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ORIGINAL ARTICLE

Anti-impact and vibration-damping design of cork-based sandwich structures for low-speed aerial vehicles

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Abstract

Nowadays, lightweight and eco-friendly composites with improved mechanical properties are highly interesting. Sandwich-structured composites are a type of high-performance structural composite that is lightweight with a high strength-to-weight ratio and excellent specific energy absorption capabilities. In this study, cork-based sandwich structures resistant to impact and vibrations were designed and produced for the possibility of being used in the protective structures of low-speed aerial vehicles. To identify and match the best combination of different face sheets with a cork core, first, aramid fabric-reinforced polymer (AFRP), carbon fiber-reinforced polymer (CFRP), and glass fiber-reinforced polymer (GFRP) face-sheet composites were produced using the compression molding method (prepreg layup). Then, sandwich structures consisting of AFRP, CFRP, GFRP, and aluminum face sheets with a fixed core layer of cork were designed and assembled. Since the design goal of these structures is to use them in low-speed aerial vehicles, impact deceleration and vibration tests were applied to face sheets and sandwich structures individually, which are the most important factors involved in these structures during flight, particularly in rotary-wing drone applications. A low-energy drop-tower system was used for the calculation of deceleration results. Besides, the vibration properties of the structures were investigated using the modal analysis method and based on the natural frequency responses of the tested face sheets and sandwich structures, damping ratios and structural stiffness were measured. According to the results, compared to other face sheets, CFRP showed better resistance along with the cork core, when the structure was exposed to impact and vibration threats. This study provides useful information on cork core sandwich structures for academic and industrial researchers in choosing the right face sheet.

Keywords Cork composites · Sandwich structures · Impact properties · Vibration damping

1 Introduction

An important factor in the design of aerial structures is their weight, because it has a direct impact on fuel consumption and maintenance costs. For this reason, the tendency toward the use of composites has greatly increased due to their high strength-to-weight ratio, high corrosion resistance, wear, vibration, and impact resistance [1]. Composites and sandwich panels are used in the design of various parts of aerial structures [2]. Sandwich structures made of composite materials provide a strong connection between the parts. The face sheets are rigid and provide the structure with high stiffness and strength, while withstanding tensile and compressive loads [3]. Shear stresses in the sandwich structure must be resisted by the cores, which typically have a low modulus of elasticity. They must also support the face sheets [4]. There are various types of core structures, such as foam, honeycomb, and others [5], and the development of lightweight

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structures with stiffness, strength, energy absorption, and vibration-damping features have been proposed over the past decade using various types of core designs and materials [6]. The optimal lightweight cellular core designs and material kinds have generally received more attention in research works [7]. Note that three factors—namely, the relative density of the core structure, the characteristics of the original material employed, and the geometry of the core materials—affect the mechanical properties of sandwich core structures [8]. Some conventional cores contain synthetic materials, which may pollute the air and water during production and waste disposal. Furthermore, there is a significant push for a shift further toward eco-friendly material options. Cork is a natural, renewable substance derived from the bark of the cork oak tree *Quercus suber* L. [9]. The elemental composition and cellular structure of the cork provide it with a unique set of characteristics, including very low permeability, hydrophobic behavior, biological inertia, significant elastic compression, and dimensional recovery [10]. Previous studies have demonstrated that using cork can improve the amount of absorbed impact energy [11] and vibration damping [12]. Cork is a natural material with respect to its sustainability and recyclability [13].

Along with the importance of core selection, due to their ability to support both compressive and tensile in-plane loads, the face sheets are a crucial component for the sandwich structure [14]. Face sheets need to have high stiffness, flexural rigidity, and tensile and compressive strength [15]. Furthermore, choosing the right face-sheet materials for certain applications requires consideration of environmental threats to dampness, fire, and so forth. Metallic and non-metallic materials are the two types used in face sheets. Steel and aluminum are the most prevalent metals in the first group, according to Ref. [16]. Aluminum face sheets are typically chosen for applications with hygienic and corrosion-resistant needs. Non-metallic skins include plywood, cement, reinforced plastic, fiber composites, etc. [17]. The fiber composites, which include glass and carbon fiber, and aramid fabric are the most pertinent types. Generally, anisotropic behavior and ease of fabrication are the two differences between fiber composite and metallic face sheets [18].

Recently, researchers found that the use of cork materials as a core in sandwich structures can be a suitable option for achieving eco-friendly structures while maintaining performance characteristics compared to common sandwich cores. Sergi et al. [19] investigated the ballistic impact behavior of agglomerated cork and of the resulting green sandwich structures produced with polypropylene (PP) face sheets reinforced with a flax/basalt intraply hybrid fabric. They found that although the ballistic resistance characteristics of cork are lower than PVC foam when both materials are used as the core of the sandwich structure, the cork's performance is rapidly improved and reaches results similar to the performance of PVC foam. Sutherland et al. [20] added a thin layer of cork (Corecork NL20) to the core of a sandwich structure consisting of a PVC foam core and a glass-reinforced plastic face sheet and found that the concept can improve the perforation resistance by up to 60% for both quasi-static indentation and impact loading rates. In another work, Fernandes et al. [21] proposed a bio-sandwich structure, made of agglomerated cork core, and flax fibers composite face sheets, and bending tests and Charpy impact tests were performed. Their result showed very promising results in terms of specific strength and toughness. An aluminum honeycomb sandwich and a cork layer were combined by Di Bella et al. [22]. Their findings demonstrate the superior performance of the cork/aluminum double-layer sandwich panels, with the largest specific energy absorption (0.501).

Damping is known as the dissipation of vibrational energy through time and distance in solid mediums and structures. Like how sound is absorbed by air, damping happens whenever friction lessens motion and disperses energy [23]. The loss factor, or ratio between the energy dissipated and the energy still present in the system throughout each cycle, is referred to as each material's damping capability [24]. Like high-speed aircraft, in low-speed aerial structures such as rotor-rotating drones, vibrations caused by rotor rotation and aerodynamic effects cause severe damage to the system. Increasing the damping of the structure can help with this vibration problem, and the rate of vibrational energy dissipation depends on the amplitude and frequency of vibrations and the damping factor refers to the amount of damping in the system [25]. Given the wide range of applications, a significant amount of research has been conducted on vibration damping and control by dampers and vibration-damping materials like cork [26].

Eco-friendly materials are a type of materials that do not harm the environment in their production, use (lifetime), or disposal and can be easily recycled [27]. Although it does not provide a return on cost in the short term, the use of environmentally friendly materials in production is very beneficial eventually. The 12th Sustainable Development Goal (Responsible Consumption and Production) [28] has been set by the United Nations (UN) to ensure consumption and production processes under sustainable objectives to prevent climate change, biodiversity decrease, and pollution. A green and sustainable design will play a key role in achieving the UN's Sustainable Development Goals. In this context, the waste left over from the tree pruning process appears to be an important sustainable material. Many studies have been conducted to reuse cork materials in the circular economy [29]. The use of cork in composite material (in all engineering fields) is both innovative and environmentally friendly [30].

This study presents a sandwich structure consisting of AFRP, GFRP, CFRP, and aluminum face sheets with a fixed core layer of cork. The authors of this study have shown in previous studies that cork has excellent capabilities for anti-impact and damping applications as a core layer in sandwich and multi-layer structures [31]. Therefore, choosing the best option among common face-sheet composites used in aerial vehicle structures with a core layer of cork is the main motivation of this study. In the first step, AFRP, GFRP, and CFRP composites were produced by the mold-pressure method, and sandwich structures were produced using them. Since these structures are proposed for use in aerial vehicles, being impact and vibration resistant are the most important factors for such applications [32]. For this aim, the produced samples were subjected to impact and vibration tests. A low-energy drop-tower system was used to measure the deceleration of the designed samples, and on the other hand, the hammer-impact system was used to measure the damping ratio and natural frequencies of the structures. In this context, the following are the main motivations for the current paper:

- Cork is a promising material, and this research will put it to the test as an alternative to traditional core materials.
- Although there is some research on cork as a core material, there is currently a lack of knowledge on the feasibility of changing and testing agglomerated cork in sandwich structures for aerial vehicles by considering higher vibration damping and lower deceleration values.
- The results will compare the structures' behavior to vibration damping and deceleration, and the final best result will be proposed for potential applications in structures of aerial vehicles.

2 Experimental details

2.1 Materials

Face-sheet composites and sandwich structures were assembled using five main components. Cork agglomerates were purchased from Ducork Inc. and aramid fabrics were supplied by Teijin Inc., whereas, glass fiber and carbon fiber textiles were provided by DowAksa B.V. Aluminum sheets were supplied from Alutem Inc. Table 1 lists the details of the components based on the manufacturers' specifications.

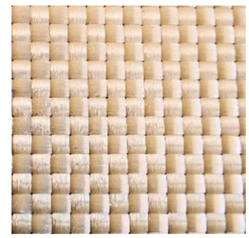
2.2 Manufacturing of face-sheet composites and sandwich structures

To produce the composite face sheets, the pressure molding method was used in such a way that two steel plates (250 mm × 250 mm) with a thickness of 10 mm were taken 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 force of 50 N was applied to the middle of the mold plate. In this work, epoxy-resin LR-160, which is acceptable for aerospace applications, was used in the form of 80% epoxy and 20% hardener. According to the density of each fabric, the number of layers of the composites was determined, which finally equalized the final weight of each sample. Therefore, 3 layers of aramid fabric (each layer; 400 g/m^2), 4 layers of glass fiber (each layer; 300 g/m^2), and 12 layers of carbon fiber (each layer; 100 g/m^2) were used. To facilitate the separation of the molds, steel plates were first wrapped in paper, and mold release wax was used to separate the molds. After molding, they were exposed to room temperature for 24 h. The manufacturing process of all samples was the same and the composites were finally produced in the dimensions of 250 mm × 250 mm. Because the multi-layers were designed in the dimensions of 50 mm × 50 mm, the face sheets were cut to the desired dimensions. After finishing the construction of face-sheet composites, the cork core layers were cut by a laser cutting machine to a size of 50 mm × 50 mm. In the last step, the cork core layers were sandwiched by epoxy-resin LR-160 to the composite and aluminum face sheets and again placed between two steel plates and exposed to 25 N force for 24 h. The face-sheet manufacturing process of composites and sandwich structures was performed at room temperature (20 ℃). Figure 1 shows the face sheets, sandwich structures and cork core layer.

2.3 Vibration tests

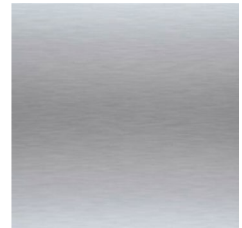
Modal analysis is the study of a system's dynamic properties, which are defined separately from the stresses placed on the system and its reaction. Understanding the vibration characteristics of mechanical structures may be studied with the help of modal analysis. It transforms the difficult-to-perceive vibration signals of excitation and responses observed on a complicated structure into a collection of easily predictable modal characteristics [33]. One viewpoint for comprehending structural vibrations is the modal domain. When structures are aroused at their natural frequencies, they vibrate or take form termed mode shapes. A structure will vibrate in a complicated combination made up of all mode forms under normal operating circumstances. The modal analysis converts a complicated structure that is difficult to grasp into a collection of disconnected single-degree freedom systems. Modal analysis is the process of identifying a structure's natural frequencies, modal damping, and mode shapes. The structure should be activated, and both the applied excitation force and the ensuing reaction vibrations, which are often acceleration, are recorded, producing a frequency response function (FRF) data set. Modal properties such as natural frequencies and damping ratios may be identified using the

Table 1 Details of the components

Cork agglomerate		
Binder	Polyurethane	
Density	170–190 kg/m^3	
Granule size	0.5–1.0 mm	
Thickness	10 mm	
Aramid fabric		
Weave	1 × 1 plain weave	
Areal density	400 g/m^2	
Linear density	3360 dtex	
Threads	62 × 62 per 10 cm	
Carbon fabric		
Weave	2 × 2 twill weave	
Density	100 g/m^2	
Tensile strength	4000 MPa	
Modulus of elasticity	500 GPa	
Glass fabric		
Weave	2 × 2 twill weave	
Areal density	300 g/m^2	
Tensile strength	4600 MPa	
Modulus of elasticity	89 GPa	

FRF data set. The use of an impact hammer is a popular method of excitation [34]. An impact hammer is a specialized measuring tool that generates a limited period of excitation levels by impacting the structure at a specific spot. The excitation force is measured during the test because the hammer is equipped with a force sensor that produces a voltage signal corresponding to the excitation force. A hammer with various hardness impact tips was used to modify the measuring frequency range. A soft rubber tip may be used for low-frequency measurements, while a hard metal tip may be used for high-frequency readings. In this study, the face sheets and sandwich structure specimens were fixed to a bench clamp and vibrated with a hammer to propagate vibrations on the structures during the vibration testing. The

Table 1 (continued)

Aluminum 2024-T3 sheet		
Ultimate tensile strength	483 MPa	
Elongation at break	18%	
Modulus of elasticity	73.1 GPa	
Thickness	0.5 mm	

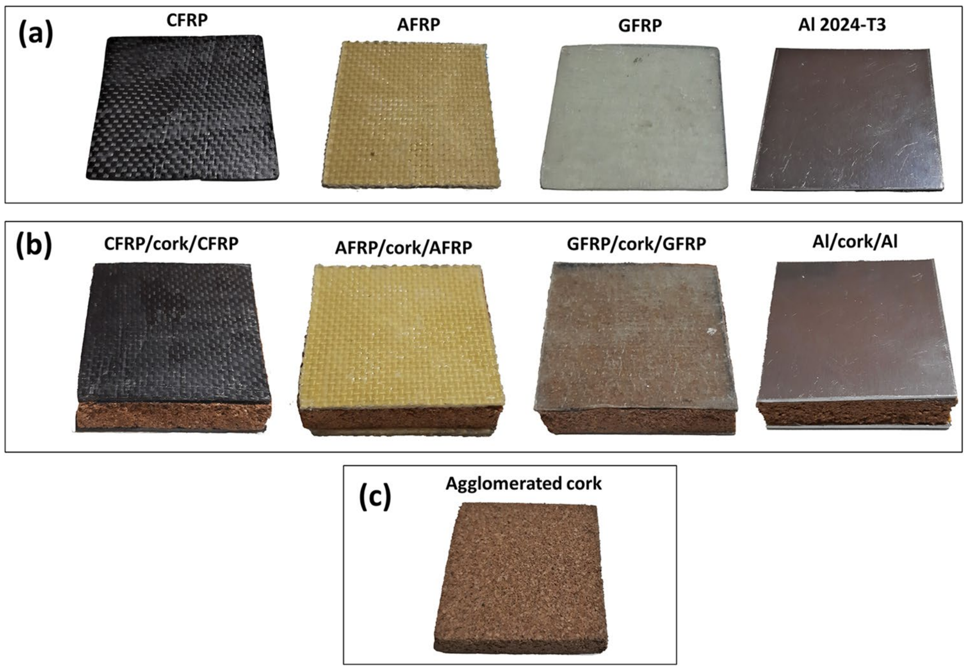


Fig. 1 **a** Face sheets, **b** sandwich structures, **c** core layer

structural damping ratio and modal stiffness of the specimens were measured using an accelerometer attached to the opposite face of the impact point. Figure 2 shows the details of the experimental vibration setup in the X-direction and Z-direction. This experimental setup included different support conditions (fixed at one end and fixed at both ends).

2.4 Deceleration tests

Sandwich structures investigated in this study are proposed for use in low-speed aerial vehicles, impact testing should be performed accordingly. Consequently, the deceleration values that show the amount of sudden speed reduction after the collision to any threat, in terms of g were considered. In the drop-tower system designed, the deceleration measurement sensor is embedded inside the impactor. It is known that the lowest value of g indicates the better resistance of the aerial vehicle structure to sudden collisions during flight. Another point for the impact test of an aerial structure is the bottom side of the test sample, which must be free to consider the same conditions as the aerial structure. For this purpose, a separate fixture was made to place the sample on it. The specimens were fixed on the fixture with double-sided adhesive and then deceleration tests were performed. The specimens were impacted by a 1 kg impactor from the heights of 0.1 m, 0.2 m, and 0.3 m. Figure 3 shows the experimental setup for the deceleration tests.

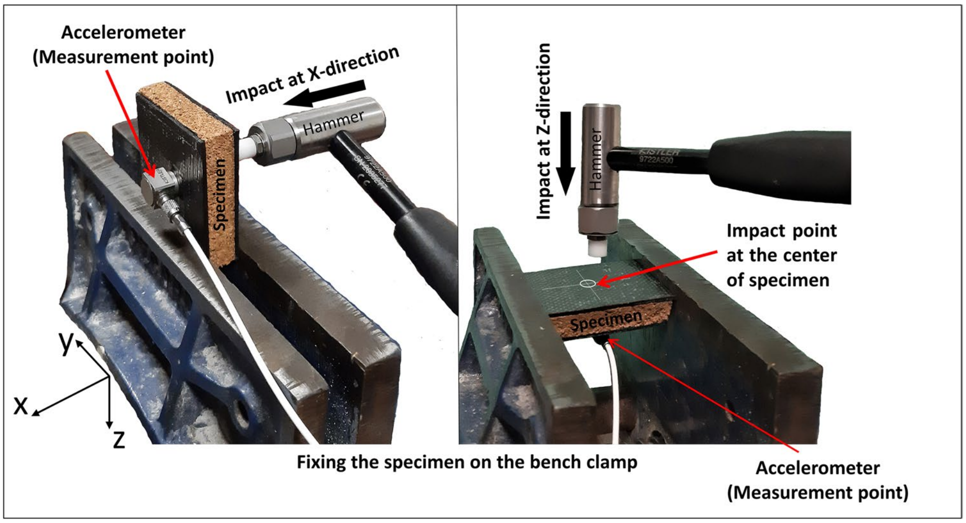


Fig. 2 Experimental setup in the vibration tests

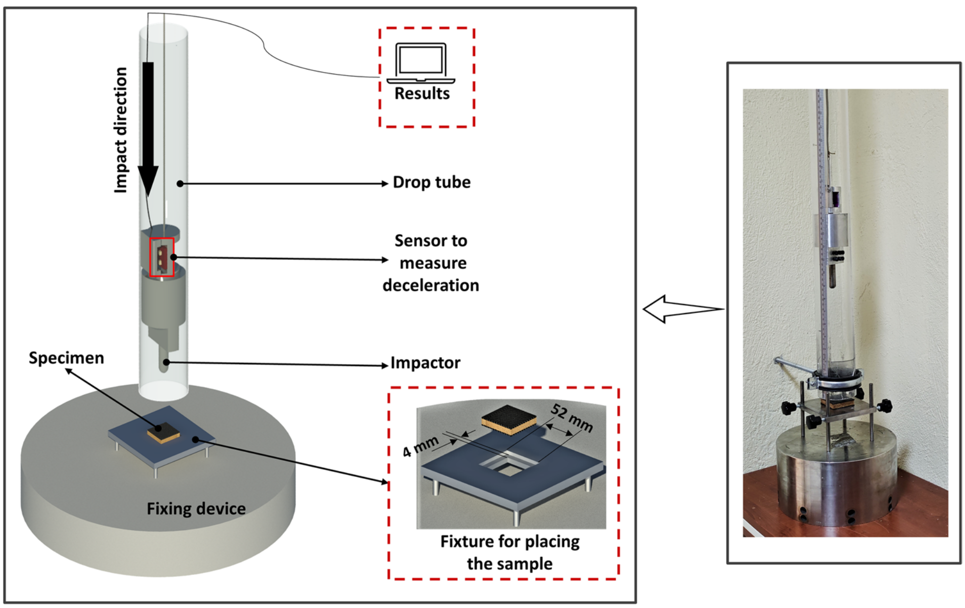


Fig. 3 Drop-tower system

3 Results and discussion

3.1 Vibration properties for face sheets and sandwich structures

Figures 4 and 5 show the FRF graphs for the face sheets and sandwich structures. The frequency spectra exhibit peaks at certain points that correspond to the natural frequencies for the structures. Face sheets show single-mode FRF plots in the X-direction. In contrast, Z-direction FRF graphs show multimodal structures. In this way, these materials can be modeled with a single degree of freedom in the X-direction and, a multi-degree of freedom in the Z-direction. Generally, the natural frequency ranges between 400 and 700 Hz. The X and Z-directions can be represented as single degrees of freedom in sandwich structures. Structures of this type are observed to have a natural frequency between 900 and 1200 Hz.

Based on the single degree of freedom models, damping ratios and stiffness coefficients of the materials were compared. The damping ratio and stiffness coefficient of the face-sheet composites are shown in Fig. 6. For the damping ratio, CFRP has a higher damping capability than the other composites in X and Z-directions. CFRP face sheet has a higher viscous damping ratio, whereas the Al face sheet has a lower one (nearly 0.04%) in the literature. The best result for the stiffness coefficient, which shows the structural resistance to deformation, is CFRP composite, followed by AFRP in the X and Z-directions. In these materials, the stiffness

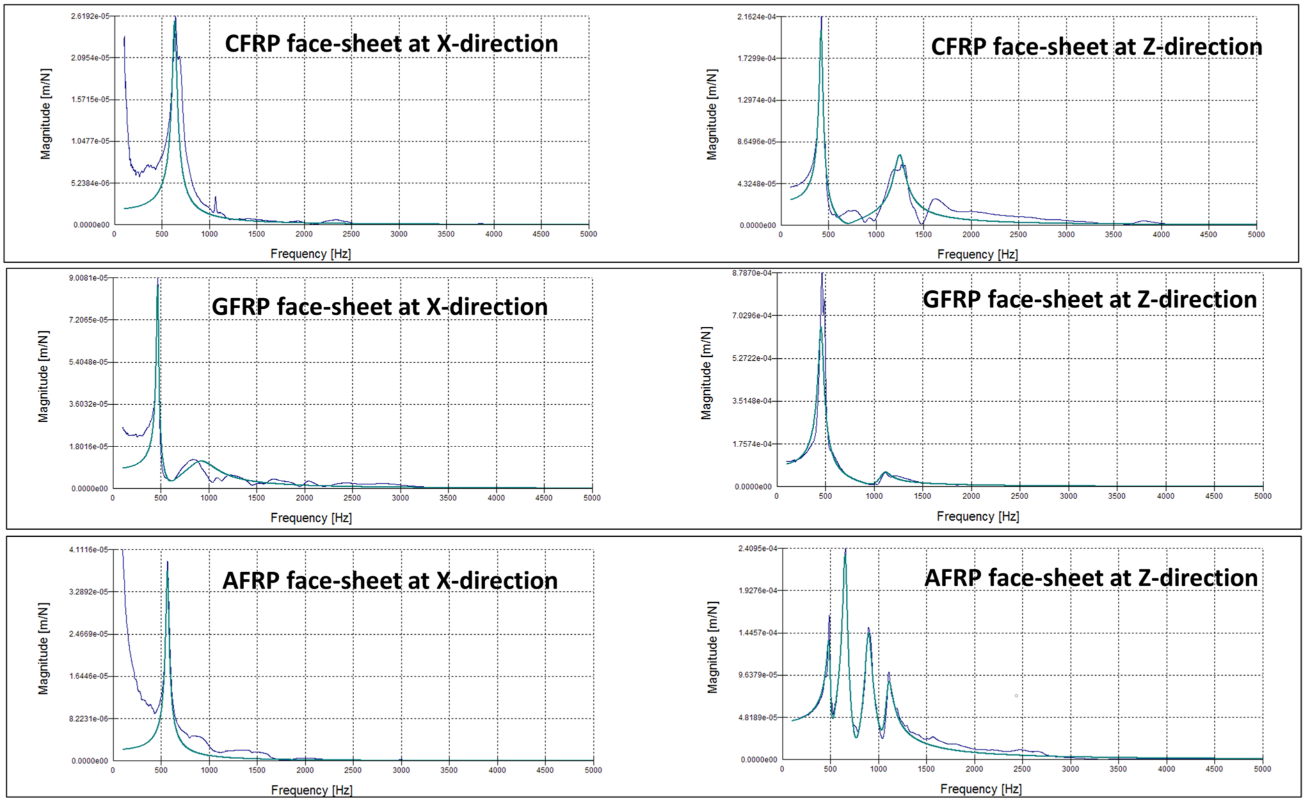


Fig. 4 The frequency response function graphs for CFRP, GFRP, AFRP face sheets in X (fixed at one end) and Z-directions (fixed at both ends)

coefficient can be interpreted by flexural rigidity. CFRP has the highest elastic modulus, whereas Al has the lowest value.

Figure 7 shows the damping ratio and stiffness coefficient for sandwich structures. CFRP shows the best results in both directions. For the sandwich structures, the damping ratio increases between 78 and 193% in the X-direction, while it increases between 35 and 210% in the Z-direction. In the same structures, the stiffness coefficient decreases between 61 and 66% in the X-direction, and between 50 and 65% in the Z-direction. The vibration conductivity of cork agglomerate is quite low. Cork agglomerate has a porous microstructure that consists of impermeable cellular grains isolated from one another. Due to its viscoelastic properties, cork agglomerates have been used as an effective damping material in various applications. Sandwich structures with cork agglomerates, therefore, have increased damping properties. Cork materials have the highest ductility among wood-based materials, and they have a lower elastic modulus. Hence, the flexural rigidity of the cork is low. As a result, the stiffness coefficient of sandwich structures with cork agglomerate remains at low values. The stiffness of a structure varies depending on the support conditions. In theory, the stiffness coefficient should be higher in the fixed both-end supports ($k = 3EI/L^3$) than in the fixed one-end support ($k = 192EI/L^3$). Both for the face sheets and sandwich structures, the stiffness coefficient increases in the fixed end support conditions.

3.2 Deceleration properties of face sheets and sandwich structures

An impact injury to a sandwich structure within or onto a quickly moving item that results from the forces applied when the object comes to a full stop or when the structure collides with an external object is known as a deceleration injury. In high-speed vehicles, deceleration injury typically occurs when a vehicle stops or slows down suddenly. In aerial structures such as drones, which have the possibility of hitting the objects around them, low deceleration values can protect the internal components. The length of the deformable structure must be of a particular stiffness to absorb all the kinetic energy, which is proportional to the square of the velocity [35]. The average mean force produced by this stiffness is multiplied by shortening the deformation to produce the absorbed energy. The overall deceleration level must be as low as possible for an acceptable injury level for the interior component of aerial vehicles, employing the greatest allowable deformation length of the proposed structure without deforming the main airframe. Figure 8 shows the deceleration results for the face sheets. According to the

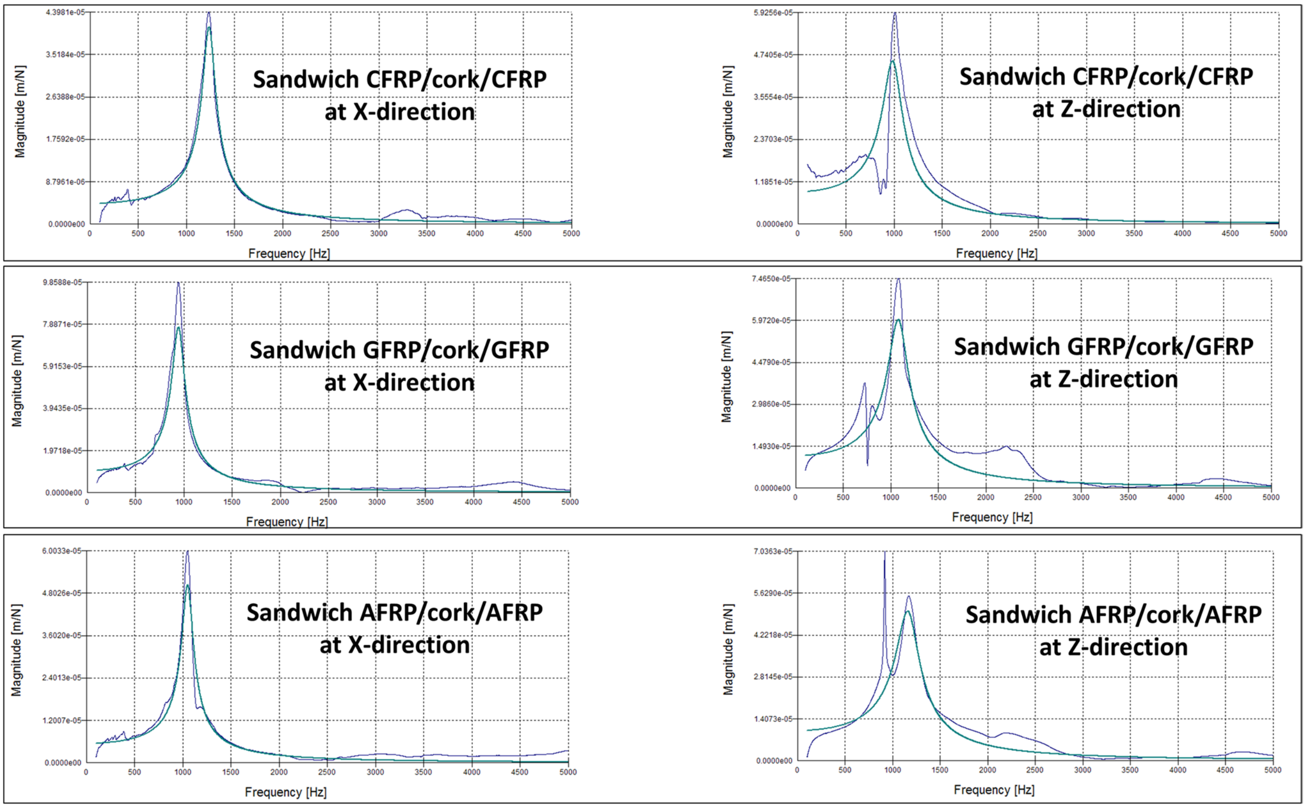


Fig. 5 The frequency response function graphs for CFRP/cork/CFRP, GFRP/cork/GFRP, AFRP/cork/AFRP sandwich structures in X (fixed at one end) and Z-directions (fixed at both ends)

results, the deceleration values for CFRP and GFRP face sheets are quite close to each other. For GFRP face sheets, 42.6*g*, 43.2*g*, and 46.1*g* are obtained while for CFRP face sheets, 40.9*g*, 44.2*g*, and 43.7*g* are observed for the heights of 0.1 m, 0.2 m, and 0.3 m, respectively. The deceleration results for AFRP face sheets are 40.6*g*, 52.0*g*, and 65.2*g* for the heights of 0.1 m, 0.2 m, and 0.3 m respectively. This shows that the deceleration values increase more than other samples with the increase of the impact height. Considering that the ultimate measurement limit of the deceleration measuring accelerometer used in this is limited and designed for low speeds, the impact force at all three heights is not enough to cause deformation on CFRP, GFRP, and AFRP. Accordingly, The biggest difference in this regard (deceleration results) is the rigidity of the material. Carbon fiber has a very high compressive resistance compared to aramid fabric and glass fiber. This leads to stronger resistance to these levels of impact forces. In Al face sheets, the deceleration values for the heights of 0.1 m, 0.2 m, and 0.3 m are obtained as 15.8*g*, 19.0*g*, and 25.9*g*, respectively, which gives the best results compared to the other composite face sheets. The softer structure of Al 2024 causes quick plastic deformation and absorbs more impact energy, but instead, the sample is damaged in the first impact and due to the large deformation, the sample can no longer be used. This quick deformation problem is not observed in AFRP, CFRP, and GFRP composite face sheets. Figure 9a shows the deformations on the face sheets.

Figure 10 shows the deceleration results for the designed sandwich structures. The cork core existing in the composite sandwich also plays an energetic role in absorbing the impact energy due to the cellular structure of the cork and the cavities between the cork granules. From the experimental results, due to the same density of the cork layer used in the core of all sandwich structures, the results completely depend on the face sheets. The deceleration values in CFRP/cork/CFRP are 26.0*g*, 71.9g, and 93.4g for the heights of 0.1 m, 0.2 m, and 0.3 m, respectively, while GFRP/cork/GFRP shows 69.1*g*, 105.8*g*, and 133.7*g* for the same heights, respectively. Since the deceleration results of CFRP and GFRP in face sheets are almost the same, these results indicate that when CFRP with a cork core layer forms a sandwich structure, it performs better than GFRP due to the high rigidity and compressibility of CFRP fibers. Al/cork/Al presents the deceleration values of 22.8*g*, 74.6*g*, and 97.4*g* for the heights of 0.1 m, 0.2 m, and 0.3 m, respectively. The values obtained for AFRP/Cork/AFRP for the heights of 0.1 m, 0.2 m, and 0.3 m are 76.6*g*, 106.5*g*, and

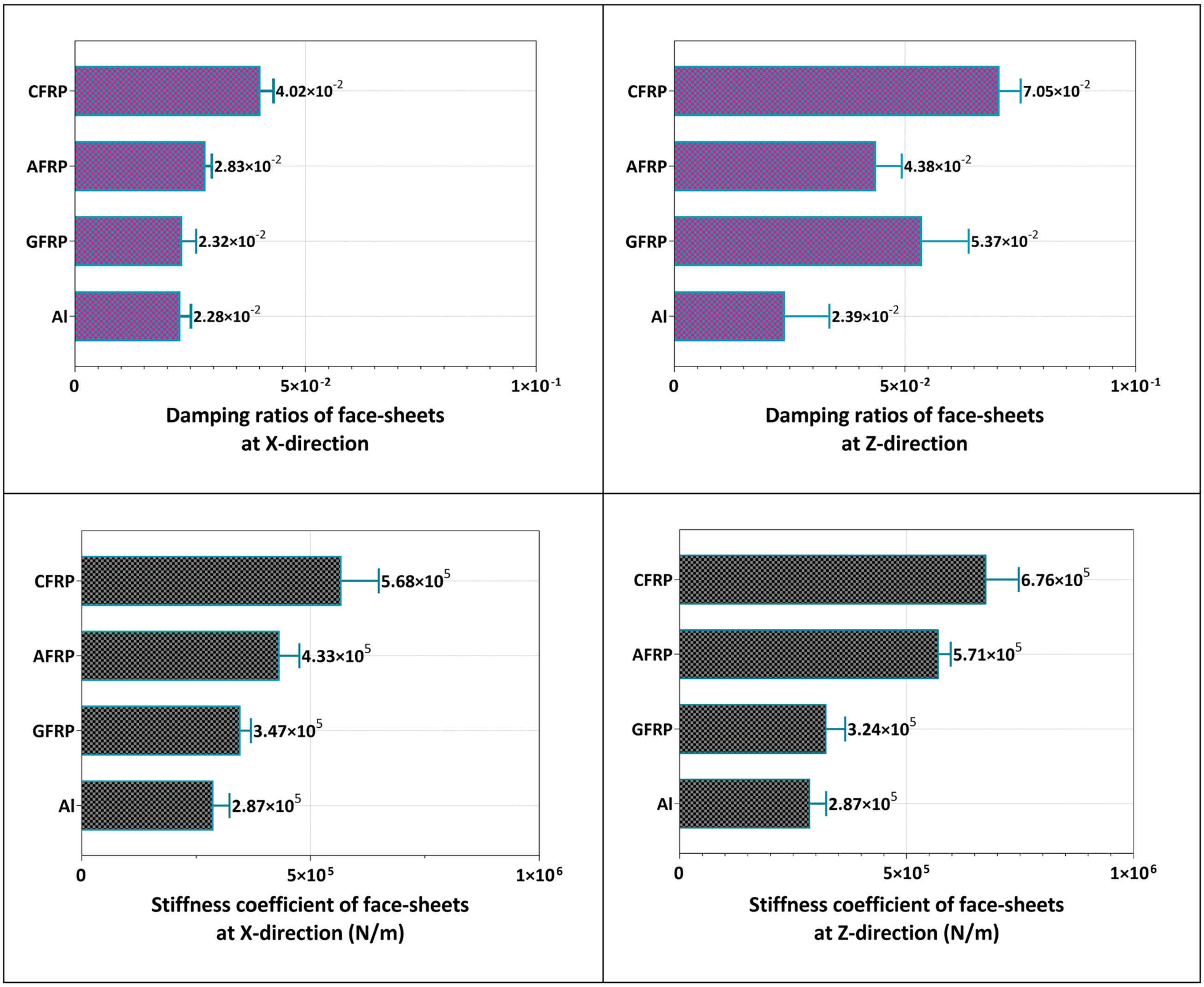


Fig. 6 Damping ratios and stiffness coefficient of face sheets at different directions

125.1g, respectively. The results of AFRP/cork/AFRP show a weaker performance compared to the other structures. One of the main characteristics of aramid fiber is the alignment of molecules along its fiber axis, which can better show its anti-impact properties in high-speed impact than low-energy impact force. Similar to Al face sheets, the deceleration values are lower in Al/cork/Al compared to the other samples. This is due to the softer structure of aluminum, and plastic deformation capability. Al face sheets show severe plastic deformation even under weak impacts. The other samples in the sandwich structures do not have any plastic deformation about the energy of the impacts. Figure 9b shows the deformation of sandwich structures after the deceleration tests.

Figure 11 shows the deceleration vs. time curves of GFRP/cork/GFRP (maximum deceleration) and CFRP/cork/CFRP (minimum deceleration) sandwich structures for 0.30 m drop heights. We can discuss about the role of face sheets by this way. The deceleration rate (curve slope) is somewhat reduced when the CFRP is used as the face sheet, and the peak base is extended over a larger time period. Moreover, it is clear that there is a reduction of 30% in the peak value by replacing the GFRP face sheets with the CFRP ones. It is possible to state that CFRP has better impact absorbing capabilities under low-energy drops. This can be associated with the deformation mechanism of face sheets that is obvious in the deceleration curves. During the impact process, CFRP face sheets provide a better energy distribution on the structure and thereby slowing down the deceleration of the impacting object while extending the impact process over a larger time period. This is because far-fields on the structure contribute to the energy absorbing mechanism and the impact energy is suppressed over a wider area instead of accumulating on the impact point. Consequently, the impacting object is stopped by a smoother

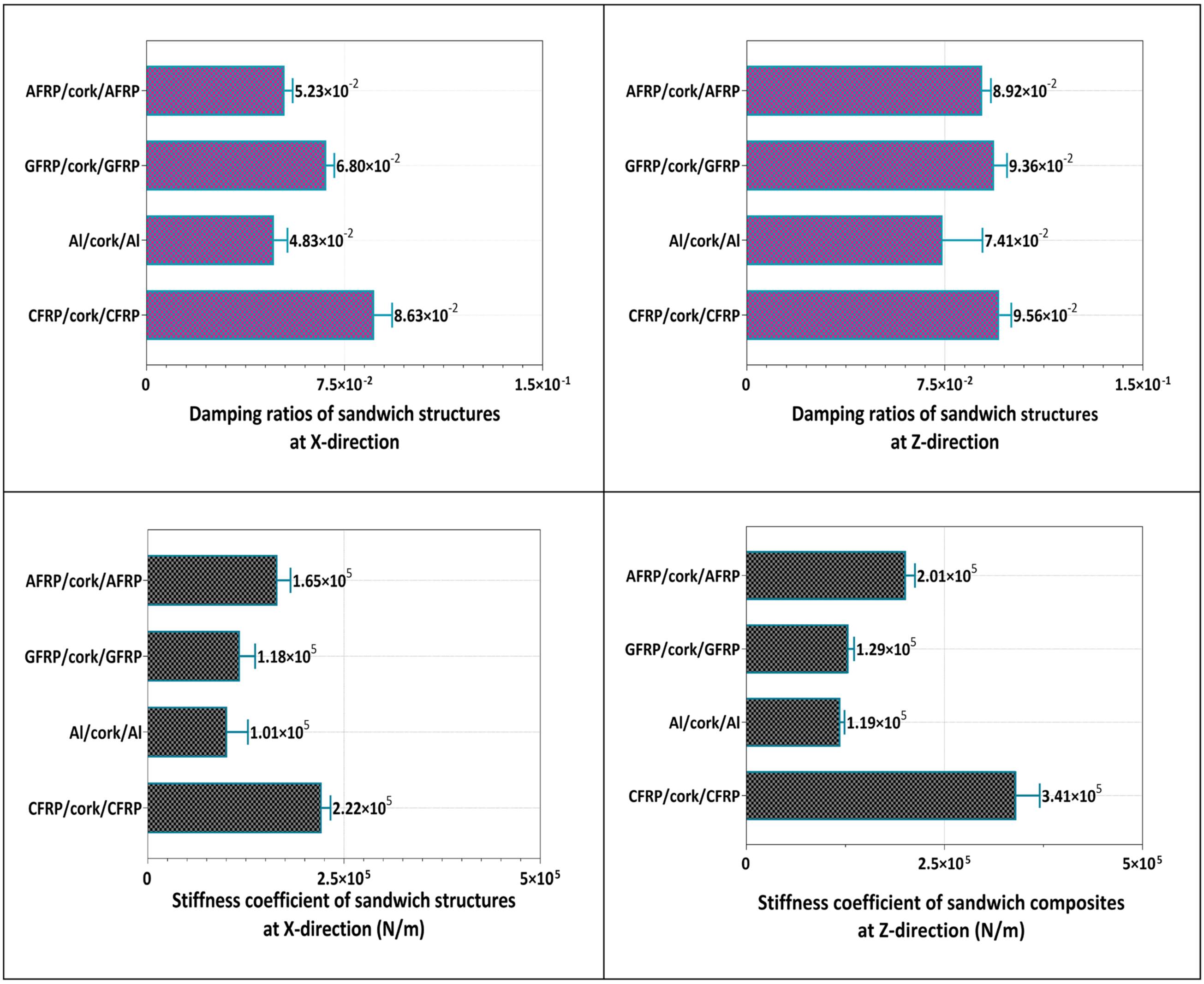
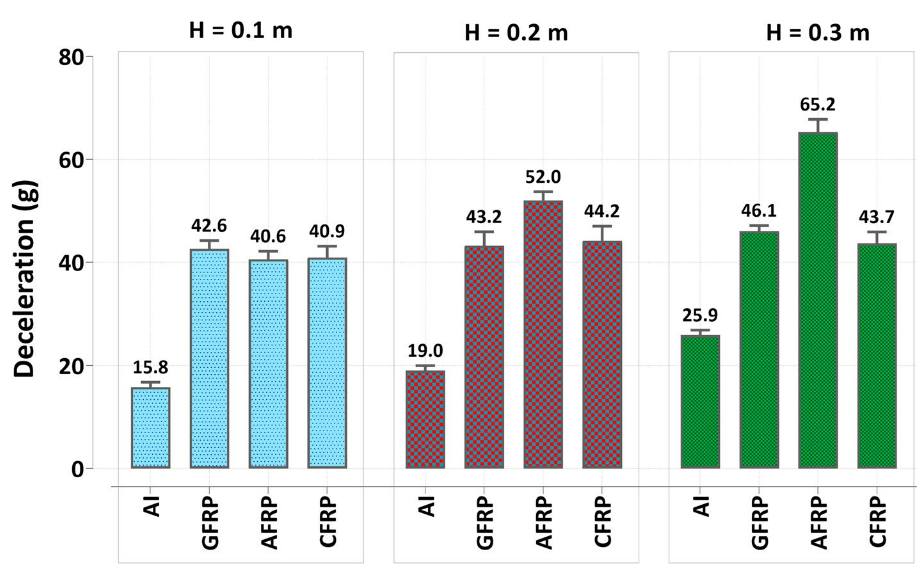


Fig. 7 Damping ratios and stiffness coefficient of sandwich structures at different directions

Fig. 8 Deceleration results of face sheets



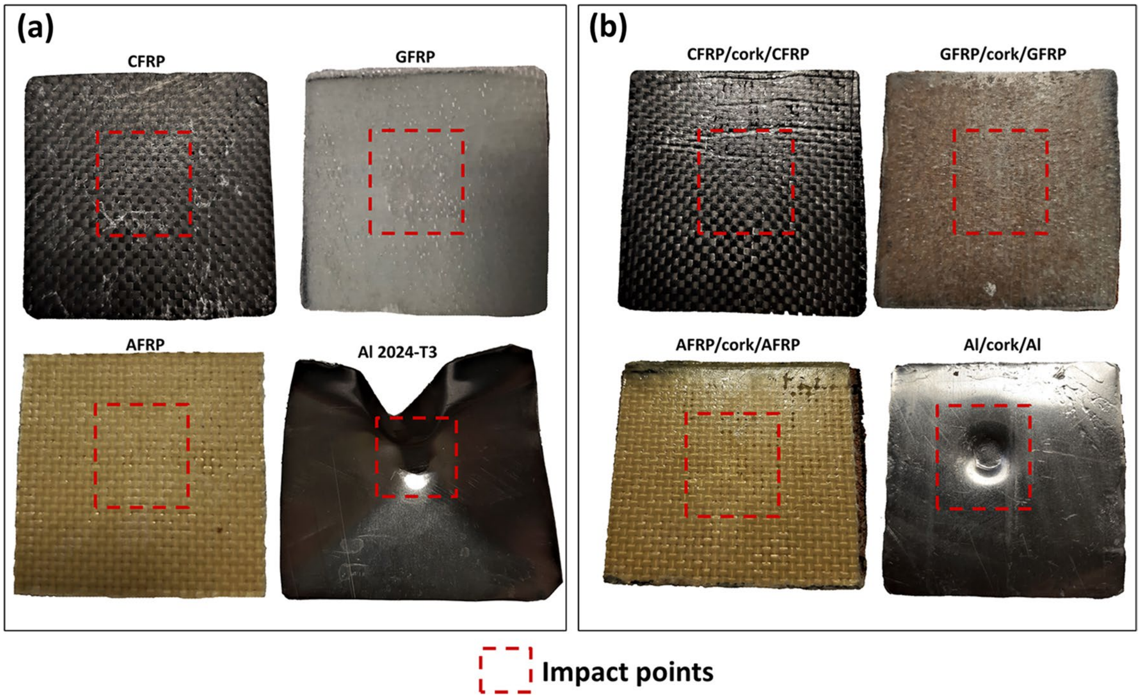


Fig. 9 Deformation of **a** face sheets and **b** sandwich structures after deceleration test from 0.30 m

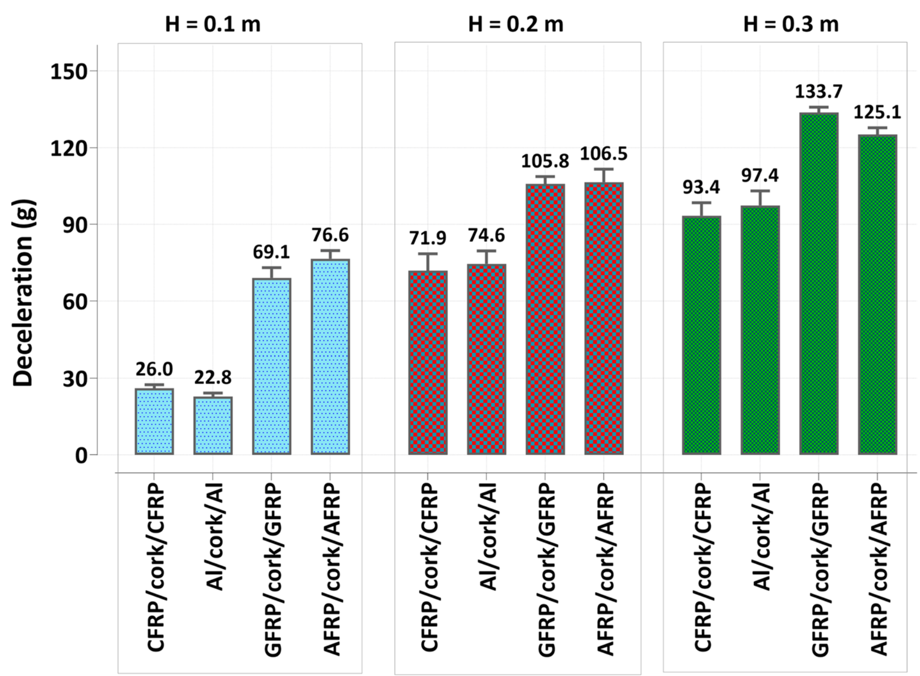


Fig. 10 Deceleration results for sandwich structures

slowdown while generating a lower level of peak deceleration on the object.

4 Conclusions

Sandwich structures with thin high-performance face sheets separated by thick low-density core outperform monolithic structures of comparable weight in bending

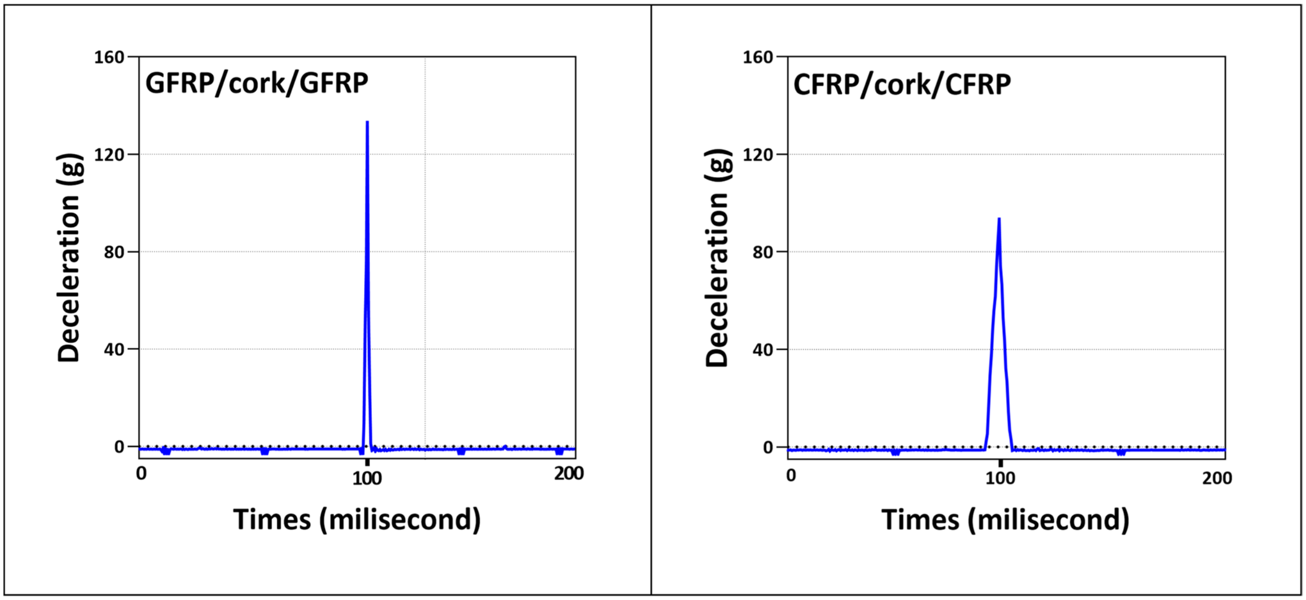


Fig. 11 Deceleration vs time curves of GFRP/cork/GFRP and CFRP/cork/CFRP sandwich structures for a drop height of 0.3 m

stiffness and strength. This work investigates a new class of impact resistance and vibration-damping sandwich structures suitable for low-speed aerial applications with different face sheets of CFRP, GFRP, and AFRP, aluminum and a fixed core layer of cork agglomerates. The main motivation of the study is to improve the anti-impact and vibration-damping properties of the sandwich structures and to increase their environmentally friendly capabilities by using cork cores. Deceleration measurements for the samples were carried out in a drop-tower system where the g-sensor was embedded inside the impactor. The damping properties and stiffness of the sandwich structures were investigated using the modal analysis method. First, the studies were conducted for the face sheets, which were subjected to the experimental work in the individual form. Next, the sandwich structures were assembled with a core material of cork agglomerates and various face sheets. Regarding the main highlights of this study's analyses, the main findings could be ranked as follows:

- In the vibration analysis, CFRP-based face sheet exhibits the highest damping and stiffness properties. Hence, the sandwich structures with CFRP face sheets and cork core can be a better option for aerial structures.
- In the deceleration analysis of the samples, although the results of CFRP and GFRP are quite close to each other, sandwich structures with CFRP face sheets leave behind those with GFRP face sheets.
- Although Al/cork/Al structure has lower deceleration results than the other samples, the deformable structure of aluminum face sheets leads to quick failure and permanent deformation.
- Sandwich structures with cork cores and CFRP face sheets are the optimum candidates for the anti-impact and anti-vibration applications in aerial vehicles.

When considering these evaluations of eco-friendly sandwich structures based on cork agglomerates, these findings are promising for considering new designs that have to approach environmental standards while maintaining or even improving efficiency.

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Data availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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