steel changed with aluminium and subsequently with magnesium, though this has solved problem to some extent, but it's not cost effective in general purpose application and lack crash protection. These challenges of present time can be addressed by using aluminium foam sandwiched panel to significantly reducing weight and simultaneously providing much needed fire resistance, crash protection.

Still there is long way for acceptance of metal foam in automobile, aerospace industry as main structural material. To make this reality it necessary to understand its behaviour in quasi static and dynamic conditions [Edwin & Daniel].

Based on the literature available on mechanical performance of metal foams, it has been found [1] that the strength and energy absorption features of closed-cell aluminium alloy foam can be enhanced through tailored designs of their microstructure. Hence, it is appropriate to build finite element model based numeric computation that link the overall macroscopic stress–strain response with the cellular structure. The morphology of closed-cell metal foam is very complex. Clusters of irregular cells and defects are basic to their structure, an example of their microstructure is shown in Fig. 4.

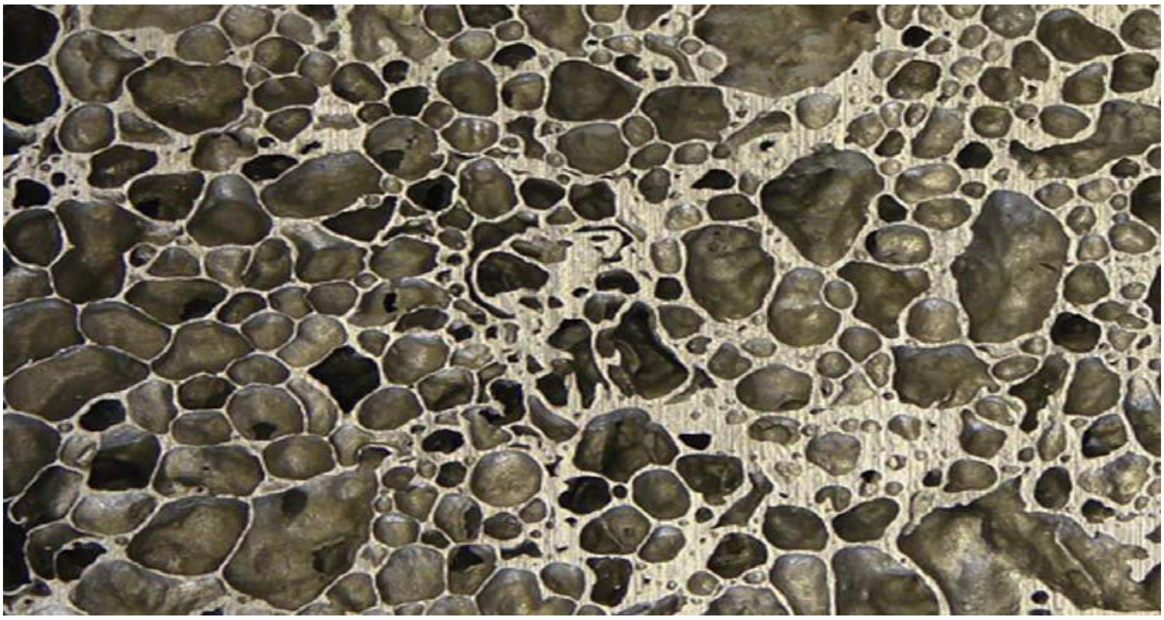


Fig. 4. Typical morphology of aluminium foam showing irregular cells

Modelling procedures are mainly based on two approaches, either phenomenological or repeating unit-cells constructed from idealized cellular structures. Although, aluminium alloy foams performance and characterization is best established empirically, very often it was found that the output of numerical models are reasonably accurate. Modelling also gives good insight into the relationship between macroscopic mechanical properties and the underlying microscopic structure.

Average strength of foam has been predicted analytically based upon experimental data and empirical relationship between average density of foam’s cell and its base material. Experiments were primary source of to determine failure location and how cell structure collapse. However, all these methods does not take cell shape into account, instead of that, these methods assumes uniform random gas pores throughout considered are of interest. Now if we want to focus on any special material property like vibrational characteristics, then we needs experimental data on it, which isn’t available much.

Repeating unit cell approach along with phenomenological approach is being used in current investigation to characterize important properties like strength, stiffness and dynamic behaviour. All the cell’s shapes chosen are repeated uniformly throughout foam’s structure in three dimension space to understand failure location under static and dynamic loading conditions. It helps to avoid multiple sample preparation and lengthy experimental procedure.

CHAPTER 2: LITERATURE SURVEY

To understand the deformation behaviour of metal foam one needs basic knowledge of geometric structure of foam and basics space filling cells system. It has established that foams systems are made up of repeating matrix geometry [2]. Once geometry of repeating unit is mathematically known then an analytical model could be used to represent cell structure. In ancient time’s Great mathematician and philosophers explained space filling structure like simple polyhedrons cubes, hexahedron and dodecahedrons etc. which can be used to represent cell like structure. Almost all natural uniform repeating regular and semi-regular cellular structure has been explained by these grate people in past. Still these are large number of irregular shapes in natural that we still can’t be explain in mathematical terms. So while modelling cellular structure one has to think of using structure that are near to natural cellular structure. Cellular materials particular metal foam can have from three to many more faces in a single cell and the arrangement of face change from one cell to another, thus making foam’s geometry very intricate.

The relationship between spatial and angular parameter has been well explained in the literature, it has been seen that cube is simplest cellular structure that can be used for space filling and easy for mathematical formulation of model. But as the geometry start getting complex mathematical relationship between different parameter become more difficult. Moreover it is better to have as many faces as possible in a unit cell to better represent cellular structure of foam. Kelvin in 1887 used soap bubble to represent cellular geometry and their relationship with others parameters [3].

2.1 Basic Approaches to Model Foam Materials

After analysing literature on metal foam it was seen that two basic modelling approach has been used to modelled metal foam: Phenomenological and Unit cell based approach.

2.1.1 Phenomenological Approach

In this approaches uses basic stress-strain compression data is used to generate yield criterion and yield surface. It used continuum based approach that mean average behaviour of foam is used in this modelling technique, which is indirect approach as it doesn’t include direct effect of cell structure in account. This approach has been used in many recent work on finite element characterisation of metal foam. Though this approach gives reasonable accuracy with time saving in solving model, it doesn’t gives any clear idea about how foam can be tailored based upon cell’s structure as it doesn’t include any direct cellular response. These models are based on ideal isotropic material behaviour from. There is mainly three studies which used this phenomenological approach: very first isotropic model was proposed by Gibson et al.[5], followed by Fleck and Deshpande‘s constitutive model[6] on metallic foams and the last one was extended from Drucker Prager yields criteria.

R. Rajendran et al [7] investigated closed cell aluminium foam for impact deformation behaviour undergoing axial impact due to free fall of a drop hammer to check the candidacy for sacrificial member of the transportation cask. They used ANSYS/LS-DYNA for carrying out numerical simulation of dynamic testing using drop test. Crushable foam material model was used for dynamics simulation. It was found out in parametric study that elastic fraction of the foam deformation energy become insignificant as the impact velocity of the hammer increases.

I.Irausquin et al [8] focused their study on dynamic compression behaviour of a closed cell aluminium foam by implementation of an isotropic hardening model contained in the finite element package ABAQUS. Dynamic compression of the foam was simulation according to the procedure of split Hopkinson pressure bar (SHPB) test for strain rate of 10^3 seg^{-1} . Low impedance materials and steel were used for transmitter and incident bar to evaluate their reliability to characterize foam. Strain wave was analysed to check the influence of composition and dimension to realize the proper material of the bars to be used in SHPB test of the selected metal foam. It was found out that Nylon and PMMA are suitable in comparison to conventional steel bar for dynamic testing of Alporas aluminium foam under SHPB conditions.

R. Rajendran et al [9] investigate closed cell aluminium foam by phenomenological approach, a stainless steel tube filled with aluminium foam was tested to check improvement for impact energy absorption features. Static compression data was used to find interaction factor for tube foam interface. A force reduction factor approximately 3.32 was found between tube and aluminium foam, which could prevent any damage due to impact. It was found that tube filled aluminium foam undergoes less deformation in comparison to aluminium foam and tube alone which shows it is more efficient. Also numbers of fold in case of foam filled tube was more in comparison to hollow tube that means it absorbs more energy and results in low impact force.

Second approach is rather more realistic then first one, it harness unit cell geometry which is easy to represent mathematical relationship for mechanical response, relative density and other feature of metallic foam. This approach is unit cell based approach, so before is important to know which geometry shapes can be used to fill three dimensional space by repeating these unit cells. In this modelling approach repeating unit cell's internal structure define the structural level approach of cellar metal. This investigation is also based upon unit cell based finite element modelling.

2.1.2 Unit Cell Based Modelling Approach

To analysis cellular material, it is necessary to understand basic space filling structures, which is then used to make a physical model that occupy three dimensional space. Thus unit cell is stepping stone for analysing foam materials. Unit cell (C) has three basic parts of which it is made of, first point in space are called Vertices (V), joining of two vertices produces edges (E) and same way more than two edges when connected one to another produces an enclosed area is known as face (F). It were Plato and Archimedes who first gave the concept of basic polyhedron by using vertices, edges and faces. Plato said there are five basic regular polyhedrons. They are regular polyhedron due to the fact that their edges length is same for all the faces. Plato suggested five polyhedrons as cube, tetrahedron, dodecahedron, icosahedron and octahedron [10]. Later Archimedes used these regular polyhedron to proposed thirteen others semi polyhedron, which shows periodicity in space and he used only regular face to make these polyhedron [11].

Now this concept of three dimensional geometry of cellular solid can be applied to analyse metal foam materials. Though metal foam or any foam material doesn't have uniform cellular cell, still there exist some topological relations. In 1746, Euler [12] gave relationship between basics cell's components e.g. number of vertices, edges and faces in a cell. Euler mathematical model, which known as Euler law is represented as:

$$F - E + V = 1 \qquad \text{(2 dimensions)} \qquad (1)$$

$$-C + F - E + V = 1 \qquad \text{(3 dimensions)} \qquad (2)$$

By using these relationship between different cell's parameters its internal angle between faces can be found out, which can be used to further determining how much volume it acquired in space.

Nature's conservational law's equally applies to cellular solid also, it say area and volume of a cell is conserved. That means when cell stacked to make a geometry in space faces of adjacent cell must match each other perfectly so that there is no void. There are only two polyhedron of five Platonic solid's and thirteen Archimedes solid's which can be used to fill space without leaving any void, these are known as space filling structure, which are cube and tetrakaidecahedron. Among these two space filling structure tetrakaidecahedron has minimum surface area for same volume occupied compared with cube lord Kelvin (1887). After almost a century later in 1994, Weaire and Phelan proposed first unit structure having minimum surface per unit volume by computational numerical methods.

Basics space filling polyhedrons

The above mentioned polyhedrons can be used to represent foam material's structure. Some of these polyhedron are explained as follows:

1. Cubic Structure

Cube is the simplest regular polyhedron that can be used to fill three dimensional space. It consist of eight vertices, twelve edges and six faces. Though it is very easy to develop relationship between its geometry and material parameters, still it doesn't accurately represent cellular feature of metal foam material. Its geometric simplicity is only beneficial when loading is axial tension or compression. But when this cubic model is loaded in others planes, it doesn't not give any reliable data [2, 13]. While filling space with cubic structure it develop a lot of parallel faces which gives very high peak to valley due simultaneous collapse of parallel wall in different cells. Also when loading is not on vertices of cell, it become difficult to predict bending and distortion. Thus cubic model isn't desirable for foam material representation.

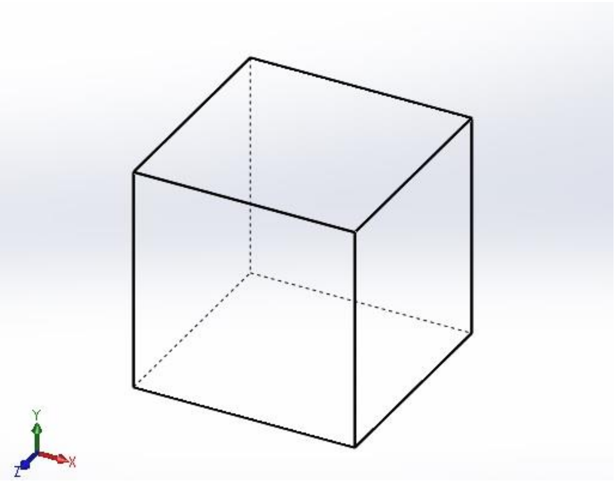


Fig. 5. Simplest space filling cubic cell

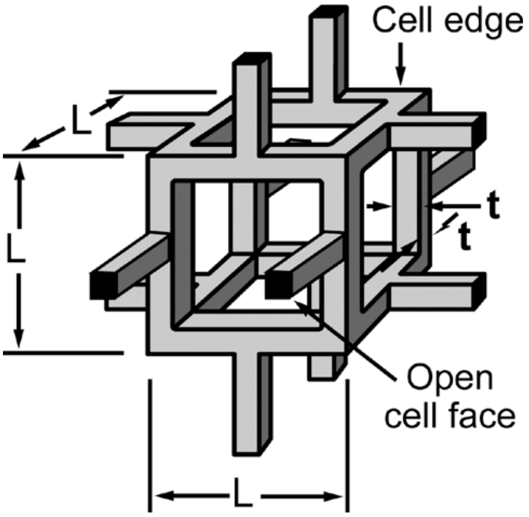


Fig. 6. Idealized cubic foam model of G&A

Large portion of work on static behaviour of foam has done by Lorna Gibson and Michael Ashby (G&A). Most of the recent time finite element models have used work by G&A's simple cubic analytical model (Fig.2) as base to investigate further into foam modelling. G&A have established relationship between structural based properties and mechanical properties as follows: Relative stiffness of foam with respect to solid material in equation (1a) followed by plastic collapse strength of both open and closed cell foam in equation (2) and (3) respectively.

$$\frac{E^*}{E_s} = \emptyset^2 \left(\frac{\rho^*}{\rho_s}\right)^2 + (1 - \emptyset)\frac{\rho^*}{\rho_s} \tag{1a}$$

$$\frac{E^*}{E_s}(\emptyset = 1) = \frac{\rho^*}{\rho_s} \tag{1b}$$

$$\frac{E^*}{E_s}(\emptyset = 0) = \left(\frac{\rho^*}{\rho_s}\right)^2 \tag{1c}$$

$$\sigma^*{}_{pl}(Open\ cell) = 0.3\sigma_{ys}\left(\frac{\rho^*}{\rho_s}\right)^{3/2} \tag{2}$$

$$\sigma^*{}_{pl}(Closed\ cell) = 0.3\sigma_{ys}\left(\frac{\rho^*}{\rho_s}\right)^{3/2} + (1 - \emptyset)\sigma_{ys}\frac{\rho^*}{\rho_s} \tag{3}$$

2. Tetrakaidecahedron Structure

In 1887, Lord Kelvin proposed most complex and accurate model to fill three dimensional space with minimum surface area per unit volume feature. According to Kelvin, tetrakaidecahedron is most efficient space filling space, it also called regular truncated octahedron. It consist of six square plane and eight hexagon planes, twenty four vertices connected by thirty six edges produces total fourteen faces to make a tetrakaidecahedron structure

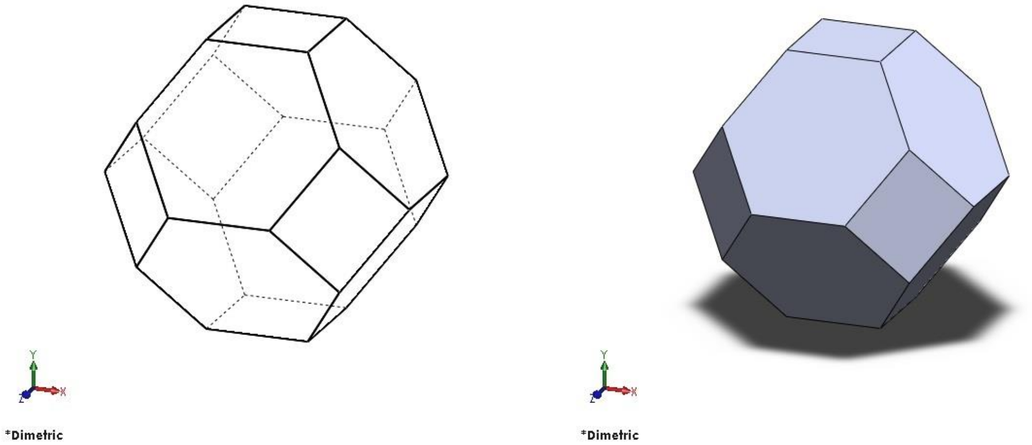


Fig. 7. Kelvin Tetrakaidecahedron unit cell structure

Most beautiful thing about this model is that it can make matrix within any structure. Analytical studies by Zhu, Knott and Mills [14] on Kelvin's tetrakaidecahedron structure shows good correlation with real foam material. Their investigation shows tetrakaidecahedron model gives nearly isotropic nature in elastic region. Though effect of relative density, face and edge shape on Young's Modulus still needs to further exploration. It was found that this model is much similar to various bubble and foams geometry available in nature.

Later on Simone and Lorna Gibson (S&G) proposed more important Kelvin-tetrakaidecahedron analytical model on cellular material, which still used as base for metal foam modelling. Current investigation also is based upon tetrakaidecahedron foam. S&G derived relationship for relative density and relative stiffness for tetrakaidecahedron foams as in equations (4) and (5) as follows:

$$\frac{\rho^*}{\rho_s} = 1.185\frac{t}{l} - 0.4622\left(\frac{t}{l}\right)^2 \tag{4}$$

$$\frac{E^*}{E_s} = 0.32\left[\left(\frac{\rho^*}{\rho_s}\right)^2 + \left(\frac{\rho^*}{\rho_s}\right)\right] \tag{5}$$

Due to geometrical close to real foam tetrakaidecahedral structure has been used as repeating unit of many recent research work done on both open and closed cell metal foam. Ref [15] has taken number of edges per face and face per cell as parameters to study their effect on its mechanical response. Most of the work on tetrakaidecahedral foam has been focused on its static behaviour such as its Young's modulus and peak stress in elastic limit. A notable work on its large strain at low strain rate has been done by S.K Nammi et al(SKN) [16], their work consider unit cell inherited from G&S tetrakaidecahedral unit cell with some modification in unit cell size.

The basic analytical tetrakaidecahedral foam model is key to S&G repeating unit and same unit cell with unit cell size difference has been taken in SKN's work and has been extended to large strain quasi static study. They have named their model's unit cell as generic repeating unit cell. A unit cell of cubic shape with dimension $4l \times 4l \times 2\sqrt{2}l$ was proposed to study tetrakaidecahedral. It was characterized by low peak to valley compare to cubic-pyramidal and cubic spherical foam. The relative density of their model given by equation (12)

$$\frac{\rho^*}{\rho_s} = 1.1837\frac{t}{l} \qquad (12)$$

There is still a lot of work that can be unearth on tetrakaidecahedral foam such as its dynamic behaviour under high strain rate. In investigation by S.K Nammi et al, they have taken mass along face edges as negligible which is the main reason of stress concentration along edges due to the sharp edges. This can be reduce by taking convex curvature along face edges, the same effect will be investigated in current work.

3. Weaire & Phelan's Unit Cell Structure

After Lord Kelvin, almost a century later Weaire and Phelan [17] proposed little more efficient space filling model based on computer optimization method to reduce surface area per unit volume. They used six tetrakaidecahedron and two dodecahedron to make their unit cell with total twelve vertices, twenty eight edges and fourteen face. By using this this cell, surface area was decreased by 0.3% over tetrakaidecahedron structure. But it lack mathematical explanation for space filling optimization.

Weaire and Phelan's model show very less anisotropy due to the fact that it has very less number of parallel faces which decreases distortion effect significantly. That's why is considered a potential candidate to present foam material, but lack of mathematical model development restrict its use, plus 0.3 isn't significant decrease in surface area, that can compensate its others drawbacks.

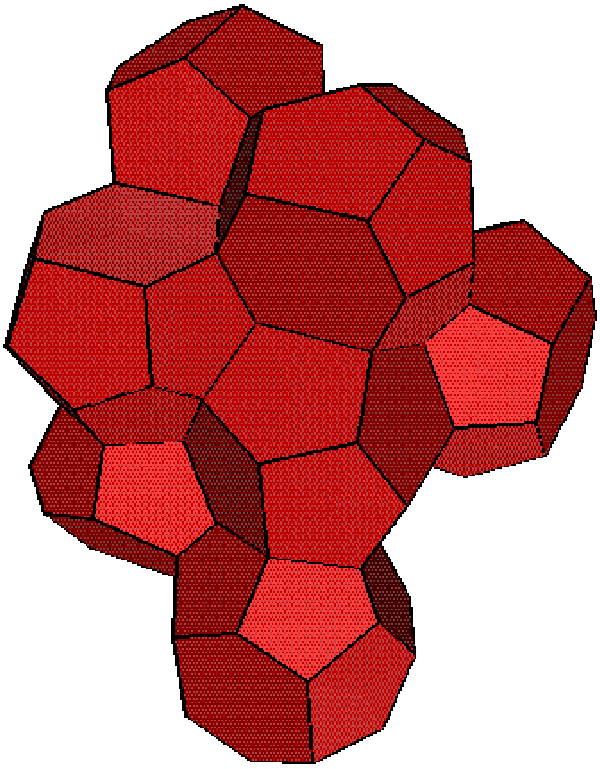


Fig. 8. Weaire Phelan Cellular space filling unit cell

During foaming process of metal foam material gas bubbles never show regular structure, they are random in nature, also it shows many clusters of solid metal. Thus a regular model like Weaire-Phelan or Kelvin tetrakaidecahedron can never represent solid metal foam under every possible ways. However these model's efficiency in space filling is promising characterisation which encourage their use for modelling real metal foam. Also during foaming process, surface tension on bubble faces pulls material from face centres towards edges and if we see in little depth, most of material is present at vertices. So the model used in current work is focusing more on this aspect of metal foams.

In all previous model based on unit cell approach, the models which have used finite element models based on large deformation (large strain) gives better understanding between global mechanical response and morphology of the cellular structure. Most of these model were on closed cell aluminium foam, which assume aluminium foam as combination of two types of unit cells, in which one is major cell which is having another smaller unit cell on its vertices. In one these model have used cube as major or large cell and another pyramid or sphere on vertices. They are modelled such a way that once sphere or pyramid is placed on vertices, all the part of large cell falling inside smaller cell is removed. Thus this makes it conglomeration of cubes, sphere and pyramids. All these models have used G&A simple cube analytical model as basis and made some refinement in that.

Another major work on unit cell based approach was done by Sigit Santosa and Tommasz Wierzbicki (SS&TW) [18],

They used little refined approach to S&G by utilising simple cube as large unit cell with addition of another smaller unit cell of pyramid shape to define aluminium foam structure [18].SS&TW modelled is better known as cruciform pyramidal is shown in Fig.3. It can been seen that they just have added pyramid shape to already modelled simple cube of G&A model. The analytical formulae for relative density and densification strain of their work has be explained in equation (6) and equation (7) respectively

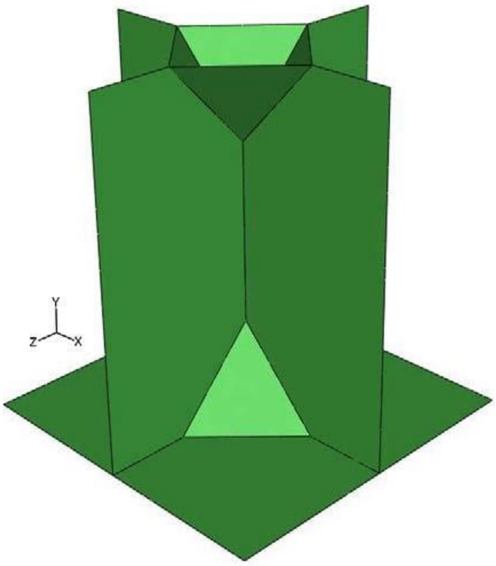


Fig .9. Cubic-Pyramidal unit cell of SS&TW

$$\frac{\rho^*}{\rho_s} = 3\frac{t}{b} + \left(4\sqrt{3} - 6\right)\left(\frac{c}{b}\right)^2 \frac{t}{b} \qquad (6)$$

$$\varepsilon_d = 1 - \frac{c\sqrt{6}}{2b} \qquad (7)$$

$$\sigma_f = 3.46\sigma_{\circ}\left(\frac{t}{b}\right)^{1.5} + 0.2\sigma_{\circ}\left(\frac{t}{b}\right) + 7.7\sigma_{\circ}\left(\frac{t}{b}\right)^2 \qquad (8)$$

Further, in later studies it was found that when pyramid was replace by sphere in unit cell proposed by SS&TW the crushing resistance of foam has decreased [19]. Cellular structure in all these studies have used sectioned with smaller spherical section. One of the notable work was done by Meguid et al[20], they have used Gaussian distribution of cell wall thickness of a multi cell model of cubic-spherical foam model. Another work by Kim et al [21] used thickness ratio of larger cubic and smaller spherical cell. All these mentioned model showed the main characteristic of aluminium foam, which is plateau region associated with compression band. The unit cell adopted in cubic spherical aluminium foam model is shown in Fig.4. Expression for relative density, densification strain & foam's stiffness can been seen in equation (9, 10&11) as follows

$$\frac{\rho^*}{\rho_s} = 3\left[1 - \frac{\pi}{4}\left(\frac{D}{W}\right)^2\right]\left(\frac{t}{W}\right) + \pi\left(\frac{D}{W}\right)^2\left(\frac{t}{W}\right) \qquad \textbf{(9)}$$

$$\varepsilon_d = 1 - 0.54\frac{D}{W} \qquad \textbf{(10)}$$

$$\sigma_f = 3.36\sigma_\circ\left(\frac{t}{w}\right)^{1.5} + 0.09\sigma_\circ\left(\frac{t}{W}\right) + 7.17\left(\frac{t}{W}\right)^2 \qquad \textbf{(11)}$$

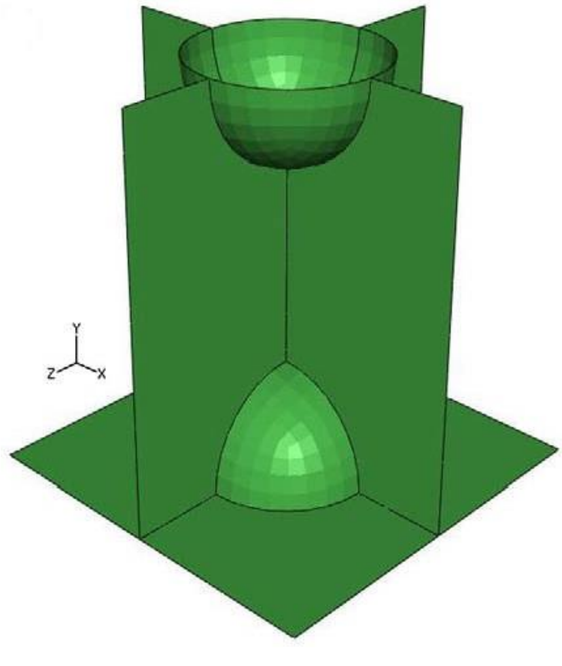


Fig. 10. Cubic Spherical unit cell model

A new unit cell model proposed by Czekanski et al [22,23] showed well matched stress strain response with real foam supplied by Norsk Hydro company limited used sphere crossed with plane along face diagonal of cube as repeating unit cell. They have used four unit in all three orthogonal directions. But their model lack mathematical analytical formulation for material and mechanical properties.

Basic properties of metal foam such stiffness, relative density, crushing resistance etc. are dependent upon the parent material's properties and the way it processed. From recent investigation on closed cell aluminium foam it has established that plateau region stress doesn't much dependent upon strain rate at which it is crushed, that means dynamic compression is very closed to quasi static compression behaviour and it has been well seen in case of 6062 aluminium alloy and Alulight. Least strain sensitive aluminium alloy are of 6000 series. Though dynamic behaviour of aluminium foam make them suitable to use for crash protection but still their low strain rate testing is necessary before dynamics testing.

In this study, the aluminium alloy (AA6063T7) material properties had been used on unit-cell material which were used in SKN. A macroscopic cellular structure was made by stacking multiple unit cells and the finite element analysis was performed on finite element code ANSYS. Quasi-static loading conditions was applied to foam and the compressive response was studied.

Gibson and Ashby [2] used theoretical approach for determining mechanical properties and other material characteristics of foam structure. Their vast work on foam is basis for theoretical relationship between the porous material and its base material. Basic cell relationship for stiffness and strength of foam structure was derived empirically from their work.

Roberts *et al* [24] investigate random cellular structure of foam by using finite element method to compute microstructure dependence of Young's Modulus and Poisson's ratio. Their investigation shows that the theoretical between Young's Modulus and density is more complex than the empirical relationship derived from Gibson and Ashby's analytical model. They have also found that certain geometries under axial compression, the forces are balanced so the central node is locked in position.

J. Banhart & J. Baumeister [26] investigated deformation behaviour of a series of aluminium and zinc foam by uniaxial testing. It was expected that deformation of metal foam is anisotropic due to the existence of a closed outer skin and with respect to the foaming direction, a series of measurement was carried out by varying the orientation of the outer skin and foaming direction.

The effect of age-hardening heat treatment on stress-strain curve and compressive strength was investigated by mechanical testing of aluminium and zinc based foam. At last the axial deformation behaviour of aluminium tubes filled with aluminium foam was tested under uniaxial loading conditions.

Mechanical testing show that form of stress-strain diagram depends upon the density of the foam, relative orientation of the testing and foaming direction. It was found from the investigation that higher densities leads to higher stresses under compression conditions but also to a reduction of the range of the important plateau region. When applied force was parallel to the outer skin, it shows higher strength and extension of the plateau region as compare to the perpendicular direction. However relative direction of force and foaming direction is of minor importance, thus investigation show foams nearly isotropic.

Guillaume Maitrejean *et al* analyse the super elastic behaviour of open-cell tetrakaidecahedral shape memory alloy (SMA) foam under quasi static loading. It was found that tetrakaidecahedral geometry is of particular interest when associated with SMA as it takes more advantage of the superelastic property of the material then foam with randomly distributed porosity.

V.R . Feldgun et al [27] proposed a two phase model to simulate shock wave impact on aluminium foam using LS-DYNA finite element code. Riemann problem solution for compressible medium (air) and foam was obtained by using numerical method as well as semi analytical and analytical methods. The equation of state proposed in this model successfully able to simulate shock wave travelled across Alporas foam.

Amir H. Roohi et al [28] proposed a model based on the random size and positioned pore in solid material, with better control on relative density of foam. Laser forming process was modelled using finite element modelling, which shows good agreement with experimental results. Modelled shows that number of smaller cell and their volume is larger compared to bigger pores. FEA conclude that relative density are mean cell size are the most significant factor effecting bending angle.

M. Altenaiji et al [29] investigated synthetic foam by compressive test to obtain stress strain curve to check its candidacy for protective material under dynamics loading. They studies the effect of volume ratio of ceramic sphere and metal matrix on mechanical properties of synthetic foam.

S.K Nammi et al [14] finite element model represented closed cell aluminium foam with a new type of repeating unit cell (RUC) from tetrakaidecahedra structure using finite element code ABAQUS. Material properties of aluminium were assigned to this unit to evaluate stiffness and mechanical behaviour of this model under large strain. Tetrakaidecdahedron structured foam model was compare with cruciform-pyramidal and cubic-spherical unit cell foam model by describing the load and global deformation response in terms of unit cell structure. It was found out that the crushing resistance and energy absorption capability of foam with this kind of RUC was higher than the cruciform-pyramidal and cubic-spherical models. The stress-strain response of their model shows a plateau phase with relatively low peak and valley stress levels and relatively flat topped curve in the neighbourhood of initial peak-stress, which is similar to aluminium foam. Further cruciform-pyramidal and cubic-spherical models produced high stiffness and initial peak stress followed by steep drop in stress level, which show their RUC is better.

CHAPTER 3: CLOSED CELL METAL FOAM

3.1 Metal Foam

Foams are special kind of materials in which gases are dispersed in high proportion within solid material. Cellular material has been there in nature for long time, wood, bone are some of natural cellular material which have pore of gases in their structure which make them lighter in weight. Because of it, wood have been used extensively in many structural applications like ship building before advent of twentieth century. Presence of large fraction of gas phase results in very low density compared to solid materials of which they are made of. Due their very low relative density they possesses high specific stiffness, strength, surface area and can absorb large amount of impact energy at approximately constant stress. In twentieth century, artificial foam like polymers foam are used at large scale for packing, puddling, insulation purposes and cushioning. They are easy to process and not so costly, so now they are being used almost in every items of comfort. But when they are subjected to high temperature they failed to serve their purpose, wood is also not suitable for high temperature applications and they don’t have high stiffness needed for structural applications. Due to all these reasons metal become popular in twentieth first century, as they high specific stiffness, strength and energy absorption capacity along with they can withstand high temperature environment compared to polymer foams.

Foams are usually classified into two categories: Open Cell and Closed Cell foams see Fig.11 Closed cell foams have gas pore separated from each other by means of solid material walls. Soap bubble is a very simple representation of closed cell metal foam’s cell structure. Due to presence of solid material along cell wall the compressive strength of closed cell metal foam is higher in comparison to open cell foams, which don’t have membranes between adjacent cell, Thus pore or cavities are interconnected and hence fluids can pass easily through them, making them suitable for heat transfer applications. Though they have low compressive strength due to less solid material, still their flow through capability make them useful for many other applications.

As metal have high melting point so metal foam like aluminium or steel foam have better thermal stability in comparison to polymeric foams, plus good mechanical strength make them suitable for many structural and energy absorption applications.

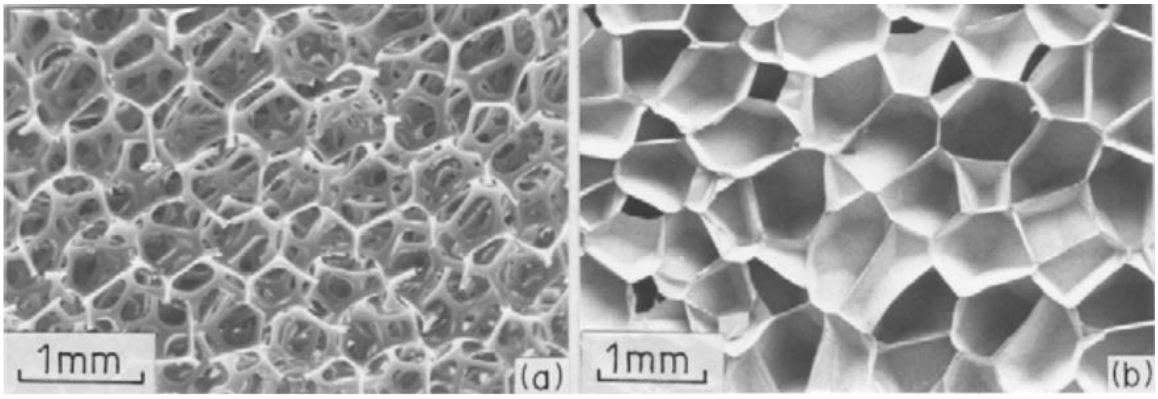


Fig. 11. (a) Open cell metal foam, (b) Close cell metal foam [6].

Nowadays special metal foam like Ni Cr Al alloy are being developed for high temperature resistance application, these metal foams can be used for fuselage for storing solid oxide rocket fuel at elevated temperatures.

Precious metal like gold, silver etc. which are epicentre of fashion cost put a lot of burden on economy of developing countries. Making jewellery porous can be a solution to reduce its import, so research is being carried to make porosity in these precious metals. Sub-micron porosity is being produce in Ni based super alloy by leaching or by some specific dissolution techniques. Ni based super alloys foams can be useful when it have good mechanical strength, ductility along with high thermal resistance & fine porosity to make fine membranes. [30]

3.2 Properties of Metal Foams

- **Mechanical Properties:** Closed-cell aluminium foam absorb huge amounts of compressive energy at a constant stress Figure 2(a) so, these are suitable for crash (impact) applications [7] and blast-resistant applications [31]. Good stiffness of these closed-cell foams make them suitable for extra lightweight structural applications. Variation in size of cell greatly influences mechanical properties [32]. The deformed cell bands formed during compression of aluminium foam can be seen in Fig. 2(b) [32]. During deformation, the cell walls buckled as shown in Figure 2(c) [33]. Stiffness of metal foam is a function of the modulus of the base metal and solid material density:

$$Foam's\ stiffness = Constant\ (E) \times \left(\frac{\rho^{foam}}{\rho_{solid}}\right)^{n}$$

Where E is Young's Modulus of solid material and n varies from 1.7 to 2.3. So different metals and alloys will not have same stiffness, so in selecting a foam may depends upon requirement of application [2, 34].

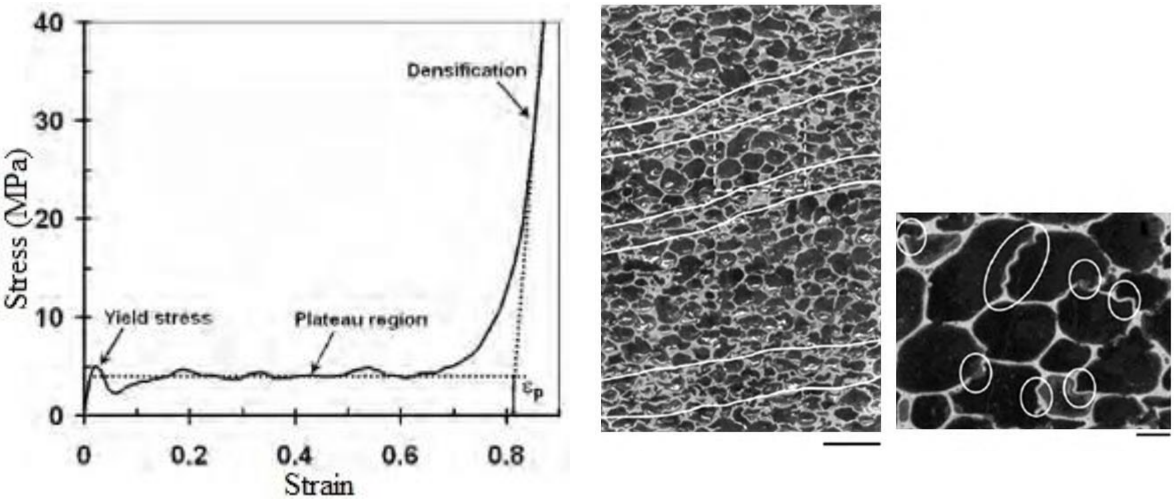


Fig. 12. (a) Approximately constant stress region unique stress-strain diagram only occur in foams (b) At approx. one third of total strain aluminium foam's cell walls starts folding [5]

- **Acoustic & Damping properties:** Aluminium foam are excellent dampers to high frequency vibration and also for sound absorption where noise pollution is main concern and also in auditorium for better perceptibility. When vibrational energy of sound travel through a medium, ratio of mechanical energy lost in medium in form of heat in a single cycle is called loss factor for that material. It was seen that for aluminium foam loss factor increases with its relative density, so instead of other dense material aluminium foam can a better choice while making sound sensitive compound. It was also seen that in mid frequency region aluminium foam perform exceptionally.

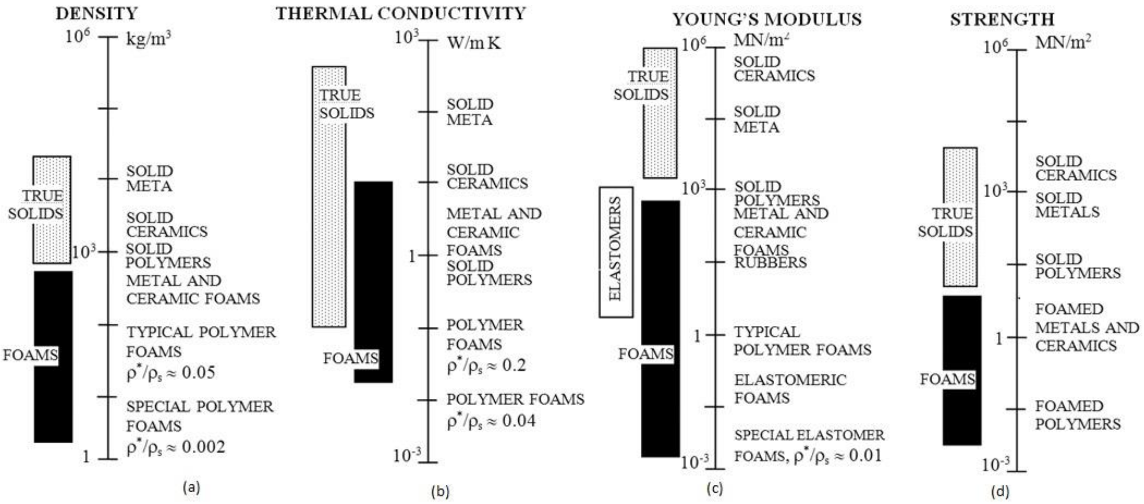


Fig. 13**.** A comparison of metal foam properties with other material [6]

3.3 Applications of Metal Foams

- **Impact Energy Absorbing Capacity:** Cellular metals can absorb huge quantity of impact energy when they are crushed, when stresses are only to compression region of the material. Foams can therefore act as impact energy absorbers, which limit accelerations in road crash situations. This mode exploits the horizontal regime of irreversible deformation in the load-deformation diagram (Fig. 12)

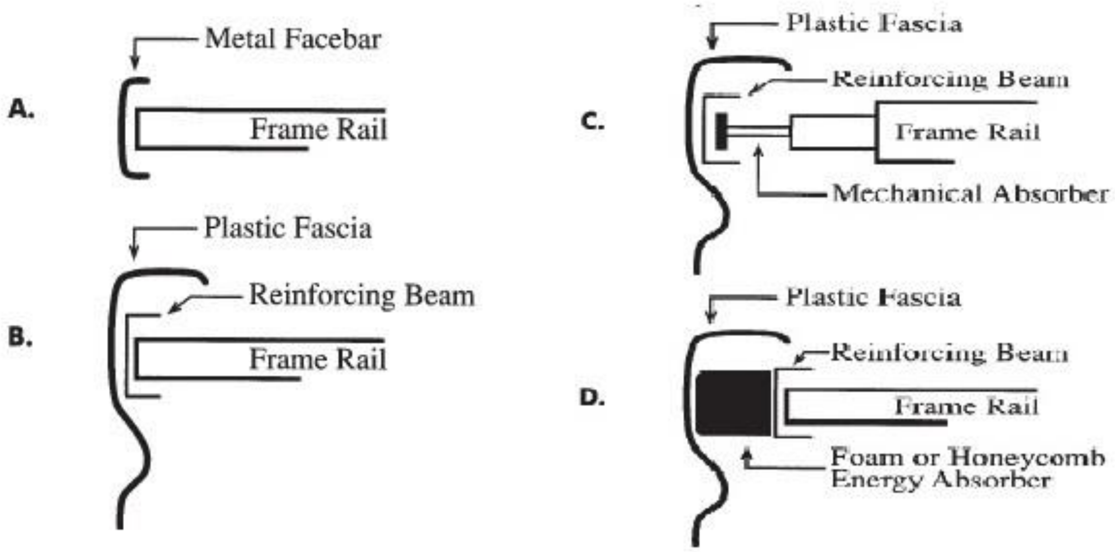


Fig. 14. Application of metal foam in bumper design principle

It has been seen that integration of metal foam in the tube increases the number of folds in comparison to empty tube & foam alone configuration during deformation, and the energy absorption capacity significantly improved. Crash bag employed in various high end car uses same principle e.g. Fig.15 & Fig.16. For given impact loading conditions, an optimum relative density for foam exist that may absorb energy to its highest capacity, thus decrease impact effect to the highest level [34].

Fig. 15. Audi technology portal pedestrian protection

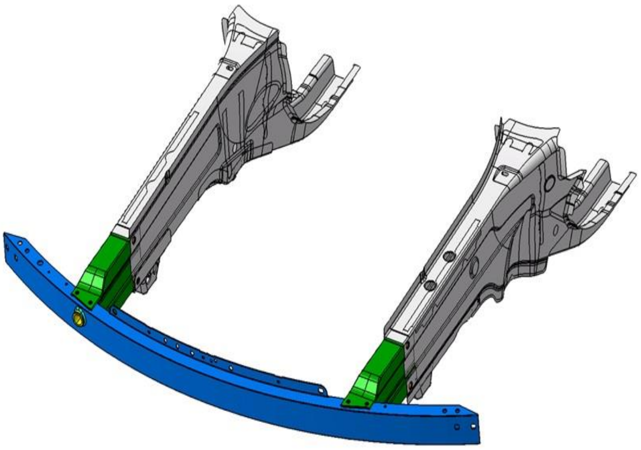


Fig. 16. All-aluminum crash management system of the Mercedes-Benz C class, the first car which uses an inserted crash box

- **Application in Space & defence industries**: Hybrid metal foam structure is being investigate to use at high speed to save Airbus from bird hit impact, while French and German Aerospace agencies in collaboration are building shields for Ariane rocket booster, that can save it from any possible debris impact problem (Fig.7-8) [35].

Fig. 17. Aluminum foam sandwiched is being used in Ariane 65 rocket

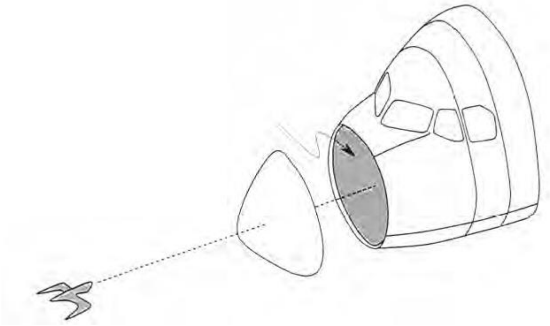


Fig. 18**.** Airbus front shield changed with metal foam

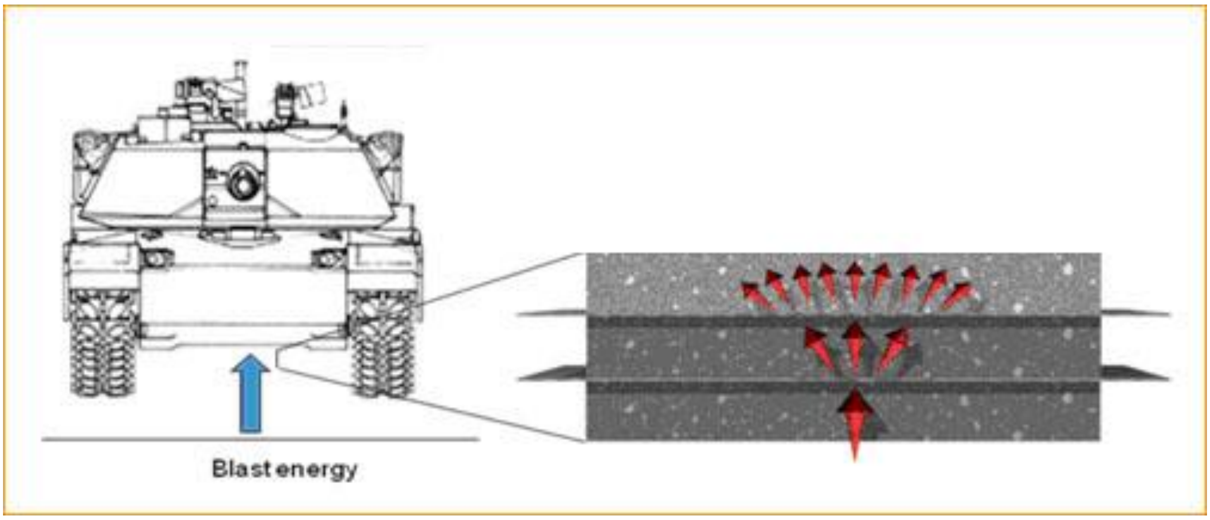


Fig. 19. Foam as protection against blast energy in tank

- **Future Applications:** Recent investigation revealed that metal foam can a potential candidate for application like heat exchanger with extended efficiency, fine porosity enable it for surface tension application, and in space it have potential for gas storage at ultra-low temperature. It can be excellently avoid any problem due to the impact of very small meteorite impact to satellites in space, along with that it can save heat pipes from damage [36]. Shape memory feature of metal foam is another feature which have great potential in future [37]. Foams can be utilize to make biomedical pump that enable blood supplies without having no movable parts. Due to its high porosity it can be utilized in Li ion batteries as electrode.[39]

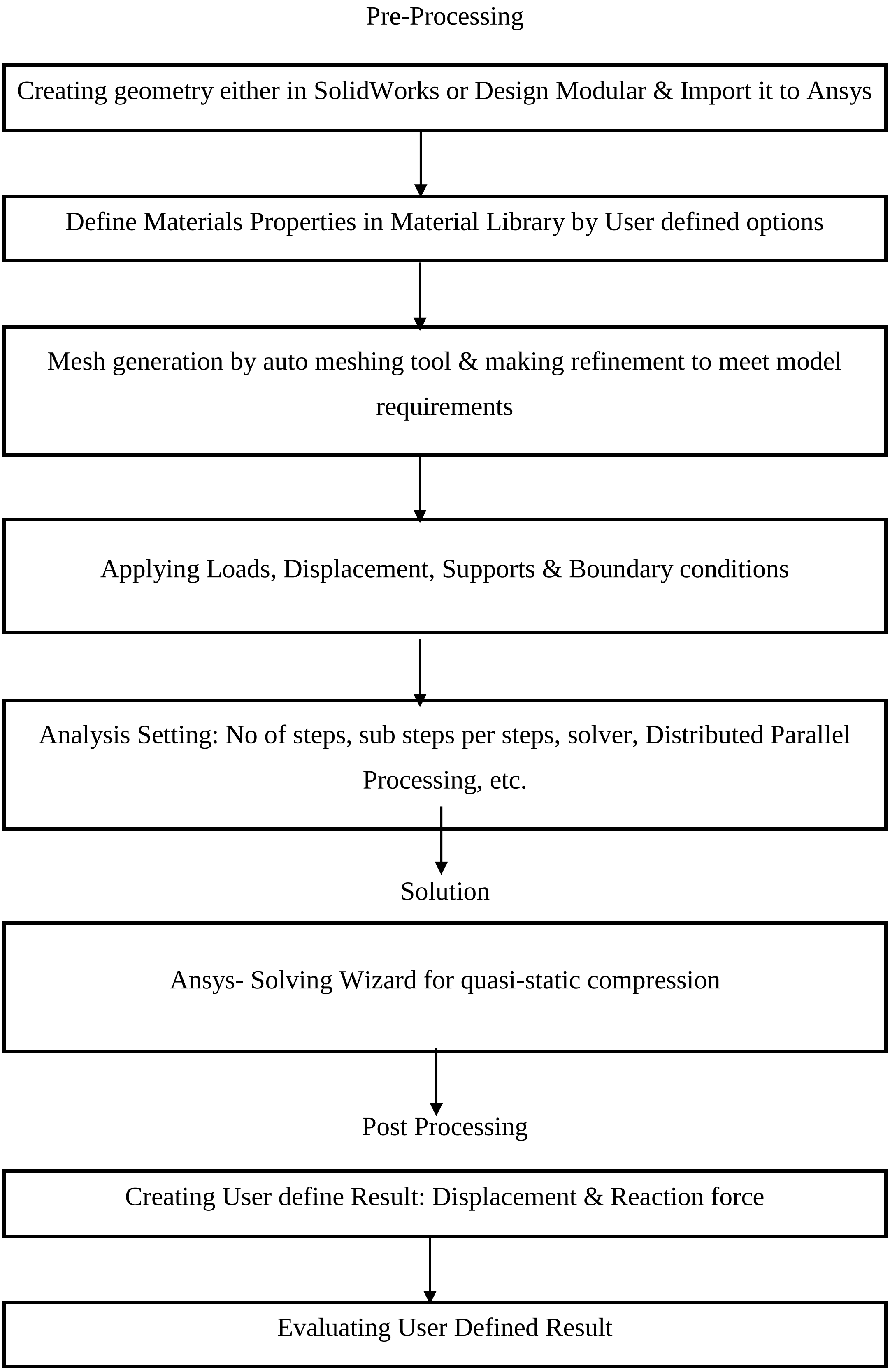
CHAPTER 4: METHODOLOGY

In this study finite element models of tetrakaidecahedral foam was constructed. It is to be noted that in this work, the repeating unit-cell for tetrakaidecahedral foam is different to the unit-cell adopted by S&G to model tetrakaidecahedral foam. Unlike S&G's model in this model curvature effect along face edges are taken into account. Initially, low strain quasi static test was performed for stiffness calculation. After that large strain crush simulations under quasi-static loading conditions was carried out on mentioned model.

4.1 Assumptions

- All cells are made of flat faces with curvature along edges so that it mimic real foam geometry.
- It is assumed that the multi cell model is cut from infinitely large core of foam, standard specimen made of 20mm length of which is slightly greater than three unit cell placed over one another. Accordingly, the multi cell model shows periodicity in loading as well as in perpendicular direction.
- The mass contained in edges of cell walls is more than the material at faces due to the curvature along face edges. It is to be noted, based on this assumption this model show relative density as $\mathbf{1.9898}\frac{t}{l}$ and it is little higher than the SKN unit cell model which is equals to $\mathbf{1.1837}\frac{t}{l}$

4.2 Modelling Methodology



4.3 Material Data

Aluminium alloy AA6063T7 properties had been assigned for finite element model used in this work. The material behaviour was isotropic multilinear hardening. It is to be noted that the previous tetrakaidecahedral model, which was introduced by SKN adopted same material properties. For comparison, identical material data in the current study. The complete material property data is given in Table 1.

Table 1. Material Properties of solid aluminium used in finite element study

Density	2700 kg/m^3
Poisson’s ratio	0.3
Young’s Modulus	69 GPa
Yield-stress	86.9 MPa
Plastic Strain	**Plastic Stress (MPa)**
0	86.9
0.000269	95.9
0.00211	101.3
0.00574	109.3
0.0149	127.3
0.0263	149.3
0.0693	169.5
0.152	171

4.4 Geometrical Data

A standard specimen of gauge length 20mm with cross-sectional area 10mm×10mm is modelled with the help of CAD package SOLIDWORKS and imported into ANSYS. SS&TW introduced and carried out a preliminary study on cubic pyramidal foam model shown in Fig.20. By varying the cell wall thickness to cell size ratio 1/114 to 1/35, SS&TW computed the crushing resistance.

An identical cell-wall thickness (t) and relative density, which was used for cubic-spherical foam shown in Fig.21 is considered for our tetrakaidecahedral foam, the edge length (l) was calculated using the formula described in equation 12. Tetrakaidecahedral foam geometric specification has been explain in Table.2. There isn’t much effect on density due to change in geometry of model from cubic pyramidal, cubic spherical and SKN's tetrakaidecahedral model. Same effect has seen in current model.

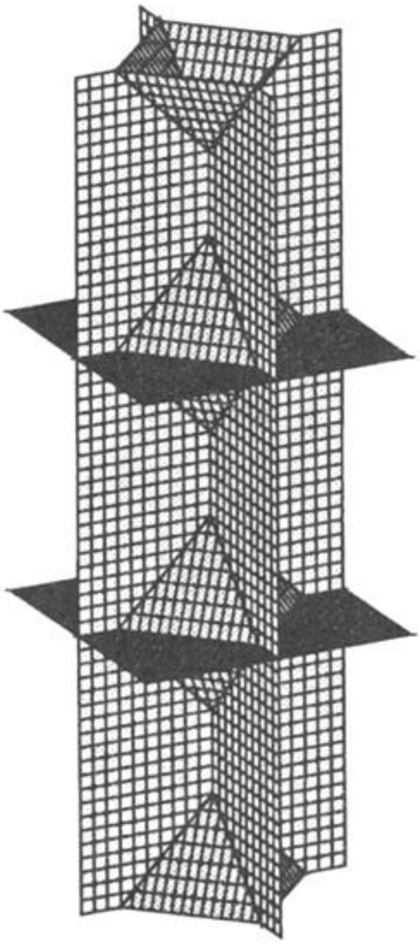


Fig. 20. Finite Element model of cruciform-pyramidal foam

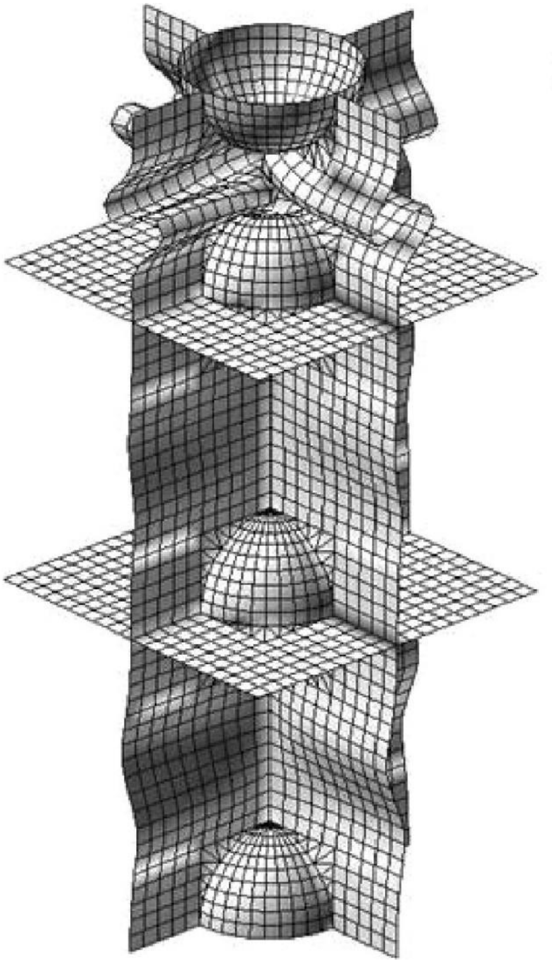


Fig. 21. Finite Element model of Cubic-Spherical foam

Table 2. Geometrical data for Tetrakaidecahedral foam used in finite element study

Tetrakaidecahedral foam		
Cell –wall thickness, t (mm)	Edge-length, l(mm)	Relative density,(ρ^*/ρ_s)
0.02	2	0.0198

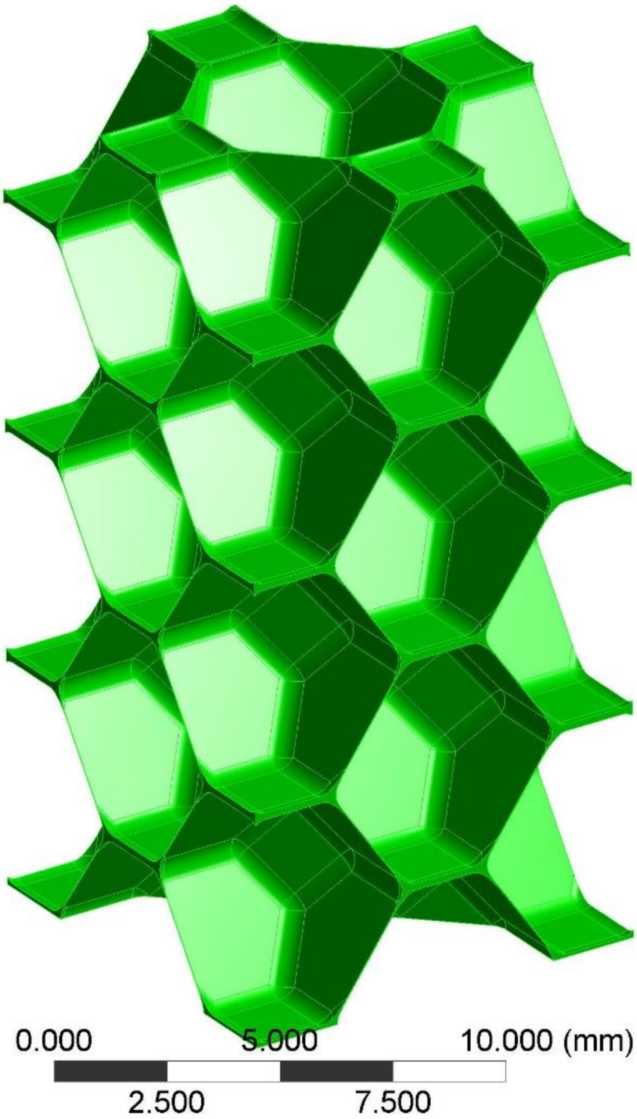


Fig. 22. Tetrakaidecahedral foam Specimen

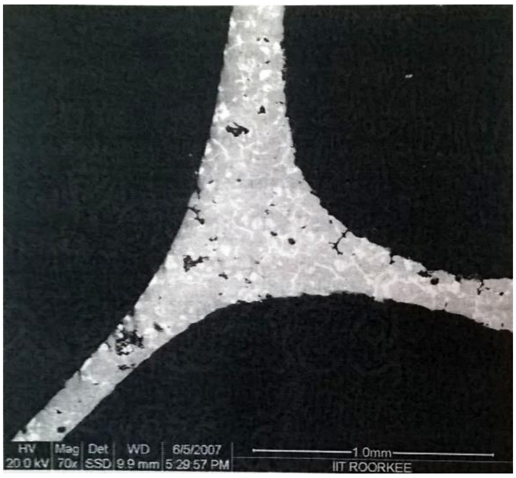


Fig. 23. SEM image of closed cell Al foam cell wall showing large convex curvature from cell wall to the edge

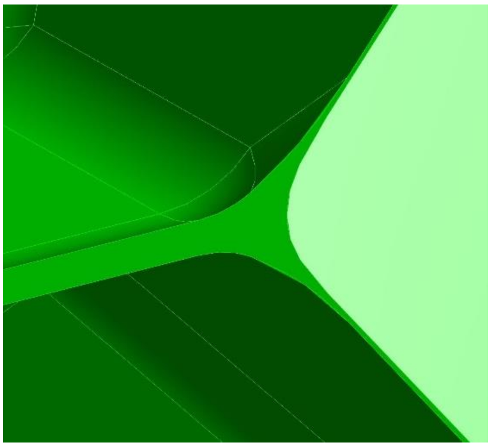


Fig. 24. FE modelled image of tetrakaidecahedral foam showing cell wall similar to real foam shown in Fig.23

CHAPTER 5: RESULTS AND DISCUSSION

The ANSYS finite element code had been employed for pre-processing, solving and post-processing. The finite element model geometry, material, boundary and loading details were defined in design modular, material library and mechanical modular respectively, which were then used as input to ANSYS solution wizard. Initially, a low strain compression study was performed to evaluate stiffness of the foam system. Then, a large-strain study under quasi-static loading was performed.

5.1 Crushing Analysis of Foam

Common types of crushing tests

- Quasi-static compression test
- Dynamic compression test
  - **Drop Test**
  - **Split Hopkinson Pressure bar Test**

Common decision for crushing analysis

Types of analysis

- Static Structural Analysis: low strain rate
- Explicit Dynamics Structural Analysis: High strain rate

5.2 Meshing Loading Boundary Conditions

Auto meshing was done with mesh tool, to achieve good result mechanical relevance was set to 100% and relevance centre to medium mesh. In this model, all the left end nodes of the model were not allowed to move in y-z plane. At the right-end of the model, a deformation (to induce 0.1% strain) was applied. A friction coefficient value of 0.2 was used for frictional contacts.

Meshing Details

- Total Elements=85386
- Total Nodes=169353
- Elements- Tetrahedral

- Minimum Element size=3.5×10^{-2} mm
- Mechanical Relevance-100
- Relevance Centre-Medium

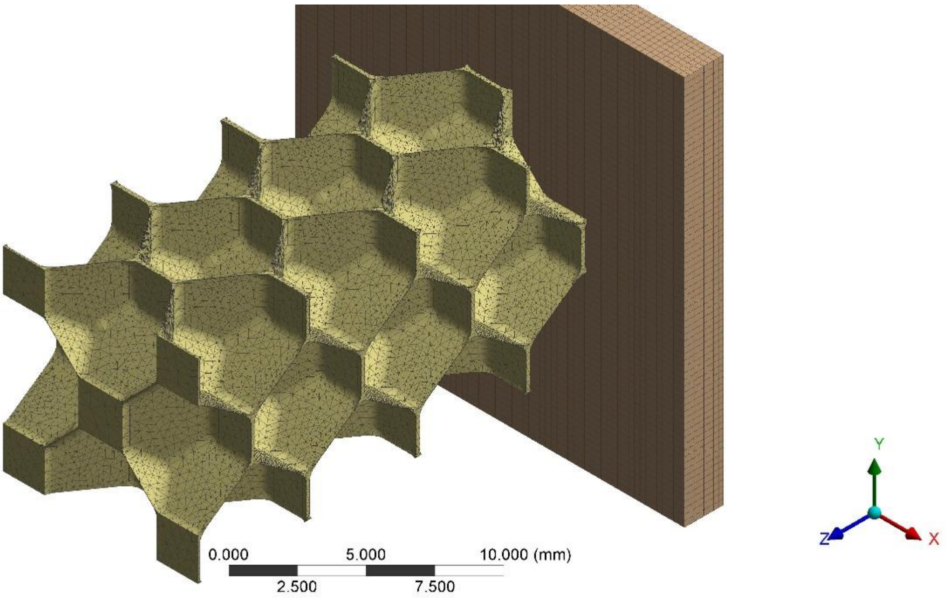


Fig. 25. Meshing of the Model (Fixed plate is hidden here)

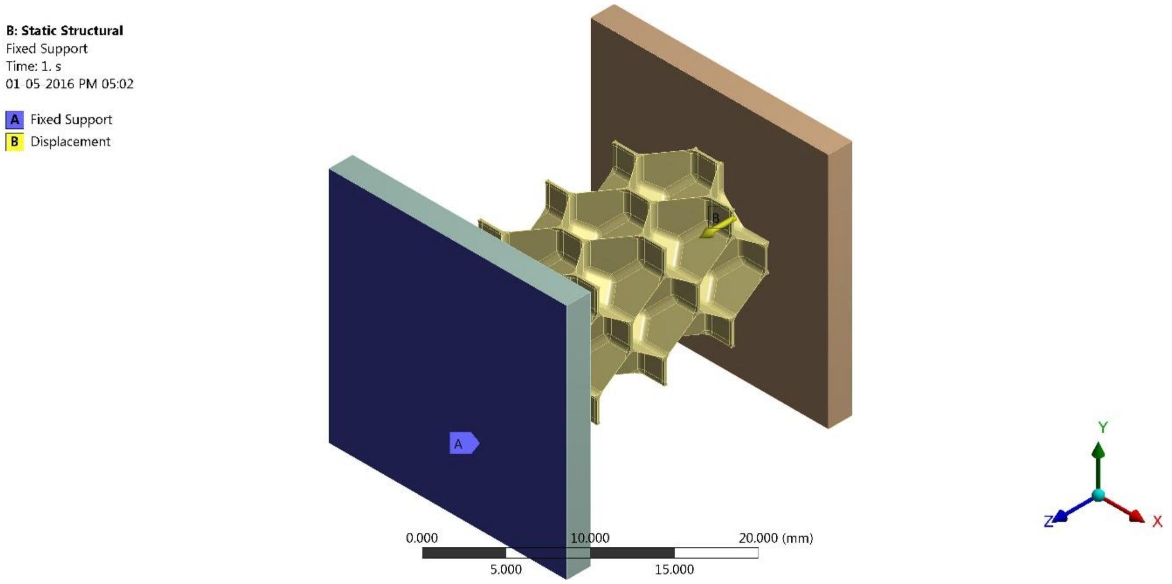


Fig. 26 Boundary and Loading conditions

5.3 Low Strain Study

Ansys mechanical modeller was used to investigate stiffness of specimen at low strain. Only 0.1 % strain was induced in specimen and calculation was performed only linear part of stress strain curve, which is a standard procedure. For this case a punch displacement of 0.02mm was used in loading direction to generate this strain value. Loading condition are shown in Fig.26

5.3.1 Stiffness Computation

Boundary and loading conditions discussed in Section 5.2.1 were applied to finite element model and the total nodal reaction forces were computed. The tributary areas for tetrakaidecahedral foam model is taken as 100 mm^2. By dividing the total reaction force on punch face with tributary area of the mentioned foam model, the stress was calculated. Stress for 0.1% strain was taken as stiffness for all foam model stated in the literature, so same has been employed here.

$$Stress = \frac{Punch\ reaction\ force}{Tributary\ area\ of\ specimen}$$

Table. 3. Low strain stress strain data for tetrakaidecahedron aluminium foam

Time (S)	Strain	Stress(MPa)	Stiffness(MPa)
3.33E-02	8.34E-06	2.68E-05	3.21E+00
6.67E-02	1.67E-05	5.36E-05	3.21E+00
0.11667	2.92E-05	9.38E-05	3.21E+00
0.16667	4.17E-05	1.34E-04	3.21E+00
0.21667	5.42E-05	1.74E-04	3.21E+00
0.26667	6.67E-05	2.14E-04	3.21E+00
0.31667	7.92E-05	2.54E-04	3.21E+00
0.36667	9.17E-05	2.95E-04	3.21E+00
0.41667	1.04E-04	3.35E-04	3.21E+00
0.46667	1.17E-04	3.75E-04	3.21E+00
0.51667	1.29E-04	4.15E-04	3.21E+00
0.56667	1.42E-04	4.55E-04	3.21E+00
0.61667	1.54E-04	4.95E-04	3.21E+00
0.66667	1.67E-04	5.36E-04	3.21E+00
0.71667	1.79E-04	5.76E-04	3.21E+00
0.76667	1.92E-04	6.16E-04	3.21E+00
0.81667	2.04E-04	6.56E-04	3.21E+00
0.86667	2.17E-04	6.96E-04	3.21E+00
0.91667	2.29E-04	7.36E-04	3.21E+00

0.96667	2.42E-04	7.77E-04	3.21E+00
1	2.50E-04	8.03E-04	3.21E+00
1.0333	2.58E-04	8.30E-04	3.21E+00
1.0667	2.67E-04	8.57E-04	3.21E+00
1.1167	2.79E-04	8.97E-04	3.21E+00
1.1667	2.92E-04	9.37E-04	3.21E+00
1.2167	3.04E-04	9.77E-04	3.21E+00
1.2667	3.17E-04	1.02E-03	3.21E+00
1.3167	3.29E-04	1.06E-03	3.21E+00
1.3667	3.42E-04	1.10E-03	3.21E+00
1.4167	3.54E-04	1.14E-03	3.21E+00
1.4667	3.67E-04	1.18E-03	3.21E+00
1.5167	3.79E-04	1.22E-03	3.21E+00
1.5667	3.92E-04	1.26E-03	3.21E+00
1.6167	4.04E-04	1.30E-03	3.21E+00
1.6667	4.17E-04	1.34E-03	3.21E+00
1.7167	4.29E-04	1.38E-03	3.21E+00
1.7667	4.42E-04	1.42E-03	3.21E+00
1.8167	4.54E-04	1.46E-03	3.21E+00
1.8667	4.67E-04	1.50E-03	3.21E+00
1.9167	4.79E-04	1.54E-03	3.21E+00
1.9667	4.92E-04	1.58E-03	3.21E+00
2	5.00E-04	1.61E-03	3.21E+00
2.0333	5.09E-04	1.63E-03	3.21E+00
2.0667	5.17E-04	1.66E-03	3.21E+00
2.1167	5.29E-04	1.70E-03	3.21E+00
2.1667	5.42E-04	1.74E-03	3.21E+00
2.2167	5.54E-04	1.78E-03	3.21E+00
2.2667	5.67E-04	1.82E-03	3.21E+00
2.3167	5.79E-04	1.86E-03	3.21E+00
2.3667	5.92E-04	1.90E-03	3.21E+00
2.4167	6.05E-04	1.94E-03	3.21E+00

2.4667	6.17E-04	1.98E-03	3.21E+00
2.5167	6.30E-04	2.02E-03	3.21E+00
2.5667	6.42E-04	2.06E-03	3.21E+00
2.6167	6.55E-04	2.10E-03	3.21E+00
2.6667	6.67E-04	2.14E-03	3.21E+00
2.7167	6.80E-04	2.18E-03	3.21E+00
2.7667	6.92E-04	2.22E-03	3.21E+00
2.8167	7.05E-04	2.26E-03	3.21E+00
2.8667	7.17E-04	2.30E-03	3.20E+00
2.9167	7.30E-04	2.33E-03	3.20E+00
2.9667	7.42E-04	2.37E-03	3.19E+00
3	7.50E-04	2.39E-03	3.18E+00
3.0333	7.59E-04	2.41E-03	3.18E+00
3.0667	7.67E-04	2.43E-03	3.17E+00
3.1167	7.80E-04	2.46E-03	3.16E+00
3.1667	7.92E-04	2.50E-03	3.15E+00
3.2167	8.05E-04	2.53E-03	3.14E+00
3.2667	8.17E-04	2.56E-03	3.13E+00
3.3167	8.30E-04	2.59E-03	3.12E+00
3.3667	8.42E-04	2.62E-03	3.11E+00
3.4167	8.55E-04	2.65E-03	3.10E+00
3.4667	8.67E-04	2.67E-03	3.08E+00
3.5167	8.80E-04	2.70E-03	3.07E+00
3.5667	8.92E-04	2.73E-03	3.06E+00
3.6167	9.05E-04	2.75E-03	3.04E+00
3.6667	9.17E-04	2.78E-03	3.03E+00
3.7167	9.30E-04	2.80E-03	3.01E+00
3.7667	9.42E-04	2.82E-03	3.00E+00
3.8167	9.55E-04	2.85E-03	2.98E+00
3.8667	9.67E-04	2.87E-03	2.96E+00
3.9167	9.80E-04	2.89E-03	2.95E+00
3.9667	9.92E-04	2.91E-03	2.93E+00

4	1.00E-03	2.92E-03	2.92E+00

5.3.2 Analysis

Low strain study is characterized by small displacement of movable punch to induce deformation just to check the linear behaviour of material, which generally comes before advent of plastic region. To investigate slope of stress-strain curve for tetrakaidecahedral foam punch was given displacement of 0.02mm (0.1% of 20mm). It was seen that after the stress value of 2.26×10^{-3} MPa at strain 7.05×10^{-4} curve's slope starts decreasing which show end of elastic region as shown in Table.3. The stiffness was calculate as 3.21 MPa for this configuration of tetrakaidecahedral foam. Stress-strain curve for this study is shown in Fig.27.

$$E^{*} = \frac{\text{Stress}}{\text{Strain}}$$

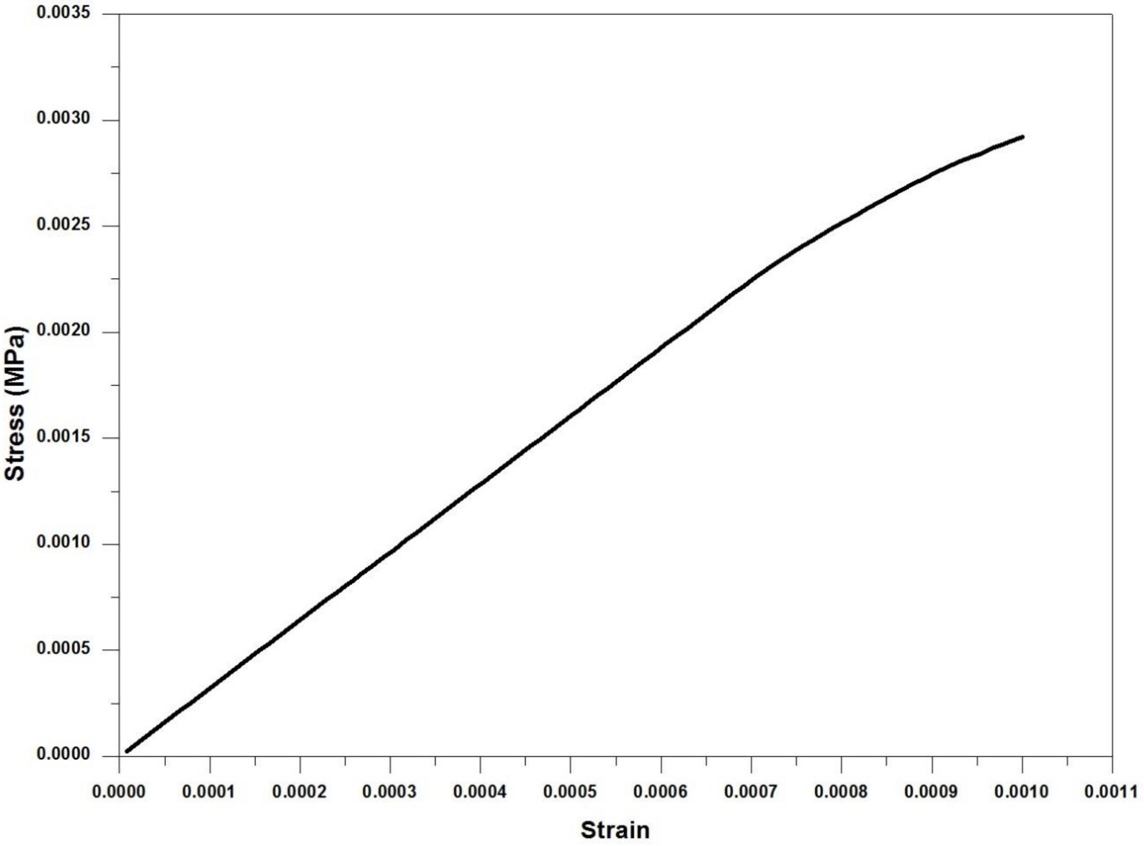


Fig. 27. Stress strain for compression of Tetrakaidecadehedron foam used for stiffness Computation

5.4 Large Strain Study

Main aim of this investigation is to study compressive response of tetrakaidecahedral foam model under quasi static loading conditions. Foam specimen is compressed by placing in between fixed rigid support and movable punch. The tetrakaidecahedral foam is compressed along longitudinal direction (Z-Direction), Fig.26 shows the arrangement made for this low strain study. To create similar condition as real testing, frictional contact are taken between foam and movable punch. A similar frictional condition was also applied to the interface between foam and the fixed rigid-plate.

To achieve quasi-static solution, the event loading duration was set as 20 steps with each step constituting minimum 80 sub-steps, 100 initial sub-steps and 120 maximum number of sub-steps. The stresses for the foam models is computed by dividing the reaction force experienced by punch with the tributary areas of unit-cell, thus stress is stated as:

$$Stress = \frac{Punch\ reaction\ force}{Tributary\ area\ of\ specimen}$$

5.4.1 Numerical Stress-Strain Plot & Deformation Pattern

Initial compression studies of this model shows reaction force after elastic region starts decreasing for small region and then starts raising again. Though foam has been crushed to 25% of specimen's total length reaction force has changed from little over 1 N to 5 N Fig.29.

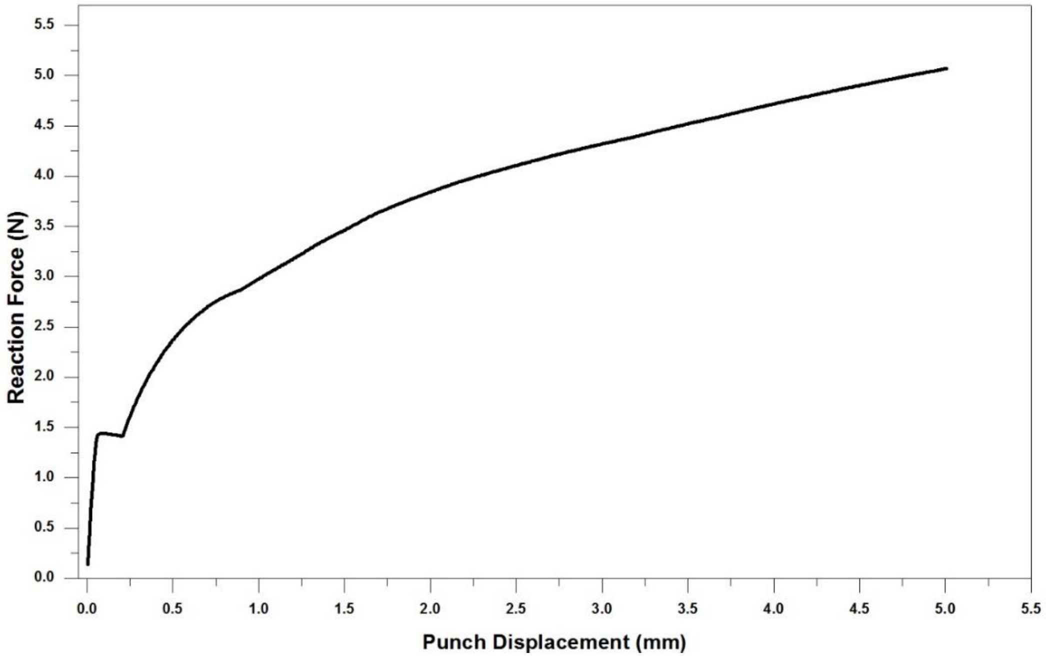


Fig. 28. Punch Displacement vs Reaction Force on punch plot for initial large strain study

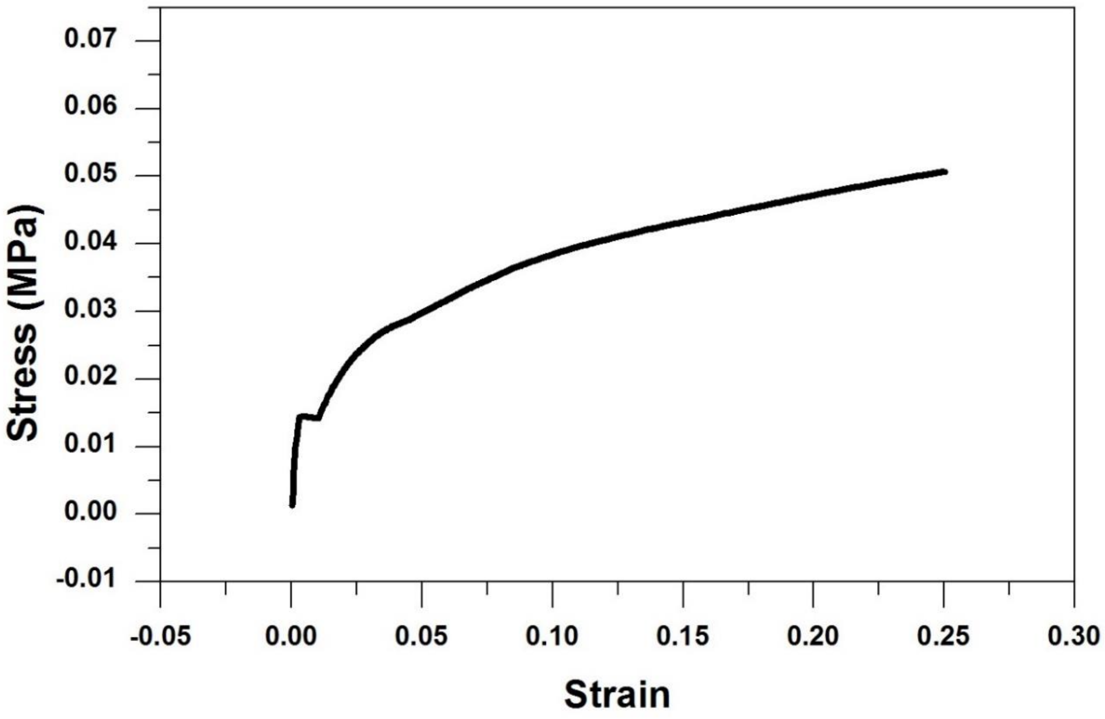


Fig. 29. Crushing Stress Strain plot for Tetrakaidecahedron foam

Fig. 30. Reaction force vs Displacement plot for Crushing Tetrakaidecahedron Al foam

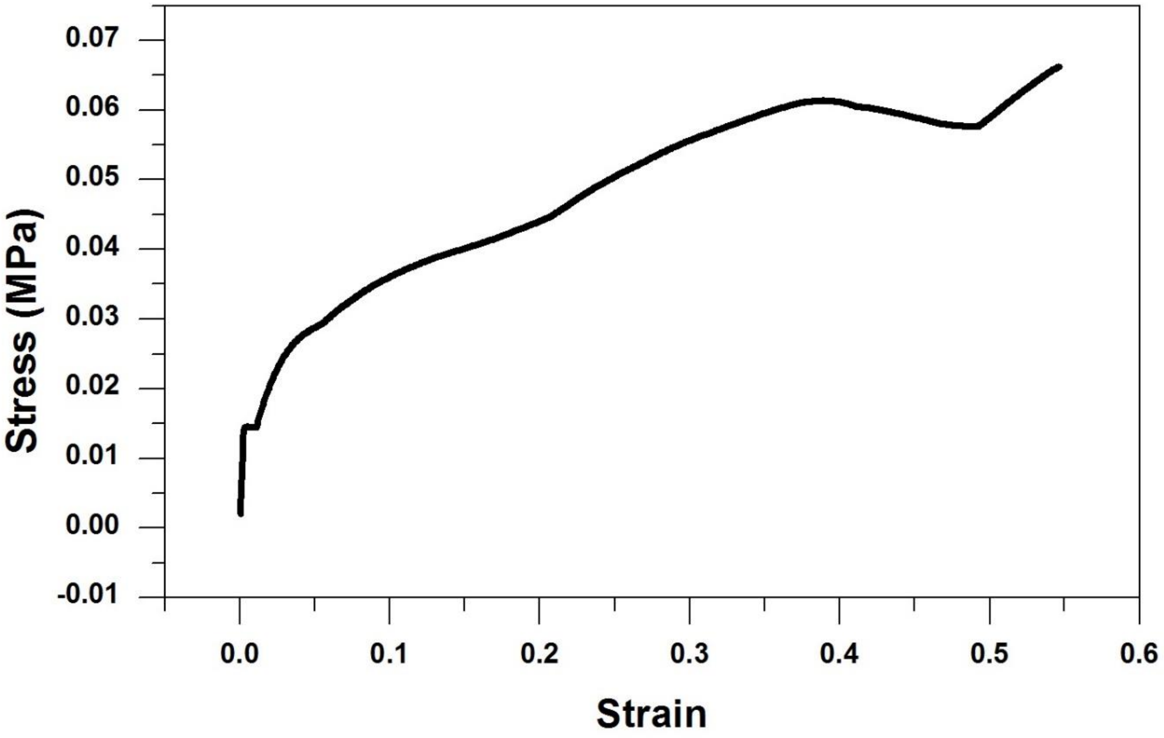


Fig. 31. Crushing Stress-Strain plot for Tetrakaidecahedral Al foam

5.4.2 Analysis

To check foam candidacy for crash worthiness it is necessary to investigate it for large strain behaviour under compression. Tetrakaidecahedron foam was initially deformed in longitudinal direction up to 5mm (25% strain) to check for initial peak which mark end of elastic region and followed by a valley region. This model show a very low peak to valley difference which show better representation of real foam. Later on punch has been given more displacement to investigate its deformation pattern to attain densification strain. After initial peak valley, stress value increased slightly associated with another sallow region of small two peak and follow by steep increase in stress, which show possibility of densification.

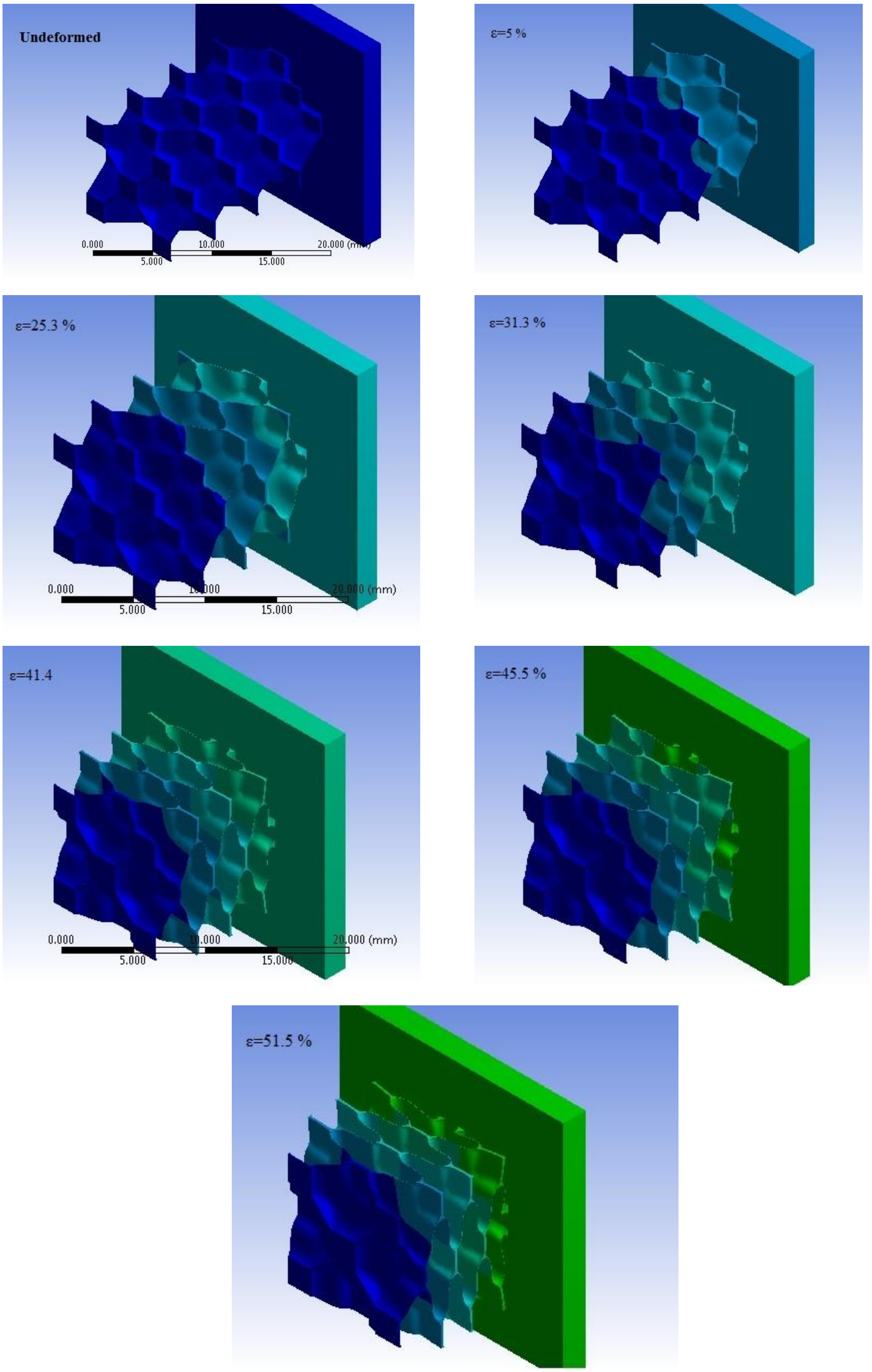


Fig. 32. Tetrakaidecahedron deformation patterns at various strain values (fixed plate is hidden here)

CHAPTER 6: CONCLUSION

Closed cell aluminium foam was represented by tetrakaidecahedral unit cell structure in this study. Stiffness obtained from low strain compression test under quasi static condition is 3.21MPa, which fall within the range seen in literature for aluminium foam. Which demonstrate current model up to standard in elastic region. In non-linear region large strain study on low strain rate was performed to check this new configuration of tetrakaidecahedral foam in which mass distribution is similar to real metal foam as stated in literature. Another pros of this model is decrease in valley region after first peak. Due to its closed cell geometry, internal contacts were not possible to define properly. Due to this reason it wasn’t able to converse beyond densification. This short coming can be avoided by using stacking unit cell horizontally, which can help in achieving even better results.

Multi-linear isotropic hardening plasticity model present in ANSYS was used to define solid aluminium mechanical properties. Non-linear investigation of this model reveal that presence of face parallel to loading direction is main reason of high peak to valley variation in stress strain plot

CHAPTER 7: FUTURE SCOPE

Objective of this study is to investigate the effect of cellular microstructure on mechanical response of metal foam. Laws of nature, equally applicable to conservation of volume and area. Tetrakaidecahedron structure has been selected on basis of its minimum surface area per unit volume over many other space filling structure and supported by its available mathematical formulation for density & stiffness etc. Limited study has been done on dynamic behaviour using unit cell based model of aluminium foam, only continuum approaches has been used so far, so dynamics response of tetrakaidecahedral foam still needs to explore.

To further improve finite element modelling of closed cell metal foam, others material characteristics like inter-metallic compound can be incorporated in unit cell based approach. Lack of mathematical explanation limited the use of Weaire-Phelan in finite element modelling of metal foam. There are numerous space filling structure explained in literature which needs to be investigated by finite element approach to check their candidacy for represent metal foam. Also demands for fuel consumption and strict safety norm are pushing automobile industry to look on available material options which give high specific strength along with crash worthiness which give metal foam edge over other material, hence its modelling play very important role in this potential area.

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