

Free Vibration Analysis of Honeycomb Beam Structured by Aluminium Alloy Face Sheets

Mehmet Gören

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
June 2022
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Mechanical Engineering.

Assoc. Prof. Dr. Murat Özdenefe
Chair, Department of Mechanical
Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Asst. Prof. Dr. Babak Safaei
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Shaban Ismael Albrka

2. Assoc. Prof. Dr. Qasim Zeeshan

3. Asst. Prof. Dr. Babak Safaei

ABSTRACT

The most fundamental linear analysis will be carried out on the honeycomb sandwich structure. To determine the natural frequency of sandwich structure with different materials used as core and effect of honeycomb core will be simulated in ANSYS Workbench RVE analysis. Considering the dynamic effects of honeycomb are quite critical, in this research unit cell method will be implemented to capture the entire effects of free vibration of honeycomb sandwich structure. This research focused on free vibration characteristics and stress states of honeycomb sandwich structures, extracting the major factors that affect the sandwich frequencies and stiffness due to materials or parameters changes. Honeycomb core is evaluated and developed for the study model. Different materials were used for the same model with star sported cores. Comparisons of different materials of each model with the same structure were made under different analyses, such as aluminium, SAN foam and carbon fibre. The analysis results determined the material and structure with one of the best strengths. Furthermore, the analysis of the tear that will occur on the beam has also been modelled and added to the study. The cracks formed in the proposed structure gave similar results to the honeycomb models in the hierarchical structure. The natural frequency is a function of stiffness to mass ratio, the proposed model was designed to have a reinforced inbuilt star shape which enhanced the vibration characteristics and it was further optimized by varying the materials of the reinforcement star shape, as a result of that SAN foam hexagonal and PVC foam star reinforcement happens to have better mass to volume ratio and higher natural frequency. In addition, increasing the foil thickness does not have significance on sandwich beam natural frequency but that

will increase the weight. The study shows that the modified core has good flexural stiffness and stress resonance resistance at a higher frequency.

Keywords: Honeycomb Core, Laminated Sandwich Beams, Finite Element Analysis, Vibration, RVE

ÖZ

Çalışma, lamine kompozit yüzey levhaları ve petek çekirdekli sandviç kirişlerin davranışını analiz etmeye ve geliştirmeye odaklanmaktadır. Çekirdek yapısı olarak kullanılan yapının farklı malzemelerle ve farklı dış etken değişkenleriyle sandviç yapının doğal frekans davranışlarını belirlemek ve petek çekirdeğinin davranışa etkisi gözlemlenmiştir. Analizlerde ANSYS'in Workbench RVE analizleri kullanılmıştır. Peteğin dinamik etkilerinin oldukça kritik olduğu düşünüldüğünde, bu araştırmada petek sandviç yapısının serbest titreşiminin tüm etkilerini yakalamak için birleşik hücre yöntemi uygulanacaktır. Bu araştırma, malzeme veya parametre değişikliklerinden dolayı sandviç frekanslarını ve sertliğini etkileyen ana faktörleri çıkararak, petek yapılı sandviç yapıların serbest titreşim karakteristikleri ve gerilme durumlarına odaklanmıştır. Petek çekirdeği, daha geniş bir çalışma alanı için geliştirildi ve değiştirildi. Yıldız destek bal peteği çekirdekli yapılar için aynı model kullanılırken birbirinden bağımsız olacak şekilde tek çekirdek yapısında farklı malzemeler kullanılmıştır. Aynı yapıya sahip her modelin farklı malzemelerinin alüminyum, SAN köpük ve karbon fiber gibi farklı analizler altında karşılaştırılması yapılmıştır. Analiz sonuçları, en iyi dayanımlardan birine sahip malzeme ve yapıyı belirledi. Ayrıca kirişte oluşacak yırtılmanın analizi de modellenerek çalışmaya eklendi. Önerilen yapıda oluşan çatlaklar hiyerarşik yapıda petek modellerine benzer sonuçlar verdi. Doğal frekans, sertlik-kütle oranının bir fonksiyonudur, önerilen model, titreşim özelliklerini artıran güçlendirilmiş bir dahili yıldız şekline sahip olacak şekilde tasarlanmıştır ve bu SAN sonucunda, takviye yıldız şeklinin malzemeleri değiştirilerek daha da optimize edilmiştir. köpük altıgen ve PVC köpük yıldız takviyesi daha iyi kütle/hacim oranına ve daha yüksek doğal frekansına sahip olduğu

kanıtlanmıştır. Ayrıca folyo kalınlığının arttırılması sandviç kirişin doğal frekansı üzerinde bir anlam ifade etmeyerek sadece ağırlığı artırmıştır. Çalışma, geliştirilmiş çekirdek yapısının daha yüksek bir frekansta iyi eğilme sertliğine ve stres rezonans direncine sahip olduğunu göstermektedir.

Anahtar Kelimeler: Bal Peteği Çekirdek, Lamine Sandviç Kiriş, Sonlu Elemanlar Analizi, Titreşim, Burkulma, RVE

TO MY LOVELY FAMILY

ACKNOWLEDGMENT

First of all, I would like to express my gratitude to everyone who has contributed to my success without making any distinction. I feel very lucky that tons of people cannot be countable.

Apart from these, I would like to thank my supervisor Assistant Professor Dr. Babak Safaei, who has been the biggest factor in completing this process academically. His working system, work ethic and ambition helped me find my way when I was lost, and he is a person I will take as an example in the future. I must express my deep acknowledgement to him for his strong guidance, strong encouragement, superb attention to detail and for helping to keep me on schedule.

In addition, I have a big debt of gratitude to Assistant Professor Dr. Mehmet Eren Uz for providing great leadership when I was doing my bachelor's. Also, to academic success, I would like again and again to thank my dear family for their unconditional mental support, financial assistance and endless love under all circumstances. Likewise, I would like to express my endless thanks to my dear friends who stood by me in my failure and success. Thank you for making me feel lucky to have you all in this world where we only have a chance to live once.

TABLE OF CONTENTS

ABSTRACT.....	iii
ÖZ	v
ACKNOWLEDGMENT.....	viii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF SYMBOLS AND ABBREVIATIONS	xv
1 INTRODUCTION	1
1.1 Sandwich Structures.....	2
1.1.1 Face Sheets.....	5
1.1.2 Core Materials.....	6
1.1.3 Adhesives	7
1.2 Main Application of HCs	8
1.2.1 Used Applications	8
1.2.1.1 Absorber.....	8
1.2.1.2 Automotive.....	9
1.2.1.3 Fan Blade	10
1.2.1.4 Morphing Aircraft	11
1.2.1.5 Marine	11
1.2.2 Potential Applications	13
1.3 Manufacturing of Honeycomb Cores.....	14
1.4 Effects of Honeycombs Sandwiches on Human Life	17
1.4.1 Advantages.....	17
1.4.2 Disadvantages	18

1.5 Definition of the Problem and Research Methodology.....	19
1.6 Need for Research (Motivation).....	20
1.7 Objectives and Scope of The Study	21
2 LITERATURE REVIEW.....	23
2.1 Beam Theory for Sandwich Structures	23
2.2 Orthotropy - Anisotropy.....	24
2.3 FEM Modelling of HCs	26
2.4 Geometric Modelling of HCs.....	27
2.5 Failure Modes of Honeycomb Sandwich Structures.....	29
3 METHODOLOGY.....	31
3.1 Geometric Modelling of Honeycomb Sandwich Beam	31
3.2 Finite Element Meshing	34
3.3 Modelling Boundary Condition	36
3.4 Analytical Models	38
3.5 Classical Honeycombs	38
3.6 Equivalent Honeycomb Sandwich Beam.....	39
4 RESULT AND DISCUSSION	41
4.1 Free Vibration of Honeycomb Beam	41
4.2 Effects of Materials on Free Vibration.....	42
4.3 Effect of Boundary Conditions (CF and CC) on Free Vibration of the Sandwich Structure	44
4.4 Effect of Hexagonal Cell Foil Thickness on Free Vibration	45
4.5 Pre-Stressed Modal Analysis on Sandwich Structure.....	46
4.6 Proposed Reinforced Star Core Model	48
4.7 Comparison of Flexural Stiffness of the Proposed Core.....	50

4.8 Elliptical Cut on Sandwich Beam	50
5 CONCLUSION, LIMITATIONS AND FUTURE RESEARCH	56
5.1 Conclusion	56
5.2 Limitations of The Research	57
5.3 Future Research.....	57
REFERENCES.....	59

LIST OF TABLES

Table 1: Advantages of HCs	18
Table 2: Disadvantages of HCs.....	19
Table 3: Failure Modes of Honeycomb Composites[78,118].....	30
Table 4: Material Properties of Honeycomb Sandwich Beam.....	34
Table 5: Analysis of Mesh	35
Table 6: Orthotropic Material Properties of RVE Proposed Core.	36
Table 7: Dimensions of the Honeycomb Sandwich Beam.....	38
Table 8: Results for Validation of RVE Models.....	42
Table 9: Variation of Density and Foil Thickness	46
Table 10: Proposed Reinforced Star-Core Model Free Vibration Response Under Clamp-Clamp.....	48
Table 11: Comparison of Material Stiffness of The Proposed Core.....	50

LIST OF FIGURES

Figure 1: Different Types of Composite Materials [11]	3
Figure 2: Three-Layer Basic Sandwich Structure	4
Figure.3: Face Sheet Materials.....	6
Figure 4: Sandwich Panels with The Different Cores [31]	7
Figure 5: Commonly Using Adhesive Materials	8
Figure 6: Typical Structure of Noise Suppressor Sheet Materials [43]	9
Figure 7: Aspects of Advanced Polymer Composites for Automotive Applications [47]	10
Figure 8: Composite Blade Structure [51]	11
Figure 9: Morphing Aircraft Pre and Post Illustration [50]	11
Figure 10: Deck Composite Material Components.....	12
Figure 11: (A) The Deployed Permanent Configuration of a Compact Lattice After Heating. This Shape is Also The Recovered Shape After Reprogramming And Heating. (B) The Reprogrammed Saddle-Cylinder Shape. (C) The Reprogrammed Compressed-Twisted Compact Shape. (D) The Reprogrammed Semi-Sphere/Dome Shape. (E) The Reprogrammed In-Plane Fan Shape [63].....	14
Figure 12: Sandwich Panel with Honeycomb Core and Adhesive Layers [65].....	15
Figure 13: (A)Expansion Manufacturing Process (B)Corrugation Manufacturing Process [66].....	16
Figure 14: A Unit Cell of Honeycomb Composite [67].....	17
Figure 15: Research Methodology	20
Figure 16: Sandwich Beam Definition [79].....	23
Figure 17: (a) Anisotropic Structure (b) Orthotropic Structure [83].....	26

Figure 18: Geometry Of RVE Model (A) Honeycomb Unit Cell; (B) Honeycomb With Star-Shaped Reinforced Unit Cell; (C) Unit Cell Angle Projection.	32
Figure 19: Proposed Core Discrete Model; (A) Plain View; (B) Side View; (C) Isometric View	33
Figure 20: Meshing (A) Hexagonal Meshing; (B) Proposed Core Meshing; (C) Equivalent Model of Hexagonal Core Meshing; (D) Equivalent Model of Proposed Core Meshing	35
Figure 21: Boundary Conditions (A)Clamped-Free; (B) Clamped-Clamped; (C) Clamped-Free With Elliptical Cut	37
Figure 22: Effect of Materials on the Natural Frequency	43
Figure 23: Effect of Deformation on Material	43
Figure 24: Directional Deformation on Mode 5 (Clamped-Free).....	44
Figure 25: Directional Deformation on Mode 5 (Clamped-Clamped).....	45
Figure 26: Variation of the Frequency For Foil Thickness.....	46
Figure 27: Frequencies of Changes with Thermal Load.....	47
Figure 28: Natural Frequency of Proposed Core (Clamped-Clamped)	49
Figure 29: Natural Frequency of Proposed Core (Clamped-Free).....	49
Figure 30: Sandwich Beam with Different Distances Elliptical Cuts.....	52
Figure 31: Position of Elliptical Cut vs Natural Frequency	53
Figure 32: First 3 Mode Shapes Contour of Sandwich Beam.....	54
Figure 33: First 3 Mode Shapes Contour of Sandwich Beam with Elliptical Cut	55

LIST OF SYMBOLS AND ABBREVIATIONS

°C	Degrees Centigrade
2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
AA	Aluminium Alloy
Al	Aluminium Element
APDL	Ansys Parametric Design Language
BM	Base Metal
BMC	Bulk Moulding Compound
CAD	Computer Aided Design
CC	Clamped-Clamped
CF	Clamped-Free
CW	Clockwise
DOE	Design of Experiment
FEM	Finite Element Model
GPa	Giga Pascal
HAZ	Heat-Affected Zone
HC	Honeycomb Composite
Hz	Frequency
mm	Millimetre
MPa	Mega Pascal
PVC	Polyvinyl Chloride
R&D	Research and Development

RRIM	Reinforced Reaction Injection Moulding
RTMM	Resin Transfer Moulding Method
RVE	Representative Volume Element
SAN	Styrene Acrylonitrile
SC	Star Core
SMC	Sheet Moulding Compounds
SRIM	Structural Reaction Injection Moulding
UC	Unit Cell

Chapter 1

INTRODUCTION

In today's world, composite materials have reached a massive use area. It has paved the way for production techniques and new application areas with the newly discovered and combined materials in specific proportions. Being so extensive and comprehensive has created many options that can be studied. In light of this, many engineering branches have been examined. They are working on it as R&D. These structures, which should be durable under many different conditions, also stand out with the complex flexibility of their geometry. However, performing a complete and assumption-free analysis is very time consuming and much more complicated. The fact that it has so many variables makes it impossible to analyse it comprehensively. However, thanks to the computational methods developed today, this case has become more manageable. The thesis will examine structures with a core honeycomb structure from the family of sandwich composites. Honeycomb Structures (HC) have taken their form from the honeycomb of bees. It provides maximum durability with minimum material. Biomimicry has been a pioneer in the discovery and development of this field. One of today's most used structures, HCs are modelled more complex than flat sandwiches. It is more complicated and complex to analyse than flat core structures. The study aims to analyse an orthotropic equivalent model of the HC. While doing this, the previously used equivalent models will be used, but the core structure will be changed. Although the different core thicknesses, designs and materials in previous studies were varied, it is still possible to improve the existing structure. More detailed

information will be given in the following chapters on the subject, and the analysis results will be discussed in detail.

The Finite Element Method (FEM) program for analysis is the ANSYS program. The ANSYS program is a FEM program that gives complete and reliable results on almost any analysis application. It has both pre and post-processing capacity. The APDL tab provides detailed and reliable sandwich composite and HC results.

In the following sections of the chapter, general information about composites will be given. Afterwards, especially HC will be emphasised. The sandwich theory will be discussed at the end of the chapter in the next chapter. In the sub-headings, the different materials used in the sandwich, their usage areas and potential usage areas will be addressed. Chapter 3 will include previous work on analysing structures, and this work model will be discussed. Chapter 4 will contain detailed descriptions of the analyses. Model, meshing, forces and boundary conditions will be addressed. In the 5th chapter, the structure analysis results will be presented. Results that have been obtained in the analysis will be discussed. The results of how the structure has developed and what kind of difference it has made will be included in this section. Afterwards, the following chapter will finalise the analysis results presented in chapter 5 in conclusion.

1.1 Sandwich Structures

Early Composite materials are artificial and widely used structures. Composite materials are a product that results from the combination of two or more materials and their unique and better properties, unlike the first materials by Mazumdar [1]. The properties that can be developed can be strength, stiffness, corrosion and wear resistance, weight, fatigue life, thermal insulation, conductivity and acoustic

insulation, depending on the area of use [2]. The fact that there are many such developable aspects requires determination according to the application and development in line with it. Although it is uncertain when it first appeared historically, it is almost a hundred years old to modernise our lives. As a result of the mishap, fibreglass is produced while writing on the milk bottle by mistake [3]. Researchers who discovered the extraordinary properties of this material have carried out numerous studies after this event. They are generally divided into three composites classified as particulate, fibrous, and laminated [4]. They all have different uses. But to give examples of these, space technology, maritime industry, medical field, robot technology, chemical industry, electrical-electronic technology, musical instruments industry, construction and building industry, automotive industry, defence industry and aviation industry, food and agriculture industry, sports equipment of examples[5–7]. And there are sectors such as electronics and medical, including such issues as bone fracture fixation plates, robotics, bio integrated electronics and active origami, which are foreseen to be used in the future [8–10].

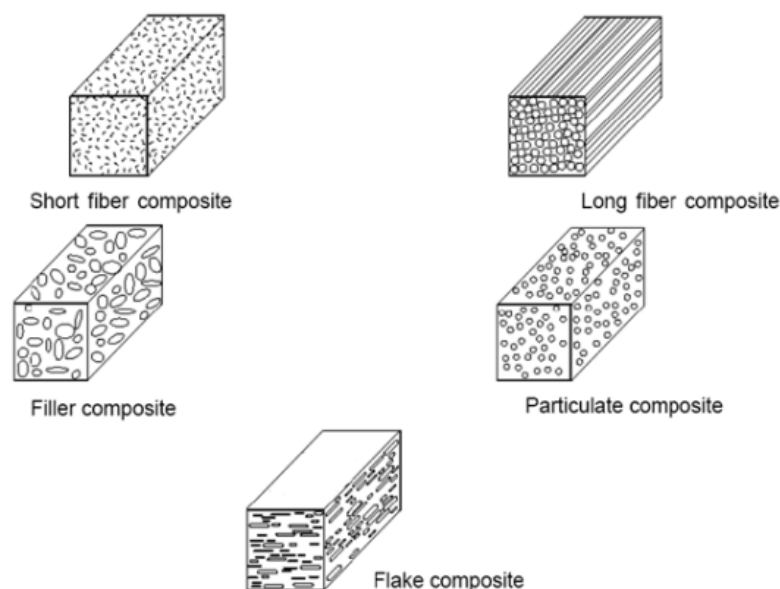


Figure 1: Different Types of Composite Materials [11]

Sandwich Composites are the structures obtained by placing a different material in another form between at least two layers. Composite materials are commonly fabricated by attaching two thin but high stiffness skins to a lightweight but thick core. Each layer can be anisotropic material, or sandwich composites can be a fibre-reinforced layer. Sandwich structures are acquired new and unique properties according to the raw materials in their structure. However, the materials in the composite do not dissolve, react or mix [11]. They consist of three different layers Top and Bottom face layers, Adhesive Layer and the Core layer, as in Figure 2.

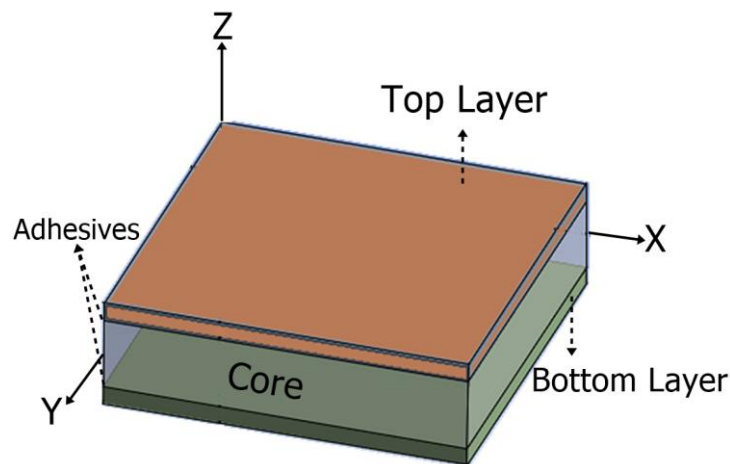


Figure 2: Three-Layer Basic Sandwich Structure

Especially in engineering applications, there are composite components that we frequently encounter. There are many reasons why composite materials are preferred. Sandwich structures have high strength, low weight, fatigue resistance, corrosion resistance, heat resistance, and electrical and acoustic insulation compared to single-phase materials [12]. Sandwich composites provide excellent mechanical properties and much lower weight than traditional monolithic materials such as steel. Sandwich composites can also be designed with extreme precision according to loading requirements. Sandwich composites are heat and moisture resistant structures. The

sandwich structure has a high hardness-to-weight ratio and a high flexural strength-to-weight ratio [13]. Sandwich composites can be strong and lightweight for applications requiring a very high-strength material with the lowest possible weight. Less weight means improved fuel efficiency, higher speed, higher payload, more extended range, and lower transportation and installation costs. It is necessary to choose between price, performance and quality. Composite components act as an imaginary bridge link between these three. Therefore, it is a suitable material type to be preferred. However, the disadvantages of sandwich structures are high production cost, the difficulty of processing the material, not being prone to mass production, almost non-recyclability, low fracture elongation and difficulty in production. Sandwich structures are used in tons of areas because they are very effective in vibration control, shock absorption, and noise reduction [14,15]. The property of the core material is significant in sandwich structures [16,17]. In a study conducted by S. Akour, when the stiffness of the core material is softer, the force transferred to the surface layers is the same proportional. Also easily implemented. However, it also has a considerable noise and vibration control ability, mainly when applied to lightweight structures [18,19]. Its widespread use has enabled many scientists to work on the subject.

1.1.1 Face Sheets

Face sheet layers are found in the outermost layers of the sandwich structure. Therefore, this layer always first interacts with the external field and forces rather than the core and adhesive layer. While carrying and spreading the force evenly throughout the entire structure, it should resist this incoming force without experiencing failure [20]. Flex and abrasion-resistant materials are used on the surface in production. As shown in Figure 3, materials are commonly used as face sheets.

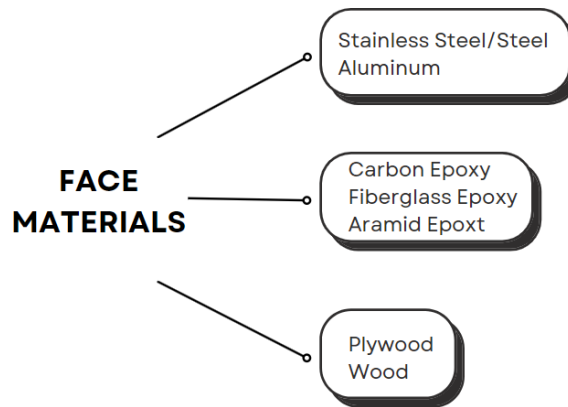


Figure.3: Face Sheet Materials

The general use of these materials is durable, flexible and accessible. We can see almost every sandwich composite; we encounter fibre bonding and weight/strength ratios [21–23]. In addition, they are designed with the same materials or the same thermal expansion coefficients to prevent failure due to different elongation coefficients as a result of thermal extension on both faces [24].

1.1.2 Core Materials

Core materials are one of the most critical components of a composite sandwich structure. Therefore, it is significantly essential to determine the material's properties correctly. Materials that require more strength and less wear resistance than face materials are generally used. It must be accessible and workable. The selected material should be stiff enough in shear to prevent sliding of the face layer. In cases where sliding occurs, the structure will not act as a sandwich [25]. It will not be able to provide strength and experience failure. In cases where failure conditions are provided by the lack of stiffness in the material, visible local buckling may occur in the outer layer [26]. In core, durable and light materials are preferred [27]. Especially material groups such as carbon fibre, glass fibre, resin, and Kevlar are pretty common. However, materials with different structures are preferred in the core. Foam and aluminium are the most commonly used ones. Especially aluminium is one of the

materials with the highest strength/weight ratio [28]. Manufactured honeycomb structural materials are typically made by layering a honeycomb material between two thin layers that provide strength in tension [29]. That forms a plate-like assembly. Typical core structures are divided into four main groups. These are Truss, Foam, Corrugated and Honeycomb [30].

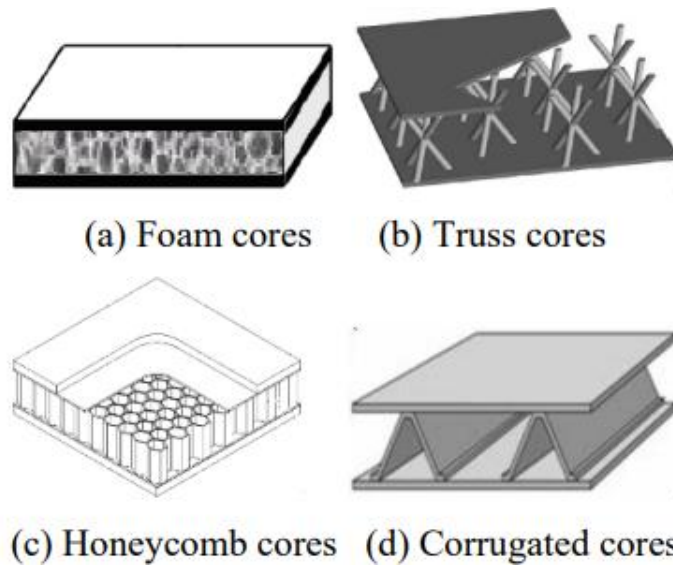


Figure 4: Sandwich Panels with The Different Cores [31]

1.1.3 Adhesives

The Adhesives composite sandwich is the main binding element of structures. Components that provide energy exchange between layers act as a bridge between two different structures and cooperate. Using the amount of the adhesive if it is too thin creates problems while using too much makes problems. Moreover, the most crucial factor in choosing the adhesive is that the adhesive should have shear stress resistance at least as much as the core material [32]. Among the remaining factors to be considered, the amount of adhesive, chemical reaction and elasticity are essential[33]. Adhesive samples used in general are shown in Figure 5 [34].

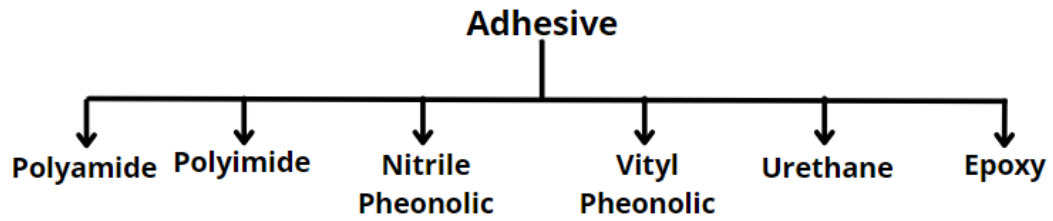


Figure 5: Commonly Using Adhesive Materials

1.2 Main Application of HCs

Honeycomb composites appear in almost every aspect of our lives. The fact that it is commonly encountered at this level is proof that it needs to be worked on. Accordingly, plenty of research has been done on sandwich structures, significantly to determine their mechanical behaviours such as tension, compression, buckling, fatigue, and thermal and acoustic performance [35–38]. Sandwich structures with honeycomb cores are widely used all around the world. Compared to typical sandwich structures, the features that make them stand out are lighter and more durable. Composite sandwiches are mainly used in aerospace and mechanical applications because they have an excellent flexural/transverse shear stiffness [39]. The areas where they are used and expected to be used in the future are available and cannot be countable.

1.2.1 Used Applications

In this section, the areas where sandwich composites are used are discussed. It is impossible to list all of the usage areas, which are quite common and have a wide usage area, completely. In general, the most frequently used areas and sectors are listed and exemplified one by one.

1.2.1.1 Absorber

Composite sandwiches are usually used for absorbing microwave waves. Many different studies have been done on this subject. Furthermore, as a result, it has been

determined that sandwich structures with two face layers give more effective results than one-layer designs [40]. In another study, it was found that graphene-based materials gave better results than other materials [41]. Studies were also conducted on MR layer thickness to panel thickness. It was determined that the ratio was directly proportional to the absorption ratio [42].

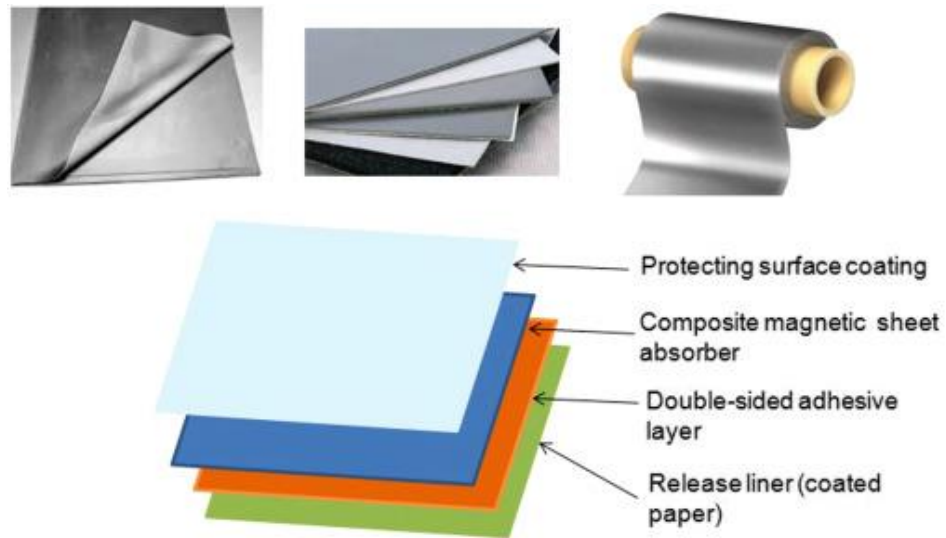


Figure 6: Typical Structure of Noise Suppressor Sheet Materials [43]

1.2.1.2 Automotive

Vehicles are the means of transportation that almost every person uses at least once every day. Most of the cars we use in our daily lives are made of composite materials. There is no doubt that it is not possible to build a car without composite material. Composites, which should have many features suitable for the car, need to be developed in almost every subject. A structure has to be both durable and flexible. There should be thermal and acoustic performance while being prepared for impacts. Besides, the wood-plastic material structure has started to be encountered frequently in these studies, trying not to harm nature [44]. It has also been determined that the

HC strength varies according to the collision speed [45]. Hybrid composite models have also been developed [46].

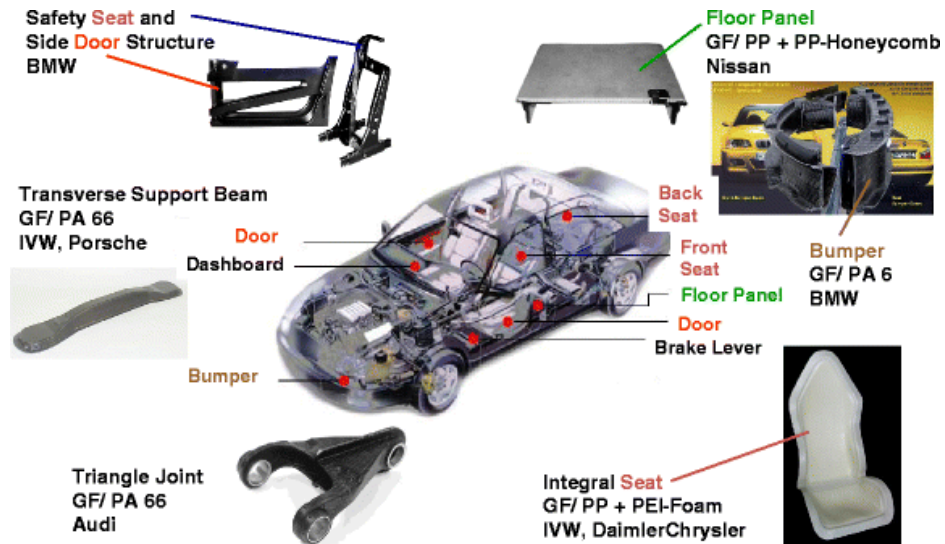


Figure 7: Aspects of Advanced Polymer Composites for Automotive Applications [47]

1.2.1.3 Fan Blade

Fan blades are used in circulation (Cooling, Heating, Mixing), push-pull applications and cutting applications. Its spread over such a vast area has also increased the studies and innovations. It even appears in jet engines [48]. It has been tried to reach the goal with many different materials. Analysis environments were created, and models were developed, considering even the bird strike during the flight [49]. In a study, the metal blade is more prone to deform to rub-induced vibrations than the composite blades at the design speed [50].

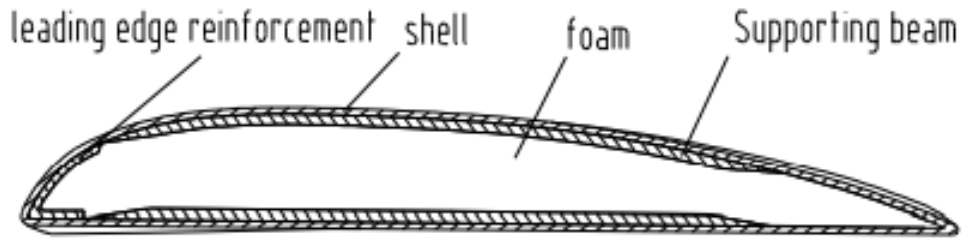


Figure 8: Composite Blade Structure [51]

1.2.1.4 Morphing Aircraft

Morphing Aircraft provide the desired configuration; It brought advantages such as increased range, fuel savings and low carbon emissions [52]. While increasing the interest in the developments in the aviation sector, it also opened the door to different technologies. The aircraft is compatible with multitasking, thanks to the morphing technology. In the past studies, the advantages and disadvantages of morphing aircraft compared to fixed-wing aircraft are also discussed. At first, the aircraft structure with two standard wings creates a design that resembles an aircraft with a small single wing surface after configuration [53], creating a fuselage structure that is less affected by the flow [54]. This structure is shown in Figure 9 below.

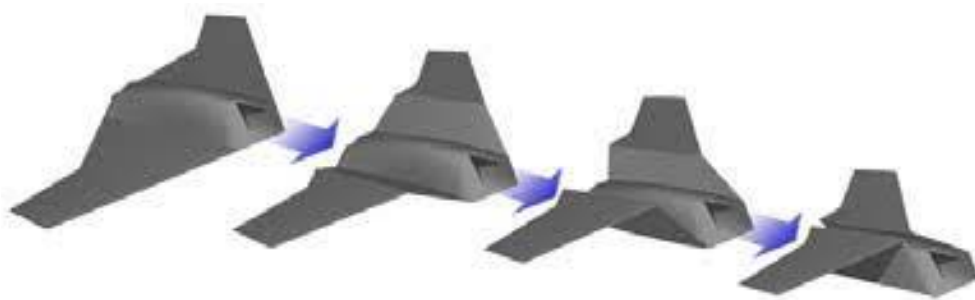


Figure 9: Morphing Aircraft Pre and Post Illustration [50]

1.2.1.5 Marine

Composite materials used in the marine environment have become very common in recent years. Specific studies have been started on them. With the increased interest

and development of the manufacturing industry, the way to produce more durable parts in large structures has been paved. Composites, which started to be used on the seas after the Second World War, were included in this field for the first time[39]. Among the foremost reasons for their inclusion is that they are light, strong and resistant to corrosion. Initial applications were made with steel, wood, and aluminium to overcome corrosion problems. The load capacity was increased by reducing the weight, and fuel-saving was achieved [55]. In addition, valves and subsea structures that can withstand the corrosive properties of water have also been developed. Generally, composite material applications in marine are hull, bearings, propeller, covers, exhaust, Superstructures, Radom, Sonar domes, and fences [56].

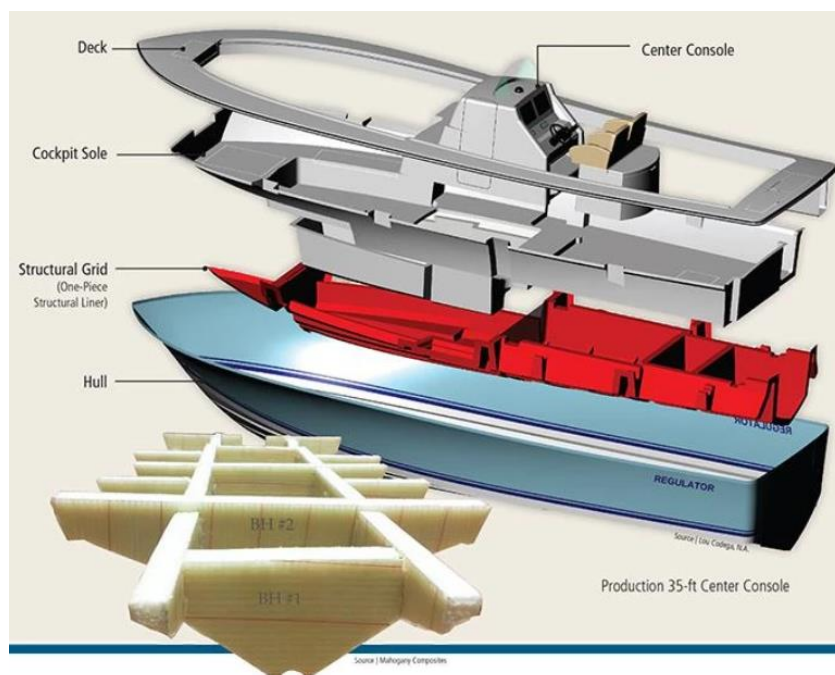


Figure 10: Deck Composite Material Components

As stated, the abrasiveness of the water increases with the salt content of the water. At the same time, the rigid structures under the water are harmful to the vehicles. It is necessary to be prepared and resilient to many different situations. Therefore, composites are widely used. Maintenance is an essential element. It has tried to prevent

the failure of fastening and connection components by using thermoset composites as they are exposed to both loads and corrosion [57]. Composites are primarily used in speed boats. Minimum weight and maximum strength are the biggest reason for this. Thanks to this, boats can sail at high speeds for a long time. The use of carbon fibre reinforced epoxy composites contributes to increased performance. Materials science and composite technology are advancing rapidly, and new composites such as epoxy blends, including the application of carbon nanotubes, are becoming even more famous for high-performance marine structures [58].

1.2.2 Potential Applications

With the covid-19 virus affecting our lives, the use of conventional materials has decreased while increasing the use of composite. The virus-induced steel prices have increased, and at the same time, they have become difficult to reach [59]. Therefore, the need for materials with the same strength has grown even more. It is pretty standard in electric cars because the car's components, such as batteries and electric motors, are heavy, so other components must be lighter than they should be. In addition, with the development of artificial intelligence and robotic applications, smart materials have also emerged [9]. Production methods called four dimensions have emerged. 4D printing is self-folding structures that can be folded sequentially and accurately. It is also known as active origami, and different studies are carried out on various subjects to increase its strength and flexibility [60,61]. There is no doubt that metamaterials will also become quite common in the future. The properties of the metamaterials are not derived from the forming materials but from their sheer size, geometry, shape, orientation, and arrangement. Metamaterials manipulate electromagnetic waves via promoting, hindering, and absorbing waves to attain an interest beyond the natural materials' potency [62]. Developments in the field of health also continue. This

prevalence will increase as the platinum used to treat broken bones is gradually replaced by composites [10]. Figure 11 Demonstration of the ability for a 4D-printed structure to be reprogrammed from its permanent shape into many different configurations that are structurally stiff at room temperature and then returned to its permanent shape upon heating.

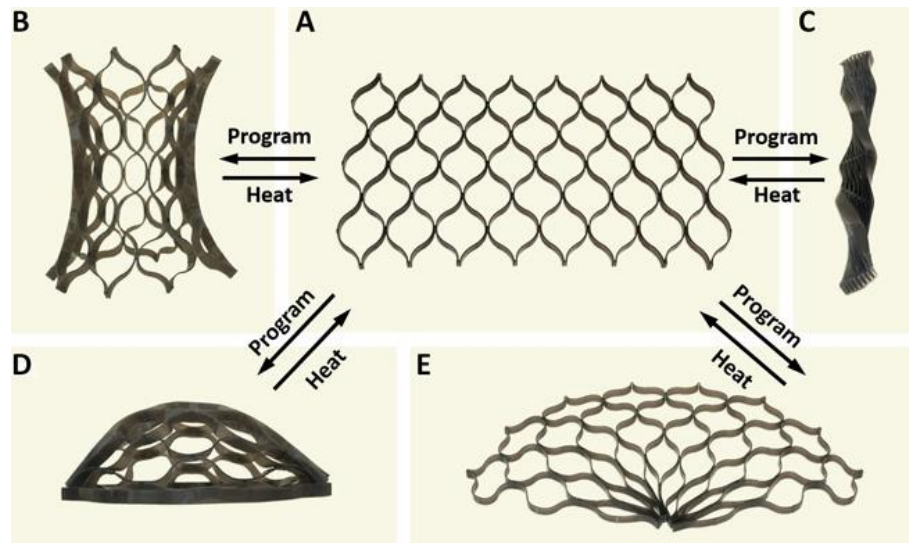


Figure 11: (A) The Deployed Permanent Configuration of a Compact Lattice After Heating. This Shape is Also The Recovered Shape After Reprogramming And Heating. (B) The Reprogrammed Saddle-Cylinder Shape. (C) The Reprogrammed Compressed-Twisted Compact Shape. (D) The Reprogrammed Semi-Sphere/Dome Shape. (E) The Reprogrammed In-Plane Fan Shape [63]

1.3 Manufacturing of Honeycomb Cores

There are many methods for producing polymer-based composite materials with desired properties and shapes. In particular, it is possible to examine the production methods used in the composite industry, where thermoset matrices are used, basically under two headings. These are Open Die Production Methods and Closed Die Production Methods. Examples of open mould production methods are Manual Laying, Spraying, and Fibre Wrapping Methods. Examples of Closed Mould Production methods are Resin Transfer Moulding Method (RTMM), Vacuum Infusion

Method, Vacuum Bagging Method, Hot Pressing Method (SMC-BMC-Prepreg), Pultrusion Method, Continuous Lamination Method, and Reactive Production (RRIM, SRIM) examples can be given [64]. A typical sandwich structure is as in the figure 12.

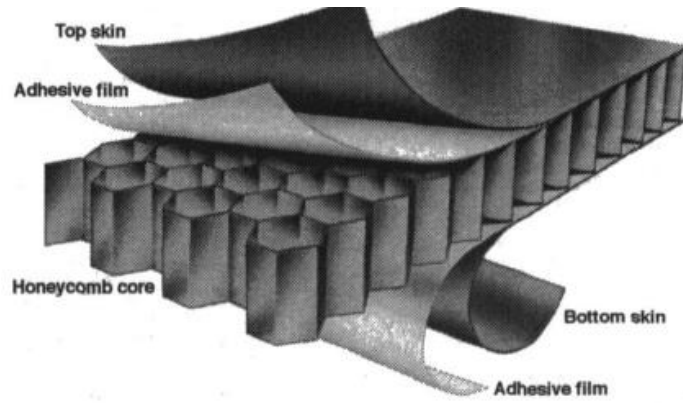


Figure 12: Sandwich Panel with Honeycomb Core and Adhesive Layers [65]

The most traditional production method for HCs is expansion manufacturing and corrugating. A Hobe block is formed by feeding on a flat sheet roll for expansion manufacturing. Afterwards, the Hobe slice is cut to the desired thickness, and as a result, an expanded panel is formed. In the corrugating method, however, the roll is shaped directly this time and divided into parts, and these sheets are combined to form blocks [66]. As shown in the figure 13, both methods are shown in the study.

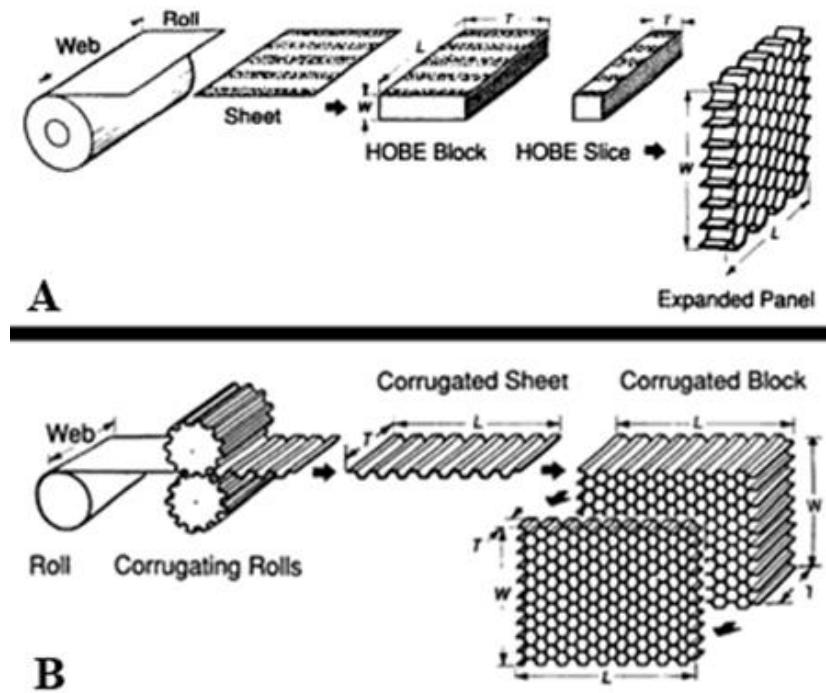


Figure 13: (A)Expansion Manufacturing Process (B)Corrugation Manufacturing Process [66]

As the number of cells per unit area in the core structure and the connection thickness increase, the resistance of core structures against bending, compression, peeling, shearing and impact forces increases. HC consists of hexagon-shaped cells, which are entirely identical to each other. Components in this structure are;

- L Total Length of HC.
- T_c Thickness of the Unit Cell.
- h_c Height of the Unit Cell.
- a Length of One Wall of The Unit Cell.
- d Distance Between Opposite Unit Cell Walls.
- W Total Width of HC.

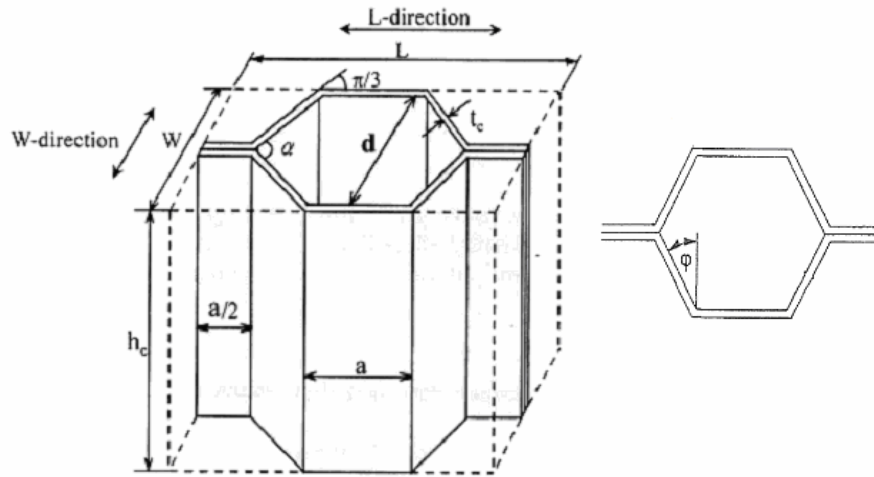


Figure 14: A Unit Cell of Honeycomb Composite [67]

Also, for a normal HC cell, the following relations are held. Since they are in HC symmetrical structure, some relations do not change, only the results obtained according to the design of the structure change.

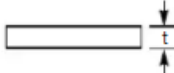
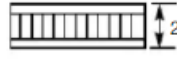
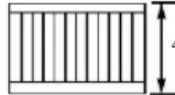
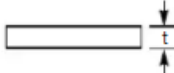
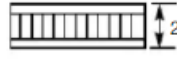
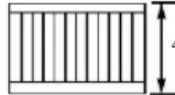
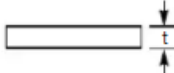
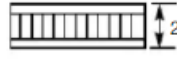
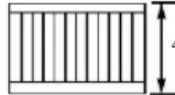
1.4 Effects of Honeycombs Sandwiches on Human Life

The positive effects of sandwich composites, found in almost every part of human life, on people are undeniably significant. For this reason, they are used dominantly in all areas of our lives. People often lead their lives unawares under the positive influence of many different composites. There are positive and negative sides to the sandwich composites, as in every situation. In this section, the positive and negative aspects will be discussed.

1.4.1 Advantages

Undoubtedly, HC has more positive aspects than negative aspects. Otherwise, it would not have been used so widely. We can tabulate its advantages as follows (Table 1). As you can see, it shows that many positive examples are possible in many different fields. But in general, the table can be limited to these main headings.

Table 1: Advantages of HCs

ADVANTAGES OF HONEYCOMB COMPOSITES																	
Vibration	HCs have a very high vibration-absorbing capacity [68].																
Yield Stress	Composites produced resistance to yield stress and can withstand huge yield forces [69].																
Elongation	The amount of elongation at fracture is higher than in metals[70].																
Fatigue	Fatigue resistance is high and allows it to be used for many years without any problems [71].																
Flexibility	It can be designed and produced to increase the usage and application area.																
Accessibility	Being open to modification increases the accessibility of materials.																
Crack Propagation	Crack propagation is minimised. When a crack occurs, it is prevented from continuing and causing damage [72].																
Corrosion	Corrosion is significantly less compared to metals. It can also be reduced to almost zero with the right coating and material selection [73].																
Fire Resistance	Composites are resistant in terms of fire resistance and fungus. They are also resistant to high temperatures [74].																
Machinability	Easily machinable and formable																
Design Flexibility	Composites can be moulded into more complex shapes than many other materials. It gives designers the freedom to create almost any shape or form.																
Weight	The stress withstands capacity is significantly increased without major weight changes [75] <table><tr><td></td><td> Solid Metal Sheet </td><td> Sandwich Construction </td><td> Thicker Sandwich </td></tr><tr><td>Relative Stiffness</td><td>100</td><td>700 7 times more rigid</td><td>3700 37 times more rigid!</td></tr><tr><td>Relative Strength</td><td>100</td><td>350 3.5 times as strong</td><td>925 9.25 times as strong!</td></tr><tr><td>Relative Weight</td><td>100</td><td>103 3% increase in weight</td><td>106 6% increase in weight</td></tr></table>		Solid Metal Sheet 	Sandwich Construction 	Thicker Sandwich 	Relative Stiffness	100	700 7 times more rigid	3700 37 times more rigid!	Relative Strength	100	350 3.5 times as strong	925 9.25 times as strong!	Relative Weight	100	103 3% increase in weight	106 6% increase in weight
	Solid Metal Sheet 	Sandwich Construction 	Thicker Sandwich 														
Relative Stiffness	100	700 7 times more rigid	3700 37 times more rigid!														
Relative Strength	100	350 3.5 times as strong	925 9.25 times as strong!														
Relative Weight	100	103 3% increase in weight	106 6% increase in weight														

1.4.2 Disadvantages

Although composite materials are useful materials, some disadvantages are encountered from time to time. These features are listed in the Table 2 below.

Table 2: Disadvantages of HCs

DISADVANTAGES OF HONEYCOMB COMPOSITES	
Fluid Infraction	HC structures are prone to fluid intrusion [76].
Cost	Composite materials are relatively costly and laborious to make.
Metal Interaction	They do not stick to metals. They cannot be used without baking.
Manufacturing Difficulty	Drilling and cutting type processes cause opening in the fibres.
Damage Assessment	It is tough to detect any malfunction in composite materials [77].

There are not many disadvantages to count. For this reason, HCs, which have few disadvantages compared to their advantages, have gained popularity. There should be no doubt that they will be used in this prevalence in the near future.

1.5 Definition of the Problem and Research Methodology

Honeycomb core sandwich structures are used frequently in several industries to manufacture parts with higher strength and lower weight than other structures. There is an industrial need to develop accurate three-dimensional (3D), non-linear numeric simulation models to analyse the mechanical behaviours of the sandwich structures. The dynamic and static analysis of mechanical properties must be performed in a 3D numerical domain in a lab environment or during industrial production. Humanity needs to create effective structures where raw materials gain value.

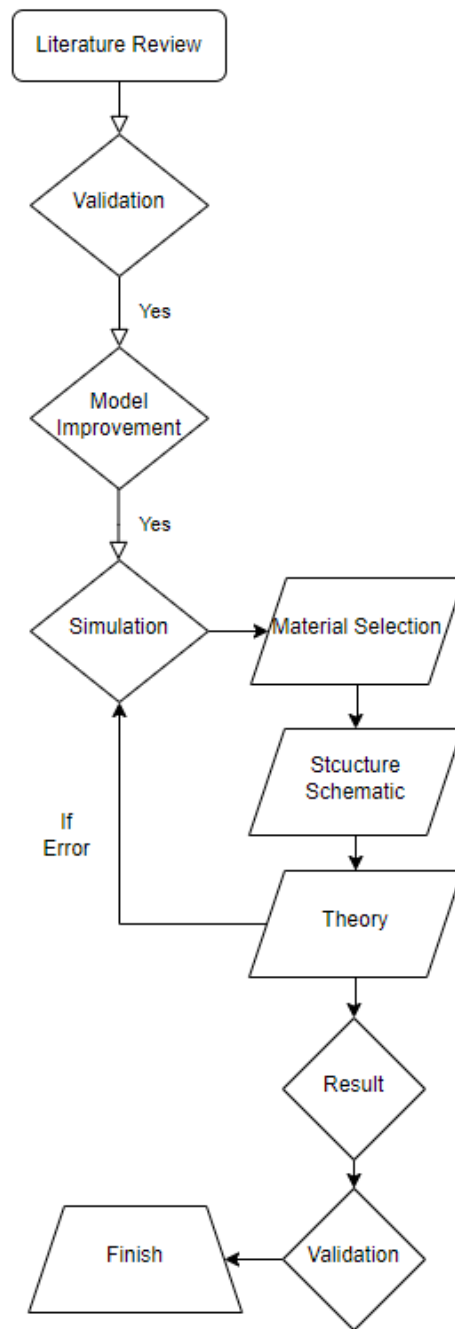


Figure 15: Research Methodology

1.6 Need for Research (Motivation)

This study focuses on analysing and developing the behaviour of sandwich beams with laminated composite face sheets and honeycomb core. Sandwich structures consist of three essential elements: faces, core and adhesives. Core members should have good capability to carry shear loads. The core is incredibly significant since it provides that

the sandwich is light also stiff enough. Honeycomb core is one of the best structurally efficient core structures, especially in stiffness-critical applications, which is assured with possible lowest density and high out-of-plane compression and shear properties. Different materials were used for a similar model. Comparisons of different materials of each model with similar structures were made under different analyses. The analysis results determined the material and structure with the best strength. It is aimed to show better strengths with fin modifications of the honeycomb structure. ANSYS was used for the analysis part. The main objective of this study is to determine the natural frequency of sandwich beams under different boundary conditions, clamp free and clamp-clamp. Valuable insight into the dynamic characteristics of the sandwich beam and detailed information on how it responds to different types of dynamic loading. The analysis did in three bending analyses and different boundary conditions. Also, different materials are used for the face and core. The study shows that the used core has good flexural stiffness and stress resonance resistance at a higher frequency.

1.7 Objectives and Scope of The Study

The natural frequencies and mode shape are functions of the structural properties and boundary conditions.

- To determine the natural frequency of sandwich beam under different configurations such as clamp-free and clamp-clamp.
- Valuable insight into the dynamic characteristics of the sandwich beam and detailed information on how it responds to different types of dynamic loading.
- To determine the effect of foil thickness on modal analysis.
- To propose a model better than the hexagonal honeycomb.

The study aims to improve the durability of the sandwich structured composites with the modification of core structures. FEM analysis method is used to get the validation results. Validation will be taken from other works and experimental work will be done in the other studies. The effects of material, thickness, fracture, heat, and support on the proposed core will be examined and the most optimal model will be revealed by comparing the results.

Chapter 2

LITERATURE REVIEW

2.1 Beam Theory for Sandwich Structures

The study is messing with the sandwich beam. Moreover, the beam theory for sandwich structure is going to be discussed. It is necessary to make some assumptions in beam theory. These are the assumptions that the beam element is made using isotropic materials, and the bonding connection is made perfectly. Elastic calculations will be made with the three-bending method. Another approach is bending theory. The plane's cross-section is perpendicular to the longitudinal axis [78,79]. It is loaded with L length b width supported and Q per unit with the central load. This geometry has been studied before and is shown in the Figure 16 below.

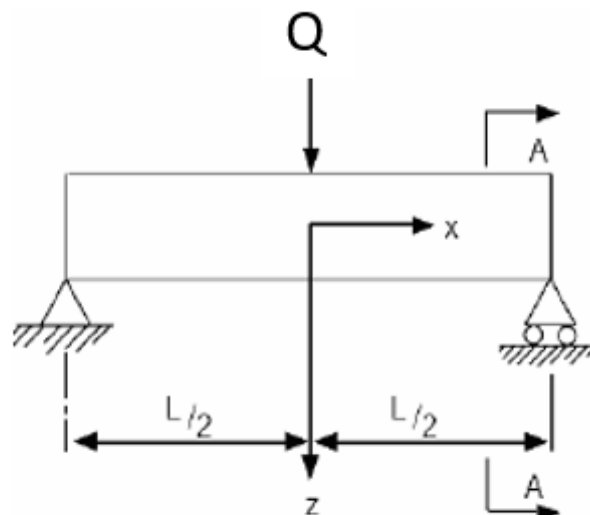


Figure 16: Sandwich Beam Definition [79]

As in the Figure 16, some relations must be provided if the beam is analysed. Also, suppose correlations are not provided or more than two edges supported the beam. In that case, it should be analysed as a panel [80].

Variables such as the flexural rigidity of the sandwich beam, axial stresses that occur at the facings under maximum bending moment, and sandwich beams with low-density cores facing stresses can be obtained from equations [78]. Different formulas have also occurred for different loading and boundary condition states [81].

2.2 Orthotropy - Anisotropy

A material is isotropic if it shows the same mechanical properties in all three axes and orthotropic if it shows independent and different properties in all three axes. Materials that show the characteristics of symmetrical material in two axes perpendicular to each other are called orthotropic. Examples of orthotropic materials are wood, most crystals, and rolled metals. Core materials are mostly orthotropic materials, while face sheet materials are generally isotropic. However, the face may also show orthotropic behaviour [82]. Hooke's stress-strain relation is a very competent relation on the subject. This relation can be written as:

$$\sigma_t = C_{ij} \cdot \varepsilon_j \quad i, j = 1, 2, \dots, 6 \quad (1)$$

C_{ij} is the stiffness matrix, which consists of 6x6 36 constants. But this number is less for elastic materials. Because stiffness matrices of elastic materials are not asymmetrical, they are symmetrical, and there are 21 independent constants [2]. The stress-strain relation of anisotropic materials is as follows.

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{pmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix} \cdot \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{pmatrix} \quad (2)$$

The independent elastic coefficients are nine for an orthotropic material. The stress-strain relations for an orthotropic material are shown below:

$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{31} \\ \tau_{12} \end{pmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \cdot \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{31} \\ \gamma_{12} \end{pmatrix} \quad (3)$$

The equations show both situations. Besides, orthotropic material has less than one refractive index, but anisotropic material has a higher one. It is the anisotropic composite material showing different properties according to the axis or axes that are measured. Measurements made along a particular axis or in a direction parallel to a particular plane will differ from values taken in other directions. The mechanical properties of a composite containing continuous and arrayed fibres are highly anisotropic; the values change according to the measuring direction; max strength and reinforcement are achieved in the longitudinal array direction of the fibres. Orthotropic materials are defined as a subclass of anisotropic materials. The properties of orthotropic materials differ in three perpendicular directions. It has three perpendicular axes of symmetry. Normal relaxations occur when loads parallel to the axis are applied to the axes. Normal and shear relaxations occur if the applied load is not parallel to the axes. Because of that, orthotropic material's mechanical properties are a function of orientation. Composites with three symmetrical planes are called orthotropic

composites. The following Figure 17 shows the structural structures of anisotropic and orthogonal materials.

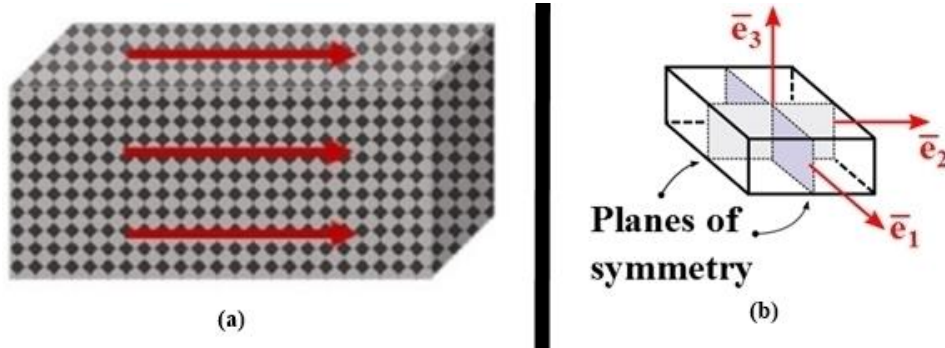


Figure 17: (a) Anisotropic Structure (b) Orthotropic Structure [83]

2.3 FEM Modelling of HCs

Honeycomb core sandwich structures have many variables as parameters. For this reason, its modelling is quite difficult. It is difficult to put this problem into a mathematical equation with many variables [84]. Different mathematical models should be used according to different core structures, loading directions, and variables to be observed. In the past, those parameters were optimised, and an energy absorption diagram was proposed for honeycomb sandwich structures [85]. In addition, studies such as failure mechanism maps have been carried out to prevent situations where structures cannot provide strength conditions [86,87]. The programs used to create these maps are usually ANSYS, COMSOL, and ABAQUS. Assistance is taken from SolidWorks and AutoCAD Inventor in the modelling part [88–90]. In the background, a spectral algorithm was devised for mathematical modelling of the honeycomb structure in the program, these equations were based on a modified thin-sheet gain scheme and a fast Fourier transform technique [91]. The adhesive mechanics between the layers must also be modelled on the structure, which must be analysed in itself and also examined as a whole [92].

Many studies have been done on this subject, but today this connection has been optimised and achieved consistent results [93]. Some works analysed the shear buckling of aluminium honeycombs and proposed improved analytical methods to calculate the buckling load [94,95]. Also, nonlinear and linear responses depend due to the situation of the load. Research has been done on the nonlinear responses of honeycomb made of aluminium in shear experiments and proposed finite element modelling with some misleading. But it helps to make it possible to correctly guess the stiffness and the critical buckling load [96]. One research proposed a nonlinear model based on damage mechanics only in compression for nonlinear behaviour [97]. There are plenty of potential designs modelled because of the improvement of mechanical properties of honeycomb cores and the challenges in further research [98].

2.4 Geometric Modelling of HCs

In recent years, several sandwich structures with improved quasi-static and dynamic properties have been introduced, comprising those based on various foam, honeycomb cores, origami cores and truss cores [99]. Katzman et al. [100] proposed sandwich structures are usually based on honeycomb core and polymeric foam materials. The mechanical property of honeycomb sandwich structures shows plenty of different behaviours combining high flexural rigidity and bending strength with low weight. Bending strength and Flexural rigidity are important mechanical properties of honeycomb sandwich beams [101]. As a result of the theoretical studies conducted in the face of this wide-variable situation, it was determined that the weight of the honeycomb core should constitute 50-66.7% of the entire sandwich structure. This weight ratio range of the honeycomb core deduced based on optimum mechanical properties offers a principal foundation for designing [102]. The honeycomb structure is in the category of core models with truss structure. Previous studies have revealed

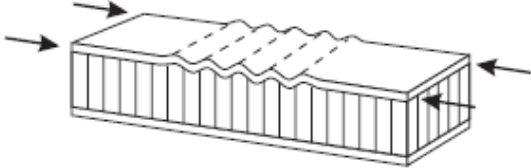
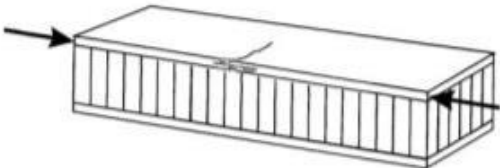
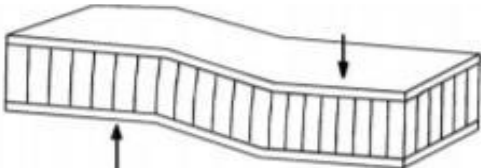
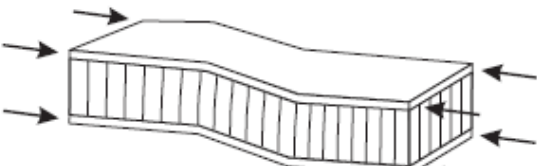
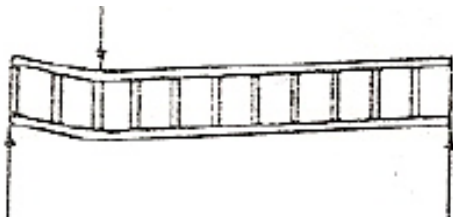
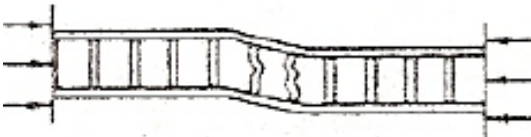
the best flexural stiffness and strength in truss-supported core structures' bending deformation [103]. Strength/Weight ratios are also valid for sandwiches with other truss structures. Many structures such as circular, triangular, square, and triangular honeycomb have been studied for the truss core structure [104,105]. In a study on square structures, sandwich structures have significantly higher compressive and shear modulus than the other sandwich panels on an equal mass basis [106]. Or even can be considered a promising candidate for multifunctional structure material in the high-end heat dissipation field [107]. The symmetrical design was exceeded, and graded corrugated truss cores were studied. It was observed in the study that the bending behaviour improved slightly. Also, a higher buckling load was observed under a three-point bending load [103]. The core structure was tried to be strengthened with extra supports without changing the symmetrical structure of the core structure. These were called ortho grids in general, and the purpose of use on the structure was to strengthen the load distribution within the structure itself [108]. Some works show that corrugated cores have better shear strengths in the longitudinal direction than those exhibited by diamond cores and more traditional foam cores. Besides, it can give outstanding ventilation characteristics, avoiding humidity retention problems that are common in cellular core materials [109]. Corrugated cores with metal sandwich beams are the significant industrial solution as structural components. Because of their high stiffness/mass ratio. However, finite element models for numerical computation of their properties leads to large models and long solution time. Because of that, a decrease of the complex shaped core to an equivalent homogenous material is usually used [110]. In a previous study comparing different core structures, it was observed that the most effective structure was honeycomb [111].

Since the honeycomb is the most optimised durable core structure, two different failures were observed in the studies on the failure situations of this structure. Ruptures on the face and collapse on the core. At the same time, it was observed that these strengths varied according to the applied test loading or impact speeds [112,113]. Also, honeycomb cell size, honeycomb wall thickness and honeycomb thickness have low effects on the penetration resistance of the sandwich panel [114]. The deflection evolution of the composite honeycomb sandwich structure can be divided into three stages under three-point bending fatigue load, rapid decline, steady decline and failure [115]. In the study on the beam, the load/weight ratio of the optimum geometry was found to be $H/L=1/8$, and experiments proved it. Here H being the total thickness of the sandwich structure, and L is the total length of the beam [86].

2.5 Failure Modes of Honeycomb Sandwich Structures

Composites can work in extreme conditions. It creates various failure models. Most of the time, HCs one side is in compression, and the other side is in tension. The core in between is exposed to different shear forces at different thicknesses. Various failures occur according to the effect of these forces on the material. In case of tension, tears may occur in the coating sheets. In the case of compressive load, the core cannot resist the incoming stress and is crushed. In the case of shear force, ruptures can occur on the structure. Various studies have been conducted to model and account for such failures [116,117]. These failure models are given in the Table 3 below.

Table 3: Failure Modes of Honeycomb Composites[78,118]

Intracell Buckling	
Facesheet Wrinkling	
Facesheet Tension Failure	
Core Shear Failure	
Shear Crimping	
Transverse Shear Failure	
General Buckling	

Chapter 3

METHODOLOGY

3.1 Geometric Modelling of Honeycomb Sandwich Beam

The software ANSYS 2021.R2 Space claim was used to create the finite element model of the honeycomb sandwich beam. The sandwich structure developed in this research has dimensions of 290 mm x 40 mm x 11 mm. The thickness of the honeycomb sandwich beam face-sheet and the core is 1mm and 9mm respectively. Moreover, the proposed structure is a honeycomb hexagonal structure with an inbuilt star-shaped reinforcement as shown in Figure 18 to investigate the natural frequency of free vibration with different boundary conditions, the inbuilt star-shaped core is assigned different materials and analysed, taking note of the total deformation reported frequency. In addition, the factors that were focused on is the mass and stiffness of the overall sandwich beam while considering the vibration characteristics, corresponding natural frequencies and mode shapes. In general, adopting the RVE method in ANSYS Material Designer, to determine the effective, or average elastic properties of the unit cell. Assuming that the unit cell is repeated uniformly over the domain of an entire structure, thereby defining the entire domain by the unit cell's effective constitutive properties. Hence, the result is an orthotropic stiffness matrix, which can then be used as a material property in larger structures. Figure 19 shows the discrete proposed core model. Material properties required in this study are tabulated in Table 4.

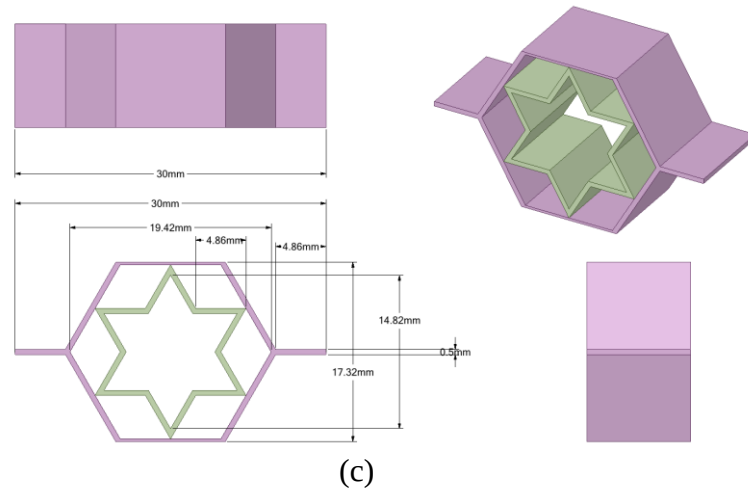
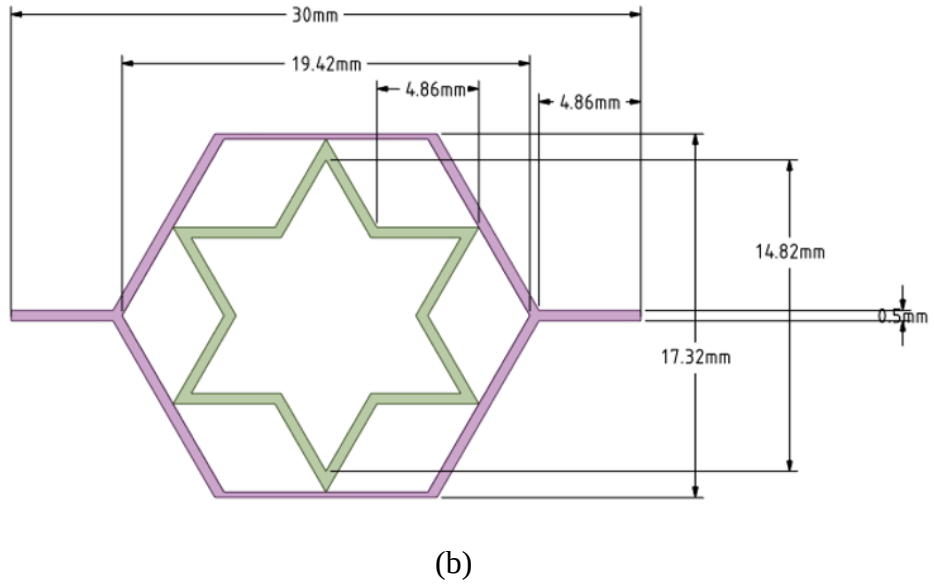
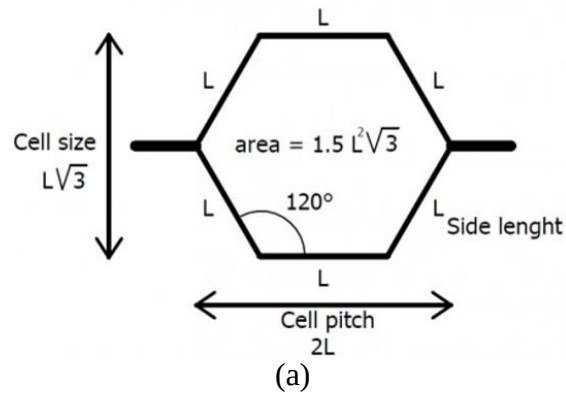
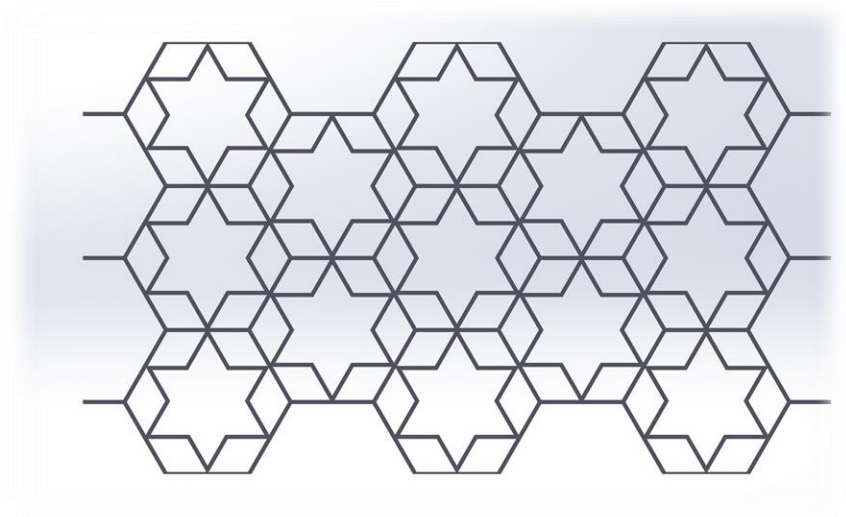
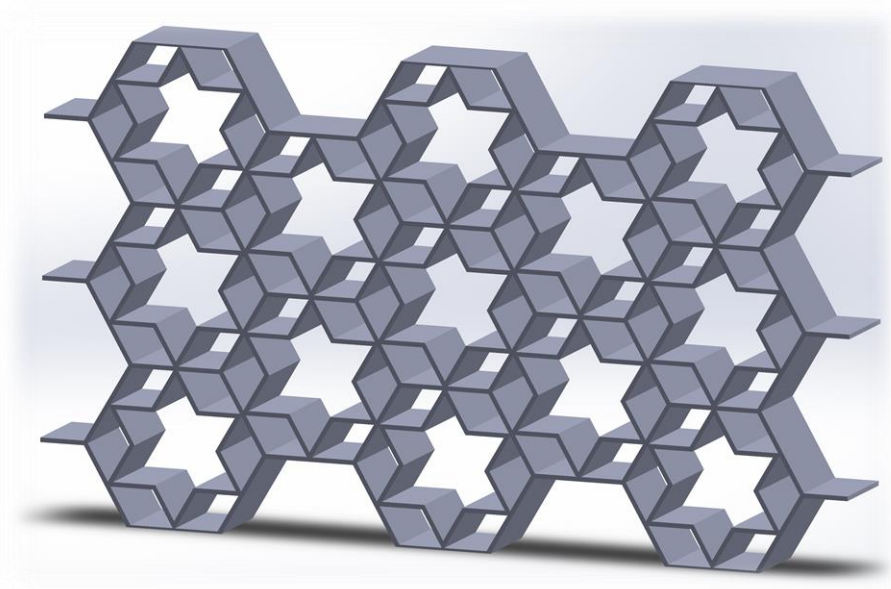


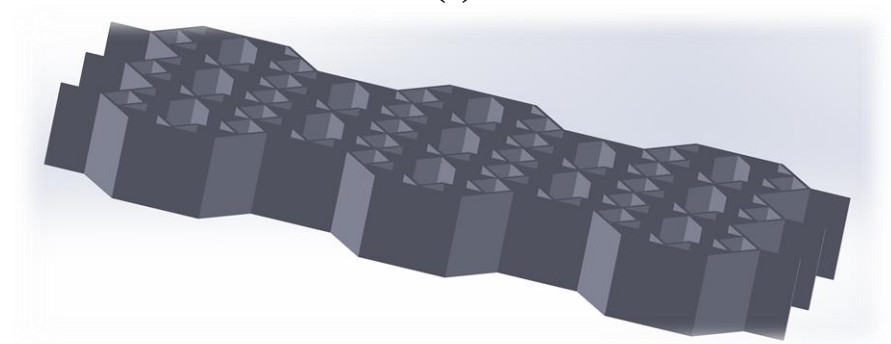
Figure 18: Geometry Of RVE Model (A) Honeycomb Unit Cell; (B) Honeycomb With Star-Shaped Reinforced Unit Cell; (C) Unit Cell Angle Projection.



(a)



(b)



(c)

Figure 19: Proposed Core Discrete Model; (A) Plain View; (B) Side View; (C) Isometric View

Table 4: Material Properties of Honeycomb Sandwich Beam

Material	Young's Modulus E (MPa)	Poisson's Ratio ν	Shear Modulus G (MPa)	Density ρ (Kg/m³)
Carbon Fibre	290000	0.2	9000	1800
SAN Foam	85	0.3	32.69	103
Aluminium Alloy	71000	0.33	26691.72	2770
PVC Foam	102	0.3	39.23	80

3.2 Finite Element Meshing

It is the conversion of geometrical entities to finite element entities. Hence, 'Mesh' in the RVE model group was selected, the mesh maximum size is 0.25 mm (half the thickness of the unit cell), and periodic meshing and conformal meshing were used as depicted in Table 5. Figure 20 shows both the equivalent model of the regular hexagonal honeycomb and the proposed star-shaped reinforced core. Hexagonal honeycomb consists of a 'unit cell' repeated many times in one or more spatial directions. This unit cell is usually a fraction of the size of the overall structure under investigation. Hence, in ANSYS Workbench 2021 a new feature called "Material Designer" is applied, a technique called "homogenization", in which the unit cell structure is considered independently. The purpose is to figure out the unit cell's effective, or average elastic properties. In addition, assuming that the unit cell is consistently replicated over the domain of an entire structure, the effective constitutive properties of the unit cell will also characterize the entire domain. In general, the result is an orthotropic stiffness matrix, which can subsequently be used as a material property in larger structures, and the honeycomb structure is replaced with 'homogenized' (effective) material properties shown in Table 6 (Material Designer gives the nine independent material constants (three elastic moduli, three shear constants, and three Poisson ratios)).

Table 5: Analysis of Mesh

Unit cell	Number of Elements	Number of Nodes
Hexagonal honeycomb	2210	4956
Proposed core	2942	6553

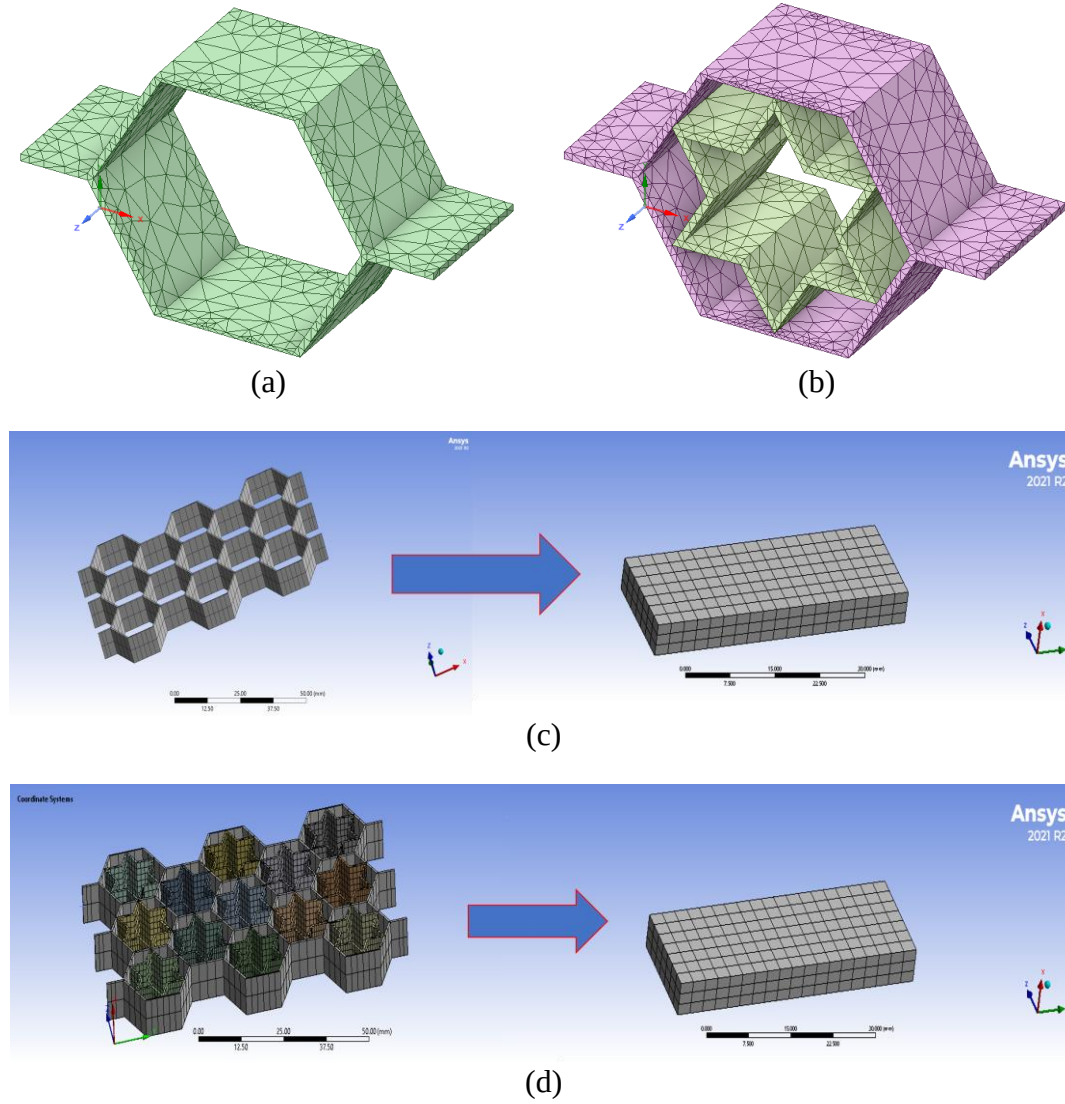


Figure 20: Meshing (A) Hexagonal Meshing; (B) Proposed Core Meshing; (C) Equivalent Model of Hexagonal Core Meshing; (D) Equivalent Model of Proposed Core Meshing

Table 6: Orthotropic Material Properties of RVE Proposed Core.

Single Hexagonal	SAN Foam	SAN Foam	SAN Foam	SAN Foam	Material Hexagonal
SAN Foam Material	Carbon Fibre	Aluminium Alloy	PVC	SAN Foam	Material Star Core
5.86	100.78	151.94	10.07	11.29	Density (kg/m ³)
0.0278	2.5332	2.4994	0.1315	0.1161	E _x (MPa)
0.0278	2.5332	2.4994	0.1315	0.1161	E _y (MPa)
4.84	1218.78	3749.12	10.215	9.3191	E _z (MPa)
0.988	0.027	0.118	0.951	0.957	ν_{xy}
0.0017	0.0003	0.0002	0.0038	0.0037	ν_{yz}
0.0017	0.0003	0.0002	0.0038	0.0037	ν_{xz}
0.00699	0.01578	0.01580	0.01142	0.01121	G _x (MPa)
0.9548	1.8960	1.8990	1.4188	1.3762	G _y (MPa)
0.9548	1.8960	1.8990	1.4188	1.37620	G _z (MPa)

3.3 Modelling Boundary Condition

The boundary condition of the sandwich beam is chosen as clamped-free and clamped-clamped for the free vibration analysis. Hence for the elliptical cut investigation, the

clamped-free is assigned, while the elliptical cut position changes along the length of the beam as shown in Figure 21 Table 7 depicts the dimension of the beam.

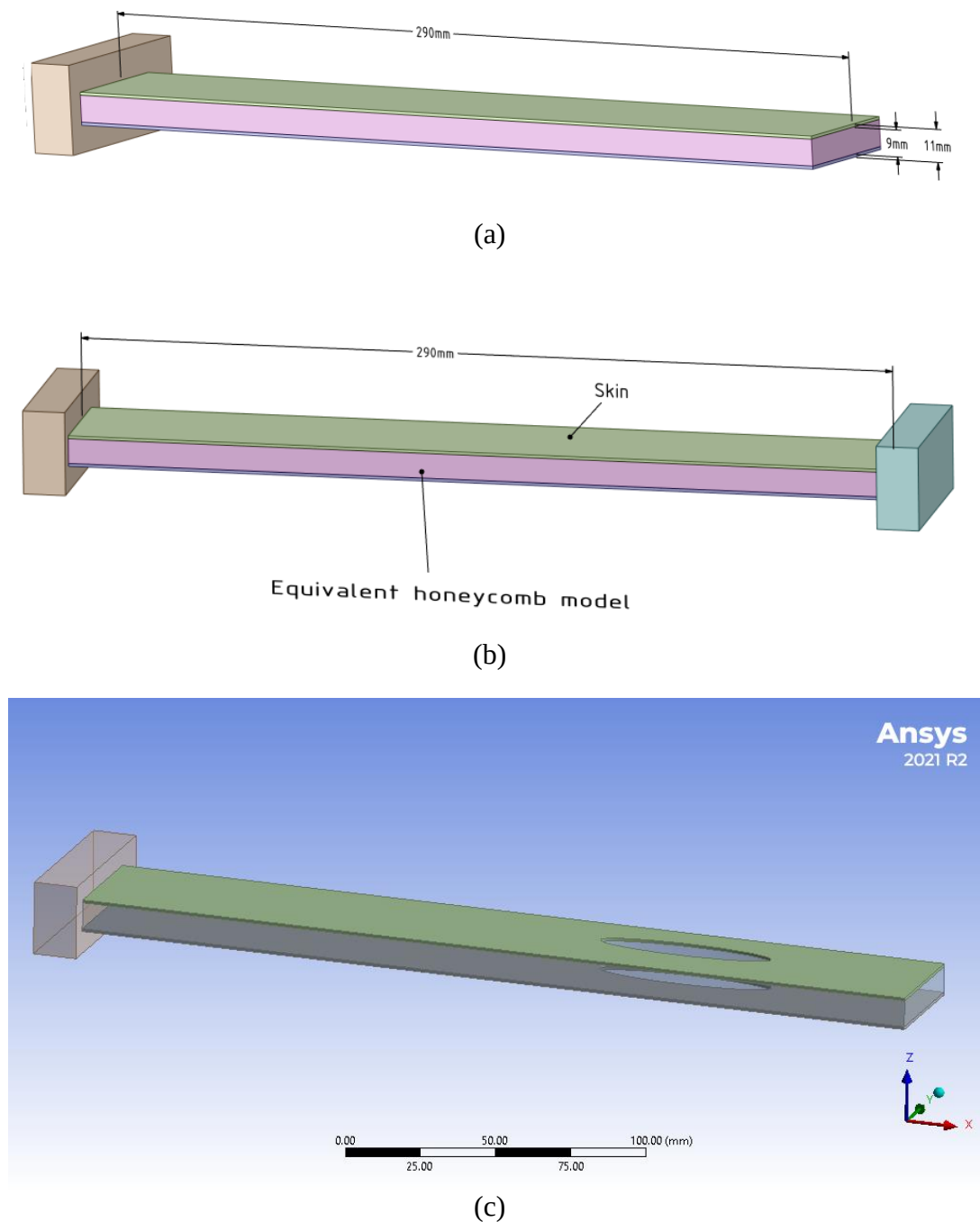


Figure 21: Boundary Conditions (A)Clamped-Free; (B) Clamped-Clamped; (C) Clamped-Free With Elliptical Cut

Table 7: Dimensions of the Honeycomb Sandwich Beam

Cell size (mm)	Core thickness (mm)	Cell thickness (mm)	Skin (mm)	Length (mm)	Width (mm)
10	10	0.5	1	290	40

3.4 Analytical Models

Using the beam theory [119] the equivalent mechanical properties of honeycombs can be obtained starting with isotropic constants of the core material- mass density, E_s - Young's modulus and ν_s - Poisson's ratio.

3.5 Classical Honeycombs

The relative density of the equivalent core is

$$\frac{\rho}{\rho_s} = \frac{\frac{t}{\ell} \left(\frac{h}{\ell} + 2 \right)}{2 \left(\frac{h}{\ell} + \sin \theta \right) \cos \theta} \quad (4)$$

The Young's moduli parallel to OX and OY are:

$$E_1 = k_1 E_s \left(\frac{t}{\ell} \right)^3 \frac{\cos \theta}{\left(\frac{h}{\ell} + \sin \theta \right) \sin^2 \theta} \quad (5)$$

$$E_2 = k_2 E_s \left(\frac{t}{\ell} \right)^3 \frac{\frac{h}{\ell} + \sin \theta}{\cos^3 \theta} \quad (6)$$

$$k_1 = \frac{1}{1 + \left(\frac{t}{\ell} \right)^2 (2.4 + 1.5\nu_s + \cot^2 \theta)} \quad (7)$$

$$k_2 = \frac{1}{1 + \left(\frac{t}{\ell} \right)^2 \left(2.4 + 1.5\nu_s + \tan^2 \theta + 2 \frac{h}{\ell \cos^2 \theta} \right)} \quad (8)$$

The in-plane Poisson's ratios can be calculated using:

$$v_{12} = c_{12} \frac{\cos^2 \theta}{\left(\frac{h}{\ell} + \sin \theta\right) \sin \theta} \quad (9)$$

$$v_{21} = c_{21} \frac{\left(\frac{h}{\ell} + \sin \theta\right) \sin \theta}{\cos^2 \theta} \quad (10)$$

$$c_{12} = \frac{1 + \left(\frac{t}{\ell}\right)^2 (1.4 + 1.5v_s)}{1 + \left(\frac{t}{\ell}\right)^2 (2.4 + 1.5v_s + \cot^2 \theta)} \quad (11)$$

$$c_{21} = \frac{1 + \left(\frac{t}{\ell}\right)^2 (1.4 + 1.5v_s)}{1 + \left(\frac{t}{\ell}\right)^2 \left(2.4 + 1.5v_s + \tan^2 \theta + 2 \frac{h}{\ell \cos^2 \theta}\right)} \quad (12)$$

The in-plane shear modulus is

$$G_{12} = k_{12} E_s \left(\frac{t}{\ell}\right)^3 \frac{\frac{h}{\ell} + \sin \theta}{\left(\frac{h}{\ell}\right)^2 \left(1 + \frac{2h}{\ell}\right) \cos \theta} \quad (13)$$

$$k_{12} = \frac{\left(1 + \frac{2h}{\ell}\right)}{1 + \frac{2h}{\ell} + \left(\frac{t}{\ell}\right)^2 \left\{ \frac{\ell}{h} (2.4 + 1.5v_s) \left(2 + \frac{h}{\ell} + \sin \theta\right) + \frac{\frac{h}{\ell} + \sin \theta}{\left(\frac{h}{\ell}\right)^2} \left[\left(\frac{h}{\ell} + \sin \theta\right) \tan^2 \theta + \sin \theta \right] \right\}} \quad (14)$$

The coefficients, or correction factors, k_1 , k_2 , k_{12} , c_{12} and c_{21} become equal to 1 if the axial and shearing force contributions to the total strain energy are neglected.

3.6 Equivalent Honeycomb Sandwich Beam

The created equivalent model is used in this research. Hence, the time spent on the analysis is reduced and the computational time decreases significantly.

The homogenization concept is regularly used in the research of the mechanical behaviour of composite materials. This method allows for the avoidance of difficulties associated with heterogeneities. Therefore, when considering the genuine constitution of material, one idealizes it by considering it continuous, which is made easier using Material Designer in ANSYS Workbench for a more efficient workflow.

Moreover, by comparing the membrane and bending stiffness of a honeycomb sandwich plate to those of an isotropic plate, the corresponding features of the honeycomb sandwich plate can be calculated.

$$t_{eq} = (3h^2)^{\frac{1}{2}} \quad (15)$$

$$E_{eq} = \frac{2}{\sqrt{3}} \cdot \frac{t}{h} \cdot E \quad (16)$$

Considering anisotropic mechanical behaviour, honeycombs are all closed-cell structures. The equivalent density is calculated by identifying a unit cell and calculating the volume fraction occupied by metal. The equivalent density is calculated by using the following [120]:

$$\rho_{eq} = \frac{2\rho_f t + 2\rho_c(H - t)}{t_{eq}} \quad (17)$$

The theory was applied to a beam with clamped-free boundary conditions in this study for the analytical comparison of the equivalent model's first modal frequency.

A simple plate's fundamental frequency is given by:

$$f = \frac{1.01}{2\pi} \sqrt{\frac{E \cdot h^2}{\rho a^4}} \quad (18)$$

Chapter 4

RESULT AND DISCUSSION

4.1 Free Vibration of Honeycomb Beam

In this section, a modal analysis of honeycomb equivalent sandwich beam is presented: Analytical approach based on the equivalent model theory, finite element analysis is presented. The results will be presented by this method numerically, analytically and compared with experimental data. The objective of this study is to parameterize honeycomb structure, on factors that can affect its natural frequencies, the effect of boundary conditions, foil thickness, and materials combination effect on modal analysis to get more insight into the vibration characteristics. In general, a proposed reinforced star core will be introduced and examined. As a result of that, the density will be considered, thereby determining the best material combination for high flexural stiffness, higher frequency and lighter weight.

Considering a classical honeycomb, with an isotropic material having $E_s = 1000$ MPa, $\rho = 1000$ kg/m³ $\nu_s = 0.3$, and with $t = 1$ mm and $L = 10$ mm, the results obtained analytically and with FEMs are presented in Table 8. However, having validated the regular honeycomb RVE with the analytical and FEM using ANSYS Material Designer method, Hence the same pattern is used for the unit cell proposed model orthotropic material properties that will be used throughout this research.

Table 8: Results for Validation of RVE Models

Regular honeycomb: $L = h = 10$ mm and $\theta = 30^\circ$						
Model	ρ (Kg/m ³)	E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	V_{12}	V_{21}
Analytic	115.5	2.18	2.18	0.56	0.96	0.96
Present	112.14	2.572	2.572	0.657	0.957	0.957
Solid 3D [121]	112.10	2.570	2.570	0.660	0.960	0.960

4.2 Effects of Materials on Free Vibration

Under the modal analysis, the sandwich beam natural frequency was investigated with different materials and their corresponding deformation. Moreover, considering the effect of free vibration of honeycomb core, Figure 22 shows a hexagonal honeycomb core with the same dimensions, having cantilever beam boundary conditions, simulated with three different materials, aluminium alloy, carbon fibre and SAN foam to investigate their natural frequencies and mode shapes. It was observed that aluminium has a much higher natural frequency, carbon fibre is slightly below while SAN foam is way below, having the lowest in all the 6 modes. As a result of that, aluminium is stiffer in later modes, especially those that are subjected to double tension and compression cyclic loading. Moreover, while considering the deformation of sandwich structure in line with their corresponding frequencies, the Figure 23 depicted the deformation of three materials of sandwich core on free vibration, as expected the SAN foam having the lowest natural frequency that will cause excitation, has the most deformation. It was observed that Carbon fibre has the lowest deformation, indicating that Carbon fibre has better stiffness to mass ratio than aluminium.

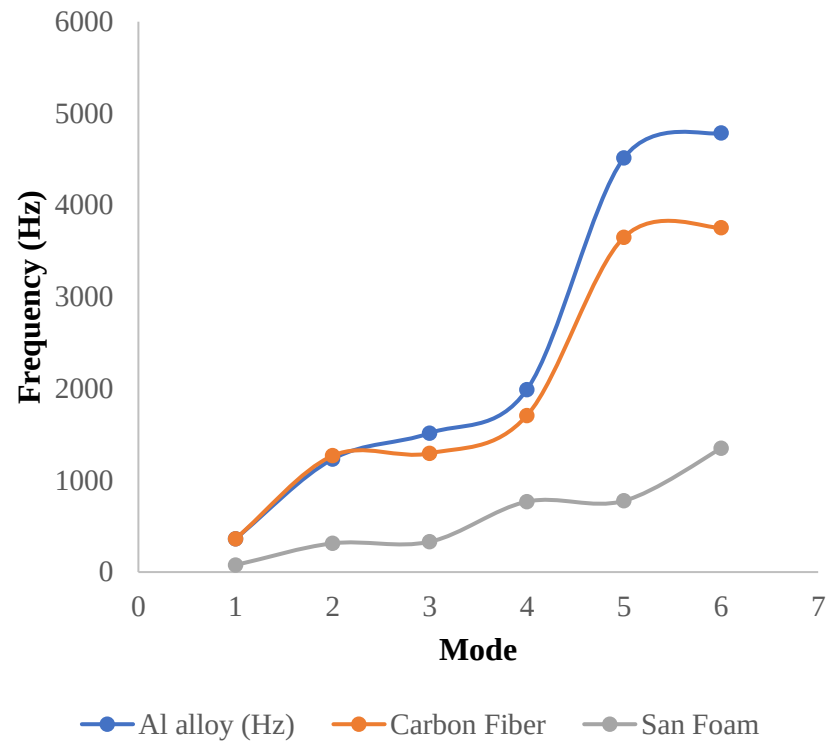


Figure 22: Effect of Materials on the Natural Frequency

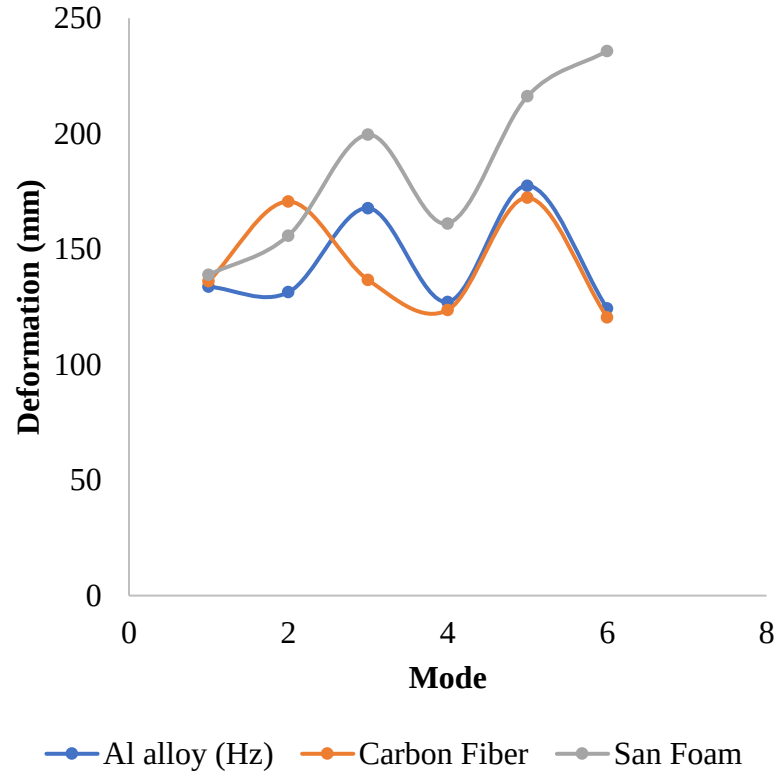


Figure 23: Effect of Deformation on Material

4.3 Effect of Boundary Conditions (CF and CC) on Free Vibration of the Sandwich Structure

Investigating two boundary conditions of sandwich structure vibration characteristics, clamp-free and clamp-clamp on free vibration. Figure 24 shows mode 5 directional deformation of the sandwich structure on clamp-free condition with 3 different materials used as core. However, Carbon fibre and aluminum core have a similar pattern of deformation while SAN foam deviated much with multiple tension and compressive stresses. Moreover, to get insight into the sandwich structure and monitor incremental changes, the clamp-clamp boundary condition was investigated in Figure 25, it was observed that the peak amplitude of the SAN foam sandwich core is higher, thereby having larger deformation and undergoing 4 tensile and compressive stresses.

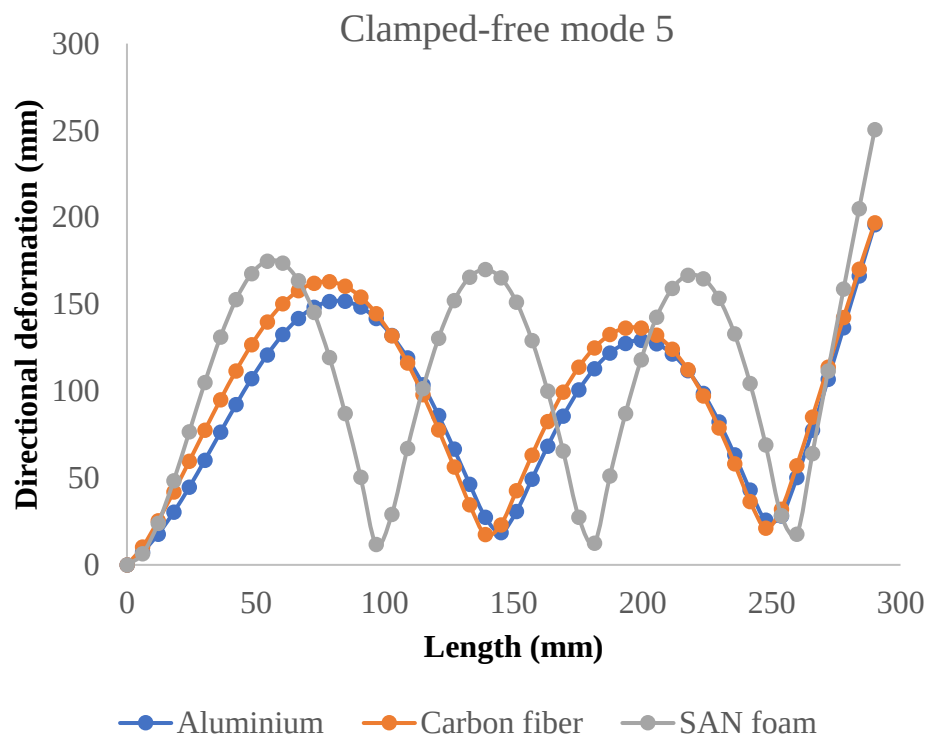


Figure 24: Directional Deformation on Mode 5 (Clamped-Free)

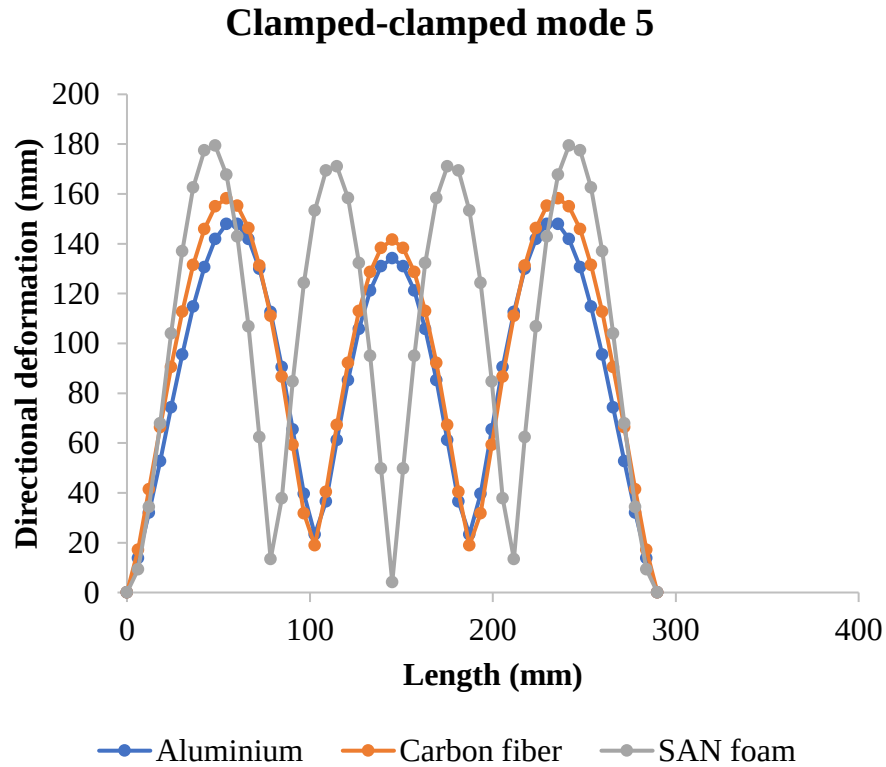


Figure 25: Directional Deformation on Mode 5 (Clamped-Clamped)

4.4 Effect of Hexagonal Cell Foil Thickness on Free Vibration

In this case, cell parameters of the hexagonal cell were considered on free vibration and the effect was investigated. Hence, the sandwich structure dimensions are the same, the cell dimension changed while the sandwich length and thickness are kept the same. Figure 26 shows the free vibration of foil thickness; it is observed that as the foil thickness increases the natural frequency decrease on the clamped-free boundary condition. In addition, the variations are closely and almost negligible, indicating that changing the foil thickness is not an effective way to alter the vibration characteristic of honeycomb sandwich structure and it will increase the weight as shown in Table 9 which illustrates that a 10% increment of foil thickness equally increases the density around 9%.

Variation of Hz w.r.t Foil Thickness for Hexagonal Honeycomb.

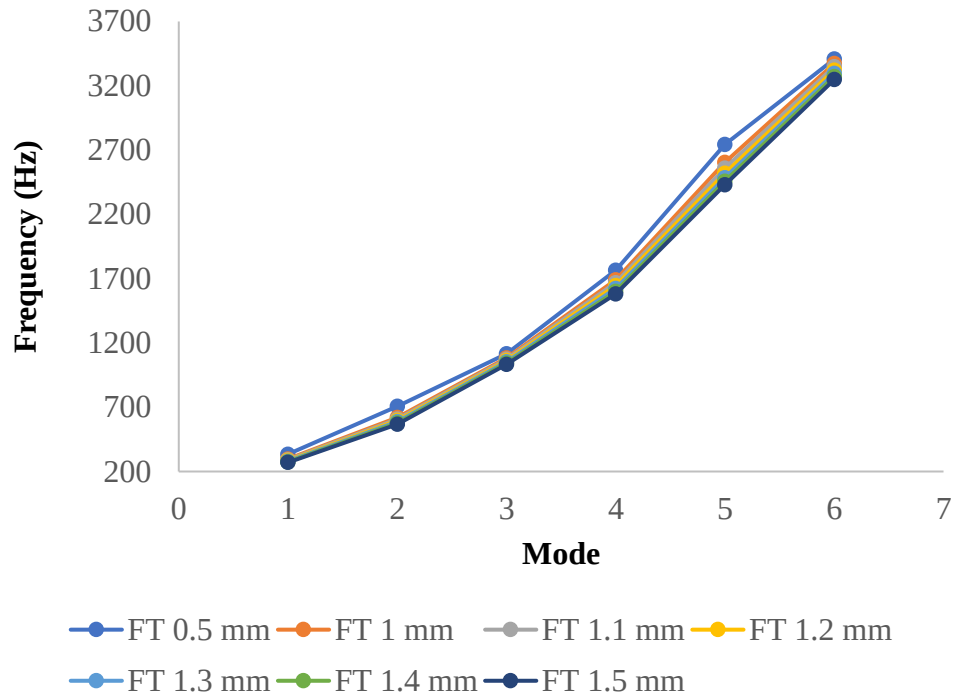


Figure 26: Variation of the Frequency For Foil Thickness

Table 9: Variation of Density and Foil Thickness

Foil Thickness	Thickness	Density (kg/m ³)	Ex (MPa)	Ey (MPa)	νxy	Gx (MPa)
1	10	385.39	403.95	403.95	0.92	104.18
1.1	10	422.34	536.20	536.20	0.91	138.88
1.2	10	459.00	689.35	689.35	0.89	180.20
1.3	10	495.38	859.31	859.31	0.88	227.69
1.4	10	531.46	1070.68	1070.68	0.86	284.47
1.5	10	567.26	1303.13	1303.13	0.84	346.21

4.5 Pre-Stressed Modal Analysis on Sandwich Structure

Investigating how the mode frequencies change with thermal load at different values of temperature. Constraining both ends of the sandwich structure, setting the displacement boundary condition to constrain in all three directions, hence, allowing the sandwich free to uniformly deform between the constraints, thereby creating a

uniform state of stress in the sandwich and the temperature was set to 22 degrees centigrade and subjected to thermal load to generate thermal stresses in the sandwich. Moreover, the total strain development is equal to the sum of elastic and thermal strain. In this case, since the bar is fully constrained in the axial direction, the total strain is zero in all cases therefore, the elastic strain develop in the sandwich is equal in magnitude but opposite in sign compared to the thermal strain. As a result, when the thermal load is more than the reference temperature, the thermal strain is positive and that makes the elastic strain negative which indicates compressive stresses on the sandwich, similarly, when the thermal load on the sandwich is less than the reference temperature, the thermal strain is negative, therefore making the elastic strain positive and tensile stresses are developed in the sandwich. Figure 27 depicts the mode frequencies changes with thermal loads.

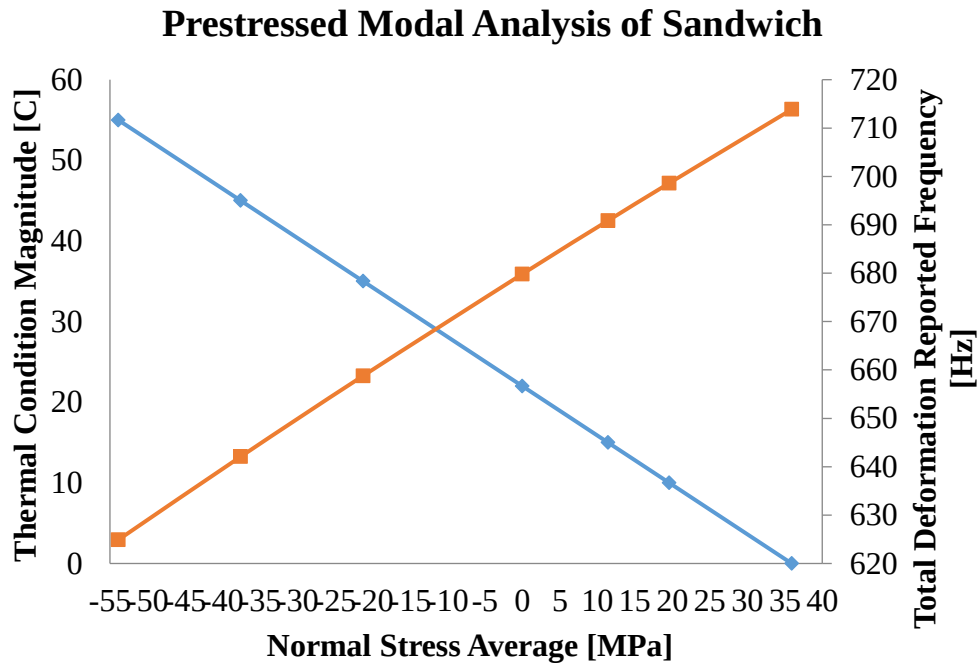


Figure 27: Frequencies of Changes with Thermal Load

4.6 Proposed Reinforced Star Core Model

The hexagonal honeycomb was further designed to accommodate a star-shaped core in the centre. However, the central core provides excellent torsional resistance while the hexagonal-shaped provides extremely lateral bending resistance. As a result of this, a simulation is carried out in ANSYS Workbench, whereby different materials are assigned to the proposed model. In this case, the regular hexagonal material is kept the same as SAN foam while the star-shaped reinforcing materials vary as SAN foam, PVC foam, aluminium and carbon fibre. Table 10 shows the natural frequency of the proposed core only under clamped-clamped and clamped-free boundary conditions. Figure 28 shows the natural frequency of the proposed core model under clamped-clamped conditions, it is observed that the core with hexagonal SAN foam material and PVC foam star-shaped reinforcement has a better stiffness to mass ratio, having higher natural frequencies than the rest. Moreover, repeating the same simulation of the proposed core natural frequency under clamped-free condition, PVC foam and SAN foam remains the best material combination for higher frequency as shown in Figure 29.

Table 10: Proposed Reinforced Star-Core Model Free Vibration Response Under Clamp-Clamp

Mode	SAN foam (SC) - SAN foam (HC)	PVC (SC) - SAN foam (HC)	AL(SC) - SAN foam (HC)	CF(SC) - SAN foam (HC)	SAN foam HC shape only
1	13.87	15.48	14.08	17.38	11.16
2	29.67	31.95	16.14	19.88	31.1
3	35.82	39.24	16.19	19.9	31.67
4	38.07	42.45	32.43	39.83	33.31
5	63.18	68.37	38.6	47.66	61.92
6	74.43	82.89	41.07	50.67	68.82
Density kg/m ³	512.88	511.88	627.95	586.1	508.39

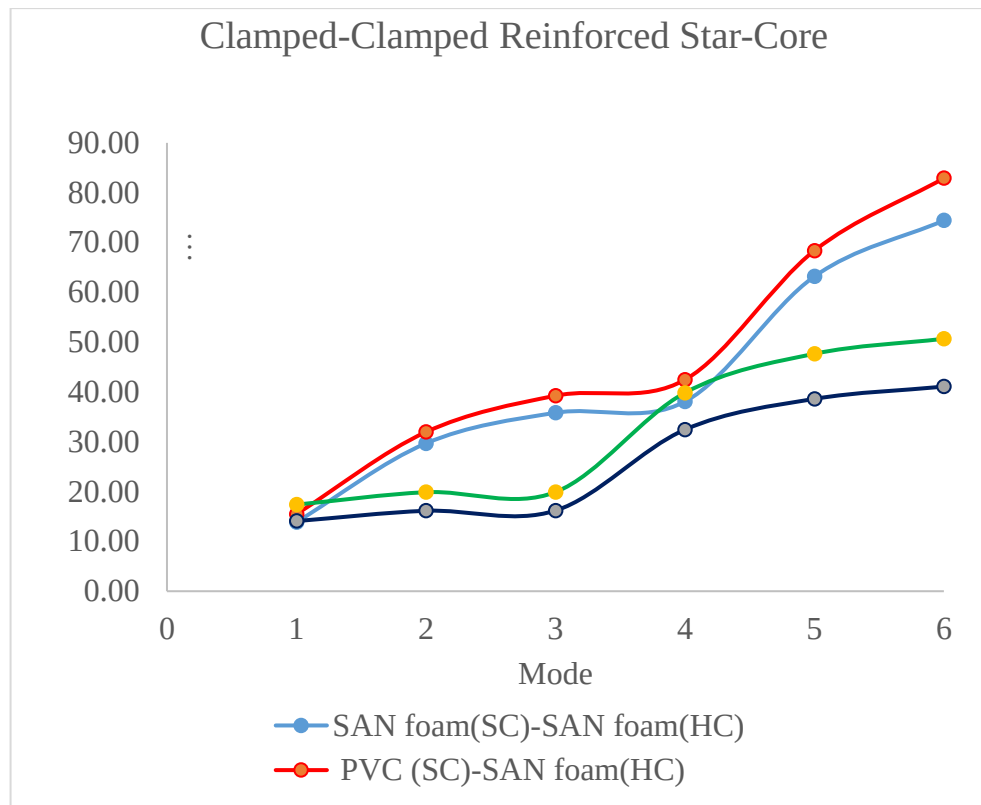


Figure 28: Natural Frequency of Proposed Core (Clamped-Clamped)

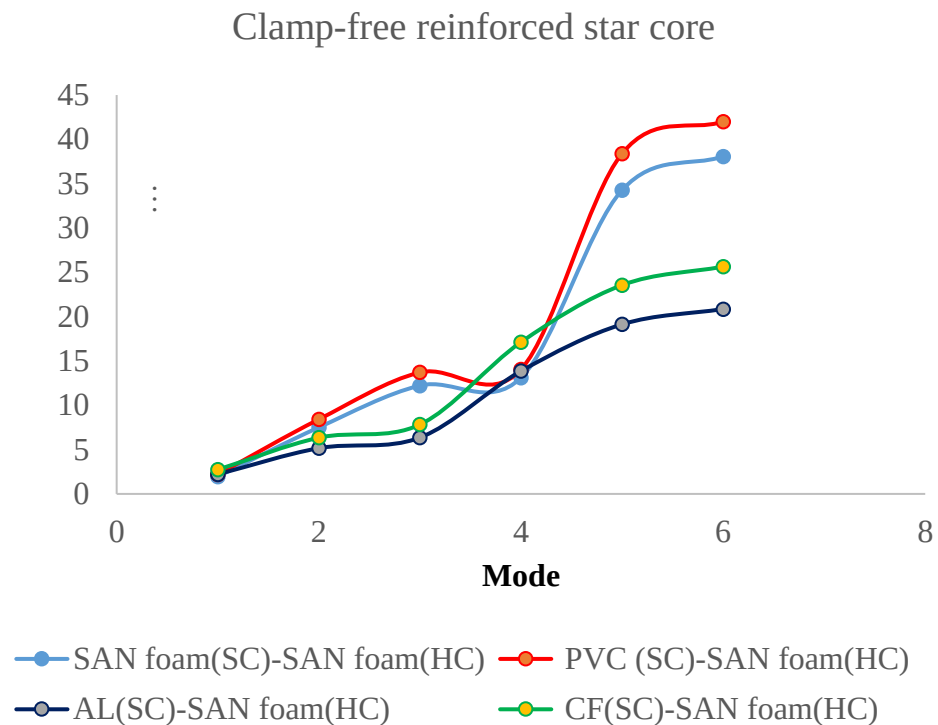


Figure 29: Natural Frequency of Proposed Core (Clamped-Free)

4.7 Comparison of Flexural Stiffness of the Proposed Core

To investigate the deformation resistance of the proposed core star-shaped reinforcement and material combination. Hence, considering the stresses acting only on the core, in this case only the core is subjected to a 3-point bending test on static structural analysis in ANSYS Workbench. The force applied is 100 N which was kept constant for all the materials combination, the hexagonal shape material is kept constant, and only the star shape reinforcement material is assigned to change. The results are obtained and shown in Table 11. In line with the results, it is observed that the stresses are almost constant, as it is irrespective of the modulus of rigidity and all proposed core has the same shape, cross-section area and applied load. However, there are significant changes in their deflection, due to the stiffness of the materials combination. In general, it is observed that the carbon fibre material used as reinforcement for the core has the lowest deformation, followed by Aluminium material reinforcement while SAN foam has the most deformation.

Table 11: Comparison of Material Stiffness of The Proposed Core

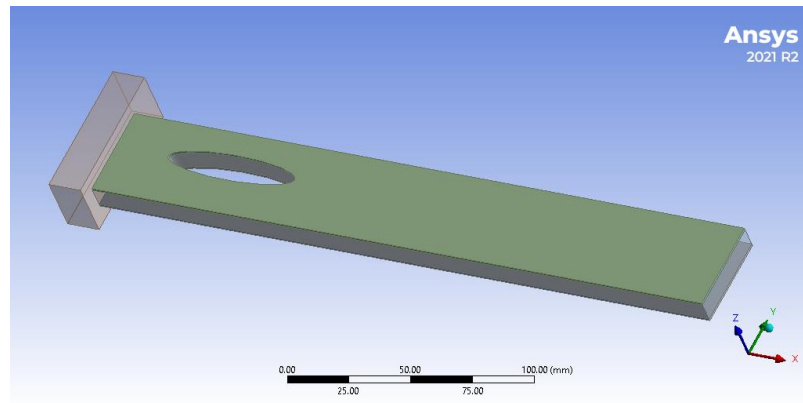
	SAN foam (SC) - SAN foam (HC)	PVC (SC) - SAN foam (HC)	AL(SC) - SAN foam (HC)	CF(SC) - SAN foam (HC)
Equivalent Stress Maximum [MPa]	6.76	6.76	6.72	6.71
Total Deformation Maximum [mm]	113683.82	100417.08	5250.74	5173.66

4.8 Elliptical Cut on Sandwich Beam

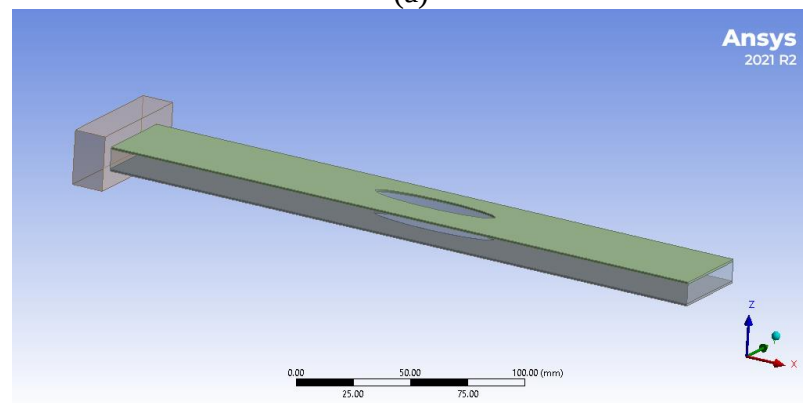
Effect of elliptical cut on sandwich beam natural frequency is studied. The sandwich beam of 290 mm X 40 mm X 11 mm and thickness of core 9mm with a 30mm elliptical

cut throughout the layers of the sandwich modal analysis is investigated with the boundary condition of free at one end and fixed at the other end. The analysis for the sandwich beam was carried out in ANSYS software.

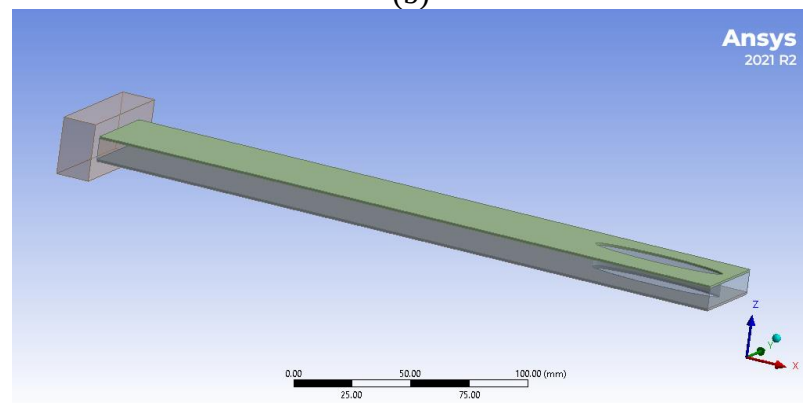
However, it was observed that cutting on the sandwich might increase or reduce its free vibration characteristic, all depending on the size, position, shape and depth of the cut. Hence, in this case, the elliptical shape cut is considered, cutting throughout the thickness of the sandwich. As a result of that, it was observed that as the elliptical cut moves closer to the fixed support as shown in Figure 30 the natural frequency is reduced. In addition to that, the sandwich elliptical cut is compared with the normal sandwich beam with no cut. However, when the cut is 255 mm away from the fixed support the natural frequency became higher than the normal sandwich beam without the cut. In general, the skin is aluminium material, and also aluminium regular hexagonal honeycomb is equally used as a core, Figure 31 shows the elliptical cut position at 6 different distances along the length of the sandwich beam towards the fixed support, illustrating that when the elliptical cut comes closer to the fixed support, the sandwich natural frequency reduces. The first 3 mode shapes of the normal sandwich beam and damaged sandwich beam are depicted in Figures 32 and 33.



(a)



(b)



(c)

Figure 30: Sandwich Beam with Different Distances Elliptical Cuts

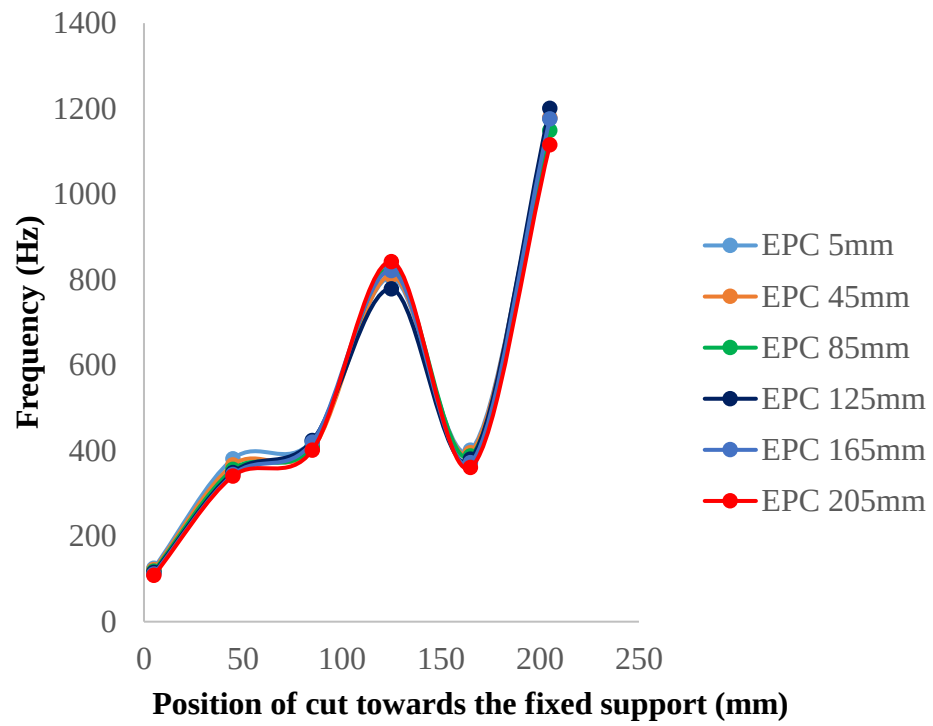
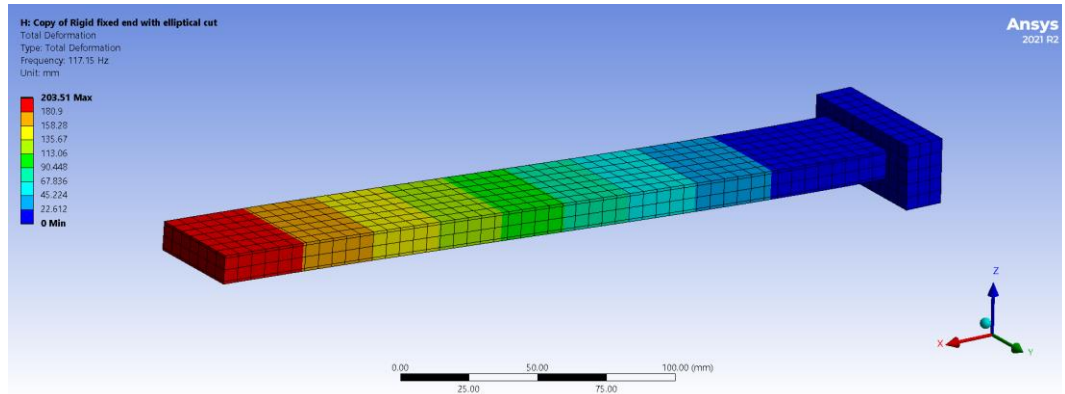
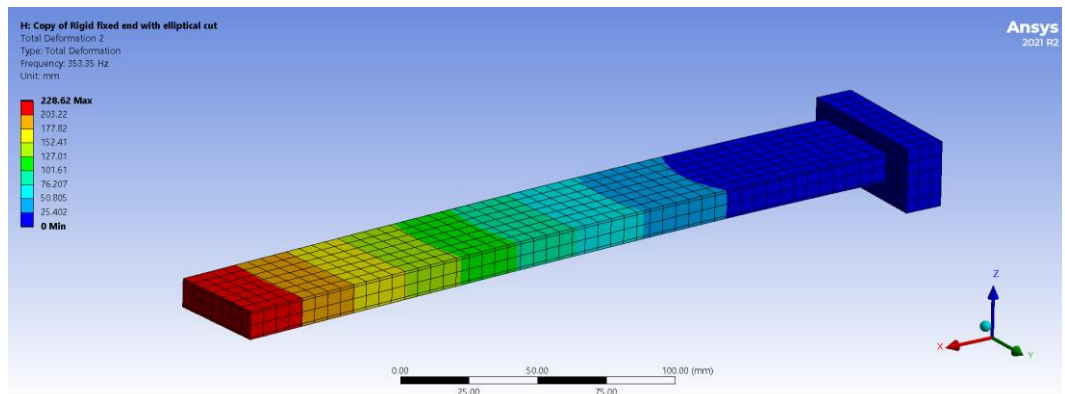


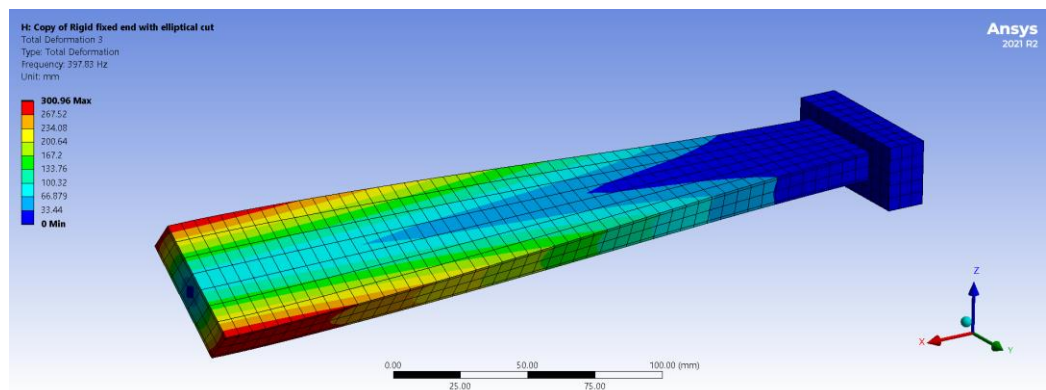
Figure 31: Position of Elliptical Cut vs Natural Frequency



Mode 1 (Bending)



Mode 2 (Bending)



Mode 3 (Torsion)

Figure 32: First 3 Mode Shapes Contour of Sandwich Beam

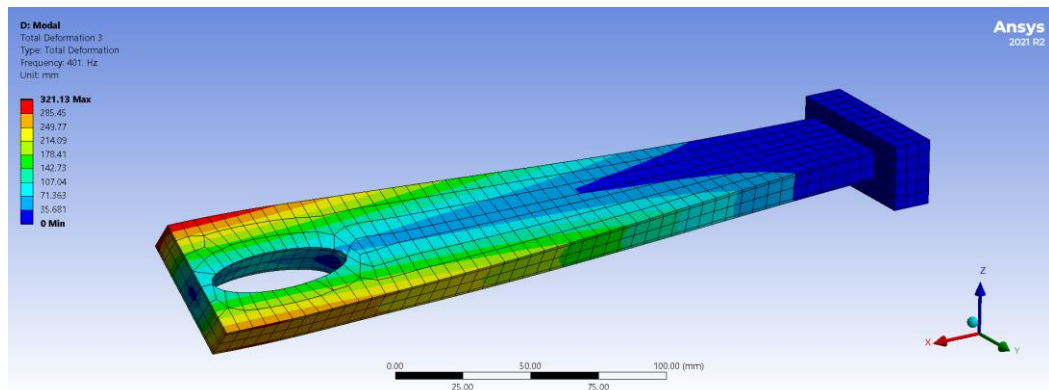
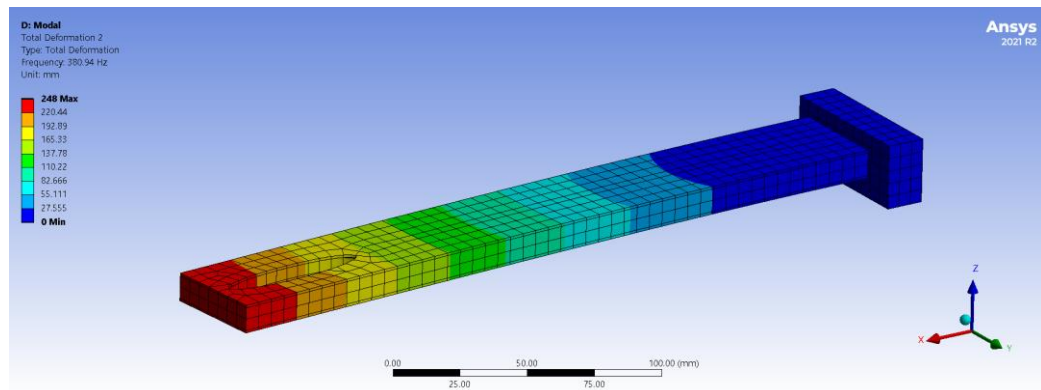
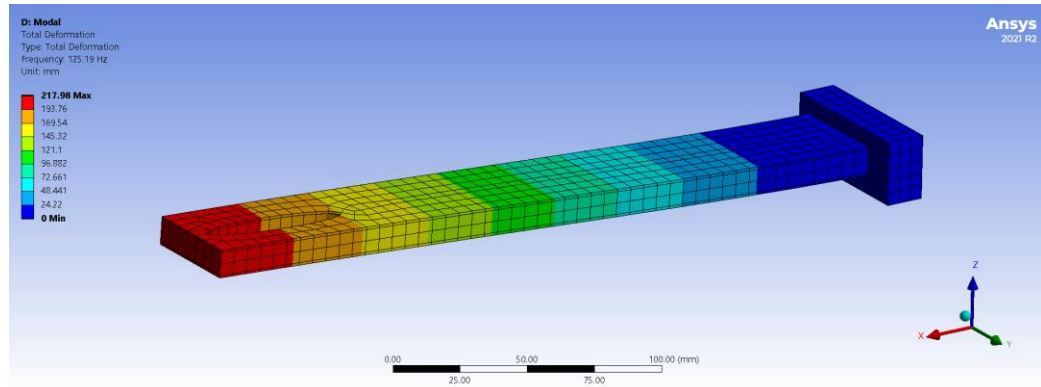


Figure 33: First 3 Mode Shapes Contour of Sandwich Beam with Elliptical Cut

Chapter 5

CONCLUSION, LIMITATIONS AND FUTURE RESEARCH

5.1 Conclusion

The results of a detailed honeycomb sandwich beam modal analysis study and simulation were shown and plotted, and significant observations were recorded. The free vibration analysis of a honeycomb sandwich beam was examined and validated using available literature, and the model was created using ANSYS software. However, the validity of the model developed in this study for the computation of in-plane mechanical properties is confirmed by the results of hexagonal RVE numerical investigations with the help of ANSYS Material Designer.

The vibrational behaviour of the honeycomb sandwich beam is affected by many factors as studied in parametric analysis results. Hence, the natural frequency changes by altering the geometry, assigning different materials, presence of crack or cut, induced thermal load and boundary conditions. The natural frequency is a function of stiffness to mass ratio, the proposed model was designed to have a reinforced inbuilt star shape which enhanced the vibration characteristics and it was further optimized by varying the materials of the reinforcement star shape, as a result of that SAN foam hexagonal and PVC foam star reinforcement happens to have better mass to volume ratio and higher natural frequency. In addition, increasing the foil thickness does not have significance on sandwich beam natural frequency but that will increase the

weight. In general, the presence of a cut in a sandwich beam will affect its natural frequency, the frequency will be reduced in fixed-fixed boundary conditions, while in fixed-free it depends on the size or depth of the cut and position of the cut, in this experiment 30mm elliptical cut throughout the sandwich beam that is 255 mm away from the fixed support increases the natural frequency while when the elliptical cut is 55 mm away from the fixed-free boundary support the natural frequency is reduced as compared with the non-damaged sandwich beam. In order, not to increase the core thickness to achieve greater stiffness for a size sensitive environment, the proposed core should be used and good materials combination should be considered.

5.2 Limitations of The Research

There is currently no test environment where the proposed core can be produced and tested with the additive manufacturing method, which is one of the production methods of the presented model. The fact that the research has not been done before has left almost every field to the researcher. Variables such as materials, analysis technique and test technique made it difficult to transform the research into experimental work.

5.3 Future Research

The study shows that the equivalent model proposed in this thesis is likely to be used as an effective preliminary design stage. But the work is not finished yet. There is still a need for further studies. For future work the possible work items to be studied are as follows:

1. Experimental validation of the equivalent model
2. Expanding the analyses to different face sheet materials
3. Investigating the effects of composite star-core sported honeycomb
4. Validation of face sheet stresses based on equivalent and honeycomb modelling by using a small size honeycomb structure.

The list of future works can be increased. However, of all the future work to be done, it is deemed that verification of the studied equivalent model by the experiment seems to be the most important one to be accomplished.

REFERENCES

- [1] Mazumdar S. Composites manufacturing: materials, product, and process engineering. CrC press; 2001.
- [2] Jones RM. Mechanics of composite materials. CRC press; 2018.
- [3] Check List of Recently Published Articles and Books on Glass 1964. Journal of Glass Studies 1965;7:141–64.
- [4] Egbo MK. A fundamental review on composite materials and some of their applications in biomedical engineering. Journal of King Saud University-Engineering Sciences 2021;33:557–68.
- [5] Vinson JR. The behavior of sandwich structures of isotropic and composite materials. Routledge; 2018.
- [6] Prabhu G, Katakam V, Sridharan VS, Idapalapati S. Uniaxial tensile failure of multi-core asymmetric sandwich composite structures with bonded repair. Composite Structures 2019;224:111025.
- [7] Hou W, Shen Y, Jiang K, Wang C. Study on mechanical properties of carbon fiber honeycomb curved sandwich structure and its application in engine hood. Composite Structures 2022;286:115302.

- [8] Nojima T, Saito K. Development of newly designed ultra-light core structures. JSME International Journal Series A Solid Mechanics and Material Engineering 2006;49:38–42.
- [9] Deng D, Yang Y, Chen Y, Lan X, Tice J. Accurately controlled sequential self-folding structures by polystyrene film. Smart Materials and Structures 2017;26:085040. <https://doi.org/10.1088/1361-665x/aa7a4e>.
- [10] Manteghi S, Mahboob Z, Fawaz Z, Bougherara H. Investigation of the mechanical properties and failure modes of hybrid natural fiber composites for potential bone fracture fixation plates. J Mech Behav Biomed Mater 2017;65:306–16.
- [11] Wang Y, Zhang Z, Xue X, Zhang L. Free vibration analysis of composite sandwich panels with hierarchical honeycomb sandwich core. Thin-Walled Structures 2019;145:106425.
- [12] Ramnath BV, Elanchezhian C, Manickavasagam VM, Narayanan RS, Sudharshan R, Pugazhendhi G. A Review On Sandwich Composites And Their Advancements. Materials Today: Proceedings 2019;16:1146–51.
- [13] Luchinsky DG, Hafiychuk V, Smelyanskiy V, Tyson RW, Walker JL, Miller JL. High-fidelity modeling for health monitoring in honeycomb sandwich structures. 2011 Aerospace Conference, IEEE; 2011, p. 1–7.

- [14] Gibson RF. A review of recent research on mechanics of multifunctional composite materials and structures. *Compos Struct* 2010;92:2793–810.
- [15] Fazzolari FA. Sandwich structures. Stability and vibrations of thin walled composite structures, Elsevier; 2017, p. 49–90.
- [16] Zhou XQ, Yu DY, Shao XY, Zhang SQ, Wang S. Research and applications of viscoelastic vibration damping materials: A review. *Composite Structures* 2016;136:460–80.
- [17] Vaithyasubramanian S, Kumar KV, Reddy KJP. Study On Applications Of Laplace Transformation: A n.d.
- [18] Mouritz AP, Gellert E, Burchill P, Challis K. Review of advanced composite structures for naval ships and submarines. *Compos Struct* 2001;53:21–42.
- [19] Akour SN, Maaitah HZ. Effect of core material stiffness on sandwich panel behavior beyond the yield limit. *Proceedings of the World Congress on Engineering*, vol. 2, 2010.
- [20] Daniel IM, Abot JL. Fabrication, testing and analysis of composite sandwich beams. *Composites Science and Technology* 2000;60:2455–63.

- [21] Mohammadabadi M, Yadama V, Dolan JD. Evaluation of wood composite sandwich panels as a promising renewable building material. *Materials* 2021;14:2083.
- [22] Tarlochan F. Sandwich structures for energy absorption applications: A review. *Materials* 2021;14:4731.
- [23] Ramnath BV, Alagaraja K, Elanchezhian C. Review on sandwich composite and their applications. *Materials Today: Proceedings* 2019;16:859–64.
- [24] Lozici-Brinzei D, Baran D, Tataru S. Fatigue analysis optimization. na; 2010.
- [25] Pokharel N, Mahendran M. Finite element analysis and design of sandwich panels subject to local buckling effects. *Thin-Walled Structures* 2004;42:589–611.
- [26] Ji W, Waas AM. Global and local buckling of a sandwich beam. *J Eng Mech* 2007;133:230–7.
- [27] Babanli M, Gurbanov N, Ismayilova K, Tanriverdiyev Y. Matrix materials used in composites. *EasyChair*; 2021.
- [28] Zhang Y, Li Y, Guo K, Zhu L. Dynamic mechanical behaviour and energy absorption of aluminium honeycomb sandwich panels under repeated impact loads. *Ocean Engineering* 2021;219:108344.

- [29] Qiao P, Davalos JF. Design of all-composite structures using fiber-reinforced polymer (FRP) composites. *Developments in Fiber-Reinforced Polymer (FRP) Composites for Civil Engineering*, Elsevier; 2013, p. 469–508.
- [30] Feng Y, Qiu H, Gao Y, Zheng H, Tan J. Creative design for sandwich structures: A review. *International Journal of Advanced Robotic Systems* 2020;17:1729881420921327.
- [31] Qiu K, Zhang W, Zhu J. Bending and dynamic analyses of sandwich panels considering the size effect of sandwich core. *International Journal for Simulation and Multidisciplinary Design Optimization* 2009;3:370–83.
- [32] Troughton MJ, editor. Chapter 17 - Adhesive Bonding. *Handbook of Plastics Joining (Second Edition)*, Boston: William Andrew Publishing; 2009, p. 145–73. [https://doi.org/https://doi.org/10.1016/B978-0-8155-1581-4.50019-6](https://doi.org/10.1016/B978-0-8155-1581-4.50019-6).
- [33] Mortensen F, Thomsen OT. Analysis of adhesive bonded joints: a unified approach. *Composites Science and Technology* 2002;62:1011–31.
- [34] Wijker JJ, editor. Sandwich Construction. *Spacecraft Structures*, Berlin, Heidelberg: Springer Berlin Heidelberg; 2008, p. 157–73. https://doi.org/10.1007/978-3-540-75553-1_10.

- [35] Chen T-J, Huang J-S. Creep-buckling of hexagonal honeycombs with dual imperfections. *Compos Struct* 2009;89:143–50.
- [36] Jen Y-M, Ko C-W, Lin H-B. Effect of the amount of adhesive on the bending fatigue strength of adhesively bonded aluminum honeycomb sandwich beams. *International Journal of Fatigue* 2009;31:455–62.
- [37] Asprone D, Auricchio F, Menna C, Morganti S, Prota A, Reali A. Statistical finite element analysis of the buckling behavior of honeycomb structures. *Composite Structures* 2013;105:240–55.
- [38] Li Z, Wang T, Jiang Y, Wang L, Liu D. Design-oriented crushing analysis of hexagonal honeycomb core under in-plane compression. *Composite Structures* 2018;187:429–38.
- [39] Castanié B, Bouvet C, Ginot M. Review of composite sandwich structure in aeronautic applications. *Composites Part C: Open Access* 2020;1:100004.
- [40] Luo H, Chen F, Wang X, Dai W, Xiong Y, Yang J, et al. A novel two-layer honeycomb sandwich structure absorber with high-performance microwave absorption. *Composites Part A: Applied Science and Manufacturing* 2019;119:1–7.

- [41] Wang Y, Du Y, Qiang R, Tian C, Xu P, Han X. Interfacially engineered sandwich-like rGO/carbon microspheres/rGO composite as an efficient and durable microwave absorber. *Advanced Materials Interfaces* 2016;3:1500684.
- [42] MalekzadehFard K, Gholami M, Reshadi F, Livani M. Free vibration and buckling analyses of cylindrical sandwich panel with magneto rheological fluid layer. *Journal of Sandwich Structures & Materials* 2017;19:397–423.
- [43] Stergiou CA, Koledintseva MY, Rozanov KN. Hybrid polymer composites for electromagnetic absorption in electronic industry. *Hybrid Polymer Composite Materials*, Elsevier; 2017, p. 53–106.
- [44] Ashori A. Wood–plastic composites as promising green-composites for automotive industries! *Bioresour Technol* 2008;99:4661–7.
- [45] Wang Z, Tian H, Lu Z, Zhou W. High-speed axial impact of aluminum honeycomb–Experiments and simulations. *Composites Part B: Engineering* 2014;56:1–8.
- [46] Ravishankar B, Nayak SK, Kader MA. Hybrid composites for automotive applications – A review. *Journal of Reinforced Plastics and Composites* 2019;38:835–45. <https://doi.org/10.1177/0731684419849708>.

- [47] Friedrich K, Almajid AA. Manufacturing Aspects of Advanced Polymer Composites for Automotive Applications. *Applied Composite Materials* 2013;20:107–28. <https://doi.org/10.1007/s10443-012-9258-7>.
- [48] Amoo LM. On the design and structural analysis of jet engine fan blade structures. *Progress in Aerospace Sciences* 2013;60:1–11. <https://doi.org/https://doi.org/10.1016/j.paerosci.2012.08.002>.
- [49] Sun Y, Zhang Y, Zhou Y, Zhang H, Zeng H, Yang K. Evaluating Impact Damage of Flat Composite Plate for Surrogate Bird-Strike Testing of Aeroengine Fan Blade. *Journal of Composites Science* 2021;5:171.
- [50] Chen Y, Tian J, Ou-Yang H, Wang A. Numerical investigation of rub-induced composite fan blade vibrations and abradable coating removals. *Composite Structures* 2019;226:111274.
- [51] Yu Z bin, Liu ZC, Leng S, Cai Y. Structure design and manufacturing of the composite blade for the icing wind tunnel. *Advanced Materials Research*, vol. 915, Trans Tech Publ; 2014, p. 721–6.
- [52] Sun J, Guan Q, Liu Y, Leng J. Morphing aircraft based on smart materials and structures: A state-of-the-art review. *Journal of Intelligent Material Systems and Structures* 2016;27:2289–312.

- [53] Weisshaar TA. Morphing aircraft technology-new shapes for aircraft design 2006.
- [54] Özgen S, Güçlü S, Şahin M, Yaman Y, Bayram G, Uludağ Y, et al. Şekil Değiştiren Uçaklar Havacılıkta Yeni Bir Devrim Yaratabilir mi. Savunma ve Havacılık 2008;22126:125–8.
- [55] Mouritz AP, Bannister MK, Falzon PJ, Leong KH. Review of applications for advanced three-dimensional fibre textile composites. Composites Part A: Applied Science and Manufacturing 1999;30:1445–61.
- [56] Lavis D. Air cushion craft. Naval Engineers Journal 1985;97:259–316.
- [57] Sukur EF, Onal G. Long-term salt-water durability of GNPs reinforced basalt-epoxy multiscale composites for marine applications. Tribology International 2021;158:106910.
- [58] Selvaraju S, Ilaiyavel S. Applications of composites in marine industry. Journal of Engineering Research and Studies 2011;2:89–91.
- [59] de Clerk E. COVID takes its toll. Steel Times International 2020;44:40–1.
- [60] Saito K, Pellegrino S, Nojima T. Manufacture of arbitrary cross-section composite honeycomb cores based on origami techniques. Journal of Mechanical Design 2014;136:051011.

- [61] Thai Tat Nguyen H, Thao Thai P, Yu B, Hagiwara I. Development of a manufacturing method for truss core panels based on origami-forming. *Journal of Mechanisms and Robotics* 2016;8:031011.
- [62] Fawzi T, Al-Talib AAM. *Composite Metamaterials: Classification, Design, Laws and Future Applications. Nanostructured Materials-Classification, Growth, Simulation, Characterization, and Devices*, IntechOpen; 2021.
- [63] Ding Z, Yuan C, Peng X, Wang T, Qi HJ, Dunn ML. Direct 4D printing via active composite materials. *Sci Adv* 2017;3:e1602890.
- [64] Rupani S v, Acharya G, Jani SS. Design, modelling and manufacturing aspects of honeycomb sandwich structures: a review 2017.
- [65] Noor AK, Burton WS, Bert CW. *Computational models for sandwich panels and shells* 1996.
- [66] Campbell FC. *Structural composite materials*. ASM international; 2010.
- [67] Paik JK, Thayamballi AK, Kim GS. The strength characteristics of aluminum honeycomb sandwich panels. *Thin-Walled Structures* 1999;35:205–31.
- [68] Yi L, Chang T, Feng X-Q, Zhang Y, Wang J, Huang B. Giant energy absorption capacity of graphene-based carbon honeycombs. *Carbon N Y* 2017;118:348–57.

- [69] Ivanez I, Fernandez-Cañadas LM, Sanchez-Saez S. Compressive deformation and energy-absorption capability of aluminium honeycomb core. *Composite Structures* 2017;174:123–33.
- [70] Tavman IH. Thermal and mechanical properties of copper powder filled poly (ethylene) composites. *Powder Technology* 1997;91:63–7.
- [71] Ma M, Yao W, Jiang W, Jin W, Chen Y, Li P. Fatigue behavior of composite sandwich panels under three-point bending load. *Polymer Testing* 2020;91:106795.
- [72] Tilbrook MT, Moon RJ, Hoffman M. Crack propagation in graded composites. *Compos Sci Technol* 2005;65:201–20.
- [73] Ferrando WA. Review of corrosion and corrosion control of magnesium alloys and composites. *Journal of Materials Engineering* 1989;11:299–313.
- [74] Mouritz AP, Gibson AG. Fire properties of polymer composite materials. vol. 143. Springer Science & Business Media; 2007.
- [75] HexWeb TM. Honeycomb attributes and properties. *Hexcel Composites* 1999;13.

- [76] Kim G, Sterkenburg R. Investigating the effects aviation fluids have on the flatwise compressive strength of Nomex® honeycomb core material. *Journal of Sandwich Structures & Materials* 2021;23:365–82.

- [77] Paget CA, Grondel S, Levin K, Delebarre C. Damage assessment in composites by Lamb waves and wavelet coefficients. *Smart Materials and Structures* 2003;12:393.

- [78] Petras A. *Design of Sandwich Structures* 2011.

- [79] Aydincak İ, Kayran A. An Approach for the Evaluation of Effective Elastic Properties of Honeycomb Cores by Finite Element Analysis of Sandwich Panels. *Journal of Sandwich Structures & Materials* 2009;11:385–408.
<https://doi.org/10.1177/1099636209102891>.

- [80] Rodrigues D, Rocha J, Menezes E, Amico S. Analysis of Sandwich Beams Using Timoshenko's Beam Theory Assisted by Software. 2017.
<https://doi.org/10.29327/151945.6-1>.

- [81] Belarbi M-O, Khechai A, Bessaim A, Houari M-S-A, Garg A, Hirane H, et al. Finite element bending analysis of symmetric and non-symmetric functionally graded sandwich beams using a novel parabolic shear deformation theory. *Design and Applications* 2021;235:2482–504.

- [82] Popa C, Tomescu G. The comparative study for the isotropic and orthotropic circular plates. IOP Conference Series: Materials Science and Engineering, vol. 147, IOP Publishing; 2016, p. 012107.

- [83] Damiani L, Eales MG, Nobbs AH, Su B, Tsimbouri PM, Salmeron-Sanchez M, et al. Impact of surface topography and coating on osteogenesis and bacterial attachment on titanium implants. *Journal of Tissue Engineering* 2018;9:2041731418790694.

- [84] Guj L, Sestieri A. Dynamic modeling of honeycomb sandwich panel. *Archive of Applied Mechanics* 2007;77:779–93.

- [85] Maiti SK, Gibson LJ, Ashby MF. Deformation and energy absorption diagrams for cellular solids. *Acta Metallurgica* 1984;32:1963–75.

- [86] Wei X, Wu Q, Gao Y, Xiong J. Bending characteristics of all-composite hexagon honeycomb sandwich beams: Experimental tests and a three-dimensional failure mechanism map. *Mechanics of Materials* 2020;148:103401.

- [87] Yuan W, Song H, Huang C. Failure maps and optimal design of metallic sandwich panels with truss cores subjected to thermal loading. *International Journal of Mechanical Sciences* 2016;115:56–67.

- [88] Wu X, Yu H, Guo L, Zhang L, Sun X, Chai Z. Experimental and numerical investigation of static and fatigue behaviors of composites honeycomb sandwich structure. *Composite Structures* 2019;213:165–72.
- [89] Wu X, Yu H, Guo L, Zhang L, Sun X, Chai Z. Experimental and numerical investigation of static and fatigue behaviors of composites honeycomb sandwich structure. *Composite Structures* 2019;213:165–72.
- [90] Yuan R, Lu S. Experimental and numerical study for effective thermal conductivity of metallic honeycomb sandwich structures. *Journal of Sandwich Structures & Materials* 2021;23:3540–57.
- [91] Belić MR, Škarka V, Deneubourg J-L, Lax M. Mathematical model of honeycomb construction. *Journal of Mathematical Biology* 1986;24:437–49.
- [92] Kondratiev A, Prontsevych O, Nabokina T. Analysis of the Bearing Capacity of Adhesive Joint of Honeycomb Cores of Sandwich Structures with the Continuous Adhesive Layer. *Key Engineering Materials*, vol. 864, Trans Tech Publ; 2020, p. 228–40.
- [93] Brown HR. The adhesion between polymers. *Annual Review of Materials Science* 1991;21:463–89.

- [94] Pan S-D, Wu L-Z, Sun Y-G, Zhou Z-G, Qu J-L. Longitudinal shear strength and failure process of honeycomb cores. *Composite Structures* 2006;72:42–6.
- [95] Pan S-D, Wu L-Z, Sun Y-G. Transverse shear modulus and strength of honeycomb cores. *Composite Structures* 2008;84:369–74.
- [96] Bianchi G, Aglietti GS, Richardson G. Static and fatigue behaviour of hexagonal honeycomb cores under in-plane shear loads. *Applied Composite Materials* 2012;19:97–115.
- [97] Gornet L, Marguet S, Marckmann G. Modeling of Nomex® honeycomb cores, linear and nonlinear behaviors. *Mechanics of Advanced Materials and Structures* 2007;14:589–601.
- [98] Qi C, Jiang F, Yang S. Advanced honeycomb designs for improving mechanical properties: A review. *Composites Part B: Engineering* 2021;227:109393.
- [99] Rejab MRM, Cantwell WJ. The mechanical behaviour of corrugated-core sandwich panels. *Composites Part B: Engineering* 2013;47:267–77.
- [100] Katzman HA, Castaneda RM, Lee HS. Moisture diffusion in composite sandwich structures. *Composites Part A: Applied Science and Manufacturing* 2008;39:887–92.

- [101] Cunningham PR, White RG. A new measurement technique for the estimation of core shear strain in closed sandwich structures. *Compos Struct* 2001;51:319–34.
- [102] He M, Hu W. A study on composite honeycomb sandwich panel structure. *Materials & Design* 2008;29:709–13.
- [103] Sun Y, Guo L, Wang T, Zhong S, Pan H. Bending behavior of composite sandwich structures with graded corrugated truss cores. *Composite Structures* 2018;185:446–54.
- [104] Ingrole A, Hao A, Liang R. Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement. *Materials & Design* 2017;117:72–83.
- [105] Ghongade G, Kalyan KP, Vignesh RV, Govindaraju M. Design, fabrication, and analysis of cost effective steel honeycomb structures. *Materials Today: Proceedings* 2021;46:4520–6.
- [106] Russell B, Deshpande V, Wadley H. Quasistatic deformation and failure modes of composite square honeycombs. *J Mech Mater Struct* 2008;3:1315–40.

- [107] Yu G-C, Feng L-J, Wu L-Z. Thermal and mechanical properties of a multifunctional composite square honeycomb sandwich structure. *Materials & Design* 2016;102:238–46.

- [108] Li G, Muthyala VD. Impact characterization of sandwich structures with an integrated orthogrid stiffened syntactic foam core. *Composites Science and Technology* 2008;68:2078–84.

- [109] Nunes JP, Silva JF. Sandwiched composites in aerospace engineering. *Advanced composite materials for aerospace engineering*, Elsevier; 2016, p. 129–74.

- [110] Järvenpää A, Lämsä J, Hietala M, Mäntyjärvi K. Mechanical Properties of a Metal Sandwich Panel Manufactured Using Longitudinally Laminated Forming Tools. *Key Engineering Materials*, vol. 611, Trans Tech Publ; 2014, p. 781–5.

- [111] Reddy SSC, Babu BS. Analytical and Numerical Analysis of Sandwich Composite Materials with Different Core Structures n.d. *Berna Kalp* 11183-91

- [112] Belingardi G, Martella P, Peroni L. Fatigue analysis of honeycomb-composite sandwich beams. *Composites Part A: Applied Science and Manufacturing* 2007;38:1183–91.

- [113] Wang Z, Tian H, Lu Z, Zhou W. High-speed axial impact of aluminum honeycomb—Experiments and simulations. *Composites Part B: Engineering* 2014;56:1–8.

- [114] Feli S, Pour MHN. An analytical model for composite sandwich panels with honeycomb core subjected to high-velocity impact. *Composites Part B: Engineering* 2012;43:2439–47.

- [115] Ma M, Yao W, Jiang W, Jin W, Chen Y, Li P. A multi-area fatigue damage model of composite honeycomb sandwich panels under three-point bending load. *Composite Structures* 2021;261:113603.

- [116] Daniel IM, Gdoutos EE, Wang K, Abot JL. Failure modes of composite sandwich beams. *International Journal of Damage Mechanics* 2002;11:309–34.

- [117] Okoli OI, Smith GF. Failure modes of fibre reinforced composites: The effects of strain rate and fibre content. *Journal of Materials Science* 1998;33:5415–22.

- [118] Marshall A. Sandwich construction. *Handbook of composites*, Springer; 1982, p. 557–601.

- [119] Gibson LJ. Cellular solids. *Mrs Bulletin* 2003;28:270–4.

- [120] Xia L-J, Jin X-D, Wang Y-B. Equivalent analysis of honeycomb sandwich plates for satellite structure. Journal-Shanghai Jiaotong University-Chinese Edition- 2003;37:999–1001.
- [121] Sorohan Ş, Sandu M, Sandu A, Constantinescu DM. Finite Element Models Used to Determine the Equivalent In-plane Properties of Honeycombs. MaterialsToday:Proceedings2016;3:1161–6. doi.org/10.1016