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Experimental characterization and modal analysis for woven composite high aspect ratio beam

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Experimental characterization and modal analysis for woven composite high aspect ratio beam

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Abstract. In modern engineering applications such as aerial vehicles, composite structures are widely implemented due to their high structural stiffness and very low weight-to-lift ratio. They also enable designers to control their mechanical properties as well as the manufacturing method and fabrication quality to achieve the required structural performance. However, various manufacturing methods and the fabrication process can be considered production imperfections. In this study, an assessment of the fabrication quality for a typical composite structure is implemented. As considered for airplane wings and helicopter blades, a high aspect ratio structure is implemented as a case study. This structure is composed of laminated woven carbon fiber/epoxy resin fabricated using the vacuum bagging production method. To characterize the mechanical properties of the proposed structure, a mechanical tensile test is carried out. An experimental modal analysis via roving hammer test is implemented to examine the dynamic behavior of the proposed structure. To assess the quality of manufacturing and fabrication quality, the obtained natural frequencies are compared with the ones computed using a numerical technique using the Finite Element Method (FEM). The analytical problem using MATLAB had been established to emphasize the experimental results. Results showed that good manufacturing quality is achieved by using the vacuum bagging production method. Also, the experimental results agree well with both the numerical and theoretical results ,Which indicates good manufacturing quality.

Keywords: Laminated composite beam; Vacuum bagging; Dynamic behavior; Experimental modal Analysis.

1. Introduction

The beam is a structural element that is used to support loads over a span or distance. The beams are typically made of steel or other metallic alloys, although other materials such as wood or composite materials can also be used. Composite materials are formed by mixing two or more distinct materials. These materials are among the most widely used materials at present due to their excellent mechanical properties compared to traditional materials in terms of durability and strength. They can also be easily tailored to withstand different loads in specific directions, and also have lightweight, which makes them the most widely used option in aviation, and aerospace structures. Additionally, they are relatively inexpensive to manufacture. To obtain a good product that fulfills the purpose for which it was manufactured, quality and method of manufacturing play a very important role. The fabrication process has a direct impact on the mechanical properties which are unique to composite materials, such as the strength and endurance with low weight. Therefore, many manufacturing methods aim to reach the best results according to the degree of difficulty and cost of each. The hand lay-up technique is the most basic method of processing composites. For manufacturing high-quality and larger composite parts, the vacuum bagging technique is used, which applies pressure to remove excess epoxy and air voids and

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increase the fiber-to-epoxy ratio to meet specific requirements. Meanwhile, the vacuum infusion technique is a closed-mold process that can produce high-performance and large-scale composites.

Studying the static and dynamic behavior of the structural component such as beam elements under various conditions is very important to understanding and explaining the behavior of more complex structures such as wings, fuselages, …etc. In the context of aircraft design, resonance is a phenomenon that occurs when the natural frequency of a wing or other structural element coincides with the frequency of an external excitation. This can result in large amplitudes of vibration in the structure, which can lead to fatigue and failure. Modal analysis is a technique used to determine the natural frequencies and modes of vibration of a system. There are several techniques used in modal analysis, including:

(1) Experimental modal analysis: This technique involves measuring the response of a system to a known excitation and using that data to determine the system's natural frequencies and modes of vibration.
(2) Numerical modal analysis: This technique uses numerical methods, such as the finite element method (FEM) or the boundary element method (BEM), to determine the natural frequencies and modes of vibration of a system.
(3) Theoretical modal analysis: This technique uses mathematical models to determine the natural frequencies and modes of vibration of a system.

In the literature, there has been a continuous interest in the topic of comparison between composite material production techniques and modal analysis for composite laminated wings adopting experimental, numerical, and theoretical techniques. In recent years, there have been several studies on the modal analysis of laminated composite beams.

Talabari et al. [1] investigate experimentally the tensile properties in a Glass/Epoxy samples manufactured by vacuum infusion, vacuum bag and hand layup process. K Abdurohman et al. [2] made a comparison process between hand lay-up, vacuum infusion and vacuum bagging method for a Plain-weave type woven glass fabric. M.Topcu et al. [3] studied the dynamic behavior of the laminated composite beam made from woven glass fibre/epoxy prepreg by different three modal analysis techniques theoretically, numerically and experimentally. V.Tita, J. de Carvalho and J. Lirani [4] studied the dynamic behavior of beams were made using the hand-lay-up process. The mechanical properties of the composite were calculated analytically using the simple rule-of-mixtures. Experimental dynamic tests were conducted to determine the related natural frequencies. The obtained results of experimental work were compared with the results of the numerical finite element model. Kumar, C.Sathish, and Rao [5] investigated the natural frequencies of fabricated laminated E-glass fiber reinforced composite beams made using hand-lay-up process. They characterize the mechanical properties of the laminated beam by using simple rule-of-mixtures. Natural frequencies were obtained experimentally using roving hammer test and numerically by using finite element software ANSYS. M Aly, I Goda, and G.Hassan [6] studied experimentally the dynamic characteristics of laminated composite beams made by using hand-lay-up technique. The experimental results were also utilized to validate the outcomes generated by the finite element software ANSYS. Priyadarshi D and Shishir Kumar S [7] Studied the dynamic behavior of a laminated composite beam made by hand-lay-up method. The mechanical properties of the composite were characterized by using a mechanical tensile test. Related natural frequencies were carried out by experimental and finite element analysis and made comparison between results. In the present study, a high aspect ratio laminated composite beam of woven carbon fiber/epoxy resin is fabricated using a vacuum bagging production technique. A mechanical tensile test is performed to determine the engineering constants. Multi-technique of modal analysis is conducted on a composite laminated beam using experimental measurements, numerical, and theoretical modal analysis. The free vibration of the beam structure is tested experimentally using a roving hammer test to measure its natural frequencies. Experimental frequency values were obtained and compared with both the numerical and analytical results. For the numerical model, the laminated beam is modeled in finite element software to simulate its dynamic behavior to calculate the natural frequencies of the concerned beam. A theoretical model is used to validate the results of experimental work for the laminated composite beam based on the Euler-Bernoulli hypothesis.

This study aims to evaluate and assess the quality of manufacturing and experimental work. Also, to identify the natural frequencies of the laminated beam, which is important as it helps to predict the dynamic response of the structure, optimize the design for specific applications and confirm the validity of models.

The organization of the rest of the paper is as follows. The following section provides the fabrication and characterization of the case study. experimental modal analysis is then presented, followed by a discussion of numerical and theoretical techniques. The main findings are presented and analyzed, and the paper concludes by summarizing the key takeaways and conclusions.

2. Case study

The case study is a simple composite laminated beam consisting of 4 layers of 200 g/m^2 woven carbon fiber [0º/90º] as reinforcement and epoxy resin as a matrix. The used manufacturing method is a vacuum bagging process [2] to compact the laminate and force out excess epoxy and air voids to increase the fiber-to-epoxy ratio. The steps of manufacturing the laminated composite beams are briefly described below,

The surface of the used mold is thoroughly cleaned to be ready for use, and a layer of sealant tape is laid down around the perimeter of the work region. The mold surface is coated with a release agent film for easy and smooth removal after finishing. The first layer of the mat is laid and resin is spread uniformly over the mat using a brush. This process is repeated till all four fabric layers are placed. A peel ply as a release fabric and a breather fabric to absorb all excessive epoxy is laid before the vacuum bag completely covered the all and tapped to the mold. After that, holes are made into the bag for vacuum ports to mount the through-bag connectors to achieve the connection between a vacuum bag and the vacuum pump/supply through the tube lines. Ensuring that there are no holes for leakage is very important for the vacuum process, the casting is cured at room temperature and under the pressure of -0.92 bar for 6 hours and finally removed from the mold, as illustrated in figure 1.

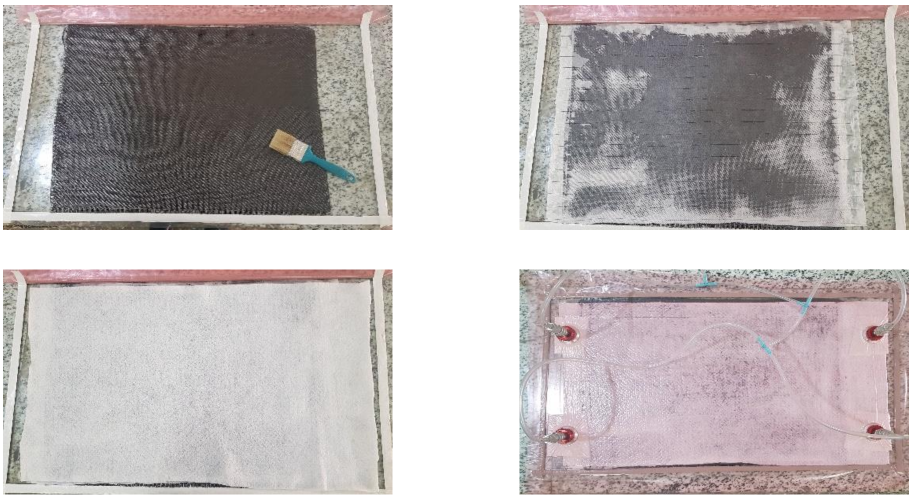
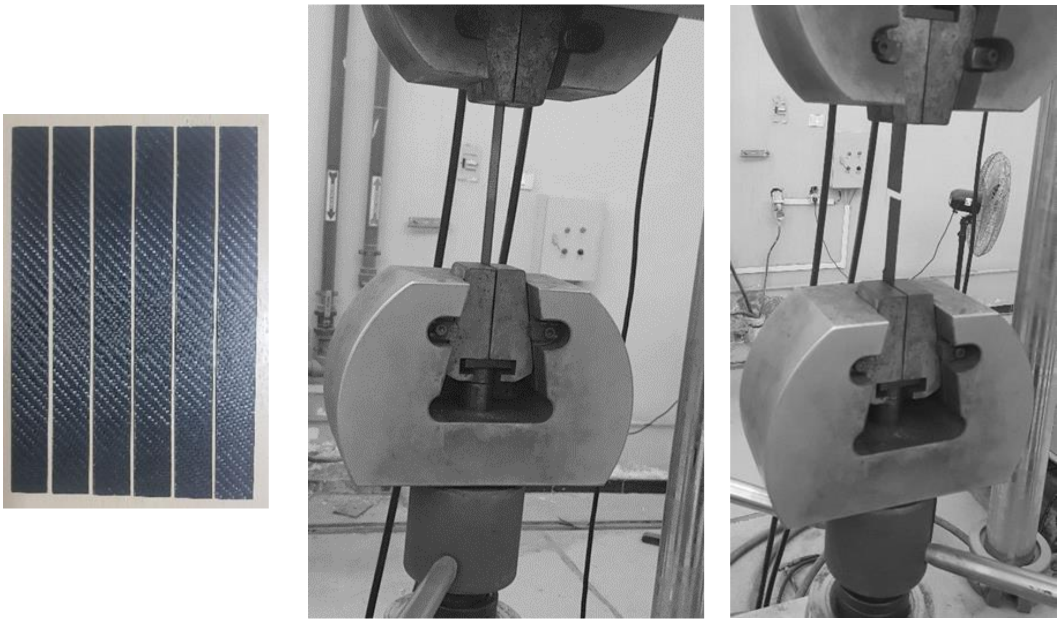


Figure 1. Vacuum bagging process of a fabricated composite laminated beam.

Laminated beams are cut from the composite plate into the size of 250 mm x 25 mm at an angle of (0º/90º) for the case study and test specimens by using a diamond-impregnated wheel. Taking into account the length of about 20 mm for fixation. According to ASTM D3039/D 3039M guidelines [8] the standard tensile test for composite materials. the material properties of the laminated composite material are found. The test specimen was loaded by MTS tensile machine (Model 661.23B-02 500KN) at room temperature ± 25º C with constant crosshead speed to determine the modulus of the elasticity figure 2. Strains and loads measurement are recorded automatically during each test. This test is repeated for five specimens and the average was taken to get accurate results. As the used reinforcement is a woven carbon fiber [0º/90º] in which the number of carbon filament counts in both orientations [0º/90º] is equal hence the Young modulus of both direction is the same. The overall data of dimension and structure properties of the case study are shown in table 1.



a. Test specimens b. Tensile test specimen before and after tension

Figure 2. Test specimens and tensile test machine.

Table 1. Dimension and structure properties of the case study

Composite material	Carbon fiber/epoxy
No. of layers	4, in the same direction
Beam length	0.230 [m]
Beam width	0.025 [m]
Beam thickness	0.0012 [m]
Density	1080 [kg/m^3]
Young modulus E_1, E_2	28*10^9 [Pa]

3. Experimental modal analysis

Experimental testing is performed to measure the free vibration of the structure [9] by using the roving hammer test, where the structure is excited by applying an external impact load (pulse) through the use of an impulse hammer. Then the FRFs (Frequency Response Functions) which relate to the response of the structure are typically measured through the accelerometer placed on it to allow the determination of the natural frequencies. The main requirements for the experimental work are mentioned below with its specifications:

1. Rigid clamp.
2. National instrument accelerometer Figure 3: (model 352-C03) A transducer is a device employed for measuring the response to vibrations (acceleration, velocity, or displacement) within a frequency range from 0.5 Hz to 10000 Hz.
3. PCB impact hammer figure 4: (model 086-C03) within measurement range of: (±2224 N pk), and sensitivity of: (±15%) 2.25 mV/N.
4. Data acquisition system (DAQ): type NI – PXIe - 4499.

5. Connectors.
6. LabVIEW Software [9].

Figure 3. Accelerometer model NI-352-C33.

Figure 4. Impact Hammer Model PCB-086C-03.

A rigid clamp is used to secure one end of the beam in place, preventing any movement in any direction, effectively creating a cantilever beam. The accelerometer is placed on the composite beam with the help of wax at 10% of the beam length measured from the fixed end to ensure that measurements are not affected by the mass of the accelerometer [3]. It is important to place the accelerometer as far away as possible from the nodes of the first three mode shapes because it is difficult to get results when the accelerometers are close to the nodal line figure 5. Connectors are used to link the impulse hammers and accelerometer to their respective channels figure 6. A data acquisition system (DAQ) is employed to collect vibration signals from the accelerometer and convert them into digital form. The structure is excited using a PCB Impact Hammer. LabVIEW software [10] functions as both a data storage device and system analyzer, processing the encrypted data from the data acquisition system and presenting it as an FRF graph.

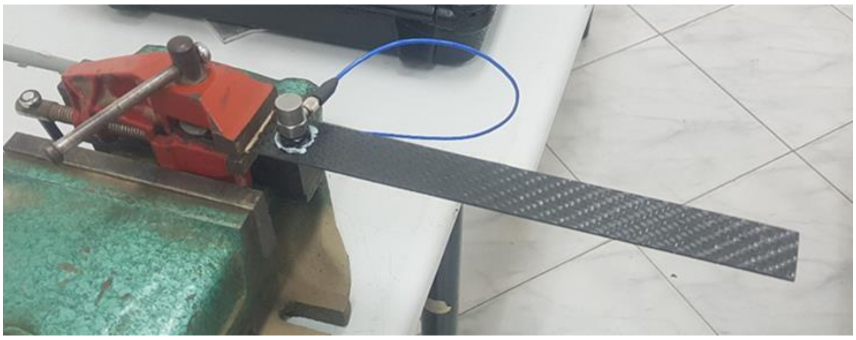


Figure 5. Beam fixation and accelerometer location.

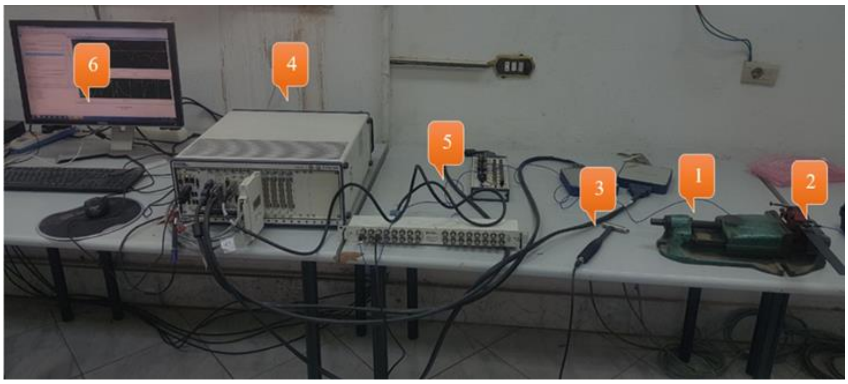


Figure 6. Complete experimental setup

4. Production quality assessment techniques:

4.1Numerical modal analysis
Numerical modal analysis is used to analyze and simulate the dynamic behavior of the structure. The numerical modal analysis [3] of the laminated composite cantilever beam is carried out in ANSYS software program through three main stages as shown in figure 7: pre-processing stage, solution stage, and post-processing stage.

In pre-processing stage: material engineering data with the help of a material design module calculator, CAD geometry, setup of ACP(Pre), meshing, boundary, and load condition are defined. ACP(Pre) module: is used to define all data related to the laminated composite beam such as fabric, material, and thickness for each layer (lamina), also defines the reference direction of 0^o of fiber direction, ply angle (orientation) of each layer and stacking sequence of the structure (laminate). For meshing: The mesh shown in figure 8 is created while considering mesh sensitivity, which is demonstrated in figure 9. The meshing process produces a total of 702 nodes and 616 elements. In solving stage: all of the input data are fed into the finite element solver and governing equations are solved on the mesh to obtain the results. In the postprocessing stage, the results of natural frequencies are evaluated and mode shapes are displayed.

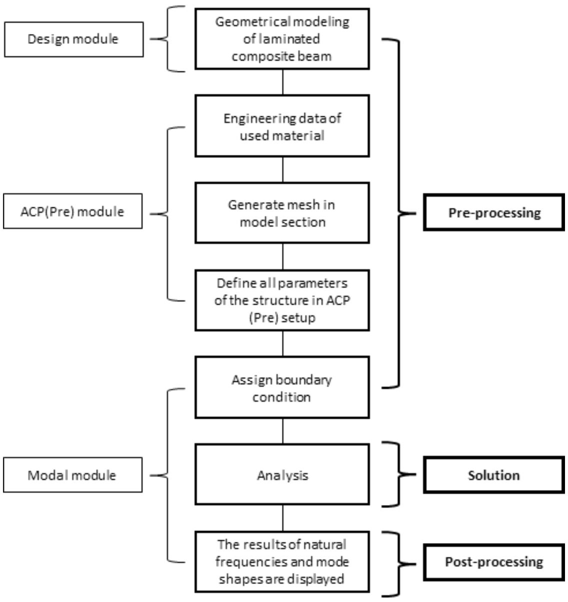


Figure 7. Flowchart diagram of numerical modeling using ANSYS software.

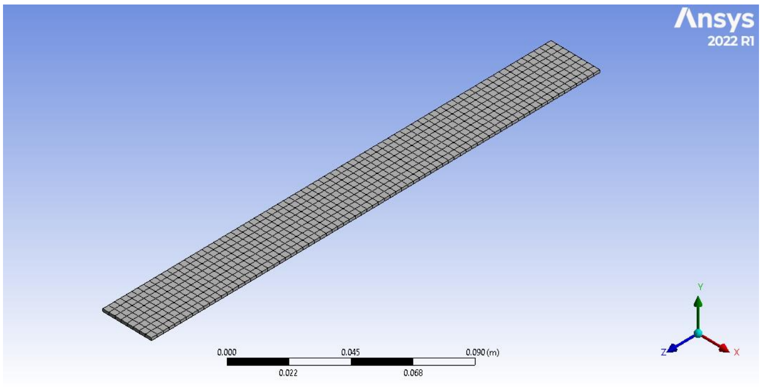


Figure 8. The meshing of the laminated beam.

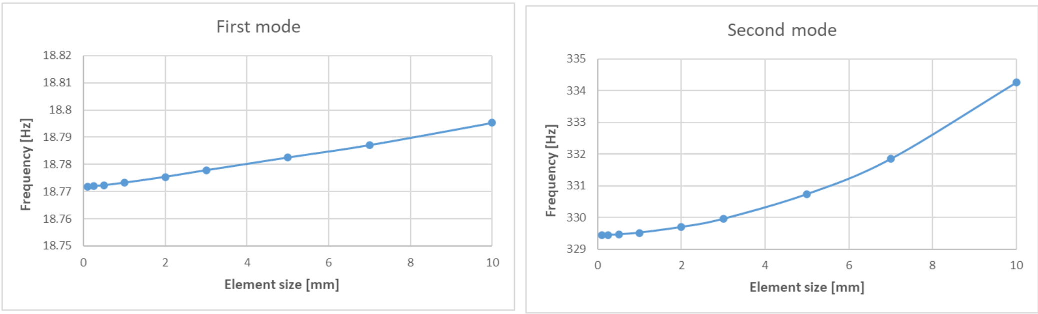


Figure 9. Mesh sensitivity.

4.2 theoretical modal analysis

A theoretical model is created to determine the natural frequency of a laminated composite beam based on Euler-Bernoulli assumption that states that the plane section which is perpendicular to the longitudinal axis of the beam before loading remains plane and perpendicular to the axis after loading

Consider a uniform cantilever beam vibrates transversally with the following data: (E.I—Product of the material Young's modulus by the inertia; L—Beam length; ρ—Density of the material; A—Beam cross-section; m— Mass per unit length; w— The transverse displacement in the z direction that varies with both position x and time t.) as shown in figure 10.

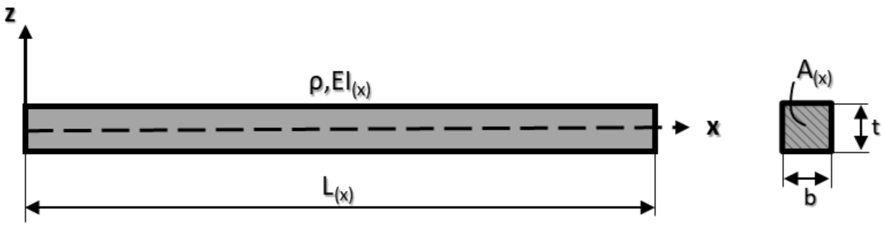


Figure 10. A uniform cantilever beam vibrates transversally.

The equation of motion for the beam is obtained by utilizing Hamilton's principle [11], which states that the change in the total energy (the sum of kinetic energy T and potential energy W) of the system over any interval of time is zero.

$$\int_{t_1}^{t_2} (\delta T - \delta U)\, dt = 0 \quad (1)$$

The variation of kinetic energy of the beam is given by,

$$\int_{t_1}^{t_2} \delta T dt = \int_{t_1}^{t_2}\int_0^L \rho.A_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial t^2}.\delta w_{(x,t)}.dxdt \quad (2)$$

The strain energy is given by,

$$\int_{t_1}^{t_2} \delta U dt = \int_{t_1}^{t_2} \left\{ \int_0^L (EI)_{(x)} \frac{\partial^4 w_{(x,t)}}{\partial x^4} \delta w_{(x,t)} dx + (EI)_{(x)} \delta \frac{\partial w(x,t)}{\partial x}\Big|_0^L - (EI)_{(x)} \frac{\partial^3 w_{(x,t)}}{\partial x^3} \delta w(x,t)\Big|_0^L \right\} .dt \quad (3)$$

Substituting equations (2) and (3) in (1), get:

$$\int_{t_1}^{t_2}\left\{\begin{array}{l}\int_0^L\left[-\rho.(A)_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial t^2}-\frac{\partial^2}{\partial x^2}\left((EI)_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial x^2}\right)\right].\delta w_{(x,t)}.dx \\ -(EI)_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial x^2}.\frac{\partial\left(\delta w_{(x,t)}\right)}{\partial x}\Bigg|_0^L+\frac{\partial}{\partial x}\left[(EI)_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial x^2}\right].\delta w_{(x,t)}\Bigg|_0^L\end{array}\right\}dt=0$$

The integral must vanish for any arbitrary values of $\delta w_{(x,t)}$, and $\partial\delta w_{(x,t)}/\partial x$, so these values have to equal zero only at $x = 0$ and $x = L$, then:

$$\int_{t_1}^{t_2}\left[-\int_0^L\left[\rho.(A)_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial t^2}+\frac{\partial^2}{\partial x^2}\left((EI)_{(x)}.\frac{\partial^2 w_{(x,t)}}{\partial x^2}\right)\right].\delta w_{(x,t)}.dx\right].dt=0$$

Finally, the non-dimensional equation of motion of free vibration of a beam is given by

$$\frac{\partial^2}{\partial x^2}\left((E.I)_{(x)}.\frac{\partial^2\varphi}{\partial x^2}\right)+(\rho.A).\omega^2.\varphi_{(x)}=0 \quad (4)$$

where, $\varphi_{(x)}$ is the mode shape, and ω is the beam bending frequency.

For a uniform beam with a constant mass per unit length ρA, and stiffness EI, the modal equation is given by

$$\frac{\partial^4\varphi_{(x)}}{\partial x^4}+\Omega^2.\varphi_{(x)}=0 \quad (5)$$

And the dimensionless mode shape is given by

$$\varphi_{(x)}=c_1\sinh(m.x)+c_2\cosh(m.x)+c_3.\sin(n.x)+c_4\cos(n.x) \quad (6)$$

where,

$\Omega^2=(\rho.A).\omega^2/(E.I)$, $m^2=\Omega$, and $n^2=-\Omega$.

5. Results and discussion

A laminated composite beam was fabricated using a vacuum bagging technique. The mechanical properties of a fabricated composite beam were determined. figure 11 shows the stress-strain curve of the mechanical tensile test. The slope of the average line of the specimens' lines represents the elastic modulus of the fabric. The slope of the average line was found about 28.2 GPa.

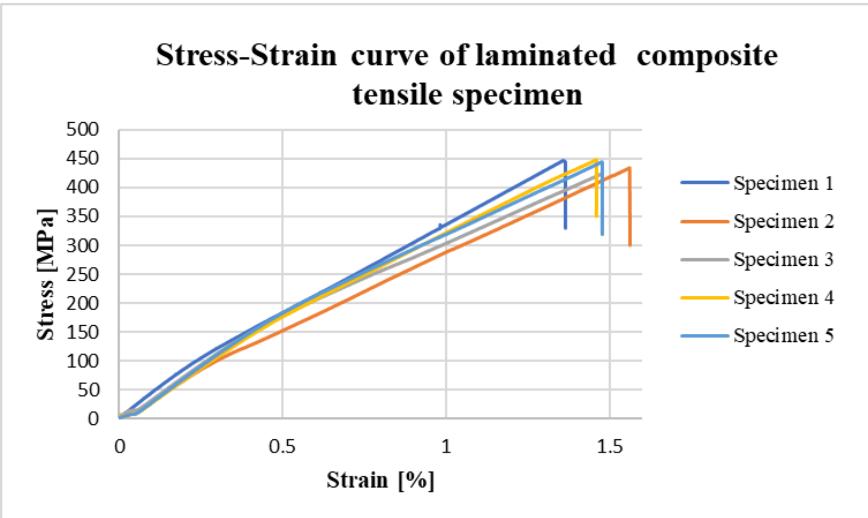


Figure 11. Stress Strain curve of laminated composite tensile specimen.

A measurement experiment was conducted to determine the natural frequencies of the laminated beam being studied. The frequency response of the beam was shown in figure 12. with the first and second modes being 18.51 Hz and 113.2 Hz, respectively.

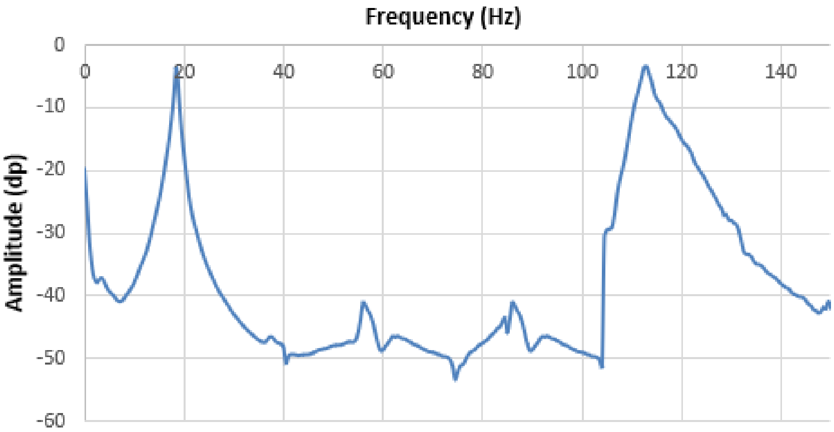
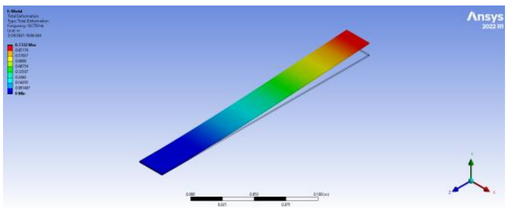
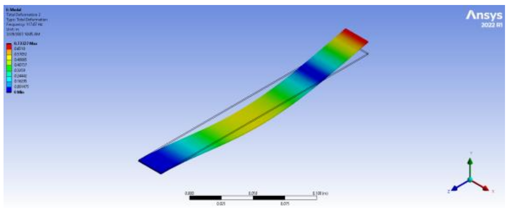


Figure 12. Output FRF graph of the experimental work.

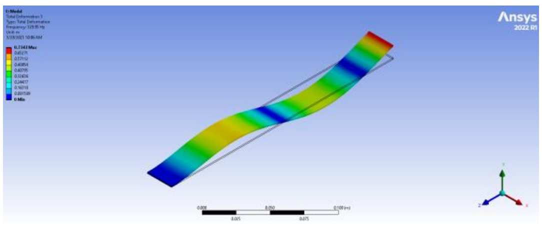
Numerical modal analyses provide an extra feature of showing the modes of vibration of the beam. The first three bending modes of vibration are shown in figure 13.



a) 1st mode.



b) 2nd mode.



c) 3rd mode.

Figure 13. Bending mode shapes of the composite laminated beam.

Table 2 compares the natural frequencies of the first three bending modes as determined experimentally, numerically, and theoretically. The findings reveal a strong concurrence between the experimental, numerical, and theoretical approaches. However, there is some deviation, which may be attributed to various factors such as measurement noise, accelerometer positioning and mass, non-uniformity in specimen properties during the experimental process, mesh quality in numerical analyses, and assumptions made in theoretical models. These factors are not considered during the theoretical and numerical analysis, as the models assume a perfectly homogeneous specimen, which is rarely the case in real-world scenarios.

Table 2. Comparison between experimental, numerical, and theoretical results.

Mode	Natural Frequency [Hz]			Deviation of experimental values [%]	
	Experimental	Numerical	Theoretical	Against numerical	Against theoretical
1st Mode	18.5	18.77	18.63	1.43	0.69
2nd Mode	113.2	117.67	116.78	3.79	3.06
3rd Mode	--	329.95	327	--	--

6. Conclusion

The current study employs both numerical and theoretical models to assess and evaluate the manufacturing and experimental processes of a fabricated composite beam. Additionally, the free vibration analysis of the beam is explored through experimental modal analysis. The modal testing results were assessed by comparing them to the results of the modal analysis performed using both the numerical and theoretical methods, which were found to be consistent with each other. The main conclusions that can be drawn from this investigation are the importance of characterizing composite materials and their significance in calculations and modal analysis. Also, according to the great convergence between the results of the three models, it is clear that it is not difficult to fabricate a good quality structure made from composite materials with certain specifications. While drawing attention to any defect that occurs during the manufacturing process that may lead to completely undesirable results.

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