ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

Numerical Analysis of Aluminum Foam for Impact Energy Absorption Purpose

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A Thesis Submitted to the Graduate school of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering (Mechanical Design Stream)

By

Seyfu Tiruneh

Advisor: Ermias G. Koricho (PhD)

Co-advisor: Mr. Behailu Mamo

Addis Ababa, Ethiopia

June 2020

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Thesis Approval sheet

The undersigned have examined the thesis entitled 'Numerical analysis of Aluminum Foam for Impact Energy Absorption purpose' presented by Seyfu Tiruneh, a candidate for the degree of Master of Science and hereby certify that it is worthy of acceptance.

Dr. Ermias G. Koricho _____	_____	
Main Advisor	Signature	Date
Mr. Behailu Mamo _____	_____	
Co-Advisor	Signature	Date
Dr. Samuel Tesfaye _____	_____	
Internal Examiner	Signature	Date
Dr. Haileleuol Sahle _____	_____	
External Examiner	Signature	Date
Mr. Araya Abera _____	_____	
Mechanical Design chair	Signature	Date
Dr. Yilma T. _____	_____	
School Dean	Signature	Date

Declaration

I declare that this work which is being presented in this thesis entitled with "Numerical analysis of Aluminum Foam for Impact Energy Absorption purpose'' is the original work of mine under the supervision of Dr. Ermias G. Koricho and Mr. Behailu Mamo. The work has not been presented elsewhere for assessment. Where materials have been from other sources, it has been properly acknowledged/referred.

Seyfu Tiruneh _____ _____

(Name of the candidate) Signature Date

This is to certify that the above declaration made by the candidate is correct to the best of our knowledge.

Dr. Ermias G. Koricho (PhD) _____ _____

(Main Advisor) Signature Date

Mr. Behailu Mamo (PhD Candidate)_____ _____

(Co-Advisor) Signature Date

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ABSTRACT

Recently, there is a high interest to use lightweight aluminum foams for automotive, railway and aerospace applications. Aluminum foam is usually used for energy absorption purpose for crashworthiness application because of its high ductility and deformability. However, to keep the safety and to avoid occupant injuries it is necessary to absorbed high impact energy generated during collision. Therefore, to absorb high impact energy, the crash box material needs a special material microstructure which is light in weight and can absorb more energy than the existing one like $CaCo_3$, SiC. B_4C etc.

In particular, the analysis of energy absorption of aluminum foam in automotive for energy absorption applications is limited. The main objective of this research is to model and analyze, impact energy absorption of aluminum foam using the numerical approach. For this purpose, first, fifteen aluminum foam CAD were developed by using Digimat multi-scale material modeling software. Second, cubic elements with circular pore shape at 5%, 10% and 15% void percentage and at 1.5mm, 2mm, 2.5mm, 3mm and 3.5mm pore sizes were modeled. Finally, the numerical analysis of impact energy was carried out by using ANSYS workbench 19.2 Explicit dynamics by applying initial low velocity was performed. The parameters such as pore size, voids percentage and inclusion particles were compared to each other to optimize the proper percentage composition and cell size for the best of energy absorption applications. The effects of pore size, foaming agent and percentage composition on energy absorption were discussed. In addition the deflections, reaction forces, accelerations, specific energy absorption, energy absorptions for all the models are also determined with variable pore size and volume of porous, and it was compared with the effects of agents on those variables.

Results showed that the Aluminum foam with 10% void fraction at bubbles (voids with air) size of 2.5 mm exhibited better energy absorption and more stable was founded to be best candidate material for impact energy absorbing device.

Keywords: Aluminum foam, Voids, Energy absorption, Acceleration, Foaming agent, Reaction force, DIGIMAT, FEM analysis.

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Nomenclature

R	Radius	C	Strain rate constant
nRi	n-Void fraction and i-bubble size	CAD	Computer Aided Design
		C_D	Cell density
A	Initial yield stress	COR	Coefficient of restitution
Al	Aluminum	E	Energy
B	Hardening constant	F	Force

FE	Finite Element	N	Number of cells
FEA	Finite Element Analysis	n	Hardening exponent
FEM	Finite Element Method	R	Radius
M	Thermal softening constant	SEA	Specific Energy Absorption
m	mass	P	Porosity
MF	Mean Field	V	Volume
MPa	Mega pascal		

ε^{pl}	Equivalent plastic strain	ρ^s	Density of the solid
ε^{*pl}	Equivalent plastic strain rate	ϕ	Void fraction
ρ^*	Relative density	K_{eq}	Equivalent kinetic energy
ρ^f	Density of the foam		

CHAPTER ONE

1. Introduction

1.1 Background of the study

Metal foams are a new class of materials of great interest due to their unique combination of properties derived from their cellular structures and metallic behavior as well as an attractive material for components of the vehicle in automotive industries for elements absorbing impact energy, increasing stiffness, outstanding physical and thermal characteristics and improving the passenger safety by reducing vibration, noise and due to their high strength to weight ratio. They are an excellent impact energy absorber, and they can convert impact energy into strain energy and absorb more energy than bulk metal at low stress due to their extended constant stress region during compression[1].

In the past, many energy absorbers had been developed which dissipate energy by crushing, cyclic plastic deformation, friction, fracture, bending, etc. with a variety of materials ranging from wood to metals and advanced fiber composites[1]. Further, thin-walled tubular structures had been used in the structural crashworthiness and their static and dynamic behavior had been studied both theoretically and experimentally in terms of the critical forces, types, modes of buckling, and the energy-absorbing properties by several researchers. The energy absorption characteristic of the structures can be improved by filling the tube with lightweight materials such as aluminum foams [2]. The filling of aluminum foam in the tubes influences the buckling modes which in turn caused higher plastic deformation and higher energy absorption [3]. In recent years the aluminum foam has shown very high potential in energy management because of its lightweight and high energy absorption characteristic. Foamed aluminum is a composite material consisting of aluminum or aluminum alloy matrix and pores filled up with a gas. This unique structure possesses an unusual combination of properties, such as low thermal conductivity, high impact energy absorption capacity, very high specific toughness and good acoustic properties, lightweight, nonflammable, ecologically harmless and easily recyclable.

Due to their high strength to weight ratio and energy absorption, metallic foams can be widely used in the automotive industry to improve passenger safety. In the case of a vehicle crash, the

occupant safety is of the prime concern and this demands that the vehicle structure should be designed to withstand high impact forces. This demand is even further supplemented with the use of the lightweight structure for higher fuel economy wherein the working stress reaches closer to the ultimate strength of materials [4]. In the case of impact/crash, the requirement is achieved through a properly designed high energy absorption system. The capability of absorbing the impact energy during vehicle collision is one of the most interesting properties of aluminum foams. Therefore, it is very important to study and develop aluminum foam composite materials for energy absorption in automotive industries, military, maritime, civil structures such as bridges and blast applications.

The property of aluminum foam to undergo plastic deformation at a constant stress level for large strain values makes it attractive for impact and crash energy absorption. Weight restrictions and safety norms of the upcoming transport industry demand the replacement of conventional materials with novel light materials having high specific energy absorption.

The energy absorption capacity per unit volume or mass and the plateau stress at which the energy is absorbed are the key deciding factor in the selection of a material for energy absorption. A proper understanding of the material behavior at high strain rates, especially the effect on plateau stress and energy absorption capacity is therefore essential for predicting the impact performance of aluminum foam [5].

Recently, there is a high interest in using lightweight metallic foams for automotive, railway and aerospace applications where weight reduction and improvement in comfort are needed. Aluminum foams have a potential for absorbing impact energy during the crashing of a vehicle either against another vehicle or a pedestrian. To effectively absorb the impact energy, a material is required to exhibit an extended stress plateau [6].

Foamed materials in general, and aluminum foams in particular, demonstrate several desired properties due to their lightweight and porous structure, which makes them usable in a wide range of applications in automotive industries. The capability of absorbing the impact energy during a car crash is one of the most interesting properties of aluminum foams. Foamed aluminum is also used for constructing bridge decks, temporary landing mats and thermal insulation wall boards due to better performance in comparison to other structural materials in terms of enhanced stability,

higher strength to weight ratios, better energy absorbing capacity and ease of manufacturing. This study focuses on the numerical analysis of aluminum foam for automotive industries for energy absorption purposes. Figure 1.1 shows the physical structure of the crash box for automotive applications.

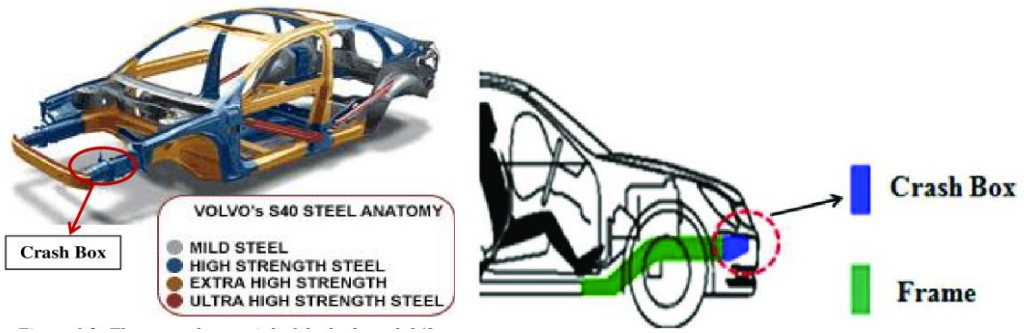


Figure 1.1: Physical structure of the crash box for vehicle application [7][8]

As shown from the above figure, the crash box structure is assembled in front of the car between the bumper beam and front car cabin/structure.

As shown in the figure 1.2 were frontal impacts the first and the most severe crash in car accidents. The recent crash statistics shows that 51% are frontal, 25% are side, 15% are rollover and 9% are rear-impact as shown in the figure below.

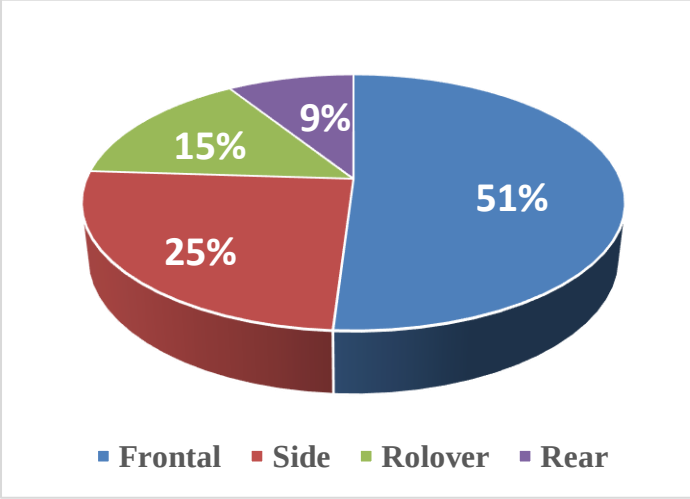


Figure 1.2: Crash statistics [9]

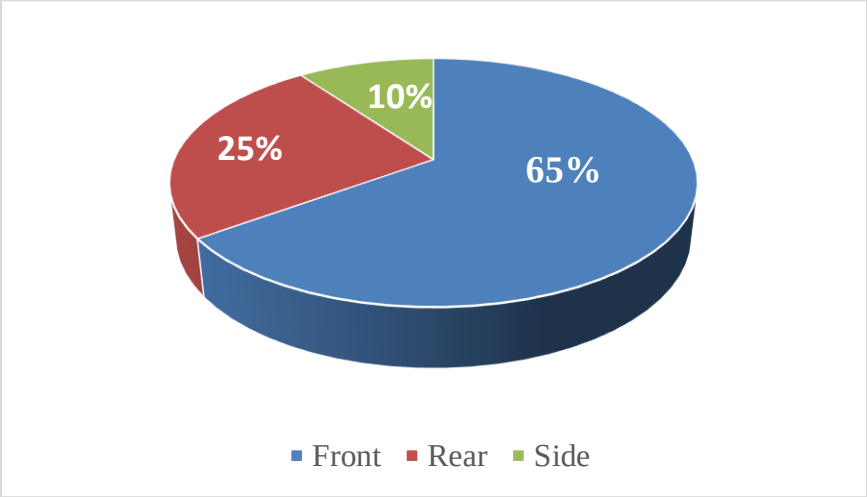


Figure 1.3: Crash statistics [10]

On the other hand, as shown in figure 1.3according to a British Vehicle Insurance Repair Research Center study on vehicles impact damage occurs: 65% were front impacts, 25% were rear impacts, 10% were side impacts[10]. Therefore, the crash box made of aluminum foam is used to dissipate crash energy using energy-absorbing foamed specimen.

1.2 Aluminum foam

Aluminum foam is a porous metallic material which is made by adding a foaming agent, such as air for bubbling a molten aluminum during manufacturing. The density of Al foam varies from 0.2 to 0.4 g/cm^3[11], which is less than by 94.8% and 85.2% density of steel and solid Al respectively. Because of its specific strength and high resistance under compressive loading, it is suitable for lightweight structures and the absorption of impact energy.

Foam structures are categorized into two main groups. These are open-cell foam and closed-cell foam. In closed-cell foams, the cells are separated from each other using thin walls. But the open-cell foams are made of struts rather than walls and therefore, the interior parts of the cell are connected. The closed-cell foams usually have higher strength and higher energy absorption capacity compared to the open cell foams[12]. Therefore, for automotive industries, especially for vehicle applications the closed-cell aluminum foams have a better capability to absorb crash energy during a collision.

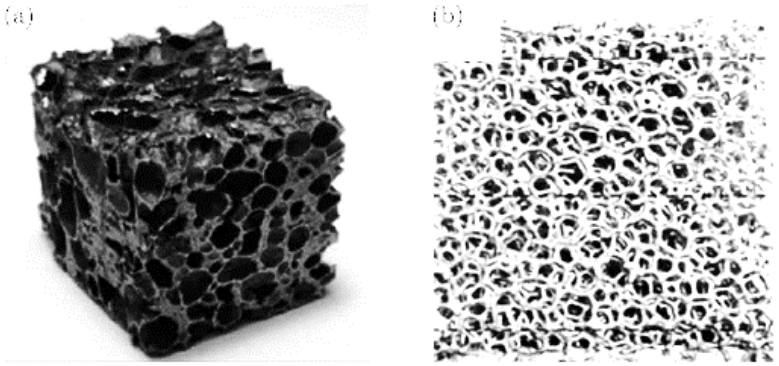


Figure 1.4: Different foam types, a) closed cell b)open cell [12].

The mechanical properties of aluminum foams are influenced by the following three factors. These are[13]:

a. The properties of solid material from which the foam is made of. e.g the microstructure of the aluminum metal.
b. The volume fraction of the solid material (Al), the so-called the relative density, and
c. The spatial arrangement of the solid (Al), the distribution of bubbles, porosity and the structure of the metal foam.

Therefore, as stated above in figure 1.2 and 1.3 crash statistics front crush on a vehicle holds from 51% - 65% than rest impact conditions. Due to these reasons, the current thesis work focused on the development of crash box material by using numerical approach. Currently, the prominent numerical property of any cellular solid material is its relative density. So, in this thesis work the mechanical properties of Al foam as a function of the material's relative density is considered. This thesis work is going to characterize the properties of the Al foam. It is possible for foams with different cellular structure and same geometry which could significantly influence the behavior and properties of the material for impact energy absorption.

Aluminum foams can be analyzed by using their porosities or number of cells (pores) that exist per unit volume. For this purpose, random distribution of bubbles (voids with air) are used than using regular pattern, because of its simplicity to distribute the bubbles by DIGIMAT on CAD model, and again to introduce new idea in this field of study. This random distribution of internal pores on CAD models are constructed based on the Voronoi method.

This paper is focused on the impact of three-dimensional (3D) porous structures Al foam at 5%, 10% and 15% porosities. The dynamic response and energy absorption of closed-cell metal foams with different porosity distributions are investigated by using finite element (FE) analysis. Random distributions of internal pores on targeted CAD are constructed with Voronoi methods. The proposed porous structure is crushed under the impact of a rigid plate with a constant velocity. The effects of varying parameters like porosity size, random distribution pattern and different foaming agents on the energy absorption are discussed. The effective way to improve the energy absorption capability of the porous structure under a constant-velocity impact is proposed for engineering design. Due to the difficulty of completely analyzing the entire energy absorption system for frontal crash box structure of a cars, this research paper will be going to conduct small volumetric element to understand its impact behavior and energy absorption capability.

1.3 Energy absorption

Energy cannot be created or destroyed, but it can be changed from one form to another form. During an impact or crash, the energy conversion takes place, in which the energy is changing form or convert into the internal potential energy of a system. Mathematically, the energy absorption is modeled by using impact theory, which states that momentum before impact and after impact is equal[14]. There are two types of impact, elastic impact, and plastic impact. The total energy is conserved throughout the impact process. Energy absorption can be determined using real-time tests such as real physical test, but due to the high cost of conducting real-time tests, ABAQUS CAE and FEM ANSYS material modeling analysis will be used in automotive industries before conducting real-time tests. By using FEM industries will reduce the cost and time of the product development process while increasing the safety, comfort, and durability of the vehicle structures.

Generally, aluminum foams are used for stiffening a structure without increasing its mass, which have high and good energy absorbed is selected, because the energy absorption rate is the measure of toughness. Herein this study, the process of energy conversion is through the impact of the vehicles with each other, with fixed or movable structures. During the impact of the vehicle, the crash box material deforms slowly and absorbs more energy because in Al foam specimen pores are distributed uniformly and crush progressively with little collapse. The uniformly distributed bubbles/cells are crush and collapse into each other. The collapse of the bubble starts from the

front crush side first and then transfer to others. Due to this bubble collapse time or deformation due to intensified stress, the energy will be absorbed.

Therefore, the purpose of the Al foam element for a car crash box is used to increase the time of change in velocity (and consequently, momentum) occurs from the impact during a collision. Crumple zones are designed to increase the time over which the total force from the change in momentum is applied to an occupant, as an average is applied to the occupants is inversely related to the time over which it is applied.

$$F_{avg}\Delta T = m\Delta V \quad \text{.....1.1}$$

Where, F- force, T- time, m-mass and V-velocity. Typically, the crash box is located in the front part of the vehicle, in order to absorb the impact of a head-on collision.

1.4 Statement of the problem

During vehicle structural component design, the overall safety, comfort, weight reduction and impact resistance during a collision should be considered. To protect the occupants of a car, different safety features such as airbags, crash box and seat belts were used for crash box structures. Among those, crash boxes are a separate structure in a vehicle that is mounted in between the mainframe of the car and front bumper. The crash box structure is expected to be collapsed with absorbing crash energy prior to the other body parts so that the extent of damage in the main cabin frame is minimized and passengers are saved their lives. The problems identified to conduct study are the loss of passenger life by car crash accidents (51% up to 65% by frontal crash), the damage of expensive car components behind the crash box and limitations of clear investigations on porous Al foam for crash box applications.

The energy absorption features of closed-cell aluminum alloy foam can be enhanced through tailored designs of aluminum matrix and particulate agents embedded in aluminum matrix microstructure. To keep the safety and to avoid occupant injuries it is necessary to absorb the kinetic energy generated during a head-on collision. Therefore, to absorb high kinetic energy, the crash box material needs a special material microstructure development which is good energy absorbing capacity and light in weight. Some of the researchers were used different filler ceramic materials such as Silicon Carbide (SiC), Cubic Boron Nitride (CBN), $CaCo_3$ powder, etc. During Al foam development for energy absorption applications, which are heavy, and affects fuel

economy. Using of the existing inclusion hard particles will result for crack propagation and for high stress intensification during impact. Other researchers investigated the geometry modifications such as Al foam sandwich panels. On the other hand, the distribution of filler and foaming agents for the microstructure of foam greatly affects the energy absorption of Al foam. But, the higher deformation of a structure to dissipate the crash energy in order to prevent injuries and improve the crashworthiness of the structure, an optimum combination of material's microstructure (pore distribution, pore size and porosity percentage) throughout the entire model is needed. So, it is necessary to model and analyze energy absorber specimen from lightweight closed-cell aluminum foam which is capable of absorbing high impact energy.

1.5 Objectives of the study

1.5.1 Main objective

The general objective of this research is to model and analyze the impact energy absorption of Aluminum foam using the numerical approach.

1.5.2 Specific objectives

The specific objectives are:

- To develop 3D model and distribute pore cells finely and randomly
- To optimize the proper pore size and porosity percentage for best of energy absorption
- To analyze deformation to sustain the structure to absorb impact energy absorption
- To determine the energy absorption
- To analyze acceleration for lightweight Al foam
- To compare the foaming agent with microstructure modification on energy absorption

1.6 Significance of the study

Composite materials have exhibited superior features of high stiffness, high strength and lower density, which have rapidly emerged in automotive engineering to replace the conventional metallic materials. Aluminum foam is an interesting composite material for energy absorption applications in automotive industries especially for vehicles during crash or collision. To meet the growing demands for structural lightweight and safety for modern vehicles, metal-foam composite structures are introduced due to their unique morphological structures. The newly developed aluminum foam will be used to absorb impact energy and its usage can be extended to many other applications in lightweight armor and mine blast containment in the military, to replace the expansive structures in the aerospace industry, in disaster, exploitations, in civil structures like bridges, etc. Therefore, it is very important to analyze energy absorber specimen from lightweight aluminum foam which is capable of absorbing high energy. The key approach of strengthening a structure is to dissipate the crash energy to prevent injuries and reduce damages in the structure. The car crash box, which is assembled on the frontal bumper subsystem of a car and made from aluminum foam has a high capability to absorb impact energy and reduce the peak reaction loading during a collision. Having this kind of components has a significant role in saving the occupant's life and protects expensive car components behind the crash box. Therefore, characterizing the mechanical properties of aluminum foam, which has a high capacity for absorbing impact energy during a vehicle collision, is a great interest.

1.7 Scopes and limitations of the study

This study covers the numerical analysis of aluminum foam material at different pore radius and void percentages for impact energy absorption purposes in automotive industries for vehicle applications. The process includes numerical modeling using DIGIMAT and FEM ANSYS software simulation of impact condition by Explicit Dynamics of aluminum foam. Followed by optimizing the proper porosity percentage and pore size for the best energy absorption application. Finally, analyzing and determining the deformation, specific energy absorption, impact energy absorption, acceleration and reaction force for Al foam and comparing the foaming agent inclusion particulates with existing additive particles at the same material configurations for impact energy absorption purpose are the main area of this study.

However, numerically introducing of different pore size cells(bubbles) at the same time on one model, regular pattern distribution of pores arrangement during CAD modeling of closed cell aluminum foam using DIGIMAT multi scale material modeling process and its fracture analysis and the thermal effects during impact simulation analysis are not included in this study.

1.8 Thesis organization

This work is organized into six chapters. The first chapter is brief description about Aluminum foam, its impact energy absorption capability; thesis background, problem statement and objectives to be achieved are discussed. The second chapter presents literature review relevant to this thesis work, which have been investigated by different researchers. The third chapter deals about methodology used, modeling the Al foam and distributing the uniform bubbles (air voids) size randomly throughout the entire foam model to accomplish this thesis, conditions and materials used. The fourth chapter is about the numerical CAD modeling process and finite element methods of Explicit dynamics for Al foam impact simulation. The fifth chapter deals with results summarized from the numerical analysis and discussions are made based on the outputs of the FEM. Finally, the sixth chapter gives conclusions achieved from this thesis work and propose future work in this field of study.

CHAPTER TWO

2. Literature Review

This chapter aims to provide a part of the work that has been done before in this area by focusing on the energy absorptions in automotive industries, military applications maritime applications, and different mechanical machine components. Different researchers conduct different analysis and follow different approaches to investigate and develop crash box for energy absorption applications. There are many types of researches and literature on energy absorptions from composite materials experimental and analytical analysis that has been published. In the past, several researchers studied different types of energy absorber systems such as frusta, circular tubes, square tubes, multi-corner metal columns, and rods for their application in impact and crash and presented the comprehensive results. Generally, as stated below, their focus were on the analytical, manufacturing process of aluminum foams, the effects of foam fillers such as SiC, Mg, Al_2O_3, etc. length, outer diameter, the wall thickness of specimen and shape optimizations.

Manmohan D. Goel [15] described the deformation and energy absorption of the single, double and multi-wall square and circular tube structure with and without aluminum foam core. This was mainly carried out for assessing its effectiveness in crashworthiness under identical test conditions. Modeling and numerical simulation of aluminum foam-filled square tubes under axial impact loading were presented. The foam-filled thin-walled square tubes were modeled as shell wherein, foam core was modeled by incorporating visco-elastic-plastic foam model in Altair RADIOSS. It was observed that the multi-wall tube structure with foam core alters the deformation modes considerably and results in a substantial increase in energy absorption capacity in comparison with the single and multi-wall tube without foam core. Moreover, the multi-wall tube foam filled structure shows mixed deformation modes due to the significant effect of stress wave propagation. But this paper only focuses on the geometrical assessment, it didn't cover or consider the effect of material densities on energy absorptions.

R. Karup pasamy et al[16]concentrated on the preparation of the foam material with better cost-effective approach. The low-density aluminum foam was produced using sand balls which are arranged in matrix form. The three different sizes of sand balls were prepared with the diameter of 3mm, 5mm and 7mm. The foams were prepared with a different pore size of 3-4mm, 5-6mm, and

7-8mm. The percentage of porosity of the aluminum foam was estimated. Also, the foams were tested under the compressive load in the Universal Testing Machine. The yield and ultimate compressive strength were measured. The result revealed that the increasing porosity of the foam resulted in better yield and ultimate compressive strength. This paper failed to characterize the mechanical properties of the Aluminum foam on a certain porosity level for energy absorption applications.

N A Endut et al [17] presented the reliable data that can be used to analyze the energy absorption behavior of aluminum foam sandwich by conducting experiment work which was a compressive test. Six experiments of the compression tests were carried out to analyze the stress-strain relationship in terms of energy absorption behavior. The effect of input variables includes varying the thickness of aluminum foam core and aluminum sheets on the energy absorption behavior were evaluated comprehensively. The result highlights that the energy absorption of aluminum foam sandwich increases from 12.74 J to 64.42 J respectively with increasing foam and skin thickness. The main focus of this paper was on aluminum foam sandwich and wall thickness, but the specimen which is made of Aluminum foam only was not analyzed for energy absorption applications.

Krishna S Pawar et al [18] reported the effect of plane crash box geometries on the energy absorption. The study was based on analytical, experimental and numerical works. Various parameters like width, thickness and filler material which affects the crash box performance were studied by using the design of experiments. In this experiment, they use ABAQUS CAE as a modeling and analysis software. This paper presented the geometrical enhancement of the crash box, rather than investigating its mechanical property which can play the most important role in energy absorption purposes.

Zhifang Liu et al [19] presented the mechanical response and energy absorption of aluminum foam-filled and empty circular tubes with different geometries that were investigated experimentally and theoretically. All specimens foam filled and empty circular tubes were compressed laterally by two rigid plates. The experimental result showed that the presence of aluminum foam filled in the circular tube changes the deformation modes comparing with empty tubes and increased the energy absorption of the foam-filled circular tubes. The relation of lateral

loading and energy absorption of the foam-filled circular tubes were obtained. The comparisons between the analytical prediction and experimental results were performed and good agreement was achieved. The limitation of this paper was the absence of the effect of the porosity of aluminum foam on the mechanical property. This is because Aluminum foam itself can be used for energy absorption applications, rather than using Aluminum foam as a filler material it is better to investigate its mechanical property for further energy absorption applications.

Vignesh Sampath et al[20] presented the energy absorption of foam-filled and empty aluminum alloy tube under dynamic, and bending were investigated numerically and experimentally. The material model for aluminum foam was based on the implementation of crushable foam with isotropic hardening combined with strain rate dependence in ABAQUS. The results indicate that the energy absorption capacity of foam-filled aluminum alloy AA7075 tubes was higher than the empty tubes. The peak loads and energy absorption values between experimental results and simulation were found to be a good agreement. At high strain rates, an increase in the energy absorption capacity was observed, which is useful for crashworthy applications. This paper investigates the aluminum foam-filled tube rather than the aluminum foam.

Yonghui Wanget et al[21]. In this paper, the experimental, numerical and analytical studies were extended to the dynamic crushing behaviors of the connectors, since they usually experience dynamic loading under blast attack. due to the increasing extreme events and threats related to blast attack on buildings, many blast-resistant facades/panels were developed to reduce the blast-induced damage on the buildings. Besides, the 'soft' connection (like energy absorption connector) was usually employed to attach the blast-resistant facades to buildings, which could further reduce the damage on buildings using dissipating part of blast energy and reducing peak blast load transferred to buildings. Moreover, the numerical and analytical models were also developed to predict the force-displacement responses of the connectors, which showed good agreement with the test results. This paper studied the effects of energy absorptions of a connector as a whole. It doesn't include the study of Aluminum foam.

Y.C. Li, J.Y. Xiong et al[22]. This paper improves the mechanical properties of aluminum foams by matrix reinforcement methods. In this study, aluminum foams were reinforced by ceramic particulates reinforcing of the aluminum matrix. For this work, three types of fine ceramics, cubic

boron nitride (CBN), silicon carbide (SiC) and boron carbide (B4C) were chosen as additions to enhance the performance of Al foams. The mechanical properties and the energy absorption of the reinforced aluminum foams were investigated by dynamic and quasi-static compression. Results indicated that the additions of the three kinds of the ceramic particle, the CBN additions to the aluminum foams showed the most significant effect on the energy absorption properties of the foam; SiC additions showed a moderate effect; whilst the B_4C showed a minor energy absorption enhancement under both conditions of dynamic and quasi-static compression.

Ankur Bisht and Brijesh Gangil [23]. This paper presented closed-cell aluminum foams with different percentages of zinc content were successfully prepared and investigated. The foamable precursors were prepared in a pit furnace by adding calcium as thickening agent, calcium carbonate as blowing agent and different percentages (0 wt.%, 0.5 wt.% and 1 wt.%) of zinc particle. The distribution of Zn elements and quassi-static behavior of the foams were investigated. The experimental results show that Zn element is uniformly distributed in cell wall matrix. The distribution of Zn elements had a significant effect on the quasi-static compressive behavior; Hence, it can be concluded that increase in percentage of Zn particles helps to increase the compressive strength, plateau region and energy absorption, in addition to providing better and uniform pores.

Minzu Liang, Xiangyu Li et al[24]. This paper presented the finite element models of two-layer graded aluminum foam and developed using the periodic Voronoi technique. Numerical analysis was performed to simulate deformation, energy absorption, and transmitted impulse of the two-layer graded aluminum foams by the software ABAQUS/Explicit. The aluminum foam material used in this study was closed-cell foam, the nuclei are generated randomly in a given space. Result shows, the Al foam with high energy absorption and low transmitted impulse to the protected structure is thus an excellent choice for securing the structure because it could meet the crashworthiness requirement.

Çağrı Ergönenç [25], as presented in this paper, closed-cell aluminum foam offers a combination of properties including low density, high specific stiffness and strength, and high energy absorption. The deformation of foam proceeds with localized deformation leading to almost a

constant plateau stress. The results show as the core thickness increases, the total internal energy of the panel increases, due to the energy absorption capability of the foam layer.

A.-H. Benouali and L. Froyen et al[26]. The aim of this work was to provide quantitative information on the cell foam morphology, regarding the shape, size and orientation of the most representative cells and the corresponding statistics. Resolving the structure of cellular foams has been subject of scientific research for many years. However, recent observations using X-ray micro-computed tomography have shown that this technique is particularly suitable for internal investigation and quality control of metal foams. This supports the mechanical behavior anisotropy stating that the foam is stiffer in transvers direction. In contrast, no preferred orientation was observed in LKR foams in any of the planes, that is in accordance with the observed isotropic mechanical behavior of LK Ranshofen foams.

Nikhil Gupta et al [27] described the characterization of foams for various properties was more challenging compared to a solid specimen of the same material. The complications of testing foams include determining the size and shape of a representative specimen of the foam material to obtain properties that were representative of the bulk material. Localized variations of the cellular structure could result in vastly different measured properties. Standard test methods, such as those described by ASTM standards, were not always directly applicable to foams, unless standards specifically developed for foams are available. In the development of Al foam structures, often closed-cell foams can be tailored to have different wall thickness, cell size, and cell shape.

J. Kadkhodapour and S. Raeisi [28], described their works in three phases. In the first part of the work, the effect of relative density on the mechanical properties of closed-cell aluminum foam was investigated by numerical methods, and the results were compared with analytical predictions and experimental data. In the second part, the effect of cell topology, including cell shape and cell size, on the material behavior was investigated for aluminum foams, regardless of relative density. It was shown that cell shape causes some changes in macroscopic material behavior, which can be explained by its effect on the pattern of deformation and local failure in the material. Different mechanisms of deformation at the cell level are considered in connection with closed-cell aluminum foams. And finally, in the third part, different patterns of failure are investigated on different scales. The deformation and failure at the cell level cause localization on the macro scale.

The cell shape and the inhomogeneity of the foam structure are investigated as the primary factors affecting the deformation and failure modes, and the results give some deeper understanding about the effect of cell shape on mechanical behavior. Also, some experimental tests are carried out to validate the numerical results.

X.C. Xia a, and X.W. Chen et al[29] presented the influences of porosity and pore size on the quasi-static compressive properties of the foams were systematically investigated. The results showed that the yield strength, energy absorption capacity and ideality energy absorption efficiency were decreased with the increase in porosity. Results showed that mean plateau strength of the foams was increased first and then decreased with increase in mean pore size. In addition, energy absorption capacities were almost the same in the initial stage, while the differences were obvious in the middle stage. From the engineering point of view, the specimens with mean pore size of 1.5 mm possess good combination of mean plateau strength and energy absorption characteristics under the present conditions.

Hamza S. Abdullahi1 and Yicheng L.S Gao [30] presented the modeling approach introduces a new method for finding the number of seeds based on the cell diameter distribution and an algorithm for computing and assigning the irregular cell wall thickness based on reverse bubble growth. Results from the foam models developed in this work were found to have better accuracy in capturing the geometrical and topological characteristics of the real foam.

M. Aboraia and R. Sharkawi et al[31] presented metallic foams were gaining ground as important new engineering materials. Aluminum foams were produced with different densities using different percentages of calcium carbonate as a foaming agent. The mechanical properties of the foamed material were tested using uniaxial- compression test. Plateau stress, densification strain and energy absorption capacity, were calculated. The obtained results show that the collapse strength and the absorbed energy of foams increase with increasing the density.

Vincenzo Crupi and Gabriella Epasto et al[32]. The aim of this paper was the analysis of low-velocity impact response of AFS (aluminum foam sandwiches) panels and the investigation of their collapse modes. Low velocity impact tests were carried out by a drop test machine and a theoretical approach, based on the energy balance model, has been applied to investigate their

impact behavior. The failure mode and the internal damage of the impacted AFS have also been investigated by a Computed Tomography system.

Vignesh Sampath and C. Lakshman et al[33] presented the energy absorption of foam filled and empty aluminum alloy tube under dynamic bending numerically and experimentally. The material model for Al foam was based on the implementation of crushable foam with isotropic hardening combined with strain rate dependence in ABAQUS. Energy absorption of foam filled aluminum alloy AA7075 tube was higher than the empty tubes. The peak load and energy absorption values between experimental and simulation were found to be in good agreement.

Tiago M. Nunes [34] Focus on the development of an aluminum structure, aiming for an optimized design, within the design parameters available for the vehicle project. FEA model of the frontal energy absorption structure for frontal impact was developed and validated with a quasi-static compression experimental procedure. A multi-objective optimization process, that can be adaptable to the future needs of the project, was developed. Several changes in the geometry were tested, focusing on specific deficits in the performance of the structure. Through this process, a compilation of the influence of several parameters on the impact performance is obtained. The optimized structure shows a significant performance improvement in the event of a frontal collision and, according to the established limits, it was expected to satisfy the legal values of safety in the tests carried out by the responsible entities.

D. Kumar Rajak and L A Kumaraswamidhas [35], This paper aimed to study the aluminum alloy foam core with mild steel tubes. The aluminum foam was made with LM25 aluminum alloy 15wt% silicon carbide particle. The mild steel foam filled tubes were tested in Universal Testing Machine. The energy absorption rate per unit volume was noted that 11.78 to 15.00 MJ/m3 and 12.49 to 17.33 MJ/m3 empty and foam filled mild steel tube respectively. This work also describes the compression movements of mild steel tube and foam filled tube with foam, variable strain rate between 10-3/s to 10/s. The compressive deformation behavior of this LM25 aluminum alloy foam filled mild steel tube and empty mild steel tube was examined in order to evaluate its specific energy absorption. It is also noted that foam filled mild steel tubes stress strain diagram exhibited more energy absorption properties.

2.1 Research gap

Different researchers conduct different analysis and follow different approaches to investigate and develop metal foams for automotive impact energy absorption applications. As reviewed from the literature several researchers studied different types of energy absorber systems such as frusta, circular tubes, square tubes, multi-corner metal columns, and rods for their application in impact and crash, and presented the comprehensive results. Generally, their major concerns are on the manufacturing process, geometry optimization, the effects of crash tube length, diameter and wall thickness of the specimen. Absence of a clear investigation and analysis on the aluminum foam for energy absorption application by introducing the uniform sizes of bubbles (voids with air) on a cubic model which are distributed randomly throughout in the cubic model element, lightweight aluminum foam for crash energy absorption application and strengthening a structure to dissipate the crash energy in order to prevent injuries and improve the crashworthiness of the structure, an optimum combination of material's microstructure (bubble distribution, bubble size and porosity percentage) throughout the entire model are identified as the main research gaps. Having those all-in minds, analyzing the lightweight elements from aluminum foam for energy absorption application will result to get best candidate material.

Focuses on the numerical study of aluminum foam for energy absorption purposes, for example, for a crash element using the numerical for automotive industries, the material behavior can be enhanced. The aluminum foam element will be developed with different porosity percentage, different bubble size and with random distribution of air voids inside the model. This paper introduces a circular cell shape, random distribution of bubbles at 5%, 10% and 15% void fractions to see the effects of bubble size, cell distribution, air voids on the energy absorption of aluminum foam.

CHAPTER THREE

3. Methods and Materials

3.1 Research Methodology

The finite element method is numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. in this research finite element method ANSYS workbench is used to conduct numerical analysis for impact conditions, to characterize the mechanical properties of Al foam. To do this the numerical CAD was modeled cell size at (1.5, 2, 2.5, 3 and 3.5) mm with random distribution of bubbles (voids with air) inside the cubic element. ANSYS workbench software have a limitation on developing the Al foam CAD with uniform cell size and with uniformly distributed bubbles (voids with air) throughout the cubic element.

For this entire analysis, basically three software are used. Those are DIGIMAT multi scale material modeling for developing foamed aluminum model CAD geometry, solid works for feature editing and plate assembly and ANSYS work bench for simulating the CAD model.

The DIGIMAT multi scale material modeling is used to overcome the limitations of Ansys on the development of the CAD Al foam with uniform cell diameter and randomly to distribute the voids inside the cubic element.

Therefore, finite element modeling of Aluminum foam consists of geometry generation, applying material properties, meshing the component, defining the boundary constraints, and applying the proper velocity and degree of freedom. These steps lead to analyze the specific energy absorption, energy absorption, force generated and deformation in the cubic Al foam specimen.

To do these all, the analysis starts from modeling of Aluminum foam with cubic 30 x 30 x 30 mm dimension. Generally, the modeling process is following the Voronoi model. In this case the first task is developing the fifteen CAD geometry at bubble radius of (1.5, 2, 2.5, 3 and 3.5) mm. After developing those CAD models, impact analysis is done on ANSYS work bench by using Explicit Dynamics module to evaluate the energy absorption of each model.

3.2 Research Methodology Design

To accomplish this research, the work started from review of related literature which are most closely related to the impact energy absorption of Al foam for automotive application purpose. The necessary and useful data are collected from different journals, books, publications and papers. The entire research analysis is done using numerical approach because of absence of sophisticated machines and equipment to manufacture and for experimental work. In numerical analysis, the total of fifteen 3D CAD models are developed with various pore size and porosity percentage, and those circular vacant voids with air are also distributed finely and randomly by using DIGIMAT multi scale material modeling, which is appropriate software for developing aluminum foam easily. Those CAD models are imported to the second software solid works for feature editing and plate assembly. The assembled CAD models are imported to ANSYS work bench, in this part all the material constants and boundary conditions are added, the contacts are defined, meshing and optimization are done. For FEM simulation analysis Explicit Dynamics section module is used.

3.3 Implicit and Explicit

Most of the software's would normally solve the dynamic equilibrium equation in an implicit approach however the foremost widespread approach that ought to be used for highly non-linear issues is to use explicit (specific) time integration scheme like a central difference scheme.

- **Implicit:** A global stiffness matrix is computed, inverted and applied to nodal out of balance force to obtain a displacement increment. The advantage of this approach is that time step size may be selected by the user. The disadvantage is the large numerical effort required to form, store, and factorize the stiffness matrix. Implicit simulations therefore typically involve a relatively small number of expensive time steps.
- **Explicit:** Internal and external forces are summed at each node point, and a nodal acceleration is computed by dividing by nodal mass. The solution is advanced by integrating this acceleration in time. The maximum time step size is limited by the Courant condition, producing an algorithm which typically requires many relatively inexpensive time steps. There are several benefits of such a procedure and therefore the most significant is that it results in an algorithmic programmed which may be simplified programmed, does not need any matrix operation procedure and more is very appropriate for a quick parallel computing methodology.

- **Comparison of explicit and implicit:** The explicit method requires short time step for an accurate solution, whereas the implicit method can give reliable results with large time steps. The implicit methods are unconditionally stable, whereas the explicit methods are mostly conditionally stable. In implicit method contact cannot be easily controlled but not in explicit.

The general summarized work flow for this research is as shown below.

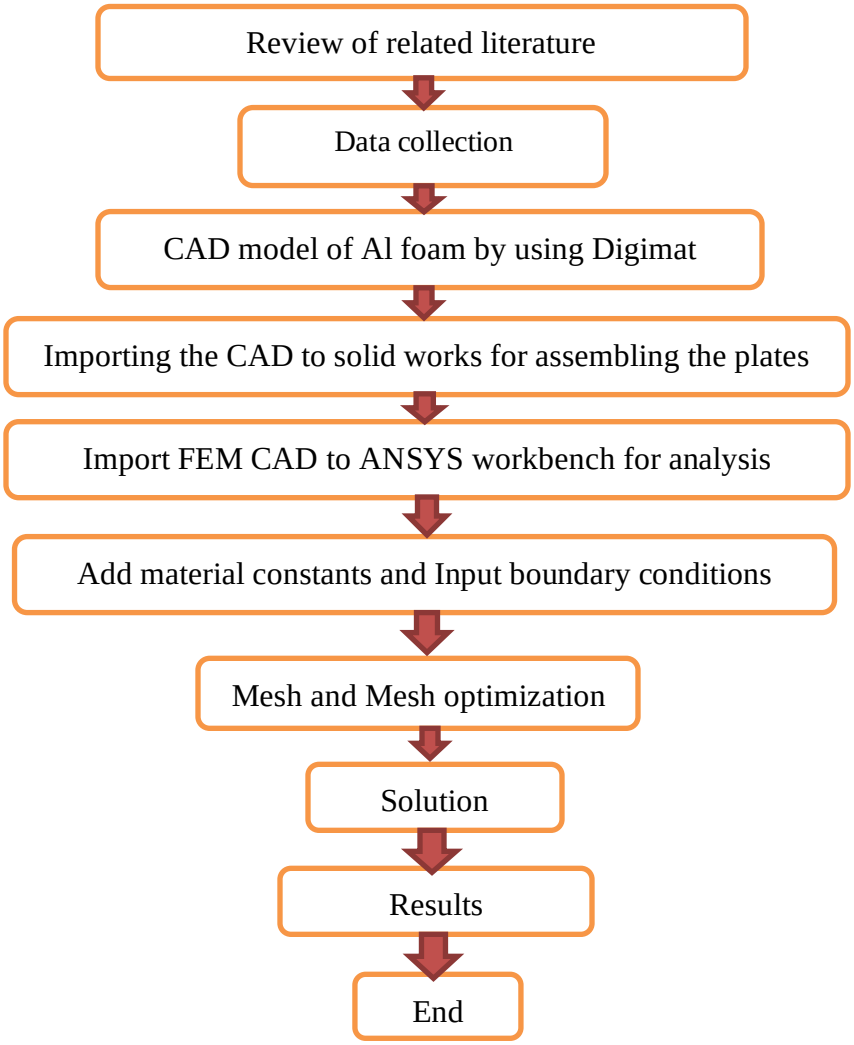


Figure 3.1: Summarized work procedure for the study

3.4 Material

3.4.1 Material description

Aluminum foam is a metallic foam material that is modeled from the Aluminum metal matrix and void with air introducing into molten aluminum metal. The air voids are created inside the metal matrix by forming hydrostatic pressure. As we know the air has light in weight. The reason to use the air as a filler material is to make the specimen more lightweight.

3.4.2 Material selection

Ultra-light metal foams are become an attractive research field both from the scientific and industrial applications viewpoints. Closed-cell metal foams, in particular, aluminum alloy ones are used as lightweight, energy-absorption and damping structures in different industrial sectors, detaining an enormous potential material with their unique structures. This unique structure makes them an excellent energy absorbing element. For example, in crash zones of lightweight structures, as well as for blast, noise and heat protection.

Nowadays, aluminum foams of high porosity have attracted much attention of researchers on materials due to their unique compression behavior that undergoes a large deformation at nearly constant nominal and/or plateau stress, and great potential for application in absorbing energy from an impact, and shock energy by plastic work dissipation in compression. For engineering design, the mechanical behavior of this material must be numerically analyzed.

Therefore, closed-cell aluminum foam offers a unique combination of properties such as low density, high stiffness, strength, and energy absorption that can be tailored through by random distribution of the microstructures [36].

The compressive stress and energy absorption ability depend on the material's density and its microstructure. In the present study, the dynamic compressive behavior of aluminum foam is studied numerically by simulation. For the entire analysis, the aluminum foam Al alloy 7075-T6 is selected. Because Aluminum alloy is better for this purpose because being a soft material allows it to deform greatly absorbing more energy than steel[37].

3.4.3 Material properties of Aluminum 7075-T6 Alloy

This category of aluminum alloy is typically found in automotive, aviation, marine and other transport applications because of its extremely high ratio of strength to density[25][27].Aluminum foam developed from Al 7075-T6 alloy is the best material for blast and impact energy absorption applications because of the following mechanical properties.

Table 3.1: Physical and mechanical properties of Al7075-T6[27]..

Properties	Values
Density (kg/m3)	2800
Poisson's ratio	0.33
Elastic modulus (GPa)	71.7
Yield strength (MPa)	503
Elongation (%)	11
Hardness (HB500)	87
Shear strength (MPa)	331

3.4.4 Material Modeling

For impact numerical modeling of the Al foam by using finite element ANSYS, the Johnson-Cook plasticity model is used. The Johnson-Cook plasticity model (Eq 3.1) describes the dependency of plastic flow stress (σ) with equivalent plastic strain (ε^{pl}), equivalent plastic strain rate (ε^{*pl}) and temperature (T*)[38].

The material model for the Al 7075-T6 is modeled using the Johnson-Cook material model contained in the FEA ANSYS code.

$$\sigma = \left[A + B\left(\varepsilon_{pl}\right)^{n}\right]\left[1 + Cln\left({\varepsilon^{pl}}/{\varepsilon^{*pl}}\right)\right][1 - T^{*}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

Where the first term represents the strain hardening of the yield stress, the second term indicates the increase in the yield stress at elevated strain rates and the final term represents the decrease in

the yield stress due to local thermal effects. A, B, C, n, and m are constants. $\left(\varepsilon^{pl}/_{\varepsilon^{*pl}}\right)$is the normalized equivalent plastic strain rate.

$$T^* = \left(T - T_{ref}\right)/\left(T_{melt} - T_{ref}\right) \quad \text{.....3.2}$$

Where T is the temperature, T_{melt} is the melting temperature of the material and T_{ref} is reference temperature. The thermal effect is not included here in this study.

Table 3.2 : J-C material model parameters for Al Alloy 7075-T6[20]

Constants	A (Mpa)	B (Mpa)	n	c	m
AA7075-T6	546	678	0.71	0.024	1.56

Johnson-Cook plasticity model is used with initial yield stress (A) 546 Mpa, hardening constant (B) 678 Mpa, hardening exponent (n) 0.71, strain rate constant (c) 0.024 and thermal softening constant (m) 1.56. The failure analysis for this aluminum nonlinear foam is plastic strain failure with maximum equivalent plastic strain of 0.75.

In using J-C material modeling, the material properties such as thermal conductivity, specific heat and melting temperature were not required because the measurements of measurements of temperatures. The proposed approach has advantages because it considers plastic strain failure, equivalent plastic strain and strain rate correlation, in addition to these it has less mathematical complexity and simplicity of formulations.

CHAPTER FOUR

4. CAD Modeling and Finite Element Analysis

4.1 Numerical Analysis

For numerical modeling process DIGIMAT multi-scale material modeling, solid works, and ANSYS workbench software tools are used. Mean that, the foam is modeled on DIGIMAT, then exported to Solid works for plate assembly and finally exported to ANSYS workbench.

Digimat-MF (mean-field) is used for the initial analyses in the process of modeling the foam element, while Digimat-FE (finite element) is the finite element-based homogenization module of Digimat which is used to model the CAD geometries of the foam in different void percentages. In order to obtain stable foams, 5%, 10% and 15% volume percentage of pores are used to increase the energy absorptions for impact and crash conditions.

4.1.1 Foam Structure Modeling

Closed-cell aluminum foam is one of a metallic type foam which is developed by injecting the air bubbles inside the aluminum metal matrix by using DIGIMAT multi-scale material modeling software. In the closed-cell aluminum foam modeling process the size of the air bubble (unit cell size) plays an important role in the energy absorption rate. Typical shapes for the bubbles (cells) in aluminum closed-cell foam can be classified into three main groups[28][39]: These are

a) Round or circular
b) Vertical elliptic and
c) Horizontal elliptic.

In this paper, around or circular bubble shape on cubic CAD geometry is introduced. Usually, the circular shape (bubble) cell model materials are easy to manufacture; this is why circular shape geometry is selected to model for the entire analysis.

4.2 CAD geometry modeling process

Digimat-FE is a micromechanical material modeling software that uses a direct, to generate realistic finite element (FE) representation of a representative volume element (RVE) of the cubic aluminum foam microstructure at a different percentage of porosity.

In this study for numerical analysis, a total of fifteen specimens are developed by using Digimat multi-scale material modeling. According to[29], recommended pore sizes for aluminum foam elements for energy absorption purposes in different application areas are between 1.5 mm to 3.5 mm[40][16]. For example, in ALPORAS aluminum foam investigation an average cell size of 3.5 mm was used[41].Following this total of fifteen cubic boxes were modeled with circular bubble (cell) shape at bubble size of 1.5mm, 2mm, 2.5mm, 3mm and 3.5mm with 5%, 10% and 15% volume void fraction.

The 3D Voronoi technique is used to generate closed-cell aluminum foam with randomly distributed cells and with uniform cell diameters, in which the 3D Voronoi model is constructed by using Digimat multi-scale material modeling software. According to the [30][42] and (Gibson and Ashby), to minimize possible boundary and size effects, the length of the cubic Voronoi foam is set at 30 x 30 x 30 mm for a cubic model with circular unit cell. It is shown in Figure 4.1 below. The number of cells (*N*) in a Voronoi foam can be calculated by

$$N = \frac{V}{(4\pi/3)r^3} \quad \text{.....4.1}$$

Where V- the volume of the cubic box, which is equal to 27,000 mm^3.

r- Radius of the cell or bubble, ranging from 1.5 mm – 3.5 mm.

For the entire analysis in this paper, five different radius values are used, mean that radius at most extremely minimum, at the most extremely maximum, at between the most minimum and the most maximum (middle point), at an average between the most minimum and middle point and at an average between middle point and the most maximum as follows.

- ✓ The most extremely minimum at 1.5mm
- ✓ The most extremely maximum at 3.5mm
- ✓ The middle point $\frac{1.5+3.5}{2} = 2.5\ mm$
- ✓ The average between the most minimum and middle point, $\frac{1.5+2.5}{2} = 2\ mm$

The average between the most maximum and middle point, $\frac{3.5+2.5}{2} = 3\ mm$

Now, the number of cells or bubbles can be calculated as follows by inserting all the r- values in the following formula

$$N = \frac{V}{(4\pi/3)r^3} \text{.....4.1a}$$

Table 4.1: Number of bubbles with respective radius

Parameters	Radius (R) (mm)	Number of bubbles (N)
R1	1.5	1910
R2	2	806
R3	2.5	413
R4	3	239
R5	3.5	150

Based on the above calculation, the total of fifteen models are developed.

4.3 Modeling and Finite Element Methods

Finite element method ANSYS workbench is used to conduct numerical analysis for impact conditions, to characterize the mechanical properties of Al foam. To do this the numerical CAD should be modeled with uniform closed-cell, with a random distribution of air bubbles inside the cubic element. ANSYS workbench software have a limitation on developing the Al foam CAD with uniform cell size and with uniformly distributed air bubbles throughout the cubic element.

For this entire analysis, three software are used: DIGIMAT multi-scale material modeling for developing foamed aluminum model CAD geometry; solid works for feature editing; and plate assembly and ANSYS workbench for simulating the CAD model.

The DIGIMAT multi-scale material modeling is used to overcome the limitations of Ansys on the development of the CAD Al foam with uniform cell diameter and randomly to distribute the voids inside the cubic element.

Therefore, finite element modeling of Aluminum foam consists of geometry generation, applying material properties, meshing the component, defining the boundary constraints, and applying the proper velocity and degree of freedom. These steps lead to analyze the stress-strain curve for determining the deformation, specific energy absorption, energy absorption, the force generated and peak and average acceleration for the cubic Al foam model.

To do these all, the analysis starts from the modeling of Aluminum foam with cubic 30 x 30 x 30 mm dimension. Generally, the modeling process is following the Voronoi model. In this case the first task is developing the fifteen CAD geometry which are containing different bubble radius between1.5 mm up to 3.5 mm, (the points are at 1.5, 2, 2.5, 3 and 3.5) mm. After developing those CAD models, impact analysis is done on ANSYS work bench to evaluate the energy absorption rate of each model. This step is used to obtain appropriate bubble/cell radius for the best of energy absorption applications.

4.4 Finite Element Methods

4.4.1 Description of FEA Methods

The process of analyzing the energy absorption rate can be done by using explicit dynamics using ANSYS workbench 19.2 software. This is done by in the form of impact by placing the foam

specimen on between one fixed rigid and moving rigid steel plate to compress the target specimen, by dynamic system by introducing very low velocity for the moving steel plate in one side and rigid steel plate on the other side of the specimen.

The numerical impact analysis of Aluminum foam specimen is used to characterize the mechanical properties of Al foam such toughness, deformation, and energy absorption in terms of their bubble cell size and percentage of porosity. For this purpose, fifteen CADs of Aluminum foam specimens with the void fractions at 5%, 10% and 15%, with the dimensions of 30 mm x 30 mm x 30 mm are modeled.

4.5 Methods and its procedure

Aluminum foam specimen is placed between the two rigid steel structural plates for impact simulation. Explicit dynamic simulations are best performed on prismatic rectangular and cubic specimens of foam with a dimension of the specimen at list seven times greater than the unit cell size in according to the ASTM standard. In modeling the specimen the minimum dimension of the specimen is greater than seven times the pore size, this is to avoid porosity size effect[26][31]. Specimens of 30 x 30 x 30 mm are placed on between the moving rigid impactor steel plate and the fixed rigid steel plate structure, as per ASTM F1976 standards[43]. In impact simulation, the following conditions, by decreasing and increasing the number of bubble cells leads to analyze, evaluate and characterize the mechanical properties of the foam. As shown in the figure 4.1 below, the foam specimen rest on a rigid wall and are impacted from the left by moving or travelling at a constant velocity rigid plate and another fixed rigid wall at the right side

4.5.1 Impact Explicit Dynamic method

Impact Testing: The crushing speed decreases from the initial impact speed to rest as the specimen absorbs the energy. But the crushing process takes place in a fraction of a second. Therefore, it is difficult to study experimentally the crushing unless provided with expensive equipment like a high-speed camera. This study applied numerical impact simulation by using finite element analysis.

In this study, the explicit dynamic simulations are performed for all cubic specimens subjected to impact under low velocity. This is used to draw a graph of specific energy absorption versus time,

deformation versus time, energy absorption vs time, etc. by decreasing and increasing the number of bubble cells and its percentage used to see its effects.

Impact simulation is used to determine material behavior at higher deformation. During the impact, the energy absorbed is extracted. This absorbed energy is a measure of the impact strength of the material.

4.5.2 Specimen for Impact simulation

The foam specimen for impact simulation is modeled with dimensions of 30 mm X 30 mm X 30 mm as shown in Figure 4.1. In modeling the specimen the minimum dimension of the specimen should be greater than seven times the pore size, this is to avoid porosity size effect[26][31]. Mean that seven times 3.5 mm pore size is equal to 24.5 mm, therefore, modeling the foam by 30mm is still good. This is why this above dimension is selected. The impact simulations are carried out using in the form of crash principle. Specimens of 30 mm x 30 mm x 30 mm are placed on between the moving rigid impactor steel plate and the fixed rigid steel plate structure. Impact simulations are carried out the same initial velocity. As shown in Figure 4.1, the foam specimen rests on a rigid wall with two degrees of freedom fixed and are impacted from the left by moving or traveling at a constant velocity rigid plate and another fixed rigid wall at the right side.

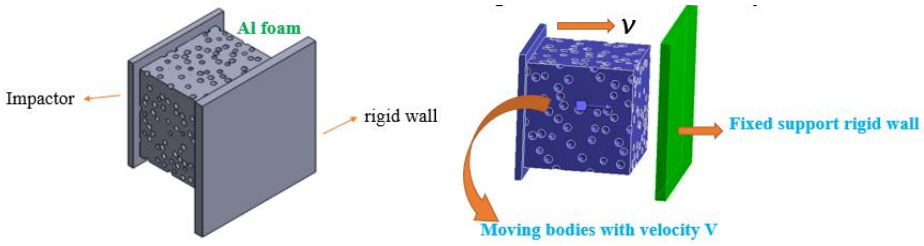


Figure 4.1: Specimen for impact simulations

4.6 Boundary conditions

For impact simulation, the CAD models are compressed uniaxially in the x-direction with constant velocity applications. This velocity is applied at the left rigid moving steel plate and on Al foam as shown in the CAD model figure 4.2 below, and the contact is assumed to be frictionless. The CAD model is also fully constrained at the right, steel plate is rigid and fixed support condition.

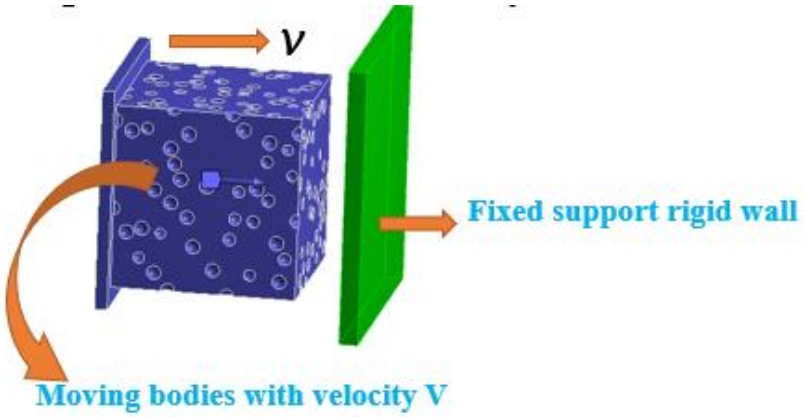


Figure 4.2: Boundary conditions

The material data used during numerical analysis on ANSYS workbench of aluminum foam are Explicit materials, aluminum 7075-T6 alloy for foam specimen and structural steel for left and right plates. Johnson-Cook plasticity model is used with initial yield stress 546 Mpa, hardening constant 678 Mpa, hardening exponent 0.71, strain rate constant 0.024 and thermal softening constant 1.56. The failure analysis for this aluminum nonlinear foam is plastic strain failure with maximum equivalent plastic strain of 0.75. For low-velocity impact simulation, For impact simulation, low velocity ranging from 1.5 to 8 m/sec can be used [32]. Using initial low velocity for impact simulation of closed cell Al foam having vacant air voids inside the model will increase the time to absorb energy and reduce the contact period between the foam specimen and impactor[44]. For this analysis 7 m/sec initial low velocity is applied. The total mass of the Aluminum foam are 0.071923 kg for 5%, 0.068138 kg for 10% and 0.064352 kg for 15%. The same impactor with the square shape of dimension 46 mm X 46 mm is used for all models. The material model for impactor has been chosen to be rigid and for the foam crushable foam. After setting the material modeling for simulation, the specimen is fixed to the platform. One side of the steel plate is fixed support while on the other side the plate is compressed against the specimen. The target CAD, that is closed cell Aluminum foam specimens are pressed by using the left steel plate.

The following are 3D CAD models developed based on the Equation 4.1 above calculations at volume fractions of 5%, 10% and 15% of air voids in which the air bubbles are randomly dispersed or distributed in the aluminum foam boxes; this is for forming aluminum foam as shown in the figure below.

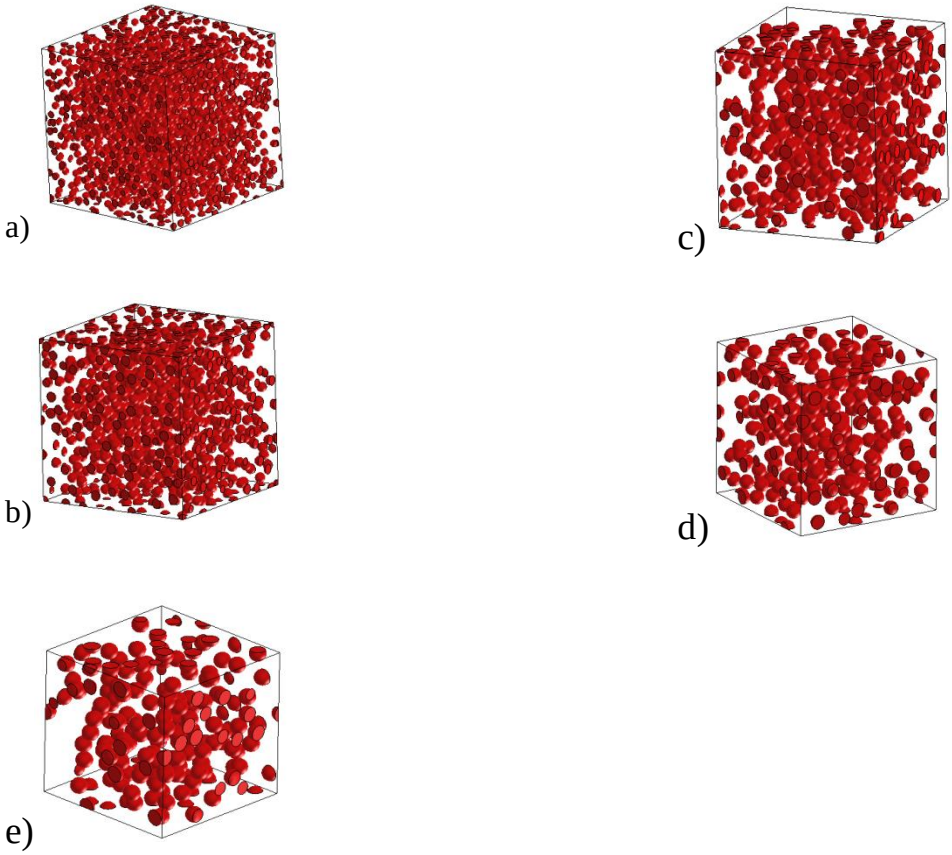


Figure 4.3: Geometrical Representation of voids inside with 10% voids of Al metal foam box at radius of:

a) 1.5 mm b) 2mm c) 2.5 mm d) 3 mm and e) 3.5 mm

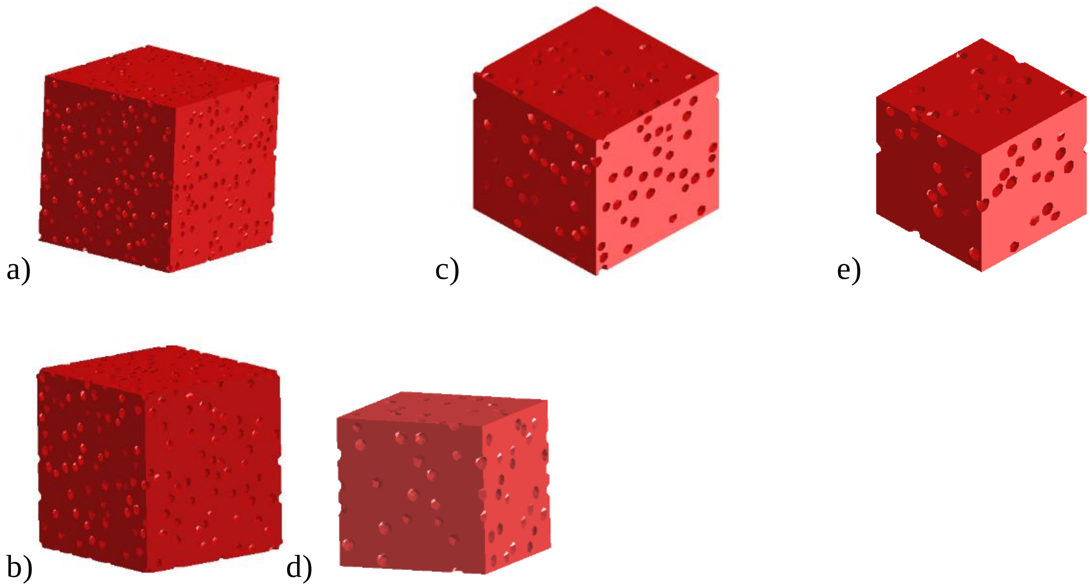


Figure 4.4: Models Representation of RVE with 10% void, at radius of: a) 1.5 mm b) 2mm c) 2.5 mm d) 3 mm and e) 3.5 mm

As shown in Table 4.1 above, as the size of the radius increases from 1.5 mm to 3.5 mm, the number of bubbles decreases from 1910 to 150.

4.7 Cell Density calculation

The cell density for this Al foam can be calculated as follows:

$$Cell\ density\ (C_D) = \frac{N}{V} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ 4.2$$

Where the N-Number cell and V- Volume of Al foam model

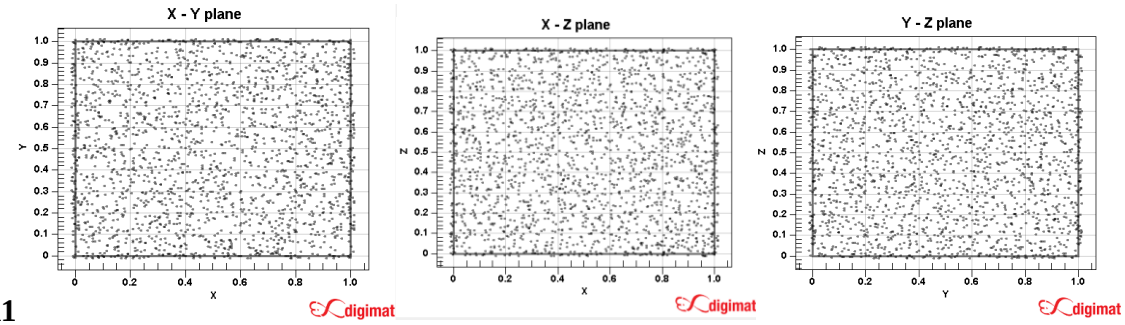
This cell density calculation is used to know the distribution density of the cells/bubbles on the entire Al foam model per volume. As expressed in the equation above, when the number of the cell decreases, the distribution density of the bubbles also decreases, because of the volume the Al foam constant. It is more clearly indicated in Figure 4.5 and Table 4.2 below.

Table 4.2: Cell density distribution for all models

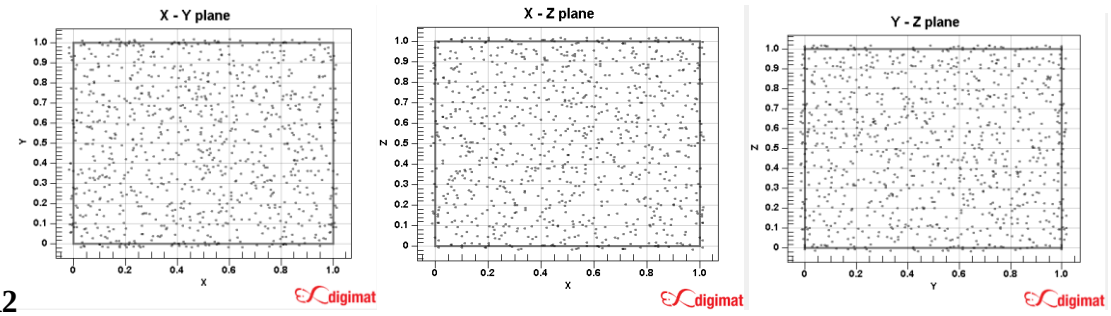
Radius R (mm)		Cell Density (CD)
R1	1.5	0.7074
R2	2	0.298
R3	2.5	0.153
R4	3	0.0885
R5	3.5	0.05556

As result shows in table 4.2 and figure 4.5, the distribution of bubbles dense for smaller radius and less dense for higher radius. This is because the analyses are conducted on the same dimension (30mm x 30mm x 30mm) of the models. Look at the following diagrams for detail.

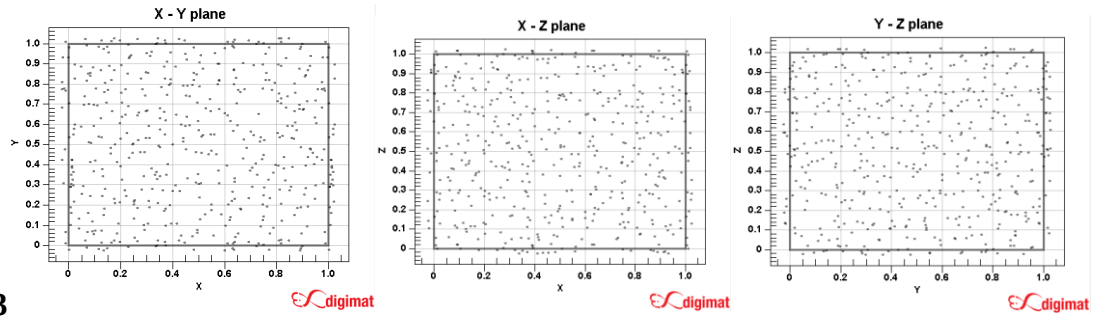
R1



R2



R3



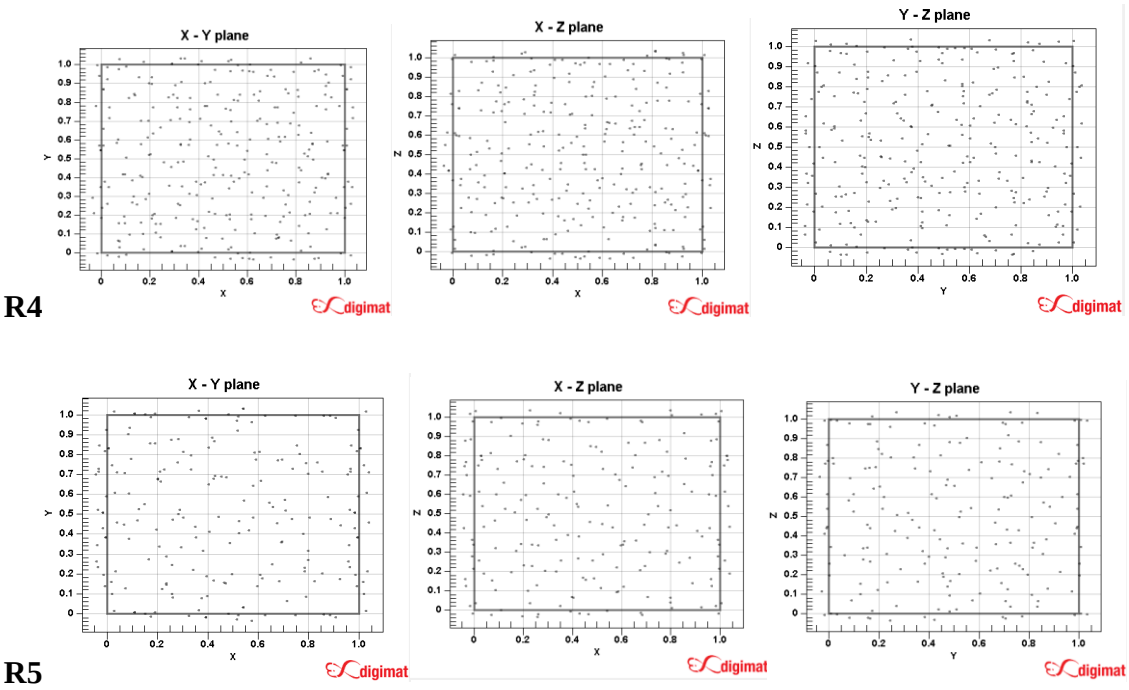


Figure 4.5: Graphical representation of the position of voids distributions inside the Al metal foam specimen for 10% at Radius of:

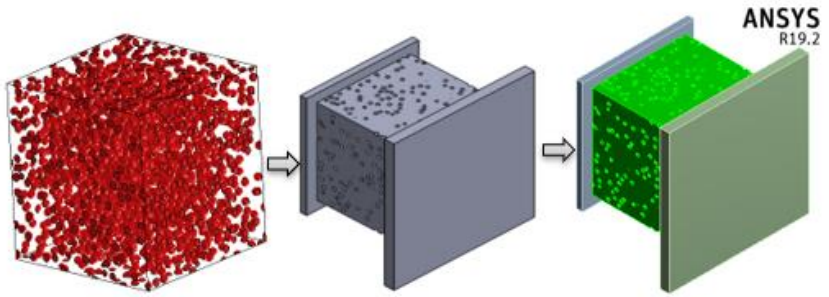
The above diagram shows the position of the random distribution of the voids in cubic element in three different coordinates.

From those distribution diagrams we can understand that the distribution of bubbles (voids with air) is randomly distributed throughout the entire foam element at R1, R2, R3, R4 and R5. Again, these diagram shows, at minimum radius the distribution of bubbles are densely populated and at large radius bubbles are more dispersed. The distribution of the bubbles for all fifteen models at 5%, 10% and 15% void fraction are in the same fashion with in the same volume and dimension.

4.8 Finite Element Modeling and Analysis

4.8.1 Finite Element Modeling and Analysis for Aluminum Foam

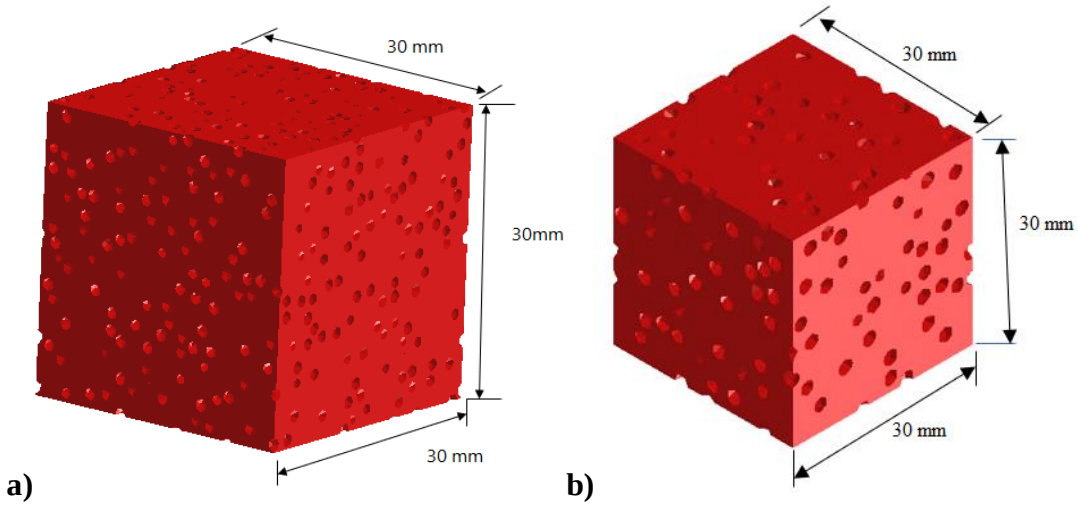
The CAD geometries of the foam elements are developed by using Digimat multi-scale material modeling. This CAD model is imported into solid works for fitness and then to ANSYS workbench 2019.2 for impact simulations as shown in the figure below respectively.



a) b) c)

Figure 4.6: CAD modeling steps a) Digimat model b) imported into solid work model c) imported into ANSYS workbench model

The above figure shows a) the CAD model developed from Digimat multi-scale material modeling software, b) the foam model imported into solid works for fitness, and c) the foam model imported into ANSYS workbench for further analysis. The further analysis for aluminum foam is done by impact explicit dynamics method on ANSYS workbench to characterize its energy absorption rate.



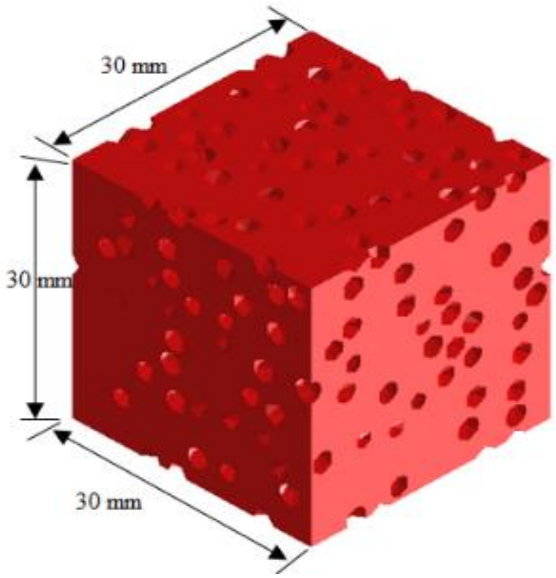


Figure 4.7: Geometrical visualization of cubic a) RVE with 5% void b) RVE with 10% void and c) RVE with 15% void at radius of 1.5 mm

During foam modeling, a relevant quantity of voids is generated in the metallic foam resulting in a low material density. Within the same dimension, density and void percentage of the specimen, the quantity of voids has also its effect on the energy absorption of the aluminum foam. This means that 150 bubbles random distributions in the same sample specimen with the same percent voids inside the Al foam, which results for large bubble diameter when compared with 1910 bubble distributions. On the other hand, 1910 bubbles random distribution in the same sample specimen with the same percent voids inside, which results for small bubble diameter, compared with 150 bubble distributions as shown in Figure 4.5 above.

The same modeling procedure and the same step is used for all models. Impact simulation is performed on these models to evaluate the energy absorption capacity.

Table 4.3: Mass and Volume the Al foam at 5, 10 and 15% composition

Model (%)	Mass (kg)	Volume (mm^3)
5	0.071923	25650
10	0.068138	24300
15	0.064352	22950

4.8.2 Impact Mechanics

In the impact theory, it is important to distinguish between elastic and plastic impact. In elastic impact, a negligible amount of energy is lost between impacting bodies. A plastic impact involves a significant amount of energy dissipation during collision. The principle of energy conservation in the elastic impact is used; the kinetic energy before impact is conserved and converted to elastic energy and the kinetic energy of the moving deformable barrier.

$$\frac{1}{2}m_A V_A^2 = \frac{1}{2}K_{eq}\delta_{max}^2 + \frac{1}{2}m_B V_0^2 \ldots\ldots\ldots\ldots\ldots\ldots 4.3$$

Where,m_A is the mass of the impactor, m_B the mass of the vehicle, V_A the velocity of the impactor before impact and $V_0$the final velocity of the impactor, $\boldsymbol{\delta}_{max}$ maximum deflection point, $K_{eq}$is an inherent characteristic of a material which depends on the reaction force and deflection of the impact structure.

An important consideration of momentum is that it can be neither created nor destroyed. Thus, the momentum before an impact is equal to the momentum after impact. At the moment of maximum deflection, the principle of momentum conservation before and after impact can be expressed as follows:

$$m_A V_A = (m_A + m_B)\, V_0 \ldots\ldots\ldots\ldots\ldots\ldots 4.4$$

By combining the above two equations $\boldsymbol{\delta}_{max}$is obtained as:

$$\boldsymbol{\delta} max = \sqrt{\frac{1}{K_{eq}}\frac{m_A mB}{m_A + m_B}V_0^2} \ldots\ldots\ldots\ldots\ldots 4.5$$

After the separation point, the conservation of energy and momentum equation can be expressed as:

$$\frac{1}{2}m_A V_A^2 = \frac{1}{2}m_A V_{A2}^2 + \frac{1}{2}m_B V_{B2}^2 \ldots\ldots\ldots\ldots\ldots 4.6$$

$$m_A V_A = m_A V_{A2} + m_B V_{B2} \ldots\ldots\ldots\ldots\ldots 4.7$$

where $v_{A2}$and v_{B2} are the final velocities of the impactor and the vehicle, respectively in separation point. In the elasto-plastic impact, the principle of linear momentum conservation satisfies, since impact forces are equal and opposite.

$$m_A V_A + m_B V_B = m_A V_{A2} + m_B V_{B2} \text{.....4.8}$$

In this case, the velocities after impact may be determined with the coefficient of restitution (COR). The coefficient of restitution is the ratio of the speed of separation to the speed of approach in a collision.

$$COR = \frac{V_{B2} - V_{A2}}{V_A - V_B} \text{.....4.9}$$

The coefficient of restitution is a number which indicates how much kinetic energy (energy of motion), remains after the collision of two objects. If the coefficient is high, it remains that very little kinetic energy was lost during the collision. An object with a COR equals 1 collides elastically, while an object with a COR of 0 will collide inelastically, effectively striking to the object it collides with, not bouncing at all. This means that, if the COR is low, it indicates that a large fraction of kinetic energy was converted into the heat or otherwise absorbed through deformation.

The material analyzed in this study is aluminum foam material which is common in energy absorption applications. Since the material is porous, and it can absorb energy at an almost constant stress level by elastic bending, plastic bending and/or crushing of the cell walls. Depending on the properties of the solid Aluminum, the global deformation of foams subjected to compression is associated with local elastic or plastic deformation. With increasing deformation, elastic bending of the cell walls turns into the collapse of the cells caused by elastic buckling in foams. From the macroscopic point of view, this could be characterized as the yield strength of the foam. The characterization of Aluminum foam is based on the physical (density and porosity) and mechanical (impact simulation) properties.

The advantage of foams over honeycombs structure is that they commonly exhibit isotropic behavior, i.e. their mechanical properties are similar in all directions.

4.8.3 Void fraction (ϕ)

Void fraction is defined as the fraction in volume of vacant space (voids with air) inside the volumetric Al model to the ratio of the total volume of the solid Al model.
Mathematically it can be calculated as follows:

$$\phi = \frac{V_G}{V_T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.10$$

where V_T- total volume of the Al cubic element and

V_G – volume the gases, which is obtained by subtracting the volume of the Al foam from the total cubic element.

4.8.4 Relative density (ρ^*)

The comprehensive test on the subject by Gibson and Ashby (1997) describes the properties of cellular materials in detail and sets forth definitions that are commonly used throughout the body of research. One of the most important parameters in relating cellular material properties is the relative density which is the ratio of the cellular material's density to the density of the solid from which it is made and given by:

$$\rho_{rel} = {}^{\rho_f}/_{\rho_s} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.11$$

Where $0 < \rho_{\mathrm{rel}} > 1$.

4.8.5 Density (ρ)

The density of Aluminum foam is calculated from its dimension as follows:

$$\rho = \frac{m}{v} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.12$$

Where ρ – density Al foam

m- mass of the Al foam

v- volume of Al

Table 4.4: Summary of void fraction, density and relative density for Al foam models

Volume Percentages (%)	Void fraction	Density (kg/m3)	Relative density
5	0.05	2664	0.951
10	0.1	2523.6	0.901
15	0.15	2383.4	0.851

4.8.6 Porosity

Porosity is known as the percentage of void spaces present in the solid Aluminum. Porosity plays a very important role as the density in deciding the foam quality. As the density of the foam decreases, the porosity increases. But the increase in porosity not helps, instead of for the foam, uniform porosity is the important parameter. In the cast parts actually, porosity is a problem, but in this aluminum foam synthesis main objective is to develop uniform size porosity. The simple concept of evaluating the % porosity, which is given by:

$$\%\ of Porosity = \frac{\rho_{Al}-\rho_{AF}}{\rho_{Al}} x100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.13$$

To determine the porosity of the aluminum foam, the density of the foam is calculated by the volume and mass of the samples. Later, the porosity (p) of the foam specimen is calculated by using the following relation.

$$P = 1 - \frac{\rho_{AF}}{\rho_{Al}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.13(a)$$

Where ρ_{AF} – the density of the Aluminum foam

ρ_{Al} – density of the pure Aluminum

Or the porosity of the aluminum foam can be calculated from the equation

$$Porosity\ \% = (1 - \rho^*)x100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.13(b)$$

Where ρ^* - the relative density of the aluminum foam.

These calculations also used to cross-check the porosity percentage of analytical analysis with porosity percentage on numerical analysis.

4.8.7 Modeling of Closed cell aluminum foam

Closed-cell aluminum foam is modeled by the means of the implementation of an isotropic hardening model contained in the FEA. The model contains the decomposition of the total strain rate into its elastic (ε_{ij}^{e}) and plastic (ε_{ij}^{p}) part[33].

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.14$$

4.9 Meshing

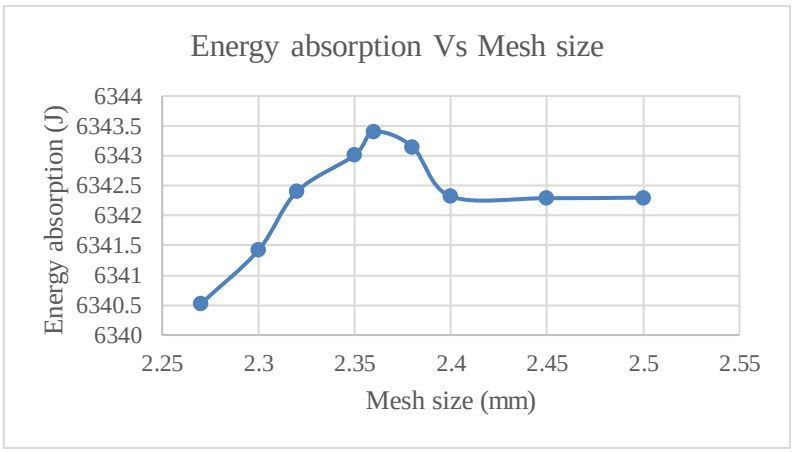
Meshing is a piecewise division of the cubic Al foam model consisting of a quadratic face pasted together along their edges. It is important to maintain the distribution between the

connectivity of the vertices and their geometric positions. For this study, a quadratic type element order with high smoothing quality and 2.4-2.5 mm mesh sizes are used.

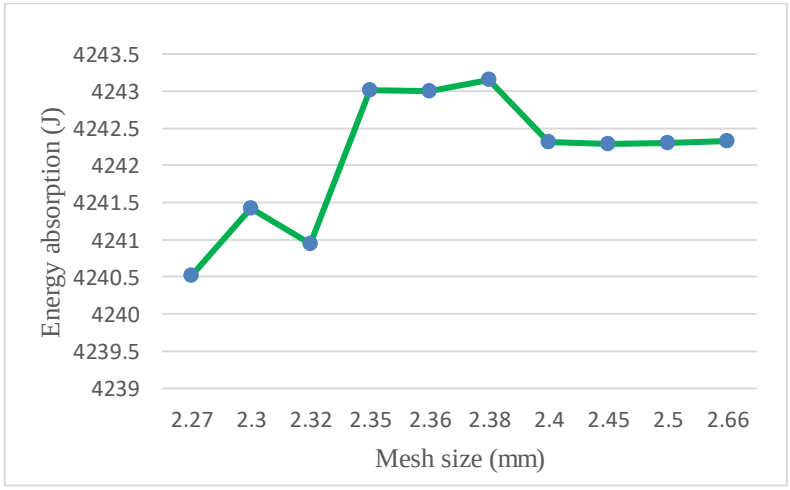
4.9.1 Mesh optimization

For numerical analysis, the mesh size plays an important role. As indicated in Figure 4.8 the values of energy absorption are low for minimum mesh size and increases as mesh size increases from 2.27 to 2.36 mm. This is because, for small volumetric element it is difficult to obtain best solution at small mesh sizes. That is because decreases up to mesh size 2.4 mm, beyond 2.4 mm mesh, the value of energy absorption goes constant. To check the mesh optimizations, the mesh sizes at (2.27, 2.3, 2.35, 2.4, 2.45, 2.5 and 2.55) mm are used. These indicate that beyond 2.4 mm, the mesh size converges as shown in the figure below. These graphs are at 5%, 10% and 15% model to show the patterns of mesh optimization.

a)



b)



c)

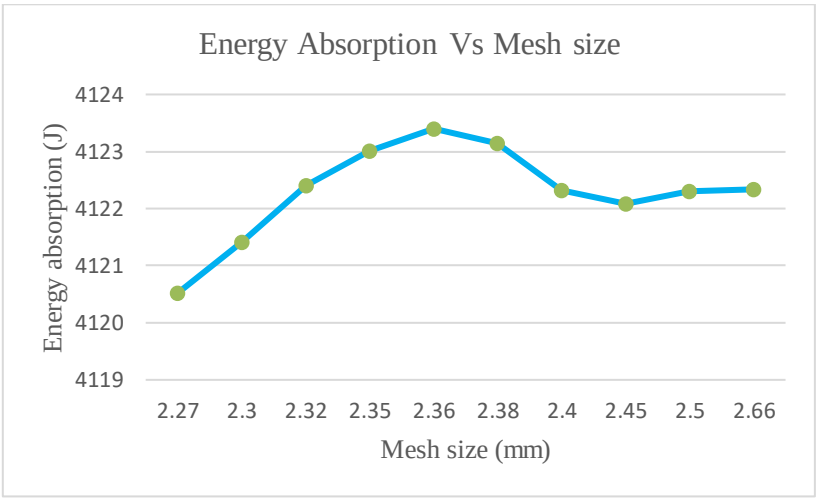


Figure 4.8: Mesh optimization for energy absorption at a) 5% b) 10% and c) 15%

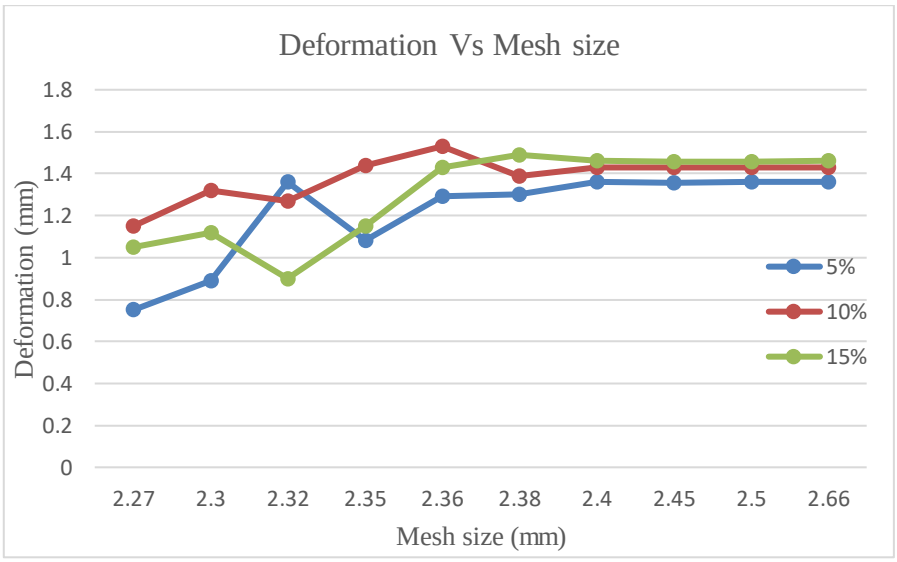


Figure 4.9: Mesh optimization for deformations

During mesh optimization, below 2.27 mm the Jacobian matrix exceeds the number of elements. For the entire analysis of this study, 2.4 mm – 2.5 mm mesh size with quadratic type element are used. For all fifteen models, the same techniques of mesh optimization are used, mean that final energy absorption analysis is taken at the mesh size point (2.4 - 2.5) mm at which the energy absorption values go constantly horizontal.

Table 4.5: Summary of mesh size for all models

Models	Mesh size
R1 at 5%	2.5
R2 at 5%	2.48
R3 at 5%	2.45
R4 at 5%	2.42
R5 at 5%	2.4
R1 at 10%	2.5
R2 at 10%	2.48
R3 at 10%	2.45
R4 at 10%	2.42
R5 at 10%	2.4
R1 at 15%	2.5
R2 at 15%	2.48
R3 at 15%	2.45
R4 at 15%	2.42
R5 at 15%	2.4

4.10 Post processing of the FEM

Explicit dynamic finite element method of a commercial software package is used to predict the deformation, specific energy and energy absorption capabilities of the Al foam. The Explicit FEM formats are best suited to incorporate various material laws and geometry conditions into an analysis. Summarized in the following diagram.

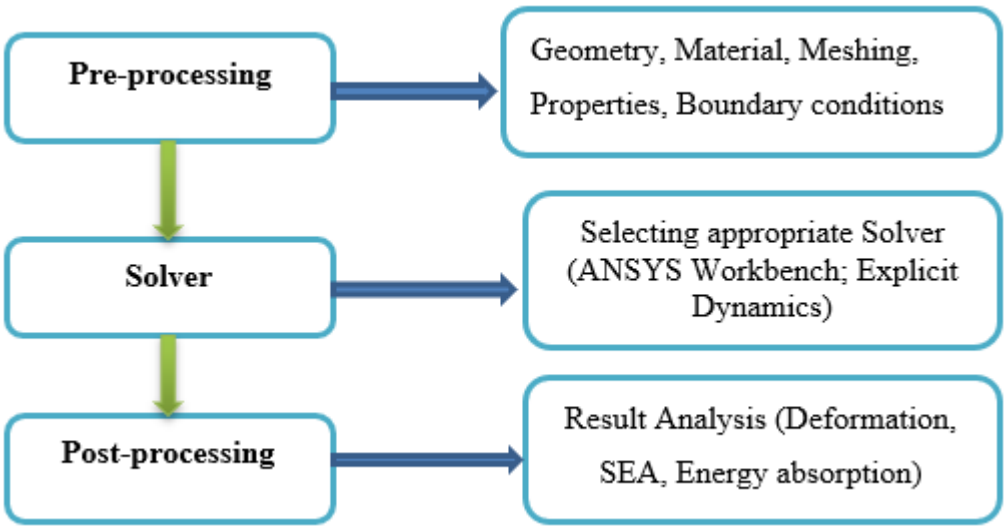


Figure 4.10: General FEA procedure

CHAPTER FIVE

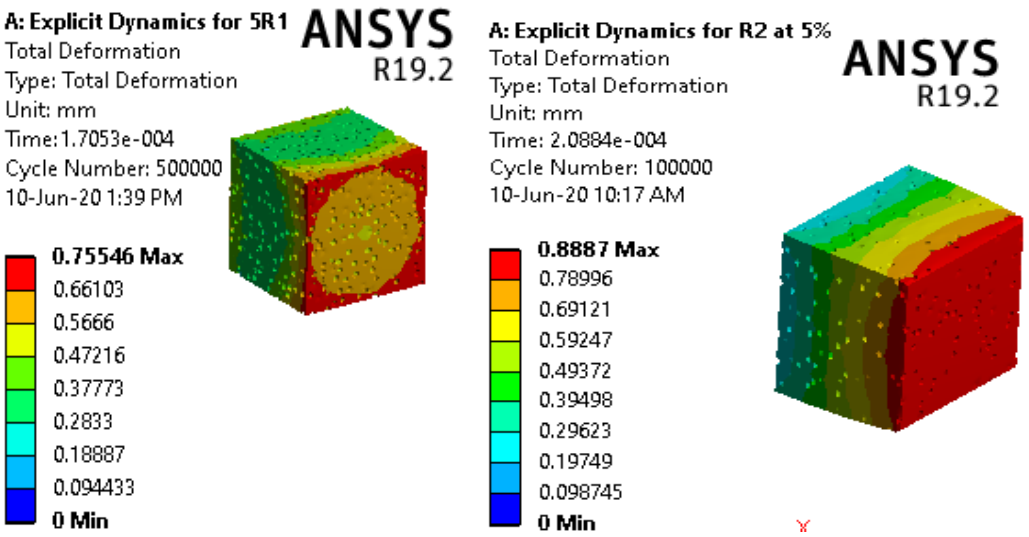
5. Results and Discussion

The results generated from an Explicit Dynamics analysis with the help of ANSYS workbench 2019.2 are summarized in the following subtopics. The total of fifteen models with 5% void fraction at radius (1.5mm, 2mm, 2.5mm, 3mm and 3.5), 10% void fraction at radius (1.5mm, 2mm, 2.5mm, 3mm and 3.5) and 15% void fraction at the radius (1.5mm, 2mm, 2.5mm, 3mm and 3.5mm) were modeled. The result from the analysis includes the total deformation, specific energy absorption, energy absorption, peak and average acceleration and reaction forces of the foam for each impact condition.

5.1 Deformation for Aluminum Foam

5.1.1 Total Deformation for Models at 5% void Fraction

Deformation for each radius ranging from R1 to R5 at 5% void fraction is shown in the following graph.



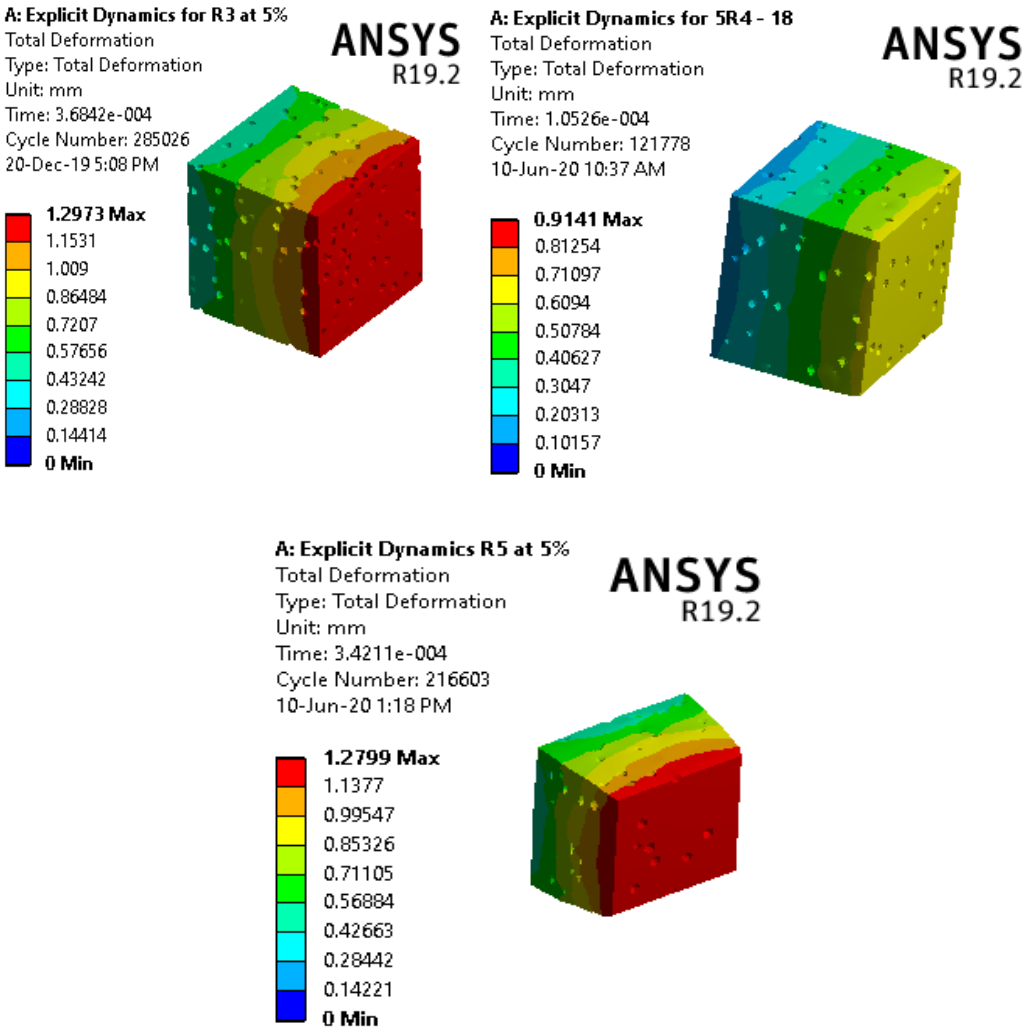


Figure 5.1: Total deformation for model at 5% voids

The following result graph shows the total deformation for Model with 5% void fraction at radius (R_1=1.5mm, R_2=2mm, R_3=2.5mm, R_4=3 mm and R_5=3.5mm).

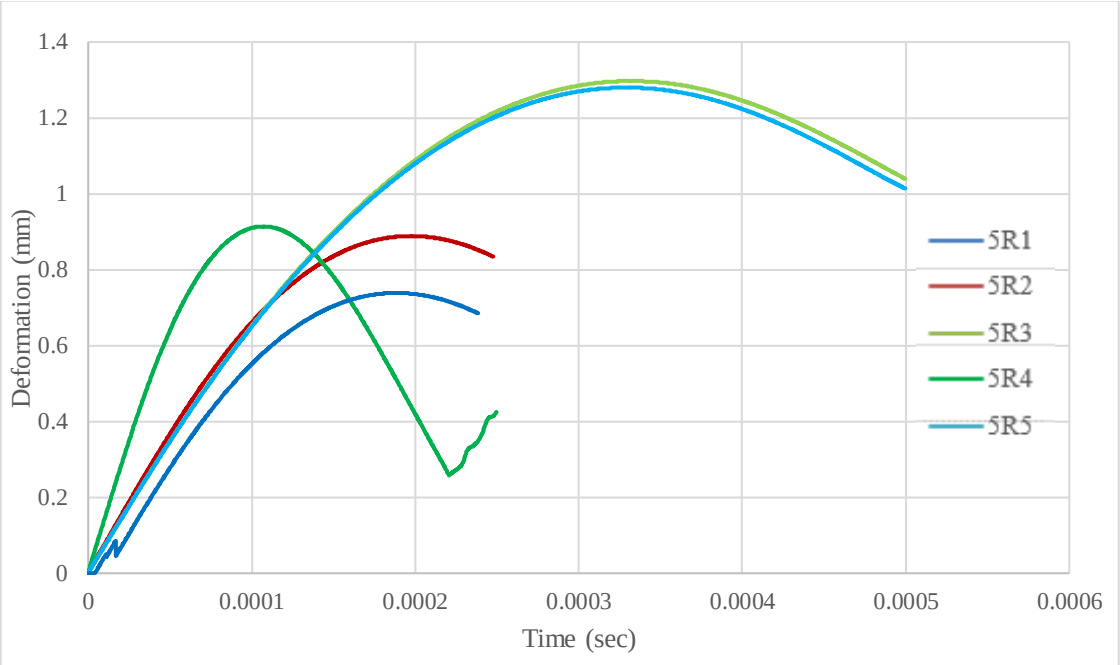


Figure 5.2: Total deformation versus Time for model at 5% voids and different pore radius

The total deformation for each Radius at 5% void fraction in volume is shown in the above figure. According to the Figure 5.2, the maximum deformation scored were 0.75546 mm, 0.83845 mm, 1.2973 mm, 0.9141 mm and 1.2808 mm for R_1, R_2, R_3, R_4, and R_5respectively. As shown in the figure, the deformation is maximum for R_3=2.5 mm and minimum for R_1 = 1.5 mm.

As shown from Figure 5.2, R1, R2, R3, and R4 at 5% are deformed earlier than and R5 at the same void percentage. This indicates that as bubble diameter increases, the probability deforming the material increases.

5.1.2 Total Deformation for Models at 10% void Fraction

Deformation for each radius from R1 to R5 at 10% void fraction is shown in the following graph.

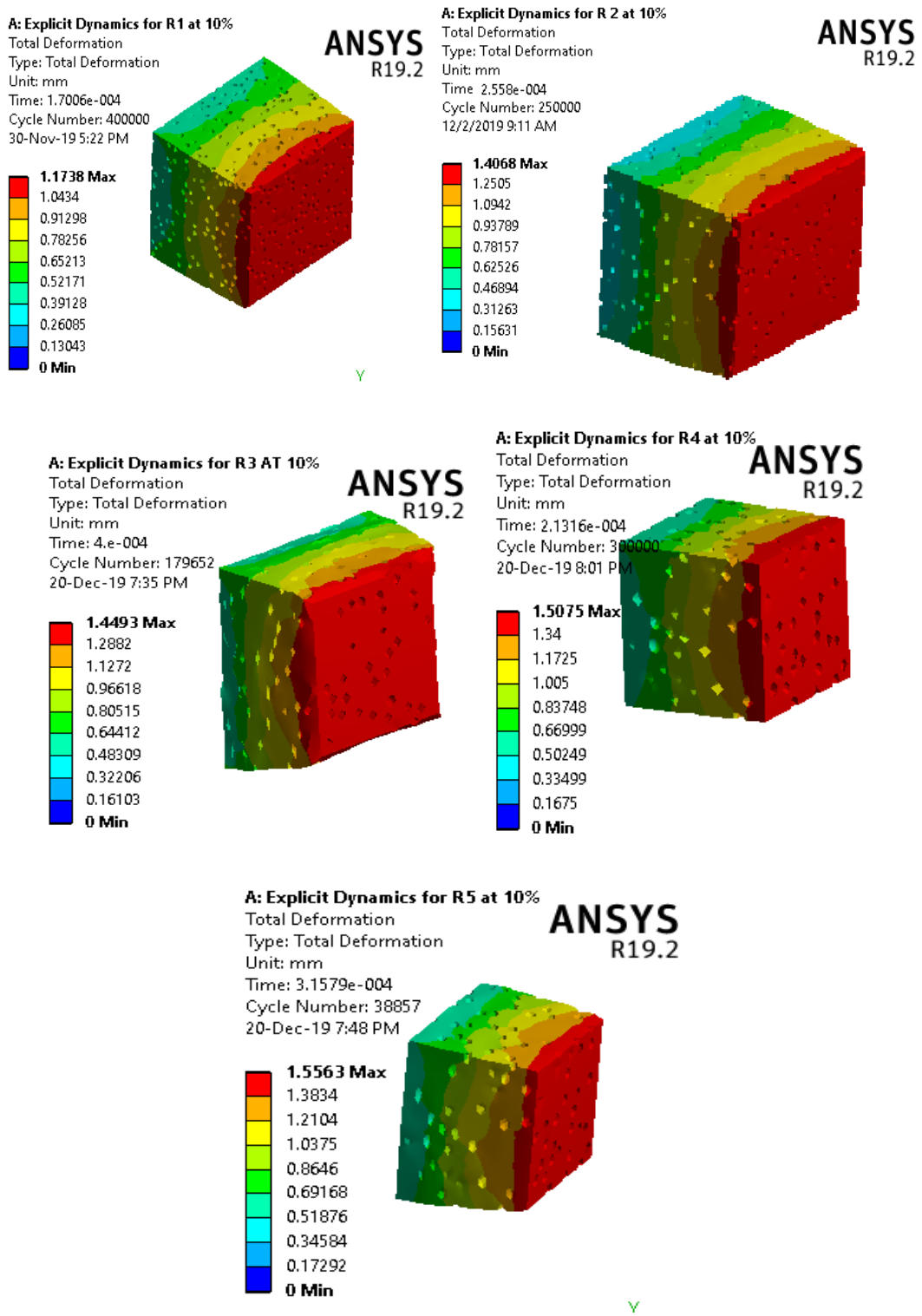


Figure 5.3: Total deformation for model at 10% voids

The following Finite Element Results were for Models with 10% void fraction at radius (R_1=1.5mm, R_2=2mm, R_3=2.5mm, R_4=3mm and R_5=3.5mm).

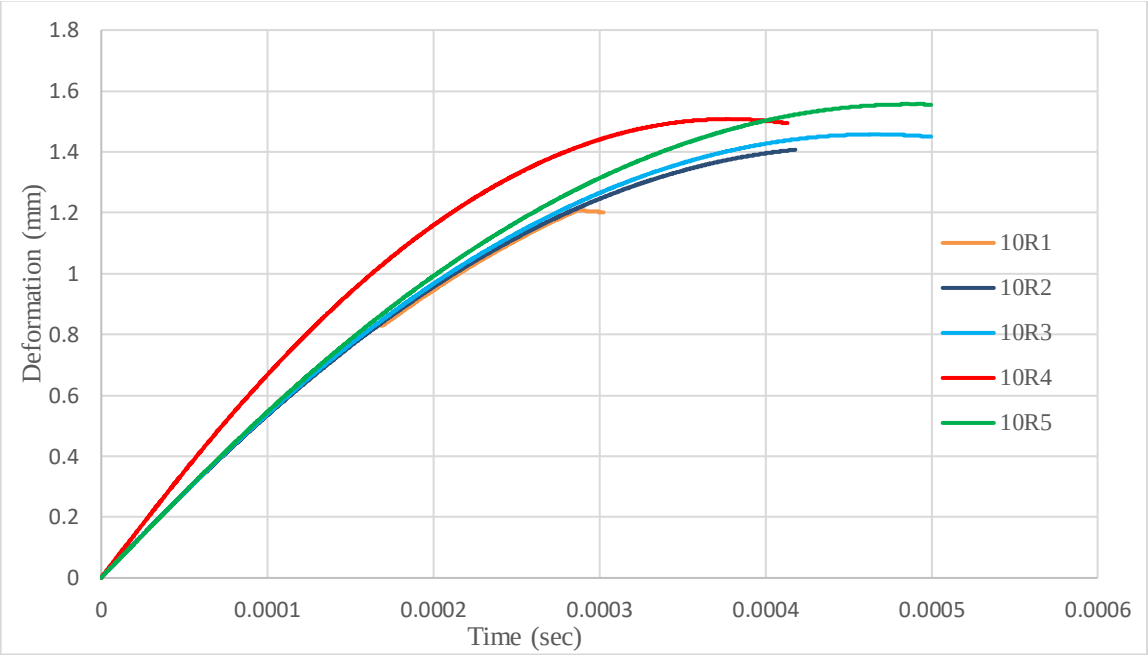


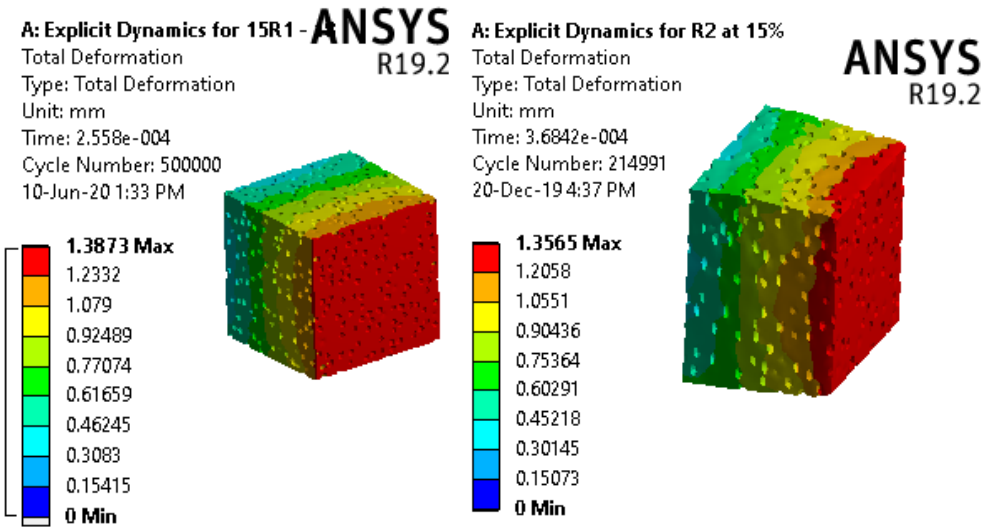
Figure 5.4: Total deformation for the models at 10% voids and different pore radius

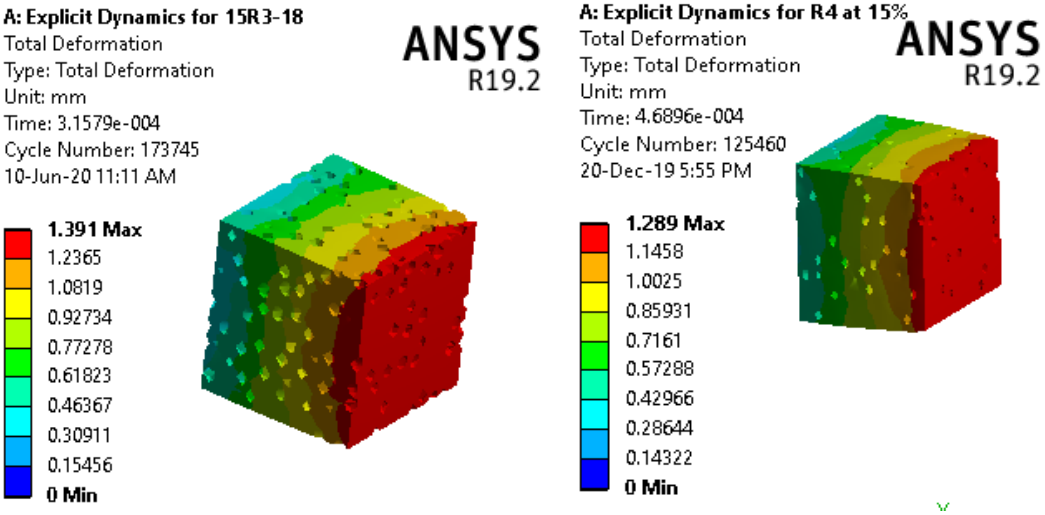
The total deformation for each radius at 10% void fraction in volume is shown in the Figure 5.4. As shown in the figure, the maximum deformation scored were 1.1738 mm, 1.4068 mm, 1.4493 mm, 1.2511 mm and 1.4674 mm for R_1, R_2, R_3, R_4, and R_5 respectively. As shown above, the deformation is maximum for R_5=3.5 mm and minimum for R_1 = 1.5 mm.

This graph clearly shows, as the number of bubbles increase, the deformation decreases: as the bubble radius goes from 3.5 mm to 1.5 mm, the deformation decreases. Specifically, in the case of Aluminum foam at 10% void fraction.

5.1.3 Total Deformation for Models at 15% void Fraction

The following graph shows the total deformation of Al foam at 15% void fraction at different bubble radius ranging from 1.5 mm up to 3.5mm.





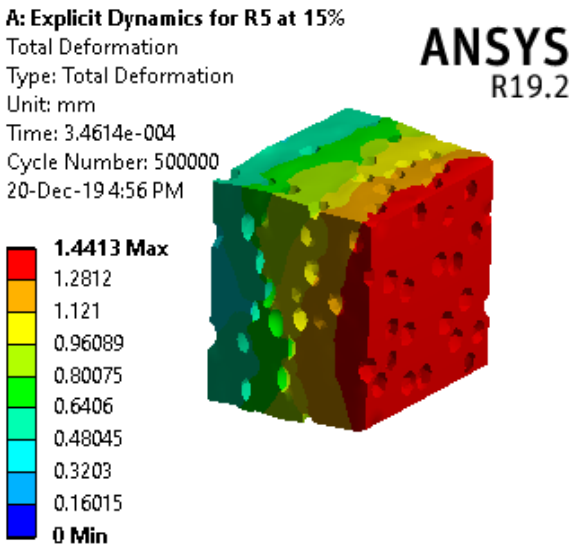


Figure 5.5: Total deformation for model at 15% voids

Deformation for each radius ranging from R1 to R5 at 15% void fraction are shown in the following graph.

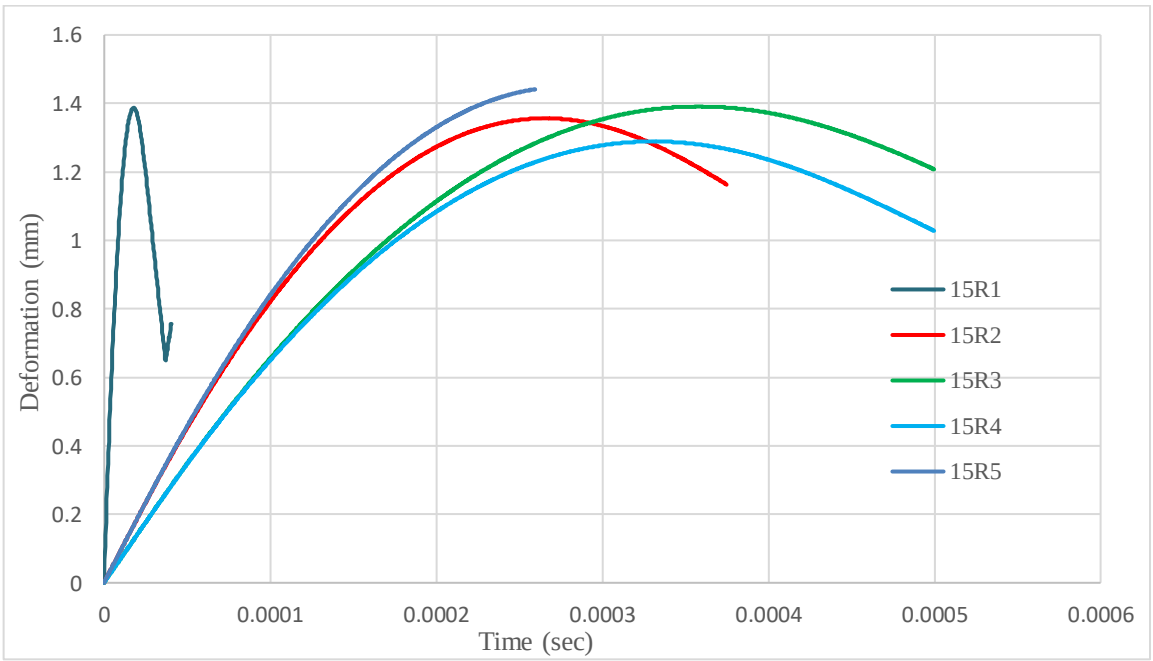


Figure 5.6: Total deformation for the models at 15% voids and different pore radius

The total deformation for each radius at 15% void fraction in volume is shown in Figure 5.6. As Figure 5.6 indicates, the maximum deformation scored were 1.3873 mm, 1.3565 mm, 1.2468 mm, 0.85476 mm and 1.4413 mm for R_1, R_2, R_3, R_4 and R_5 respectively. As shown above the deformation is maximum for R_5=3.5 mm and minimum for R_4 = 3 mm.

but, the deformation at R1 with 15% void fraction deforms earlier than the others. As shown, it increases rapidly and it decreases rapidly within a short period of time.

The following column graph shows the overall total deformation the Al foam at 5, 10 and 15% of void fractions.

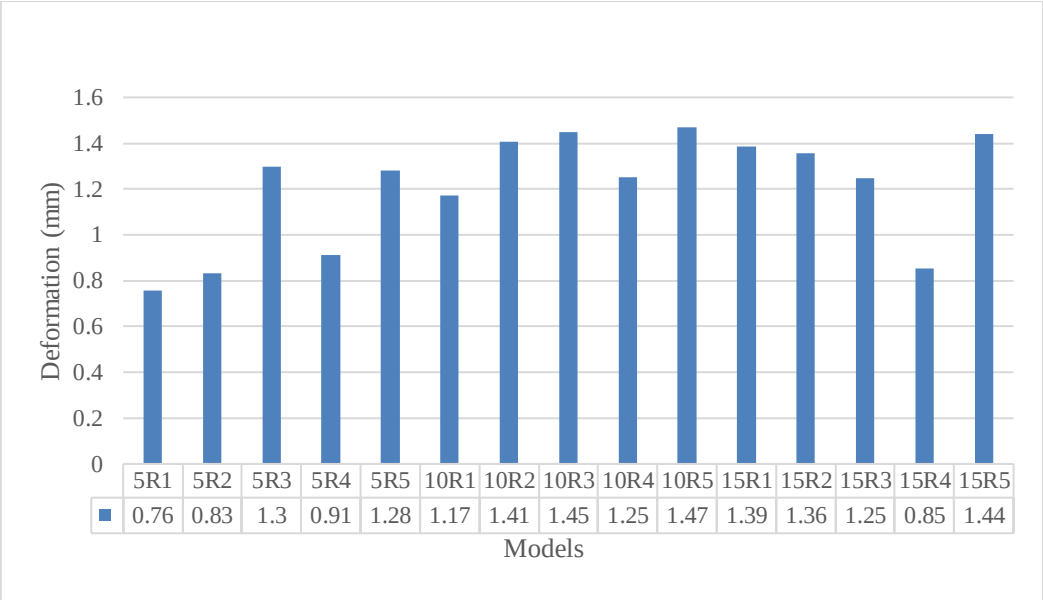


Figure 5.7: Column graph for overall maximum deformation for all models at 5%, 10% and 15%

As shown in Figure 5.7, the deformation slowly increases up to the middle area of the graph. This means that almost around domed shape like feature. As the number of void percentage increases from 5% to 10%, the deformation increases slowly. Then, after 10%, it decreases slowly and further again it shows a little bit increase in deformation, but still, it is lower than the middle value. According to this graph, the development process of Al foam, at a lower percentage (below 5%) of air voids the material is high brittle and at a high percentage (above 15%) of air voids, the material is also high stiffness. These indicate that the material at the low void percentage and high void percentage couldn't absorb more energy. Therefore, in the modeling of closed-cell foam element for energy absorption purpose optimization of bubble size and its percentage composition is crucial. According to this graph for the best of energy absorption, the optimum composition of air voids for Al foam development is at 10% void fraction. Figure 5.7 shows the deformation length of Al foam models for each simulation case resulting from applying the initial constant velocity of 7 m/sec.

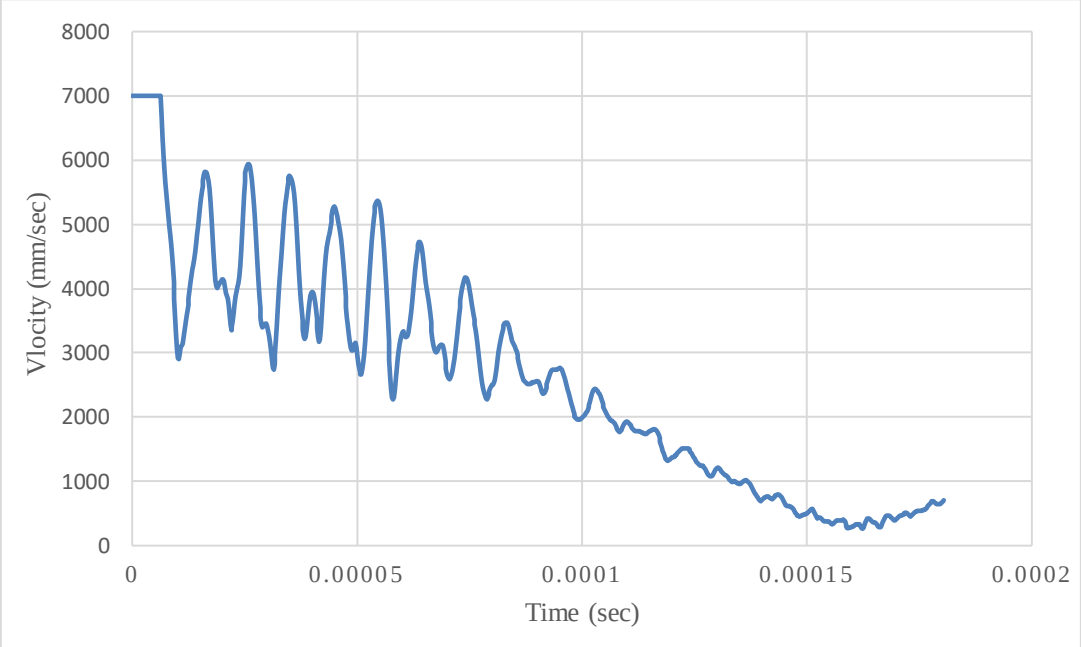
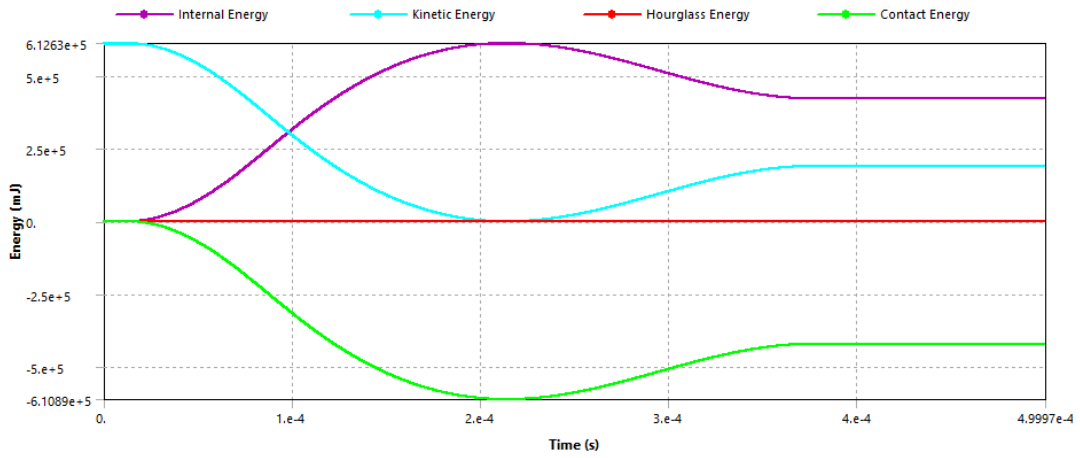


Figure 5.8: Velocity pattern

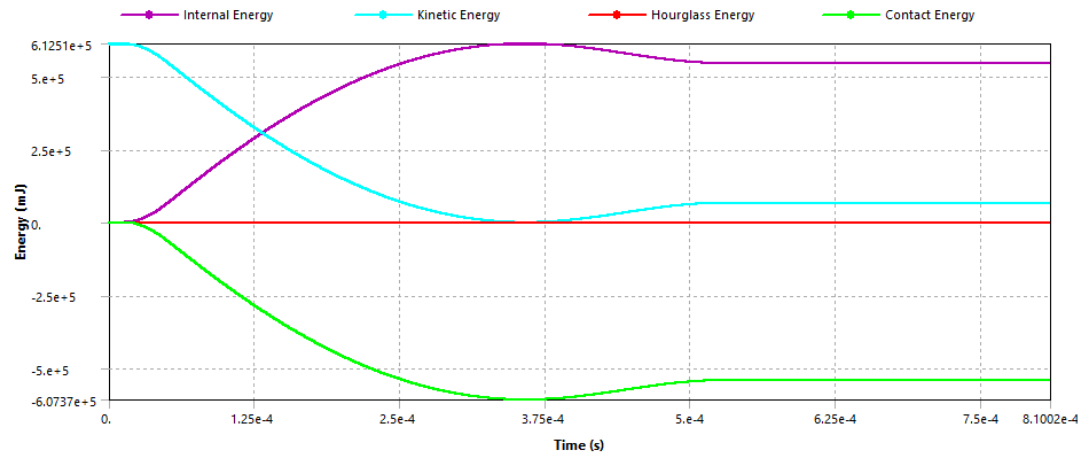
Figure 5.8 shows the pattern of the velocity of the Aluminum foam due to impact. During a vehicle crash or impact occur, the kinetic energy decreases, potential energy increases and velocity decreases with in a fraction of time. Figure 5.8 and Figure 5.9, shows the way how the initial velocity of Al foam during impact is dissipated. During velocity reduction pattern in above graph, it shows zig zag. This is because of the presence of vacant air voids inside the Al foam model. Meaning that during impact of the Al foam containing so many air voids inside the model, the collapse of the bubbles will not take place within the same time, why because the distribution of the bubbles are randomly. The deformation of the bubbles is progressively and slowly. As shown in figure above, as time increases the zig zag pattern decreases, this also indicates that as collapse of the bubbles increases, the zig zag pattern decreases in the overall structure (system) of the model during impact.

5.2 Energy conversion

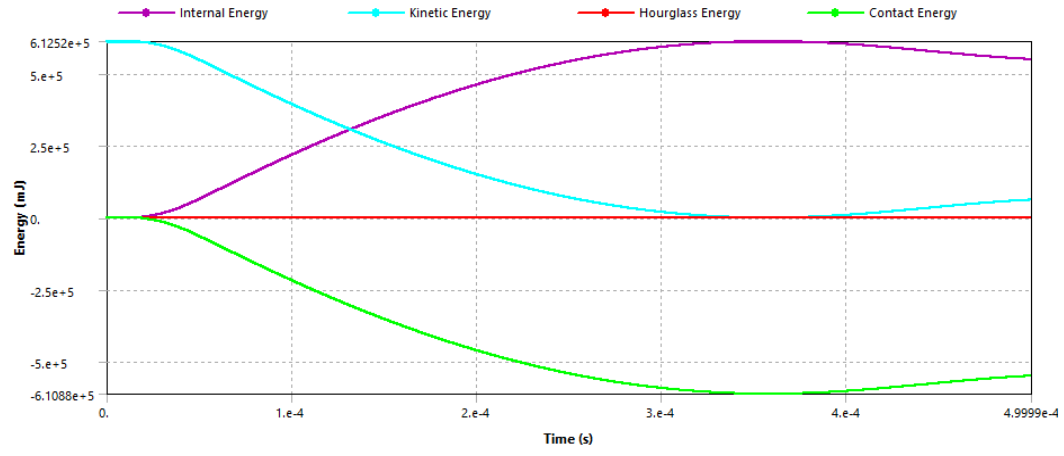
The energy balance or the energy developed and released during impact simulation is as shown in the following figure.



a)



b)



c)

Figure 5.9: Energy conversion during simulation for model a) 5% b) 10% c) 15%

Figure 5.9 illustrates the way how energy is converted from one form to another form of energy for Al foam models at 5%, 10% and 15% porosity compositions respectively. As shown in figure 5.9, during impact, the internal energy developed, the kinetic energy and contact energy decreased and hourglass energy goes constant. As shown at a) for 5% Al foam model the total kinetic energy is absorbed within 22.5 milliseconds, at b) for 10% Al foam model the total kinetic energy is absorbed within 35 milliseconds, at c) for 15% Al foam model the total kinetic energy is absorbed within 38.5 milliseconds, at those specific times the bubbles are collapsed. But, after the total absorption of energy, the kinetic and contact energy increased. This because the parent metal, that is Al alloy element has its own ductile property, which in turn this property leads the specimen to regain into its original position after applied force is released, and again these shows that the materials exhibits the spring back characteristics. This leads to the decrease in Internal energy and increase in kinetic energy in the same pattern but, in opposite direction.

The time taken to absorb energy is a key factor to decide the best material composition model form among all other models. Following this, the models at 5% absorbs energy at 22.5 milliseconds, the models at 10% absorbs energy at 35 milliseconds and the models at 15% absorbs energy at 38.5 milliseconds. Therefore, the model that shows the optimum time to absorb impact energy during collision is considered to be best candidate material.

5.3 Specific Energy Absorption for Aluminum Foam

The maximum Specific Energy absorption (SEA) was obtained directly from the ANSYS workbench simulation for all models.

5.3.1 Total specific Energy Absorption for Models at 5% void Fraction

Figure 5.10 shows the total specific energy absorption for models with 5% void fraction at the radius R_1=1.5mm, R_2=2mm, R_3=2.5mm, R_4=3mm, and R_5=3.5mm.

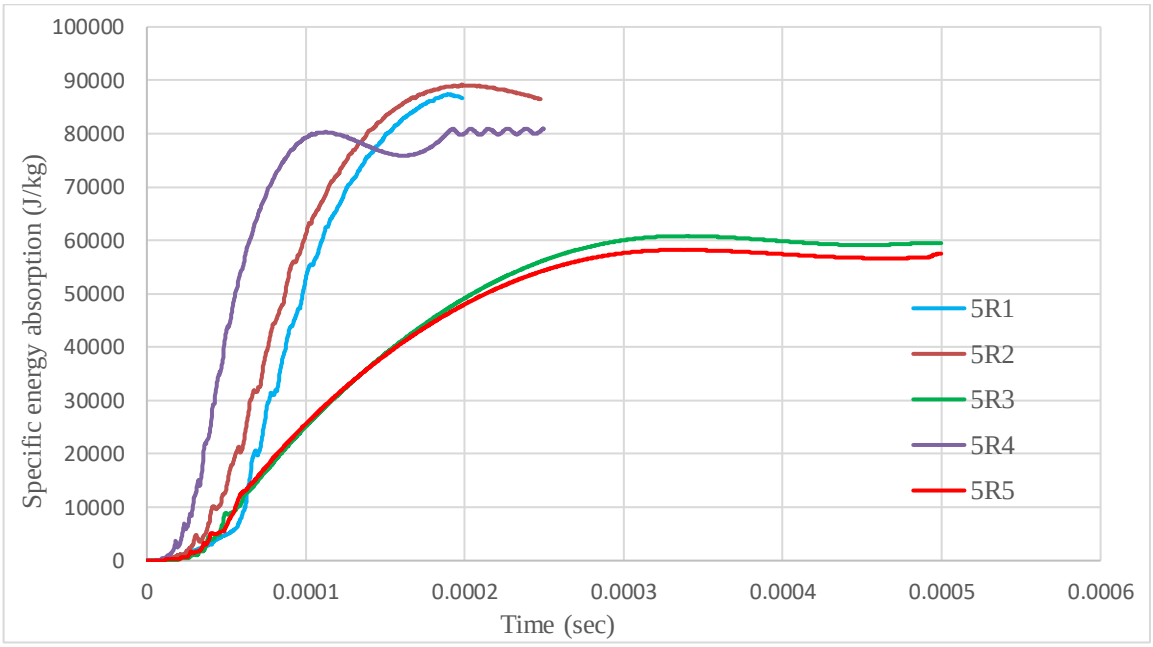


Figure 5.10: Total specific Energy Absorption for 5% voids and at different pore radius

As shown in the figure 5.10, the total maximum specific energy absorption for the model at 5% void fraction were 87995 J/kg, 89702 J/kg, 60820 J/kg, 80998 J/kg and 60665 J/kg.

5.3.2 Total specific Energy Absorption for Models at 10% void Fraction

Similarly, Figure 5.11 shows the Models with 10% void fraction at various radiuses (R_1=1.5mm, R_2=2mm, R_3=2.5mm, R_4=3mm, and R_5=3.5mm).

Total specific energy absorption for each radius at 10% void fraction are shown in the following graph.

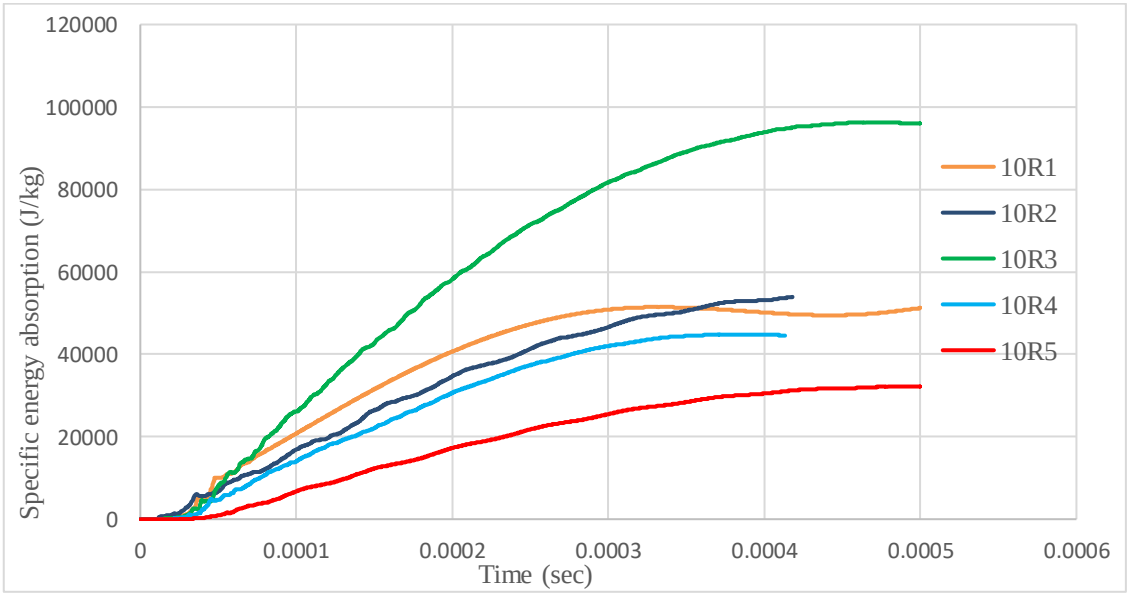


Figure 5.11: Total overall specific Energy Absorption for 10% voids and at different pore radius

The total maximum specific energy absorptions for the models at 10% void fraction were 45358 J/kg, 53935 J/kg, 96017 J/kg, 44811 J/kg, and 35111 J/kg.

5.3.3 Total specific Energy Absorption for Models at 15% void Fraction

Figure 5.12 shows the total overall Specific energy absorption for each Model at 15% void fraction for all radius (R_1=1.5mm, R_2=2mm, R_3=2.5mm, R_4=3mm and R_5=3.5mm).

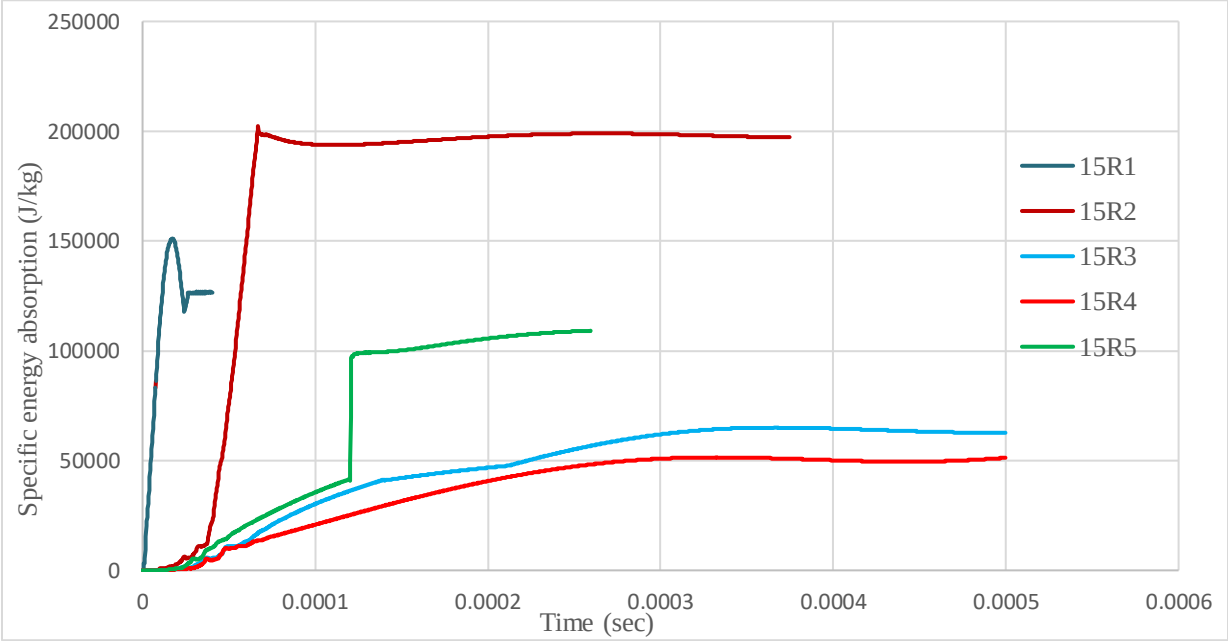


Figure 5.12: Total specific Energy Absorption for model for 15% voids and at different pore radius

The total maximum specific energy absorption for model at 15% void fraction were 151110 J/kg, 202350 J/kg, 65027 J/kg, 51447 J/kg and 109120 J/kg.

Specific energy absorption is one of the most important factors in the design of structures of vehicles where the weight efficiency is the main consideration and has often been taken as the design criteria for lightweight requirements[45]. A higher Specific energy absorption indicates greater efficiency of the Al foam in terms of energy absorption capability.

5.4 Energy absorption Analysis for Aluminum Foam

To assess the crashworthiness of the studied Al foam or compare the performance of different foam structures, it is necessary to establish proper criteria. These criteria must correlate the numerical results with the quality of the structures in several fields[34].

In determining the crashworthiness, specific energy absorption (SEA), energy absorption (EA), crash load efficiency (CLE) and mean crashing force (MCF) are crashworthiness indicators that have been used to evaluate the crashworthiness.

The specific energy absorbed (SEA) shows the capability of a structure to absorb the deformation energy. Specific energy absorption (*SEA*) is represented as the absorbed energy (*EA*) per structure mass[45]. In other word, it denotes the energy absorbed per unit mass of the absorber, which can be calculated as:

$$\text{SEA}\left(\frac{\text{J}}{\text{kg}}\right) = \frac{\text{Energy (J)}}{\text{Mass of the moving structure}}$$

$$SEA = \frac{EA}{M} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.1$$

Where M – Total mass of the moving structure

EA – Energy absorption during impact.

By rearranging equation (5.1) above from this formula we can calculate total Energy absorption, which is given by:

$$EA(J) = SEAxM \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.2$$

5.4.1 Total Energy Absorption for Models at 5% void Fraction

According to the above formulation and equation, the energy absorption for each Model with 5% void fraction at radius (R_1=1.5mm, R_2=2mm, R_3=2.5mm, R_4=3mm and R_5=3.5mm) are calculated as follows.

EA for Radius Rn at 5% void fraction

$$EA = SEA\ x\ M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.2(a)$$

Total energy absorption for each radius at 5% void fraction are shown in the following graph.

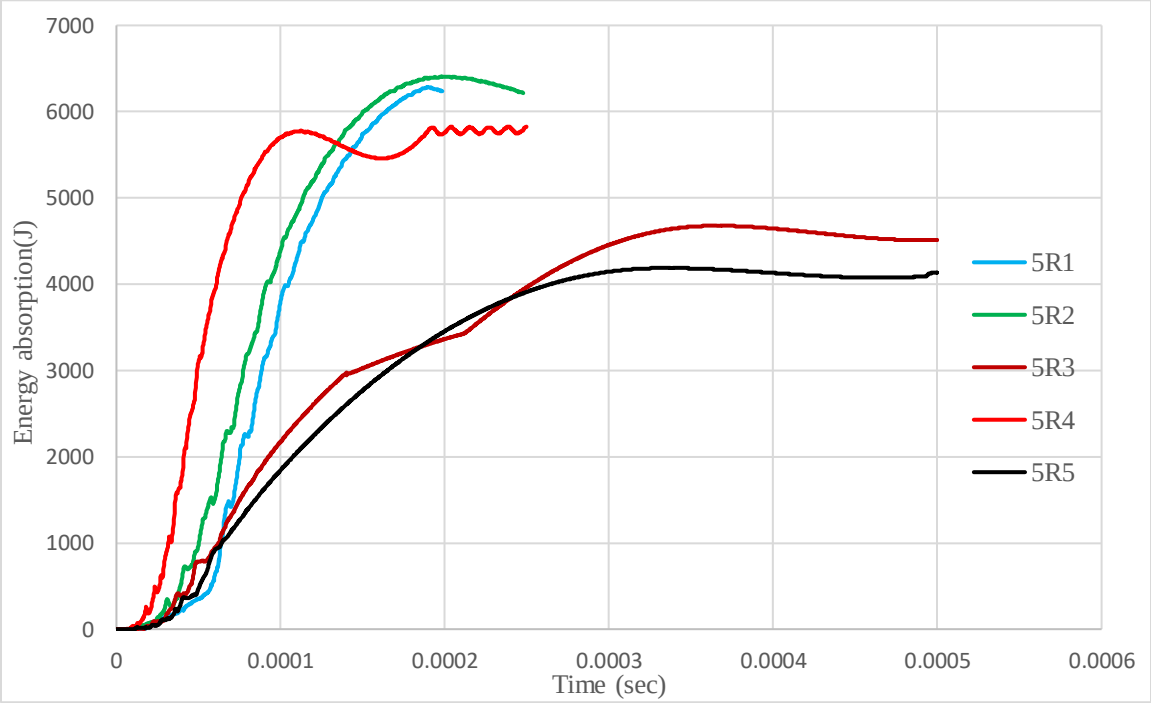


Figure 5.13: Total Energy Absorption for 5% voids at different pore radius

Figure 5.13 shows, the energy absorption for Models R1, R2, and R4 at 5% increases rapidly for the first half of the given time and then decreases slowly. But, for models at R3 and R5, the energy absorption increases slowly and smoothly, then continues constantly. The maximum scored absorbed energy were 6282.69 J, 6409.56 J, 4374.36 J, 5825.62 J, and 4187.43 J for R1, R2, R3, R4 and R5 respectively.

5.4.2 Total Energy Absorption for Models at 10% void Fraction

EA for Radius Rn at 10% void fraction

$$EA = SEA \; x \; M \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.2(b)$$

Total energy absorption for each radius at 10% void fraction are shown in the following graph.

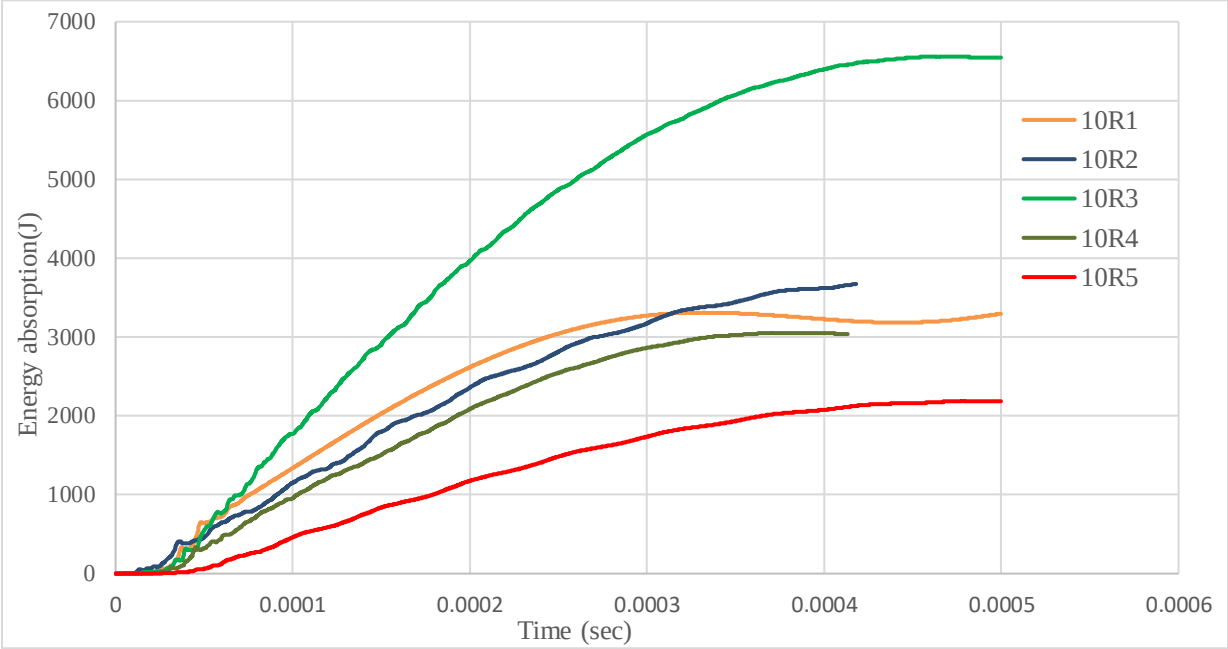


Figure 5.14: Total Energy Absorption for 10% voids at different pore radius

In figure 5.14, the maximum scored absorbed energy were 3090.603 J, 3658.023 J, 6554.37 J, 3053.33 J, and 2187.98 J for R1, R2, R3, R4 and R5 at 10% void fraction respectively. Among those, the energy absorption for the model at R3 is maximum. This indicates that the optimum composition of the air voids to develop Al foam for the best impact energy absorption application is at 10% with bubbles size of 2.5mm. these is also shown clearly in Figure 5.17 below.

5.4.3 Total Energy Absorption for Models at 15% void Fraction

EA for Radius Rn at 15% void fraction

$$EA = SEA\ x\ M \text{.....} 5.2(c)$$

Total energy absorption for each radius at 10% void fraction are shown in the following graph.

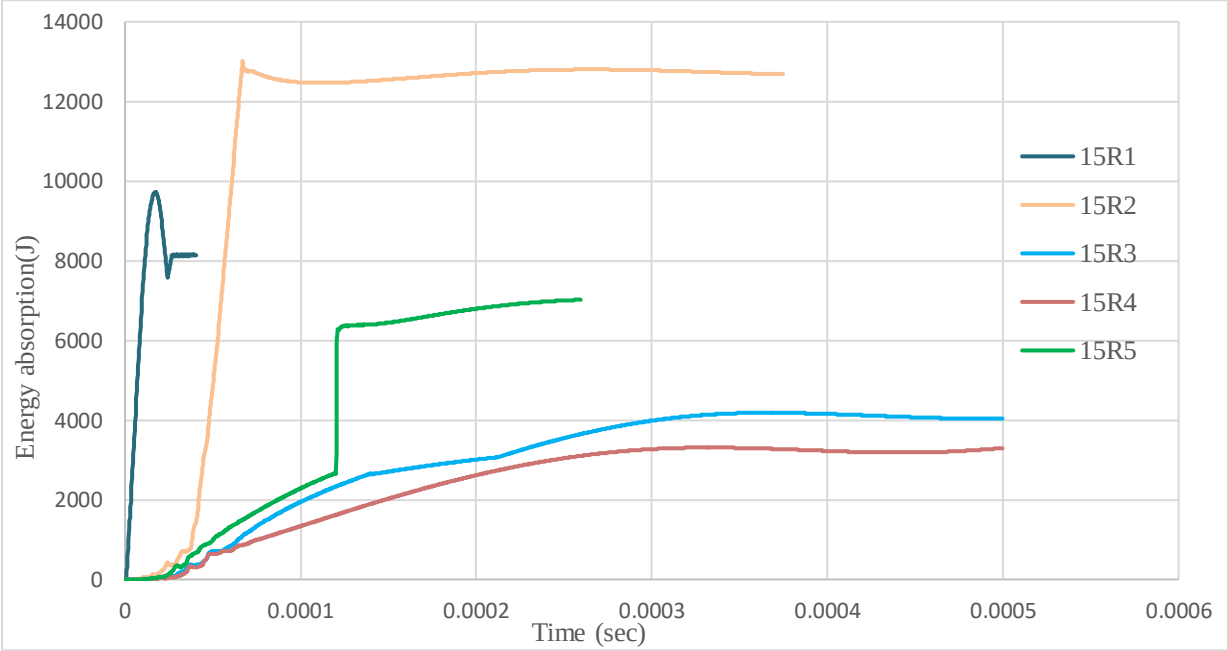
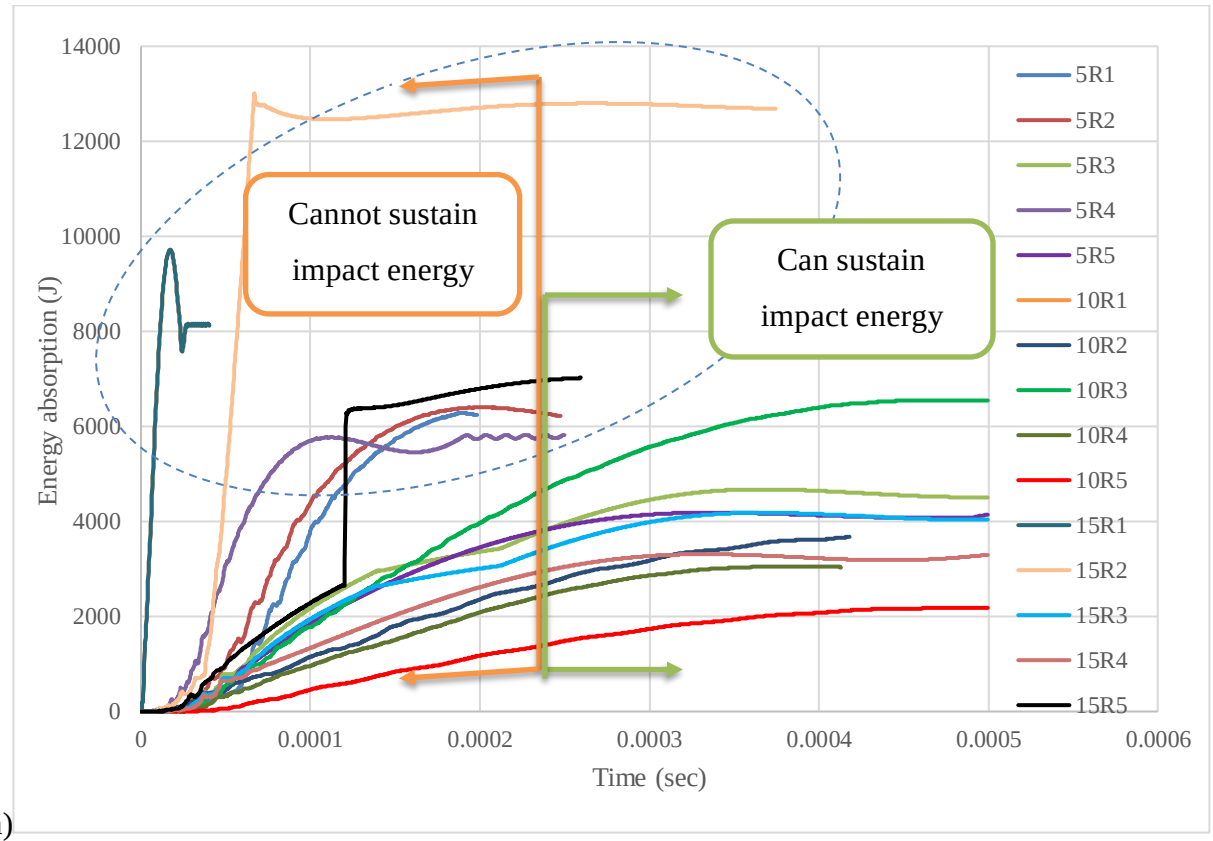
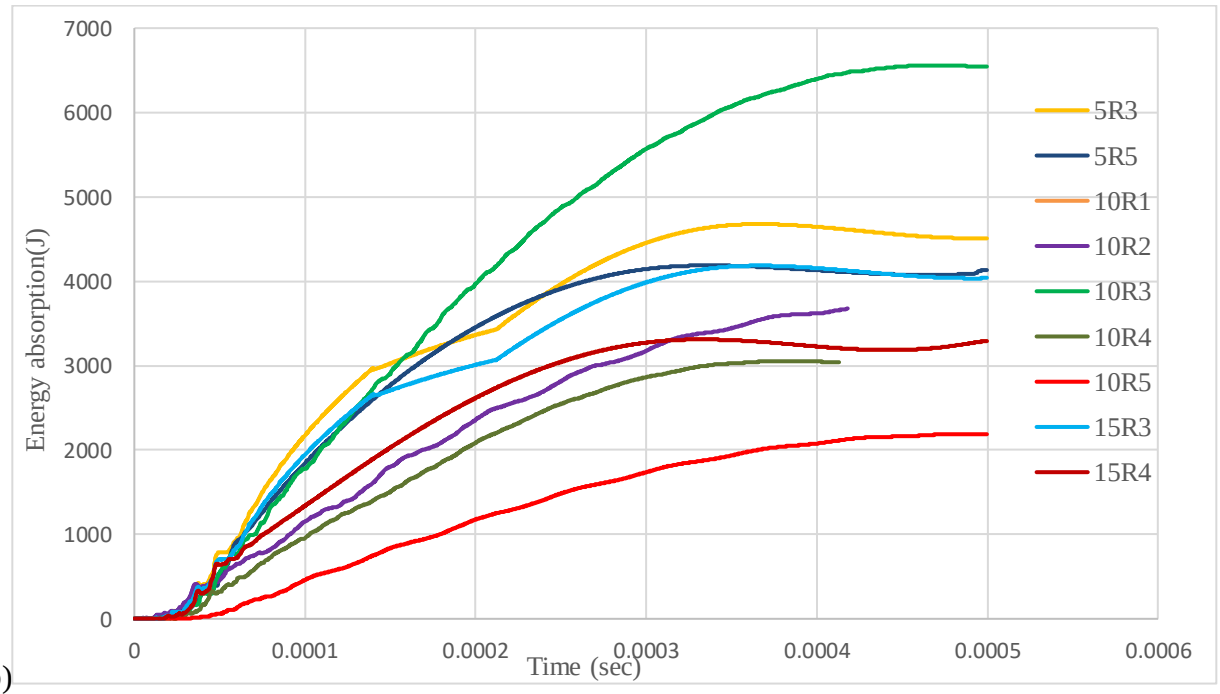


Figure 5.15: Total Energy Absorption for 15% voids at different pore radius

In Figure 5.15, the energy absorption for models at R1, R2 and R5 show the rapid increases, again rapid decrease for R1, and constant for R2 and R5, but for models at R3 and R4 are smooth. The maximum scored absorbed energy were 10177.71 J, 13628.88 J, 4081.12 J, 3385.97 J, and 7349.56 J at 15% void fraction for R1, R2, R3, R4 and R5 respectively.



a)



b)

Figure 5.16: Total overall Energy Absorption comparison for all models at 5%,10% and 15%

Figure 5.16a, shows the comparison of the total overall energy absorption for all fifteen l foam models. The energy absorption for the model of with radius of 5R1, 5R2, 5R4, 15R1, 15R2 and 15R5 are at the higher region with minimum time of deflection. As this shows, the increase of percentage composition of air voids beyond 10% decreases the stiffness of the material relatively compared to 10% void foamed Aluminum foam. As shown in this figure, the graph lines which are encircled by broken line didn't show slow and progressive collapse of bubbles, which are not good for impact and crush energy absorbing applications. As shown in Figure 5.16a above for models of lower air percentage compositions, the energy absorption decreases slowly. This means that the material at lower and higher air composition has relatively low stiffness characteristics.

The first selection of Al foam models strongly depends on the time taken to deform the structure during impact. As shown in Figure 5.9 above simulation result, the best and optimum time is recorded for models at 10% voids fraction. This leads to the selection of the optimum composition of air voids for the best of energy absorption.

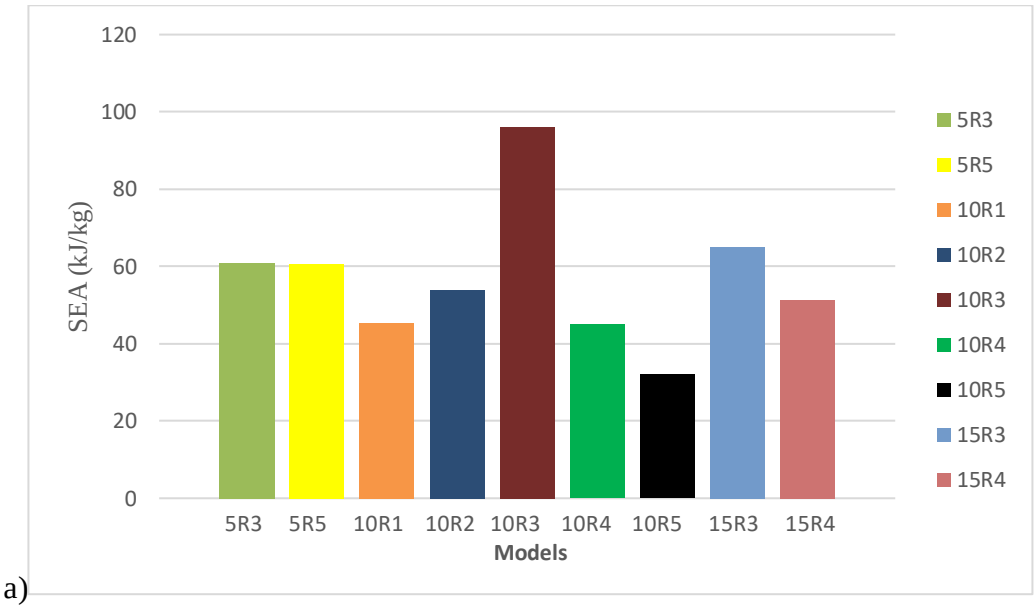
Second, as shown in Figure 5.16a above, encircled by broken line and shown by vertical red block line with arrow in to the left side materials are cannot sustain good impact energy. But the graphs which are shown by vertical green block line with arrow into the right side can sustain best impact energy during collision as shown in figure 5.16b.

Therefore, from those graphs which are shown by vertical green block line with arrow to the right side, and at figure 5.16b, the graph line which are having maximum energy absorption is 10R3.

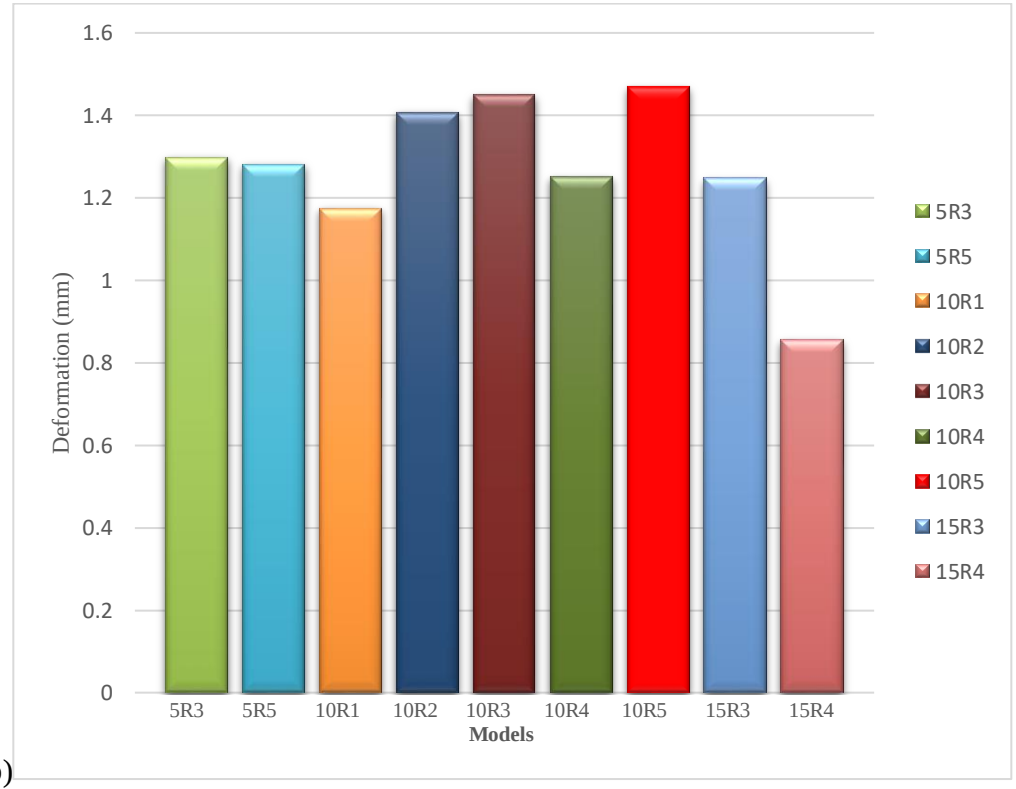
Figure 5.16b, shows the energy absorption capacity of the rest Al foam models after rejecting the poor impact energy absorbing models.

Finally, according to Figure 5.16b, 10R3 is selected as best and appropriate material for this intended application, because it has maximum impact energy absorption capacity than other models as indicated in Figure 5.16b.

Due to this reason graph lines which are encircled by broken line and vertical red block line with arrow into the left side are rejected from the comparison as shown in figure 5.16a.



a)



b)

Figure 5.17: a) Specific Energy Absorption and b) Deformation Vs Time comparisons

Figure 5.17, shows the specific energy absorption (SEA) and deformation vs time graph after rejecting six models above. Now, the specific energy absorption is related to the deformation length, by which the energy is absorbed by Al foam through its deformation behavior. However,

when the deformation is low, its energy absorbing efficiency is low[46]. So, the model with higher deformation must be selected for the best of energy absorption applications.

According to the figure 5.17 (a) and (b), as deformation length increased, the SEA also increased. The three highest deformations from the rest of nine models were 1.47 mm, 1.45 mm and 1.41 mm for 10R5, 10R3 and 10R2 respectively. And again, the three highest SEA from the rest of nine models were 60820 J/kg, 96017 J/kg and 65027 J/kg for 5R3, 10R3 and 15R3 respectively. Now, the comparison is in between those five models, those are 5R3, 10R2, 10R3, 10R5 and 15R3. Therefore, among these 10R3 model absorbs more specific energy and energy absorption (96017 J/kg and 6554.37 J respectively) than other five models as comparison made on figure 5.17 and 5.18.

5.4.4 The effect of percentage composition on the impact energy absorption

Figure 5.16 shows that most of the graphs for the model at 15% void fraction are at the upper region, but the increases of those graphs are rapidly within a short time, mean that there is a high disturbance of the graph there. Then as seen, the graphs for model at 5% void fraction, they all are in the lower region compared to the 15% and 10% void models. On the other hand, the graphs for the models at 10% void, are in between the two models. As seen clearly on the Figure 5.16 and Figure 5.17 above next to the highly disturbed graph, we get a good smooth graph, which is maximum in energy absorption than the other all models. This model is the Al foam with a 10% void fraction at a radius of 2.5mm. The characteristics of the material to absorb good impact energy for automotive applications should exhibit a slow and progressive collapse bubbles (voids with air) and a smooth energy absorption graph. As shown in Figures 5.17 and 5.18, 10R3 absorbs the energy by 44.18% more than models at 5%, 53.41% more than models at 15% and 43.9% more than the other models with in the same percentage composition.

5.4.5 The effect of Pore size on the impact energy absorption

As shown all the graphs above and figure 5.18 below, the increase of pore from 1.5 mm to 3.5 mm leads to the decrease of the stiffness characteristics of the Aluminum foam. This implies that the material with low stiffness results for low impact energy absorption.

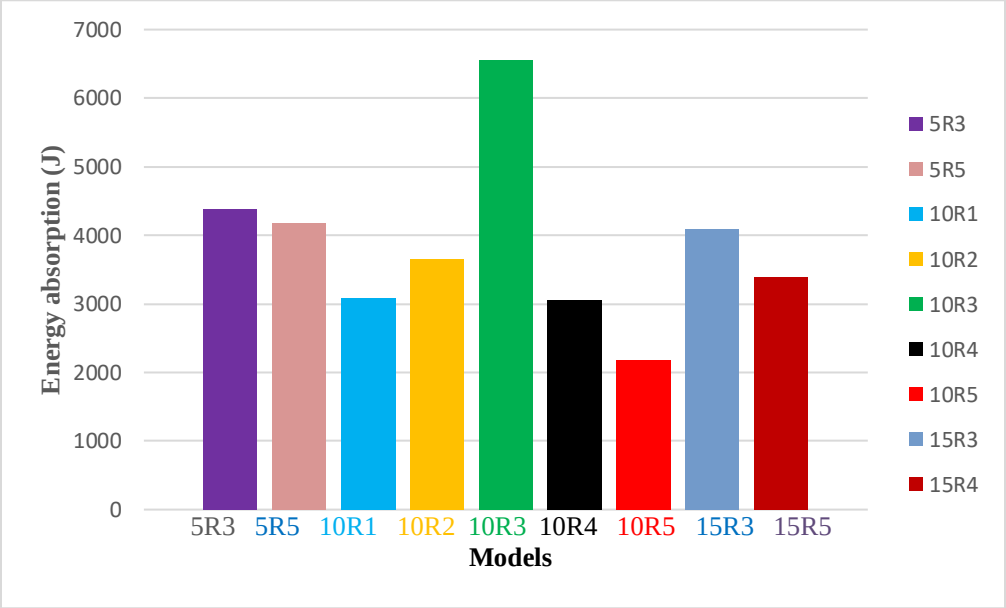


Figure 5.18: The energy absorption vs Model

As shown in figure 5.18 for the model at 5%, the energy absorption decreases when the bubble radius increases from 1.5 mm to 3.5 mm. For model at 10% void fraction gives the parabolic shape, which means that minimum at starting for minimum bubble radius and increases with increase in radius up to 2.5mm, then decrease slowly for higher bubble radius. Therefore, Figure 5.17 and figure 5.18, show the optimum bubble size with respective percentage composition of Aluminum foam for the best of impact energy absorption applications. Herein this figure model with 10% at radius R3 = 2.5 mm bubble size absorbs energy by 44.18% more than models at 5%, 53.41% more than models at 15% and 43.9% more than the other models with in the same percentage composition.

5.5 Acceleration

Acceleration is typically an indicator of the crash severity of a vehicle and it correlates with the occupant safety which to the amount of force the restraint system would need to manage during a car crash.

According to the Federal motor vehicle safety standard (FMVSS), New Car Assessment Program (NCAP) and insurance institute for highway safety collaboration at National Highway Traffic Safety Administration in USA, the peak acceleration for all vehicles was settled not to be more than 43g. But by vehicle classes the acceleration range for pickups is 36-49g, for multi-purpose

vehicles 39-51g and for passenger cars 39-48g[47]. Therefore, the foam models with the peak acceleration of more than 43g and the average acceleration below 30garenot selected for the intended purpose. The value of accelerations in [g] is obtained by dividing the values of acceleration in 'm/s^2' by gravitational acceleration constant (9.81 m/s^2).

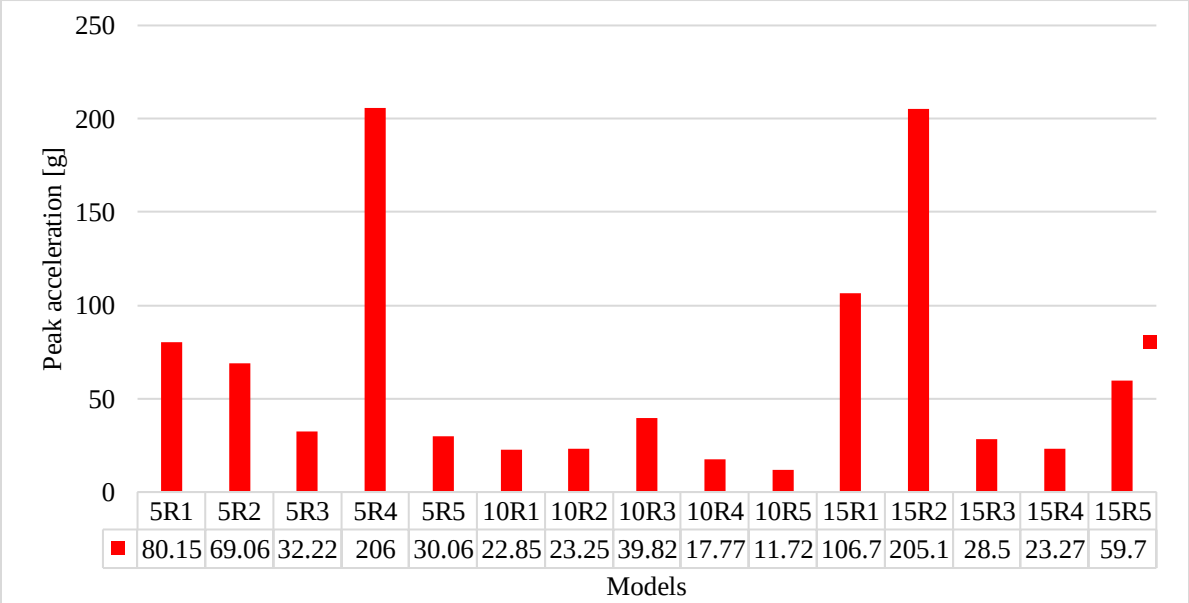


Figure 5.19: Peak Acceleration for Al foam models

As shown in Figure 5.19, the models which meet the requirement (the peak acceleration less than 43g) are 5R3, 5R5, 10R1,10R2, 10R3, 10R4, 10R5, 15R3 and 15R4.

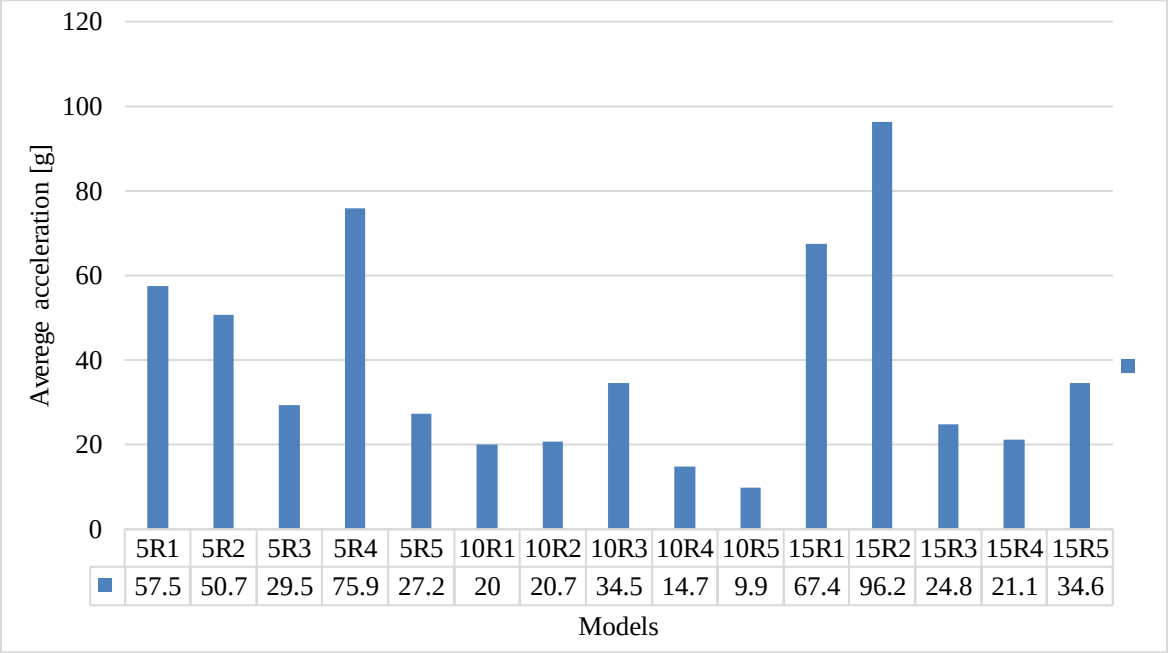


Figure 5.20: Average Acceleration for Al foam models

As shown in Figure 5.20, the models which meets the requirement (mean than that the acceleration is above 30g) are 5R1, 5R25R4, 10R3, 15R1, 15R2 and 15R5.

The Al foam models which meet both requirements (peak acceleration below 43g and average acceleration above 30g) for the intended applications are only 10R3 and 15R5. But, when the two models are compared for the energy absorption applications, the Al foam model at 15% with a radius of 3.5mm doesn't show good impact energy absorption characteristics. Therefore, the Al foam model at 10% void fraction with a radius of 2.5 mm meets the requirement, which means 7.35% safe.

In addition to deformation analysis, SEA analysis and energy absorption analysis, acceleration analysis is also another additional analysis to evaluate the best candidate material for crash applications. Therefore, from those all fifteen Al foam models, 10R3 Al foam model is selected than the other models because of the above all simulation analysis.

5.5.1 Comparison of a foaming agent on the impact Energy absorption

In the process of foaming Aluminum foam for impact energy absorption applications in automotive and aerospace engineering fine ceramic Silicon Carbide (SiC) and Boron Carbide (B_4C) foaming agents were used as additions to enhance the performance of Al foams. Results indicated that the

additions of the ceramic particle such as SiC showed a moderate effect; whilst the B_4C showed a minor effect on energy absorption enhancement of Al foam[16][35].

But now this research introduces another foaming agent called bubbles (void with air) for Aluminum foaming for impact energy absorption purposes. In this research paper the total of fifteen models at three (5%, 10% and 15%) different percentage composition and at 1.5mm, 2mm, 2.5mm, 3mm and 3.5mm bubble radii are done, then the best percentage composition and best bubble radius are optimized by using Explicit dynamics for impact analysis for the best of energy absorption, and finally, these results are compared with an existing foaming agent as shown below in figure 5.21.

As stated [22] above SiC, $CaCo_3$ and B_4C are used for foaming agent for closed cell aluminum foam material microstructure development for energy absorption applications. So, having this all-in mind this study also introduces those hard inclusion particles inside the aluminum foam instead of vacant voids, to see clearly the effects of the foaming agent on impact energy absorption.

The following graph shows the comparison of different foaming agents for energy absorption applications.

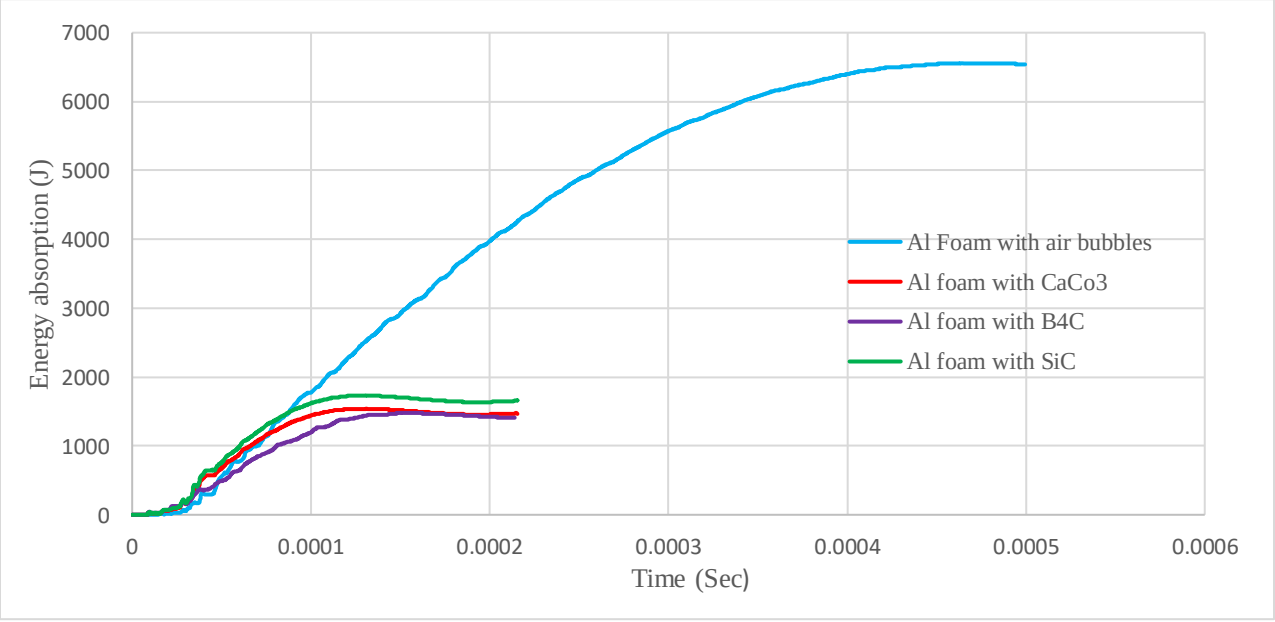


Figure 5.21: Comparison of Al foaming agents for energy absorption

The comparison of the impact energy absorption is done with existing foaming agents like $CaCo_3$, B_4C and SiC with in the same dimension (30x30x30m) mm as shown in appendix A, within the

same applied initial velocity, within the same volume and within the same percentage composition. But the mass of the hard inclusion particles are 0.15302 kg of SiC, 0.141 kg of CaCo3, 0.13618 kg of B4C and the mass Al foam is 0.068138 kg.

As shown in Figure 5.21 above, the maximum energy absorbed by the models is 6554.876 J, 1653.84 J, 1540.2 J and 1476.69 J for Al foam with bubbles (voids with air), Al foam with SiC, Al foam with $CaCo_3$ and Al with B_4C respectively. Herein as indicated in this figure, using bubbles (voids with air) for Al foaming enhances or increases the energy absorption capacity of the candidate materials from 1653.84 J, 1540.2 J and 1476.69 J to 6554.876 J than using SiC, $CaCo_3$, and B_4C respectively. In addition to these, when the new Al foam at 10% void fraction is compared to the other existing foaming agent called silicon carbide, its energy absorption was increased by 92.8% from 17.33 MJ/M^3 to 242.77 MJ/M^3 and 86.4% from 33MJ/M^3 to 242.77 MJ/M^3[35][48].

5.6 Reaction Force

During Al foam impact simulation, the reaction forces are applied in the opposite direction of the movement of the foam model. Mean that in the opposition of the applied initial velocity. A very important application of reaction force is improving and reducing injuries. In many cases, an object needs to be brought to rest from a certain initial velocity. This means there is a certain specified change in momentum. If the time during which the momentum change can be increased then the force that must be applied will be less and so it will cause less damage on occupants and car components. The following graph shows the reaction force generated during impact.

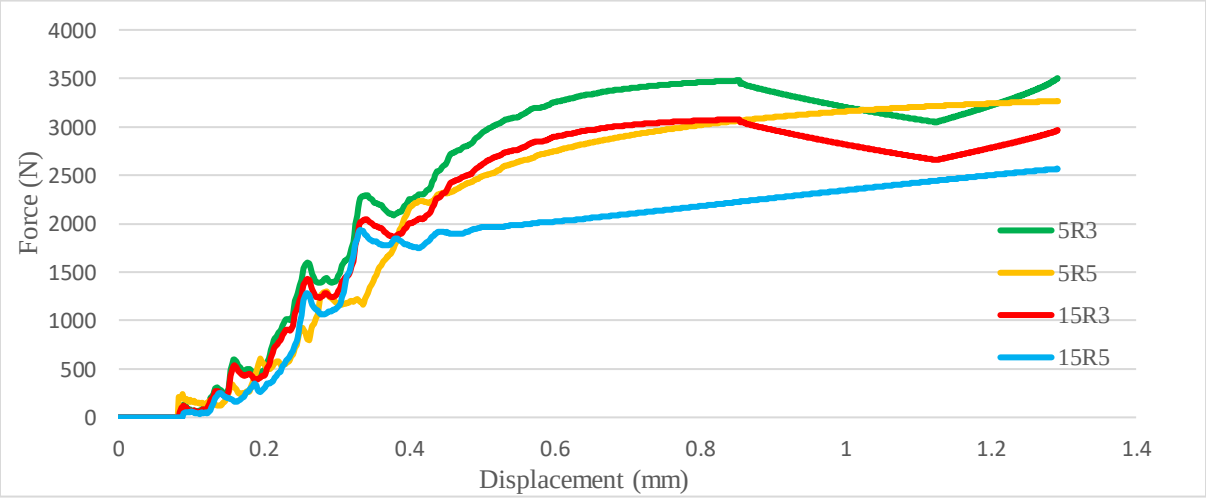


Figure 5.22: The overall reaction force generated versus displacement

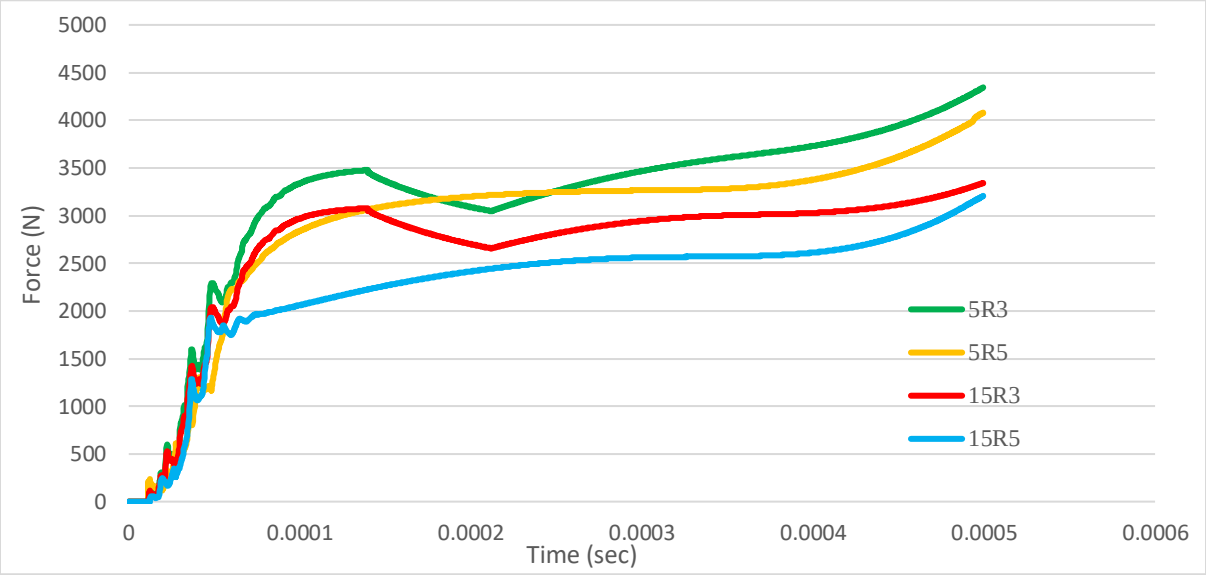


Figure 5.23:The overall reaction force generated versus time

As shown in Figure 5.22 above, maximum force is generated with respect to deformation and as shown in Figure 5.23 above, maximum force is generated with respect to time during impact. Therefore, those two respective figures show as minimum reaction forces is transferred to the occupants to minimize the damages.

This spongy Aluminum foam is a particular material for a crashworthy structure that is designed to crush in a controlled way during a collision. This material increases the time taken for the vehicle to slow down force transferred to the occupant during collision. This reduces the force exerted on the passengers. The deformation of this Al foam also absorbs more energy during a collision.

5.6.1 The effects of percentage composition on reaction force

The reaction force versus displacement and time graph for selected models at 5%, 10% and 15% aluminum foam with pore size of 2.5 mm are shown in the figure 5.22 and 5.23 above. The comparison is made to check the reaction force capability of the candidate material with the other models with in the same pore size. Therefore, as shown in figure above as percentage composition increases from 5% to 15% the reaction force decreases.

The selection of the Al foam model regarding to the reaction force depends on its application. So, depending on its specific application, the best aluminum foam model can be selected. But the presented figures constitute an initial guidance for this work. These guiding values presented in above for the selection assumes a constant impact area throughout the head on collision and rigid structure.

CHAPTER SIX

6. Conclusion Recommendation and Future Works

6.1 Conclusion

In the numerical analysis of closed-cell Aluminum foam for energy absorption purposes, specifically for vehicle frontal impact condition applications, the four major factors are considered. First, the deformation should be kept low as much as possible to save occupant life and for vehicle component safety. Second, the energy absorption capacity of Al foam should be kept high. Third, the peak acceleration of the foam during impact shouldn't exceed 43 g to avoid brain skull damage of the occupants. Fourth, the weight of the foam material should be low as much as possible for fuel economy.

Therefore, from the previous results and discussions, the closed-cell Aluminum foam model with 10% void fraction at bubble size radius of 2.5 mm could fulfill the crashworthiness requirements as compared with other models. So, it is selected as a new material to manufacture impact structures for automotive and aerospace engineering companies.

The following conclusions are drawn from this research paper.

- The energy absorption capacity of closed cell Al foam at pore size of 2.5 mm with 10% porosity percentage composition were 6554.876 J.
- To absorb 6554.876 J of impact energy during collision, the candidate closed cell Al foam deforms maximum of 1.4493 mm.
- The mass of the closed cell Aluminum foam with air bubbles were reduced by 7.3% from 0.14104 kg to 0.068138 kg and 6.8% from 0.13618 kg to 0.068138 kg than using $CaCo_3$ and B_4C foaming agents respectively. These obviously shows that using air as a foaming agent makes the specimen lighter than using other particles.
- The peak acceleration for new closed cell Aluminum foam material was 39.82 g and average acceleration was 34.5 g. These means that, from design point of view it is 7.4% safe and 13.04% more stable.
- The energy absorption capacity of closed cell Al foam with bubbles (void with air) were increased by 74.77% from 1653.84 J to 6554.876 J, 76.5% from 1540.2 J to 6554.876 J

and 77.4% from 1476.7 J to 6554.876 J than using SiC, $CaCo_3$ and B_4C foaming agents respectively, and increased from 17.33 MJ/M^3 to 242.77 MJ/M^3 and from 33 MJ/M3 than using Silicon Carbide as a foaming agent and Aluminum foam filled steel. These results indicate that, foaming of closed cell Al metal with randomly and finely distributed pores (void with air) increase the stiffness of the materials to absorb more energy with optimum time.

- As percentage composition decreases the rection force increases, as shown in figure 5.22 and 5.23 above with in the same pore sizes, volume and initial velocity.

6.2 Recommendation

During the analysis of closed cell Aluminum foam for energy absorption, type and distribution of filler material have a great role on deformation, acceleration, force and energy absorption capacity Aluminum foam for impact energy absorption applications in automotive and aerospace engineering. Specially, the unique microstructure of Al foam with high specific energy absorption and light weight, attracts the interest to develop lightweight and fuel-efficient vehicle structures.

In this study the results of fifteen foam models were discussed by combining two parameters (percentage composition and bubble size) and the effects of different filler agents on four major factors (deformation, acceleration, reaction force and energy absorption). This study shows Aluminum foam model with air bubbles at 10% void fraction and 2.5 mm cell size better performance than the other models studied here.

Finally, it is recommended that the closed cell Aluminum foam with randomly and finely distribution of bubbles (void with air) at 10% void fraction and 2.5 mm bubble size is more suitable material to develop vehicle impact structures.

6.3 Future works

In this thesis the effects of bubble size, filler material and its void percentage compositions are studied and optimized. Other influencing factors are not included. So, this work is restricted to the specific cases. However, for the best of energy absorption applications, this paper can be extended to the other situations listed below.

- Conducting the experimental test on the developed Al foam specimen to check the accuracy of the results.
- By introducing the different bubble sizes on Al foam, mean that smaller size in the front and larger bubbles in behind by adopting another geometry.
- Analyze this study numerically by introducing the effects of bubble shape and strain rate.
- Can be modified by using regular pattern bubble distribution

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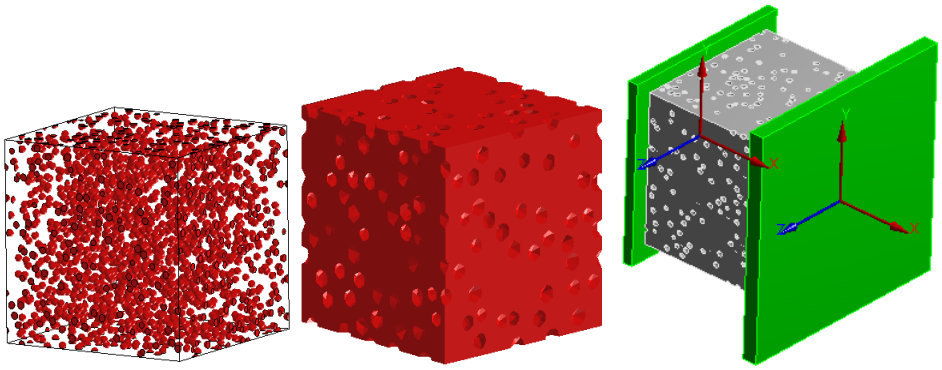
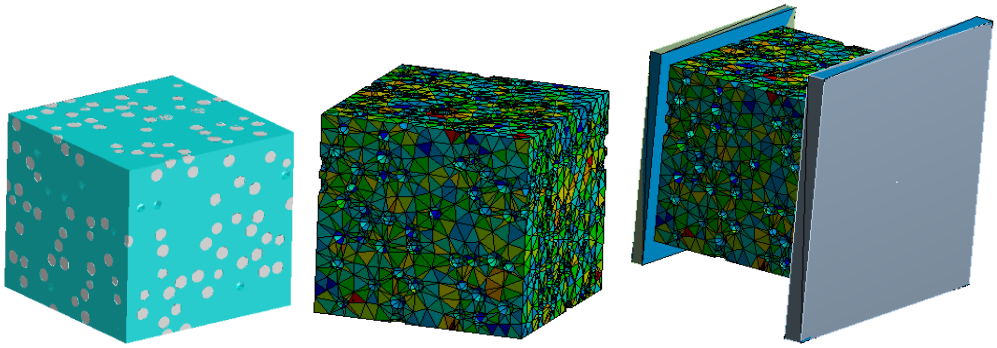
APPENDIX A: Foaming Agents

Foaming agents

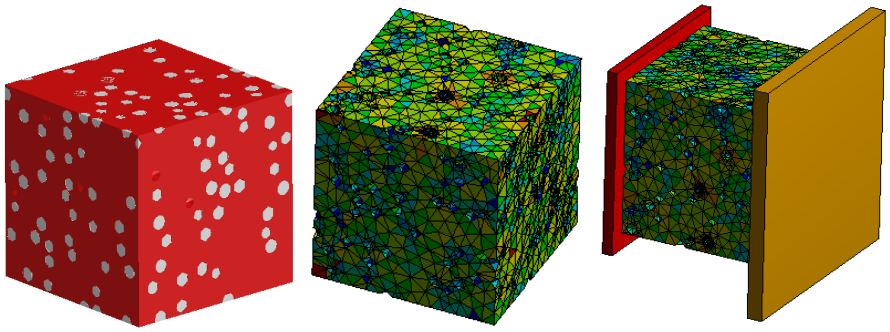
a. Air bubbles foaming agent



b. SiC foaming agent



c. $CaCo_3$ foaming agent



d. B_4C