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Design optimization of sandwich core

Mohammad Tauhiduzzaman
University of Texas at El Paso, mtauhiduzzaman@miners.utep.edu

DESIGN OPTIMIZATION OF SANDWICH CORE

MOHAMMAD TAUHIDUZZAMAN

Master's Program in Computational Science

APPROVED:

____
Pavana Prabhakar, Ph.D., Chair

____
Vinod Kumar, Ph.D.

____
Natasha Sharma, Ph.D.

____
Charles Ambler, Ph.D.
Dean of the Graduate School

Dedication

Dedicated to my parents.

Mohammad Khaleduzzaman and **Farida Yesmin**

DESIGN OPTIMIZATION OF SANDWICH CORE

by

MOHAMMAD TAUHIDUZZAMAN, B. Sc. ME

THESIS

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Abstract

Ultralight sandwich structures comprising of low-density core with stiff facings have attracted significant research interest for their considerable weight saving applications. The aircraft industries are focusing on decreasing the structural mass to lower the manufacturing and operating costs. Design analysis of the sandwich cores using finite element analysis has been developed as a promising concept to feature sandwich structures with maximum strength, stiffness, and reduced weight. To obtain multifunctional behavior of sandwich panels, a profound investigation of geometrical and mechanical properties in the transverse plane is required because it is very susceptible to any kind loadings. Structural optimization is one of the key factors for designing lightweight structures, where the main concern is not merely to ensure an intricate design, but also to identify the limiting factors and resolve the issues by generating optimum values of the main parameters.

This thesis presents the design optimization of multifunctional sandwich panels in two chapters. The first chapter reports the shape optimization approach of four different core topologies considering three-dimensional isotropic patterns that are optimally designed for minimum weights. Additive manufacturing technology is a suitable and amenable method for the construction of sandwich structures because it ensures strong bonding between the facings and core to reduce the slipping. Fused deposition modeling method is employed to build the 3D printed structures. Short beam shear tests were carried out on the initially non-optimized structures to generate the structural response. Peak loads and deformations were recorded to compare the flexural properties. To obtain the new design of the sandwich cores with optimum stiffness and reduced weight shape optimization task is performed by ABAQUS. Stress and weight are the design variables to carry out the optimization method. Shape optimization process deals with the coordinates of surface nodes; eventually, it creates a new design of the cores that demonstrates versatile performance. Finally, based on the output of the optimization procedure new STL files are imported in the additive manufacturing machine to produce the optimized structure. Optimized panels are

subjected to short beam shear test again to investigate their performance that has changed by employing shape optimization. Comparison using the mechanical properties are subsequently performed for the optimized and non-optimized panels to demonstrate the overall responses numerically. Results show that optimized structures are significantly lighter that perform decently from the strength standpoint with diverse characteristics such as ductility and brittleness.

Algorithms, like a genetic algorithm, mimics natural process can be employed in the structural optimization technique. In this paper, both finite element analysis and genetic algorithm are employed to obtain the optimum result of the cross- sectional area for truss structures. The area is the main variable for this optimization technique that can be expressed by the array of binary numbers to carry out genetic algorithm operation and subsequently stress analysis is performed using the material properties. Since minimization of the weight is the objective function, so decreasing the cross-sectional areas subjected to a higher stress of the truss members and allowable stress operates as a stopping criterion for this iterative process. Finally, stress analysis and genetic algorithm create a possible solution set for areas and weight of the unit cell for the truss structure is determined. FEA is conducted by combining FEA (using ABAQUS) and genetic algorithm that is implemented in MATLAB.

The findings shown in this thesis have established appropriate weight saving technique for sandwich structures. The work provided a solid foundation for structural optimization that utilizes finite element package and a robust tool genetic algorithm which is not found in the commercial software packages.

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Chapter 1: Introduction

1.1 Cellular materials

The emergence of sandwich composites introduced a considerable progress for the aerospace and different engineering industries due to their multifunctional features. Sandwich panels consist of a lightweight core material that exhibits high flexural stiffness, is covered by two facesheets which are stiff skins. Sandwich construction is based on the concept of cellular materials. The word cell derives from the latin word cella which means enclosed space [1]. Cellular materials consist of solid struts or plates which are interconnected in a certain pattern to construct the edges and faces of a structure. Well known cellular materials are highly porous such as wood, coral, bone, and bee honeycombs. Even though porosity reduces the strength and stiffness, its light interior core with regularly spaced pores and hard outside layer form a structure that can resist bending loads efficiently [2]. The performance of these natural structures has spurred the designers to create an artificial structure, known as a sandwich structure, that mimics the design of cellular solids. Design integrate multi-functional behavior in a single material such as stiffness, strength, damping, insulation and many more. The geometric interactions and properties of the constituent materials of sandwich composites have attracted interests and provided a great opportunity for diverse implementations. Diverse characteristics of cellular materials offer different engineering applications in aviation, automotive, construction and packaging industries. Dweib et al. presented a work using VARTM technology to manufacture sandwich panels for structural applications[3]. Wang et al. utilized shock tube experiments to represent the dynamic behavior of sandwich panels [4]. Damping properties of sandwich cantilever beams were investigated by Yim and his co-authors where they mentioned viscoelastic core thickness has a great effect in reducing damping factor [5]. A general concept of conventional material is the more energy it absorbs, the heavier it will be. But sandwich structure consumes less material and yields more energy that made them environmentally friendly. Apart from this, freedom of design, extreme cost savings, non-

corrosiveness, sound insulation characteristics encouraging the designers to investigate in detail that outperform previous accomplishment.

1.2 FEA importance for design

Finite element analysis is the idealization of the physical system by employing a finite number of elements that subjected to given loads or boundary conditions. Performing finite element analysis for three-dimensional sandwich panels offer the designers to control several aspects such as model the geometries, boundary conditions, loadings and material properties [6]. Typically, three steps are followed to perform FEA: (i) initial geometry is created and required material properties and boundary conditions are applied (ii) analysis steps generate results by solving the associated equations (iii) at last results are interpreted in the post-processing stage. One distinct nature of sandwich composite panel is it combines the positive properties of individual materials that, if well designed, cause the material to behave smartly. Design of sandwich structure is an iterative process that feature a sandwich structure with advanced mechanical properties such as maximum flexural strength and stiffness with minimum weight and cost. To predict the behavior of sandwich composites under a definite loading conditions such as transverse load, shear load structural analysis is performed. Analyzing the responses, designer can identify the regions which are very prone to failure, strength and stiffness along a definite direction. Additionally, several software packages are introducing commercial FEA programs with optimization process integrated into it. This thesis explores the methods to minimize the total weight of sandwich composites for multiple core geometry Incorporation of finite element modeling with experimental validation has been proved an excellent approach for acquiring high strength to weight ratio and further investigation reveals that multiple objectives can be optimized by employing genetic algorithm [7], [8], [9], and [10]. Hutchinson and Xue presented work that discusses the optimization of the sandwich plates under impulsive loading. They utilized square honeycombs to obtain the optimal distribution of the mass between faces and core. Finite element modeling was performed to demonstrate the structural response [11]. Wadley et al. studied the fabrication and

structural performance of sandwich structure where topology optimization was performed on metallic, open cell, and truss cored sandwich structure that enabled them to obtain better structural performance and later they showed a comparison with honeycomb sandwich structures with respect to relative low densities [12]. Wicks and Hutchinson report a study of optimal truss plates designed for minimum weight to verify the performance as compression panels [13]. Budiansky showed a comparison of different optimal compression columns with various sandwich cores such as foam filled tubes, hollow tubes and core foam sandwiches and it was established that the optimal core proposes significant weight savings [14]. Deshpande and Fleck report a study on sandwich beams consisting of tetrahedral core were subjected to 3-point bending load to measure the upper bound expression of collapse mechanism that allow them to select the sandwich beams of minimum weight [15]. Previously, most of the research performed took into account a particular type of structure and established an optimal design. In this paper, four different sandwich cores are considered and new models are proposed for each structure through the incorporation of shape optimization technique. At the end, the failure mechanisms of these structures are analyzed. To validate the models, it is important to verify the structural behavior under loading conditions. As a result, it is important to select a manufacturing method that will allow the designers to work freely without any penalties. Additive manufacturing technology provides this freedom to the designers so that they can innovate.

1.3 Thesis goals

The primary objectives of this thesis paper are to: (i) investigate the possible methods to obtain lightweight sandwich panels that can deliver enhanced mechanical properties (ii) explore and characterize the possible design optimization technique which considers important mechanical properties as the main objective (iii) predict the mechanical behavior of the optimized structures by employing finite element analysis (iv) address the additive manufacturing technology as an unique method to verify the performance of design optimization procedure.

1.4 Thesis outline

This thesis presents the design optimization of multifunctional sandwich panels in two chapters. The aim of chapter two is to report a design optimization procedure for four different sandwich structures considering three-dimensional isotropic patterns that are optimally designed for minimum weights. This study explains about four unique core topologies, the reason for employing shape optimization procedure for design optimization, and ensuring enhanced geometric design. Additive manufacturing section includes the explanation of manufacturing process by employing fused deposition modeling which is a suitable and amenable method to construct sandwich structures. In the modeling section, the procedure to establish the structural property such as modulus of elasticity E, for four different panels is described along with the results from shape optimization based on the material properties. Sandwich construction and experimentation section describe about geometrical design of unit cells what are followed to construct the panels by employing ABS material. Strength for sandwich composites can be obtained by conducting short beam shear test on each specimen. Experimental results section contains a detailed comparison of the performance of optimized structures with respect to initial structures. An investigation was carried out on the failure mechanisms for the four different sandwich panels what described in failure analysis section. By comparing the outcomes, the significance of this novel approach is summarized in conclusion. Chapter three aims at sizing optimization of the lattice truss unit cell that is repeated in the core by employing a robust tool genetic algorithm.

Chapter 2: Design optimization of sandwich core and manufacture through additive manufacturing

2.1 Classification of sandwich structures

For what sandwich structures concerns, all of the credit goes to Fairbairn, who has been considered as the first person to describe the principal of this absolute lightweight structure. The first remarkable application for the sandwich structure is the successful landing on the surface of the moon. Also, the World War II Mosquito aircraft is often quoted as being the first major application [16]. Structural behavior of sandwich panels depends on the stiffness of the face and core materials, geometric relationships between face and core thickness and the span [17]. A wide variety of materials such as wood, foam, polymer can be used as the for sandwich structure, but the selection process is intricate. Thickness and strength are the primary factors of core material to carry the shear and compressive load through thickness direction. High strength and lightweight property of core materials stabilize the facings and prevent failure induced by the design loads. Facings should have enough strength to carry the axial, bending, and in-plane shear loading. Generally based on the topology of core materials, sandwich composites can be classified as stochastic and periodic types. Sandwich composites with the periodic topology demonstrate superior structural performance and it can sustain loads greatly compared to stochastic foam. Periodic structures maintain periodicity in three dimensions by repeating the unit cells. A random distribution of pores and voids within the boundary construct the stochastic architecture. In this paper, the three different types of sandwich core structures viz. prismatic, lattice truss, and honeycomb are accounted to apply shape optimization technique. Open cell and closed cell concept is an important feature of three dimensional sandwich composite to analyze- prismatic and lattice truss cores are open along X and Z directions, but honeycomb core is a closed cell structure. Prismatic core contains a periodic pattern of triangular, diamond shape prismatic cells. Core elements contain the inclination angle and degree of corrugation that construct the complete unit cell. Lattice truss cores usually contain tetrahedral, pyramidal and kagome cell type. Usually these structures are open cell, therefore, the mode of truss deformation can be determined. Honeycomb

structure is an array of hollow cells typically triangular, hexagonal, and square shape geometry that reduce weight of the panel. The facings of the honeycomb sandwich structure act like an I beam because it can carry the load where the top face is in tension and the bottom face is in compression. The facesheet attachment with the core increase the efficiency of the structure by increasing the moment of inertia, distributing the shear and axial loads in order to produce an efficient structure which can be used for aircrafts, marine crafts, racing cars, constructional industries, and high-speed trains. Figure 2.1, illustrates about the core topologies of sandwich composites. Stiffness and strength of the sandwich remarkably depend on the topological patterns. To obtain lightweight structure it is also important to ensure the low density of core material. Performance of sandwich structure directly depends on the shape and topology of the structures.

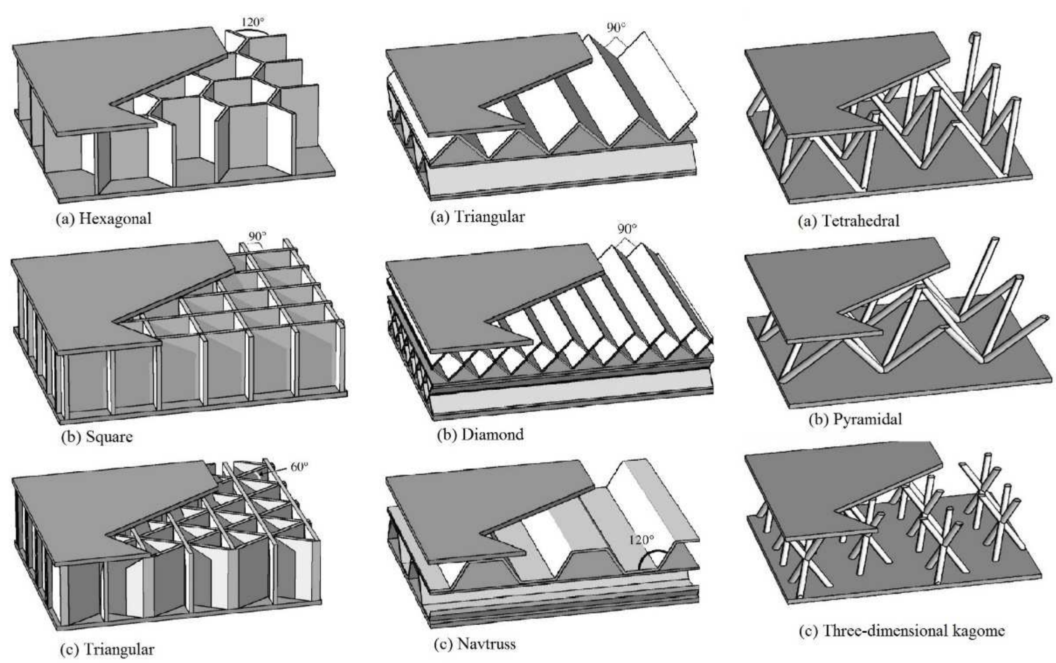


Figure 2. 1: Different types of sandwich structures [18]

One of the most important features of sandwich composites is relative density. Reduced weight lowers the production cost, which translates to reduction in fuel consumption. Eventually, this has an outstanding impact on the energy consumption. An optimum design with reduced

weight increases the performance of the structure. For example, if three vehicles are considered with identical mechanical properties but disparity exists only in the structural mass, the car with the less total mass will have a better performance since it will be more efficient. Although the mechanical properties are same, the energy consumption is directly related to the structural mass. It dictates that the vehicles with higher mass will consume more energy compared to lower mass. From this it is clear, the importance to design optimization in order to achieve the less possible weight. Nowadays, airplane manufacturers are focusing more on economic and environmental aspects, therefore, the lightweight issue draws the attention that reduce fuel consumption. For example, Boeing 787 Dreamliner shown in Figure 2.2, utilize composite material more than 50% of its total material that reduce the weight considerably.

Figure 2.2: Boeing 787 Dreamliner breakdown material [19]

Now the question arises what would be the most efficient way to reduce that weight while ensuring an optimized design. One might propose using metal alloys or new materials with improved the mechanical properties but they tend to be expensive. Improvement in the geometric design of the core material is considered as the most effective method to create a new, improved structure increased bending stiffness and strength. Topology, shape, and size are all three major areas of geometric configurations. The aim is to optimize the design of the sandwich panels with

maximum stiffness and at the same time reduce the weight. Design variables are affecting the cells of the truss core. This paper presents a shape optimization technique for the prismatic, lattice truss, and honeycomb sandwich cores. Stress and volume were two design variables considered to carry out the optimization method. Volume is the primary constraint in this shape optimization technique [20].

2.2 Additive manufacturing

Additive manufacturing technology opens up an excellent opportunity for researchers to create prototypes as it is cost efficient and accurate design can be made. The ability to replicate objects without using expensive molds made it so popular in multiple industries including motor vehicles, aerospace, electronics [21]. The process of joining materials layer by layer using the 3D model data as opposed to the subtractive method that removes material is called additive manufacturing. In this process, materials are deposited through a nozzle and afterward bonded together by using paper, metal, and plastic. Creating an object through additive manufacturing process follows three steps which are pre-processing, production and post-processing. In the preprocessing stage, 3D cad files are used to provide the coordinates for the material when printing and estimate the total amount of material required. Production stage includes heating the ABS materials and depositing it along the extrusion path. Finally, in the post-processing stage, the support material is removed. Figure 2.3 schematic, shows what steps are followed to build a sandwich composite by additive manufacturing process. To build sandwich composites following steps are followed:

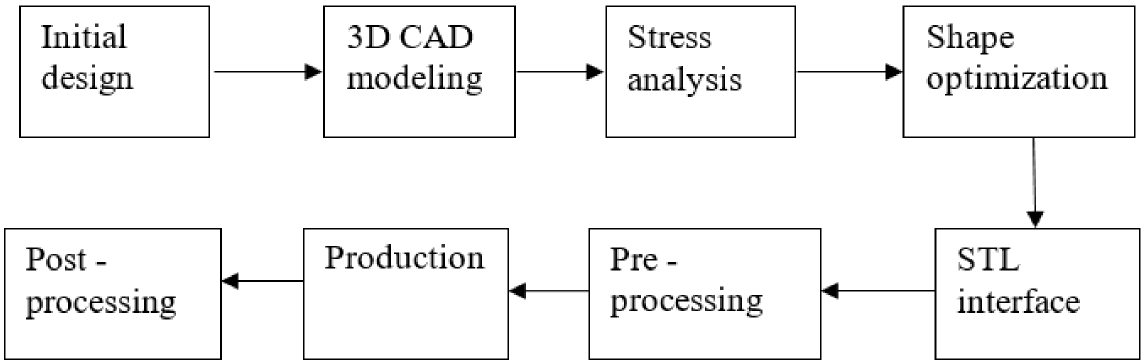


Figure 1.3:Data flow in additive manufacturing

Additive manufacturing technology dates back to 1980's with the development of stereolithography where liquid polymer solidified by using a laser [22]. Later, another additive manufacturing process was developed called fused deposition modeling method where thermoplastic materials are feed to a machine, and eventually, extrusion takes place to print the objects. Polymer matrix composites used to build composite materials are comprised of a variety of short or continuous fibers bonded together by an organic polymer matrix. Thermoplastic and thermosets are two types of polymer matrix composites where thermoplastic materials have a unique feature. Heating up the thermoplastic materials makes it soft. Eventually, it solidifies when the temperature drops. Different types of thermoplastic materials are available such as ABS, PLA, PVA. For the initial design and shape optimization, different core structures were established. By employing additive manufacturing technology, such as ABS material, a comparison of the weight of the structures at the two stages will validate the shape optimization technique for sandwich composites. Typically, failure of sandwich structures under service conditions is frequently due to core shear, face fracture, delamination, buckling and occurs at regions where higher local stress is present. Inhomogeneous stress distribution in the design areas is far from being an optimized design. Limited manufacturing technology was a major issue to meet the design requirements according to the manufacturer [23]. Of late, new manufacturing options have been developed. Therefore, designers should be able to offer an optimum design of complex shape that will represent enhanced mechanical properties in service conditions. At present, it is possible to observe

the test results virtually and manufacture a prototype. Finite element analysis has become an indispensable part of the design process since it helps to develop an optimum design.

2.3 CAD Modeling

Modeling of the sandwich panels with the dimensions of 7.2 inch* 1.84 inch * 1.6 inch is carried out through ABAQUS. The optimization of sandwich composites core consists of following four steps. In step 1, CAD modeling is performed in SOLIDWORKS by following the geometry of the initial design. Due to unknown material properties for different core design, it is required to fabricate the structures and determine the properties. In step 2, short beam shear tests are carried out to obtain the load vs. displacement plots and subsequently material properties are determined by employing trial and error method. Later, in step 3, stress analysis is conducted using tetrahedral mesh elements on the design. In step 4, design optimization is performed on the core area keeping the facesheets unchanged by applying objective function and constraints. The following sections describe the initial design of all four sandwich panels.

2.3.1 Prismatic core

Figure 2.4, represents the unit geometry of prismatic sandwich core. The unit cell is repeated along the X direction to construct the topology of prismatic core. Prismatic core topology makes a symmetric open cell sandwich structures. This sandwich is closed along X and Y directions but open at Z direction.

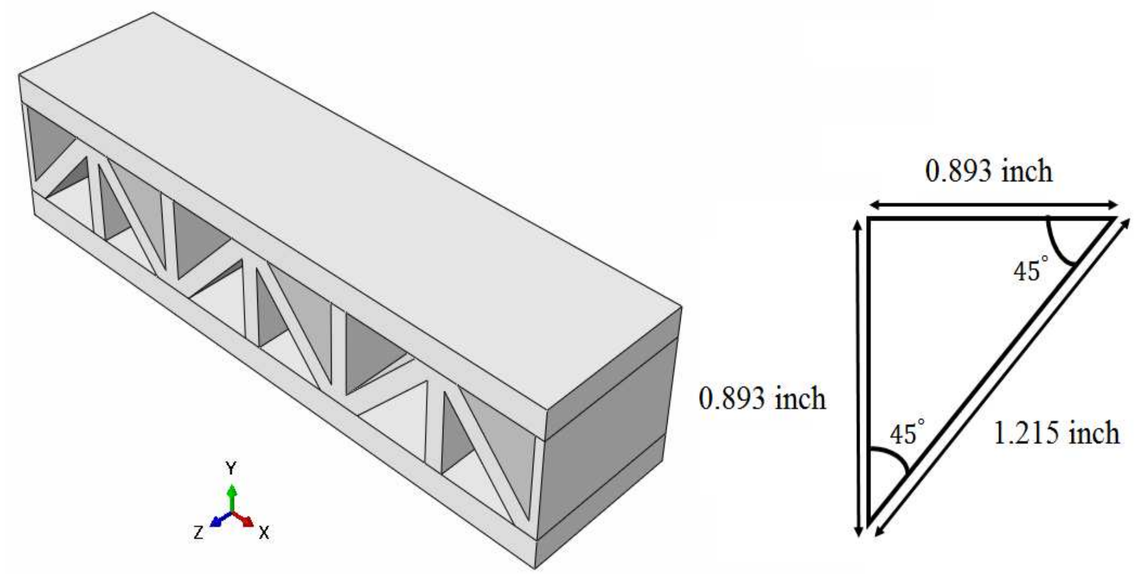


Figure 2.4: Prismatic sandwich core topology with unit cell

Pitch distance between the unit cells = 2.4 inch

Total number of repeating unit cell, n= 3

Angle, $\theta = 45^{\circ}$

Volume of the prismatic sandwich structure = 7.2 inch * 1.84 inch * 1.6 inch.

2.3.2 Lattice truss sandwich structure

Typically, lattice truss topologies are pyramidal, tetrahedral, octet and collinear trusses. Figure 2.5, is the unit cell of the tetrahedral lattice truss structure. The arrangement of trusses follows the unit cell geometry along the X direction to construct the symmetric tetrahedral lattice truss sandwich composites. Lattice truss core is a completely open cell sandwich structure.

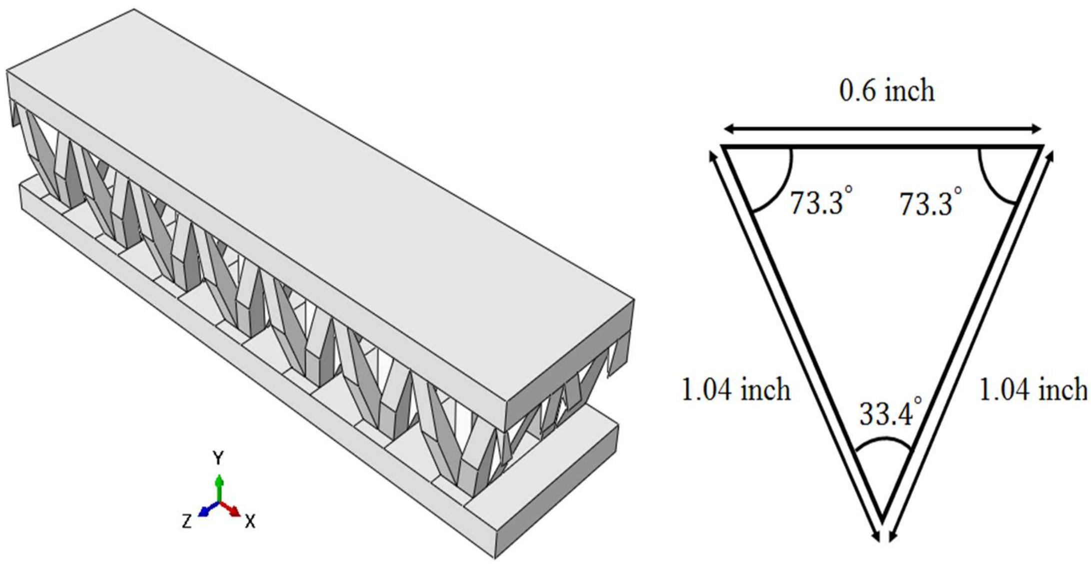


Figure 2.5: Lattice truss sandwich core topology with unit cell

Length of the truss member = 1.04 inch

Distance between two truss member = 0.6 inch

Angel, $\theta = 73.3^{\circ}$

2.3.3 Square honeycomb

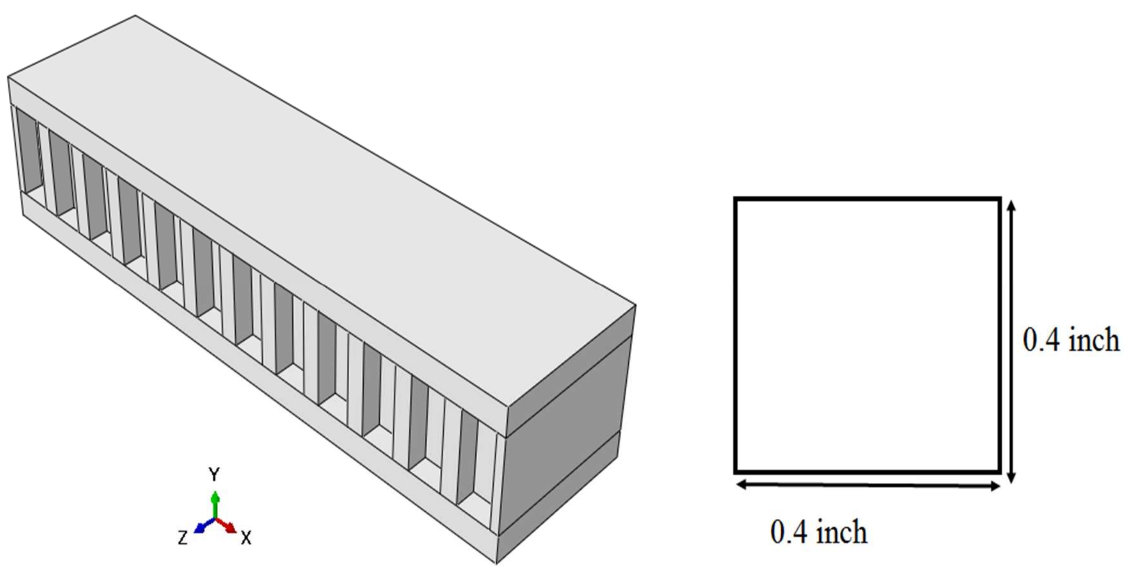


Figure 2.6: Square honeycomb core topology with unit cell

Dimension of the unit cell = 0.4 inch * 0.4 inch

Total number of unit cell, n = 36

Square honeycomb core topology includes square unit cells, separated by a thick wall, is a closed cell sandwich composites with high strength and low density. Figure 2.6, demonstrate the unit cell and square honeycomb structure topology. The unit cell arranges the core topology by repeating in X and Y directions. Honeycomb structures feature different geometry such as square, hexagonal and triangular which are arrays of hollow cells. Honeycomb topology provides low density and high relative out of plane compression as well as out of plane shear.

2.3.4 Hexagonal honeycomb

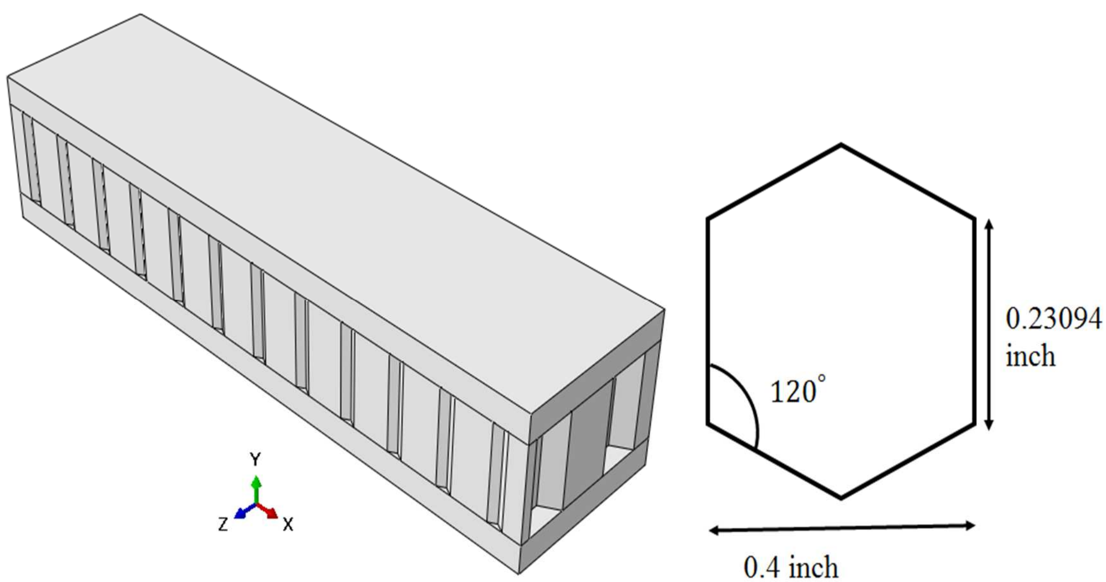


Figure 2.7: Hexagonal honeycomb core topology with unit cell

Vertical pitch distance = 1.03923 inch.

Horizontal pitch distance = 0.6 inch.

Total number of unit cells, n = 63.

Figure 2.7, illustrates the unit cell and a closed cell hexagonal honeycomb structure. It is repeated vertically and horizontally to form the core topology. The afterward addition of the facesheets complete the full structure geometry.

2.4 Determination of material properties

One of the challenging factors for modeling is acquiring material properties, particularly young modulus, as inputs for FEM. Young modulus states the intrinsic material property which is not influenced by the structure. On the contrary, stiffness refers to the structural property greatly affected by the geometrical shape of the object/structure. Slope in the linear region of the load vs. displacement curve dictates about the stiffness of that structure. Mimicking the load vs. displacement response from the short beam shear tests through ABAQUS, the material property for each structure was evaluated. Initially, an arbitrary Young modulus value was assumed in order to carry out the finite element method simulation for all sandwich structures. Subsequently, the force vs. displacement graph was generated by the combine operator from ABAQUS. To assess preciseness of the presumed young modulus value, a slope of the force vs. displacement curve was determined in a homogeneous fashion like stiffness. If the slope obtained from the linear region of ABAQUS generated plot for a certain young modulus value is close enough to the experimental slope, then that mechanical property was recorded. The following young modulus values are obtained after employing the trial and error method for a definite time on each sandwich structures. Figure 2.8, shows the steps of finding young modulus value for a definite sandwich structure.

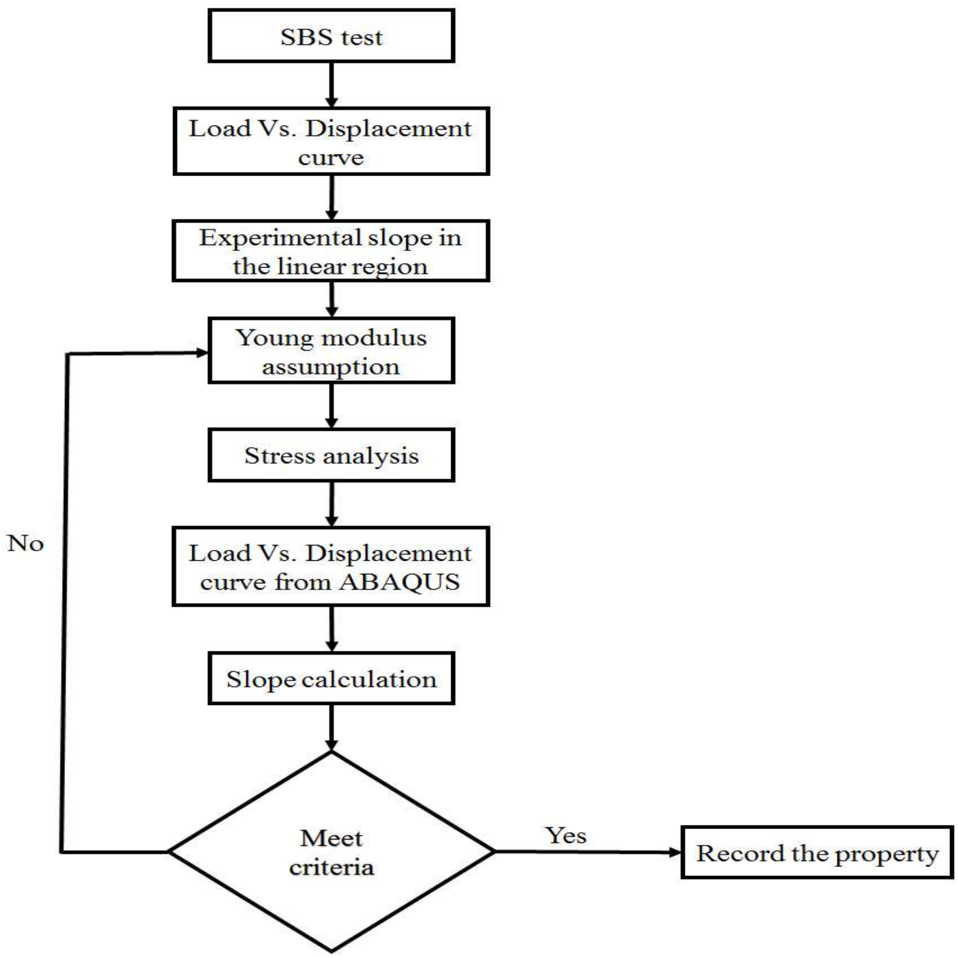


Figure 2.8: Flow chart of material property determination

2.5 Design optimization

Structural optimization is an approach to find the best possible way of a design of the structure with minimum material consumption that can meet other requirements at the same time. Optimization refers to the achievement of best outcome while satisfying certain restrictions [24]. Structural optimization can be classified into three broad categories: topology, shape, and size. Topology optimization refers to the variance of element-node connectivity by which a given material with an initial distribution is changed, material is removed from the design area and efficient topologies are determined. Shape optimization offers drastic improvement of the structures. New design is achieved by automatic modifications of the nodal points, but the topology of the material remains unchanged. Size optimization is concerned with the cross-section of the

materials and thickness. Typically, shape optimization is applied where stress and strain concentrations are required to homogenize on the surface. Non-parametric and parametric approaches were followed to accomplish this optimization task. In parametric optimization, the geometric model is defined by parametric variables which are considered as design variables [25]. Nonparametric optimization weighs nodes as the design variables and manipulates it to achieve the optimized figure. To propose a new design for the core sandwich, ABAQUS is utilized. Figure 2.9 illustrates the shape optimization workflow in ABAQUS. To initiate the optimization task we need to consider three factors:

- What is the criterion for best design: objective functions?
- What are the constraints?
- What are the design variables?

During shape optimization by ABAQUS, design area, design responses, design variables, objective functions, and constraints are required to be generated. Design area refers to the region of the model where design variables will be modified due to structure optimization. In our case, design area such as the core structure for all panels and design variables such as volume and stress will be modified.

Table 2.1: Terminology and corresponding variable of shape optimization

Terminology	**Variable**
Design variables	Stress and Volume
Objective function	Minimization of maximum stress
Constraint	Volume (50% of the initial volume)

During a shape optimization, mesh smoothing area is generated to establish a linkage between the surface nodes and the inner nodes. If there is no connection between the inner and surface nodes, then structural optimization technique can distort the surface elements. Tetrahedral mesh elements have been created on which mesh smoothing can be applied. Two different types

of algorithm are available to continue to mesh smoothing operation. Constrained Laplacian mesh smoothing algorithm is applicable for a greater model, and a local gradient is used for a small model where some nodes are less than 1000 in the mesh smoothing area. Four of the model contain total number of nodes more than 1000, so Constrained Laplacian mesh smoothing algorithm is applied in the design area to perform mesh smoothing operation.

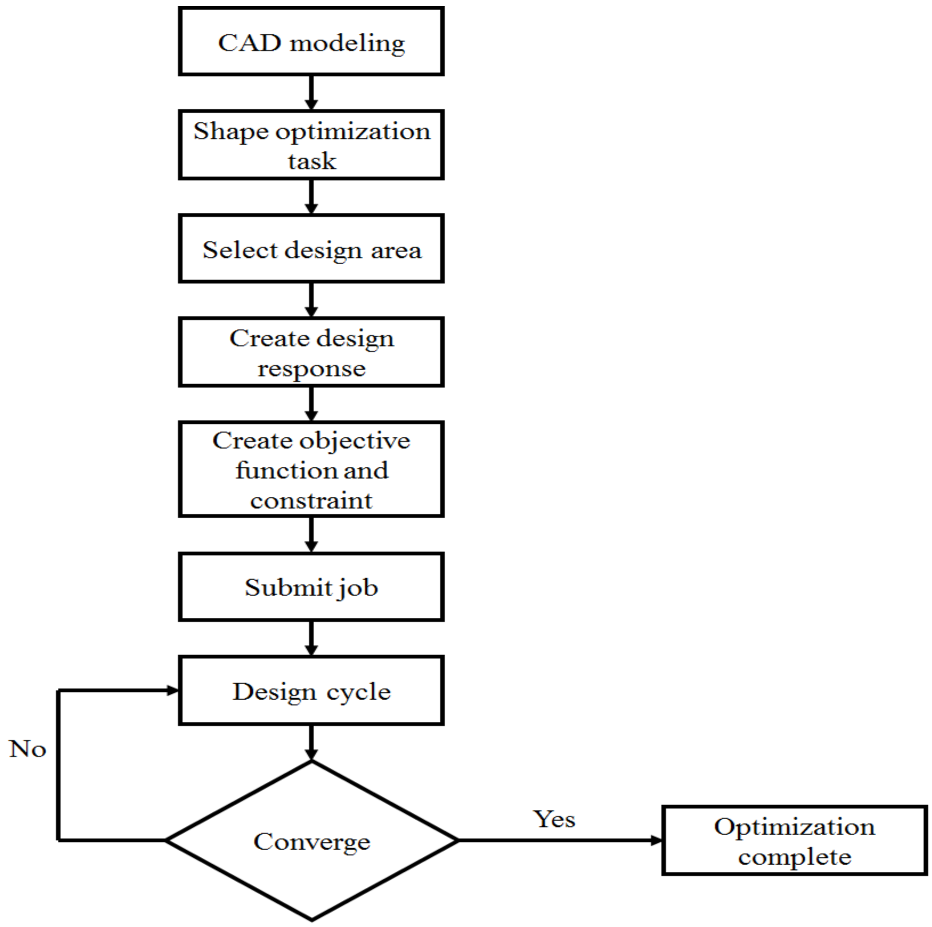


Figure 2.9: ABAQUS shape optimization flow chart

2.6 Simulation results

Structural analysis of sandwich panels is based on the young modulus value, was determined in section 2.4, is considered for the elastic three-dimensional isotropic pattern

sandwich structures such that the results can be easily compared with the experimental outcomes. For any linear elastic three dimensional solid, the equilibrium equations are

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + f_x = 0 \quad (1)$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + f_y = 0 \quad (2)$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + f_z = 0 \quad (3)$$

Stress and strains for the isotropic homogeneous material are calculated using the Young Modulus E and Poisson ratio ϑ. Material properties are independent of the position since all of our structures are homogeneous. Consequently, stress analysis employs these two material properties to obtain stress due to displacement boundary conditions. The following relation represents the dependency of stress and strain on Young Modulus and Poisson ratio.

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} 1/E & -\vartheta/E & -\vartheta/E & 0 & 0 & 0 \\ -\vartheta/E & 1/E & -\vartheta/E & 0 & 0 & 0 \\ -\vartheta/E & -\vartheta/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} \quad (4)$$

The bottom face, right side face and rear cross-sectioned face are restrained and cannot deform freely. Uniform displacement, 0.1 percent of the total thickness, which gives us the stress analysis result. The role of uniform displacement is to impose out of plane loading, which approximates the experimental procedure to some extent. Mesh generation requires intricate geometry of the model that also certify no holes in the geometry. Four of the models contain tetrahedral mesh elements, Table 2.2, shows the total number of nodes and elements, and element type that are to conduct the finite element analysis.

Table 2.2: Number of nodes, elements, and element types corresponding to different cores

Core	No. of nodes	No. of elements	Element types
Prismatic core	137951	86915	C3D10
Lattice truss core	129473	77840	C3D10
Square honeycomb core	162873	105766	C3D10
Hexagonal honeycomb core	175994	115608	C3D10

2.6.1 Prismatic core

Optimization and stress analysis results procedure generate the contour plots of von-mises stress. Figure 2.10, represents the stress analysis and optimization results for the prismatic core sandwich structure. Figure 2.11, depicts the area of the maximum von-mises stress. Since the objective function is to minimize the maximum stress by reducing the volume, so the design cycles search for a state when stress distribution is optimum around the core region. It is observed that after optimization the von-mises stress increased for the prismatic core.

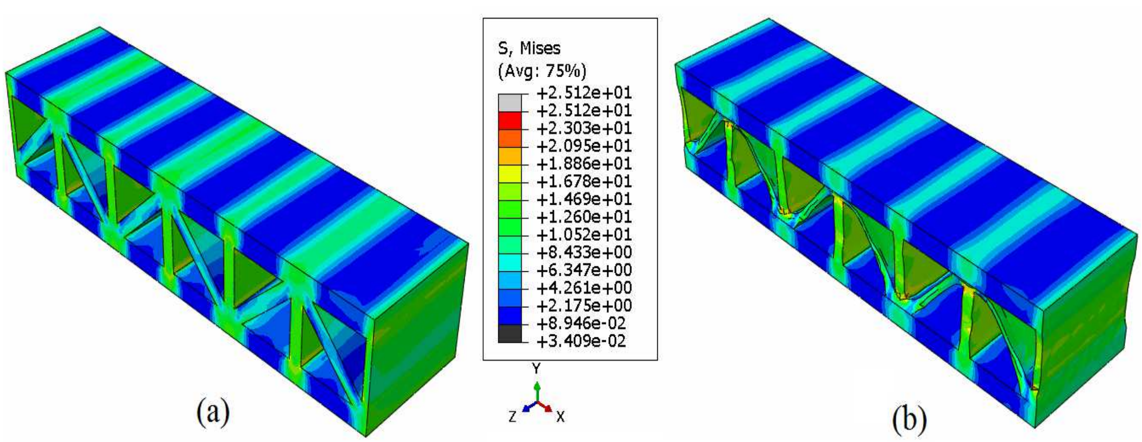


Figure 2.10: Stress analysis and optimization results with contour plots for prismatic sandwich structure (a) Stress analysis (b) Optimized figure

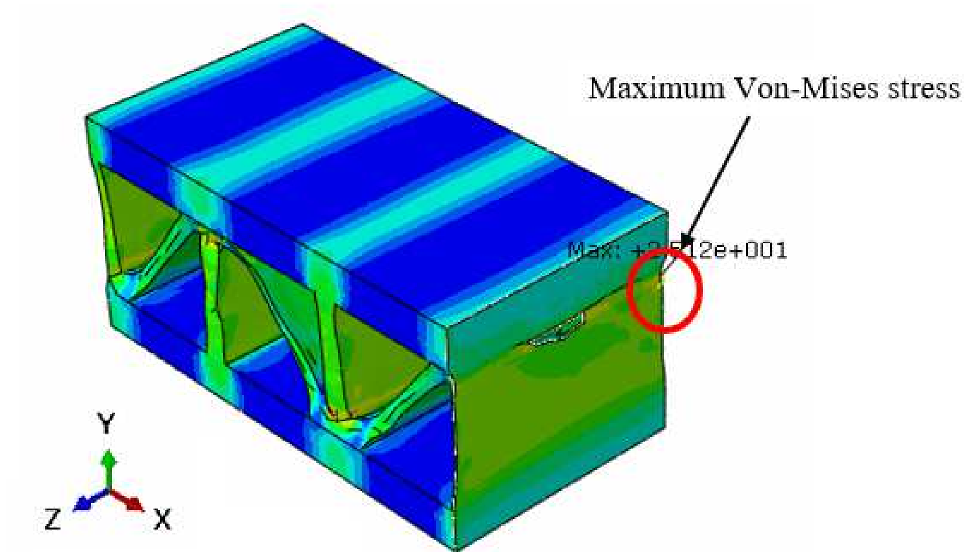


Figure 2.21: Maximum von-mises stress region

2.6.2 Tetrahedral lattice truss core

Figure 2.12, demonstrate the stress analysis and optimization result for pyramidal lattice truss sandwich core. Trusses are the main members in the core region that are considered for optimization. Design optimization reduces the thickness of the slender members. Figure 2.13, depicts the maximum von-mises stress region at the junction of the top facesheet and the nodal points where truss members joined.

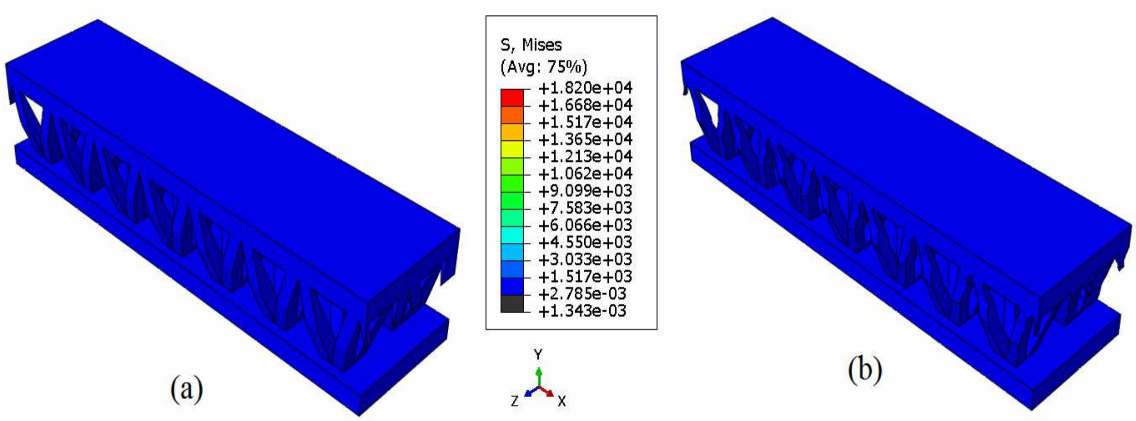


Figure 2.32: Stress analysis and optimization results with contour plots for tetrahedral lattice truss core sandwich structure (a) Stress analysis (b) Optimized figure

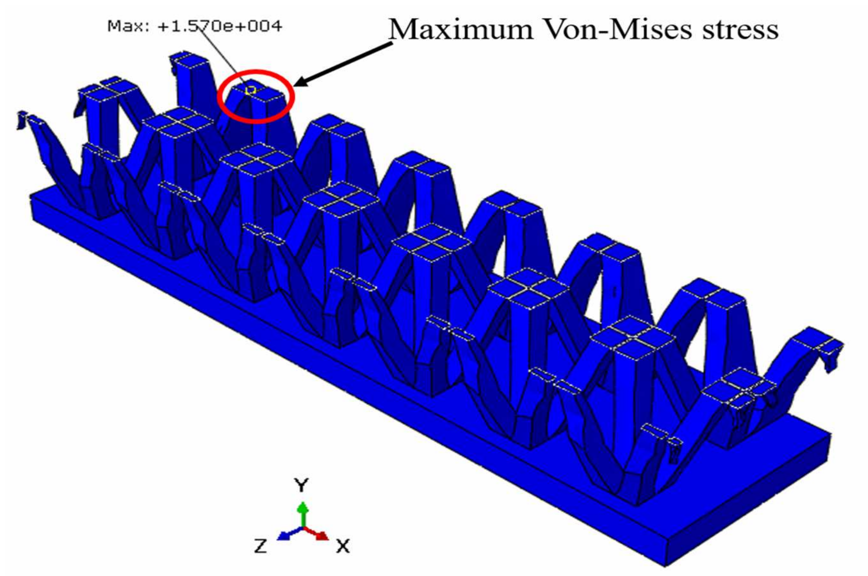


Figure 2.13: Maximum von-mises stress region

2.6.3 Square honeycomb core

Stress analysis and optimized results clarify that the thickness of the core show a discrepancy with its initial behavior. Comparison of the two behavior asserts the discrepancy of the shape of the core and stress distribution. Figure 2.14 a and b, is the evidence of the previous statement. Figure 2.15, indicates maximum von-mises stress region for square honeycomb core.

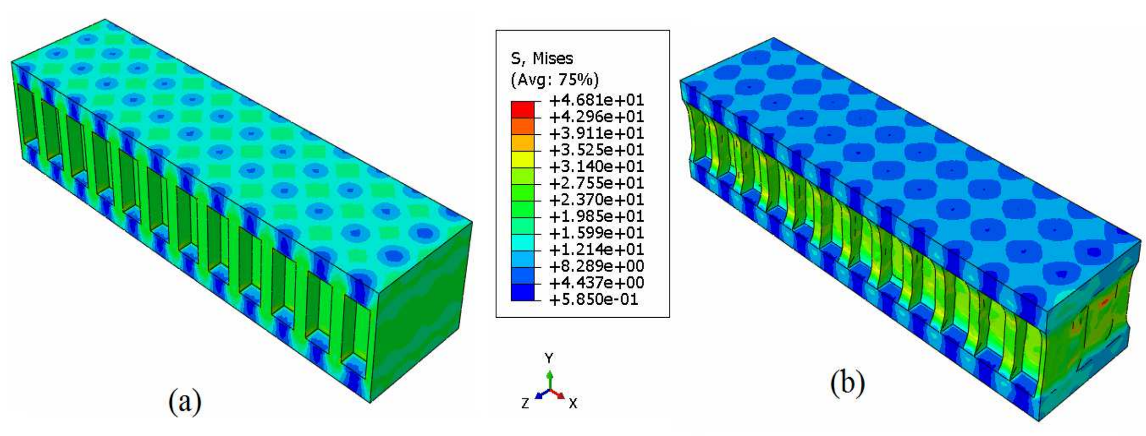


Figure 2.14: Stress analysis and optimization results with contour plots for square honeycomb sandwich structure (a) Stress analysis (b) Optimized figure

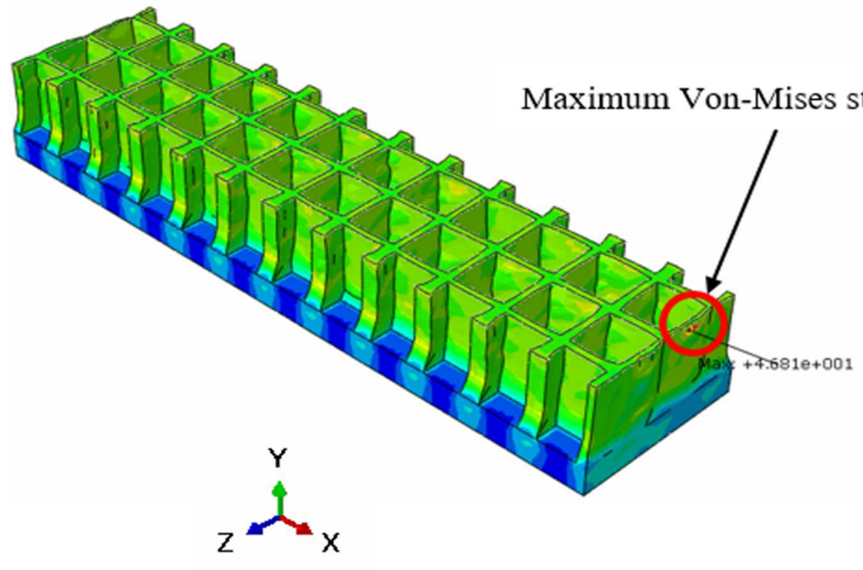


Figure 2.15: Maximum Von-Mises stress region

2.6.4 Hexagonal honeycomb core

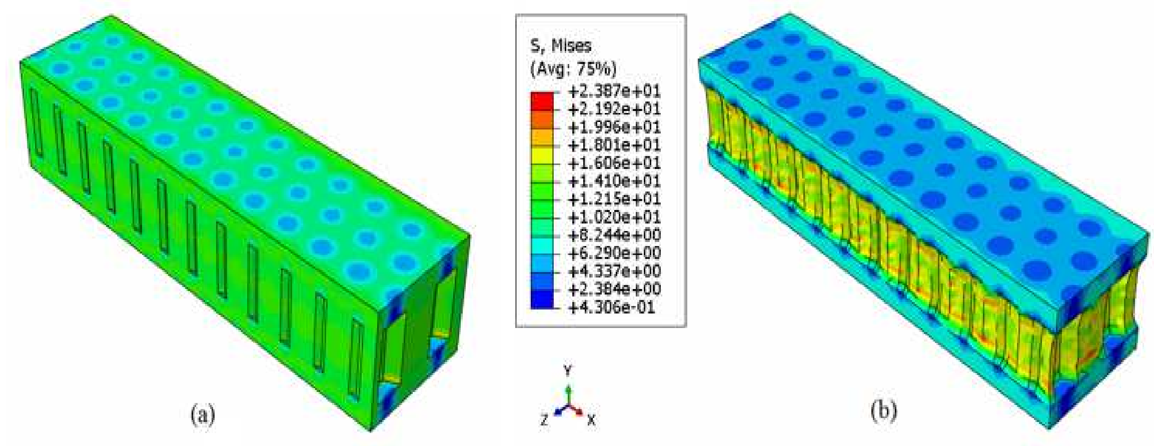


Figure 2.16: Stress analysis and optimization results with contour plots for hexagonal honeycomb core sandwich structure (a) Stress analysis (b) Optimized figure

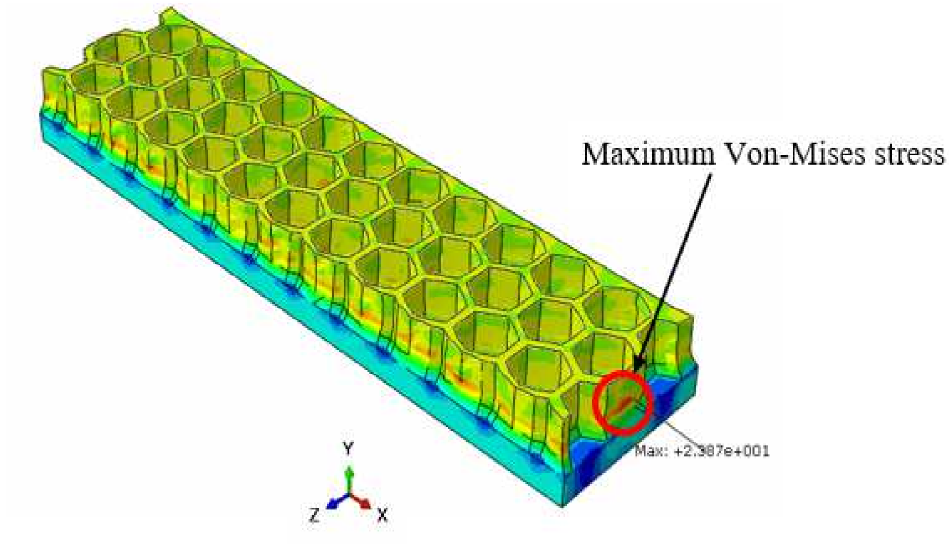


Figure 2.47:Maximum Von-Mises stress region

The optimization of hexagonal honeycomb reports that Figure 2.16 a and b, illustrate the contour plots obtained from stress analysis and optimization for each model that allow us to identify the region where maximum von-mises stress is occurring. Figure 2.17, depicts the maximum von-mises stress region for hexagonal honeycomb core.

2.7 Sandwich construction and experimentation

2.7.1 Construction

Sandwich construction requires three elements such as a pair of facings, lightweight core, and an attachment that will transmit the shear and axial load. Manufacturing through conventional process includes preciseness in application temperature, pressure, and provision of important tools and fixtures to obtain desired shape. However, employing the additive manufacturing technology benefits us from the complexity of manufacturing process. Stratasys patented Uprint machine uses FDM technology to bring the models into real shape. Pinpoint accuracy is obtained due to its highly advanced, powerful and stable platform that deliver to work seamlessly with the CAD software [26]. During printing in the Uprint, the print head extrudes with precision the semi-liquid plastic filament along the surface on which the model grows. Printing direction is analogous for the non-

optimized and its corresponding optimized structures that allow us to infer a comparison between them. Fused deposition method by UPrint ensures that there is no slipping between the core and facesheets. Thermoplastic material ABS (Acrylonitrile-Butadiene-Styrene) is employed to manufacture the sandwich composites. Due to high impact resistance, strength and stiffness, ABS material is frequently used in structural applications. Moreover, good machinability and excellent dimensional stability are important features to produce prototypes. The name of the material identifies its family with versatile performances [27]. Sandwich panels are made of ABS material that is supplied by Stratasys©.

Acrylonitrile: Chemical resistance, heat resistance.

Butadine: Impact strength, toughness.

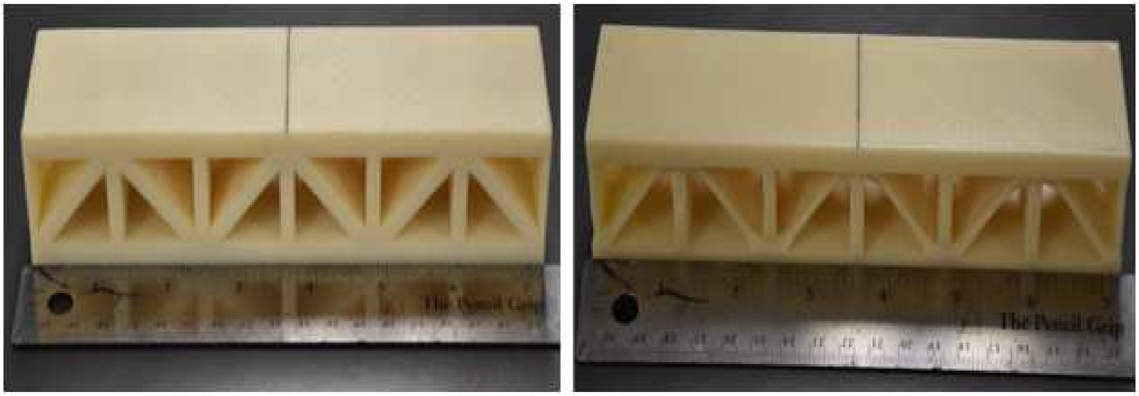
Styrene: Rigidity, mouldability.

Table 2.3: Thickness of core and facesheets

Item	**Thickness (inch)**
Facesheet	0.3
Core	1.0

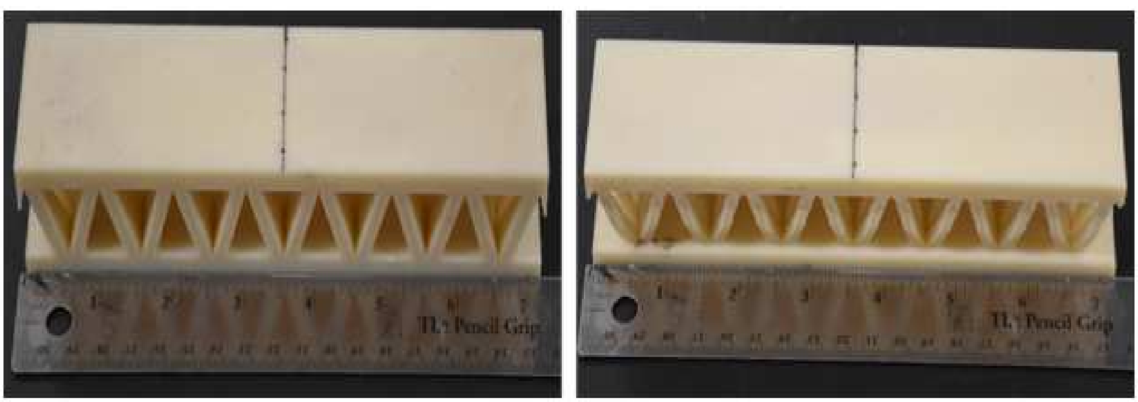
Support material is an important consideration when 3D printing technology deals with the third dimension. Gravity can cause dimensional inaccuracy during printing because the overhanging structures are may fall down due to scarcity of support structures. Support material work as a scaffold paces such that they can hold the structure in correct position. Figure 2.18, 2.19, 2.20, 2.21, are the non-optimized and optimized 3D printed structures for different cores with identical dimension. Thickness of core and facesheets remain same after optimization, as can be seen in Table 2.3, except thickness of the slender members. Since the support material is very difficult to remove by manually so FDM technology offers a special support material that can be dissolved in chemical bath [28]. Although the dissolution process consumes incredibly high amount of time but at the same time it is safe because no handling is required. Moreover, after the

estimated amount of time the sandwich structures are collected from the chemical bath with desired dimensional accuracy.



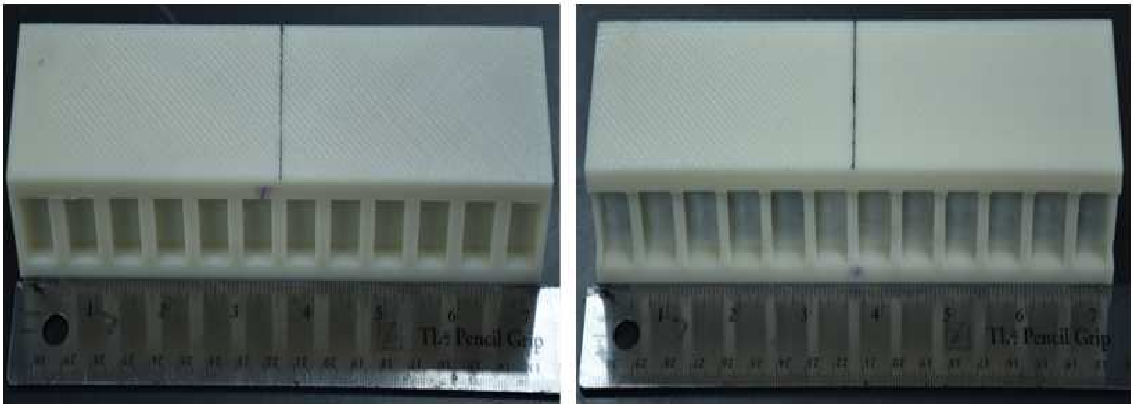
(a) (b)

Figure 2.18: Prismatic core sandwich structures (a) Non- optimized (b) Optimized



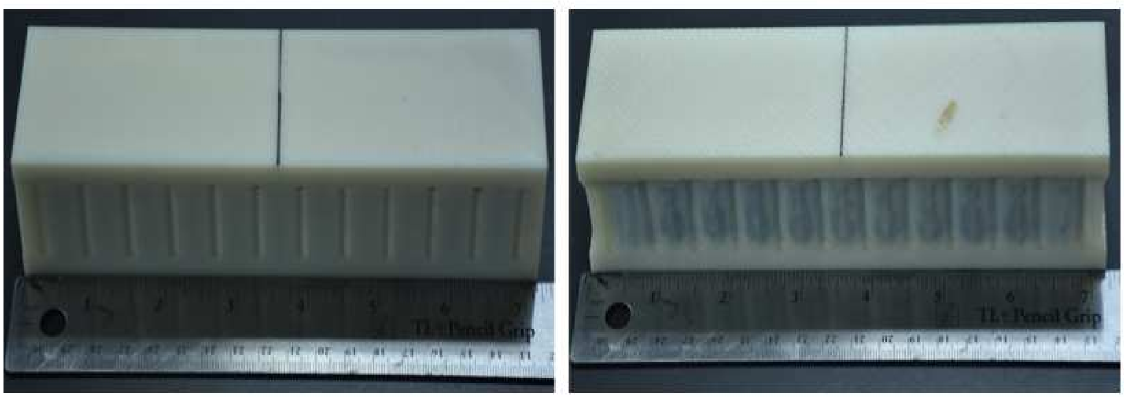
(a) (b)

Figure 2.19: Lattice truss core sandwich structures (a) Non- optimized (b) Optimized



(a) (b)

Figure 2.20: Square honeycomb core sandwich structures (a) Non- optimized (b) Optimized



(a) (b)

Figure 2.21: Hexagonal honeycomb core sandwich structures (a) Non- optimized (b) Optimized

2.7.2 Experiment

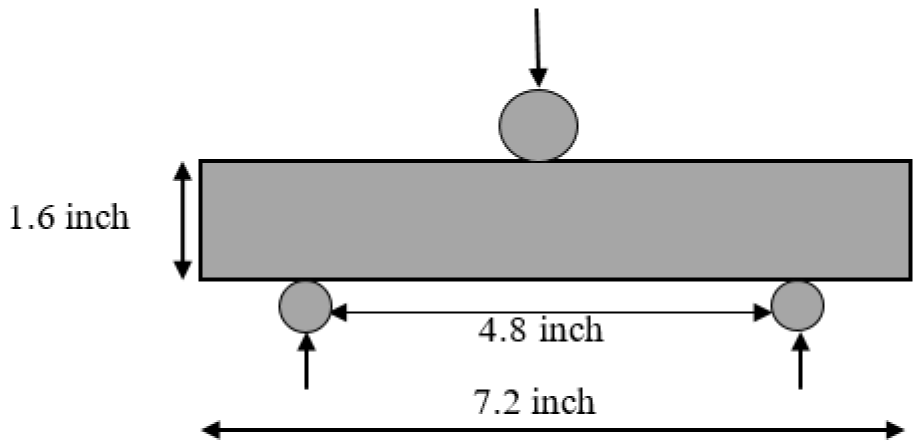


Figure 2.22: Specimen set up

The flexural test is significant to ensure the quality of materials. The process involves the application of a force to a specimen, commonly at the middle section, while being in roller supports. The main idea is how much it can deform and the peak load under out of plane. Different tests available to check the performance of the sandwich panels under concentrated loading such as short beam shear test, three-point bending, four-point bending. Short beam shear test is one kinds of flexural test where flexural strength, flexural stress, peak load, deformation and yield point are the key analysis. Since the length of the specimen is very short compared to the thickness so that this test method can determine the strength of the composite materials when it is placed on three-point loading. A load is applied perpendicularly to the longitudinal axis of a specimen. ASTM standard D2344 for short beam strength of polymer composite materials was used as a guideline to carry out the short beam shear test. Figure 2.22, shows specimen dimension, span to thickness ratio, loading indenter and support roller for the experiment. Before performing any test, the machine was calibrated. Specimen configuration includes consummate geometry such as length, width, and thickness according to the standard. Instron 5969 series machine is used to perform the experiment. Displacement and peak load are monitored using the Bluehill testing software. Moreover, displacements of the central loading point by crosshead relative to supporting

rollers are captured at 10 second intervals as the test progressed by a resolution digital camera. Specimen are placed in a three-point loading system, applying loads through roller of 0.250 inch diameter and supports are 0.125 inch which are provided by Mcmaster-carr©. Both are cylindrical in shape; specimen span to thickness ratio is 4.0. The crosshead speed is kept constant throughout the experiment which is 0.05 inch/min. Figure 2.23, the experimental setup of the short beam shear specimen, the span to thickness ration and loading point.

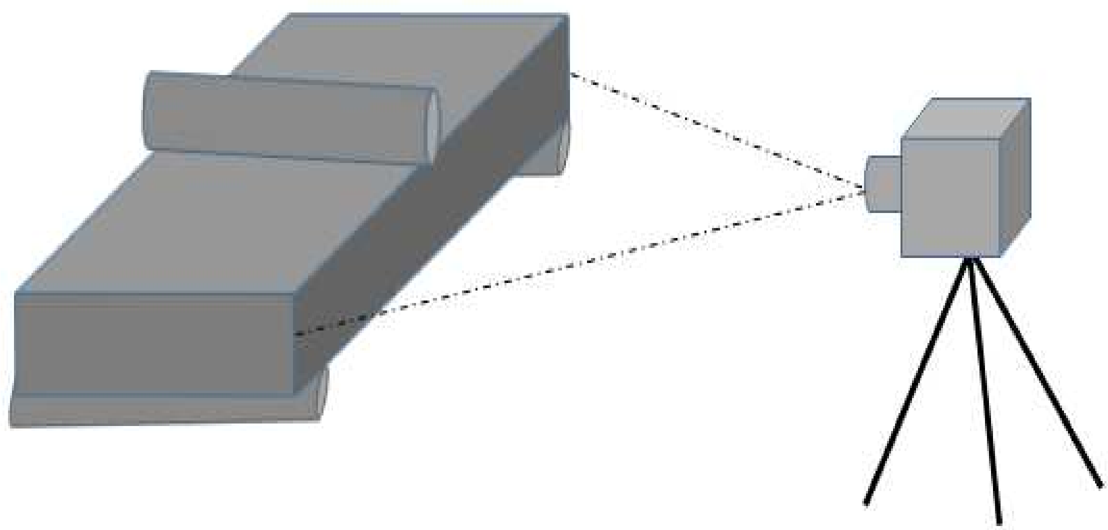


Figure 53: Experimental setup

2.8 Observations

In this section, the experimental results employing the short beam shear test are compared between the non-optimized structures against those structures obtained using the shape optimization. The following synopsis represents at best attempt to compile the information for the four different sandwich panels with different unit cell topologies. For a better approximation, three samples for each model were manufactured to assess the mechanical properties and provide a complete understanding.

2.8.1 Prismatic core

The load-displacement curve can be analyzed using four parameters to describe the deformation stages: the elastic behavior, peak load, crack initiation and propagation stage, and plateau region. It can be noticed that crack initiation and propagation includes two major characteristics: the core failure, and the face sheets yielding. Point 1 corresponds to the elastic stage, point 2 corresponds to peak load, point 3 corresponds crack initiation and propagation stage, and point 4 refers to plateau region.

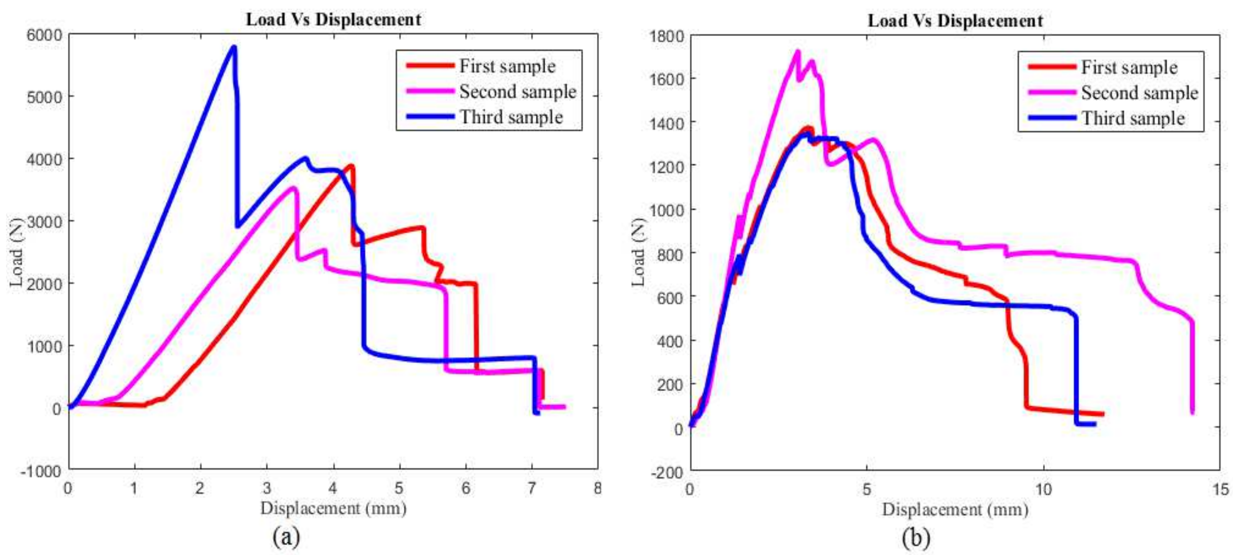


Figure 6: Load Vs. Displacement curve for prismatic core (a) Non-optimized samples (b) Optimized samples

As can be seen in Figure 2.24a, the onset of load-displacement curve for each non-optimized structures are deformed in a linear elastic pattern until a peak load is reached. No load drops are observed up to this point. Afterward, a sudden decrease of loads is seen due to the failing of the strut members in the crack initiation and propagation region; core failure is assumed to start from this point. A progressive increase of load is marked thereafter; this nonlinear region indicates that facesheet yielding commences at a small range along with struts failure. Sudden significant load drops refer to the yielding of the bottom face sheet causing the response to advance into

plateau region. Finally, yielding of the top skin ensures the collapse near the indenter. Slopes in the linear region are determined for each non-optimized and optimized structures that characterize the stiffness in the elastic region. The steepest slope is observed for sample three with respect to other non-optimized structures. Additionally, peak load is considerably higher for sample three. In the case of optimized structures, having a smaller linear region, sample three demonstrates higher stiffness compared to one another. Sample two includes highest peak load corresponding to other curves. On the contrary, it can be observed that from Figure 2.24b as the load increases, the brief linear elastic region succeeded by some minor load drops occur after obtaining the threshold value of plastic regime, owing to the failure of the strut members. Then it reaches the peak load, remarkably lowered due to the shape optimization. Nonlinear advancement along through the third stage follows a progressive decrease of the load that is subjected to the collapse of the core member. After interestingly, the face sheets conveyed the load for a limited time in the plateau region. At this instant, the crack propagates in the top skin quite earlier than the bottom one. For all responses, ultimate failure is characterized by a sudden major load drop causing a cracking sound in the plateau region. Progress in deformation for the optimized samples justify more ductile behavior than the non-optimized samples which display brittleness. Figure 2.25 a and b, illustrate the phase of the third sample for different critical loading points during the advancement of the load-displacement curves.

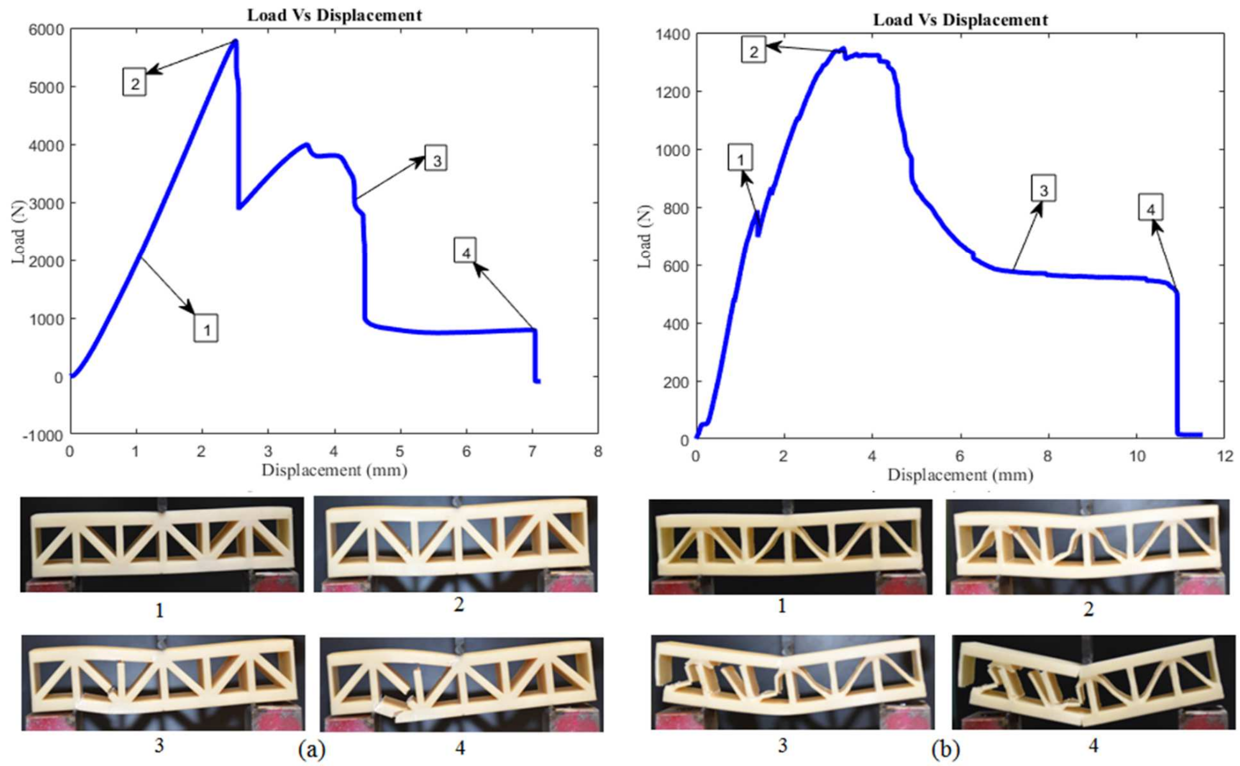


Figure 7: Critical loads with images for third samples (a) Before optimization (b) After optimization.

2.8.2 Lattice truss core

The plots of load against displacement of lattice truss core as depicted in Figure 2.26 a and b, are quite similar in their pattern with the exception of the attainment of peak load and displacement for each panel.

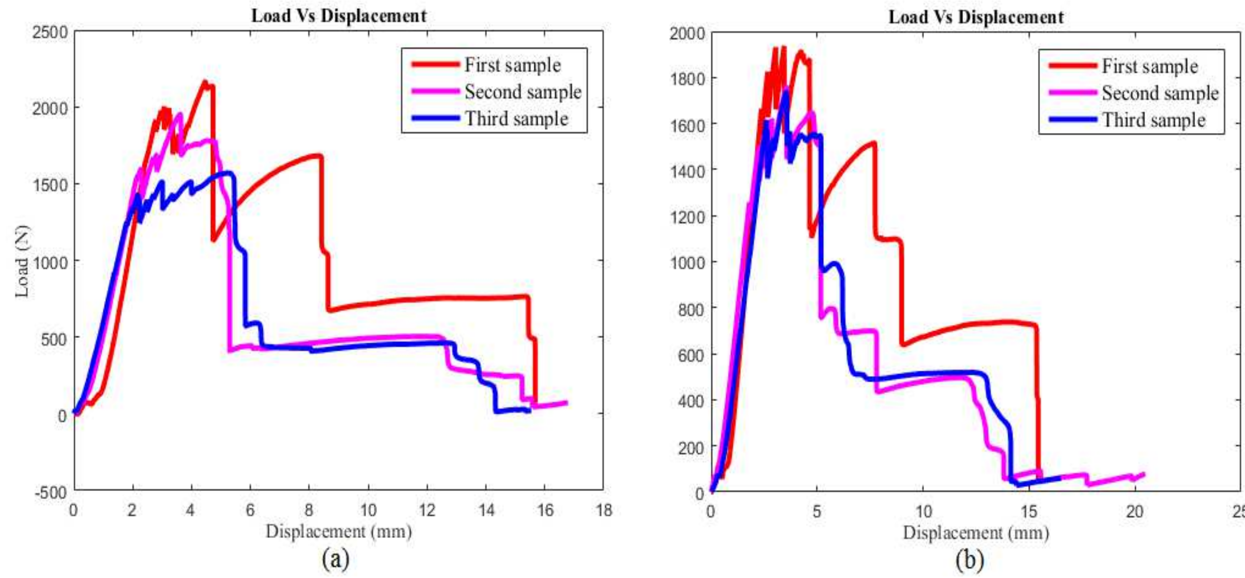


Figure 8: Load Vs. Displacement curve for lattice truss core (a) Non-optimized samples (b) Optimized samples

Different key features can be identified by analyzing the curves. Those are linear elastic behavior (point 1) followed by an elasto-plastic phase that is characterized by some minor load drops(point 2) and this response continue until the peak load (point 3) is reached. Then load decreases suddenly due to the failure of truss core members; during this phase, load is carried by facesheets primarily and then enters into plateau region(point 4) and ultimately crush of the facesheets (point 5) terminate the plastic response. As the load progress, the linear progression of the curves identifies that core truss members carry the flexural load. Gradual failure of the truss members in the core cause minor load drops that proceed up to peak load is achieved. It is noticed that the nonoptimized load-displacement curves represent almost similar slopes in the linear region; first sample is assumed much stiffer than others. It can be observed that the first sample shows highest peak load corresponding to other samples and third sample is the lowest. Major load drop occurs after obtaining peak load that is the indication of core failure. Plateau region display the significance of skins attachment that delivers strength to the structure, while the curves contain a prolonged portion is verifying the skins are carrying the load. Top skin fails much earlier than the bottom one; major load drops in the plateau region identify the facesheets failure and

termination of curves advancement as well. Figure 2.27 a-b, show the images of the structures at different phase, suggesting shape optimization can generate almost similar mechanical properties such as peak load and displamcement with reduced weight.

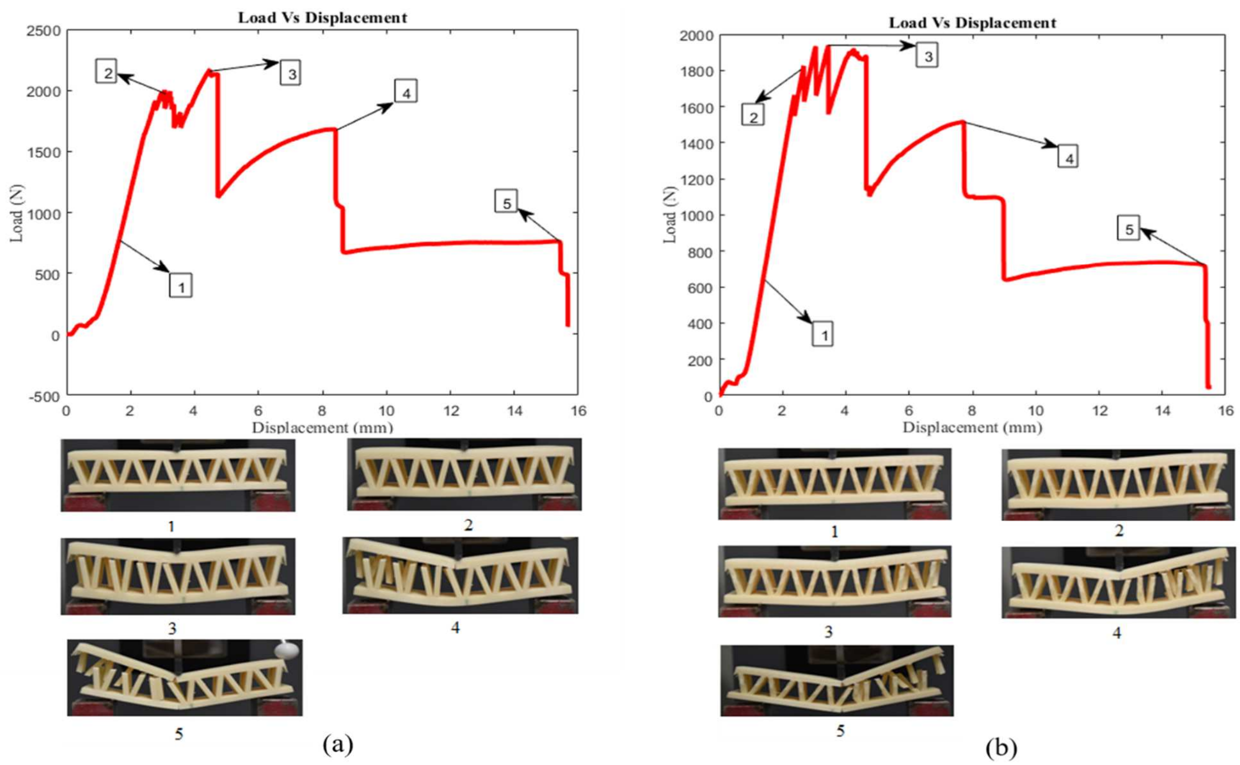


Figure 9: Critical loads with images for first samples (a) Before optimization (b) After optimization.

2.8.3 Square honeycomb

Honeycomb structures are very hard closed cell where the core carries the shear loads and the facings carry the bending load. Three key features are observed during the progression of the curves for square honeycomb cores: the elastic stiffness to describe the elastic response, elasto-plastic stage, and ultimate failure of the structure. Point 1 corresponds to the elastic region, point 2 represents elasto-plastic phase, and Point 3 refers to ultimate failure. It can be mentioned that square honeycomb core carries load linearly at the onset of the load- displacement curve that indicates very high stiffness. As the load increases, the non-optimized responses experience a

trivial load drop while it enters into next stage. Non-optimized structures load carrying capacity reach to a tremendous level that is termed as peak load; right away a sudden major load drop is observed which always coincide with a cracking sound during the test. In all the responses of non-optimized structures, peak load terminates the advancement of the curves. Optimized curves exhibit further deformation is causing the reaction to continues loading beyond the peak load. Figure 2.28 a and b, show the comparison between the non-optimized and optimized samples where sample 3 generates very huge load in either case, sample 2 and sample 3 respectively.

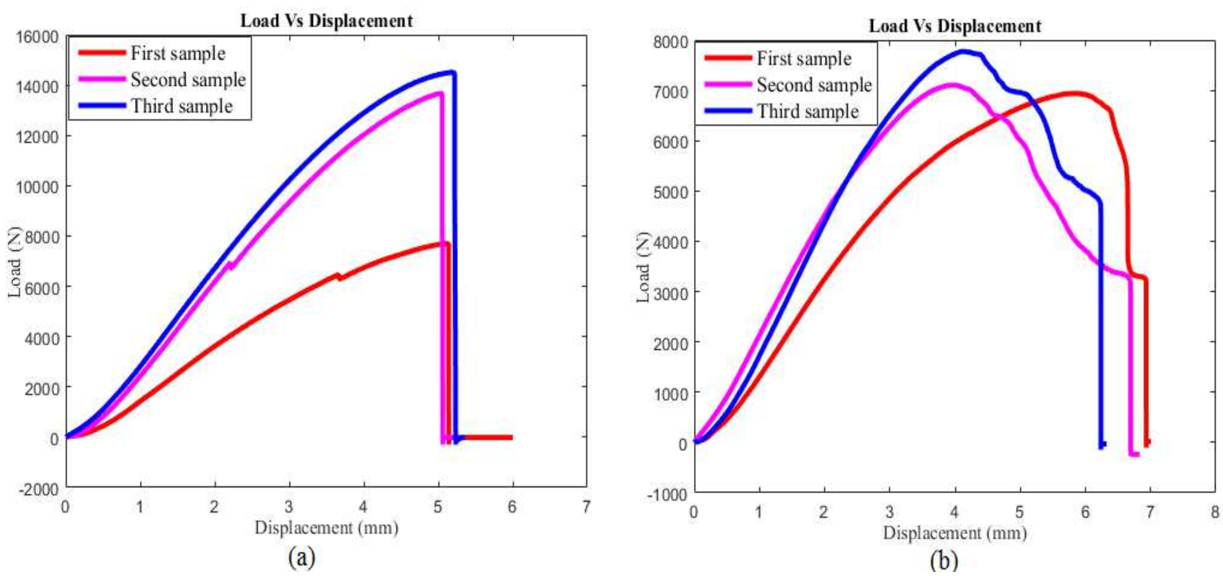


Figure 10: Load Vs. Displacement curve for lattice truss core (a) Non-optimized samples (b) Optimized samples

Figure 2.29 a and b, depict the condition of the second sample at different stages when it is subjected to a short beam shear test. It suggests that initially core material is carrying when it passes through the linear elastic region, followed by the second stage when facesheets carry the load along with core, and finally yielding of the bottom facesheet at the mid-section ensures the failure of optimized structures. The optimized samples failure is identified by creating a crack near the support roller. Shape optimization impart ductility to the composites, therefore, optimized samples exhibit more deformation with reduced peak load and weight.

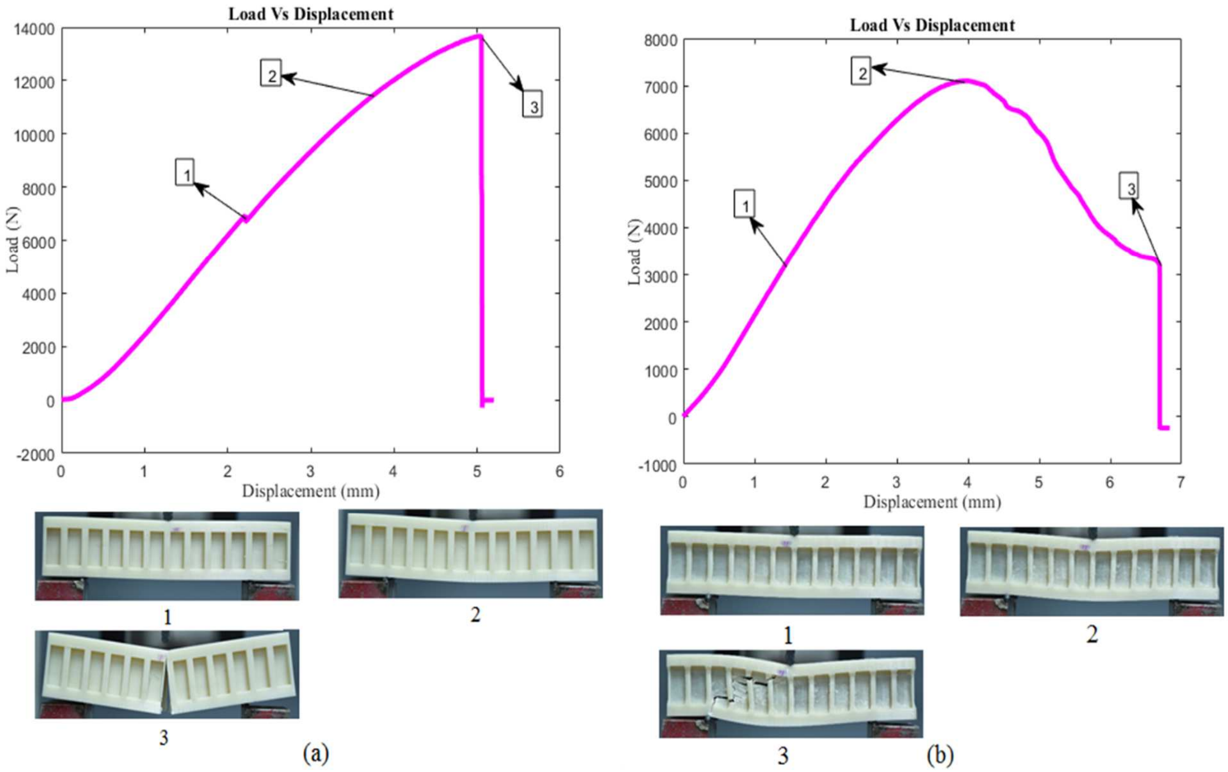


Figure 11: Critical loads with images for second samples (a) Before optimization (b) After optimization

2.8.4 Hexagonal Honeycomb

Characteristic of load-displacement curves for the hexagonal core are presented in Figure 2.30 a and b. In cases of hexagonal honeycomb cores, elastic behavior dominates with specific load-displacement features are as follows: i) Load increases linearly corresponding to elastic behavior where mainly core is conveying the load with considerable stiffness (point 1) ii) Following that a peak value is obtained (point 2) and yielding of the facesheets thereafter.

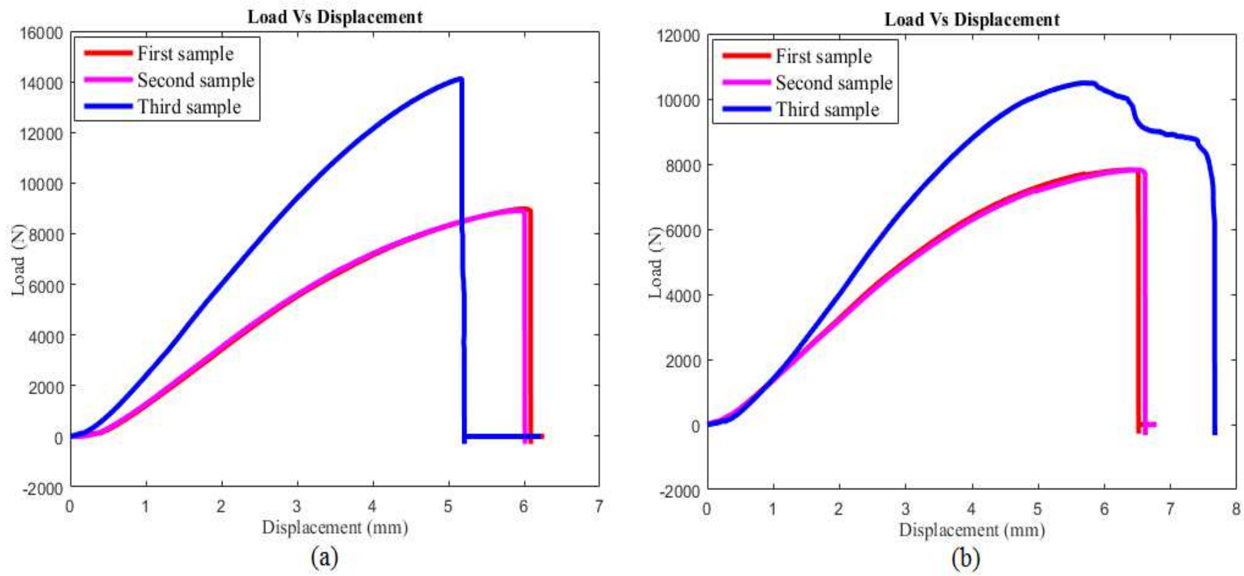


Figure 2.30: Load Vs. Displacement curve for lattice truss core (a) Non-optimized samples (b) Optimized samples

There is no such difference in the failure pattern between the primary and latter configurations. However, one disparity is observed for sample 3 which exhibits peak load, afterward instead of collapse, the load decreases smoothly that corresponds to plastic yielding well beyond the linear elastic regime. This implies that optimized sample 3 displays more ductile behaviour compared to its non-optimized one. Figure 2.31 a and b, illustrate the images of sample 2 at two different critical points, taken during the test, represent the comparison of two configurations. Non-optimized structures can carry load slightly higher than optimized one. On the contrary, deformation also increased slightly for the optimized case. Ultimately shape optimizaiton imaprts high bending stiffness combined with low weight on hexagonal honeycomb core.

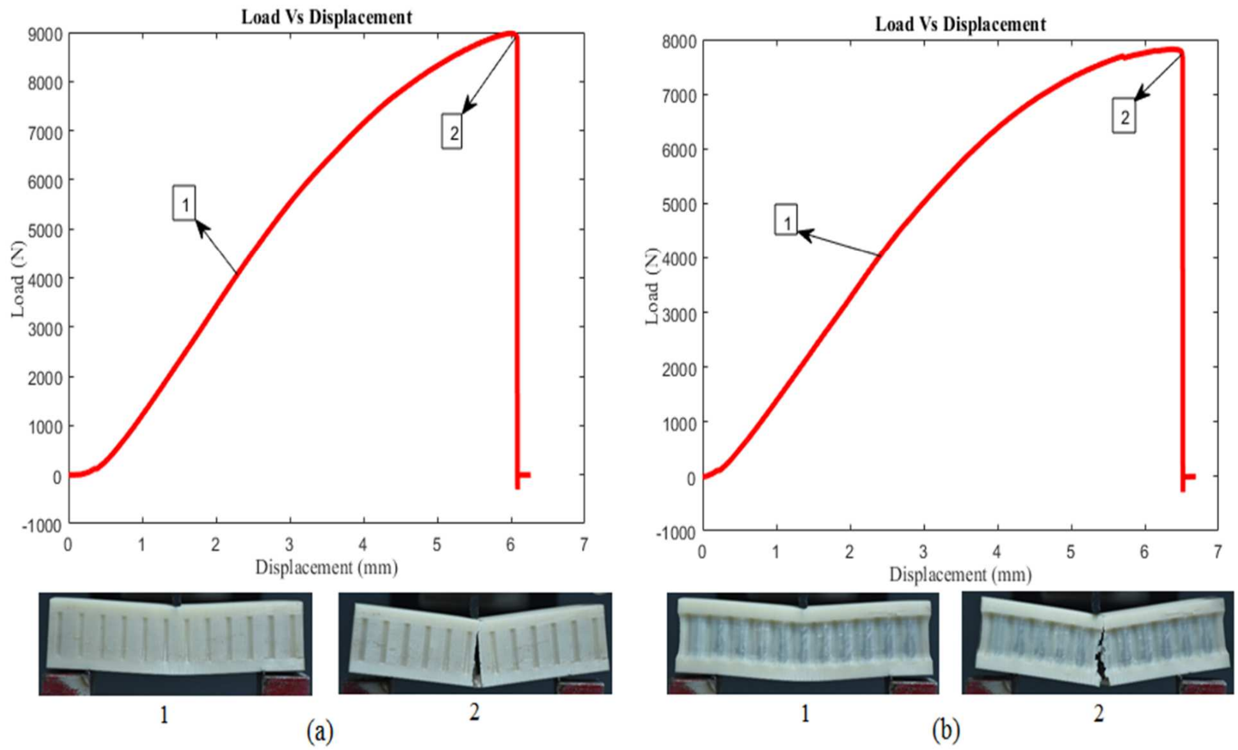


Figure 2.31: Critical loads with images for second samples (a) Before optimization (b) After optimization

2.9 Data analysis

Short beam shear tests performed, under static loading, on ABS sandwiches with identical dimension point out that different peak loads and deformations can be obtained for the same topological structure due to shape optimization. As can be seen from table 2.4, shape optimization reduces peak load drastically for some cores, and at the same time increase the displacement. Comparing the performance of prismatic cores, it is highlighted that peak load drops due to shape optimization for prismatic cores and displacement increase almost twice. It is interesting to note that lattice cores performance is remarkable, because the measured peak loads and displacements are consistent even after weight reduction. Honeycomb cores generates a discrepancy with the previous investigation due to its abrupt reduction of peak loads. This implies that weight reduction affects peak strength adversely and displacements differs slightly with non-optimized case.

Table 2.4: Mechanical properties and average weights comparison of different sandwich cores

Cores	**Sample**	**Before optimization**			**After Optimization**			**Weight reduction %**
		Peak load (lbf)	**Displacement (inch)**	**Average weight (gm)**	**Peak load (lbf)**	**Displacement (inch)**	**Average weight (gm)**	
Prismatic	Sample-1	869.48	0.281	199.33	308.8	0.461	163.49	17.98
	Sample-2	789.17	0.296		387.6	0.561		
	Sample-3	1298.32	0.28		302.58	0.57		
Lattice truss	Sample-1	448.76	0.619	167.34	435.27	0.61	153.27	8.41
	Sample-2	438.44	0.661		395.92	0.793		
	Sample-3	352.64	0.567		390.09	0.568		
Square honeycomb	Sample-1	1730.45	0.202	267.32	1560.29	0.283	215.17	19.51
	Sample-2	3071.85	0.199		1596.94	0.263		
	Sample-3	3260.46	0.206		1747.46	0.246		
Hexagonal honeycomb	Sample-1	2018.06	0.239	261.56	1758.05	0.256	218.43	16.49
	Sample-2	2002.28	0.237		1757.14	0.204		
	Sample-3	3171.7	0.26		2357.98	0.301		

Plastic deformation is remarkable for square honeycombs, even it is small, reveals that the optimized samples can be applicable where both the load carrying capacity and durability are important factors. Performance of hexagonal honeycomb is worth to mention because two of the samples represent a decent load drop and with similar displacements. It is evident that significant improvement is the weight reduction because it rigorously establishes the idea that optimized structures show a very good qualitive and quantitative correlation with the non-optimized cores for homogeneous stress distribution confined in the core of sandwich composites. Table 2.5, summerises the statitscal response for all test samples.

$$F^{sbs} = 0.75 * \frac{P_m}{b*h} \tag{5}$$

P_m = Peak load observed during the test

b = Specimen width, (in)

h = Specimen thickness, (in)

According to ASTM D2344, short beam strength allows us to determine strength of the structures depending on the peak load obtained from the experiments. Since a number of tests are conducted for different cores, so the average value of the strength, standard deviation, and co-efficient of variation can be determined using the following formulas

Average, $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$ (6)

Standard deviation, $S_{n-1} = \sqrt{\frac{\sum_{i=1}^{n} x_i^2 - n(\bar{x}^2)}{(n-1)}}$ (7)

Co-efficient of variance, $CV = 100 * \frac{S_{n-1}}{\bar{x}}$ (8)

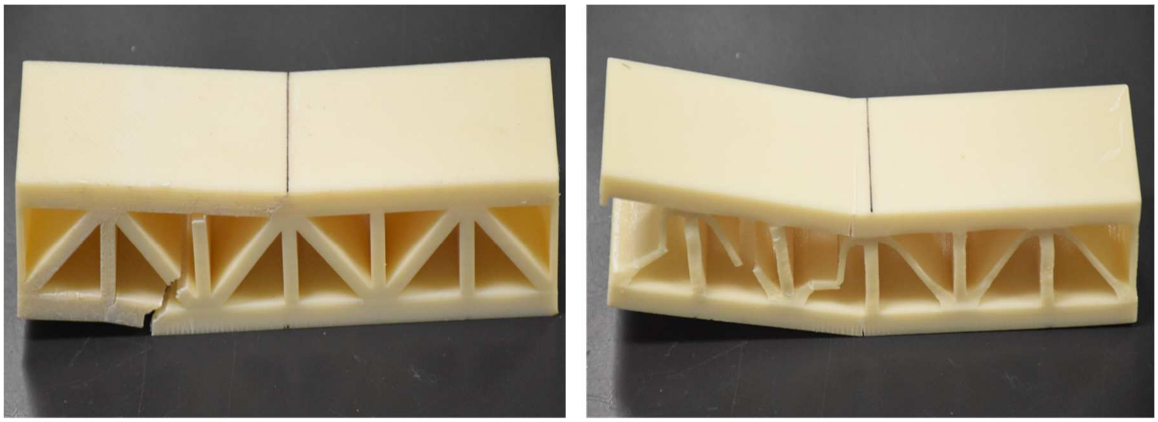
Table 2.4: Statistical analysis based on mechanical properties

Before optimization				After optimization			
Strength	**Average**	**Standard deviation**	**Co-efficient of variance**	**Strength**	**Average**	**Standard deviation**	**Co-efficient of variance**
221.505				78.668			
201.0453	251.101	69.736	27.772	98.743	84.832	12.074	14.232
330.754				77.0839			
114.324				110.887			
111.695	105.285	13.443	12.768	100.863	103.709	6.261	6.037
89.837				99.378			
440.842				397.492			
782.570	684.677	212.530	31.041	406.829	416.499	25.269	6.067
830.619				445.175			
514.112				447.873			
510.092	610.737	170.853	27.975	447.641	498.741	88.307	17.706
808.008				600.708			

2.10 Discussion

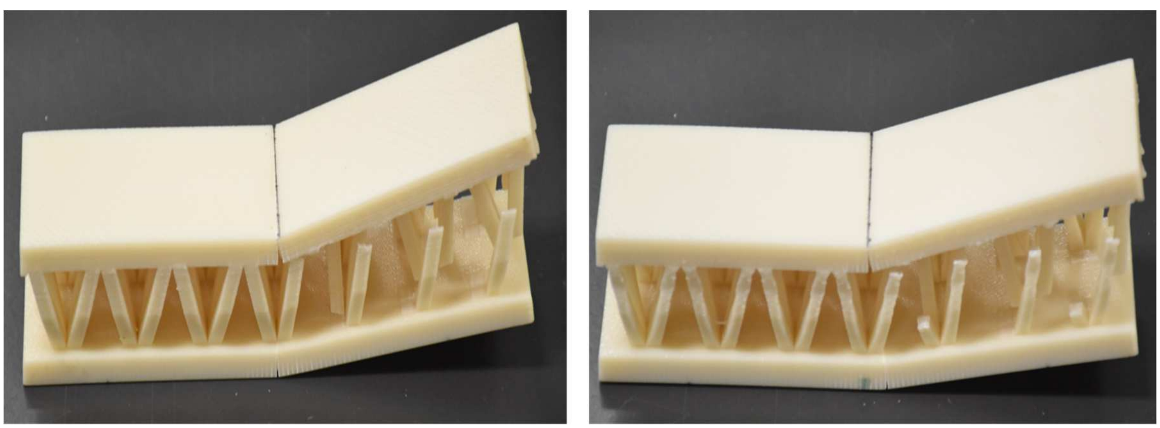
Observation and data analysis results demonstrate the performance of sandwich beams, suggesting that the weight saving technique incorporated some unique features by altering the shape of the structures. Overall performance of these sandwich panels depend on the core strength, topology, and geometrical dimensions. Note that, core strength governs the peak load, enables energy absorption, controls the failure modes for different type of topologies and geometrical shapes. Depending on the loading behavior the initiation and propagation of failure modes are investigated. Possible failure modes include core failure, facesheet failure, global buckling. Core failure is a common failure mode in sandwich composites under short beam test where test specimen are placed on a three point loading. Initially core carry the shear loading, failure occurs when the maximum shear stress reaches the shear strength. Facesheet provides the reinforcement to the cores and carry the bending loads. During bending, facesheets may fail since compressive force is acting on the top facesheet and bottom facesheet experience tensile force. The failure criteria reveal that the sandwich beams may undergo a mixed failure mode such as core shear initiates the core failure, later facesheet failure causing the complete failure of sandwich structures. Figure 2.32, 2.33, 2.34, 2.35, illustrate the failure modes for the non-optimized and optimized samples. Failure of prismatic cores follows core shear macro buckling. The sharp drop of load is identified when the core fails due to shear and later buckling of the facesheets. Lattice truss cores failure is governed by a combination of core shear buckling and debonding of the struts from the facesheets. Debonding of the strut members decrease the load carrying capacity of the sandwich panels. Therefore, peak load is always observed before the core failure. Non-optimized square honeycombs experience global buckling and optimized sample undergo core shear failure. Optimized hexagonal honeycomb samples reveals a discrepancy in their failure mode. Sample three fails by core shear macrobuckling and remaining global buckling ensures the failure of remaining two samples. Load vs displacement response evidences the difference of the failure

modes for optimized structures. Non-optimized samples ensure failure by global buckling of the structures.



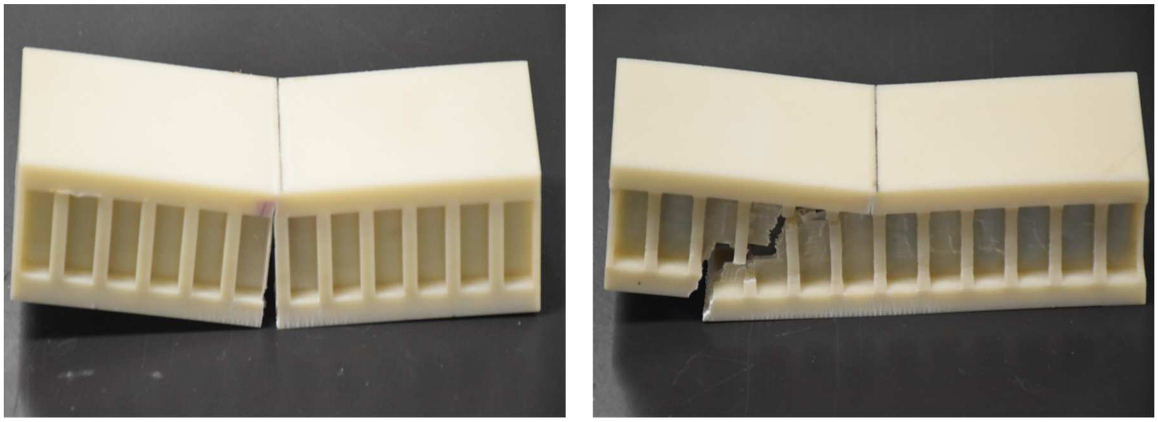
(a) (b)

Figure 2.122: Failure of prismatic cores (a) Non-optimized (b) Optimized structures



(a) (b)

Figure 13.33: Failure of lattice truss core (a) Non-optimized (b) Optimized structures



(a) (b)

Figure 2.34: Failure of square honeycomb core (a) Non-optimized (b) Optimized structures

(a) (b)

Figure 2.35: Failure of hexagonal honeycomb core (a) Non-optimized (b) Optimized structures

2.11 Conclusion

Three-dimensional geometry is developed for all sandwich beams and incorporated into the commercial FE software, ABAQUS, to conduct the stress analysis and optimization. The behavior of all sandwich panels subjected to displacement boundary conditions is investigated at first. Later shape optimization technique is introduced to obtain better performance by homogeneous stress distribution and reducing consumption of material. A series of experiments have been conducted on the non-optimized and optimized sandwich panels to evaluate mechanical properties such as peak loads and deformations. To perform a meaningful comparison from the

weight standpoint, it is important to demonstrate the weight difference of the non-optimized and optimized structures. Comparison of the load vs. displacement curve demonstrates that the optimized structures vary significantly due to their plastic behavior which enhances durability. There are several compelling reasons, why the structures are considered isotropic material. Properties of orthotropic material are direction based, so stress analysis requires Young Modulus and Poisson ratio in three principal directions. It should be mentioned that determination of Young Modulus along three directions includes various steps. In this paper, isotropic structures are placed on three-point loading subjected to through thickness direction later Young Modulus is determined by trial and error method for a particular structure. With respect to orthotropic materials, more experiments are needed to perform to obtain the structural properties that lead us to determine material properties. To avoid this complexity linearly elastic isotropic material is a good option to evaluate the feasibility of polymer additive manufacturing process in constructing optimized sandwich structures. Finally, investigation of failure modes of different sandwich structures reveals that shape optimization technique-importing some unique features to the core that cause it to behave nicely. Although polymer sandwich structures are not popular yet in manufacturing industries but this novel approach signifies that depending on the loading capacity these structures can be employed to obtain better mechanical performance. Some conclusions can be drawn from this study which will provide special guidance to design sandwich structures:

(1) Generally speaking, weight gain of the sandwich panels enable them to sustain more load. However, although the optimal shape of the core plates and strut members reduces stiffness for some structures at the same time it reduces weight and enhances mechanical properties.

(2) In this study, four different core topologies are explored and experimented to justify the acceptance of shape optimization process. It refers that any topological pattern in the sandwich core is competent to apply design optimization.

Chapter 3: Structural truss optimization by finite element analysis and genetic algorithm method

3.1 Introduction

Truss structures are normally slender members joined together at their ends, having triangular and pyramidal shapes and used extensively in bridges, platforms, towers, and other structural applications. Few reasons behind the prevalent use of trusses are light weight, small deflection compared to other plain members, long span, and carry considerable loads. The members of a truss are connected at joints in a manner that permit rotation, and the individual structural members act as bars, i.e. structural members that can only carry axial force in either tension or compression [29]. The main objective of this chapter is to utilize genetic algorithm effectively and optimize different parameters of a truss structure. Genetic algorithm can be used to minimize the total weight of a structure by optimizing the area, stress etc. in the members.

A recurring challenge in structural optimization is to ascertain a design of the structure that can carry maximum load as well as provide both the longevity and strength. Structure in mechanics defined by J. E. Gordon is "any assemblage of materials which is intended to sustain loads" [30]. On the contrary, optimization means making the most effective use or finding the best possible result for a problem. Thus, structural optimization means a perfect design of any assemblage of materials that carry loads in an efficient way. Many methods have emerged in the last few decades for the development of structural optimization. Algorithms, like genetic algorithm, mimics natural process can be employed in the structural optimization technique. In case of complex truss structures, finite element analysis is used to determine the deformation and stresses in structures. In this paper, both genetic algorithm and finite element analysis are used to optimize truss structures. Genetic algorithm, similar to nature, is a set of possible solutions, and they compete with each other for propagation. It is mainly based on the idea of evolutionary algorithm, avoiding any kind of anticipation of the mathematical model. Darwin's theory, the striking concept of the evolutionary theory eventually inspired the genetic algorithm invented by John Holland (1960)

and was further developed by Holland and his students at the University of Michigan [3]. Adaptation is a phenomenon which is occurring simultaneously in nature and can be imported into a computer system. Genetic algorithm exhibits the basic concept of evolutionary algorithm and has different operators that create a possible solution set instead of only one solution. Now-a-days genetic algorithm is ubiquitous and different areas within solid mechanics, such as structural optimization, multiscale materials modeling, creep detection methods are utilizing this algorithm extensively.

3.2 Motivation

Structural optimization involves the efficient and inexpensive design of truss structures while satisfying all conditions of the design criteria. Optimization of trusses can be executed to obtain the minimum cost of a truss structure by using less material while minimizing the weight of the whole structure. In this paper, the main intention of studying truss structures is for the structural optimization of sandwich structures. This lightweight core, shown in Figure 3.1, can be replaced by a truss structure.

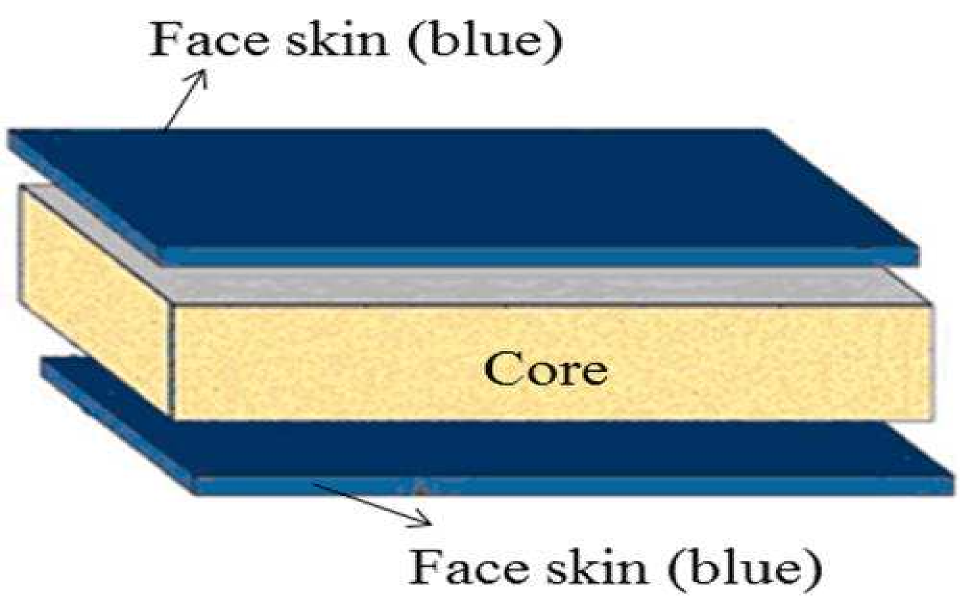


Figure 3.1: Sandwich structure [31]

Truss is a structure that consists of straight bars joined together at their ends called nodal points. Trusses are subjected to tensile or compressive normal forces when loads are applied on the truss structure. Analysis of truss structures gives us the stresses in the members and deflection of each member due to external loads. Stresses in these members inversely depend on their cross-sectional area. That is, stresses increase when the area is reduced, and vice-versa. These members need to be designed such that their stresses are within the allowable stress for the material. Truss optimization based on design varaible can be divided into three categories: 1) Sizing 2) Configuration or shape 3) Topology. For instance, in sizing optimization cross-sectional area is the design variable and the nodal coordinates and connectivity between the members are fixed, whereas nodal coordinates are the main variable in configuration optimization. For topology optimization, design variables are number of nodes and connectivity between the nodes. There are different kinds of truss structures, such as tetrahedral, pyramidal, diamond textile etc. Pyramidal lattice truss core is showin in figure 3.2. Stress analysis with genetic algorithm optimization for an unit cell of the truss structure gives a general idea about the behavior of the the entire structure. Figure 3.3, shows a general two dimensional truss structures. A repeating unit cell of a truss structure is shown figure 3.4, which is analyzed using FEA and optimized using GA in this paper. The unit cell is comprised of three different bars namely AC, BC, and AB; lengths and cross-sectional area vary from bar to bar. The AC, BC, and AB bars cross- sectional areas are consecutively 0.0065 m^2, 0.0077 m^2, and 0.0097 m^2 whereas the lengths are 19m, 29.07m, and 22m. Different types of structural supports are there for the truss structure and each of them is employed for certain purpose. Point A involves pin support, subjected to restrain the displacement both the X and Y directions. Point B is assumed to be capable for restrain only the normal displacement. An external load of 689.48 MPa is acting at point C and P is representing the external load.

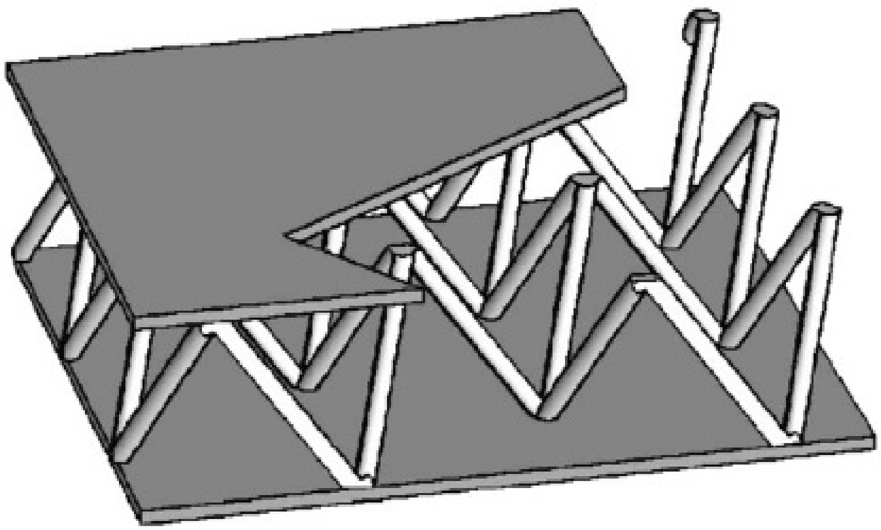


Figure 3.2: Tetrahedral lattice structure [18]

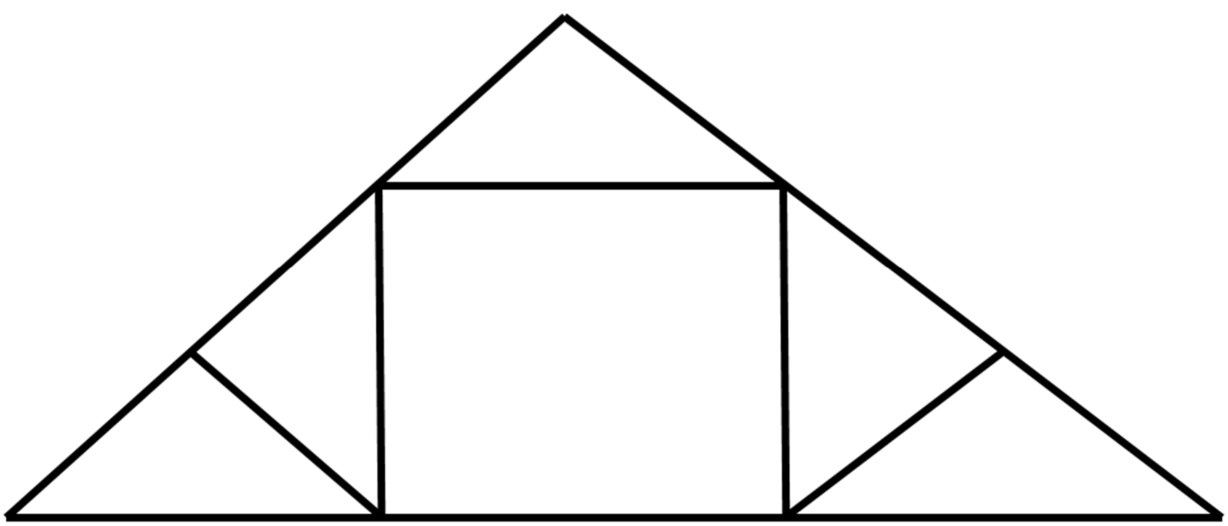


Figure 3.3: 2DTruss structure

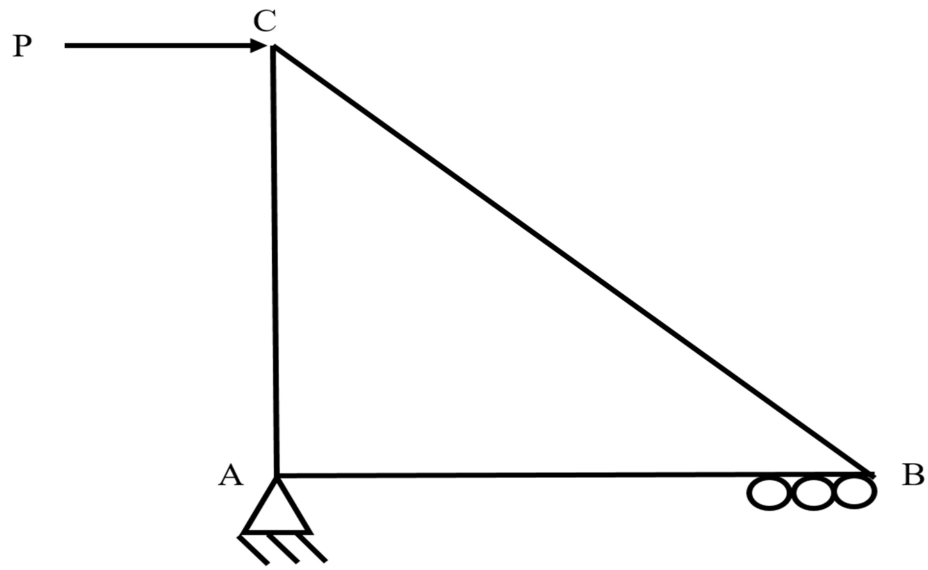


Figure 3.4: Unit cell of a truss structure

3.3 Genetic Algorithm

Genetic algorithm is an evolutionary algorithm which is population based metaheuristics that uses stochastic method. The term stochastic means that the possible solution are random and always create a set of possible solutions unlike deterministic solution. Genetic algorithm consists of the following items:

3.3.1 Chromosomes

A genetic algorithm is expressed by an array of binary bits, which is either 0 or 1, and the length of the array depends on the number of parameters. This array is also called chromosomes. In nature, each chromosome is responsible for certain characteristics, and the bits also contain certain characteristics. So, the main concern is the selection of these parameters. Before selection of the parameters, fixing the objective function, the key factor of genetic algorithm is need to import and by which fitness function can be evaluated. The objective function clears the idea of a number of parameters and there is a certain range for each parameter.

3.3.2 Population

Population is the possible solutions which are the genotype, they compete with each other to be selected for further operation. Each competitor of a population is called individuals and it is a static object whereas population is adapting always. Population may have a spatial structure where the structure is defined clearly to specify a population. The size of the population does not change during the operation, but the parent selection and survival selection affect the individuals considerably. The best individuals are selected for the next evolutionary operation and the worst individuals are replaced by the new one.

3.3.3 Fitness value

Fitness function is also called the evolution function, representing the requirements of the adaptation. More accurately, the fitness values of different population delineate the improvements or declination. Typically, in different optimization problems, the objective function and the fitness function are identical. Since genetic algorithm performance is determined by the convergence rate, fitness value is an unavoidable part to carry out the whole process.

3.3.4 Selection

Six different types of selection methods are there to select the individuals and create offspring. The Roulette wheel selection (RWS), the stochastic universal sampling (SUS), the linear ranking selection (LRS), the exponential rank solution (ERS), the tournament selection (TOS), the truncation selection (TRS) are six different methods. Loss of diversity, selection variance, and selection intensity are three important factors of different selection methods.

Roulette Wheel Selection

Roulette wheel selection or stochastic sampling with replacement is based on the fitness value of each individual. The probability of individuals is directly proportional to the fitness value, which means each individual can occupy an area in the roulette wheel and the fittest individuals eventually occupy largest area in the roulette wheel. The circumference of the roulette is assumed

as the summation of all fitness values. The probabilities of each individual are determined by the total fitness value and then cumulative probability is determined.

$$p_i = \frac{f_i}{\sum_{j=1}^{n} f_i} \tag{9}$$

A bunch of random numbers equal to size number of individuals in a population is generated to find the minimum difference between the random number and cumulative probability. The roulette wheel is divided into different segments and after one full spin the pointer points to one of the segments, most probably the widest segments. So it is clear that the chance of selecting an individual for following operation is proportional to the width of the segment. The main advantage of roulette wheel is it maintains the diversity by considering each individual is competent for selection. Although there is more chance to select an individual which has more fitness value, it restrains itself not to discard the chance of selection any of individuals in a population.

Stochastic universal sampling

Stochastic universal sampling (SUS) developed by Baker is a single phase sampling algorithm with minimum spread and zero bias [32]. This is a multiple selection pointer instead of single selection which process is followed in roulette wheel. It is clear that there are multiple pointers which can select multiple individuals. Normally, there are n pointers and also main 1/n space between them. These equally spaced n pointers take place on a line and select n individuals.

Linear ranking selection

The name represents that ranking is the main concept of linear ranking selection. In this process, the individuals are sorted according to their rank. As observed before, the more the fitness values the greater chance of selection. Similarly, the rank highest is assigned to the best individual and lowest rank assigned to worst individual. For instance, the rank n is for highest one and 1 for the lowest one.

Exponential rank selection

Like linear ranking selection, exponential ranking selection also follows the same rule in sorting the individuals. But the main difference of these two selection processes is the probabilities of the individuals are calculated exponentially.

Tournament selection

Tournament selection is one of the most popular selection methods due to its simplicity. A certain number of individuals are selected randomly from a population and those individuals compete to get selected for next operation. Obviously the individual with highest fitness value win this competition. Tournament selection process also maintains the diversity by creating chance for each individual whatever the fitness value is. Tournament selection is efficient because it has no complexity of sorting the individuals, and low susceptibility of stronger individuals.

Truncation selection

Truncation selection is often used by breeders from a large population. The main parameter of truncation selection is the truncation threshold *trunc*. In this case, a certain number of individuals are selected as parents, the values ranging from 50%- 10% and remaining individuals are not counted. This method is not popular because it may discard one or more eligible individuals. When the population size is large then it may play a greater role.

3.4 Genetic operators

The performance of genetic algorithm depends on its operators considerably. Crossover and mutation are two main basic operators that help the mating parents to create offspring and converge the solution. Crossover is called convergence operator and mutation is the divergence operator. There are many ways to perform crossover and mutation.

3.4.1 Crossover

In the real world, new offspring are created when two mating parents exchange their genes. Usually, the mechanism is chromosomes of mating parents are split in one or two random positions and swap their genes with each other. In genetic algorithm, mating parents carry the array of binary

bits and random numbers are generated to fix the position of being swapped. Single point crossover, N point crossover, uniform crossover, flat crossover are four different kinds of crossover operator.

Single point crossover

In this case, a random position is created and two mating chromosomes are divided into right and left sections. The offspring creation specially performs by swapping operation. The range of random numbers depend on the population length. The binary bits before this position of first parent and every bit after this position of second parent are copied by the offspring 1. Similarly, in creation of offspring 2 also followed by this process.

N point crossover

Instead of one point, N points are chosen to fix the position in the binary array. N point crossover creates three portions for a single chromosomes and the second portion is assumed to be swapped.

Uniform crossover

For uniform crossover, each position is carrying a certain probability and swapping occurs randomly. The mechanism is, for each bit whether first parent or second parent contribute to create new offspring. If a certain number position of the first offspring carry the bit of the second parent, then the same position of next offspring carries the bit of the first parent.

Shuffle crossover

Before swapping, each parent chromosome is shuffled which means binary bits of parent chromosomes change their position randomly. Subsequently they create a random position for swapping and the created offspring are also shuffled back to their previous position.

3.4.2 Mutation

Mutation is the divergence operator of genetic algorithm used to maintain genetic diversity. Like biological mutation, it normally changes one or more bits from its initial state. Usually, the

probability of mutation for all bits in a chromosome is the same. Random number generation helps to implement the mutation operator effectively. Mutation helps to avoid the local minima's trap which could trap the algorithm in local minimum. The probability of mutation is lower than the probability of crossover because it may diverge the solution. So a small probability of mutation ensure ergodicity and well stocking. There are many different forms of mutation which are discussed below:

Twors Mutation

In this mutation operator, two random bits are chosen to be mutated in a chromosome.

Parent 1: A B C D *e f g h*

Child 1: A B C h e f g *D*

Center inverse mutaion

In this case, chromosome are divided into two sections and mutation is obtained in the offspring by switiching their position of the two sections.

Parent 1: A B C D e f g h

Child 1: e f g h A B C D

3.6.3 Reverse sequence mutation

A random sequence is chosen limited by two positions and the new generation contains the reversed sequence.

Parent 1: A B C D e f g h

Child 1: A e D C B f g h

Throas mutation

A random sequence is chosen for mutation, the first and the consecutive two bits after the first bit of the sequence can switch their position and create a new offspring. The first bit takes second postion, the second bit comes to the last position and the last bit becomes the first bit.

Thrors mutation

Similar to throas mutaion, in this case a random sequence is chosen, but it is not mandatory that the remaing bits are the successors of the first bit. It could be any couple of bits after the first bit [33].

3.7 Evolution strategy

There are different kind of evolution strategies to select the parents for the following generation from the children created from the previous generation. It has a great importance in the genetic algorithm because sometime it may happen that the best chromosomes are selected as parents for the next generation. If the best chromosomes are not selected for the further propagation then it might degrade the performance of the genetic algorithm. To avoid this problem best chromosomes are copied for the next generation and then the rest chromosomes follow the same strategy. Four different kinds of selection strategies are there:

3.7.1 P, C strategy

After mutation P parents create C offsprings. Fitness value is the main criterion to measure which offsprings are best. So fitness value calculation for each C children and sorting of them give us a clear idea about which are selected as parents. All individuals are sorted by according to their fitness value and P individuals are selected.

3.7.2 P + C strategy

P parents create C children after mutation and in this case the best P and C chromosomes are selected for the next generation parents. P and C are sorted according to the fitness value and best chromosomes are selected.

3.7.3 P/ R, C strategy

In this case, P parents create C children after crossover and mutation. For each individual of the C children fitness value is calcualted and then sorted. So the best P individuals are selected. The main difference between P, C strategy and this strategy is crossover operation.

3.7.4 P/ R+ C strategy

For this strategy it almost follows the same rules of P+ C strategy except the use of crossover. After crossover and mutaion P parents create C offsprings and then all individuals are sorted according to their fitness value. Finally, form the sorted P and C indviduals P parents are selected for next generation parents [34].

3.8 Stress analysis

For structural optimization problem, a commercially accredited simulation software (ABAQUS) is used to perform stress analysis Material properties are required to plug in into ABAQUS to carry out stress analysis.

Density = 2786 Kg/m^3

Young Modulus = 200 GPa

Poission Ratio = 0.3

Allowable stress = 172 MPa.

Since, the main variable assumed is cross- sectional area in sizing optimiztion, all of the other variables remain constant. Area is related to the internal load and the allowable stress.

$$A = \frac{F}{\sigma} \tag{10}$$

Before incorporation of the genetic algorithm, stress analysis needs to be carried out on the unit cell to get the stress in each bar (element). For this unit cell, an external load is applied to the nodal point C, a pin support on the nodal point A and roller support on B. ABAQUS gives us the stress for each bar element and the corresponding deformation. Stresses for each bar is important to identify which bars are in tension or compression. The stress generatioin in a bar indicates whether the bar is exceeding the allowable stress or still has capability to carry more stress. The area is different for each bar, and hence, the calculation of the weight of the total cell depends on the differnet cross- sectional area of different bars. Here, the stress contours and deformation along X and Y axes are given. The red color represents the highest stress and deformation of the bar and

blue color the lowest values. Two different trials are shown here to obtain the maximum stresses acting on each bar and to check whether it exceeds the allowable stress. Flow charts usually manifest the total process of an algorithm; here figure 3.5 shows the methodology of this optimization process. Unless the finite element analysis(fea) and genetic algorthm satisfy the stopping criterion, several trials will be carried out to obtain the optimized results.

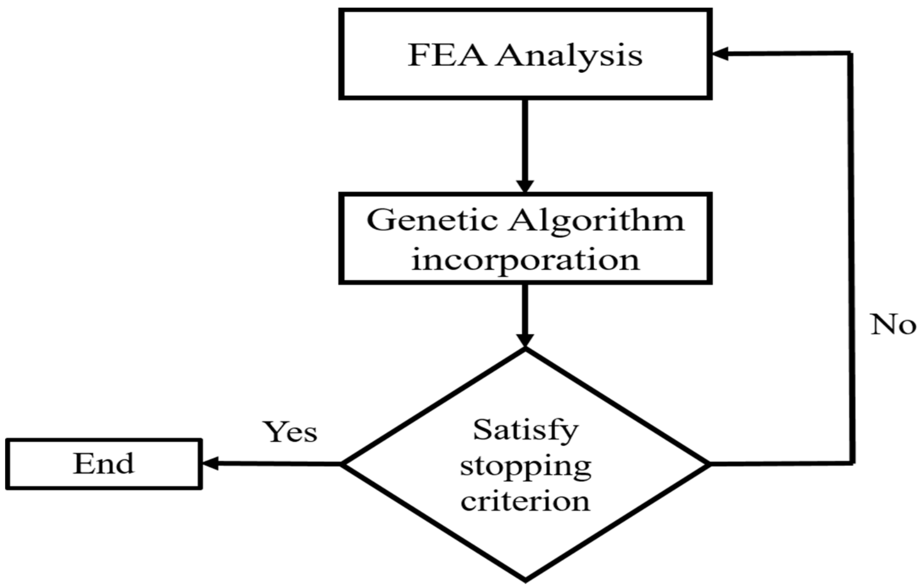


Figure 3.5: Flowchart of methodology

3.8.1 First trial

In the first trial, the values of initial cross sectinal areas, lengths, and external load of 689.48 MPa are taken to perform the stress analysis in ABAQUS. On the contrary, genetic algorithm use the stresses only and give us the area as well as total weight. Figure 3.6 shows the stress along the bar AB, AC, and BC. Finite element analysis divide the unit cell into three diffeent nodal points and elements.

Axial stress

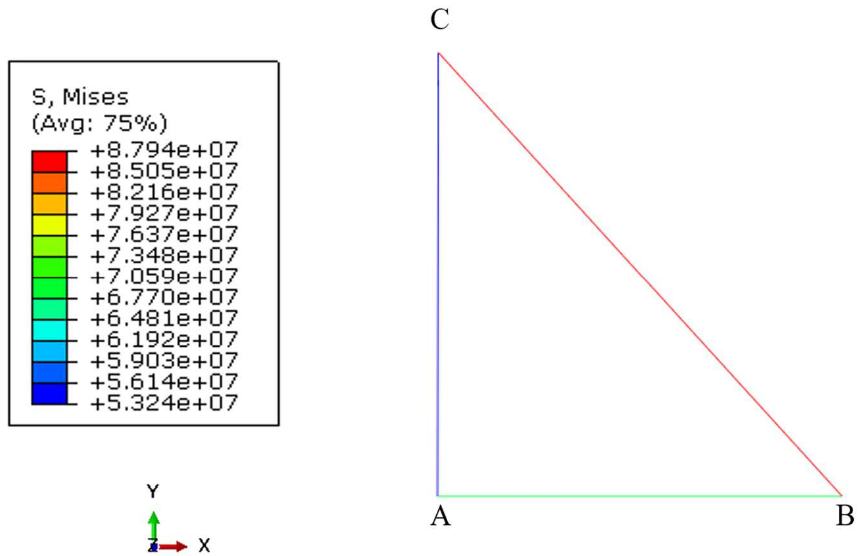


Figure 3.6: Axial stresses along three bars

Deformation

Deformation along the X and Y axes are shown in figure 3.7 and 3.8.

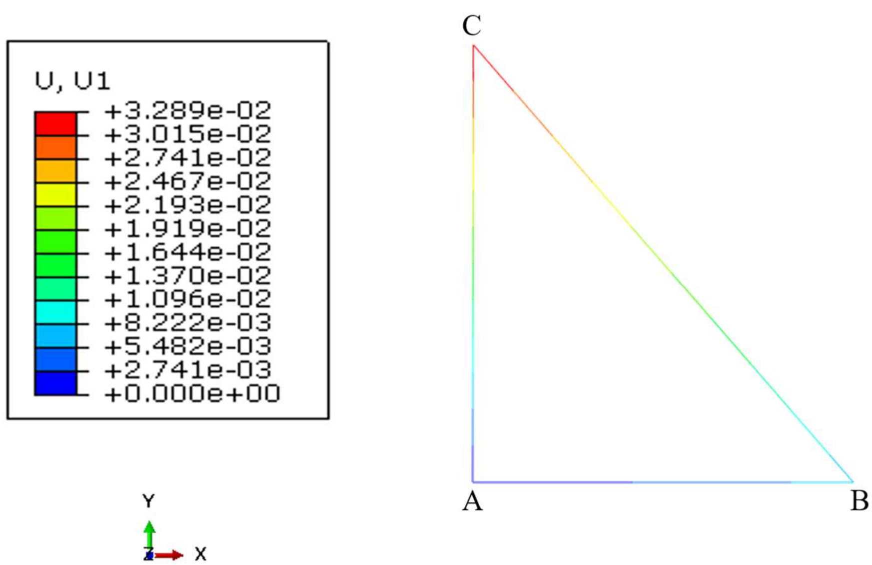


Figure 3.7: Displacement along X axis

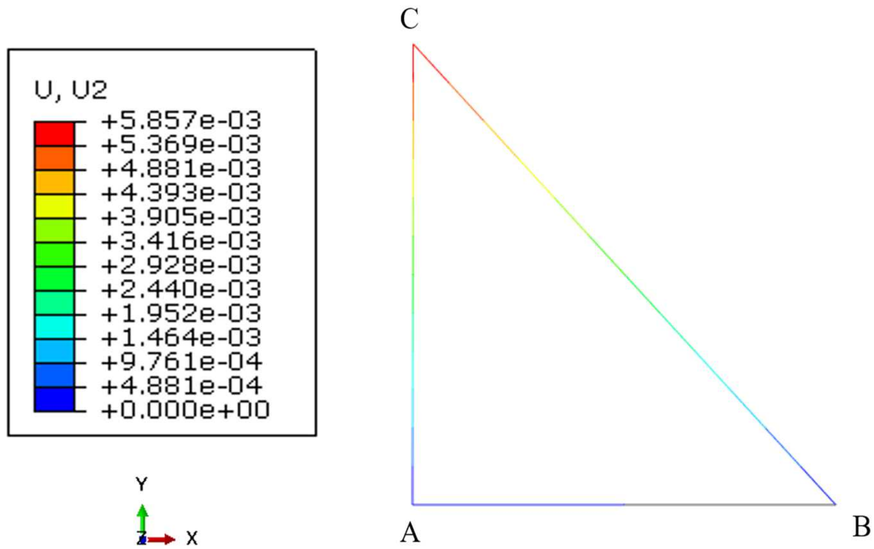


Figure 3.8: Dispalcement along Y- asis

3.8.2 Second trial

After the successful completion of the first stress analysis, the genetic algorithm is used for optimization as explained in the next section. The second trial uses all the optimized areas for stress analysis.

Axial Stress

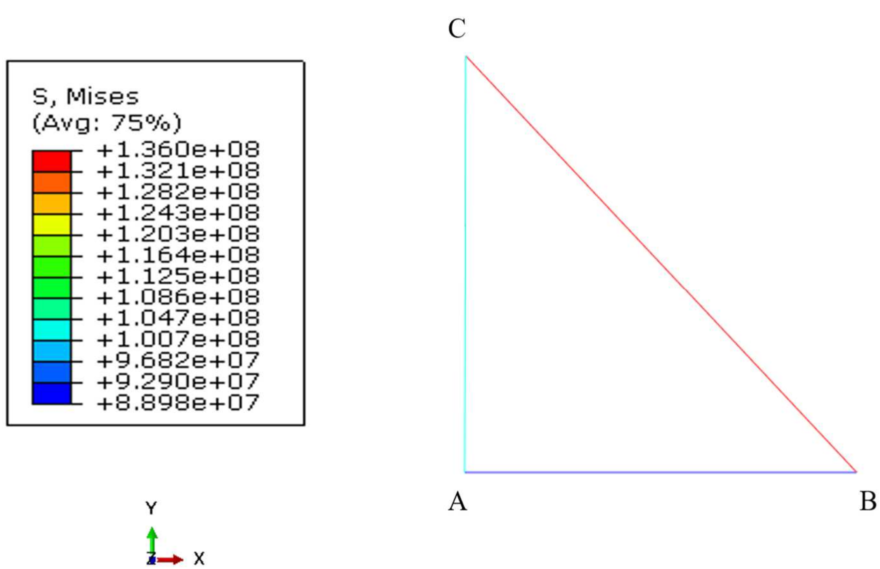


Figure 3.9: Axial stresses along three bars

Deformation

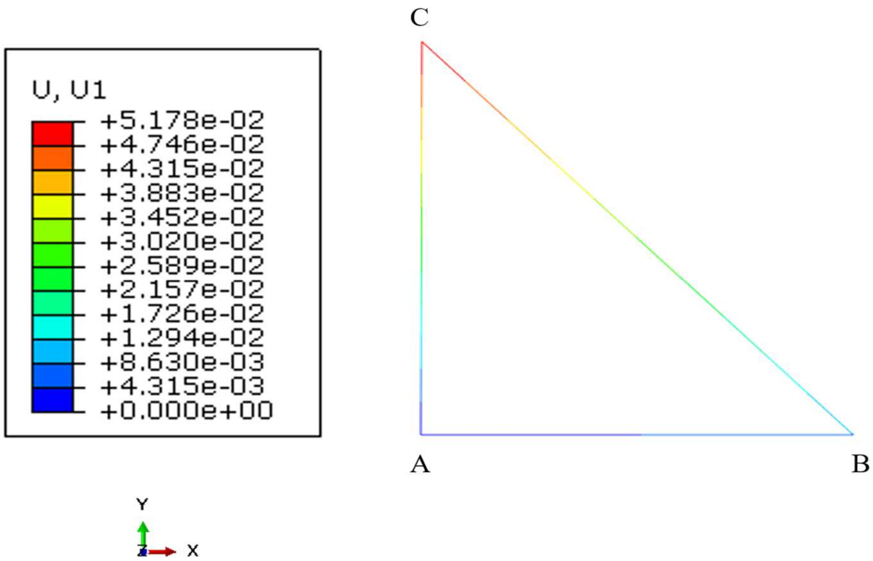


Figure 3.10: Displacement along X axis

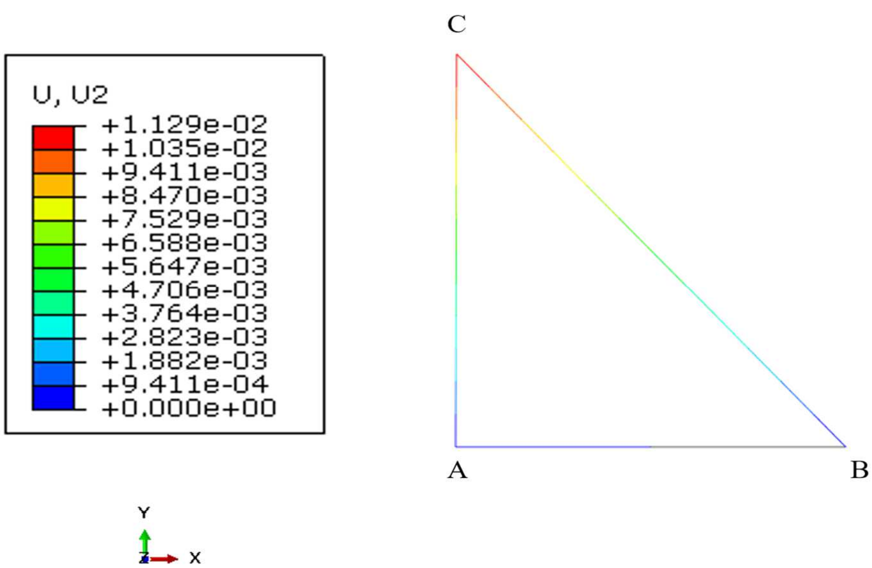


Figure 3.11: Dispalcement along Y- asis

Table 3.1: Stress along bars (First trial)

Elements	Stress (N/m^2)
Element 1(AC)	$5.324 * 10^7$
Element 2(BC)	$-8.794 * 10^7$
Element 3(AB)	$6.896 * 10^7$

Table 3.2: Stress along bars (Second trial)

Elements	Stress (N/m^2)
Element 1(AC)	$1.014 * 10^8$
Element 2(BC)	$-1.362 * 10^8$
Element 3(AB)	$8.868 * 10^7$

So in the first trial, the stresses are very low compared to the allowable stress, but when the optimized areas are used for the second trial, the stresses appear to be very close to allowable stress.

3.9 GA incorporation

Genetic algorithm is required to conduct in this optimization procedure. All of the GA (genetic algorithm) components work instantaneously to get the solution. Since external load is constant, incorporation of the genetic algorithm using the stress gives the optimum area for each bar. The possible solution set for areas are used again to determine how much stress will be carried by the unit cell. In the next portion of this paper, a clear explantation of using the evolutionary algorithm is explained, and the data provided here are obtained during the implementation of genetic algorithm in MATLAB. The flowchart of the total process depicts the idea of natural selection.

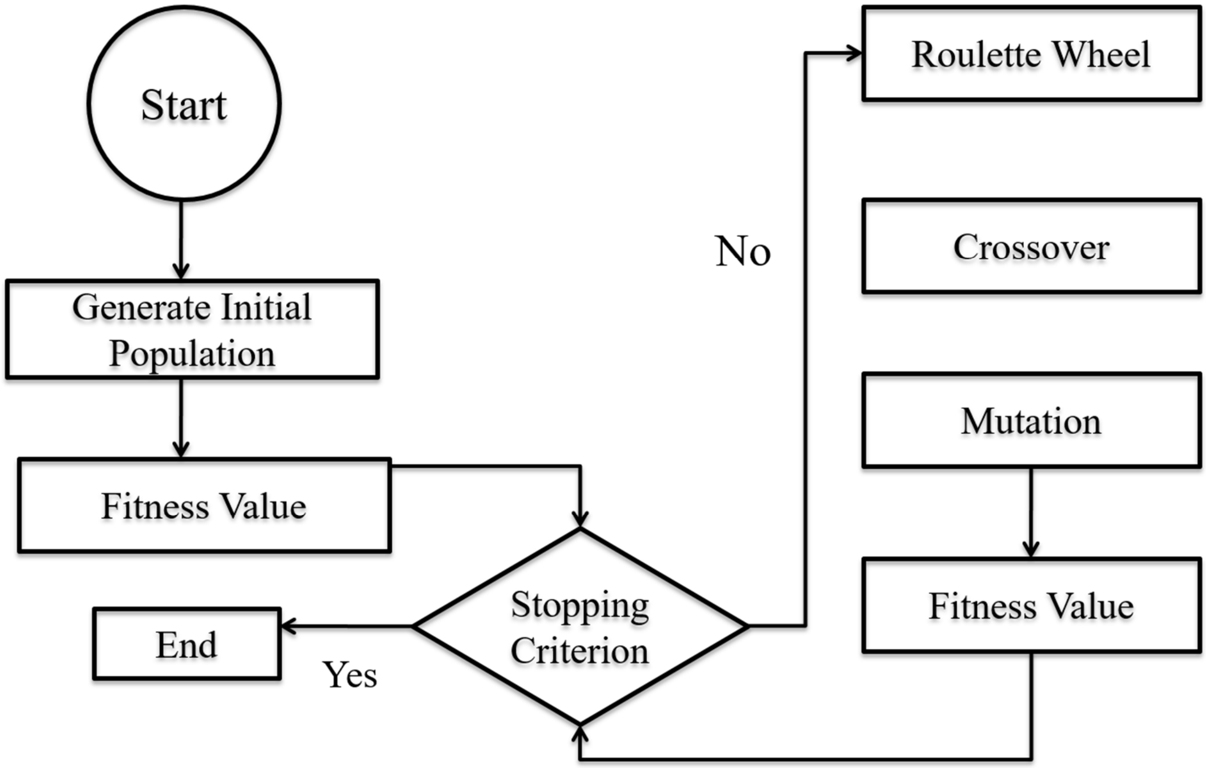


Figure 3.11: Flow chart of GA

As cross-scetional area of a bar is the main parameter of the whole procedure, the population creation ranged between lower limit and upper limit. The lower boundary of the area is 0.0049 m^2, which means a pool of individuals are required to be created that will not cross the range. Total population size is an assumed arbitrary number, but should be sufficient such that important values are nto lost. In this case, the polpuation size is 30. The total iteration run for a fixed number of generation and after certain iteration it reaches the saturation point. Drastic change is obseved for the first few generation, but, finally converges to stop the iteration.

X_1 = 01111101011111011011 ; X_2 = 01111110110101101100;

X_3 = 01111111101110011110; X_4 = 01111111101110110011;

X_5 = 10000000100010110101; X_6 = 10000000111101100001;

X_7 = 10000001101000011011; X_8 = 10000101111101101011;

X_9 = 10000111001011101010; X_{10} = 10001000111100000100;

X_{11} = 10001000111100111000; X_{12} = 10001001100110000101;

X_{13} = 10001011001101111110; X_{14} = 10001100010110010011;

X_{15} = 10001101011100100011; X_{16} = 10001101011101010010;

X_{17} = 10001111111100110100; X_{18} = 10010000011111010101;

X_{19} = 10010001011011011110; X_{20} = 10010001011011110011;

X_{21} = 10010001110000110011; X_{22} = 10010011000001110001;

X_{23} = 10010011010100010100; X_{24} = 10010100011011010010;

X_{25} = 10010100011011010100; X_{26} = 10010101111101010101;

X_{27} = 10011000110111000111; X_{28} = 10011001010100000100;

X_{29} = 10011010100000101011; X_{30} = 10011010110011001000;

After creating initial population, fitness value is calculated for each individual. Fitness value is calcuted by using stress and internal load. For each individual the fitness value is calculated:

A_1 = 644595e-8; A_2 = 578376e-8; A_3 = 542796e-8; A_4 = 626150e-8;

A_5 = 608521e-8; A_6 = 577906e-8; A_7 = 568365e-8; A_8 = 511579e-8;

A_9 = 633497e-8; A_{10} = 510079e-8; A_{11} = 513795e-8; A_{12} = 592763e-8;

A_{13} = 574544e-8; A_{14} = 560980e-8; A_{15} = 616787e-8; A_{16} = 593942e-8;

A_{17} = 522426e-8; A_{18} = 582478e-8; A_{19} = 558041e-8; A_{20} = 621433e-8;

A_{21} = 602518e-8; A_{22} = 627972e-8; A_{23} = 532775e-8; A_{24} = 528314e-8;

A_{25} = 539036e-8; A_{26} = 537553e-8; A_{27} = 534140e-8; A_{28} = 541931e-8;

A_{29} = 578738e-8; A_{30} = 563666e-8;

Sorting the fitness values clarify which chromosomes are best to be selected as parents for the next generation. Since the main objective is to minimize the weight, the individual which has the lowest area is considered the best. Based on the area, a pool of mating chromosomes is created and undergoes the selection process. Among different selection processes roulette wheel is an effective one that can create a new population. The fitness value of this new population is the key factor to determine the chromosomes that undergo crossover operation. Random value is an indispensable part to continue with GA process. As the evolutionary algorithm is a kind of

stochastic method, the impact of random values is considerable. After crossover the new offsprings are created. As explained earlier, ellitism is a criteria which can ignore best chromosome so the offspring and parents both are sorted to select best individuals. So this population is ready for mutation. The mutation operator selects the best chromosome and changes the bit from its initial state. The valid offspring facilitate the process of obtaining new population and the final new population is the result for one iteration. After a certain number of iterations the possible solution set will be created. In this case the possible solution sets are:

Z_1 = 011111000000000010010; Z_2= 011111000000000010010;

Z_3 = 011111000000000010010; Z_4= 011111000000000010010;

Z_5 = 011111000000000010010; Z_6 = 011111000000000010010;

Z_7 = 011111000000000010010; Z_8 = 011111000000000010010;

Z_9 = 011111000000000010010; Z_{10} = 011111000000000010010;

Z_{11} = 011111000000000010010; Z_{12} = 011111000000000010010;

Z_{13} = 011111000000000010010; Z_{14} = 011111000000000011010;

Z_{15} = 011111000000000011010; Z_{16} = 011111000000000011010;

Z_{17} = 011111000000000011010; Z_{18} = 011111000000000011010;

Z_{19} = 011111000000000011010; Z_{20} = 011111000000000011010;

Z_{21} = 011111000000000110010; Z_{22} = 011111000010000000010;

Z_{23} = 011111000010000000010; Z_{24} = 011111000010000010010;

Z_{25} = 011111001000000000001; Z_{26} = 011111001000000000010;

Z_{27} = 011111001000000000010; Z_{28} = 011111001000000000010;

Z_{29} = 011111001000000000010; Z_{30} = 011111001000000000010;

The obejctive function is to minimize the total weight of the structure. This iterative process and stress analysis can be performed for the whole lattice truss strucrture, and consequently, the total weight of the whole structure is obtained.

3.10 Result and Discussion

The different cross- sectional area for three different bars are used to calculate the total weight of the structure. The following parameters are used to quantify the weight of the optimized unit cell

Density = ρ, Length = L, Minimum Area = A

Weight, $W = \rho * L * A$ (11)

Genetic algorithm is used after the first trial and it generates the area for each bar and also the weight of the unit cell. Areas and weight for different bars after operation are given in the table below.

Table 3.3: Weight and Area of the bars

Bar	**Area(m^2)**	**Weight(kg)**
AC	$507922 * 10^{-8}$	311.3156
BC	$500226 * 10^{-8}$	405.1281
AB	$500036 * 10^{-8}$	264.6891

3.11 Conclusion

Size, shape, and topology optimizaiton, all are important for the truss and applying evolutionary theory at the same time can evolve a well behaved structure that might perform beyond our imagination. Similar application for the 3D truss structure is also effective as well. Finally, there is no doubt about the efficiency of the genetic algorithm. MATLAB coding is important for the genetic algorithm. In conclusion, structural optimization is always a blessing for human kind.

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Vita

I am Mohammad Tauhiduzzaman from Bangladesh. I have earned my Bachelor degree (BSc in Mechanical Engineering) from Khulna University of Engineering and Technology (KUET), Khulna, Bangladesh. Following my graduation, I served for a renowned manufacturing company in Bangladesh named Tasnim Chemical Complex Limited (TCCL). I have completed my degree requirement for Masters in Computational Science here at the University of Texas at El Paso. This thesis includes the research works throughout my graduate study under the supervision of Dr. Pavana Prabhakar.

The works include in this thesis have been published in the following publications:

1. Mohammad Tauhiduzzaman, Md. S. Islam, Dr. Pavana Prabhakar, "Design optimization of sandwich core and manufacture through additive manufacturing" Presented at "Southwest Emerging Technology Symposium", Wyndham Hotel, El Paso, Texas, April 9th , 2016.

2. Mohammad Tauhiduzzaman, Dr. Pavana Prabhakar, "Structural truss optimization by finite element analysis and genetic algorithm method" Presented at 5th Southwest Energy Science and Engineering Symposium", Wyndham Hotel, El Paso, Texas, April 5th , 2015.

3. Mohammad Tauhiduzzaman, Dr. Pavana Prabhakar, "Structural truss optimization by finite element analysis and genetic algorithm method", Poster presented at 2015 annual workshop of The University of Texas at El Paso- New Mexico (UTEP/ NMSU), El Paso, Texas, 7th Novemeber, 2015.

Mohammad Tauhiduzzaman, email: *mtauhiduzzaman@miners.utep.edu*

This thesis was typed by Mohammad Tauhiduzzaman.