ANTI-IMPACT AND VIBRATION-DAMPING DESIGN OF CORK-BASED SANDWICH STRUCTURES FOR ROTARY-WING DRONE CAGE APPLICATIONS

Dissertation

MOHAMMAD RAUF SHEIKHI

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Doctorate Degree (PhD) Dissertation

Department of Airframe and Powerplant Maintenance

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FINAL APPROVAL FOR THESIS

This thesis titled ANTI-IMPACT AND VIBRATION-DAMPING DESIGN OF CORK-BASED SANDWICH STRUCTURES FOR ROTARY-WING DRONE CAGE APPLICATIONS has been prepared and submitted by MOHAMMAD RAUF SHEIKHI in partial fulfillment of the requirements in "Eskişehir Technical University Directive on Graduate Education and Examination" for the Degree of Doctorate Degree (PhD) in Airframe and Powerplant Maintenance Department has been examined and approved on 28/02/2023.

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ABSTRACT

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This dissertation presents environmentally friendly sandwich structures with cork cores that show improved resistance to impact and vibration. The first part of the dissertation evaluates the combination of various common face-sheet materials in aerospace applications with a cork core to determine the best structure against impact and vibration. The results showed that a sandwich structure with CFRP face-sheets and a cork core performed best in terms of resistance to impact and vibration. In the second part of the dissertation, a drone cage was built using the CFRP/cork/CFRP sandwich structure and compared to cages made with a coarse-grained cork core and a PVC foam core. The results of impact and vibration tests showed that the cork-based cages had lower peak deceleration, a higher damping ratio, and greater structural stiffness, providing better protection for rotary-wing drones. The dissertation provides a promising solution for constructing drone cages that are environmentally friendly and offer superior protection against impact and vibrations.

Keywords: Drone cage, Vibration damping, Rotary-wing drone, Sandwich structures, Cork composites.

ÖZET

DÖNER KANATLI DRONE KAFESİ UYGULAMALARI İÇİN CORK BAZLI SANDVİÇ YAPILARIN ANTİ-DARBE VE TİTREŞİM SÖNÜMLEYICI TASARIMI

MOHAMMAD RAUF SHEIKHI

Uçak Gövde ve Motor Bakımı Anabilim Dalı

Uçak Gövde ve Motor Bakımı Bilim Dalı

Eskişehir Teknik Üniversitesi, Lisansüstü Eğitim Enstitüsü, Şubat 2023

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Bu tez, darbe ve titreşimlere karşı gelişmiş direnç gösteren cork çekirdekli çevre dostu sandviç yapılar sunmaktadır. Tezin ilk bölümü, darbe ve titreşimlere karşı en iyi yapıyı belirlemek için havacılık uygulamalarında yaygın olarak kullanılan çeşitli ön yüzey malzemelerinin cork çekirdekli kombinasyonunu değerlendirmektedir. Sonuçlar, CFRP yüzey tabakaları ve bir mantar çekirdeği olan bir sandviç yapının darbe ve titreşimlere karşı dirençte en iyi performansı gösterdiğini gösterdi. Tezin ikinci bölümünde, CFRP/mantar/CFRP sandviç yapısı kullanılarak bir drone kafesi inşa edilmiş ve iri taneli cork çekirdekli ve PVC köpük çekirdekli yapılan kafeslerle karşılaştırılmıştır. Çarpma ve titreşim testlerinin sonuçları, cork tabanlı kafeslerin daha düşük tepe yavaşlama, daha yüksek sönümleme oranı ve yapısal sertliğe sahip olduğunu ve döner kanatlı dronlar için daha iyi koruma sağladığını gösterdi. Tez, çevre dostu olan ve darbe ve titreşimlere karşı üstün koruma sağlayan drone kafesleri inşa etmek için umut verici bir çözüm sunmaktadır.

Anahtar Sözcükler: Drone kafesi, Titreşim sönümleme, Döner kanatlı drone, Sandviç yapılar, Cork kompozitler.

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With heartfelt gratitude,

MOHAMMAD RAUF SHEIKHI

28/02/2023

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Eskişehir Technical University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

ζ	:	Damping ratio
k	:	Spring stiffness
c	:	Damping coefficient
SDOF	:	Single degree of freedom
SI	:	The International System of Units
m	:	Mass
FRF	:	Frequency response function
MDOF	:	Multi degree of freedom systems
CFRP	:	Carbon fiber-reinforced polymer
AFRP	:	Aramid fabric-reinforced polymer
GFRP	:	Glass fiber-reinforced polymer
PD	:	Peak deceleration

1. INTRODUCTION

A sandwich structure is a type of composite material made up of multiple layers with different physical and mechanical properties. The layers are usually composed of two outer skins, or face-sheets, often made of a strong, lightweight material such as aluminum, carbon fiber, or fiberglass, with a core layer in between, made of a material with good insulation properties, such as foam or honeycomb.

The advantages of sandwich structures are [1]:

a) Lightweight: The combination of lightweight face-sheets and low-density core materials makes sandwich structures lighter than solid structures with the same strength.
b) Strength: The combination of different materials in a sandwich structure can result in high strength-to-weight ratios.
c) Stiffness: The core layer in a sandwich structure provides stiffness, helping to distribute loads evenly and resist deformation.
d) Insulation: The core layer in a sandwich structure can also provide insulation, helping to keep heat in or out, depending on the intended application.
e) Durability: Sandwich structures are resistant to damage and can last for a long time with proper care and maintenance.

In summary, sandwich structures offer a combination of strength, stiffness, and low weight, making them an ideal choice for a variety of applications, including aircraft, boats, and architectural designs [2].

The face-sheets provide most of the strength and stiffness of the structure, while the core acts as a spacer, providing insulation and maximizing the face-sheet to face-sheet distance to reduce the risk of damage. Common core materials used in sandwich structures include foam (such as polystyrene, polyurethane, or PVC), honeycomb, balsa wood, and metal honeycomb. The choice of core material depends on the specific application and desired properties, such as strength, stiffness, fire resistance, impact resistance, vibration properties, and weight [3]. In recent years, it has become popular to use new cellular-based material cores for sandwich structures. Since environmental concerns are also considered in new designs, a material that can meet the needs of the structure while also helping to reduce environmental pollutants is ideal. In this thesis, we seek to design a sandwich structure based on a cork core. Cork is a sustainable substance harvested from the bark of an oak tree. The use of cork as a core has been ordered in recent years, but there is no comprehensive study that simultaneously examines it in terms of impact resistance and vibration damping.

The aim of this study is to investigate the use of cork cores in sandwich structures for aerial vehicle applications and evaluate their resistance to impact and vibration. The study is divided into two main parts. In the first part, the aim is to determine the best combination of face-sheet materials and cork cores for use in sandwich structures for low-speed aerial vehicle applications. For this purpose, several sandwich structures consisting of carbon fiber-reinforced polymer (CFRP), aramid fabric-reinforced polymer (AFRP), glass fiber-reinforced polymer (GFRP) composite face-sheets, and aluminum (Al) with a fixed cork core were produced. The impact and vibration resistance of these sandwich structures were evaluated using a drop-tower impact test and a modal analysis system based on a hammer. In the second part of the study, the aim was to construct a drone cage using the CFRP/cork/CFRP sandwich structure and evaluate its resistance to impact and vibrations. For this purpose, three different types of cages were made, two of which were based on fine-grained and coarse-grained cork cores, and another type was made with a PVC foam core. The impact and vibration resistance of these cages were evaluated using the peak deceleration (PD) system and vibrations based on modal analysis.

1.1. Impact and vibration resistance in aerial structures

Impact resistance is crucial in aerial structures, particularly in rotary-wing drones, as it determines the structure's ability to withstand collisions or crashes. A drone with high impact resistance is more durable and less likely to sustain significant damage during an accident, reducing maintenance costs and increasing operational reliability. Additionally, impact resistance is also essential in ensuring the safety of the pilot, crew, and passengers. By providing a robust and durable structure, rotary-wing drones with high impact resistance can maintain stability during high-stress scenarios and provide a higher level of safety for all onboard. Vibration resistance is crucial in aerial structures, especially in rotary-wing drones, as it affects the stability and performance of the drone. Excessive vibrations can cause damage to the drone's components, reducing its lifespan and leading to malfunctions. Additionally, vibrations can also affect the accuracy of the drone's sensors and navigation systems, making it difficult to control the drone and achieve stable flight. To mitigate the effects of vibrations, drone manufacturers typically design and test their drones to ensure that they can withstand high levels of vibration, and often use vibration-damping materials and technologies to reduce the impact of vibrations on the drone's components. Moreover, vibration damping is important in rotary-wing drone structures for several reasons:

a) Increased flight stability: Vibrations can cause instability in flight, leading to reduced control accuracy and potentially dangerous situations. Damping these vibrations can greatly improve flight stability and overall performance.
b) Prolonged component life: Vibrations can cause fatigue and stress on the drone's components, leading to decreased lifespan. Damping these vibrations can help extend the life of the components, reducing maintenance and replacement costs.
c) Improved payload performance: Vibrations can negatively affect the performance of sensors, cameras, and other payloads mounted on the drone. By reducing these vibrations, the payloads can perform more accurately and effectively.
d) Reduced noise levels: Vibrations can cause noise emissions, which can be a major issue in urban and populated areas. Damping these vibrations can help reduce noise levels and improve the drone's overall impact on the environment.

In general, rotary-wing drones' vibration damping is one of the most important factors in determining their level of safety, dependability, and performance.

1.2. Rotary-wing aerial vehicles and importance of their safety

Nowadays, rotary-wing drones (as shown in Fig. 1.1) are used for many applications including agriculture [4], search and rescue [5], mapping and surveying [6, 7], order delivery [8], transport and medicine [9, 10], mine inspection [11], etc., and their increasing use, drones must perform more complex functions than before. Drones are an increasingly practical tool for sending packages faster, more sustainably, and less expensively to previously inaccessible locations. As a result, many logistics firms are thinking about utilizing drones in e-commerce industries [12].

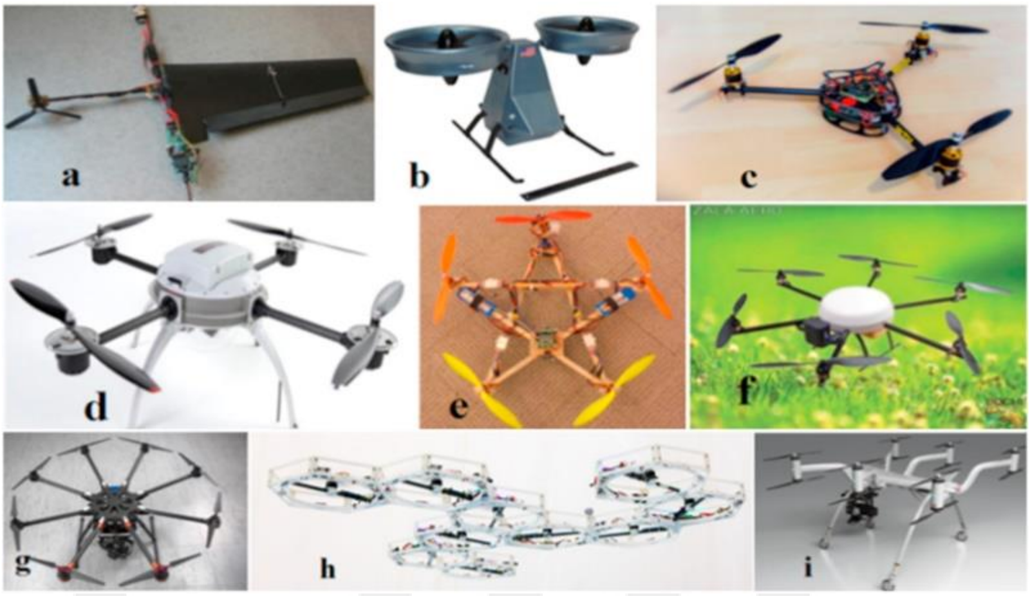


Figure 1.1. *Various types of rotary-wing drones [13], (a) mono-copter [14], (b) twin-copter [15], (c) tri-copter, (d) quad-copter [16], (e) penta-copter, (f) hexa-copter [17], (g) octo-copter [18], (h)deca-copter [19], (i) dodeca-copter [20].*

Rotary-wing drone safety is crucial since they have the potential to inflict catastrophic harm to people, property, and the environment if they fail or are used incorrectly. They fly at low altitudes and near people and structures, increasing the possibility of a collision and harm. Furthermore, they include whirling blades that, if they come into contact with people or objects, can inflict serious damage and harm. Furthermore, rotary-wing drones can be outfitted with payloads that pose extra safety hazards, such as sharp objects or dangerous compounds. When flying rotary-wing drones, it is critical to follow manufacturer standards and regulations, as well as correct training and maintenance methods. On the other hand, the increased use of drones for last-mile delivery [21] has raised the possibility of them colliding with obstacles, people, or even civil aircraft in flight. This risk is exceptionally high at airports where planes ascend or descend at low altitudes during takeoff or landing. So, current delivery drones can be dangerous for people, and safety issues arise because users are exposed to unprotected rotating propellers. Having a suitable cage can reduce these risks. Fig. 1.2 shows the delivery drone.

Figure 1.2. *Delivery drones [22, 23].*

In addition to the importance of designing a cage structure that does not reduce the flight capabilities of the drones, lightness, and resistance to impact and vibration can be its most important factors. Considering that the most important advantage of sandwich structures is their excellent strength-to-weight ratio, designing a sandwich structure with a light core and resistance to impact and vibration can improve the quality of drone cages. Additionally, during operation, user access to these areas is limited to prevent injury to bystanders from exposed propellers. Drones cannot deliver to people who are stuck in traffic, on a slope, or in places where a drone cannot land, such as a window or balcony. These challenges, taken together, eliminate the possibility of person-to-person and last-centimeter deliveries, in which packages can be safely delivered directly into the recipient's hands or in difficult-to-reach, cluttered locations. One approach to ensuring safe handling for last-centimeter delivery is to encase the propellers in a protective cage. A dense cage structure improves safety by preventing users from gaining access to the propellers.

1.3. Scope of the thesis and motivation

The scope of the doctoral dissertation is to develop environmentally friendly sandwich structures with cork cores that have good resistance to impact and vibration, and to evaluate their performance through laboratory tests. The main motivation behind this dissertation is to find a suitable material for the construction of a drone cage that can provide better protection against impacts and vibrations, which is crucial for the stability and safety of rotary-wing drones.

In the first part of the dissertation, the best combination of common face-sheets (CFRP, AFRP, GFRP composite face-sheets, and non-composite Al) with a fixed cork core was explored through laboratory tests of deceleration and vibration. The results showed that the CFRP face-sheet provided better resistance to impact and vibrations and was chosen as the final structure for the drone cage. In the second part of the study, the drone cage was built based on the CFRP/cork/CFRP sandwich structure, and its performance was compared with cages made of PVC foam core. The cork-based cages showed better performance in terms of peak deceleration, damping ratio, and structural stiffness, indicating their superior ability to absorb and dissipate energy from impacts and vibrations.

The main contribution of this dissertation is the development of an environmentally friendly sandwich structure with cork cores that can provide better protection for rotary-wing drones against impacts and vibrations.

1.4. Methodology

The methodology adopted for the experiments of the thesis is as follows:

a) Preparing and cutting glass-fiber, carbon-fiber, and aramid-fabric based on the same densities.
b) Manufacturing of carbon-fiber, glass-fiber, and aramid-fabric composites by hand-lay-up method with compression mold.
c) Preparation of CFRP/cork/CFRP, GFRP/cork/GFRP, AFRP/cork/AFRP, and Al/cork/Al sandwich structures.
d) Performing a deceleration test in the form of a low-energy drop-tower system on manufactured sandwich structures.
e) Conducting vibration tests on the fabricated sandwich structures.
f) Manufacturing of drone cages based on CFRP/fine cork/CFRP, CFRP/coarse cork/CFRP, and CFRP/PVC foam/CFRP sandwich structures.
g) Perform a deceleration test on the fabricated drone cages.
h) Perform a vibration test on the drone cages.

1.5. Outline of thesis

Chapter 1 describes the introduction and motivation of the thesis. Chapter 2 includes a detailed review of cork, and sandwich structures and their properties, and in this chapter, we reviewed the importance of vibration damping and deceleration in aerial structures. In chapter 3, the sandwich structures made in the form of small samples (50 × 50 mm) are subjected to deceleration and vibration tests, their results are discussed, and the best structure is selected among them. Chapter 4 explains how to build a drone cage based on a CFRP/cork/CFRP sandwich structure and perform deceleration and vibration tests on it. To compare the cage proposed in this study, another cage based on CFRP/PVC foam/CFRP is made, and the test results are discussed. Conclusions and recommendations are provided in Chapter 5.

2. LITERATURE REVIEW, MATERIALS, AND METHODS

2.1. Sandwich structures

A sandwich structure is a type of composite material that consists of multiple layers of different materials, typically with a low-density core material sandwiched between two high-density outer layers [1]. This type of structure is widely used in various engineering applications, such as aerospace, marine, and construction, due to its combination of light weight, high strength, and stiffness [24]. The core material of a sandwich structure is usually a foam, such as polystyrene, polyurethane, cellular based materials, or honeycomb, that provides insulation and resistance to compressive loads. The outer layers, or face-sheet, are typically made of high-strength materials such as fiber-reinforced composites or metals, that provide the sandwich structure with its strength and stiffness. One of the key advantages of sandwich structures is their ability to withstand both compressive and tensile loads, making them suitable for use in applications where both types of loads are present. They also offer a high degree of resistance to fatigue and impact loads, making them suitable for use in harsh environments [25].

In summary, sandwich structures are a type of composite material that consist of a low-density core material sandwiched between two high-density outer layers. They are widely used due to their combination of light weight, high strength, with stiffness and are suitable for applications where both compressive and tensile loads are present, as well as in harsh environments. Fig. 2.1 shows the typical form of sandwich structure.

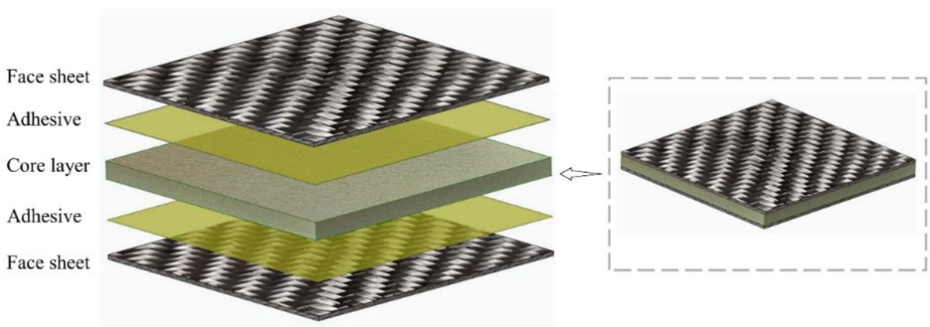


Figure 2.1. *Sandwich structure.*

2.1.1. Advantages

Sandwich structures enable the optimization of weight-critical structures such as airplane components, space structures, sporting products, naval structures, and wind turbine blades [24, 26, 27]. The sandwich concept, in addition to offering a very efficient load-carrying structure, allows the creation of multi-functional structures. They also have a strong tolerance to jet outflow fatigue. However, in other circumstances, the thickness, material, or both faces may differ since one face may be the principal load-carrying, low-temperature section while the other face must endure a higher temperature, corrosive environment, and so on [1]. The sandwich is not a material with distinct mechanical qualities; rather, it is a structure that must be constructed for the applications to which it will be put. Sandwich construction is becoming increasingly essential in buildings due to its superior flexural stiffness-to-weight ratio when compared to monocoque and other designs. The sandwich structure has reduced lateral deformations, stronger buckling resistance, and higher natural frequencies consequently. As a result, sandwich construction frequently results in a lower structural weight than alternative layouts for a given combination of mechanical forces. Sandwich structures are an important part of composite structural design technology [28]. The core materials chosen for the sandwich structure's core come in a range of material kinds, shapes, and qualities. The optimal material for the resulting structural application is frequently determined by the end-use application, and the sandwich's composition is only constrained by the materials' availability and the creativity of the engineer. Sandwich panels' main benefit is that their rigidities may take on any value depending on various geometrical factors. So, the designer has the option to choose a material solution that is optimized. Comparing sandwich structure to aluminum and composite laminate construction, the former has higher bending stiffness at a lower weight [29].

2.1.2. Face sheet materials

In aeronautical applications, sandwich structures typically use either aluminum, carbon fiber reinforced polymer (CFRP), or fiberglass reinforced polymer (FRP) as the face-sheet material. These materials are chosen for their high strength-to-weight ratio, corrosion resistance, and ability to withstand high stress and temperature fluctuations. The choice of material depends on various factors such as cost, desired weight, and specific requirements of the application. The face-sheets of honeycomb core structures used in aircraft construction are made of aluminum, fiberglass, Kevlar, or carbon fiber. Because carbon fiber face-sheets cause aluminum honeycomb core material to deteriorate, they cannot be utilized together. Titanium and steel are employed in high-temperature structures for specialized purposes. Many components like spoilers and control surfaces have very thin face-sheets sometimes just 3 or 4 plies. According to FAA, these face-sheets are not impact-resistant [30]. As stated by Du, the most often utilized sandwich panel face-sheets are CFRP and GFRP composites [31].

2.1.2.1. CFRP face-sheet properties

CFRP is a composite material made of carbon fibers embedded in a polymer matrix (typically epoxy). It has high strength, stiffness, and low weight, making it a popular material for various applications, especially in aerospace, automotive, and sporting goods industries [32]. The properties of CFRP can be tailored by controlling the type and orientation of carbon fibers, as well as the composition and processing of the polymer matrix. Compared to traditional materials like metal, CFRP has superior resistance to corrosion and fatigue, and is more thermally and electrically insulating. In terms of manufacturing, CFRP components are typically made using layering and bonding techniques, such as hand lay-up, vacuum bagging, or resin transfer molding. The high-performance properties of CFRP come at a cost, however, as the material is more expensive and challenging to manufacture compared to traditional materials [33].

We've likely seen carbon fiber in everything from auto racing to sporting goods. Its sleek, black finish is ready to spot, and it looks great. But what makes carbon fiber a popular choice is performance. That's because when created properly, a carbon fiber part will deliver unmatched strength and stiffness for its weight. In fact, when looking at strength-to-weight comparisons, carbon-fiber outperforms most traditional building materials. Graphite fibers contain up to 95% carbon, which yield the highest ultimate tensile strength in the FRP industry. Tensile strength is the pressure required to pull both ends of any length until it breaks [34]. What's more, carbon fiber also dominates the industry for compressive strength, the capacity of materials to withstand loads that compress or tend to reduce size and flexural strength, the ability to resist deforming under load. It makes sense that carbon fiber is chosen for the strong and most precise parts because it combines the industry's best in ultimate tensile, compressive, and flexural strength, along with excellent heat resistance and machinability. When creating carbon-fiber reinforcements, individual carbon-fibers are bundled and processed to create a variety of fabrics, tapes sleeves, and tow. Each of these selections and textile forms embody the inherent strength of carbon-fiber [32, 35]. But this strength is only fully realized when combined with the resin during the lamination process. This step is necessary and selecting the right resin for the project is crucial. Carbon-fiber parts can be created using the same processes from hand layup to vacuum bagging that would be use with other reinforcements. No special tools or equipment are necessary. When it comes to use carbon-fiber is ideal when maximum strength and low weight ratios are the target. Carbon-fiber parts are used in aerospace and aircraft, automotive and racing, and military and marine industries. It also good for sporting goods, used for items like snowboards and skis, and it's excellent for use in aircraft [36].

2.1.2.2. GFRP face-sheet properties

Fiberglas is the foundation of the composites industry. It's frequently the best overall choice among reinforcements, and even materials like metal and wood for making parts that combine excellent strength, low weight, and great cosmetics [37]. When fabricating, it's easy to handle, sand and machine, and it conforms to even the most complex shapes. It is widely used for all these reasons. In fact, it's so popular that it might be difficult to get through the day without touching something that contains fiberglass. Over time, this has led to a common misconception. You might hear someone refer to their boat or bathtub as "fiberglass". In fact, these products are not simply fiberglass, but fiberglass composites created using reinforcement and resin. When combined, the two bond chemically and mechanically to form hard composite laminate parts [34].

2.1.3. Sandwich core materials

A sandwich core is a material used as a structural core in sandwich construction. It is composed of two thin stiff facings typically made of metal or composite materials that are bonded to a lightweight, low-density core material. The core material is often foam, but can also be honeycomb, balsa wood, or other materials. The main function of the core is to provide stiffness, while reducing the weight of the sandwich panel. The core material provides most of the panel's resistance to compression and shear, while the face-sheets provide most of its resistance to bending. The use of a sandwich core construction allows the creation of a strong and lightweight structures, which is why it is often used in a wide range of applications such as aircraft fuselages, boat hulls, and wind turbine blades. The core of a sandwich material provides structural support, reduces weight, and helps distribute loads evenly across the panel. The type of core material used, as well as its thickness and arrangement, can affect the strength, stiffness, and other properties of the sandwich panel [38].

There are several materials that can be used as the core in sandwich structures. Some of the most common ones include:

a) Foam: It is one of the most widely used core materials in sandwich structures. It is lightweight, has good compressive strength, and can be manufactured in different densities to suit different applications. Examples of foam used as sandwich core material include polystyrene, polyurethane, and closed-cell PVC foam [39].

b) Honeycomb: It is another popular core material in sandwich construction. It is made of a repeating pattern of hexagonal cells that provide high strength-to-weight ratio. Honeycomb is also resistant to crushing and has good energy-absorbing properties. Common materials used to make honeycomb cores include aluminum, Nomex, and Kevlar [40].

c) Balsa Wood: It is a lightweight, softwood that has been used as a core material in sandwich construction for many years. It is relatively inexpensive, readily available, and has good compression resistance. However, balsa wood is not as durable as some other core materials and is susceptible to moisture damage [41].

d) Metal Foams: They, such as aluminum and titanium foams, are becoming increasingly popular as core materials in sandwich structures. They provide high strength, good energy-absorbing properties, and good fatigue resistance [42].

The choice of core material depends on the specific requirements of the application and the desired properties of the sandwich structure, such as strength, stiffness, weight, cost, and environmental resistance.

Cellular material is important for the core material of a sandwich structure, as it provides several advantages over solid materials. Cellular materials (as shown in Fig. 2.2), such as honeycomb, cork, and foam cores, are lightweight and have a high strength-to-weight ratio [43]. This is particularly important for sandwich structures, as the lightweight core reduces the overall weight of the structure, while the outer face-sheets provide the necessary strength and stiffness. Furthermore, the cellular structure of the core material provides additional benefits. For example, honeycomb cores have a high resistance to shear forces due to their hexagonal cell shape, which makes them well-suited for high-stress applications. Foam cores, on the other hand, have a high energy absorption capacity due to their ability to compress and deform under load. In addition, the cellular structure of the core material can also provide thermal and acoustic insulation properties, which can be beneficial for certain applications. Overall, the use of cellular core materials in sandwich structures offers a range of advantages, including a high strength-to-weight ratio, resistance to shear forces, energy absorption capacity, and insulation properties. These advantages make cellular core materials an attractive choice for a wide range of applications, from aerospace and automotive to construction and marine industries.

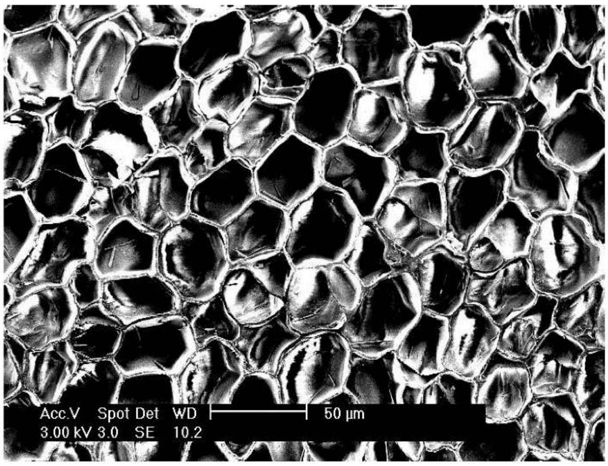


Figure 2.2. *Cork cellular structure [44].*

Different core designs are important because they can offer different mechanical properties. For example, honeycomb cores have a high stiffness-to-weight ratio, which makes them well-suited for applications where lightweight structures with high stiffness are required. Foam cores, on the other hand, are more compressible and can absorb energy, making them useful in impact-resistant applications [27]. Other core designs, such as balsa wood and metal foams, offer unique properties that can be advantageous for specific applications. Balsa wood, for example, is a natural material that is lightweight and has good impact resistance, making it useful in marine and aerospace applications. Metal foams are highly deformable and can absorb large amounts of energy, making them useful in crash-resistant structures. Overall, the choice of core material and design depends on the specific application and the desired properties of the sandwich structure. Fig. 2.3 shows various core designs for sandwich structures.

In aeronautical applications, sandwich structures are widely used due to their high strength-to-weight ratio, which is critical for aircraft design where weight reduction is a key consideration. The choice of core material and design is particularly important for aeronautical applications, where the structure must withstand high loads and severe environmental conditions. Honeycomb cores, for example, are commonly used in aircraft structures due to their high strength-to-weight ratio and stiffness, which allows for high load-carrying capacity. Foam cores, on the other hand, are used in aircraft interiors as they can provide sound insulation and vibration damping. Balsa wood cores are also used in aeronautical applications due to their excellent strength-to-weight ratio, as well as their natural resistance to impact and moisture. They are commonly used in aircraft flooring and interior panels. Metal foam cores are another type of core material that is gaining interest in aeronautical applications due to their high energy absorption capabilities, making them suitable for impact-resistant structures such as crash-resistant seats and bulkheads. Overall, the choice of core material and design in aeronautical applications is critical to achieving the desired balance of weight reduction, strength, and durability required for safe and efficient aircraft design [45, 46].

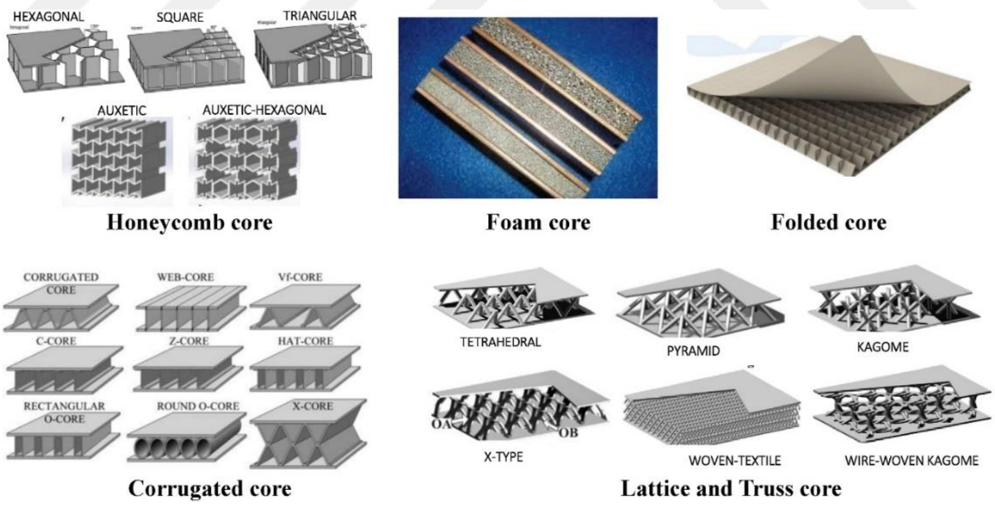


Figure 2.3. *Sandwich structures with various core designs [47].*

2.1.3.1. Foams

With large truss core structures, the space in the core might be used for liquid storage or as a heat exchanger. Foam or solid cores are reasonably affordable and can consist of balsa wood and an almost endless array of foam/plastic materials. Although the density of balsa is less than half that of traditional wood products, it is significantly higher than the density of other forms of structural cores [30]. On homebuilt and lighter aircraft, foam cores are used to provide strength and shape to wing tips, flight controls, fuselage sections, wings, and wing ribs. As a core material, several foams can be employed, including [1, 3, 30, 48, 49]:

a) Polystyrene foam (EPS and XPS): Aircraft grade Styrofoam with a tightly closed cell structure and no spaces between cells. A thermoplastic material with excellent compressive strength and strong resistance to water penetration; it may be shaped into airfoil forms using a hot wire.
b) Polyurethane foam (PU): Another thermosetting material is polyurethane, which is frequently used to make the fuselage, wing tips, and other curved parts of small aircraft. It is reasonably affordable, fuel-resistant, and compatible with most adhesives; hot wire cuts are not allowed, and it can be easily contoured with a big knife and sanding tools.
c) Polypropylene foam (PP): Used to create the forms of airfoils; it can be cut with a hot wire; it is compatible with most adhesives and epoxy resins; polyester resins should not be used with it since it dissolves in fuels and solvents.
d) Polyvinyl chloride foam (PVC): A closed cell medium-to-high density foam that can be vacuum shaped into complex forms and heated to bend it. It is also compatible with polyester, vinyl ester, and epoxy resins. It has great fire resistance, durability, and compression strength. Examples include Airex®, Klegecell®, and Divinycell®. In this thesis we used Divibycell-based PVC foam for foam-based drone cage.

Expanded polytetrafluoroethylene foam (ePTFE): Expanded polytetrafluoroethylene (ePTFE) foam is a microporous material made from polytetrafluoroethylene (PTFE) resin. It is a lightweight, flexible, and durable material that has a wide range of applications, including use as a filter membrane, insulation, and in medical devices. The unique properties of ePTFE foam, such as its chemical resistance and non-stick surface, make it ideal for use in a variety of industries.

2.1.4. Applications of sandwich structures

Sandwich structures have been used in the aerospace and aeronautical industry for many decades. The concept of sandwich structures dates to the early 20th century, but their use in aerospace and aeronautics started in the mid-1930s. During World War II, sandwich structures were used in aircraft components such as control surfaces, wing skins, and fuselage sections. The use of sandwich structures continued to grow in the post-war years as aircraft design moved towards more efficient and lightweight structures. In the 1950s, the development of new materials, such as fiberglass and carbon fiber composites, allowed for even lighter and stronger sandwich structures. These materials were used extensively in the construction of the first generation of supersonic aircraft, including the Concorde and the Soviet Tupolev Tu-144. In the 1960s, the use of sandwich structures became even more widespread as the demand for lightweight, high-strength structures grew. The Apollo spacecraft used sandwich structures extensively, including the Lunar Module, which used a sandwich structure for its landing legs. The 1970s saw the introduction of composite materials such as Kevlar, which further increased the strength and durability of sandwich structures. The use of sandwich structures continued to expand in the 1980s and 1990s with the development of advanced composite materials and new manufacturing techniques [50].

Due to the outstanding performance of this aircraft, many aviation designers, notably in England, came to agree that the sandwich construction is fundamentally superior to build an airplane that is more effective and performs better. As a result, several aircraft design teams started looking into improved methods for creating sandwich structures as well as better materials for the cores and facings. The first sandwich panel made entirely of aluminum wasn't created until 1945. Hexcel Corporation was founded by two young World War II veterans in the late 1940s, and throughout the years, it has contributed more than any other company to the development of sandwich structures. Using the concept of virtual displacements, Hoff also developed the differential equations and boundary conditions for the bending and buckling of sandwich plates in 1948 [51], although he primarily focused on the buckling of panels under edgewise compression. A broad small deflection hypothesis for sandwich plates was published by Libove and Batdorf in the same year [52]. The improvement of adhesives used to attach face-sheets to cores marked the true breakthrough. For usage with honeycomb, adhesives with the proper rheology which refers to the flow during curing were created. When the face-sheets were being bonded, the adhesives remained on the honeycomb cell edges. Earlier adhesives flowed down the cell walls rather than staying on the top honeycomb surface. As a result, a strong attachment to the top skin was not feasible to develop. When curing, most adhesives at the time released volatile gases, thus the aluminum honeycomb cores had to be perforated (simple pinholes had to be cut in the foil before it was assembled into a core) to enable the gases to escape [2]. A proper core-to-facing connection might be prevented, and the core may even burst out if the core is not punctured and pressure builds up inside the cells. Nowadays, most adhesives are 100% solid and don't emit volatiles. As a result, honeycombs no longer need to be perforated. Currently, if air is not desired in the cells, the sandwich core is often perforated for space applications.

Sandwich structures are widely used in the aeronautical and aircraft industry due to their high strength-to-weight ratio and excellent resistance to fatigue. Some of the current applications of sandwich structures in this industry are [45]:

a) Wing structures: Sandwich structures are used in the construction of aircraft wings to reduce their weight and improve their strength. The use of sandwich structures in wings can reduce the weight by up to 30% compared to traditional metal structures.

b) Fuselage structures: Sandwich structures are also used in the construction of aircraft fuselages to reduce weight and improve structural integrity. They are commonly used in the construction of the cockpit and passenger compartment.

c) Helicopter blades: Sandwich structures are used in helicopter rotor blades to reduce their weight and improve their performance. They are commonly used in the construction of composite blades that are more durable and resistant to damage than traditional metal blades.

d) Control surfaces: Sandwich structures are used in the construction of aircraft control surfaces, such as flaps and ailerons, to improve their aerodynamic performance and reduce their weight.

e) Interior components: Sandwich structures are used in the construction of interior components of aircraft, such as overhead bins, lavatory partitions, and seat structures, to reduce weight and improve structural integrity.

Overall, sandwich structures play a critical role in the design and construction of modern aircraft and spacecraft, and their use is expected to continue to grow as new materials and manufacturing techniques are developed.

Sandwich structures have been extensively utilized virtually in every sector of the industry, including the aerospace and marine, civil engineering, and automotive sector [53]. In aircraft applications, laminated graphite-epoxy, and carbon-epoxy face-sheets with an aluminum or Nomex honeycomb core are typical. The dimensional changes in sandwich constructions for major components in commercial aircraft with carbon fiber-reinforced plastic face-sheets and a polymethacrylimid foam core were examined by John et al. [54]. Chai et al. [55], consider the impact of geometrical factors and an elastic basis on the panel flutter and thermal buckling of sandwich panels with pyramidal lattice core. For lower RCS and superior aerodynamic performance, folded core sandwich constructions were used for the fuselage [56]. In the study of Caliri et al. [57], composite lattice core sandwich constructions were presented as a replacement suggestion for the engine hood. Additionally, the fascination with morphing airplanes led to the development of novel composite corrugate sandwich architectures [58]. Marine structures are frequently made of sandwich constructions with auxetic cores and glass-epoxy or glass-vinyl ester facings. Imbalzano et al. [59], examined the applicability of auxetic and honeycomb sandwich panels for armored vehicles in terms of blast protection. To comparing the blast resistance capabilities of several auxetic composite panel designs, parametric studies were carried out [60]. In civil engineering, sandwich structures typically consist of two glass-epoxy or glass-vinyl ester facings and a closed-cell or open-cell foam core. The ability to increase the application in lightweight civil infrastructure was made possible by the development of FRP sandwich panels with improved core structures [61]. Possible use in the biomedical field is provided by smart materials employed in smart sandwich structures. The hybrid composite sandwich construction with glass/epoxy facings and a flax/epoxy core has been shown to be an excellent option for bone fracture repair with mechanical qualities like human cortical bone.

The most common composite sandwich manufacturing methods are autoclave cure, press cure, and vacuum bag cure. Face-sheet laminates can be pre-cured and then bonded to the core, in one process, or a mix of the two. Sandwiches have long been used in packaging materials such as corrugated paper board. This style of construction is used to make lightweight "planks" for cabin furnishings, monolithic fairing shells with plastic facing skins, and to stiffen flying control surfaces. The ailerons and rudder of the British Aerospace Jaguar, for example, are made of aluminum honeycomb, whilst fiberglass- and aluminum-faced honeycomb are extensively utilized in the wings and tail surfaces of the Boeing 747. In service, several issues, mostly disbonding and internal corrosion, have arisen [62].

In Airbus aircraft, composite sandwich constructions are used in a variety of ways. Aerodynamic fairings, coverings, and doors are examples of typical exterior constructions. Radomes, belly fairings, leading and trailing edge fairings, engine cowlings, and landing gear doors are some examples. Furthermore, the Airbus fleet has a range of composite sandwich control surfaces (e.g., rudder, aileron, spoiler). Fairings and floor panels in the passenger compartment are two examples of composite sandwich applications within the aircraft. Fig. 2.4 depicts the composite sandwich used in the A380, A350, and B787aircraft. To meet the various criteria, contemporary composite sandwich constructions use a range of material combinations. Face-sheet materials are mostly glass fiber and carbon fiber reinforced prepregs with epoxy resin matrices, whereas core sandwich materials are NOMEX® honeycomb.

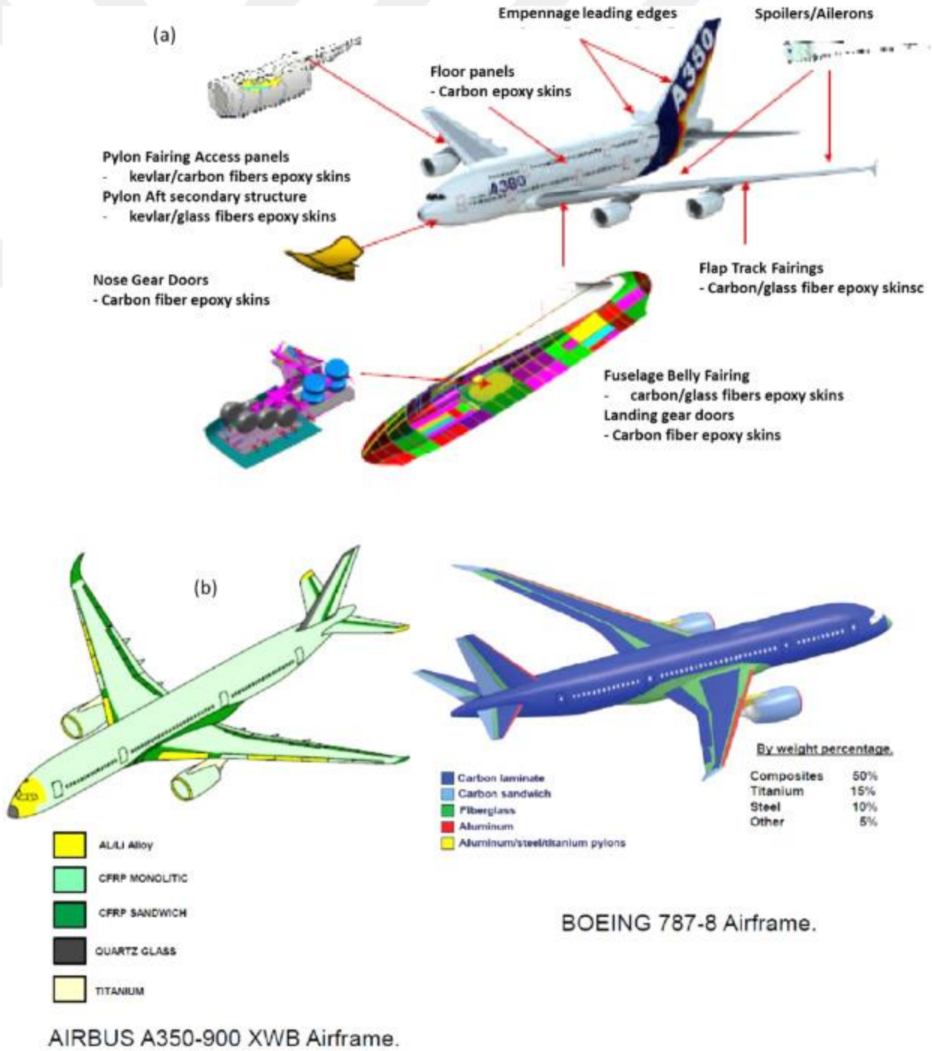


Figure 2.4. *(a) Sandwich structures in A380 [63], (b) Sandwich and composite structures A350 and B787 composite Aircraft [45].*

Less hazardous phenolic resins are used in the fabrication of surface layers of cabin interiors due to fire, smoke, and toxicity standards (FST). ROHACELL® PMI hard foam is used in the production process (lost tool, e.g., hat profiles for A340 and A380 rear pressure bulkhead). Airbus vertical tail planes are made up of five key structural components: Fairings on the leading edge (including tip and dorsal fin), Trailing edge fairings, Center box structure (containing the interface to the fuselage), Fin - fuselage fairing.

2.2. Cork materials

The world of aerospace technology has seen the use of many high-tech materials. Alloys of steel, aluminum, titanium, and composites like carbon fiber, plastics, and occasionally wood-based materials like cork. Since ancient times, when some of its principal characteristics were calculated and used, wood has piqued man's interest. In some cases, the engineering properties of wood-based materials have meant that it fits the bill perfectly. Wood has a lengthy history in aviation, in fact, it has been used for a long time. The H-4 Hercules, often known as the Spruce Goose, had the most enormous wingspan and was made completely of wood, yet it is feasible to acquire airplanes that fly no faster than a vehicle. Flying to space, on the other hand, is an order of magnitude more in terms of forces, energy, and velocities. Cork is an impermeable substance obtained from the phellem layer of bark tissue of Quercus suber (the cork oak), which is native to southwest Europe and northwest Africa. Cork has a long history as an industrial material, and it's utilized because it's impermeable, flexible, and insulating. Corks is also used in rockets as insulation. The entire construction is coated with cork. This is a small launch vehicle from the vector launch. Cork is an excellent insulator and may be used in many layers. We may also link it with synthetic polymers to make it stronger, and it will perform just as well in preventing cryogenic fuel from overcooling the spacecraft's exterior and overheating it in flight. Cork is a natural product and it is composed of several cells such as 42 million cells per centimeter cube. The cells are generally structured with five wall layers and the inside of the cells is filled with air [64]. For this reason, the bigger part of the cork is just air, which makes this natural material very light. Cork is such a lightweight material that it floats on water. The density of cork is about 0.24 grams per cubic centimeter. Despite its low density, cork shows impermeable characteristics to fluids due to its closed-cell microstructure. In addition to these properties, cork is very flexible and durable under harsh environmental conditions [65]. Moreover, cork is an imperishable material although it is a natural substance. Cork is supplied from the cork oak forests on the Mediterranean coasts. Portugal and Spain are the biggest cork producers in the world because about 70% of the cork forests are in the territories of these two countries. Cork production is sustainable because the cork tree is not cut down to obtain cork; only the bark is stripped to harvest the cork. The tree continues to live and grow. The sustainability of production and the easy recycling of cork products and by-products are two of its most distinctive aspects [66]. Cork oak forests also prevent desertification and the refuge of various endangered species. Leading companies, especially in the aerospace sector, make investments in cork. However, there is a lack of human resources in the field since syllabuses in engineering programs focus on technical sides rather than including the environmental effects of engineering materials. Prior to cork use in major sectors, it was used as bottle stoppers in the first applications. In the next periods, cork wastes were compressed into panels, and they were used as lifejackets for sailors since cork floats on water. Because cork is a kind of wooden product, cork panels were used in floor coverings. Cost-effective and recyclable materials were produced by producing cork panels from cork wastes. To reinforce the cork panels, different kinds of additives such as gelatin, dextrin, casein, and polyurethane were mixed with cork granules before the molding process. The elemental composition and cellular structure of cork give it a unique set of characteristics, including very low permeability, hydrophobic behavior, biological inertia, significant elastic compression, and dimensional recovery [65]. Previous studies have demonstrated that using cork has the potential to improve the amount of absorbed impact energy [67-71] and vibration damping [72-74], and it is well known that cork is a natural material with respect to sustainability, and recyclability [66, 75]. Cork has an excellent thermal insulation (gaseous components of cellular structure present low conductivity of heat and noise transmission), very high acoustic resistivity (reduced sound propagation due to the materials low density), resistant to fire (slow burning due to low mass composition and cellular structure), damping (a cellular structure that is highly effective in energy dissipation), elasticity and compressibility (due to a flexible and closed microcellular structure with internal gas), chemical resistance (a combination of suberin, ceroids and tannins provides great resistance to humidity and chemicals), impermeability to liquids and gases (the presence of suberin in the cell walls renders it impermeable), abrasion resistance (the honeycomb cells are highly resistance to friction), lightness (over 50% of its volume is air, making it very light).

2.2.1. Cork morphology and properties

Cork is a type of natural closed-cell foam made up of microscopic hollow hexagonal prism-shaped cells that are organized in a structure that fills the available area without intercellular spaces (Fig. 2.6). A material made up of empty, open, or closed cellular units with a solid fraction < 30% of the total volume is referred to as a cellular material in the field of materials science. However, they are polyhedral volumes with solid sides that are in touch with the neighboring cells in materials with closed cells. The distribution of the solid in the cell faces and edges determines the characteristics of cellular solids. In such materials, the three-dimensional organization of the individual cells as well as their geometry, size, and variability play a significant influence. The one-cell layer of phellogen gives cork its regular structure of closed cells, which develop unidirectionally outward in the direction of the tree's radial growth (Fig. 2.7). The physiological rhythm of the tree, which resulted in the production of growth rings, causes periodic fluctuations in cell size and density. Cork is made of a natural combination of various biosynthesized polymers, and its alveolar cellular structure is like that of a honeycomb (suberin, lignin, cellulose, and hemicelluloses). The cellular membranes are somewhat impermeable and filled with a gas that is typically thought of as air and takes up almost 90% of its volume [44]. According to Castro and Silva [67], the mechanical characteristics of materials made from cork are significantly influenced by this cellular arrangement.

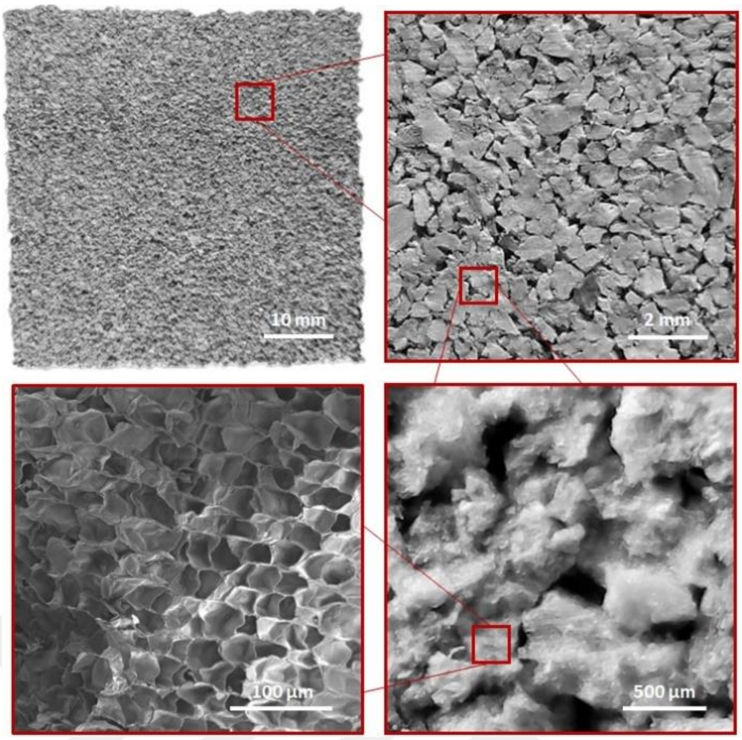


Figure 2.5. *Microstructural views of cork [76].*

Table 2.1 summarizes the mechanical properties of cork composites. As a result of the compressed gas activity present in the interior of the cork cells, the cells become curled and bent when squeezed, with little to no lateral expansion. More specifically, when cork is squeezed in the radial direction, the corrugations' amplitude rises, the cell bases perpendicular to the R direction align, and the cell walls fold and pack because of the corrugations.

Table 2.1. *General mechanical properties of cork.*

Property	Description
Elastic Modulus	The elastic modulus of cork composites ranges from 2 to 8 GPa, depending on the type of matrix used and the processing conditions.
Tensile Strength	The tensile strength of cork composites is in the range of 5 to 15 MPa.
Compressive Strength	The compressive strength of cork composites is higher than their tensile strength, ranging from 10 to 20 MPa.
Shear Strength	The shear strength of cork composites is in the range of 4 to 10 MPa.
Impact Strength	The impact strength of cork composites is dependent on the type of matrix and the processing conditions, but is generally in the range of 10 to 40 kJ/m^2.

It's important to note that these values can vary depending on the specific composition and processing of the cork composite. The extremely poor heat transmission qualities of cork are caused by both the gas concentration and the cell size, which together account for the features of cork insulation. Cork's outstanding insulating qualities are made possible by the fact that its cells are far smaller than those of other popular materials. Conduction, which is dependent on the amount of solid in the structure and less effective for expanded cork as thermal insulation, convection, which is significant only for high volumes of gas and thus does not contribute much, and radiation, which is less effective as cell size decreases, are the three ways that heat can be transmitted. The more times heat must be absorbed and re-radiated, the smaller the size [77].

2.2.2. Eco-friendly properties of cork

The cork oak (Quercus suber L.), an evergreen oak that is distinguished by the presence of a noticeable thick, furrowed bark and a continuous covering of cork on its outer half, is the source of cork, a natural product. The cork oak's fame, economic significance as a cork producer, and decorative appeal in many parks and urban places across the world are all down to its cork bark. The importance of cork oaks as a buffer against soil erosion and desertification was recognized in the ecologically vulnerable regions of southern Europe and northern Africa, where this oak species primarily integrates multifunctional agro-forestry systems known as "montado" in Portugal and "dehesa" in Spain [78]. Without harming the tree's health, cork may be removed from the stem, and the tree will then regenerate a new cork covering. During the lengthy lifespan of the cork oak, this serves as the foundation for the sustainable production of cork. The Southern Mediterranean countries, particularly Portugal, stand out with over 50% of the total production in the European Union, which is the world's largest producer of cork. The cork oak forests in southern Europe are very well suited to the semi-arid climate, avoiding desertification and offering the ideal home for a variety of animal and plant species.

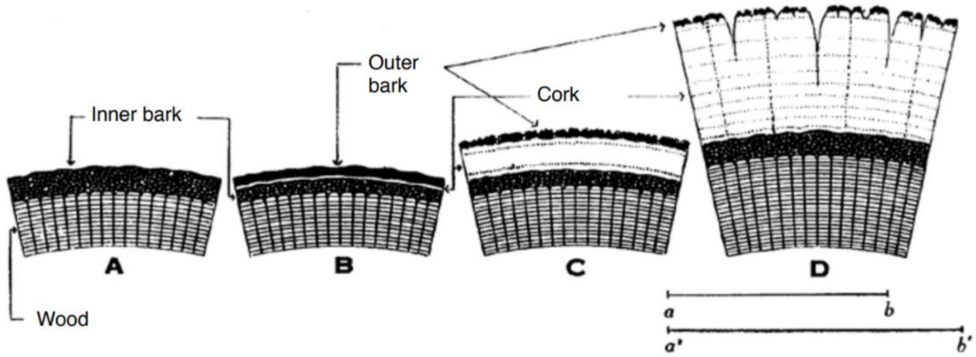


Figure 2.6. *The growth process of cork [79].*

Additionally, cork harvesting is a natural, sustainable process that lowers subsequent carbon footprints as the globe looks for ecologically beneficial products. Expanded agglomerated cork is produced only using a superheated steam in boilers that are powered by granules acquired from byproducts [44]. Additionally, agglomeration occurs using cork's own resin, producing a product that is entirely ecological and natural, an advantage that is very challenging for competing materials to match. A significant waste created during the production of cork construction goods is cork powder. As a result, there is no cork byproduct that is not re-used, appreciated, or used in some form. The fact that cork items are thus used is also highly essential from an environmental perspective because cork is a long-lasting renewable product that promotes CO2 fixation. Moreover, a cork oak tree that is harvested on a regular basis will produce between 250% and 400% more cork than if it was not harvested, resulting in increased CO2 fixation. According to Sargianis' research, switching from synthetic foam cores to natural cork cores might give significant gains in acoustic and vibrational performance in applications such as aircraft cabins or wind turbine blades [80]. Considering that cork oak trees can spend up to 30 years to mature, a decrease in cork's economic viability may result in insufficient investment in cork forests. Saving the cork oak, growing forest areas, improving the quantity and quality of cork produced, and creating new products with higher added value are all critical.

The writers of this thesis [81] explored an experimental research of multi-layer composites made of cork and warp-knitted spacer fabrics (WKSF) for anti-impact applications. A laser cutting equipment was used to design and produce composites in eight distinct designs. In addition to anti-impact behavior, eco-friendly features were studied for each configuration using LCA. The LCA findings considered parameters such as human health impacts (HHI), ecosystem quality impacts (EQI), and resource impacts (RI). When it comes to the eco-friendliness of multi-layer composites, full-cork structures lead the LCA measures since cork is a natural material with fewer carbon emissions than WKSF.

2.2.3. Cork composites

Cork composite is a material made by combining cork particles with synthetic materials such as polyurethane or PVC, resulting in a composite material with unique properties. Cork composite is often used for flooring, wall tiles, and other construction applications due to its durability, light weight, and insulating properties. It can also be produced in various colors, patterns, and textures to mimic the appearance of natural cork or other materials. Agglomerating is the activity of agglutinating granulates, which are made by grinding scraps, parings, virgin cork, cork pieces, or stopper production and then used to reduce weight, and other types of inferior quality cork, which give rise to agglomerates through the application of heat and pressure in autoclaves, involving steam from superheated water [82]. Gil reports that the first agglomerated cork stoppers were created in the early 1900s using a variety of glues, including dextrin, casein, gelatin, urea-formaldehyde, and amine, and that polyurethane was employed in 1968. Agglomerated corks, floor coverings, joints, etc. are created from cork composites, which are formed of granules that have been linked together using various synthetic or natural binding agents, such as urethane, melamine, and phenolic resins. The strength of the agglomerate and, consequently, its applicability, are determined by the physical and chemical properties of the binders [77]. Fig. 2.8 shows the agglomerate types of cork composites.

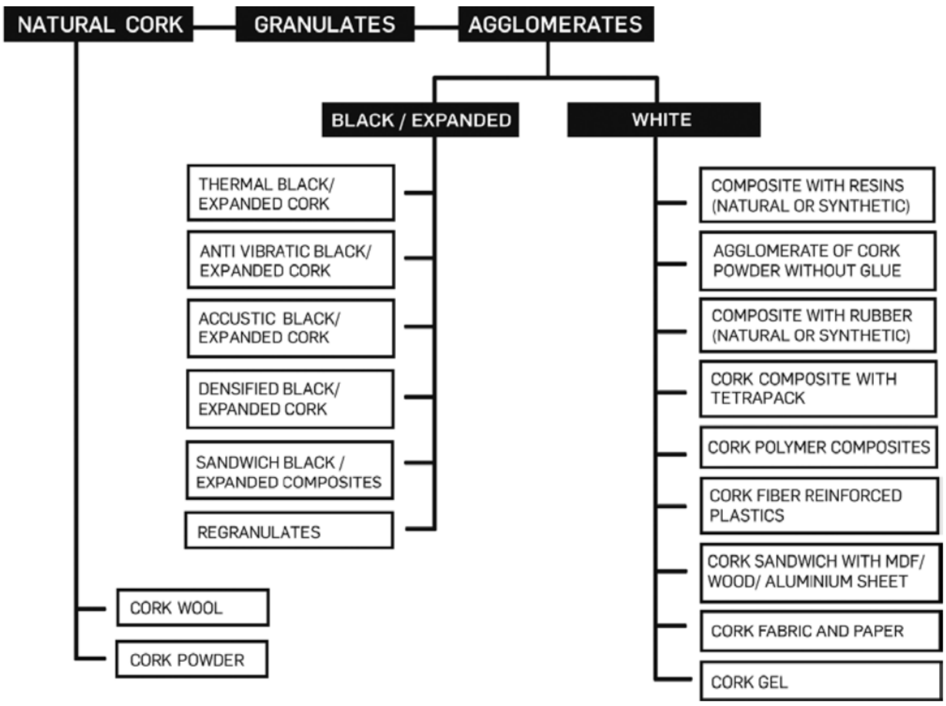


Figure 2.7. *Cork agglomerates types [82].*

2.2.4. Cork composites in aerospace application

In aerospace applications, cork is used in laminate form. To produce cork laminates, stripped cork layers from the cork oaks are grounded into different size of granules. Then, the cork granules are mixed with a polymer matrix, generally polyurethane and molded into desired dimensions of panels. Fig. 2.8 shows different cork panels.

Figure 2.8. *Cork panels in different thicknesses.*

Although neat cork panels are ready for installation in aerospace applications, these panels are also used with elastomer coatings, metal coverings or rubber granules. Elastomer coatings protect the cork panels from external conditions such as humidity, sharp impacts, and heavy loadings. Metal covers are used for producing sandwich cork composites. Rigidity and stiffness are increased by using metal skins on the cork panels. These sandwich structures are generally used in flooring applications as well as prefabricated houses. Rubber mixed cork granules are common in civil engineering applications. Rubber/cork panels are used for increased flexibility especially for floor coverings. Cork laminates are applied in aerospace structures for the isolation of vibrational and thermal loadings. In aircraft, cork laminates are bonded on the mating surfaces of brackets to suppress the vibrations in the joints. Boeing 737 and combat helicopter Atak are some of the platforms using cork covered brackets from aircraft industry. Air vehicles are subjected to unavoidable vibrational loadings during flights and therefore, the structures are reinforced by vibration isolators to lower the vibrations. The joints such as brackets are important application areas because the undesired vibrations may unfasten the joints and may lead to the disassembly of components. Fig. 2.9 shows a cork cover bonded on a bracket.

Figure 2.9. *Cork cover on a bracket.*

Apart from aircraft applications, space vehicles take advantage of cork composites both for suppressing the undesired vibrations and insulating the vehicle from heat sources. In solid rocket boosters, engine skirting, nose cone, frustum, forward and aft skirt, external tank attach ring covers, assembly and tunnel covers are applied with cork panels.

These sections are protected by composite laminates from heat and vibrations. In addition to these loadings, cork panels are also used for impact protection against space debris. Due to the viscoelastic behavior of cork, it provides quite good anti-impact properties according to early studies. Fig. 2.10 presents the cork application areas in a space vehicle.

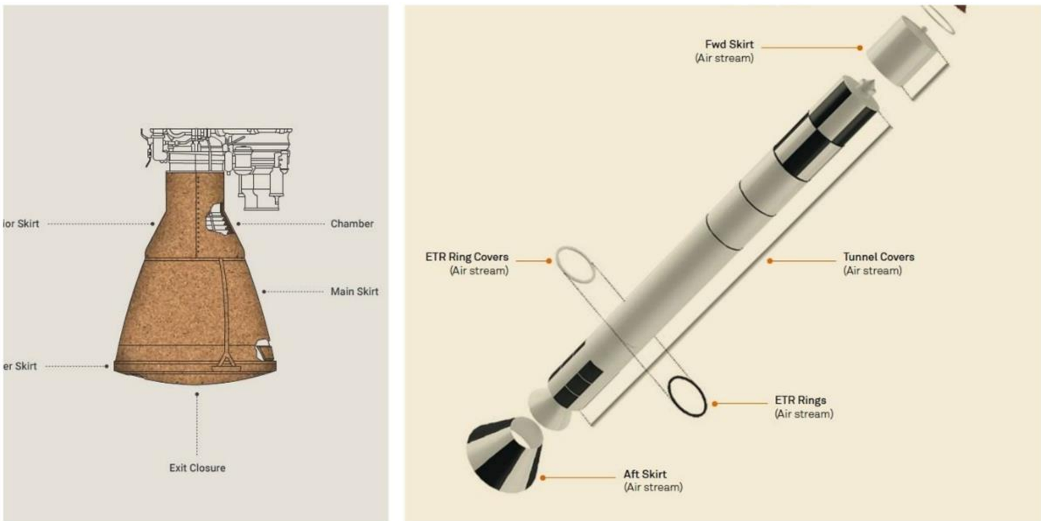


Figure 2.10. *Cork application areas in a space vehicle [83].*

2.3. Basics of modal analysis and forced vibration

Vibration Modal Analysis is a process used in mechanical engineering to study the dynamic behavior of structures and mechanical systems. The aim of modal analysis is to determine the natural frequencies, mode shapes, and damping ratios of a system. These characteristics are useful for understanding the system's dynamic behavior and for designing or improving its structural stability, strength, and performance [84]. Vibration Modal Analysis is often used in a variety of applications, including:

a) Structural engineering: Modal analysis is used to evaluate the natural frequencies and mode shapes of buildings, bridges, and other structures to ensure they meet safety and performance standards.
b) Mechanical design: Modal analysis is used to optimize the design of mechanical components such as engines, turbines, and gearboxes by improving their natural frequencies and reducing the risk of resonant vibrations.

c) Aerospace engineering: Modal analysis is used to evaluate the dynamic behavior of aircraft structures, including wings, fuselages, and empennages, to ensure they meet safety and performance standards.
d) Automotive engineering: Modal analysis is used to evaluate the dynamic behavior of vehicles and their components, including suspension systems, engines, and powertrains, to improve their performance and safety.
e) Control systems: Modal analysis is used to determine the natural frequencies and mode shapes of control systems, such as robots and machines, to improve their stability and performance.

Forced vibration is a type of mechanical vibration that occurs in a structure when an external force is applied to it repeatedly or with a constant amplitude. This external force can come from many sources, including wind, traffic, machinery, and earthquakes. The resulting vibration causes the structure to oscillate at a frequency that is determined by the properties of the structure and the magnitude of the applied force. The importance of understanding forced vibration lies in the potential for this vibration to cause damage to the structure. If the vibration frequency coincides with one of the natural frequencies of the structure, it can amplify and cause resonant vibration, leading to excessive deformations and fatigue failure. By understanding the characteristics of forced vibration and its effects on structures, engineers can design structures that are less susceptible to this type of damage and ensure the safety and stability of the structure over time.

Fig. 2.11 depicts a system with a single degree of freedom (SDOF) comprised of a mass, a spring, and a damper. The mass can vibrate only in the vertical direction. X represents the displacement of the mass from its equilibrium position, whereas F represents the external force acting on the mass. The differential equation that governs the mass's motion is given in Eq. A.1.

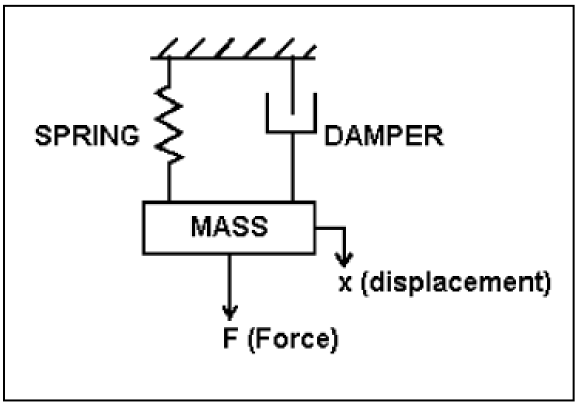


Figure 2.11. *Vibratory system with single degree of freedom.*

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{2.1}$$

The system vibrates if there is no external force operating on the system and the mass is moved from its equilibrium position and then released. This vibration is known as a free vibration since there are no forces operating on the system. As the damper dissipates the energy, this vibration vanishes (thus, it is sometimes referred to as transitory). Therefore, the vibration is known as a damped vibration. Without a damper, the vibration would never stop and continue forever, and the frequency of vibration is calculated in Eq. 2.2. The subscript n shows the natural frequency. k is the spring stiffness (N/m) and m is the mass (kg).

$$\omega_n = \sqrt{\frac{k}{m}} \tag{2.2}$$

If a damper is present, the frequency of vibration is calculated in Eq. 2.3. The subscript d shows the damped natural frequency. ζ is the damping ratio and calculated as follows (Eq. 2.4). c is the damping coefficient.

$$\omega_d = (\sqrt{1-\zeta^2}\sqrt{\frac{k}{m}} \tag{2.3}$$

$$\zeta = \frac{c}{2\sqrt{km}} \tag{2.4}$$

The motion of an SDOF system with damping is given below (Eq. 2.5). x_0 is the initial displacement.

$$x(t) = x_0 e^{-\zeta\omega_n t}\cos(\omega_d t) \tag{2.5}$$

Hammer testing involves striking a mechanical structure with an instrumented force hammer, which induces natural vibrations in the structure. Using either a displacement sensor, which measures the displacement [m], a velocity sensor, which measures the velocity [m/s], or an accelerometer, which measures the acceleration [m/s^2], the free vibration is detected. From the measurements of the hammer (force) and the accelerometer (acceleration), it is possible to establish the structure's modal mass, stiffness, and damping. Modal analysis is the determination of mass, stiffness, and damping values.

In a hammer test, one point of the structure is excited, and the response is measured at the same position. The term for this is "direct transfer function." The hammer blow excites all masses, and the total response at the point of excitation is measured. Depending on the contact period between the structure and the hammer, a hammer blow stimulates a structure throughout a specific frequency band. The frequency response function (FRF) of the structure is determined by using the time response and Fourier spectra of the hammer and accelerometer inputs. This function provides the structure's dynamic stiffness as a function of frequency. This data is quite valuable for evaluating the performance of the structure. The two most prevalent FRF representations are magnitude/phase and real/imaginary parts. Determination of mass, rigidity, and damping from the frequency response function is given below (Eqs. 2.6-2.8).

$$m = \frac{k}{(2\pi\omega_n)^2} \tag{2.6}$$

$$k = \frac{-1}{2\zeta \, \mathrm{Im}_{\min}} \tag{2.7}$$

$$\zeta = \frac{\omega_2 - \omega_1}{2\omega_n} \tag{2.8}$$

In practical applications, such as the structure of a mechanical system, we do not deal with a single mass-spring-damper system, but rather with complicated structures that possess more than one degree of freedom and are hence referred to as multi degree of freedom systems (MDOF).

The technique of isolating an object, such as a piece of equipment, from the source of vibrations is known as vibration isolation. Passive vibration isolation employs materials and mechanical connections that absorb and attenuate these mechanical vibrations. Active vibration isolation consists of sensors and actuators that generate disruptive interference to cancel out incoming vibration. The ratio of vibration of the isolated surface to that of the source is the transmissibility. Vibrations cannot be avoided entirely; however, they can be significantly decreased. Regarding forced vibration with damping, transmissibility can be defined in Eqs. 2.9 and 2.10. $r = \sqrt{2}$ is a critical value and changes the behavior of the damping ratio. Below this value, increasing damping ratio decreases transmissibility.

$$\frac{F_{TR}}{F_0} = \frac{\sqrt{1+(2\zeta r)^2}}{\sqrt{(2\zeta r)^2 + (1-r^2)}} \tag{2.9}$$

$$r = \frac{\omega}{\omega_n} \tag{2.10}$$

2.4. Peak deceleration

Peak deceleration is a term used to describe the maximum rate of decrease in velocity that occurs after a collision or an impact event. It refers to the highest point reached in the deceleration process, which is the rate at which an object slows down. This measurement is important in the study of the dynamics of impacts, such as in car accidents or the collision of structures with obstacles, as it provides valuable information about the severity of the event and the forces involved. In these types of incidents, peak deceleration can be used to assess the potential for injury to occupants or damage to structures and to design safety systems that can mitigate such effects. There are several factors that can be effective in reducing peak deceleration during a collision or impact event:

a) Absorbing materials: The use of materials that have the ability to absorb energy can help to reduce peak deceleration. This is often achieved through the use of crumple zones in vehicles or the inclusion of energy-absorbing materials in structures, such as foam padding or shock-absorbing elements.
b) Restraining systems: Safety systems such as seat belts, airbags, and other restraint devices can help to limit the movement of occupants and reduce the forces experienced during a collision.
c) Design of the impact surface: The design of the surface that a structure collides with can also play a role in reducing peak deceleration. For example, using materials with a high degree of deformability, such as rubber, can reduce the severity of the impact by absorbing some of the energy of the collision.

d) Vehicle design: The design of the vehicle or structure can also affect peak deceleration. For example, designing a vehicle with a low center of gravity can help to reduce the potential for rollovers and reduce the severity of impacts.
e) Velocity: The speed of the vehicle or object involved in the collision can also play a role in determining peak deceleration. Lower speeds generally result in lower peak decelerations and less severe impacts.

To sum up, minimizing peak deceleration may assist to lessen the intensity of collisions and the possibility of injury or damage. Materials, design, and safety systems that work together to mitigate the impact of crashes are used in effective approaches for lowering peak deceleration. Peak deceleration is the maximum change in velocity (rate of change of position) over a given time interval, and it can be calculated using the following formula:

$$(a) = \frac{\Delta v}{\Delta t} \tag{2. 11}$$

Where a is peak deceleration, Δv is the change in velocity and Δt is the time interval over which the change in velocity occurs. It is important to note that this formula assumes that the change in velocity is constant over the time interval Δt, which is not always the case in real-world scenarios. In complex cases, peak deceleration can be calculated by finding the derivative of velocity with respect to time, also known as the acceleration, and then finding the maximum value of the acceleration function. This process can be accomplished using calculus. For example, consider a particle moving along a curved path with a velocity function $v(t)$. The acceleration of the particle can be calculated using the derivative of the velocity function:

$$a(t) = \frac{dv(t)}{dt} \tag{2.12}$$

The peak deceleration can then be found by finding the maximum value of the acceleration function:

$$\text{Peak deceleration} = \max\left[a(t)\right] \tag{2.13}$$

It is important to note that this process can become quite complex, especially if the velocity function is not easily differentiable or if the path is not well-defined. In such cases, numerical methods or simulations may need to be used to calculate the peak deceleration.

2.4.1. The role of materials in reducing peak deceleration

Materials play a significant role in decreasing peak deceleration in various applications. The choice of material and its properties such as strength, stiffness, and energy absorption can affect the amount of deceleration experienced during an impact event. For instance, in automotive engineering, the use of materials such as high-strength steel, aluminum alloys, and composite materials in car body structures can help absorb energy during a crash and reduce the peak deceleration experienced by the occupants. Similarly, in sports equipment, the use of materials such as foam, gel, and other energy-absorbing materials can help reduce the peak deceleration experienced by the athletes during impact. It is important to note that the optimization of peak deceleration reduction through material selection is a complex process that involves a trade-off between various factors such as weight, cost, and manufacturability. An optimal solution will depend on the specific requirements and constraints of the application.

Cork materials can be used to reduce peak deceleration. Cork is a natural material that is known for its excellent energy absorption properties. It is made from the bark of the cork oak tree and is composed of a network of air-filled cells that can compress and absorb energy during an impact event. This makes cork a suitable material for applications where peak deceleration reduction is important, such as in packaging and cushioning, sports equipment, and automotive engineering. For example, in the packaging industry, cork materials can be used as cushioning in packaging to absorb shock and reduce peak deceleration during shipping and handling. In sports equipment, cork materials can be used in protective gear such as gloves and shin guards to reduce the peak deceleration experienced by athletes during impact. In automotive engineering, cork materials can be used as soundproofing and vibration-damping material to reduce peak deceleration and improve the ride comfort of vehicles. It is important to note that cork materials may not be the best choice for all applications, as other materials such as foam, rubber, and composites may offer superior energy absorption and peak deceleration reduction properties for specific applications. The optimal material choice will depend on the specific requirements and constraints of the application.

Furthermore, sandwich structures can be effective in reducing peak deceleration. Sandwich structures consist of two thin outer layers (face-sheets) and a thicker inner core made of lightweight and low-density material, such as foam or honeycomb. The face-sheets provide the strength and stiffness required to support loads, while the core provides energy absorption during impact. Sandwich structures are commonly used in a variety of applications, such as aerospace, marine, and sports equipment, where peak deceleration reduction is important. In these applications, the sandwich structure can effectively absorb energy during an impact event and reduce the peak deceleration experienced by the structure or the occupants. For example, in the aerospace industry, sandwich structures are commonly used in aircraft structures and components, such as wing skins and fuselage panels, to reduce weight while maintaining strength and stiffness. In marine applications, sandwich structures are used in the construction of lightweight and high-strength hulls and decks. In sports equipment, sandwich structures are used in helmets and protective gear to reduce the peak deceleration experienced by athletes during impact. It is important to note that the design and optimization of sandwich structures for peak deceleration reduction is a complex process that involves trade-offs between various factors such as weight, cost, and manufacturability. An optimal solution will depend on the specific requirements and constraints of the application.

3. ANTI-IMPACT AND ANTI-VIBRATION DESIGN OF ECO-FRIENDLY CORK-BASED SANDWICH STRUCTURES FOR AERIAL VEHICLES

In this chapter, we explored the potential use of sandwich structures with cork cores as an environmentally friendly alternative for aerospace applications. Sandwich structures are composite materials made up of a core material, such as cork, sandwiched between two face-sheet materials. The face-sheet materials used in this chapter were CFRP, AFRP, GFRP, and Al. The chapter aimed to determine the best combination of face-sheet materials to use with a cork core that would offer the best resistance to impact and vibration. To do this, laboratory samples were produced, and tests were conducted to measure the impact deceleration and vibration resistance of the different sandwich structures. In the impact deceleration test, a drop-tower impact deceleration test was used to calculate G values using a sensor embedded in the impactor head. The results showed that the sandwich structures with CFRP face-sheets and a cork core exhibited the best resistance to impact. In the vibration test, a modal analysis system based on the hammer was used to calculate the values of the damping ratio and stiffness of the sandwich structures. The results showed that the CFRP/cork/CFRP sandwich structure had the highest damping ratio and stiffness, indicating better vibration resistance. The findings of this study suggest that the use of sandwich structures with cork cores and CFRP face-sheet materials can provide an effective and sustainable solution for low-speed aerial applications. By using environmentally friendly materials, the researchers hope to reduce the environmental impact of aerospace applications while still providing high-performance materials.

3.1. Introduction

A sandwich structure is a type of composite material widely used in various engineering fields. It consists of two thin and stiff outer layers, called face-sheets, bonded to a lightweight core material. Sandwich structures are known for their high stiffness and strength-to-weight ratio, which make them ideal for use in applications where weight reduction is critical, such as aerospace, automotive, and marine industries. However, the use of synthetic foam or balsa wood as core materials in sandwich structures has raised concerns about their environmental impact. Synthetic foam is typically made from petroleum-based products and can take centuries to decompose, contributing to pollution and ecological damage. Balsa wood, on the other hand, is a natural material, but its production requires extensive use of land and water resources, which can cause deforestation and soil erosion. In recent years, researchers have focused on finding sustainable and renewable alternatives to synthetic foam and balsa wood as core materials in sandwich structures. One such alternative is cork, a natural material that comes from the bark of the cork oak tree. Cork is renewable, biodegradable, and can be harvested without harming the tree, making it a more environmentally friendly option for core materials in sandwich structures. The use of cork as a core material in sandwich structures is not new. It has been used in the past for applications such as insulation and flooring. However, its use in sandwich structures for high-performance applications such as aerospace has been limited due to its low stiffness and strength compared to synthetic foams or balsa wood. To overcome this limitation, researchers have focused on developing sandwich structures with cork cores that can provide better stiffness and strength while maintaining their environmental advantages. This has led to the development of composite cork, a type of cork that is reinforced with a polymer matrix, such as epoxy or polyurethane. Composite cork has a fine-grained structure that provides better stiffness and strength compared to natural cork, making it suitable for use as a core material in sandwich structures. Previous studies have demonstrated that using cork can improve the amount of absorbed impact energy [67-71, 85-87] and vibration damping [72-74], and it is a natural material concerning sustainability, and recyclability [66, 75].

A face-sheet is a thin, flat layer that is used as the outer surface of a sandwich structure. Sandwich structures are composite materials that consist of a core material, which is typically lightweight and low in strength, and two face-sheets that are attached to the top and bottom of the core to provide additional strength and stiffness to the structure [88]. The face-sheets are typically made of a high-strength material such as metal, fiberglass, or carbon fiber, and they serve to distribute and transfer loads between the core and the external environment. The primary function of the face-sheet is to protect the core material from damage and to provide the structural support that is necessary to carry the applied loads. The face-sheet also provides a smooth, flat surface that can be easily finished and painted to achieve the desired aesthetic appearance [89].

CFRP is a type of composite material that is often used as a face-sheet in sandwich structures. CFRP is made of carbon fiber, which is known for its high strength, stiffness, and durability, and a polymer resin, which serves to bond the fibers together and provide additional structural support. CFRP face-sheets offer several advantages over other face-sheet materials, including a high strength-to-weight ratio, corrosion resistance, and excellent fatigue performance [90, 91]. These properties make CFRP an ideal material for use in high-performance applications where weight savings and durability are critical. In sandwich structures, CFRP face-sheets are typically used in combination with a lightweight core material such as foam or honeycomb. The face-sheets are bonded to the core using an adhesive, and the resulting sandwich structure provides high strength and stiffness with minimal weight. One challenge in using CFRP face-sheets is achieving proper bonding between the face-sheet and the core material. Specialized adhesive bonding techniques and surface preparation are typically required to achieve a strong and durable bond between the two materials. Overall, CFRP face-sheets is a popular choice for high-performance sandwich structures due to their exceptional strength, stiffness, and durability. However, their use may be limited by factors such as cost, manufacturing complexity, and the specific requirements of the application [32].

GFRP is a type of composite material that is commonly used as a face-sheet in sandwich structures. GFRP is made of glass fibers that are embedded in a polymer resin, which serves to bond the fibers together and provide additional structural support [92]. GFRP face-sheets offer several advantages over other face-sheet materials, including high strength, stiffness, durability, and good resistance to corrosion and impact. These properties make GFRP an ideal material for use in applications where weight savings and durability are important. In sandwich structures, GFRP face-sheets are typically used in combination with a lightweight core material such as foam or honeycomb. The face-sheets are bonded to the core using an adhesive, and the resulting sandwich structure provides high strength and stiffness with minimal weight. One of the main advantages of using GFRP face-sheets in sandwich structures is their affordability compared to other composite materials such as CFRP or aramid fiber composites. GFRP face-sheets can be produced in large quantities at relatively low cost, which makes them a popular choice for many applications. However, the use of GFRP face-sheets may be limited by their lower strength-to-weight ratio compared to other materials, as well as their susceptibility to environmental degradation over time. Therefore, the selection of GFRP face-sheets in sandwich structures must take into account the specific requirements of the application and the expected environmental conditions [37].

AFRP is a type of composite material that is sometimes used as a face-sheet in sandwich structures. AFRP is made of aramid fibers, which are known for their high strength, stiffness, and durability, and a polymer resin, which serves to bond the fibers together and provide additional structural support. AFRP face-sheets offer several advantages over other face-sheet materials, including high strength-to-weight ratio, excellent impact resistance, and good fatigue performance. These properties make AFRP an ideal material for use in applications where weight savings, durability, and resistance to impact are important. In sandwich structures, AFRP face-sheets are typically used in combination with a lightweight core material such as foam or honeycomb. The face-sheets are bonded to the core using an adhesive, and the resulting sandwich structure provides high strength and stiffness with minimal weight. One of the main advantages of using AFRP face-sheets in sandwich structures is their exceptional impact resistance, which makes them a popular choice for applications such as armored vehicles or ballistic protection. AFRP face-sheets also offer good resistance to environmental degradation, making them suitable for use in harsh environments. However, the use of AFRP face-sheets may be limited by their higher cost compared to other composite materials such as GFRP or CFRP. Therefore, the selection of AFRP face-sheets in sandwich structures must consider the specific requirements of the application and the available budget [93].

All three types of face-sheets, CFRP, GFRP, and AFRP, have unique advantages and disadvantages that make them suitable for different aeronautical applications. CFRP face-sheets are the strongest and stiffest of the three materials and offer exceptional fatigue performance, making them ideal for high-performance applications such as aircraft wings, where weight savings and durability are critical. GFRP face-sheets offer good strength and stiffness, are more affordable than CFRP, and provide excellent resistance to corrosion, making them a popular choice for a variety of aeronautical applications such as aircraft interior panels, fairings, and rotor blades. AFRP face-sheets offer exceptional impact resistance, making them ideal for applications such as aircraft armor, cockpit doors, and other protective structures. In summary, the choice of face-sheet material for aeronautical sandwich structure applications depends on the specific requirements of the application, such as the desired weight, strength, stiffness, durability, and impact resistance. Each material has unique advantages and disadvantages, and the optimal choice will depend on the specific tradeoffs that are necessary for the particular application [45, 46, 94].

Eco-friendly core materials in sandwich structures refer to materials that are used in the middle layer of a sandwich structure that are environmentally sustainable and have a low carbon footprint. These materials are typically lightweight, strong, and have good insulating properties. Some examples of eco-friendly core materials used in sandwich structures include natural fibers, recycled plastics, and bio-based materials such as bamboo, cork, and jute. By using eco-friendly core materials in sandwich structures, it is possible to create structures that have a reduced impact on the environment while still maintaining the necessary structural integrity and performance. Cork is a commonly used eco-friendly core material in sandwich structures due to its unique properties [82]. Cork is a lightweight, durable, and naturally buoyant material with good thermal and acoustic insulation properties. It is also non-toxic, renewable, and biodegradable, making it a sustainable and eco-friendly choice for the core layer of sandwich structures. Cork cores can be used in a variety of sandwich structure applications, such as in aerospace, automotive, and marine industries, as well as in construction and building materials. Cork cores can provide excellent impact resistance, high compression strength, and they can also dampen vibrations and noise. Additionally, cork cores can be easily shaped and molded to fit specific design requirements, making them a versatile material option for sandwich structures [95].

Also, the face-sheets of sandwich structures used in aeronautical applications are commonly made of aluminum alloys. Aluminum is a popular choice because it is lightweight, corrosion-resistant, and has good mechanical properties, such as high strength and stiffness. The face-sheets are typically fabricated using various methods, including sheet forming, machining, or extrusion, to produce the required size, shape, and thickness [89]. The aluminum face-sheets are usually bonded to the core material using an adhesive to create a sandwich structure. The core material is usually made of a low-density material, such as foam, honeycomb, or balsa wood, which provides stiffness and helps to distribute loads between the face-sheets. The sandwich structure with aluminum face-sheets has a wide range of aeronautical applications, including aircraft wings, fuselage panels, helicopter rotor blades, and interior components. In aircraft wings, sandwich structures are used to reduce weight, increase stiffness, and improve aerodynamic performance. In fuselage panels, sandwich structures are used to reduce weight and increase resistance to damage. In helicopter rotor blades, sandwich structures are used to reduce vibration and improve durability. In interior components, sandwich structures are used to improve acoustic and thermal insulation. Overall, the use of aluminum face-sheets in sandwich structures is an effective way to reduce weight, increase stiffness, and improve durability in aeronautical applications [96].

Vibrational damping is important in sandwich structures of aerial vehicles because it helps to reduce the amplitude and duration of mechanical vibrations that can cause damage to the structure and compromise the safety and performance of the aircraft. Sandwich structures consist of a core material sandwiched between two face-sheets, and the core material can act as a source of vibration. By incorporating damping materials, such as viscoelastic polymers or metallic dampers, into the sandwich structure, the energy of the vibrations can be dissipated and the resulting stress on the structure can be minimized. This can lead to increased durability and longevity of the aircraft, as well as improved passenger comfort and stability during flight.

Minimum peak deceleration is an important consideration in sandwich structures of aerial vehicles because it helps to ensure the safety of the passengers and crew in the event of an impact or crash. Sandwich structures are commonly used in the construction of aircraft due to their lightweight and high strength-to-weight ratio, but they must also be able to withstand the forces that can occur during a crash landing or other impact. The peak deceleration is the maximum acceleration experienced by the aerial vehicle and its occupants during an impact, and it can have a significant impact on the survivability of the crash. By designing sandwich structures to minimize peak deceleration, the energy of the impact can be absorbed more gradually, reducing the stress on the structure and the passengers. This can help prevent catastrophic failure and increase the likelihood of survival in the event of an accident. There are various methods that can be used to minimize peak deceleration in sandwich structures, such as the use of energy-absorbing materials and the optimization of the structure's geometry and stiffness. Ultimately, the goal is to design a sandwich structure that can effectively absorb and dissipate the energy of an impact, while minimizing the peak deceleration and maximizing the safety of the aerial vehicles and their passengers.

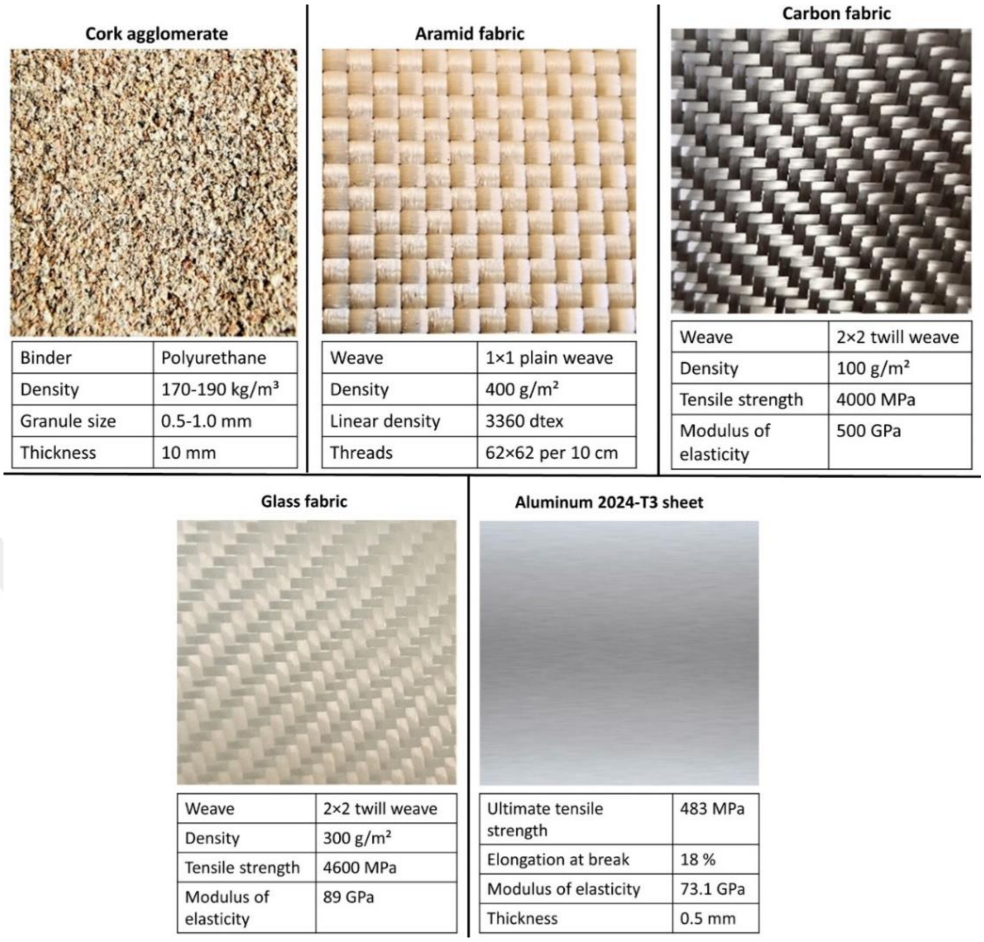
Structural stiffness is an important consideration in sandwich structures of aerial vehicles because it can affect the strength, stability, and performance of the aircraft. Sandwich structures are composed of two face-sheets that are separated by a core material, and the stiffness of the structure is determined by the properties of these materials and their configuration. In order for an aerial vehicle to maintain stability and control during flight, it must be able to resist the forces and loads that are placed on the structure, such as wind gusts, turbulence, and maneuvers. This requires a certain level of structural stiffness to prevent excessive deformation or failure of the aircraft. A structure that is too flexible or not stiff enough can result in excessive deformation, flutter, or other instabilities that can compromise the safety and performance of the aircraft. On the other hand, an overly stiff structure can also be problematic, as it can result in increased weight and reduced energy absorption during impact events. Therefore, it is important to strike a balance between stiffness and weight in the design of sandwich structures for aerial vehicles. Overall, the importance of structural stiffness in sandwich structures of aerial vehicles lies in its ability to provide the necessary strength and stability for safe and effective flight, while also minimizing weight and optimizing performance [97].

This chapter explores the use of environmentally friendly sandwich structures with cork cores as a potential alternative for aerospace applications. Several studies showed that cork has excellent capabilities for anti-impact and damping applications as a core layer in sandwich and multi-layer structures [76, 98, 99]. The chapter investigates the performance of sandwich structures consisting of carbon fiber-reinforced polymer, aramid fabric-reinforced polymer, glass fiber-reinforced polymer face-sheet composites, and non-composite Al with a fixed cork core against impact and vibration. Laboratory-size samples were produced, and tests were conducted using a drop-tower impact deceleration test and modal analysis system. The results indicate that the CFRP face-sheet and CFRP/cork/CFRP sandwich structure offer better resistance to impact and vibration, making them suitable for low-speed aerial applications. The use of these environmentally friendly sandwich structures with cork cores could potentially provide a sustainable and effective solution for aerospace applications.

3.2. Experimental details

3.2.1. Materials

Five major components were used to build sandwich structures and face-sheet composites. Ducork Inc. provided the cork agglomerates, Teijin Inc. provided the aramid fabrics, and DowAksa B.V. supplied the glass fiber and carbon fiber textiles. Alutem Inc. provided the aluminum sheets. According to the requirements of the manufacturers, Fig. 3.1 lists the specifics of the components.



Cork agglomerate

Binder	Polyurethane
Density	170-190 kg/m³
Granule size	0.5-1.0 mm
Thickness	10 mm

Aramid fabric

Weave	1×1 plain weave
Density	400 g/m²
Linear density	3360 dtex
Threads	62×62 per 10 cm

Carbon fabric

Weave	2×2 twill weave
Density	100 g/m²
Tensile strength	4000 MPa
Modulus of elasticity	500 GPa

Glass fabric

Weave	2×2 twill weave
Density	300 g/m²
Tensile strength	4600 MPa
Modulus of elasticity	89 GPa

Aluminum 2024-T3 sheet

Ultimate tensile strength	483 MPa
Elongation at break	18 %
Modulus of elasticity	73.1 GPa
Thickness	0.5 mm

Figure 3.1. *Characteristics of materials used in this chapter.*

3.2.2. Production of sandwich and face-sheet composites

The pressure molding (prepreg manufacturing) method was used to create the composite face-sheets (Fig. 3.1b), with two steel plates (25 cm × 25 cm) with a thickness of 10 mm considered at the top and bottom of the mold, and the composites were placed between them while four clamps with the same amount of compressive force pressed the corners of the mold. A 50 N force was applied to the center of the mold plate (Fig. 3.1c). Epoxy-resin LR-160 was employed in the form of 80% epoxy and 20% hardener, which is suitable for aerospace applications (Fig. 3.1a). The number of layers of the composites was determined based on the density of each fabric, which eventually equalized the ultimate weight of each sample. As a result, three layers of aramid fabric (400 g/m2), four layers of glass fiber (300 g/m2), and 12 layers of carbon fiber (100 g/m2) were employed. Steel plates were initially covered in paper to simplify mold separation, then mold release wax was used to separate the molds. They were left at room temperature for 24 hours after molding. The manufacturing technique was the same for all samples, and the composites were eventually manufactured in 25 × 25 cm dimensions (Fig. 3.1d). The face-sheets were trimmed to the necessary proportions because the multi-layers were created in 5 cm × 5 cm dimensions. After completing the face-sheet composite structure, the cork core layers were laser cut to a size of 5 cm × 5 cm. Finally, the cork core layers were sandwiched by epoxy-resin LR-160 to the composite and aluminum face-sheets and put between two steel plates for 24 hours under 25 N force (Fig. 3.1f). The face-sheet fabrication of composites and sandwich structures was carried out at room temperature (20 °C). The face-sheets, sandwich structures, and cork core layer are shown in Fig. 3.2.

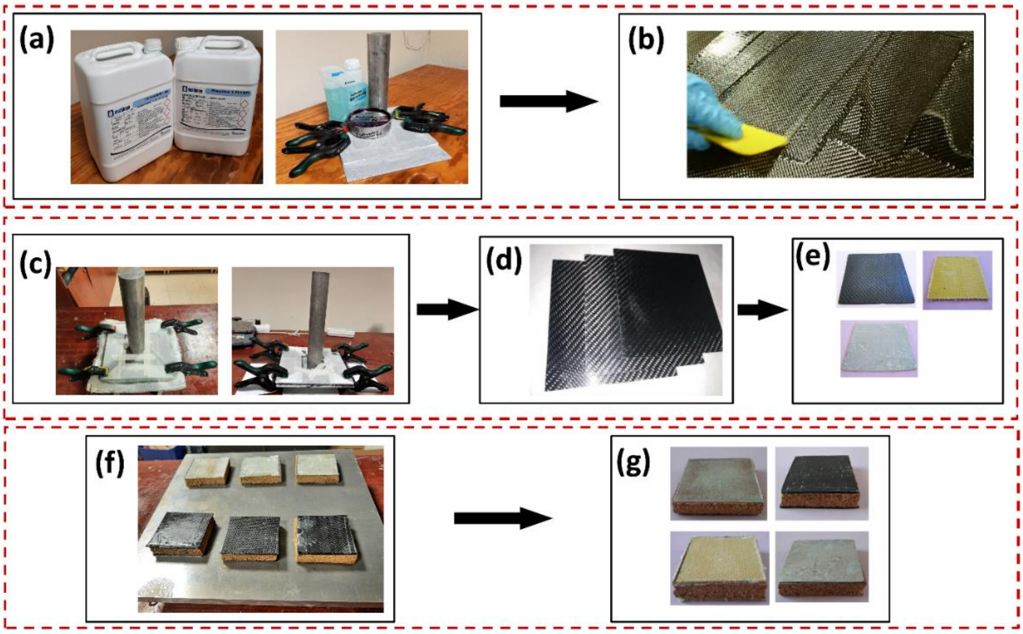


Figure 3.2. *Manufacturing process of sandwich structures and face-sheet composites.*

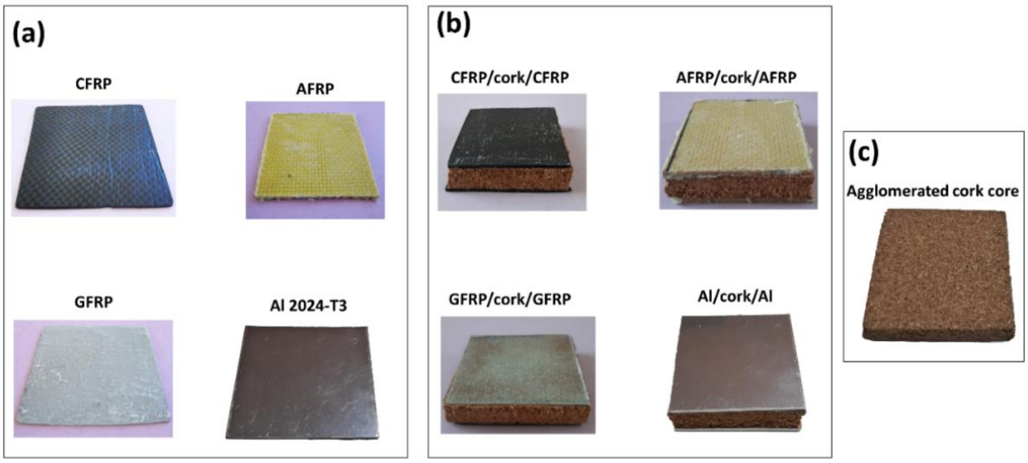


Figure 3.3. *(a) face-sheet composites and (b) sandwich structures (c) cork core.*

3.2.3. Vibration tests

Vibration modal analysis can be performed using various experimental and computational methods, including experimental modal analysis, finite element analysis, and system identification. The choice of method depends on the complexity of the system and the level of detail required in the analysis. The modal domain is one point of view for understanding structural vibrations. Structures vibrate or take on mode forms when stimulated at their natural frequencies. Under typical working conditions, a structure will vibrate in a complex mix of all mode configurations. The modal analysis reduces a complex and difficult-to-understand structure to a collection of unconnected single-degree freedom components. The structure should be activated, and the applied excitation force as well as the resulting response vibrations, which are often acceleration, should be recorded, yielding a Frequency Response Function (FRF) data set. The FRF data set may be used to identify modal features such as natural frequencies and damping ratios. A popular method of activation is the use of an impact hammer [100]. An impact hammer is a specialized measurement instrument that creates a short duration of excitation levels by pounding a specified place on the structure. During the test, the excitation force is measured since the hammer is fitted with a force sensor that generates a voltage signal proportional to the excitation force. To change the measurement frequency range, a hammer with varying hardness impact points was utilized. A soft rubber tip can be used for low-frequency measurements while a hard metal tip can be used for high-frequency readings. During vibration testing for this research, face-sheets and sandwich structure specimens were secured to a bench clamp and vibrated with a hammer to propagate vibrations on the structures. The structural damping ratio and modal stiffness of the specimens were measured using an accelerometer affixed to the face that was opposite the impact position. Fig. 3.3 displays the characteristics of the experimental vibration setup in the X and Z axes. This experimental setup had several degrees of support (fixed at one end and fixed at both ends).

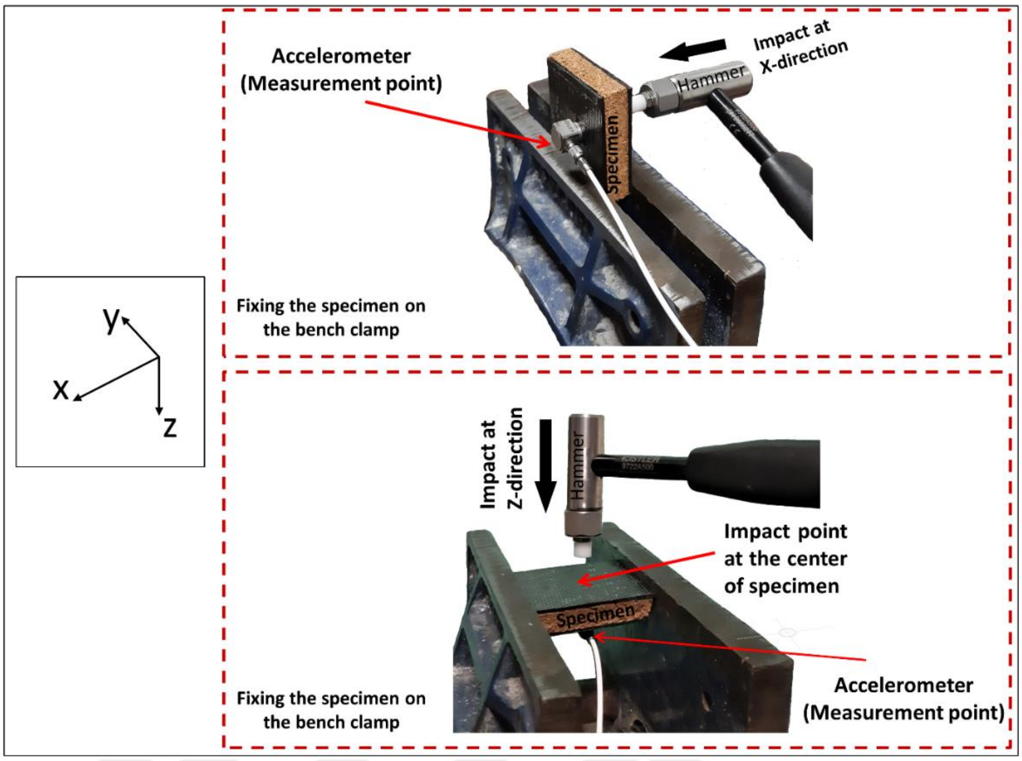


Figure 3.4. *Experimental setup in the vibration tests.*

3.2.4. Deceleration tests

Peak deceleration is the maximum rate of reduction in velocity experienced by a vehicle or object during a collision or impact. It is often given in gravity units (g), where one g equals the acceleration due to Earth's gravity. A low peak deceleration is desirable since it is directly proportional to the severity of harm sustained after an accident. Because the structure or body is subjected to significant forces, a high peak deceleration can cause severe damage or death. A low peak deceleration, on the other hand, minimizes the stresses on the body or structure and can assist to reduce the degree of injuries and damages in an accident and carshing. As a result, automotive manufacturers and safety engineers aim to build vehicles and safety systems that will limit peak deceleration in the event of an accident, lowering the risk of injury and increasing survival rates. Because the sandwich structures explored in this work are intended for usage in low-speed aerial vehicles, deceleration testing should be carried out appropriately. As a result, the peak deceleration values in units of g that represent the magnitude of an abrupt speed drop following contact with any threat were studied. The deceleration-measuring sensor is incorporated into the impactor of the drop-tower system. The lower the amount of g, the stronger the resistance of the aerial vehicle structure to unexpected collisions during flight. The experimental setup for the deceleration testing is shown in Fig. 3.4.

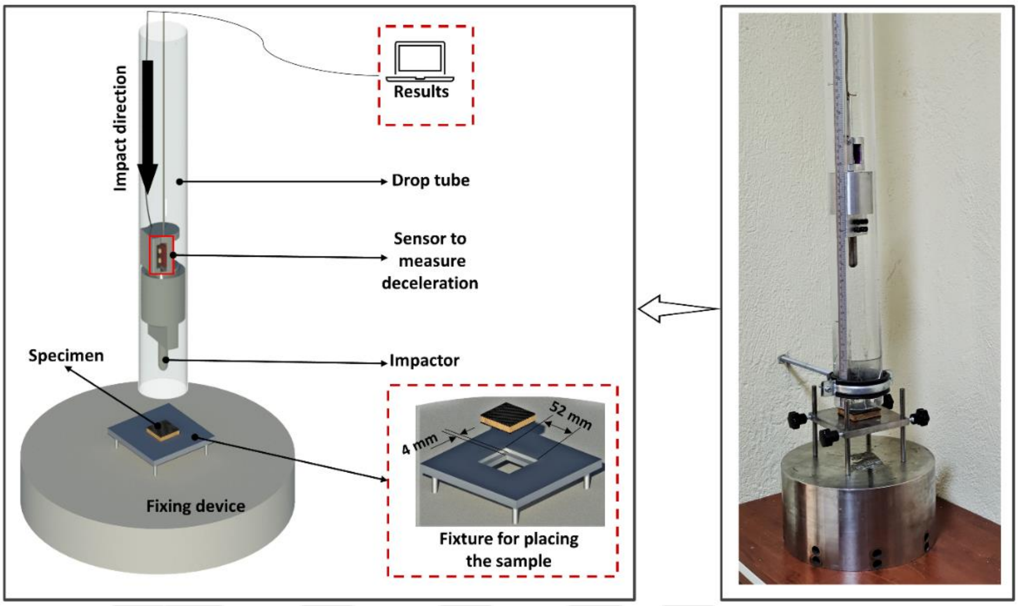


Figure 3.5. *Drop tower-based deceleration test system.*

3.3. Results and discussion

3.3.1. Vibration properties for face-sheets and sandwich structures

The FRF graphs for the face-sheets and sandwich structures are shown in Figs. 3.5 and 3.6. The frequency spectra include peaks that correspond to the inherent frequencies of the structures. In the X-direction, face-sheets display single-mode FRF charts. Z-direction FRF graphs, on the other hand, exhibit multimodal features. These materials may therefore be described with a single degree of freedom in the X-direction and several degrees of freedom in the Z-direction. Natural frequencies typically vary between 400 and 700 Hz. In sandwich structures, the X and Z directions may be represented as single degrees of freedom. This sort of structure has a natural frequency that ranges between 900 and 1200 Hz.

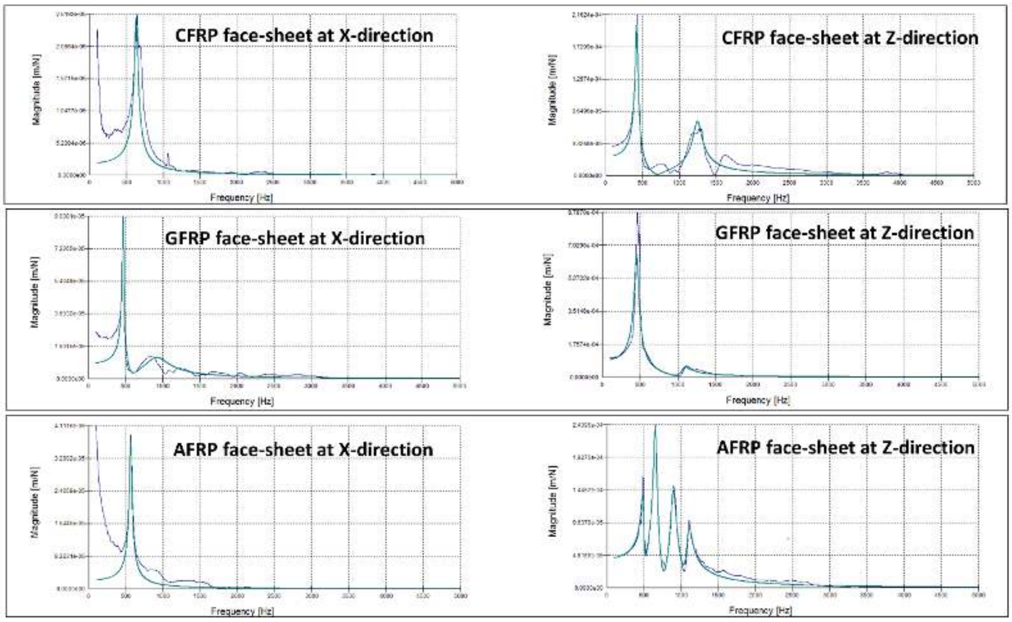


Figure 3.6. *Graphs of frequency response functions for CFRP, GFRP, and AFRP face-sheets in the X (fixed at one end) and Z directions (fixed at both ends).*

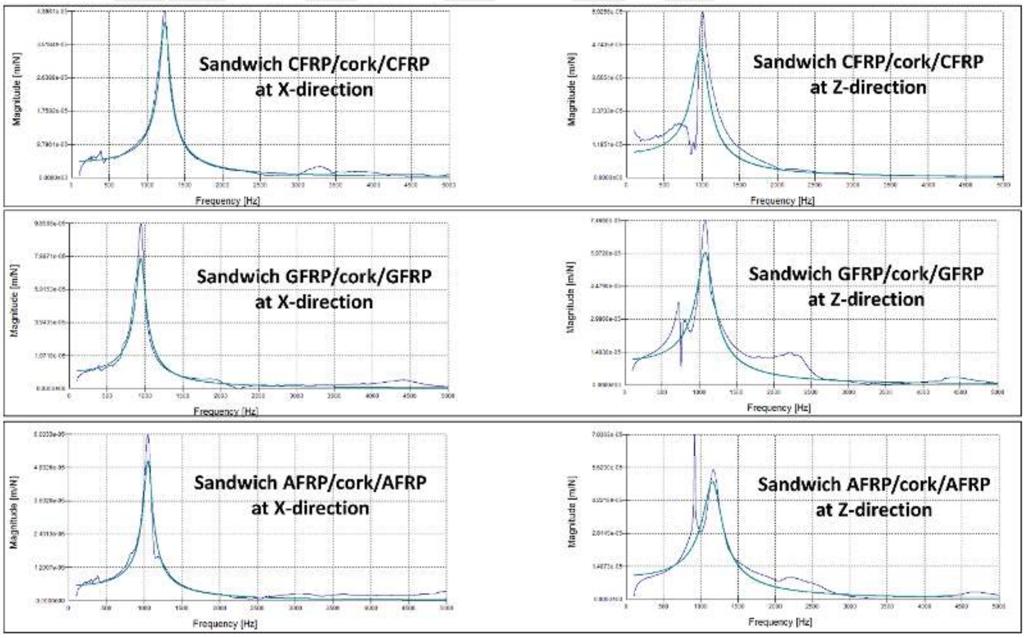


Figure 3.7. *The frequency response function graphs for CFRP/cork/CFRP, GFRP/cork/GFRP, and AFRP/cork/AFRP sandwich structures in the X and Z directions (fixed at one end) (fixed at both ends).*

The damping ratios and stiffness coefficients of the materials were examined using single degree of freedom models. Fig. 3.7 depicts the damping ratio and stiffness coefficient of the face-sheet composites. In terms of damping ratio, CFRP outperforms the other composites in the X and Z axes. In the literature, the CFRP face-sheet has a larger viscous damping ratio, but the Al face-sheet has a lower one (almost 0.04%). In the

X and Z-directions, CFRP composite outperforms AFRP in terms of stiffness coefficient, which measures structural resistance to deformation. Flexural rigidity may be used to understand the stiffness coefficient in certain materials. CFRP has the greatest elastic modulus, whereas Al has the lowest.

The damping ratio and stiffness coefficient for sandwich structures are shown in Fig. 3.8. In both directions, CFRP produces the greatest outcomes. The damping ratio rises between 78% and 193% in the X-direction and between 35% and 210% in the Z-direction for sandwich constructions. The stiffness coefficient drops between 61% and 66% in the X-direction and 50% to 65% in the Z-direction in the same structures. Cork agglomerate has a low vibration conductivity. Cork agglomeration has a porous microstructure made up of impermeable cellular grains that are separated from one another. Cork agglomerates have been employed as an efficient dampening material in a variety of applications due to its viscoelastic qualities. As a result, sandwich structures containing cork agglomerates have improved damping qualities. Cork materials have the best ductility and lowest elastic modulus of any wood-based material. As a result, the cork's flexural stiffness is poor. Consequently, the stiffness coefficient of cork agglomerate sandwich structures stays low. A structure's stiffness changes based on the support circumstances. In principle, the stiffness coefficient of fixed both-end supports (k=3EI/L3) should be greater than that of fixed one-end supports (k=192EI/L3). In the fixed end support circumstances, the stiffness coefficient rises for both face-sheets and sandwich structures.

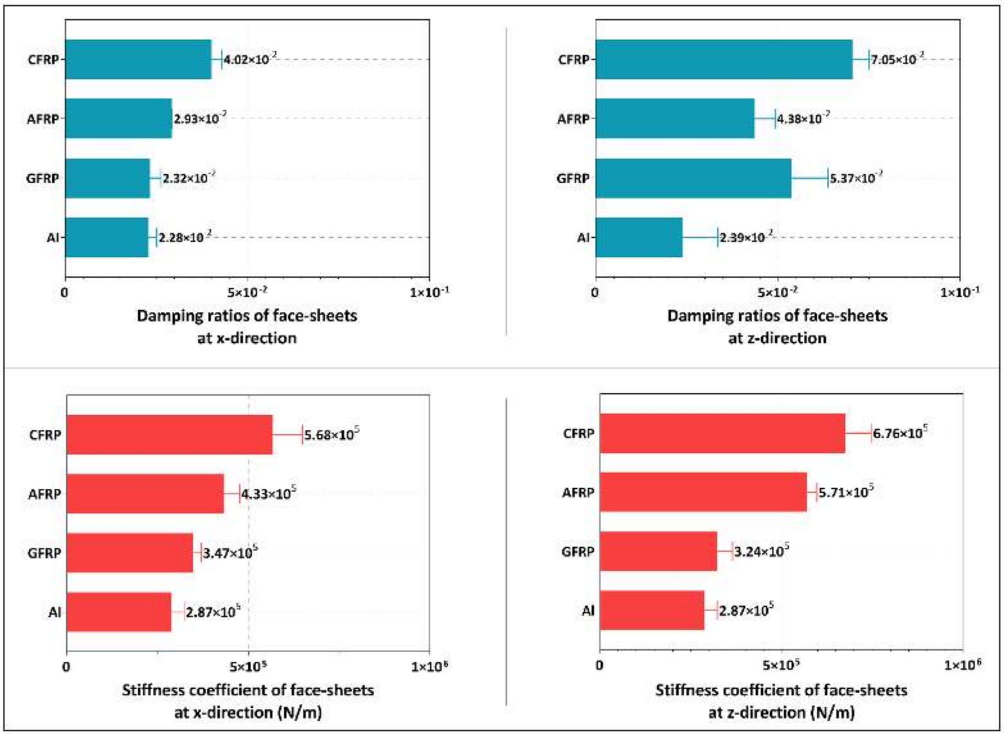


Figure 3.8. *Damping ratios and stiffness coefficients of face-sheets in various orientations.*

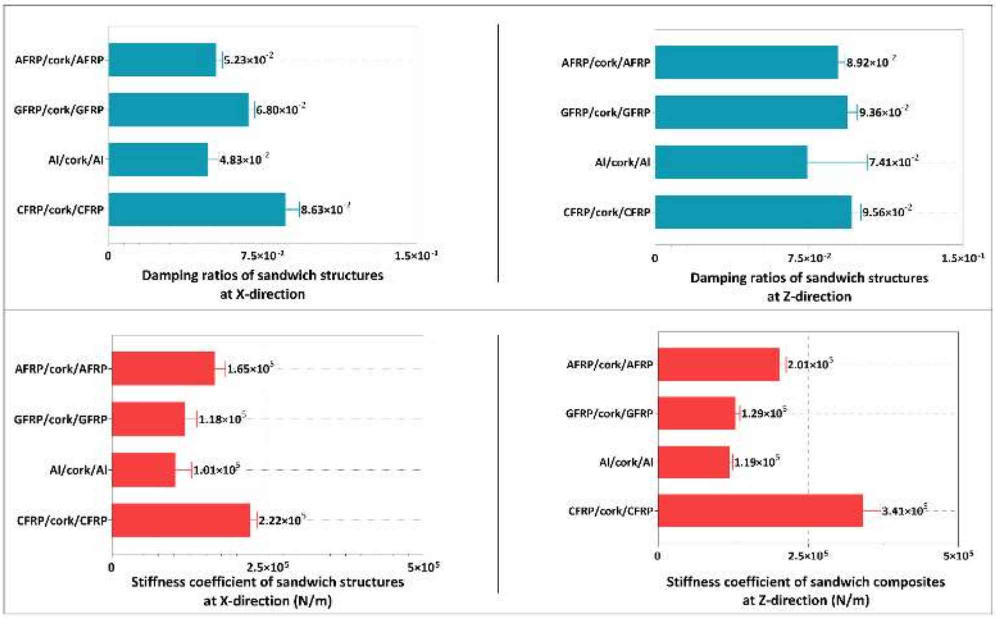


Figure 3.9. *Sandwich structure damping ratios and stiffness coefficients in various directions.*

3.3.2. Face-sheet and sandwich structure deceleration characteristics

Sandwich structures are commonly used in aerospace applications because they offer several advantages over other types of materials. They are lightweight, which is important for aerial vehicles like aircraft, and they have a high stiffness-to-weight ratio, which means they can provide a high level of structural strength while using minimal materials. However, during sudden deceleration events, such as a crash landing, the forces on the structure can be very high, and this can cause the structure to deform or fail. To minimize the effects of these forces, engineers use several techniques to design sandwich structures that are more resistant to damage. One technique is to use materials in the core of the sandwich structure that has high energy-absorption properties. This means that they can absorb a large amount of energy before they start to deform or fail. This can help to reduce the peak deceleration forces that the structure experiences during a sudden deceleration event. Another technique is to design the core material so that it deforms in a controlled manner under stress. This can help to distribute the forces more evenly throughout the structure and reduce the concentration of forces in any one area. By doing this, the structure is less likely to fail in any one area, and the occupants of the aircraft are less likely to be injured. A third technique is to use tailored stiffness in the face-sheets to direct the distribution of the force. By varying the stiffness of the face-sheets, engineers can control how the forces are distributed throughout the structure. This can help to reduce the peak forces experienced by the structure and increase the likelihood of survival for the occupants of the aircraft. Overall, minimizing peak deceleration in sandwich structures of aerial vehicles is an important consideration in aerospace engineering, as it can help to improve the safety of aircraft and reduce the risk of injury or damage during sudden deceleration events.

Fig. 3.9 presents the face-sheet composite peak deceleration results. The results demonstrate that the deceleration values for the face-sheets of CFRP and GFRP are relatively close. At heights of 0.1 m, 0.2 m, and 0.3 m, respectively, 42.6 g, 43.2 g, and 46.1 g are obtained for GFRP face-sheets, compared to 40.9 g, 44.2 g, and 43.7 g for CFRP face-sheets. The deceleration results for AFRP face-sheets are 40.6 g, 52.0 g, and 65.2 g, respectively, at heights of 0.1 m, 0.2 m, and 0.3 m. This shows that the deceleration values increase more than in other samples as the impact height rises. In comparison to the other composite face-sheets, the deceleration values at heights of 0.1 m, 0.2 m, and 0.3 m in Al face-sheets are 15.8 g, 19.0 g, and 25.9 g, respectively. The sample is damaged in the first hit and cannot be used because of the large deformation caused by Al 2024's softer structure, which causes quick plastic deformation and absorbs more impact energy.

The composite face-sheets made of AFRP, CFRP, or GFRP do not have this problem with fast deformation. Fig. 10a depicts the face-sheet deformations.

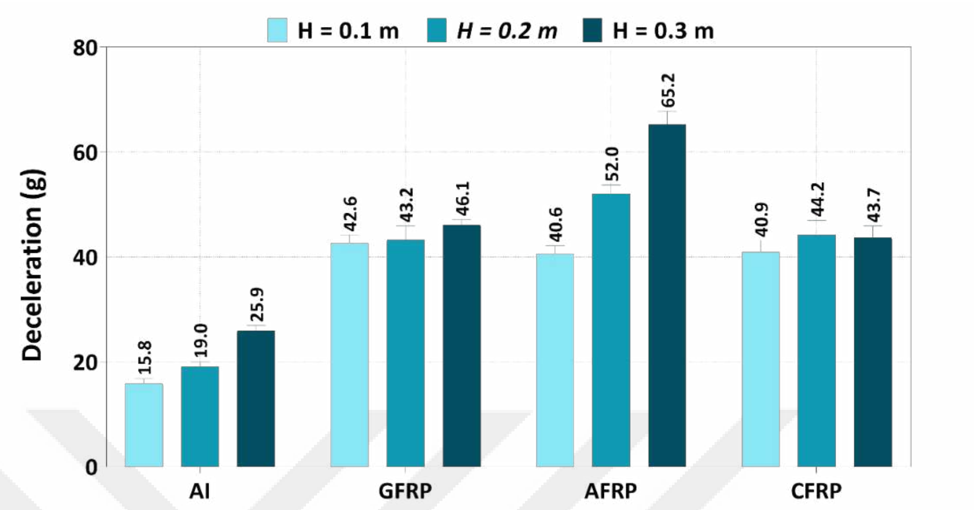


Figure 3.10. *Face-sheets composite deceleration findings.*

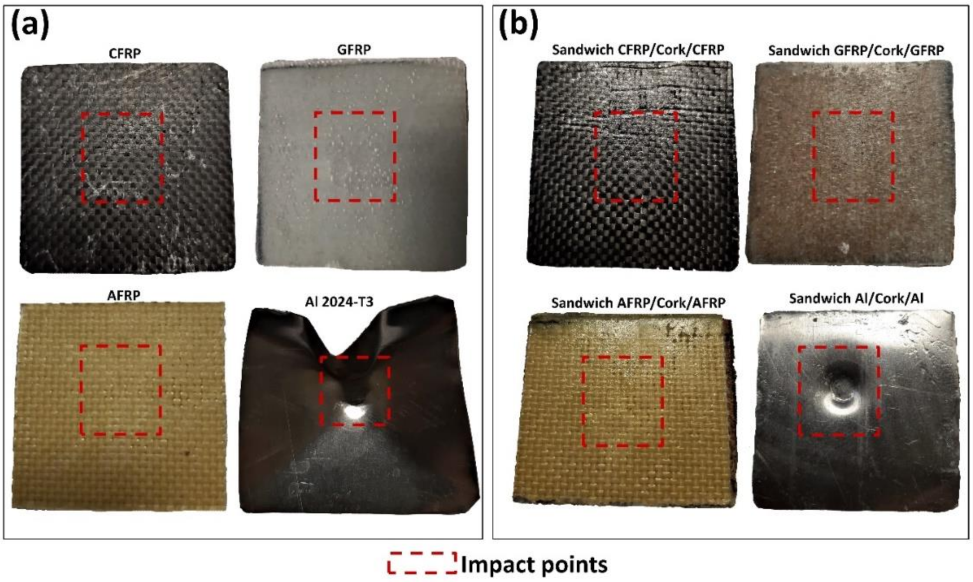


Figure 3.11. *Face-sheet and sandwich structure deformation following drop testing from 0.30 m.*

The deceleration findings for the proposed sandwich structures are shown in Fig. 3.11. CFRP/Cork/CFRP has deceleration values of 26.0 g, 40.2 g, and 50.4 g at heights of 0.1 m, 0.2 m, and 0.3 m, respectively, while GFRP/Cork/GFRP has values of 69.1 g, 105.8 g, and 133.7 g for the same heights. Because the deceleration results of CFRP and GFRP in face-sheets are almost identical, these findings suggest that when CFRP with a cork core layer forms a sandwich structure, it outperforms GFRP. Deceleration values for

Al/Cork/Al are 22.8 g, 74.6 g, and 97.4 g at heights of 0.1 m, 0.2 m, and 0.3 m, respectively. For heights of 0.1 m, 0.2 m, and 0.3 m, the values obtained are 76.6 g, 106.5 g, and 125.1 g, respectively. Although the robust structure of aramid fibers is ideal for impact resistance, the findings of AFRP/Cork/AFRP demonstrate a lower performance when compared to the other samples. Like Al face-sheets, the deceleration values in Al/Cork/Al are lower than in the other samples. This is owing to aluminum's softer structure and plastic deformation capacity. Even with little hits, Al face-sheets exhibit considerable plastic deformation. The remaining samples in the sandwich structures show no plastic deformation because of the impact energy. The deformations in the sandwich structures following the deceleration tests are shown in Fig. 10b.

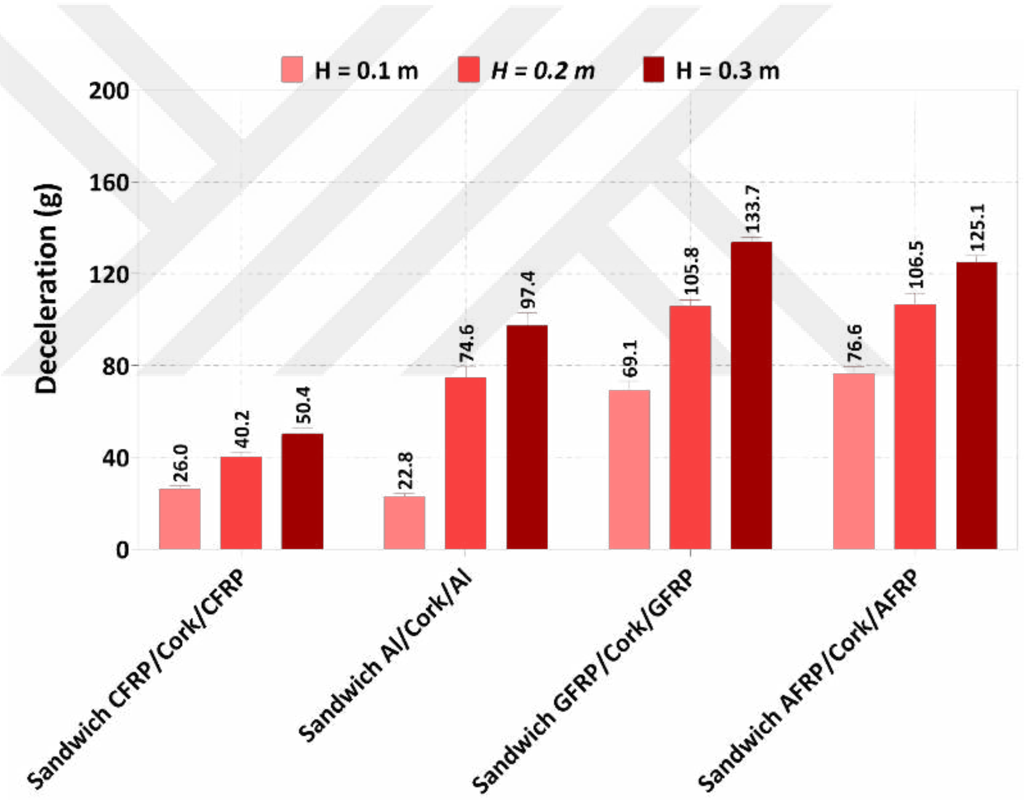


Figure 3.12. *Deceleration results for sandwich structures.*

The deceleration vs. time curves for a 0.30 m drop height for GFRP/cork/GFRP (highest deceleration) and CFRP/cork/CFRP (lowest deceleration) sandwich constructions are shown in Fig. 3.12. We may investigate the function of the cork core layer with various face-sheets. When the CFRP is inserted in the face-sheet, the deceleration rate (curve slope) is somewhat lowered, and the peak base is prolonged over a longer duration.

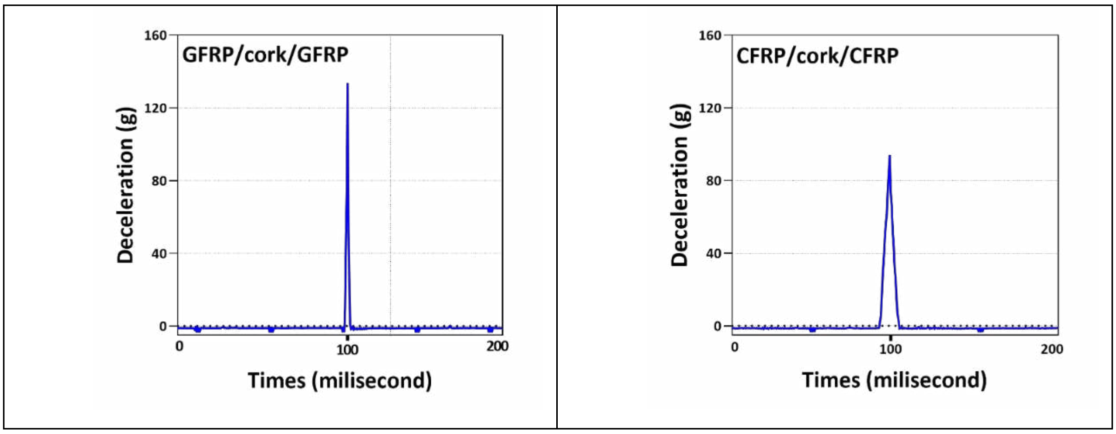


Figure 3.13. *Deceleration vs. time curves for sandwich structures made of GFRP/cork/GFRP and CFRP/cork/CFRP during a 0.3 m drop height.*

4. ECO-FRIENDLY DRONE CAGE DESIGN BASED ON SANDWICH STRUCTURES FOR MULTI-ROTOR AERIAL VEHICLE APPLICATIONS

4.1. Introduction of the chapter

Rotary-wing drones, also known as multirotor or multicopter drones, are unmanned aerial vehicles (UAVs) that are equipped with multiple rotating blades. These blades work together to generate lift and allow the drone to hover in place, move in any direction, and even perform complex aerial maneuvers. The number of blades on a rotary wing drone can vary, but the most common configuration is a quadcopter, which has four blades [13]. These drones have found a wide range of applications across various industries, including:

a) Agriculture: Rotary-wing drones are used for crop monitoring and mapping, crop spraying, and soil analysis. They help farmers to quickly identify areas in need of attention and improve efficiency and productivity [101].

b) Delivery: Drones are being used for package delivery, especially in remote or hard-to-reach areas. They reduce delivery times, minimize transportation costs, and increase accessibility [102].

c) Surveying and mapping: Rotary-wing drones equipped with high-resolution cameras and sensors can be used to generate accurate maps and surveys. This is useful in fields like construction, mining, and real estate [7].

d) Search and Rescue: Rotary-wing drones are equipped with cameras, thermal imaging, and other sensors that can help search and rescue teams quickly locate missing persons and assess dangerous situations [103].

e) Inspection and Maintenance: Drones can be used for inspections of infrastructure, such as bridges, pipelines, and power lines, without the need for human workers to be in dangerous locations [104, 105].

f) Film and Photography: Rotary-wing drones equipped with high-quality cameras are used in film and photography to capture aerial footage and images, providing a new perspective on things.

g) Law enforcement and security: Rotary-wing drones equipped with cameras and sensors can assist law enforcement and security personnel in monitoring and surveillance operations [106].

These are some of the most common applications of rotary-wing drones. The versatility and ease of use of these drones make them a valuable tool in many industries, and their usage is likely to expand in the future. Due to its flexibility and versatility in a broad variety of applications, the use of rotary-wing drones has greatly increased over the last decade. Therefore, ensuring that these unmanned systems are safe is more crucial than ever before, both for the sake of the systems' own pricey internal components and for the protection of the humans who are in their immediate vicinity. To prevent the aerial vehicle from being damaged in the event of an accident, a protective structure in the form of a cage can be installed around it. A drone cage is a physical barrier used to restrict and control a drone's motions. It is often utilized in industrial and commercial situations where drone safety is crucial and there is a need to reduce the possibility of accidents or other safety concerns. The requirement for a drone cage is determined by your individual circumstances, such as the kind of drone you use, the area in which it is operated, and the legislation and safety recommendations that apply to your region. However, if we want to operate drones in a potentially dangerous environment, we should consider employing a drone cage to protect people, property, and the drone itself. To design a drone cage, the following factors should be considered:

a) Size and dimensions: The size of the cage should be compatible with the size of the drone and allow enough room for it to move and fly.
b) Material: The material used should be sturdy and durable enough to withstand collisions and impact while also being lightweight.
c) Ventilation: Proper ventilation is important to prevent overheating and ensure the longevity of the drone and its battery.
d) Accessibility: The cage should have an easy-to-open door or hatch to allow the drone to enter and exit the cage.
e) Security: The cage should be secure enough to prevent unauthorized access to the drone and protect it from theft.
f) Interference: The cage should be designed to minimize electromagnetic interference to ensure the drone can communicate with its remote control.
g) Environmental conditions: Consideration should be given to environmental factors such as wind, rain, and extreme temperatures to ensure the cage can withstand these conditions.

Figure 4.1 shows some examples of creative designs for drone cages collected from the literature.

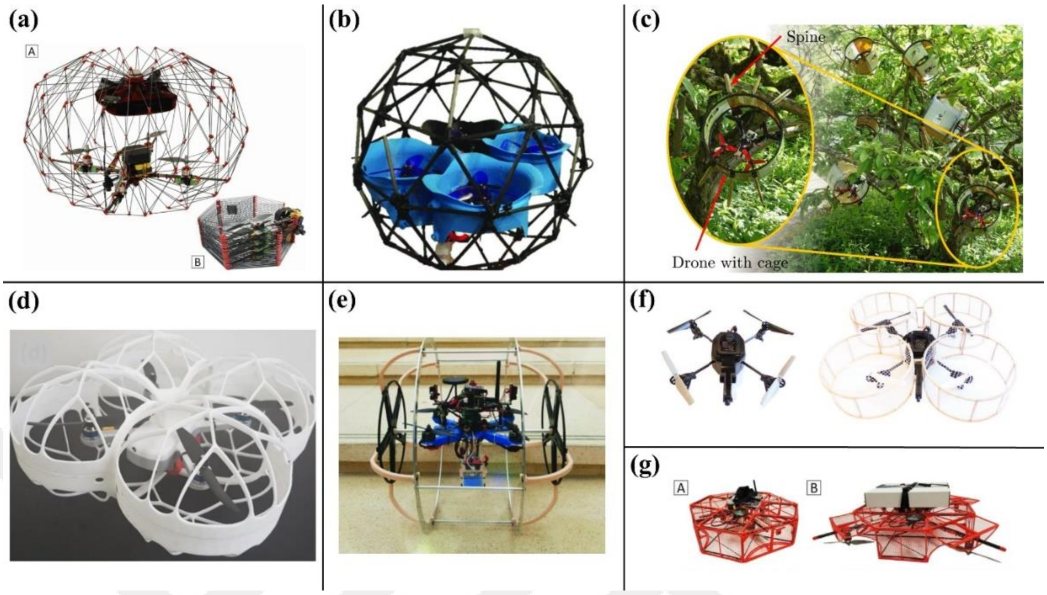


Figure 4.1. *Drone cage designs: (a) [107, 108], (b) [109], (c) [110], (d) [111], (e) [112], (f) [113], (g) [114].*

Vibration damping [115] in sandwich-structured composites refers to the reduction of unwanted vibrations or oscillations in the material. Sandwich composites typically consist of a core material (such as foam or honeycomb) sandwiched between two outer skins or face-sheets. The core material provides a low-density, high-stiffness region that helps reduce structural weight, while the face-sheets provide high strength and stiffness. The damping properties of sandwich-structured composites result from the combination of the damping of the core material and the face-sheets, as well as the interaction between them. The core material may have inherent damping properties, such as viscoelasticity, and the face-sheets can be designed with specific damping treatments to increase their damping capabilities. Additionally, the interface between the core and face-sheets can also contribute to damping, as energy is dissipated at the bondline. In general, sandwich-structured composites have high levels of damping compared to other composite materials, making them useful for reducing unwanted vibrations in various structures and systems.

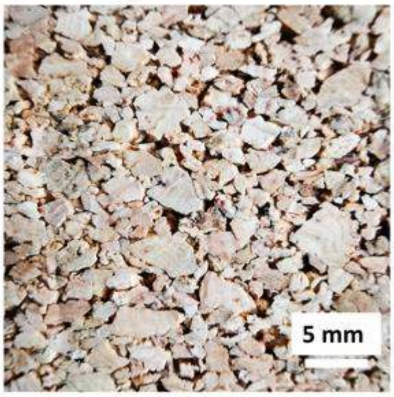
This chapter presents eco-friendly sandwich structure designs that are resistant to impact and vibration and intended for use in applications using rotary-wing drone cages. Drone cages have a sandwich structure formed by a face-sheet made of carbon fiber and core layers of cork material that range from coarse to fine. After the carbon fiber face-sheets were manufactured using a procedure called compression molding, a water jet cutting machine was used to cut the components for the drone cage. The vibration test was performed on a set of sensitive locations on the drone cage using a modal analysis system. This system assessed the frequency responses given by the hammer impacts, which calculated the damping ratios and the stiffness coefficients of the cage. The low-energy drop system was used to carry out the impact deceleration test, and the devised system computed the g deceleration values that the UAV cage experienced due to falling cages from three different heights. A cage with a sandwich structure based on a PVC foam core layer was also constructed to compare the anti-impact and anti-vibration performance of cork-based cages with that of a PVC foam core layer-based cage. When compared to PVC foam, the findings indicate that cork has the potential to enhance the performance of sandwich structures by an additional 30% in terms of vibration and an additional 25% in terms of deceleration decrease. We have great expectations that the development of a protective sandwich structure made of cork will serve as an example of an innovative approach to the use of environmentally friendly natural materials in sandwich structure construction.

4.2. Experimental details

4.2.1. Materials

Sandwich structures were built with four major components. Ducork Inc. supplied fine and coarse cork agglomerates. DowAksa B.V. supplied carbon fiber textiles, while Diab Inc. supplied PVC H130 divinycell foam. Fig. 4.1 displays component data based on manufacturer specifications.

Coarse-grained agglomerated cork



Binder	Polyurethane
Density	170-190 kg/m³
Granule size	2-6 mm
Thickness	4 mm
Modulus of elasticity	16-35 MPa

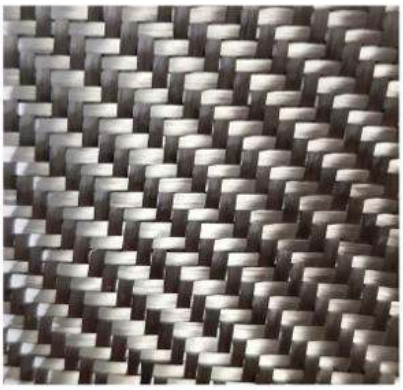
Fine-grained agglomerated cork

Binder	Polyurethane
Density	170-190 kg/m³
Granule size	0.1-1.5 mm
Thickness	4 mm
Modulus of elasticity	18-50 MPa

PVC H130 divinycell Foam

Weave	2×2 twill weave
Density	120-130 kg/m³
Tensile strength	4.8 MPa
Thickness	6 mm
Modulus of elasticity	15-30 Mpa

Carbon fabric



Weave	2×2 twill weave
Density	100 g/m²
Tensile strength	4000 MPa
Thickness in composite form	1.5 mm
Modulus of elasticity	500 GPa

Figure 4.2. *Materials information.*

4.2.2. Manufacturing of face-sheet composites, sandwich structures and drone cages

The face-sheet of sandwich structures utilized in the fabrication of drone cages was selected to be carbon fiber. Carbon-fiber composites with dimensions of 50 by 50 cm were created for this purpose utilizing the mold-pressure process. The carbon fibers were cut using a router cutting machine, and the layers of cork and PVC foam were cut with a laser cutting machine and transformed into cage components. Carbon fiber face-sheets were epoxy-glued to cork and PVC foam core components to make sandwich structures, and each component of the drone cage was manufactured. Finally, the cage components were put together, and the cage was built. Fig. 4.2 depicts the assembled sandwiches, while Fig. 4.3 depicts the drone cage manufacturing procedures. Table 4.2 explains the drone cages, and Fig. 4.4 illustrates the completed drone cages.

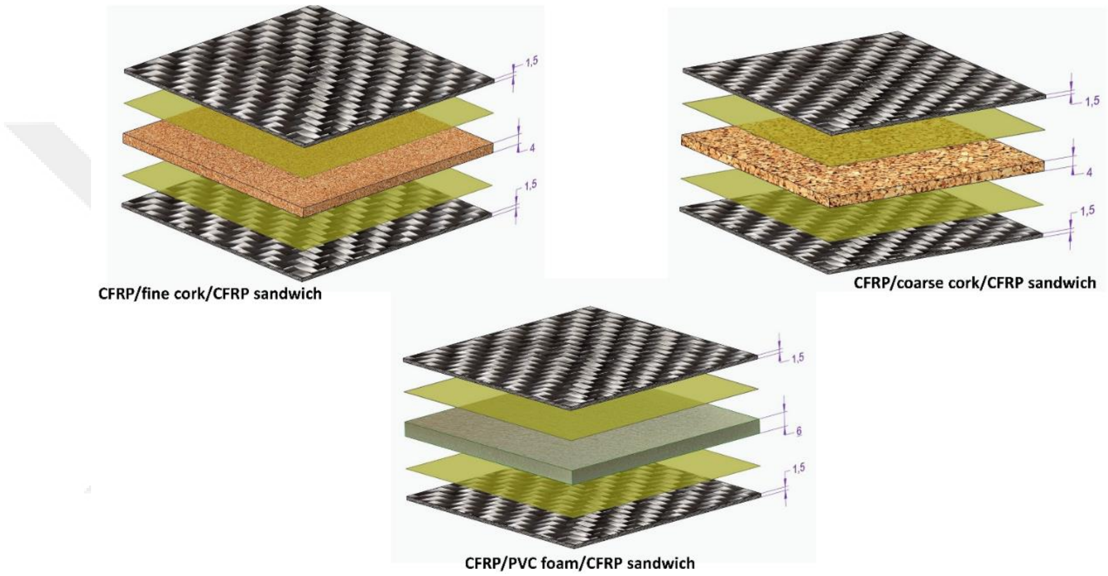


Figure 4.3. *CFRP/fine cork/CFRP, CFRP/coarse cork/CFRP, CFRP/PVC foam/CFRP sandwiches.*

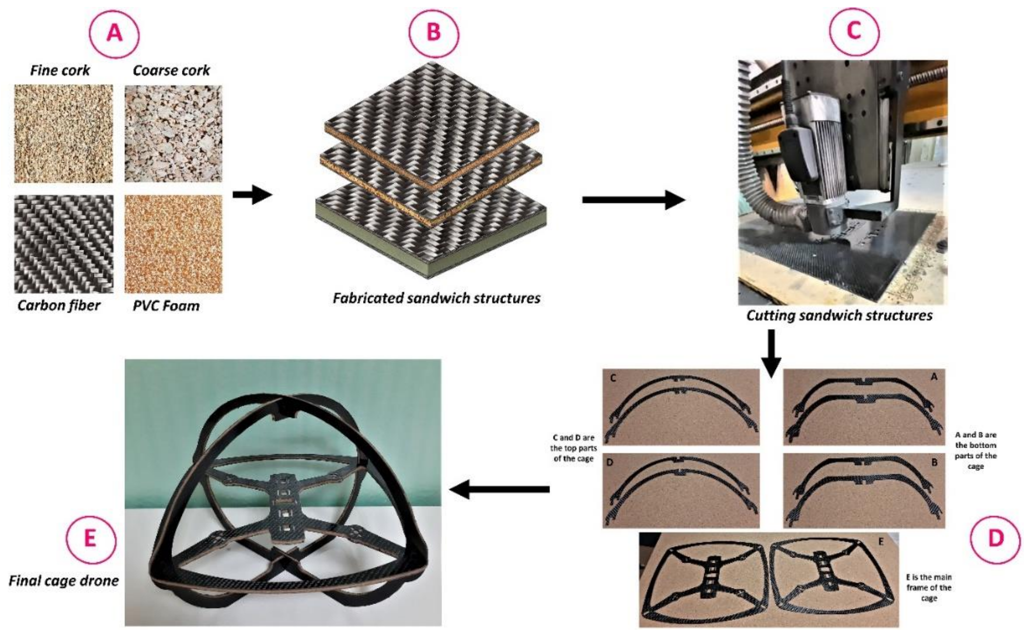


Figure 4.4. *Manufacturing process of drone cages.*

Table 4.1. *Cage design detail.*

Cage code	Description
Cage-A	CFRP/fine cork/CFRP sandwich-based cage drone
Cage-B	CFRP/coarse cork/CFRP sandwich-based drone
Cage-C	CFRP/PVC foam/CFRP sandwich-based drone

Cage-A **Cage-B** **Cage-C**

Figure 4.5. *Drone cages.*

4.2.3. Vibration test

As shown in Fig. 4.7, E is the location of the main airframe of the drone, and A, B, C, and D, are the locations of the drone rotors. The rotation of the rotors and the collision of the cage with its surroundings can cause the structure to vibrate. It is obvious that a cage that can dampen the vibrations entering the structure has better efficiency. One of the main reasons for using cork in the production cage for this research is the excellent performance of cork in vibration damping. To investigate the vibration test of the cage structure, the modal-analysis vibration system based on the hammer was chosen. In this method, frequencies are sent to the structure by small hammer blows, and the sent frequency responses give us a set of the structure's vibration behavior. The damping ratio as the main factor for structural damping and the structure stiffness coefficient that can show the compatibility of the cork and PVC foam core layers and the carbon fiber face-sheet were chosen as vibration test outputs. The location of the rotors and the main airframe of the drone, which are the critical points of the cage, were selected for vibration test points. Vibration tests were applied on 4 selection points of each rotor A, B, C, and

D, and 12 points of the main airframe locations. Figs. 4.5, 4.6, and 4.7 show the modal-analysis-based force vibration system and the points determined for vibration testing.

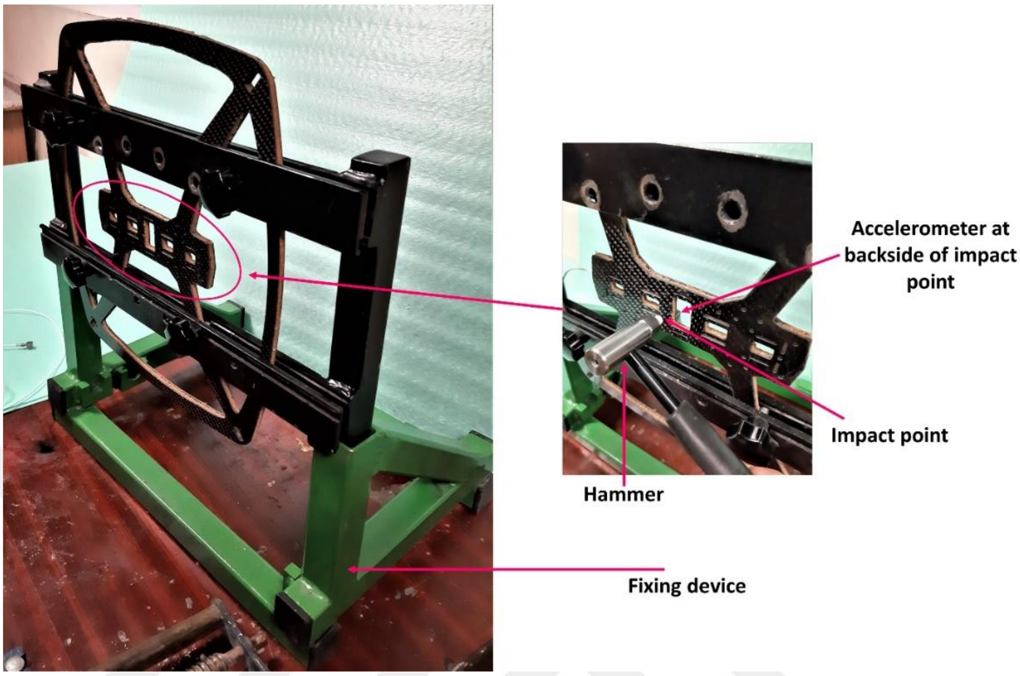


Figure 4.6. *Experimental vibration setup for main frame of drone cage.*

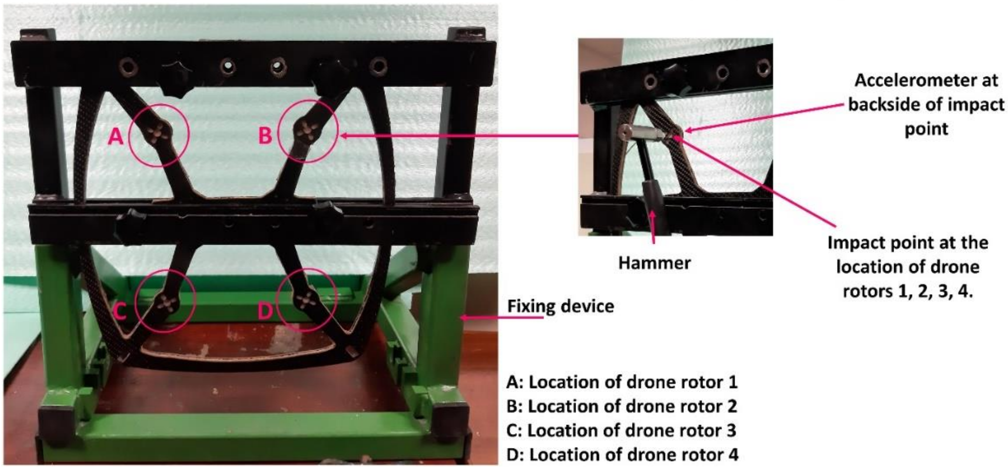


Figure 4.7. *Experimental vibration setup for drone rotor locations.*

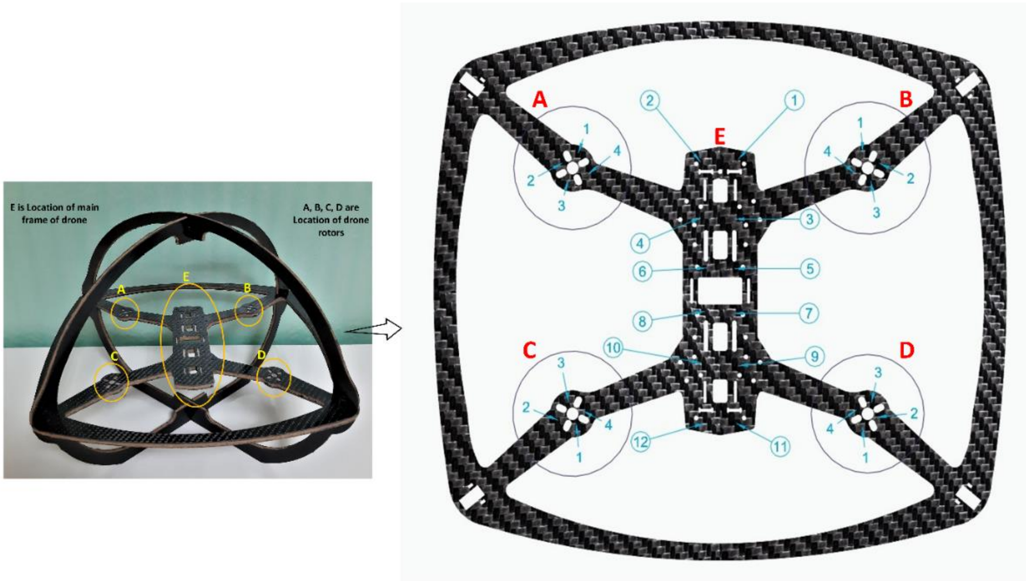


Figure 4.8. *Vibration test points in the A, B, C, D, and E zones.*

4.2.4. Deceleration test

The most important function of the cage to protect the drone is impact resistance. Rotor-rotating drones can be used for special purposes such as going into tunnels, and closed environments, delivering orders to customers and hospitals, etc. These applications can expose the drone to surrounding obstacles and cause serious damage to the drone. Therefore, the cage must be resistant to the impacts. Several studies have been conducted on the anti-impact behavior of cork materials, and the results have shown that cork as a core layer of sandwich panels can increase the impact resistance of the structure. To analyze the deceleration characteristics of designed cages, a sensor that can measure g values was designed. The sensor was embedded in the center of the cages, and then the cages were released from heights of 0.2, 0.4, and 0.6 meters. The accelerometer measures the impact's deceleration during collision, and then a signal conditioner transfers that data to the data acquisition card. The data is recorded using LabVIEW software. Fig. 4.8 depicts how to measure the cage's deceleration.

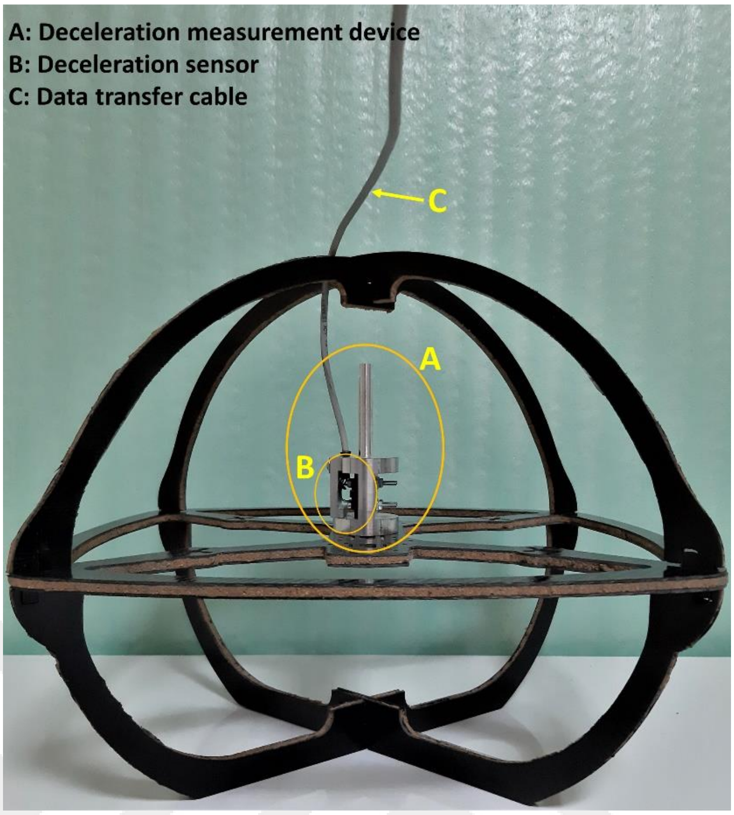


Figure 4.9. *Experimental deceleration test on cage.*

4.3. Results and discussion

4.3.1. Vibration results of drone cages

4.3.1.1. Frequency response functions

Figs. 4.9 and 4.10 shows the frequency response function graphs for the A, B, C, D, E areas of the drone cages. The frequency spectra exhibit peaks at certain points that correspond to the natural frequencies for the structures. An examination of the frequency response functions reveals a single and multimodal structure. Based on a single mode approach (one degree of freedom), Table 3 shows the natural frequency values.

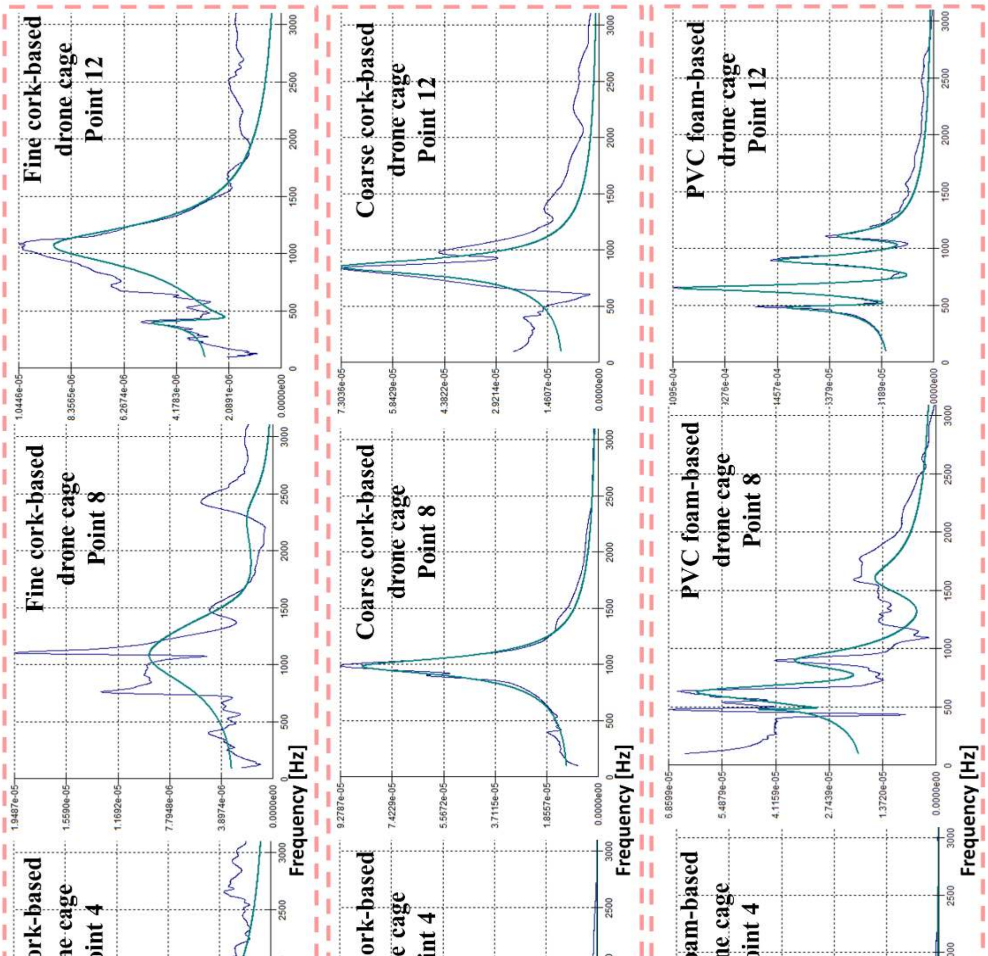


Figure 4.10. *The frequency response function graphs for main frame of the drone cages.*

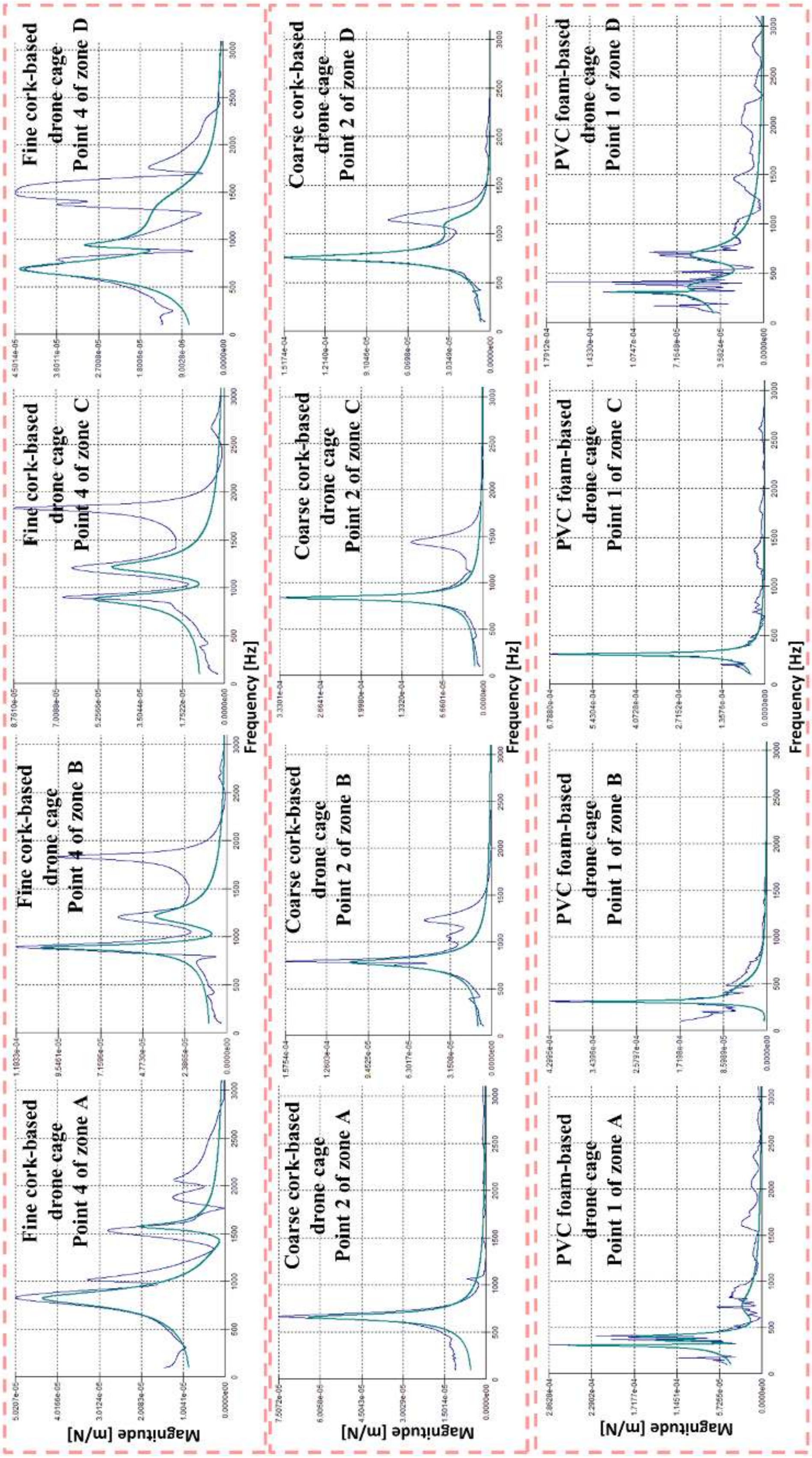


Figure 4.11. *The frequency response function graphs for drone rotor locations.*

Table 4.2. *The range of changes in natural frequencies in zones A, B, C, D, and E of drone cages.*

Area	**Natural frequency (Hz)**
Zone E of fine cork-based drone cage	1050 ± 80 Hz
Zone E of coarse cork-based drone cage	950 ± 50 Hz
Zone E of PVC foam-based drone cage	680 ± 70 Hz
Zone A of fine cork-based drone cage	780 ± 60 Hz
Zone A of coarse cork-based drone cage	620 ± 45 Hz
Zone A of PVC foam-based drone cage	385 ± 65 Hz
Zone B of fine cork-based drone cage	815 ± 95 Hz
Zone B of coarse cork-based drone cage	725 ± 55 Hz
Zone B of PVC foam-based drone cage	415 ± 45 Hz
Zone C of fine cork-based drone cage	890 ± 35 Hz
Zone C of coarse cork-based drone cage	785 ± 85 Hz
Zone C of PVC foam-based drone cage	355 ± 55 Hz
Zone D of fine cork-based drone cage	725 ± 100 Hz
Zone D of coarse cork-based drone cage	815 ± 85 Hz
Zone D of PVC foam-based drone cage	465 ± 65 Hz

Natural frequencies are a measure of how a structure responds to vibration or oscillation. When a structure is subjected to an external force, it will vibrate at a certain frequency that is determined by its physical properties, such as its stiffness, mass, and damping. The natural frequency of a structure is the frequency at which it will vibrate when subjected to a small external force. In general, higher natural frequencies can indicate that a structure is stiffer and more resistant to vibration. This is because a stiffer structure will require a higher force to achieve the same amount of displacement, resulting in a higher natural frequency. However, natural frequencies alone do not necessarily indicate that a structure is better or worse than another structure. When evaluating the performance of a structure, it is important to consider a range of factors, including stiffness, strength, weight, durability, and cost. For example, a structure with a high natural frequency may be desirable for applications that require low levels of vibration, such as in precision machinery or aerospace applications. However, for other applications where weight is a primary concern, a lightweight structure may be more important than a structure with high natural frequencies. Additionally, the specific requirements of the drone cage design may also play a role in determining which cage is "better". For example, the drone may need to perform specific tasks that require a certain level of stiffness or durability. Therefore, it is important to consider the entire design and all its requirements when evaluating the performance of a structure, and not just focus on one factor such as natural frequencies.

4.3.1.2. Damping ratios of drone cage structures

Fig. 4.11 shows the damping ratios for zone E of Fine, Coarse, and PVC foam-based drone cages.

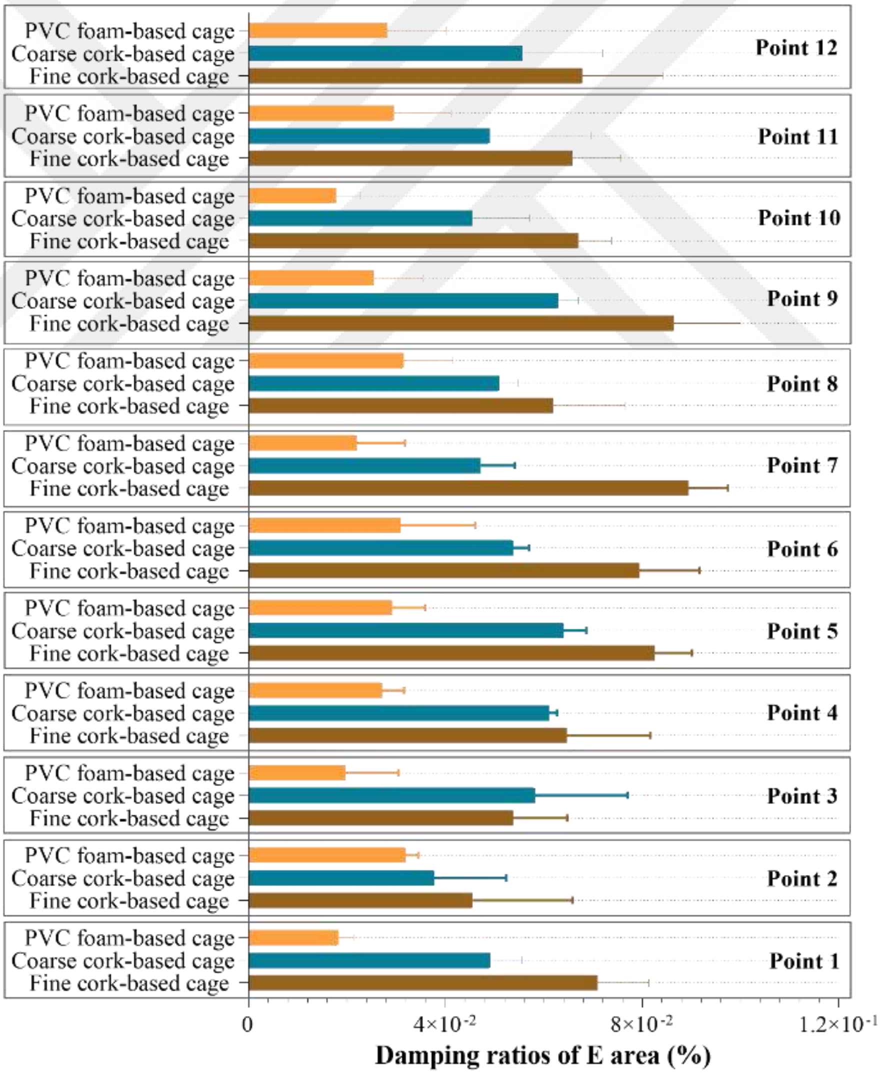


Figure 4.12. *Damping ratios of Zone E of drone cages.*

Fig. 4.12 shows the values of damping ratios of A, B, C, and D zones of drone cages. In terms of different zones, cork materials have a higher damping ratio than PVC foam materials. However, the coarse cork and fine cork damping ratios did not differ significantly. With a high loss factor, cork is an excellent damping tool. Due to its closed, cellular structure, filled with air, cork has a higher loss factor than PVC foam-based materials, which is essential for damping and consequent energy dissipation.

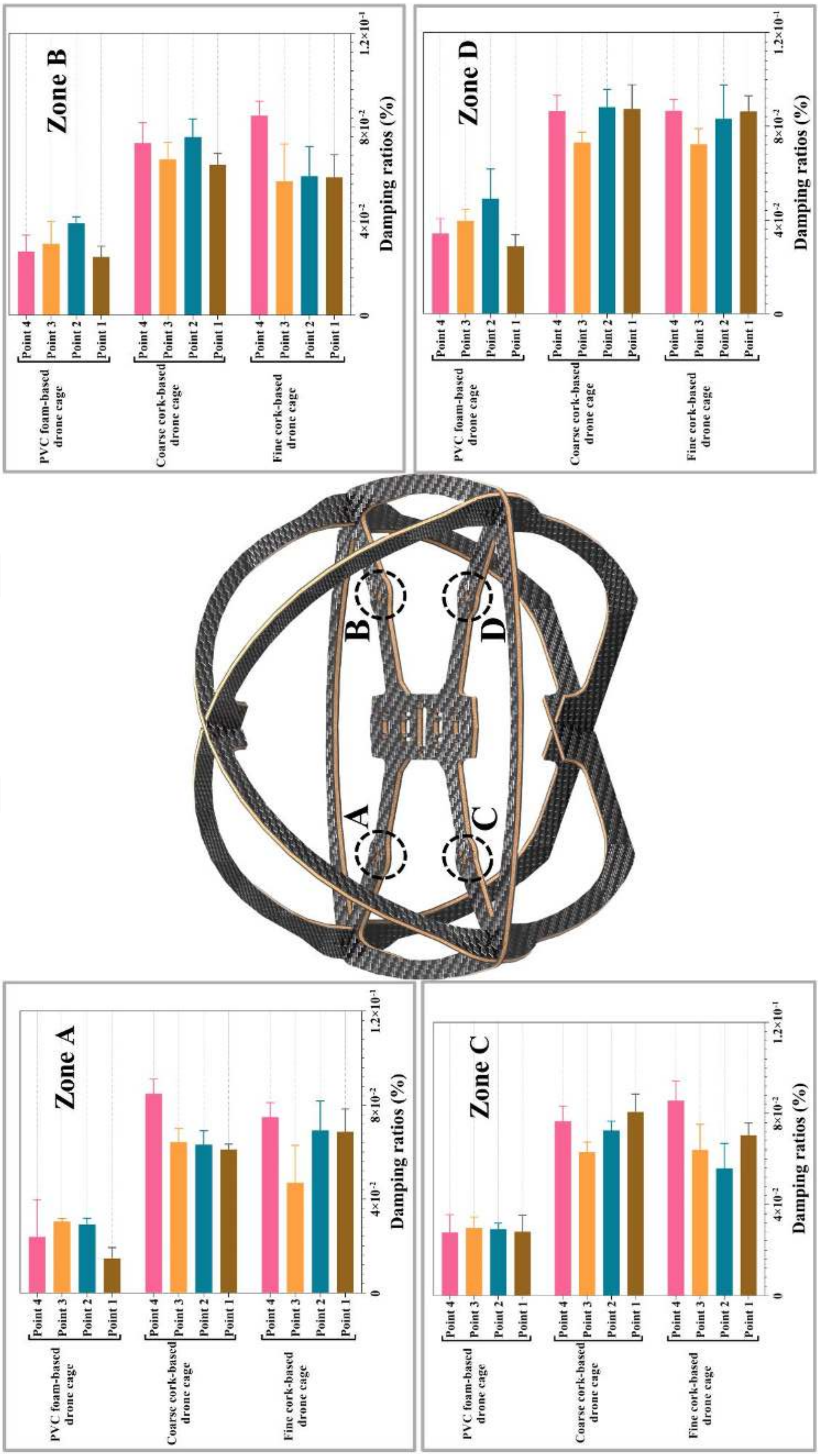


Figure 4.13. *Damping ratios of A, B, C, and D regions of drone cages.*

Modal analysis is a technique used to determine the natural frequencies and damping ratios of a structure. In this case, the modal analysis was performed on three drone cages that have sandwich structures with fixed CFRP face-sheets and different core materials, namely fine-grained cork, coarse-grained cork, and PVC foam. Damping ratio is a measure of the rate at which the vibrations in a structure decay over time, and it is an important parameter in determining the dynamic response of a structure. Higher damping ratios imply that the structure dissipates more energy when it vibrates, and thus, it will have a lower amplitude of vibration. The results obtained from the modal analysis indicate that the damping ratios in the cages based on fine-grained cork and coarse-grained cork are higher than in PVC foam-based cages. This suggests that the cages with cork cores exhibit higher energy dissipation during vibration and thus will experience lower vibration amplitudes. This is because cork has a higher internal friction than PVC foam, and this frictional energy dissipation is responsible for the higher damping ratios observed in the cork-based cages. Additionally, it is worth noting that the size and distribution of the cork grains within the cores could also affect the damping ratios. The cages with coarse-grained cork may have exhibited higher damping ratios than those with fine-grained cork due to the larger grains creating more frictional contact and thus leading to more energy dissipation. However, further analysis would be necessary to confirm this hypothesis. In summary, the higher damping ratios observed in the cork-based cages suggest that they are better able to dissipate energy during vibration, resulting in lower vibration amplitudes compared to the PVC foam-based cages.

4.3.1.3. Structural stiffness results of drone cages

Fig. 4.13 presents the stiffness coefficient values of Zone E for the cages.

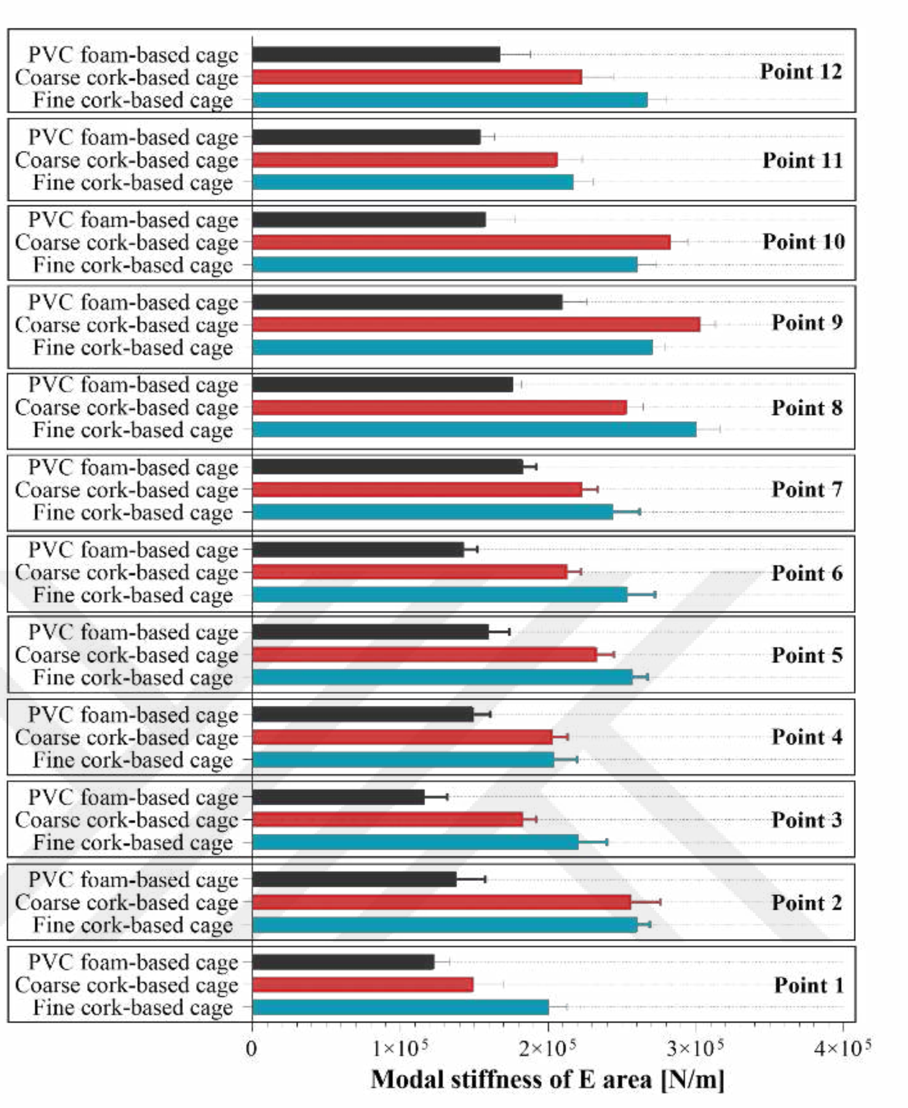


Figure 4.14. *Modal stiffness results of zone E for the drone cages.*

Fig. 14 depicts the values of stiffness coefficients of A, B, C, and D zones of drone cages. Cork material has a modulus of elasticity between 18-50 MPa, while PVC foam has a modulus of elasticity between 15-30 MPa. The high rigidity of cork is due to its high modulus of elasticity. Also, fine grains increase the rigidity of structures in general. Fine grains increase grain boundaries, inhibiting the movement of dislocations. This increases rigidity.

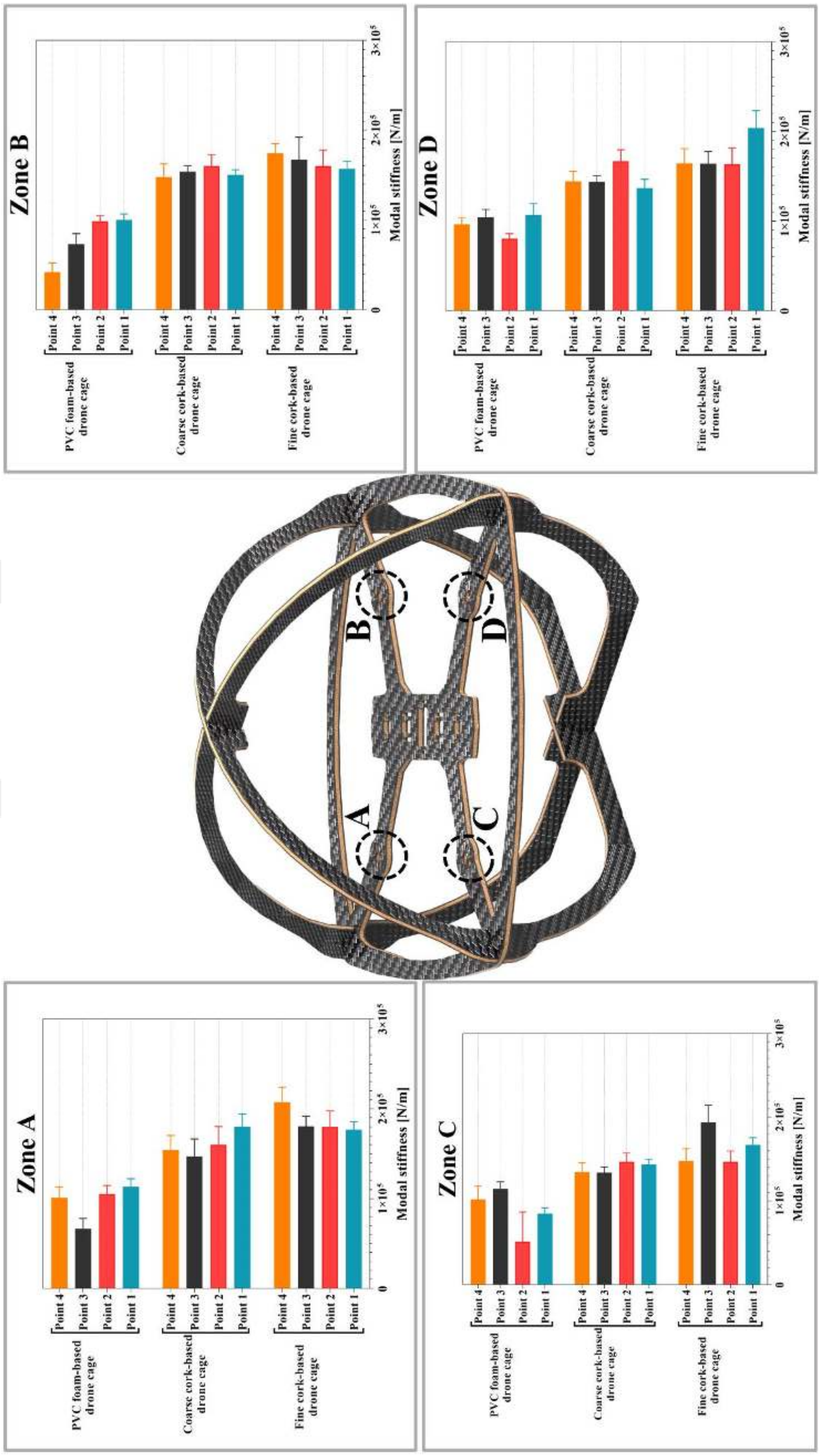


Figure 4.15. *Stiffness coefficients of A, B, C, and D zones of drone cages.*

Firstly, it's worth noting that the stiffness of a structure is a measure of its ability to resist deformation when subjected to a load. In the case of these drone cages, the stiffness values were measured by performing modal analysis, which is a technique that can be used to determine the natural frequencies and mode shapes of a structure. The natural frequency of a structure is directly related to its stiffness, with a higher natural frequency indicating a stiffer structure. Cork is a natural material that is known for its low density, high compressive strength, and low thermal conductivity. These properties make it a popular choice for use in sandwich structures, as it can provide good mechanical performance while also being lightweight. In comparison, PVC foam is a synthetic material that is also commonly used as a core material in sandwich structures. PVC foam typically has lower compressive strength and higher thermal conductivity than cork, which can result in lower stiffness values for structures that use it as a core material. In addition to material properties, the geometric configuration of the sandwich structures can also have an impact on stiffness values. The thickness of the face-sheets and the core material can both influence the stiffness of a sandwich structure. In this case, the cages had fixed CFRP face-sheets, but different core materials. The thickness and configuration of the cores in each zone of the cages were kept constant, but the type of core material was different. It's possible that the cork cores had a more optimal thickness and geometry for the specific zones, resulting in higher stiffness values compared to the PVC foam core. It's important to note that there may be other factors at play as well. For example, the manufacturing process used to create the cages, as well as any imperfections in the samples, could also affect the stiffness values. Nevertheless, based on the known properties of the core materials and the geometry of the cages, it seems plausible that the observed higher stiffness values in the cages based on fine-grained cork and coarse-grained cork can be explained by their material properties and/or their optimal geometric configuration.

4.3.2. Peak deceleration properties of drone cages

We apply a controlled force to the cage during the peak deceleration test to imitate the impact of an accident or collision. Using an accelerometer sensor, we then measure the deceleration that happens at the time of impact. The maximal deceleration that happens during the collision is referred to as peak deceleration. Peak deceleration is a critical metric for determining the cage's capacity to protect the drone and its cargo in the case of a crash. A greater peak deceleration means that the cage is less efficient in absorbing and dissipating impact force, transferring more force to the drone and its cargo. This might cause damage to the drone or its components, as well as harm to anybody or anything close. A smaller peak deceleration, on the other hand, shows that the cage is more successful in absorbing and dissipating impact force, resulting in less force being delivered to the drone and its cargo. In the case of an accident or collision, this might lessen the chance of damage or harm. We may analyze the strength and resilience of the cage design by measuring the peak deceleration during the test and make any required revisions to guarantee that it delivers the best combination of protection, weight, and performance. This may assist the designer in developing a more secure and effective circular cage design that can protect the drone and its cargo in the case of a crash or collision. Fig. 15 shows the deceleration values for fine cork, coarse cork, and PVC foam-based drone cages. As shown in the figure 15, for fine cork-based drone cage, the deceleration values are 66.1, 88.8, and 117.7 g, while for coarse cork-based drone cage, these values are 65.3, 92.9, and 109 g. The deceleration values for PVC foam-based drone cage are 82.6, 109.3, and 142.1. The combination of cork with carbon-fiber in the sandwich structure of the cages is better able to repel the impact force and finally less g is introduced into the structure. Although PVC foam has high strength compared to other core foams, its soft and flexible structure compared to PVC foam is better able to establish a connection with carbon-fiber layers and the impact force after the passage with the carbon-fiber layer is better damped by the cork. Cork is extremely durable and has a high friction coefficient, so it will survive repeated impacts or rubbing/abrasion extremely well.

Figure 4.16. *Peak deceleration results of different cages.*

5. CONCLUSION AND FINAL REMARKS

This doctoral thesis showed sandwich structures with cork cores that are good at resisting impacts and vibrations and are also good for the environment. The study was divided into two separate parts. In the first part, an attempt was made to find the best combination of common face-sheets available in aerospace applications with a fixed core of cork, which works better against impact and vibration. For this purpose, sandwich structures consisting of CFRP, AFRP, GFRP composite face-sheets, and non-composite aluminum with a fixed cork core were produced. Composite face-sheets were produced by the pressure molding method (prepreg). The core of the cork was selected from the composite cork type with a fine-grained structure. In the first part, sandwich structures were produced in the form of laboratory samples, and deceleration and vibration tests were performed on them. In the deceleration test, a drop-tower impact test structure was used, where G values were calculated by a sensor embedded in the impactor head. The vibration test was also performed by a modal analysis system based on the hammer, which calculated the values of the damping ratio and stiffness of sandwich structures. The results of both tests showed that the CFRP face-sheet can show better resistance to the impact and vibrations of the structure, and therefore the CFRP/cork/CFRP sandwich structure was chosen as the final structure for the construction of the drone cage.

In the second part of the study, the drone cage was built based on a CFRP/cork/CFRP sandwich structure. In this section, three different types of cages were made, two of which were based on fine- and coarse-grained cork cores, and another type was made with a PVC foam core so that cork cages could be compared with those made with a PVC foam core. The stages of making the cage were as follows: First, CFRP composite face-sheets with dimensions of 50 cm by 50 cm were produced by the prepreg method. The cores of fine- and coarse-grained cork and PVC foam were cut by laser cutting to the same dimensions of 50 cm by 50 cm. CFRP composite cores and face-sheets were glued together by special glue, and sandwich structures were made in dimensions of 50 cm by 50 cm. Then, the three types of CFRP/fine cork/CFRP, CFRP/coarse cork/CFRP, and CFRP/PVC foam/CFRP structures were cut and converted into drone cage parts by a router cutting machine. The manufactured parts of the cage were finally assembled, and three types of cages were successfully produced. To evaluate the impact and vibration tests on the cages, as in the first part, the peak deceleration (PD) system and vibrations based on modal analysis were used. For the vibration test, the cages were divided into five different zones, and in each zone, several different points were used for hammer impact to make the general behavior of the cages more accessible based on more data. PD values were also measured in terms of G by a sensor placed in the center of the cage.

Based on the results of the PD, damping ratio, and structure stiffness tests, it is possible to state the circular cages for protecting rotary-wing drones from impacts and vibrations with cork as the core material were more resistant to impacts and vibrations than the cage with a PVC foam core. The cork-based cages showed lower peak deceleration and higher damping ratios and structural stiffness, indicating a superior ability to absorb and dissipate energy from impacts and vibrations, thus providing better protection for the rotary-wing drones. The use of CFRP face-sheets in all three cages provided a strong and durable outer layer that contributed to the overall effectiveness of the cage design. These results suggest that cork is a promising material for use as a core in sandwich structures for impact and vibration protection in rotary-wing drone applications.

In summary, the following may be regarded as the PhD thesis's conclusion:

a) Cork can be used as the core of sandwich structures that can withstand impact and vibrations on the structure, particularly in low-speed aerial vehicles.

a) The vibration research shows that the CFRP-based face-sheet has the best damping and stiffness qualities. Sandwich structures with CFRP face-sheets and cork cores may therefore be a preferable choice for aerial structures.

b) Regarding the lowest amount of PD after the deceleration test, both in sandwich structures and drone cages, the CFRP/fine cork/CFRP sandwich structure showed the lowest PD.

c) Although the findings of the deceleration results of CFRP and GFRP samples in face-sheets are relatively close, sandwich structures with CFRP face-sheets outperform those with GFRP face-sheets.

d) Although the Al/Cork/Al structure has a lower deceleration result than the other samples, the aluminum face-sheets' deformable structure leads to early failure and irreversible deformation.

e) Another point that can be mentioned is that the connection between the face-sheets and the cork core was very good, and it showed that the porous surface of the cork can absorb the adhesive well and a stronger connection can be made with the face-sheets compared to other core materials that have a smooth surface.

f) The results of the lowest PD and the highest damping ratios and stiffness of the sandwich structures used in this study showed that the drone cages that had sandwich structures with a cork core had better performance compared to the cage based on PVC foam, with significant improvements that can be considered in design and application of structures for low-speed aerial vehicles and drone caged.

One of the limitations in this study was the lack of use of high-energy impact, which could demonstrate the behavior of structures in that range of impact energy, but nevertheless, the authors of this study are sure that the amount of impact energy used for PD results acceptable for showing that the CFRP/cork/CFRP sandwich structure can be a good option for use in low-speed aerial vehicles such as rotary-wing drones. Furthermore, because of the ease of construction, cost-effectiveness, and potential environmental impact of these sandwich structures with a cork core, they can be suggested as suitable candidates for use in the industry.

Based on the results of the study, the following suggestions can be made for future work in this field:

a) Optimization of cork core properties: The study found that fine granulate cork cores were more effective in reducing peak deceleration values compared to coarse granulate cork cores and PVC foam cores. Further studies can be conducted to optimize the properties of cork cores, such as their density, porosity, and mechanical properties, to improve their performance as a core material in sandwich structures.

b) Evaluation of cork core durability: The study only evaluated the impact and vibration resistance of cork cores; further studies can be conducted to evaluate their durability and performance in real-world conditions. This would involve exposing the cork cores to environmental factors, such as temperature, humidity, and UV light, and evaluating their performance over time.

c) Development of new face-sheet materials: The study found that CFRP face-sheets provided the best resistance to impact and vibration. However, other face-sheet materials with improved mechanical properties and better impact resistance can be developed and evaluated for use in sandwich structures with cork cores.

d) Expansion of the study to other aerospace applications: The study focused on the use of cork cores in drone cages, but they can also be evaluated for other aerospace applications where impact and vibration resistance are important, such as fuselages, wings, and helicopter blades.
e) Evaluation of other types of cork cores: The study only evaluated composite cork cores with fine-and coarse-grained structures. Other types of cork cores, such as solid cork and engineered cork, can also be evaluated for their impact and vibration resistance, and compared to composite cork cores.
f) Sandwich structures and cages should be put through a deceleration test with high-impact energy. This will show how the structures behave from the point of view of the lowest PD to the point after the structures fail.
g) If the purpose of some designs is to use these types of structures based on cork cores for high-speed aerial vehicles, ballistic tests can be performed on the structures. Even in ballistic tests, we believe that cork-core sandwich structures can provide promising results.
h) We suggest that in a separate study, the tests performed on the cages should be adjusted so that they are performed during the flight of the drone.

In conclusion, there is significant potential for further research and development in the use of cork cores in sandwich structures for aerospace applications. These suggestions provide a starting point for future studies in this field.

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CURRICULUM VITAE

Education and Professional Background:

- 2023- Ph. D. in Aircraft Airframe and Engine Maintenance, Eskisehir Technical University, Turkey (It is the oldest and most prestigious civil aviation school and only university offering this PhD program in Turkey)
- M.Sc. in Aerospace Engineering, Shahid Beheshti University, Tehran, Iran
- B.Sc. in Mechanical Engineering, University of Tabriz, Tabriz, Iran

Published articles:

1. **Sheikhi, Mohammad Rauf**, Selim Gürgen, Onder Altuntas, and Mehmet Alper Sofuoğlu. "Anti-impact and vibration-damping design of cork-based sandwich structures for low-speed aerial vehicles." *Archives of Civil and Mechanical Engineering* 23, no. 2 (2023): 71. (IF = 4.042, Q1)
2. **Sheikhi, Mohammad Rauf**, Selim Gürgen, and Onder Altuntas. "Energy-Absorbing and Eco-Friendly Perspectives for Cork and WKSF Based Composites under Drop-Weight Impact Machine." *Machines* 10, no. 11 (2022): 1050. (IF = 2.899, Q2)
3. **Sheikhi, Mohammad Rauf**, and Selim Gürgen. "Anti-impact design of multi-layer composites enhanced by shear thickening fluid." *Composite Structures* 279 (2022): 114797. (IF = 6.603, Q1)
4. **Sheikhi, Mohammad Rauf**, and Selim Gürgen. "Deceleration behavior of multi-layer cork composites intercalated with a non-Newtonian material." *Archives of Civil and Mechanical Engineering* 23, no. 1 (2022): 2. (IF = 4.042, Q1)
5. **Sheikhi, Mohammad Rauf**, and Selim Gürgen. "Micro-milling Operation of UHMWPE Composites with PTFE and Aramid Reinforcements." *Applied Composite Materials* (2022): 1-16. (IF = 2.368, Q3)
6. **Sheikhi, Mohammad Rauf**, Behrang Shamsadinlo, Özgür Ünver, and Selim Gürgen. "Finite element analysis of different material models for polyurethane elastomer using

estimation data sets." *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 43 (2021): 1-12. (IF = 2.361, Q2)

7. Shamsadinlo, Behrang, **Mohammad Rauf Sheikhi**, Ozgur Unver, and Bora Yildirim. "Numerical and empirical modeling of peak deceleration and stress analysis of polyurethane elastomer under impact loading test." *Polymer Testing* 89 (2020): 106594. (IF = 4.931, Q1)
8. **Sheikhi, Mohammad Rauf**, and Hakan Aygun. "Assessment of emission and environmental parameters of different commercial high by-pass turbofan engines throughout landing and take-off cycle." *Environmental Progress & Sustainable Energy* 42, no. 1 (2023): e13974. (IF = 2.824, Q3)
9. Aygun, Hakan, **Mohammad Rauf Sheikhi**, and Mehmet Kirmizi. "Parametric study on exergy and NOx metrics of turbofan engine under different design variables." *Journal of Energy Resources Technology* 144, no. 6 (2022). (IF = 3.07, Q2)

Published book & book chapters:

1. **Sheikhi, Mohammad Rauf**, Hakan Aygun, and Onder Altuntas. "Aeroengines: Principles, Components, and Eco-friendly Trends". In *Materials, Structures and Manufacturing for Aircraft*, pp. 127-151. Cham: Springer International Publishing, 2022.
2. Kaya, Esad, **Mohammad Rauf Sheikhi**, Selim Gürgen, and Melih Cemal Kuşhan. "Aluminum-Lithium Alloys in Aircraft Structures". In *Materials, Structures and Manufacturing for Aircraft*, pp. 1-25. Cham: Springer International Publishing, 2022.
3. **Mohammad Rauf Sheikhi**, Selim Gürgen, and Melih Cemal Kuşhan. " Shear thickening fluid in spall-liner applications ". in *Advances in Healthcare and Protective Textiles Book-The Textile Institute Book Series*, pp. 487-508. Publisher: Elsevier, 2023.

Published conference papers:

1. "Aerogels in aerospace applications", **Mohammad Rauf Sheikhi**, Selim Gürgen, Onder Altuntas, Melih Cemal Kuşhan, International Symposium on Aircraft Technology, MRO &Operations (ISATECH), June 28-30, 2021, Budapest, Hungary.
2. "Anti-impact composites under impact conditions", **Mohammad Rauf Sheikhi**, Selim Gürgen, Onder Altuntas, Melih Cemal Kuşhan, International Symposium on Aircraft Technology, MRO &Operations (ISATECH), June 28-30, 2021, Budapest, Hungary.
3. "Cork composites in aerospace applications", **Mohammad Rauf Sheikhi**, Selim Gürgen, Melih Cemal Kuşhan, International Symposium on Aircraft Technology, MRO &Operations (ISATECH), June 28-30, 2021, Budapest, Hungary.
4. "Role of 3D spacer-fabrics in recyclable lightweight cork composites as an ideal core material for impact energy absorbing structures", **Mohammad Rauf Sheikhi**, Onder Altuntas, Selim Gürgen, The 5th International Conference on Alternative Fuels, Energy and Environment (ICAFEE 2021): Future & Challenges, 16-18th October 2021, Erciyes University, Kayseri, Turkey.
5. "Deceleration behavior of super-lightweight XPS foams: number of layers effect", **Mohammad Rauf Sheikhi**, Selim Gürgen, Onder Altuntas, Melih Cemal Kuşhan, International Symposium on Sustainable Aviation, August 03-05, 2022, Melbourne, Australia.
6. "Investigation production of polyurethane elastomer material using shape deposition manufacturing method", **Mohammad Rauf Sheikhi**, Selim Gürgen, Melih Cemal Kuşhan, 8th International Fiber and Polymer Research Symposium, 18-19 June 2021, Eskisehir Osmangazi University, Turkey.
7. "Force attenuation properties of multilayer polyurethane and 3D fabric composites", **Mohammad Rauf Sheikhi**, Selim Gürgen, International Symposium on Electric Aviation and Autonomous Systems, July 19-21, 2022, Maribor, Slovenia.
8. " Effects of design variables on exergy and environmental parameters of commercial turbofan engine (ID: 104)", Hakan Aygun**, Mohammad Rauf Sheikhi,** Hakan Caliskan, TUBA World Conference on Energy Science and Technology, August 8-12, 2021, Turkish Academy of Sciences (TÜBA), Turkey.
9. "Searching of thermodynamic performance metrics for turbofan engine used in commercial aircraft at several power setting", Hakan Aygun**, Mohammad Rauf**

Sheikhi, 6th International Conference on Advances in Mechanical Engineering, 20 - 22 October 2021, İstanbul, Turkey.

10. " Assessment and prediction of thermodynamic metrics of small turbojet engine at different working points ", Hakan Aygun**, Mohammad Rauf Sheikhi**, International Symposium Energy Management and Sustainability, 06-08 April 2022, Geel, Belgium / Istanbul, Turkey.
11. " Effects of combustor parameters on mini turbojet performance under real conditions ", Hakan Aygun**, Mohammad Rauf Sheikhi**, 3rd International Conference on Applied Engineering and Natural Sciences (ICAENS 2022), July 20 - 23, 2022, Konya, Turkey.

Awards:

- Awarded as best Ph.D. researcher (Model) for the 2021-2022 academic year in Xi'an Jiaotong University of China. Link: http://news.xjtu.edu.cn/info/1033/189087.htm