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Research Article

Modal Analysis of Sandwich Structure Using Finite Element Approach

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ABSTRACT

In automotive, aviation, marine and advanced engineering applications, sandwich structures are increasingly preferred due to their superior properties such as high strength to weight ratio, wear resistance, and good surface quality. In this study, the natural frequencies and mode shapes of sandwich structures were investigated, and the effects of different boundary conditions and material combinations on their vibration characteristics were evaluated. Modal analyses were performed using the Finite Element Method (FEM) via ANSYS software, and the generated model was validated by comparing with existing literature data. In the model, carbon steel and carbon fiber reinforced plastic (CFRP) were used as the face sheet materials, while polyurethane elastomer matrix fiber and PVC foam were used as the core material. According to the results, the sandwich structure with a PVC foam core exhibited a 178.6% increase in the first natural frequency compared to the structure with a polyurethane elastomer matrix fiber core. Boundary conditions had a significant impact on natural frequencies, with the completely fixed (C–C–C–C) configuration yielding values 28.6% higher than the completely free (F–F–F–F) condition. Sandwich structures with fully CFRP face sheets showed a 27.7% higher natural frequency than those with hybrid face sheets. These findings demonstrate that the dynamic performance of sandwich structures is highly sensitive to boundary conditions as well as the types of core and face sheet materials, emphasizing the importance of appropriate material and geometric configuration in engineering design.

Introduction

Continuous advances in technology have led researchers to develop lighter, more durable and functional new material systems. In this context, sandwich structures, which offer mechanical advantages such as high strength to weight ratio, superior energy absorption capacity, and long-term durability are widely used in many engineering and industrial fields such as aviation, automotive, marine and construction [1, 2]. Sandwich structures are multilayer composite systems composed of thin, and high-strength face sheets and a low-density yet rigid core material [3]. In such structures, the face sheets primarily bear bending loads, while the core material provides shear rigidity and ensures effective load distribution. Additionally, the core material plays a crucial role in damping impacts and vibrations acting on the structure [4]. The most striking feature of sandwich structures is that the type, thickness, and geometry of both the face sheets and the core material can be optimized with great flexibility, depending on application requirements. This enables the design of high-performance structures tailored to specific engineering problems. Core materials are generally optimized for both lightness and mechanical strength [5]. Materials such as polyurethane foam, polyethylene terephthalate (PET) foam, balsa wood, cork, and PVC foam are widely preferred because they provide sufficient structural stiffness despite their low density [6]. In addition, the combination of these core materials with different face sheets significantly affects both the static and dynamic performance of sandwich structure. Accurate understanding and modeling of the mechanical characteristics of sandwich structures is of critical importance for engineering designs. In particular, understanding the vibration behavior of these structures is essential to ensure structural integrity and reliable performance under dynamic loading conditions.

Various studies have been conducted in literature on the modal analysis of sandwich structures. Manoharan et al. performed a modal analysis of hybrid laminated composite panels with viscoelastic core using ANSYS software. Their study revealed that fiber orientations, laminate stacking sequences, and boundary conditions significantly affect the natural frequencies and mode shapes of composite panels [7]. Similarly, Apalak et al. investigated the effect of fiber orientations, number of layers, and boundary conditions on natural frequency of graphite/epoxy plates and reported that these parameters have a considerable impact on vibrational behavior [8]. Kumar et al. investigated the vibration behavior of honeycomb core sandwich composite panels using the finite element method and carried out the modeling with ANSYS APDL software. The study indicated that the surface plate thickness and core material type are key determinants of the natural frequencies and mode shapes of the structure [9]. Jalali and Doğan performed a modal analysis of laminated composite sandwich panels using ANSYS and ABAQUS software, and especially emphasized the effects of fiber orientation, layer stacking sequence, and boundary conditions on the natural frequencies [10]. Hose et al. analyzed the natural frequencies of graphene sheet reinforced polymer composite plates using ANSYS software. They showed that changes in geometry, boundary conditions, and aspect ratio significantly affect the vibration characteristics of the structure, even when the density is kept constant [11]. Prashant et al. performed a theoretical modal analysis of cantilever beams made from two different materials and experimentally determined the natural frequencies, damping ratios, and mode shapes. The experimental findings were found to be in good agreement with the theoretical results. It was also observed that, for beams with identical cross-sections and lengths, the natural frequency of aluminum was higher than that of mild steel [12]. Potluri et al. performed static structural and modal analyses using ANSYS Workbench software to investigate the effect of core and face plate thicknesses on natural frequencies of sandwich structures [13]. Lashin and El-Nady studied the effects of material selection and boundary conditions on the natural frequencies and mode shapes of sandwich beam structures which were modeled using MSC-PATRAN/NASTRAN software. The results obtained for aluminum solid beams, CPVC solid beam, and Aluminum-CPVC sandwich beam were compared with analytical data. Kheirikhah et al. investigated the effects of fundamental parameters such as groove geometry, boundary conditions, composite layer properties, and thickness ratio on the natural frequencies of corrugated sandwich structures [14]. Maraş and Yaman investigated the vibration behavior of fiber metal laminate (FML) plates using numerical and experimental methods and found a strong agreement between the two approaches. In their studies, they revealed that the location of the aluminum layers and the boundary conditions have significant effects on the natural frequencies [15]. In a separate study, Maraş and Yaman numerically analyzed the vibration behavior of sandwich syntactic foams using a finite element method based on Higher Order Shear Deformation Theory (HSDT). The numerical results were compared with experimental data, which showed a high level of agreement [16]. Maraş, investigated the free vibration and buckling behaviors of sandwich plates composed of fiber metal laminate (FML) face sheets and a balsa wood core using the Generalized Differential Quadrature (GDQ) method. The developed model demonstrated an agreement of over 97% with reference results in the literature. In addition, the effects of various design parameters on the natural frequencies and buckling loads were comprehensively evaluated [17]. In a separate study, Maraş and Yaman performed free vibration analysis of fiber-metal laminated (FML) composite plates under different boundary conditions using Differential Quadrature (DQ), Generalized DQ (GDQ) and Harmonic DQ (HDQ) methods. The numerical results showed a high level of agreement with experimental data. This is the first comprehensive study in the literature to demonstrate the reliable applicability of DQ-based methods for vibration analysis of FML structures [18].

This study aims to determine the natural frequencies and mode shapes of sandwich structures using ANSYS software. The study is structured in two main stages. In the first stage, the accuracy of the numerical model developed in the ANSYS environment was evaluated by comparison with previous studies in the literature, and the model's validity was verified. In the second stage, the effects of different boundary conditions and material combinations on the vibration characteristics of sandwich structures were systematically investigated.

The study specifically contributes to the determination of optimal layer arrangements and material selection for enhanced vibration performance. In particular, the comparative modal analysis of PVC foam and polyurethane elastomer matrix fiber cores, combined with CFRP and carbon steel face sheets, enables a direct comparison of these materials' vibration performance addressing a gap identified in the literature. Furthermore, a more comprehensive and versatile analysis of modal behavior was achieved by jointly evaluating multiple parameters (core material, face sheet configuration, and boundary conditions), thus making a novel contribution to the existing body of knowledge.

Material Properties and Finite Element Model

In this study, Finite Element Analysis (FEA) method was used to investigate the vibration behavior of sandwich structures, and the models were created using the commercial software ANSYS. The sandwich structure was modeled as consisting of two stiff face sheets and a low-density core layer in between. Carbon steel and CFRP, which offer high mechanical strength and rigidity, were preferred as the face sheet materials. The CFRP layer was defined as an orthotropic material with the fiber orientation set to [0°]. Polyurethane elastomer matrix fiber and PVC foam, which are distinguished by their lightness and energy absorption capacity, were used as core materials. The material definitions were made in the ANSYS Engineering Data module, and the elastic modulus, density, and Poisson's ratio of each material are presented in Table 1.

Table 1. Mechanical properties of core and face sheet materials used in the sandwich structures [4, 19, 20]

Properties	Carbon steel	Carbon fiber reinforced plastic	Polyurethane elastomer matrix fiber	PVC foam
E_1 (GPa)	200	120	0.90195	0.056
E_2 (GPa)	-	7.9	-	-
E_3(GPa)	-	7.9	-	-
ν_{12}	0.3	0.33	0.36	0.27
ν_{13}	-	0.33	-	-
ν_{23}	-	0.33	-	-
G_{12} (GPa)	-	5.5	-	-
G_{13} (GPa)	-	5.5	-	-
G_{23} (GPa)	-	5.5	-	-
ρ (kg/m^3)	7850	1580	1098	60

The geometry was created using ANSYS Design Modeler with dimensions of 300 x 300 x 28 mm. The core thickness was set to 20 mm, and each face sheet had a thickness of 4 mm. The model used is the same as the model in the Ariesta et al. [19] study. Figure 1 shows the three-dimensional geometric design of the sandwich structure.

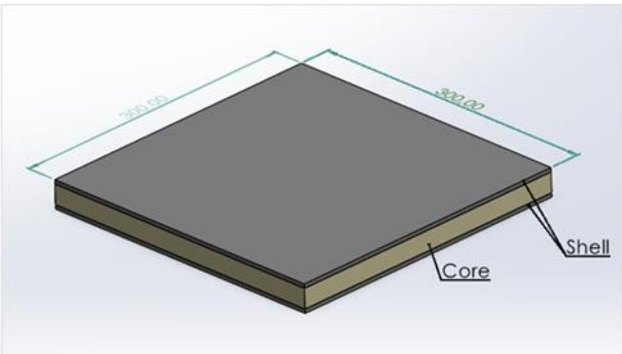

Figure 1. The three-dimensional geometric design of the sandwich structure

To ensure the accuracy and validity of the analysis results, a suitable mesh structure was created, establishing an optimal balance between mesh quality, computational accuracy, and solution time. The mesh consisted of hexahedral (brick) elements, which are suitable for structural dynamic analyses involving both layered composite and isotropic materials. The model consists of 8000 elements and 48093 nodes in total.

After generating the mesh structure, the model was configured according to the specified boundary conditions, and the Block Lanczos algorithm was preferred for the modal analysis in the free vibration analysis. As a result of the analysis, the first five natural frequencies and their corresponding mode shapes were obtained.

Figure 2 shows the modeling steps of sandwich structures; Figure 3a shows the three-dimensional model created in the ANSYS software, while Figure 3b shows the created mesh structure.

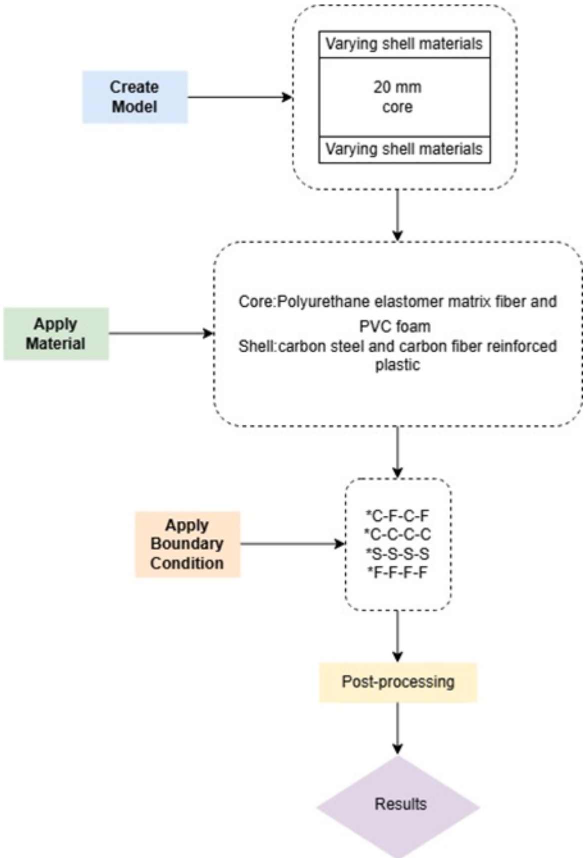

Figure 2. Flowchart of the numerical modelling steps for sandwich structures

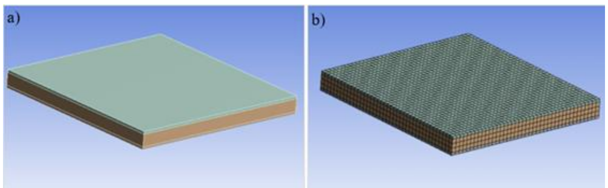

Figure 3. Geometrical model of the sandwich structure a) before meshing b) after meshing

Simulation Validation and Literature Comparison

The numerical analyses performed in this study were implemented using ANSYS software. To ensure the reliability and validity of the analysis model, the natural frequency results obtained from the simulations were compared with data from the literature. Accordingly, the material properties, layer thickness and geometric dimensions used in the modeling process were fully defined in accordance with the parameters specified in the study conducted by Ariesta et al. using ABAQUS software. Modal analysis was performed under clamped-free-clamped-free (C-F-C-F) boundary conditions. The natural frequency values and mode shapes obtained from the numerical analysis were compared with those reported by Ariesta et al.; similarities were evaluated, and the validation level of the model was revealed. The comparison of the results obtained in this study with those in the literature is presented in Figure 4.

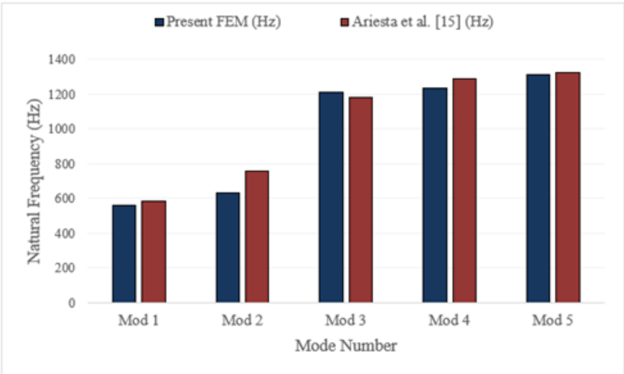

Figure 4. Comparisons of the natural frequencies of the sandwich structure obtained by the present FEM and Ariesta et al. [19]

In order to evaluate the accuracy of the numerical model, the obtained natural frequencies were compared with those reported in the study conducted by Ariesta et al. [19], which used ABAQUS software. Percentage error rates were calculated for each mode in the comparisons made. Accordingly, deviations of 4.15% for the first mode, 17.06% for the second mode, 2.77% for the third mode, 4.30% for the fourth mode, and 0.81% for the fifth mode were obtained. These results confirm that the model demonstrates a high level of agreement with literature, particularly with errors below 5% in four out of five modes, thus validating its reliability for the modal analysis of sandwich structures.

When the obtained natural frequency results are compared with those of the study conducted by Ariesta et al. [19] using ABAQUS software, both analysis results show generally similar trends. This supports the validity of the modeling approach used in the present study and increases the reliability of the parametric analyses performed in the subsequent stages. However, limited differences were observed in the natural frequency values. The main reason for these differences is the nuances that arise in the analysis algorithms, mesh generation strategies, boundary condition implementation methods, and solution methods of different finite element software such as ANSYS and ABAQUS. Although both programs are based on the finite element method principle, they have some structural differences in terms of the element types used, numerical stability of the solvers and accuracy levels. Therefore, such differences can lead to certain deviations in the natural frequency values, in higher order modes and complex boundary conditions. This situation reveals that the comparison of simulation results should focus not only on numerical values but also on the general vibration behavior and mode shapes.

Results

Case 1: Effect of change in the core material

In Case 1, the effect of varying the core material on the dynamic properties of sandwich structures was evaluated. To provide a comparative analysis, the carbon steel was used as the constant material for the top and bottom face sheets in all models and only the core material was changed. In this context, polyurethane elastomer matrix fiber and PVC foam were used as core materials, and both configurations were analyzed using the modal analysis method. The modeling process was carried out under C-F-C-F boundary conditions, and natural frequency values were obtained for each vibration mode.

The comparison of natural frequencies obtained for polyurethane elastomer matrix fiber and PVC foam core materials are presented in Figure 5. It was observed that changing the core material directly affected the total mass and stiffness of the structure; thus, it caused differences in natural frequencies. These findings are consistent with previous studies [4, 6], which reported that the total mass and stiffness of the structure caused differences in frequencies.

The analysis results indicated that the sandwich structure with a PVC foam core exhibited higher natural frequencies compared to the structure with a polyurethane elastomer matrix fiber core. This situation can be explained by the relatively lower density and higher stiffness/weight ratio of PVC foam. On the other hand, although polyurethane elastomer matrix fiber has a higher density, it results in lower natural frequencies.

When the obtained frequency values are examined in detail, it is seen that the natural frequencies increase significantly as the mode number increases for both materials. The PVC foam core structure exhibited much higher frequencies than the polyurethane elastomer matrix fiber core structure, especially in the higher modes (Mode 3, 4, 5). This difference is related to the system becoming more sensitive to stiffness and mass distribution in higher modes. For example, while the frequency value obtained for PVC foam in Mode 5 is 4826.9 Hz, this value is 1313.4 Hz for the polyurethane elastomer matrix fiber core.

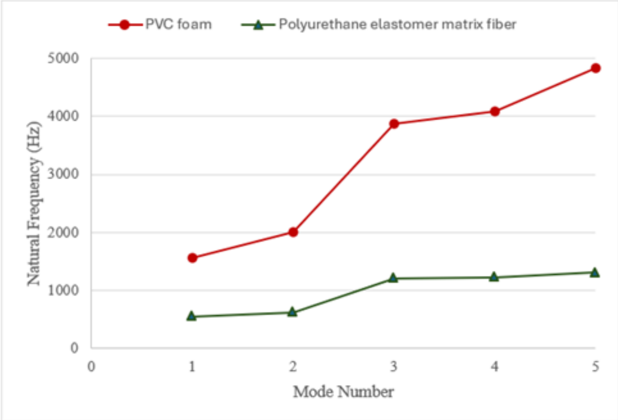

Figure 5. Effect of core material on the natural frequencies of sandwich structures

The comparison of mode shapes obtained for polyurethane elastomer matrix fiber and PVC foam core materials is presented in Figure 6. In both cases, the first mode shape shows the classical bending mode characteristic. However, differences are observed in frequency values and deformation magnitudes. The PVC foam core structure vibrates at a higher frequency, indicating a stiffer system. The larger deformation, the more energy the system can carry (high frequency oscillations) and the clearer separation of the mode shape. The polyurethane elastomer matrix fiber structure, on the other hand, reveals that the system is more flexible with lower frequency and less deformation. At higher modes, vibration behavior becomes more complex and multiple nodes appear in the mode shapes.

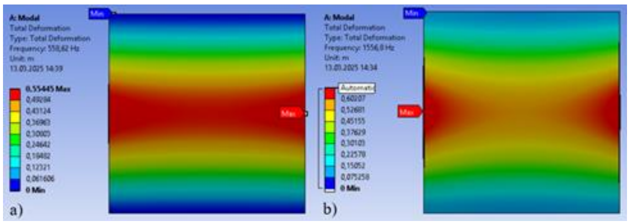

Figure 6. Contour plot of the first mode shape for a) polyurethane elastomer matrix fiber b) PVC foam as core

An important advantage of sandwich structure with PVC foam cores is the light achieved thanks to their low density. The reduction of the total mass of the structure not only allows for higher natural frequencies but also provides operational convenience in terms of transportation and assembly. In addition, PVC foam cores generally require less processing in the production process and are more cost-effective. With these features, PVC foam stands out as a preferable core material, especially in engineering applications where cost and weight sensitivity are critical.

Case 2: Effect of change in the boundary conditions

The dynamic behavior of sandwich structures with carbon steel face sheets and a polyurethane elastomer matrix fiber core was investigated under different boundary conditions. In this context, the effects of completely fixed (C–C–C–C), completely simply supported (S–S–S–S) and, completely free (F–F–F–F) boundary conditions on the natural frequencies of the structure were analyzed. The first five natural frequency values for each boundary condition are presented in Figure 7, and the corresponding first mode shapes are presented in Figure 8.

The boundary conditions applied in the model directly affect the stiffness of the sandwich structure. As shown in Figure 7, the highest natural frequency values are obtained under C–C–C–C boundary conditions. This situation is due to the fact that the mentioned boundary condition provides the most restrictions on the system and maximizes the stiffness of the structure. The natural frequencies obtained under S–S–S–S boundary conditions are lower than the C–C–C–C boundary condition, but higher than the frequencies obtained under F–F–F–F boundary conditions. This situation shows that the S–S–S–S boundary condition partially reduces the stiffness of the structure and causes a decrease in natural frequencies. On the other hand, the lowest natural frequency values are observed under F–F–F–F boundary conditions. This condition is evaluated as the configuration where the free vibration behavior of the structure occurs most dominantly by providing the least restrictions on the system.

The results show that the boundary conditions have a decisive effect on the dynamic behavior of sandwich structures. The changes observed in the frequency values depending on the boundary conditions are consistent with the studies reported in the literature [21, 22], which reveal that the boundary conditions significantly affect the vibration characteristics. While increased structural rigidity leads to higher natural frequencies, a greater degree of freedom results in a decrease in natural frequency values.

In addition, when high-order natural frequencies such as the 3rd, 4th and 5th modes are evaluated, it is clearly seen that the effect of the boundary conditions continues. Under the C–C–C–C boundary condition, thanks to the maximum restriction of the system from all sides, the structure can maintain high frequency values even in more complex mode shapes. For example, while the C–C–C–C configuration reaches a high value of 2091.1 Hz in the 5th mode, the same mode remains at 1952.5 Hz in the S–S–S–S boundary condition and only at 1211.7 Hz in the F–F–F–F condition. This clearly demonstrates that stiffness directly affects the high mode frequencies and significantly changes the resonance behavior. In addition, the equal frequency values (1211.7 Hz) observed in the 4th and 5th modes under the F–F–F–F boundary condition suggest that some symmetric modes overlap under this structure or that the structure exhibits repetitive mode characteristics. This overlap shows that mode separation becomes difficult in systems with high degrees of freedom and complex dynamic responses may arise.

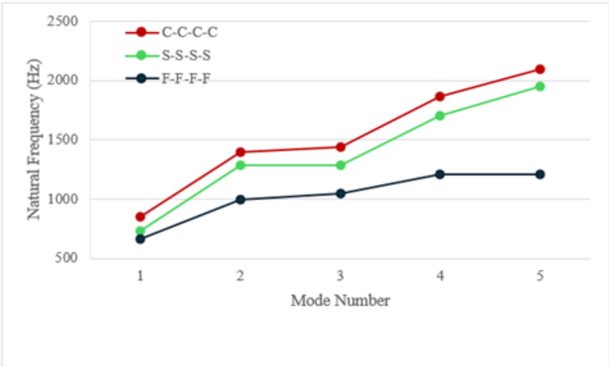

Figure 7. Effect of boundary conditions on the natural frequencies of the sandwich structure

Figure 8 presents the first mode vibration patterns of the sample under different boundary conditions. Since all edges of the sample were fixed under the C-C-C-C boundary condition, the maximum displacement occurred at the center of the structure and a symmetrical doming mode was observed. Under the S-S-S-S boundary condition, it was observed that the maximum displacement was not located exactly at the center as a result of allowing the edges to displace. In the analysis performed under the F-F-F-F boundary condition, the displacement distribution showed an asymmetrical character due to the edges of the sample being completely free. In this case, the maximum displacement shifted towards the edges. The obtained mode shapes show that the boundary conditions have a significant effect on the vibration behavior of the sandwich structure.

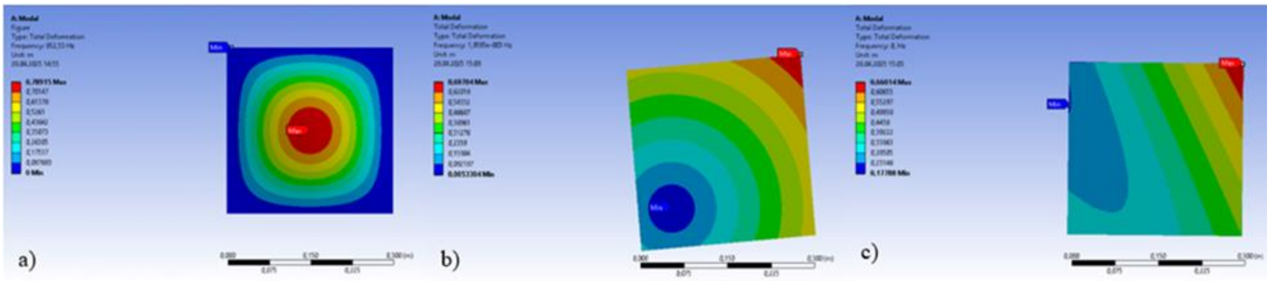

Figure 8. Contour plot of first mode shape under boundary condition a) C-C-C-C b) S-S-S-S c) F-F-F-F

Case 3: Effect of change of shell material

In this case, the dynamic behavior of the examined sandwich structures was analyzed by considering different shell material configurations. In the first configuration, both face sheets were made of CFRP, while the core layer consists of a fixed sandwich structure. In the second configuration, the upper and lower shell materials differed; one was CFRP, and the other was carbon steel. To investigate the effects of these shell material combinations on the modal characteristics of sandwich structures, the obtained natural frequency values were evaluated comparatively. Numerical analyses were carried out under C–F–C–F boundary conditions. The findings regarding the effects of shell material variation on the vibration behavior of the structures are presented in Figures 9 and 10.

When Figure 9 is examined, it is evident that the materials used in the face sheets of sandwich structures significantly influence their natural frequencies. The configuration with CFRP on both surfaces exhibits higher natural frequency values across all modes compared to the configuration with one CFRP and one carbon steel face sheet. This can be associated with the fact that the CFRP has a higher modulus of elasticity than carbon steel, thus providing greater structural rigidity. Despite its high density, carbon steel offers lower rigidity than CFRP in terms of elastic properties, and this reduces the overall rigidity of the structure, causing the natural frequencies to decrease. The difference between the natural frequencies is more pronounced, especially in the third, fourth and fifth modes. This finding shows that the effect of the shell material on high-order modes is greater. A similar trend is observed in the first and second modes, but the frequency difference becomes less pronounced. As a result, the preference of high stiffness materials in the face sheets increases the overall stiffness of sandwich structures and contributes to an increase in their natural frequencies. The findings are in line with the generally accepted trend in the literature that an increase in structural stiffness increases natural frequencies [10]. The use of CFRP on both surfaces improves the vibration performance of the sandwich structure and allows for higher frequency responses.

In sandwich structure design, the material selection for the face sheets has a direct impact on the mechanical performance of the structure. If the structure operates in a way that will receive loads from both surfaces and symmetrical vibration behavior is desired, the use of carbon fiber on both surfaces offers the optimum solution. In this case, both the bending rigidity of the structure increases, and the mode shapes become symmetrical and predictable. On the other hand in cases where the structure is subjected to loading primarily from one side—such as in applications like protective shields or cladding panels—using carbon fiber on one face and carbon steel on the other may serve as a cost-effective alternative. This hybrid structure can provide sufficient structural performance in certain applications while significantly reducing production costs.

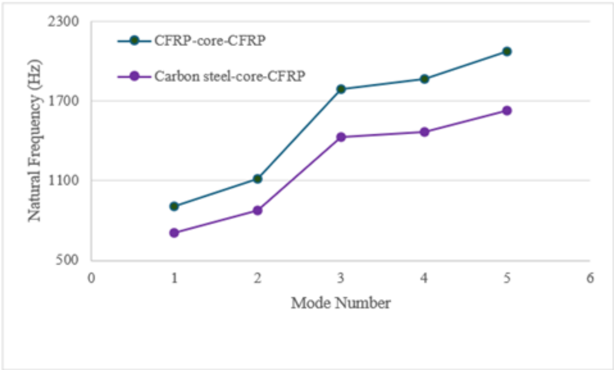

Figure 9. Effect of face sheet material on the natural frequencies of sandwich structures

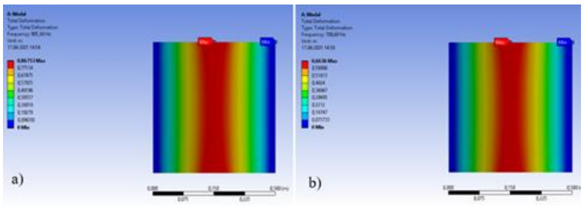

Figure 10. Contour plot of first mode shape of a) CFRP-core-CFRP b) carbon steel-core-CFRP

Conclusions

In this study, a modal analysis of sandwich structures was performed, and their natural frequencies were obtained. The results were compared with previously published studies, and after determining that the sandwich structure model was designed correctly, parametric studies were started. In these parametric studies, the effects of different boundary conditions and material combinations on the natural frequencies were found.

The main findings obtained from this study are as follows:

1. It shows that the sandwich structure with a PVC foam core has higher natural frequencies compared to the one with a polyurethane elastomer matrix fiber core material.

2. The results indicate that boundary conditions significantly affect the dynamic behavior of sandwich structures. As structural rigidity increases, natural frequency values increase, and as the degrees of freedom increase, the natural frequencies decrease. In addition, the observed isofrequencies in some modes reveal that the system has symmetric vibration modes.

3. It has been observed that changing the face sheet material has a decisive effect on the natural frequencies of sandwich structures. The use of CFRP layers increases structural stiffness and increases the natural frequency values.

In conclusion, both boundary conditions and material combinations play a critical role in the dynamic behavior of sandwich structures. Stiffer boundary conditions and higher-stiffness materials increase the natural frequencies of the system and improve its vibration resistance. Therefore, both appropriate boundary conditions and material must be carefully selected to achieve the desired dynamic performance in engineering applications.

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