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Modal Analysis of Specific Composite Sandwich Structures

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HIGHLIGHTS

- Honeycomb composite core was manufactured using the corrugated method.
- A new vibration test rig design was proposed.
- Forced vibration tests were performed on the manufactured specimens.
- All-carbon fiber showed the highest frequency response among all specimens.
- Honeycomb cores have higher damping compared with foam cores.

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ABSTRACT

Composite sandwich structures are gaining attention due to their inherent properties, such as lightweight, low density, and high strength. The forced vibration response of these structures was studied experimentally to investigate the effects of external loads on these structures. In this work, four composite sandwich structures were manufactured using carbon fiber, glass fibers, and foam and tested on a specially designed vibration test rig by hitting the specimen with an impact hammer. The response was recorded by an accelerometer attached to the specimens. The accelerometer signal was amplified, and the input and output signals were transferred to LABVIEW via a data acquisition card and were processed in MATLAB. The impact hammer acts as an external excitation source, and the frequency response function was found for each specimen under various edge boundary conditions. Bode plots were plotted for each test, and the peak frequency and the phase difference were compared. It was found that composite sandwich specimens made of carbon fiber skins and carbon fiber honeycomb core showed a higher frequency response among all specimens (400 Hz). Furthermore, it was found that the foam core layer reduces the phase difference between the input and output signals from (360 degrees) to (180 degrees) compared with other honeycomb cores. Therefore, the procedure outlined in this research can be applied to other structures to investigate their vibration response. In addition, this work could be beneficial for the diagnosis of structure stability using a forced vibration response procedure.

1. Introduction

Sandwich structures are kinds of structures that were developed to enhance the lightweight properties of structures [1]. These structures are widely used in industry for their lightweight with low density, especially in aerospace applications. Sandwich structures are comprised of top and bottom skins separated by a core layer. Originally, metals were used in manufacturing sandwich structures such as the top and bottom skins. However, the demand for lightweight structures with advanced materials made the researchers seek alternatives for producing sandwich structures [2]. Accordingly, the researchers employed composite materials in manufacturing sandwich structures and, thus, they changed to composite sandwich structures.

The composite materials used in manufacturing composite sandwich structures were continuous, chopped, or other materials. Continuous fibers were available in the form of unidirectional fibers or woven fabrics. The latter comprised continuous fibers stacked in two perpendicular directions to form a woven fabric. Chopped fibers were made from the original continuous fibers by cutting the fibers into very small-length fibers. Chopped fibers can be used to manufacture sandwich skins and cores by adding them to 3D printers and mixing them with resin or polymers [3]. Additionally, other materials could be used in manufacturing composite sandwich structures, such as jute fabrics [4].

Composite sandwich structures can be made from any combination of composite materials in the sandwich configuration. Honeycomb composite sandwich panels were manufactured using the corrugated method [5] and were tested experimentally. In addition, additive manufacturing was implemented in manufacturing composite sandwich structures [6].

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The vibration response of sandwich structures was studied in the literature to find the natural frequencies of vibration and their mode shapes [7–9]. Sandwich vibrations were studied analytically by deriving a set of equations of motion based on plate theory and solving it to yield the natural frequencies of vibration [10,11]. Layer-wise method [12], shear deformation theory [13], and other modified plate theories [14] were presented by researchers to derive and solve the equations of motion for sandwich plates. However, it was found that the forced vibrations of composite sandwich structures need to be investigated because little information was available in the literature regarding this important field of study [15].

Classical plate theory was the simple and basic method used to analyze sandwich structures [16, 17]. However, this theory proved inadequate for the sandwich structure analyses. It ignored the transverse shear effects and thickness effects [18]. First-order shear deformation theory and modified methods were proposed by some researchers to include transverse shear stresses in the dynamic analysis of sandwich panels [19, 20]. An assessment of the available computational models of multilayer plates made of the anisotropic laminate was presented [21].

In this work, composite sandwich panels were manufactured from carbon fibers, glass fibers, and foam in various configurations. Four composite sandwich specimens were manufactured using the hand lamination method for the skins and the corrugated method for the honeycomb core. These manufactured specimens were tested on a specially designed vibration test rig. The vibration rig components were demonstrated, and the testing method was explained in detail. Experimentally, the forced vibration action was performed using an impulse force supplied by hitting the composite sandwich specimens with the impact hammer. The response of each specimen to the impact hammer load was recorded and analyzed. Frequency response functions were derived and plotted using Bode plots. Amplitude and phase plots were presented for each case, and the plots were discussed. Several sandwich plate boundary conditions were presented, and the results were compared. The importance of the current work arises from manufacturing a honeycomb sandwich panel from composite materials. The other value of this work was the experimental investigation of the response of sandwich structures to externally applied loads which is particularly important for the aerospace industry.

2. Experimental Part

2.1 Composite Sandwich Manufacturing

Three materials were used in this research for manufacturing composite sandwich panels: glass fiber, carbon fiber, and foam. All the manufactured specimens comprise composite skins and foam or composite core. Table 1 lists the sandwich specimens used in the current analysis for vibration testing.

Table 1: Sandwich specimen configurations for the current analysis

Specimen	Core material	Skin material	Core height	Cell size	Sandwich dimensions	Notes
1	Carbon fiber	Carbon fiber	1cm	1cm	25cm×25cm	Honeycomb core
2	Glass fiber	Glass fiber	1cm	1cm	25cm×25cm	Honeycomb core
3	Foam	Carbon fiber	3cm	-	25cm×25cm	
4	Foam	Glass fiber	3cm	-	25cm×25cm	

Both glass and carbon fibers were in the form of a woven mat in which the fibers were arranged in two perpendicular directions. For all specimens, glass and carbon woven fabrics with 3k (3000) fiber volume were purchased from local suppliers. The woven fabrics were supplied in rolling mats with (1m) roller width and were cut to the required length. The resin used in this analysis was (EL2 EPOXY LAMINATING RESIN), purchased from Easy Composites Ltd. This resin was mixed with hardener and then applied to glass and carbon fibers during hand lamination, and the final part was left to cure for (24) hours at room temperature. The mixing ratio of the epoxy with the hardener was in the order of 100:30.

Extruded Polystyrene, or simply XPS foam, was utilized in this research as a core layer of the sandwich specimens (3 and 4). This foam was supplied in plain sheets from local suppliers and at a relatively low cost. The thickness of the foam layer was (3 cm), representing the sandwich core height in this analysis.

For the sandwich upper and lower skins, the fiber hand lamination method was used to fabricate the skins. Sandwich skins were manufactured separately using the laminating method and were joined with the core layer after curing. Both glass and carbon fibers were cut to the desired dimensions and were laid on a flat surface. This flat surface was chosen as a glass sheet to provide a very fine surface finish with minimum defects to the sandwich skins. After laying the first fiber layer, a layer of epoxy resin (mixed with hardener) was added to the fiber layer and spread over the fiber with a brush. The next fiber layer was added to the first layer, and the resin was spread again. This process continued until all fiber layers were laid on each other with the resin. To remove excess resin and bubbles in the resin, another glass sheet was laid on top of the laminated fibers, and the excess resin was allowed to escape from the sides. To prevent resin on the glass sheet from sticking after curing, the glass sheet was coated with wax to facilitate the laminate removal. Finally, the skins were left to cure at room temperature for (24) hours before being extracted from the glass sheet.

For the composite honeycomb core, composite sandwich cores were manufactured from glass and carbon fiber laminates using the corrugated method [22]. To achieve the honeycomb structure for the core, a special mold was modeled in SOLIDWORKS and then manufactured using a 3D printer, as shown in Figure 1a. Figure 1b shows a 3D printed upper and lower halves of the corrugated mold for manufacturing honeycomb sandwich panels.

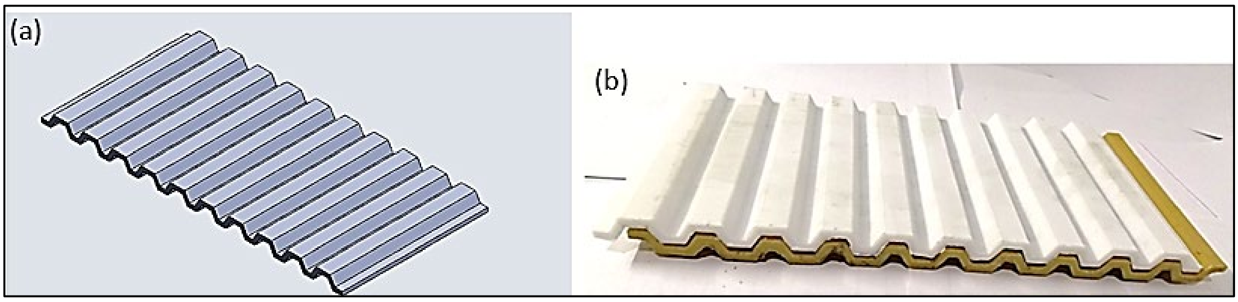

Figure 1: (a) Half-honeycomb mold 3D model using SOLIDWORKS, (b)3D printed corrugated mold

Honeycomb manufacturing started by cutting the woven fibers to the required size and then laying them on the mold. The resin with hardener was mixed and added to the fibers with a brush layer by layer until the required thickness was met. Each laminate is comprised of three layers of woven fibers with epoxy resin. The other half of the honeycomb mold was inserted into the mold and pressed firmly against the lower mold to force the fibers to take the honeycomb shape. This honeycomb shape was maintained during curing by securing the upper half to the lower mold throughout the process. The excess resin was allowed to escape through the mold sides, leaving a half honeycomb laminate free of bubbles and laminating defects.

The half-laminated honeycomb core shown in Figure 2 was then taken from the mold and cut to the required thickness of the sandwich core. After cutting, the honeycomb strips were joined together with resin on a flat table to form the final shape of the honeycomb core. The top and bottom surfaces of the honeycomb core were then ground and polished to get a smooth surface and to enhance the contact surface between the core and the skins. Finally, the manufactured composite core was assembled with the top and bottom skins using the same laminating resin and was pressed firmly until full resin curing.

Figure 2: Half laminated honeycomb core before being cut

Figure 3a shows a sample glass fiber honeycomb core laid on the bottom skin before adding the top skin layer. The manufactured sandwich specimens are shown in Figure 3b.

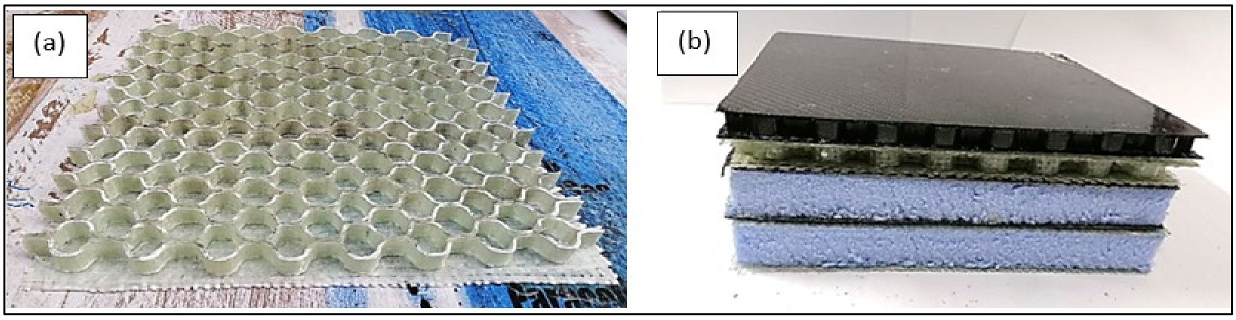

Figure 3: (a) Sample glass fiber honeycomb core before joining the top skin (b) Final sandwich specimens

The procedure mentioned above is applied to all sandwich specimens with honeycomb core. However, for the sandwich specimens with a foam core, the sandwich specimens were manufactured in one step. First, the same hand lamination method was used to manufacture the sandwich's lower skin. Then, the foam core was laid over the lower skin laminate before curing, and, finally, the top skin was laminated on top of the core layer. The whole process was performed before resin curing, and the final sandwich panel was left to dry for (24) hours to yield the final part.

2.2 Experimental Setup

The manufactured sandwich specimens were mounted on a testing frame and were used in the current analysis for vibration tests, as illustrated in Figure 4.

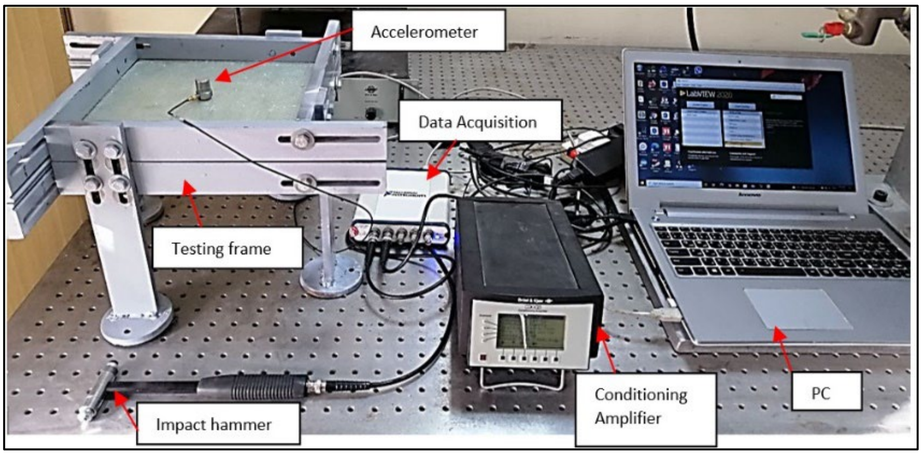

Figure 4: Experimental setup

The main items of the experimental setup are shown in Table 2.

Table 2: List of experimental setup parts

Item No.	Name	Description
1	Mounting Frame	Universal sandwich mounting frame manufactured in Iraq
2	Impact Hammer	Manufactured by PCB PIEZOTRONIC Inc.
3	Accelerometer	ICP (Integrated Circuit Piezoelectric) by PCB PIEZOTRONIC Inc.
4	Data Acquisition	NI DAQ 4431 by National Instruments
5	Conditioning Amplifier	By Bruel & Kjaer Inc.
6	PC	Personal Computer
7	Connecting Cables	BNC cables and USB cables

In this research, a novel universal sandwich mounting frame was manufactured for testing composite sandwich panels. The frame comprises twelve pieces in which. Every four pieces have an identical shape. The main idea behind the frame design was to manufacture universal sandwich support for mounting various sandwich configurations on the same frame. In addition, the manufactured frame can handle various sandwich sizes according to its slots limit. The manufactured frame offered various combinations of sandwich edge boundary conditions. Simply supported (SSSS) , fixed (Cantilever), one free edge (SSSF), and two opposite free edges (SSFF) boundary conditions can be easily attained using this frame. Figure 5a shows a composite sandwich specimen made of carbon fiber and mounted on the frame under (SSSF) boundary condition. Figures 5b and 5c illustrate the same sandwich specimen mounted on the frame for the (SSFF) and cantilever boundary conditions, respectively.

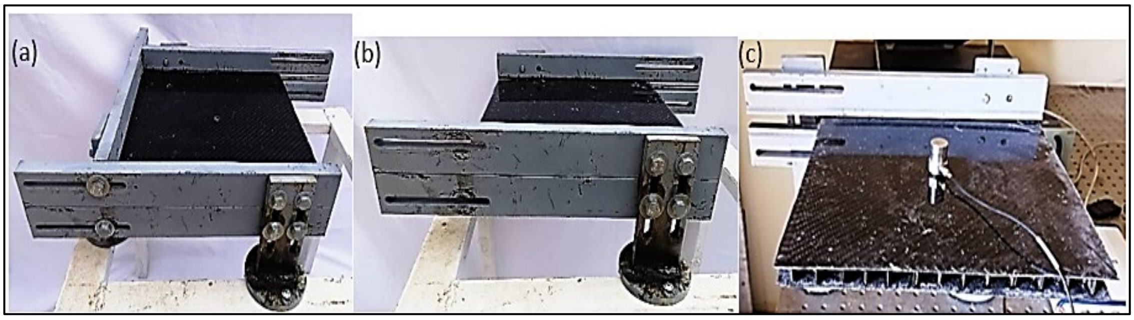

Figure 5: Carbon fiber sandwich specimen under various boundary conditions: (a) Three edges simply supported and one edge free, (b) Two opposite edges simply supported and the remaining edges free and (c) Cantilever

Triangular grooves Figure 6 can be used to get the simply supported edge condition and the gap between the upper and lower parts for fixed boundary conditions.

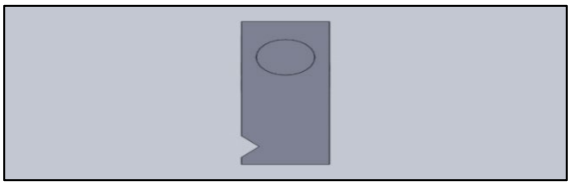

Figure 6: Groove detail for fixing sandwich edges

The sandwich specimens were hit by the hammer at specific points shown in Figure 7a on the upper skin, and the response was recorded by the accelerometer. Impacting the sandwich specimen with the hammer results in an input pulse which is an exciting force for the system. Therefore, the main purpose of the impact hammer was to excite the sandwich specimens with an impulse force to excite the structure's natural frequencies. However, when impacting the specimen with the hammer, care should be taken as it might lead to false or highly distorted impulse signals. Therefore, it is recommended that the structure be hit several times in different locations to get the exact response to the exciting force. The impulse signal was transmitted via a data acquisition and recorded on a computer using LABVIEW.

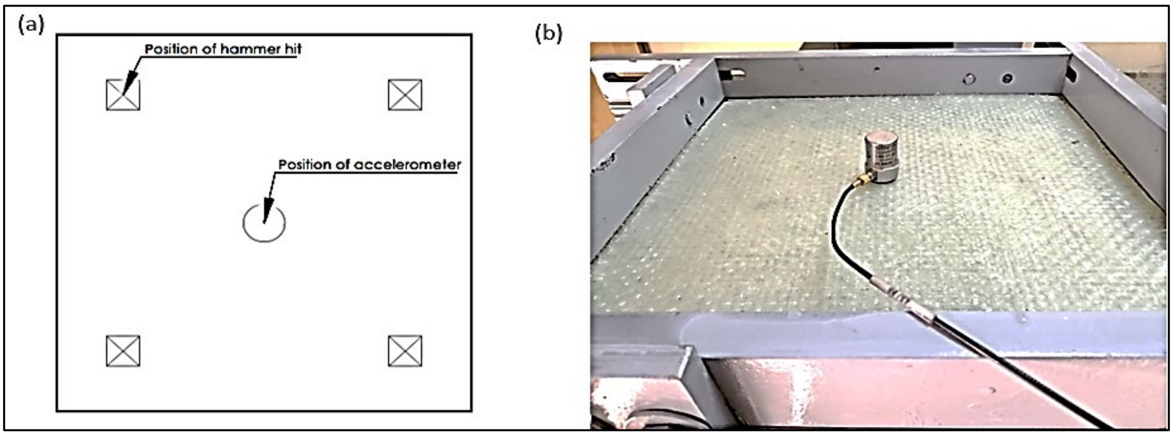

Figure 7: (a) Position of hammer hit and accelerometer, (b) ICP accelerometer mounting

An ICP (Integrated Circuit Piezoelectric) accelerometer was used to measure the vibration response of the sandwich specimens to the input excitation from the hammer. The accelerometer was mounted using the screw on the top surface of the sandwich specimens. The accelerometer was located at the center of the sandwich's upper skin to capture the structure's response to the hammer's exciting force. The accelerometer sensitivity was (98 mV/g) with a frequency range of (0.8-20000 Hz) and was mounted on the sandwich specimen as shown in figure 7b. ICP accelerometers need signal conditioner equipment to amplify the accelerometer output signal to be recorded by LABVIEW. Therefore, a conditioning amplifier was used in this research and was connected between the accelerometer output and the data acquisition input.

In this research, (NI DAQ 4431) data acquisition card with BNC input jacks was used to transfer both the hammer and amplified accelerometer signal to the computer. The output signals were transferred to the computer via a USB port and were saved in an XLSX file format. The number of samples to be read was set to be (1000) at a rate of (5000 Hz).

2.3 Frequency Response Function

The frequency response function (FRF) analysis was performed in this research to estimate the transfer function of the test specimens under applied load. The frequency response function can be found by dividing the output signal (ICP accelerometer) by the input signal (Impact hammer). FRF analysis was performed in MATLAB, and the results were reported. Both the input signal (from the impact hammer) and the output signal (from the ICP accelerometer) were imported as column vectors to MATLAB. Figure 8a shows a sample input-output plot for a specific signal recorded by performing vibration tests with an impact hammer. After importing the input and output signals, the Transfer Function Models tool was used to obtain the transfer function of the two signals. The number of poles and zeros was set for every signal to fit the output signal. For example, the signal in Figure 8a was set several poles of (5) and the number of zeros to be (5) to yield a fitting curve percentage of (90%), as shown in Figure 8b.

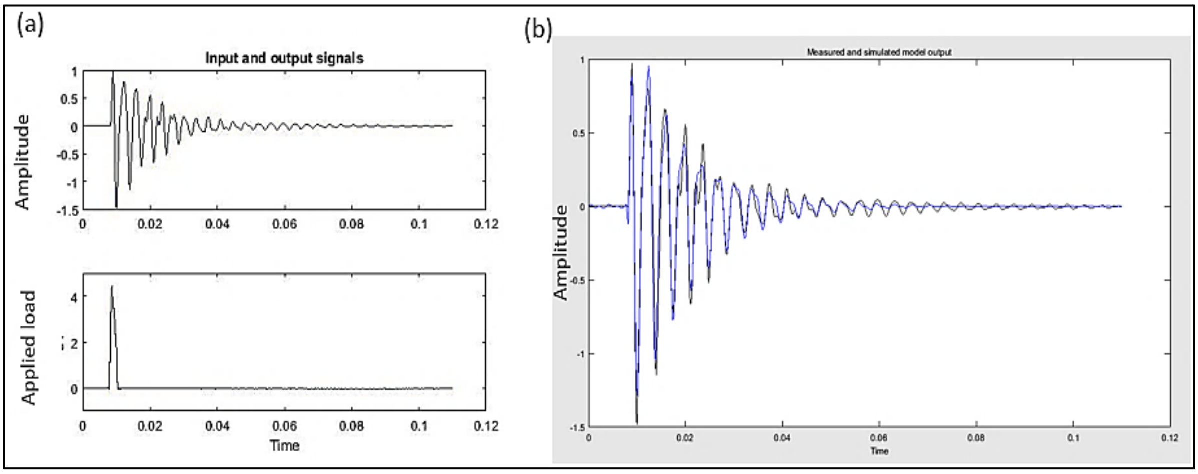

Figure 8: (a) Sample input and output signals, (b) corresponding input signal after setting its poles and zeros

The system's transfer function can then be observed from the signal toolbar in which the numerator and the denominator depend on the number of poles and zeros. For example, the transfer function (TF) of the signal shown in Figure 8b is:

$$TF = \frac{-0.07326S^5+355.5S^4+3.399*10^5S^3+3.909*10^9S^2-4.895*10^{11}S+1.073*10^{14}}{S^5+1260S^4+1.47*10^7S^3+1.581*10^{10}S^2+3.605*10^{13}S+3.124*10^{16}}$$

The signal's frequency response was represented by the BODE plot, which comprises the signal's magnitude and phase. It is worth noting that BODE plots have two parts; magnitude and phase. The magnitude part of the plot represents the intensity of the system's response to the applied excitation, while the phase part represents the phase shift of the system compared with the input force.

3. Results and Discussions

This section presents the results of the vibration tests performed on the manufactured composite sandwich specimens. Several combinations of boundary conditions were assigned, and the bode plots were constructed for each test.

3.1 All Simply Supported (SSSS) Boundary Condition

In this case, the composite sandwich specimens were tested using the experimental setup. All four edges of the sandwich panel were simply supported, and the panel was hit with an impact hammer at one point (near the corners). The sandwich panel dimensions were (25 cm×25 cm) with a honeycomb core of height (1cm). Figures 9a, 9b, 9c, and 9d demonstrate the bode plots for specimens 1, 2, 3, and 4, respectively, with SSSS boundary conditions. It can be shown from the Bode plots that each rise in the magnitude plot (peak frequency) corresponds to a specific phase difference in the phase plot. This phase difference shows how the sandwich structure responds to the input excitation before and after reaching this peak frequency. In this case, the highest the value of the phase difference between the input and the output signals, the highest the damping ratio of the structure. For instance, for specimen 1, the peak frequency appears at (400 Hz) with an associated phase difference of (540 degrees). This value was compared with specimen 2, which showed a peak frequency of (150 Hz) with a phase difference of (540 degrees). This means that both specimens have the same damping with different peak frequencies.

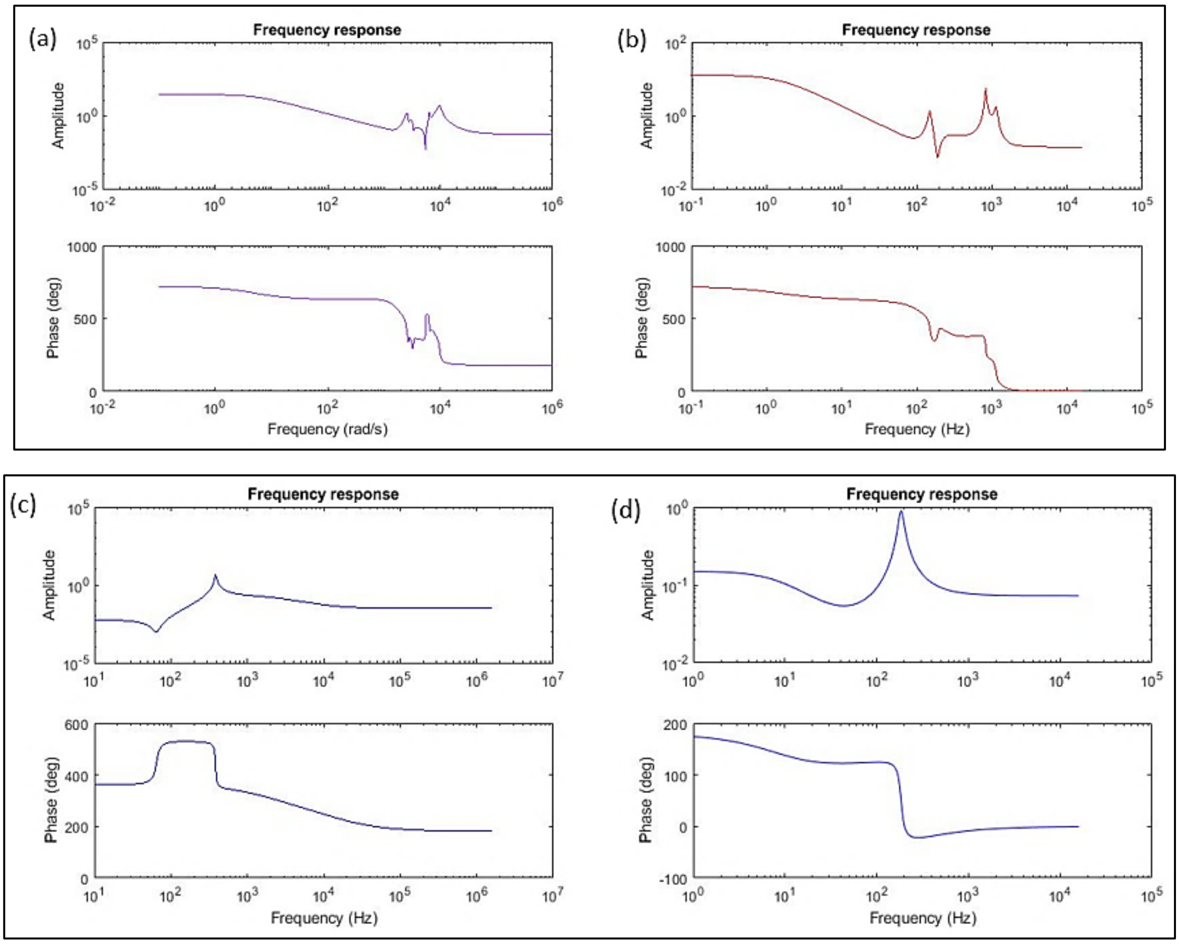

Figure 9: Bode plot for the SSSS case for (a) specimen 1, (b) specimen 2, (c) specimen 3, (d) specimen 4

3.2 SSSF Boundary Condition

The same sandwich specimens were mounted on the vibration test rig in this case. However, three edges of the composite sandwich panel were simply supported while one edge was free. Figures 10a, 10b, and 10c illustrate the magnitude and phase parts of the bode plot for the response of specimens1, 3, and 4, respectively, for the case of SSSF. Again, peak frequencies and phase shifts were recorded and compared. The highest peak frequency was recorded for specimen 1 at (350 Hz) while the largest phase difference between the input and output signals was reported for specimens 1 and 2 at (360 degrees). This illustrates that the honeycomb core composite sandwich structures showed higher damping than foam core sandwich panels. In addition, the highest peak frequency indicates the highest value of the natural vibration frequency.

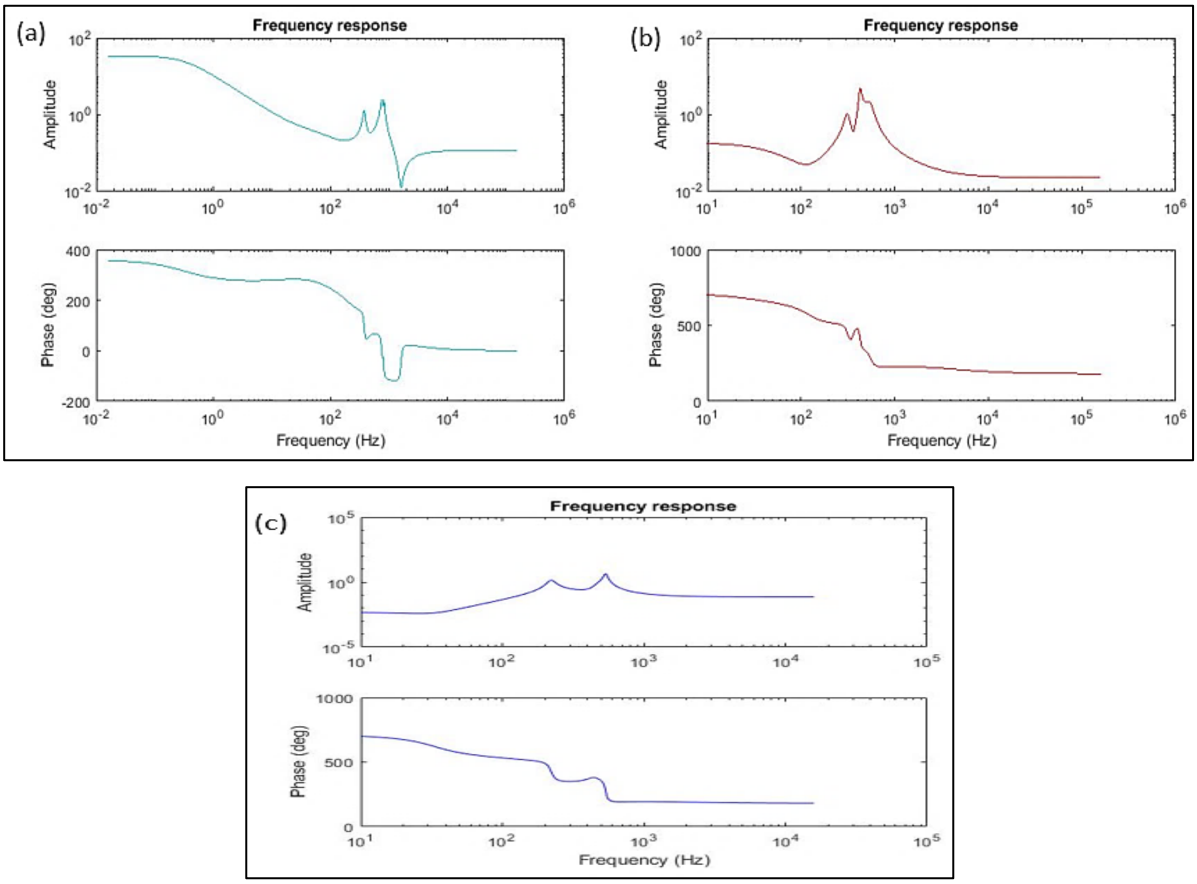

Figure 10: Bode plot of the SSSF case for (a) specimen 1, (b) specimen 3, (c) specimen 4

3.3 SSFF Boundary Condition

In this case, two opposite sandwich edges were assigned a simply supported boundary condition while the remaining edges were set free. Figures 11a, 11b, 11c, and 11d show the bode plot (magnitude and phase) for the SSFF case for specimens 1, 2, 3, and 4, respectively. In this case, the highest peak frequency was (550 Hz) for specimen 1, while the highest phase difference was (900 degrees) for specimen 2.

3.4 Cantilever Boundary Condition

The last case in this section is the cantilever boundary condition which represents fixing the sandwich specimens from one edge and leaving the remaining edges free to vibrate. Figures 12a, 12b, 12c, and 12d show the bode plot (magnitude and phase) for the transfer function for the case of the cantilever sandwich plate of specimens 1, 2, 3, and 4, respectively.

For this point, the four manufactured specimens were tested under the specified boundary conditions. The next section summarizes the experimental results and provides comparisons and interpretations for the behavior of the specific composite sandwich panels under an external impulse force.

3.5 Results and Discussion

Table 3 summarizes the bode plots' Figures (9 to 12) in the peak frequency and phase difference. The peak frequency represents the frequency in which the amplitude rises sharply after the initial disturbance (by the impact hammer). These peak frequencies might be the fundamental natural frequencies of the structure or not, depending on the exciting force. For example, if the exciting force was sufficient to excite the natural frequencies of vibration, these peaks might be the resonance frequencies of the specimen. However, exciting the natural frequencies of the manufactured specimens in this research was not the main focus of the study. Instead, the specimen response to the exciting force was considered, and, accordingly, the Bode plots were constructed. The phase difference between the input and output signals is listed in Table 3.

Table 3: Summary of the peak frequency (in Hz) and phase difference (in degrees) results

Specimen	Bode plot element	SSSS	SSSF	SSFF	Cantilever
1	Peak Frequency	400	350	550	500
1	Phase Difference	540	360	540	540
2	Peak Frequency	150	170	150	100
2	Phase Difference	540	360	900	540
3	Peak Frequency	350	300	280	326
3	Phase Difference	180	180	360	180
4	Peak Frequency	180	210	200	200
4	Phase Difference	180	180	360	180

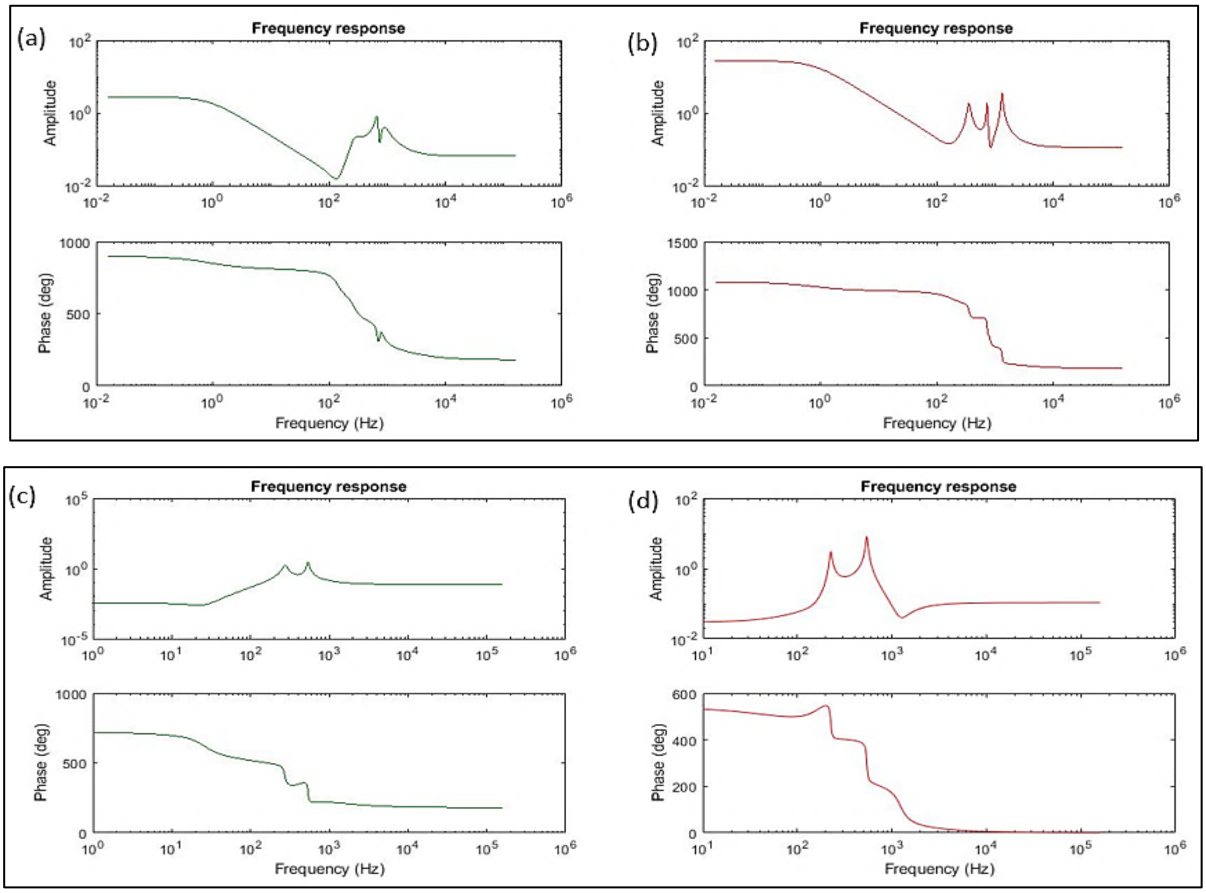

Figure 11: Bode plot for the SSFF case for (a) specimen 1, (b) specimen 2, (c) specimen 3, (d) specimen 4

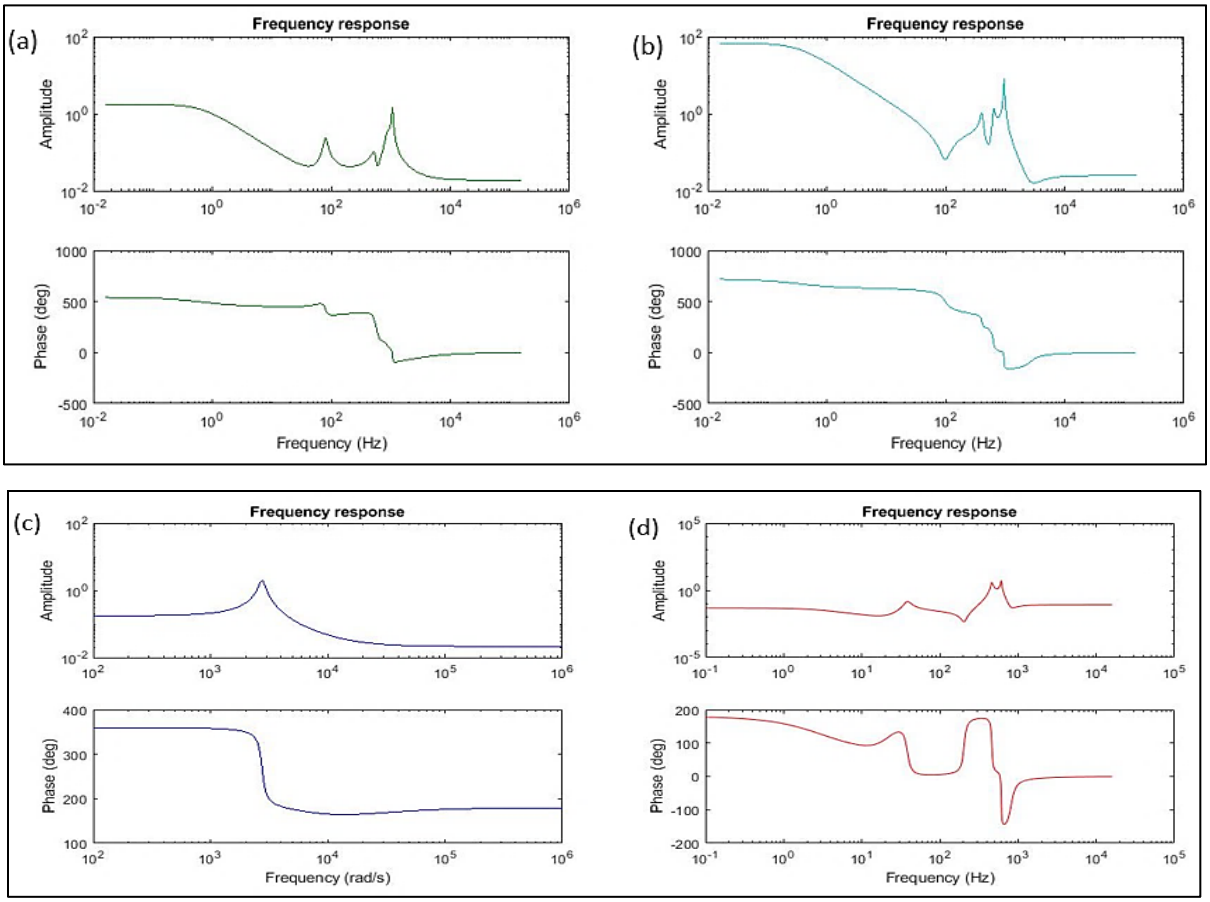

Figure 12: Bode plot for the cantilever sandwich panel case for (a) specimen 1,(b) specimen 2, (c) specimen 3, (d)specimen 4

It can be concluded from Table 3 that the peak frequency for specimen 1 was the highest value among other specimens for all combinations of the boundary conditions. Furthermore, specimen 3 ranked the second highest peak frequency among other frequencies, while specimen 4 ranked the third. These results were accepted by considering the material properties of the skins and core materials for the four specimens.

The highest values of the peak frequency denote higher values of the natural vibration frequency, which means that the structure was not affected by lower input frequencies. This higher peak value was favorable in the engineering design of structures as it shifts the natural frequencies to higher values. In other words, the structure can resist higher input frequencies without failure.

The phase difference between the input and output signals was highest for the case of honeycomb cores (360-900 degrees), while this phase difference value reduces for the case of foam core sandwich panels (180-360 degrees). This means that the foam core composite sandwich panels respond more quickly to the applied load than the honeycomb core composite sandwich structures. This might be because of the increased structural rigidity for the foam core due to the increased contact area between the core and the skins. Thus, the honeycomb sandwich specimens possess a higher damping ratio than foam core sandwich structures.

It has been shown through this research that four combinations of composite sandwich specimens were manufactured and tested. Deciding on a suitable composite sandwich configuration was a great challenge for designers. Knowing the dynamic response of these structures to applied loads helps in this decision. As shown in the results, composite honeycomb sandwich panels possess higher peak frequency and damping rates, making them suitable for applications requiring higher damping and resonance frequencies. However, if the cost parameter was included in the selection criterion, glass fiber composite sandwich panels overcome the carbon fiber sandwich panels. Therefore, this research helped designers to choose the type of composite sandwich panel that suits their design criteria using a forced vibration-based approach.

4. Conclusions

In this work, composite sandwich structures were manufactured and tested experimentally. A special vibration test rig was manufactured, and the composite sandwich panels' forced vibration response was recorded. Four specimens were manufactured and tested via an impact hammer, plotting the frequency response function. It was concluded that the specimen made of all-carbon fiber material for the skins and the core layer showed the best frequency response for the applied load. For example, all carbon fiber specimens (specimen 1) showed the highest peak at a frequency of (400 Hz) for the SSSS case. However, the composite sandwich specimen with glass fiber skins and foam core represented the lowest frequency response to the impulse load at a frequency of (150 Hz) for the same boundary condition. It can be further concluded that the composite honeycomb cores' response to applied load was slower than the foam cores. This was visible through the foam cores' phase difference, which was as much as (360 degrees) compared with honeycomb core sandwich specimens. Thus, the honeycomb sandwich structure's damping was higher than the foam core sandwich panels.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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