Evaluation and modeling the static and free vibrational behaviours of AA3003/CFRP honeycomb sandwich structures

Ragavan R and Pitchipoo P

1 Department of Mechanical Engineering (R&AC), PAC Ramasamy Raja Polytechnic College, Rajapalayam/TN, India
2 Department of Mechanical Engineering, PSR Engineering College, Sivakasi/TN, India

E-mail: ragavan.mech2011@gmail.com

Keywords: AA3003, CFRP, honeycomb sandwich, mechanical properties, damping factor

Abstract
Honeycomb structures are widely applied to many aerospace applications nowadays. Research in the successful manufacturing of sandwich composites itself is a thrust area to many advanced materials researchers. Nevertheless, in real service conditions, all the produced sandwich structures are commissioned after many machining processes. Abrasive water jet machining is one of the exclusive methods of machining high brittle structures. Honeycomb structures layered with carbon or Kevlar taps possess very high brittle kind of behaviors. Henceforth, Abrasive Water Jet machining can be adopted for producing net designed shape. The present work investigates enhancing the mechanical response of AA3003 honeycomb of 0.4 mm cell-wall thickness after skinned with carbon fiber epoxy composite layers. Composite layers of 0.6 mm are staked on both sides and glued using Araldite. 12 h oven curing has been employed at 60 °C. Conditioned samples have proceeded for standard mechanical characterizations in addition to the free vibrational and damping properties. A novel approach to measure the sandwich panel’s damping is experimented with in this work by conducting impact hammer excitation to stimulate the possible modes in the integrated system. Finally, the mechanical properties of sandwich panels are investigated by simulation software along with the experimental methods. Further, the analytical results are compared, and the results reveal that an increase in core thickness enhanced the sandwich composites’ damping behavior. Coupons have been taken from various regions to balance the uncertainty. The experimental results show the significant enhancement of the aluminum core’s rigidity due to the composite lapping.

1. Introduction
Two thin sheets, which are stiffer, are bound together between the softcore, known as sandwich composite. Due to low strength, the sandwich is usually constructed with higher thickness to increase the bending strength. In common, several metals’ honeycombs are mainly staked as core in sandwich sheets to impart more significant static and dynamic strengths. On the other side, the aerospace and automotive industries require flat panels of lightweight structures to enable smoother installation, and they are good with sealing the undesired airflow. The Aluminum Honeycomb Sandwich (AHCS) panels consist of two aluminum plates as face sheets and aluminum honeycomb of the hexagonal cell as core material. A durable adhesive resin glues together the face sheets and core.

Many researchers have studied the mechanical properties of aluminum with CFRP honeycomb core. Several reports are found on the numerical modeling of honeycomb structures for various conditions like compression [1], low-velocity impact [2], and three-point bending [3]. Jianfeng Wang et al [4] have investigated the properties of high temperature cured carbon composite with aluminum honeycomb. A three-point bending test has been employed to study the core thickness and density effects and the peeling test results.

Henrik Eschen et al [5] have suggested a phenomenon for manufacturing planar sandwich panels in an automated manner by constituting NOMEX honeycomb and fiber composite face sheets. Process chain
optimization, honeycomb potting, and sandwich laying are conceptually defined in work. The single and double-hump curves that belong to load-displacement relations are narrated with the support of experiments [6]. The report specifies that greater failure stages are noted for the top and bottom than the honeycomb core indicated from the energy-displacement curve. On the other hand, the machining of sandwich composites has also received attraction. Kunxian Qiu et al [7] have presented the defects experienced during the machining of the honeycomb core. For an entrance angle of 17° and 80°, most machining defects like irregularities and burrs are noted. Based on the experimental results, a model for the cutting force has been developed to anticipate the milling force for various cutting conditions like feed, speed, and tool angle. Yong Xiao et al [8] have researched the honeycomb bending during the dynamic configuration of various configurations of CFRP beams filled with honeycombs. Further, the sandwich and another kind of hybrid stacking viz., interlaced hybrid sequences, are explored and reported [9]. A kevlar49/S-glass laminate and IM7-carbon/boron laminates are developed and analyzed to know the hybrid stacking sequence’s generalized effects. ASM Ashab et al [10] have studied the first extension of the out-of-plane indentation of a honeycomb made of aluminum with varying loading velocities. Honeycomb dynamic properties and quasi-static mechanical properties are investigated comparatively towards the effect of strain rate. By employing the compression and bending examinations, the NOMEX honeycomb sandwich’s fatigue and static behaviors are analyzed [11]. Experimental data are adopted to develop numerical simulation to predict fatigue endurance. In the meantime, necessary stiffness values are fed into the model as obtained from the experiments. Most automobile and space material sectors prefer carbon/epoxy laminates as face sheets for the sandwich composites due to their lightweight, corrosion protection, and flexibility in manufacturing [12–14].

The experimentation done by Thomsen et al [15] on various CFRP sandwiched composites with honeycomb reports that intra-cell buckling might offer an accurate prediction about the compression response of the sandwich composites than the classical design formulae. Yahaya et al [16] have conducted projectile impact studies to compare honeycomb efficiency with monolithic plates and foams and reported that the honeycomb sandwich has outperformed within the impulse range 2.25–4.70 kNms m⁻². Kantha Rao et al [17] have conducted 3-point bending studies to compare the Aluminum honeycomb with plain aluminum. The properties are evaluated for varying load conditions, such as axial compression and lateral crushing [18]. Modeling such a system through analytical and numerical shows a good deal with the experimental results [19]. To prove the independence in honeycomb’s core height, Zhang et al [20] have developed prediction at the compression test and confirmed that the honeycomb’s compressive behavior depends on the core’s density.

Additionally, the role of vibrational behaviors is also attracting material engineers, since most aerospace and automotive components are failed due to resonance and other properties [21, 22]. Recent researchers mainly focus on the modal analysis of vegetable fibers, since they assume that the vegetable fiber composites are the best alternatives to the synthetic fiber composites [23]. Generally, the influences of fiber length and weight percentage on mechanical properties and free vibration characteristics are mainly analyzed by the researchers [24]. Berthelot [25] has measured the damping parameters of unidirectional beams of glass fiber and Kevlar fiber composites as a function of fiber orientation and evaluated the results using the Ritz method and concluded that beam and plate damping depend on the vibration modes. Rajini et al [26] have investigated the effect of nanoclay addition on free vibration response using the impact hammer method for the MMT/Coconut-sheath hybrid polymer composite. The resonant amplitude of vibration is significantly influenced by modal damping associated with each mode of the structure. Generally, damping associated with fiber-reinforced composite structures is higher than the conventional metal structures, due to the viscoelastic behavior, fiber-matrix interaction, and damping due to damage [27, 28].

Here, the sandwich structures’ strength and stiffness with carbon fiber-reinforced panels and an aluminum honeycomb core material are studied. The effects of material density and thickness are analyzed by mechanical testing. The optimal combination of sandwich structure parameters to reinforce the material could be obtained by analyzing the test results. In most of the reported cases on sandwich structures’ dynamic properties, the blasting and impact methods are employed. In contrast, in the present study, the dynamic property is uniquely evaluated through a non-destructive technique.

2. Fabrication process

2.1. Materials

AA3003 Honeycomb sandwich panels have been purchased from Eco earth solution OPC Pvt Ltd, Maharashtra, India, and the carbon fiber sheets are purchased from Veermak Industries Pvt Ltd, Coimbatore, India. The Araldite used as a binder has been obtained from a nearby local market in Madurai, Tamilnadu. Table 1 shows the basic properties of the carbon/epoxy sheet and honeycomb used in this study.
2.2. Fabrication of composite

Aluminum honeycomb sandwich panels are produced through a simple compression route. Sandwiches are fabricated with three different core thicknesses viz., 15, 25, and 35 mm. Pre-cured carbon/epoxy materials are prepared to pack two extremities. Araldite has been used as a binder. The AA3003 and CFRP are bonded together with the adhesive material (Araldite) carefully by avoiding bubble formation, as shown in figure 1, and loaded in the compression molding machine with 2.0 MPa. The loaded sandwich is left aside for 12 h for full curing, followed by the abrasive water jet machine to be sized according to the test requirements.

The codes followed, and the related properties of the fabricated sandwich composite are presented in table 2. The densities and hardness of the sandwich composite are linearly increasing with the increase in core thickness. In the meantime, the density is found almost stable in all cases.

2.3. Static testing

Compression characterization has been carried out in a UTM with a specimen dimension of 50 × 50 mm. The specimen is fixed between two adjustable grips of computerized UTM and the test was conducted at a...
1 mm min$^{-1}$ crosshead speed as shown in figure 2. The flatwise compression is conducted according to ASTM C365. An average of five is reported in the discussion.

Also, three-point bending was conducted as per ASTM C393 by keeping the specimen dimension 200 $\times$ 50 mm. Theoretical modeling and simulation were done in software in the explicit dynamic module. Results are compared for design competency, and a good deal is found between the experimental and the theoretical approaches.

2.4. Modal analysis

The impact hammer excitation method has been employed (figure 3) to study the fabricated sandwich composites’ vibrational behaviors as a function of core thickness. The specimen’s frequency response function is analyzed using the FFT Analyzer, which consists of an impact hammer and accelerometer for excitation and collecting the frequency response, respectively. The sandwich composite is fixed at one end as a cantilever beam using a C-clamp and excited at another end. The impulse is given several times, especially in three different
3. Results and discussions

3.1. Mechanical characterization
Flexural and compression tests are conducted as per ASTM standards. The experimental results are presented in the following figures and tables. The three-point bending test has been driven by loading at mid-span, as described in the ASTM C393. The specimen’s width is kept twice the over-all sandwich thickness, and length is 220 mm uniformly. The sandwich structure has been loaded with a steel bar indenter. Figure 4 shows the bending stress variation, which is conducted flatwise on the fabricated sandwich structures. A linear progressive loading on the sandwich is noted in figure 4(a). The load required to make the plastic strain is increasing trend concerning the core thickness. The force required to deflect the 15 mm core composite is less compared to the other observed composites. A linear incremental trend is noted with the results obtained. The force applied is the maximum with t35mm core sandwich composites.

On the other hand, the stress generated is higher with the intermediate core dimension. At the onset, the stress-induced is the maximum with a 15 mm core sandwich, and the meanwhile progressive plastic strain noted in figure 4(b) reveals no increase in stress generation. At the same time, other sandwich composites have produced linear stresses which are reported in several literatures [4].

Figure 5, illustrates the fractured samples taken from the three-point bending. Face sheet fracture placed on the supporting end is failed with the cross-cracks that have grown in the middle. A typical load transferring mechanism noted with the fractured image attributes the proper adhesion establishment between the honeycomb and carbon/epoxy face sheets. Further, in all the experiments, the honeycomb crashing is not noticed, and hence, the usage of narrow plates during the experimentation has been avoided, as suggested in ASTM C393. Further, the no-slip during the investigation is also noticed, and it proves the correctness of
experimentation. Also, the same experiment has been modeled and analyzed using a software tool. The carbon fabric and Araldite epoxy properties are obtained from the supplier and fed into the further analysis model. The aluminum honeycomb model has been developed using the specific module. Gluing and meshing are done to perform the analysis in an explicit module. While the simulation, the nodes constructed for each core thickness are 62,500, 70,000, 92,200, and the elements are 35,480, 39,840, 51,980 for 15C, 25C, and 35C, respectively obtain accurate simulation.

Figure 6 illustrates the simulated deformation of the fabricated honeycomb composites in all the 3-core thicknesses. The 3-point bending experiment is simulated with a crosshead speed of 1 mm min$^{-1}$, and simulation is stopped with the deflection of 2 mm maximum. Figure 6(a) represents the stress distribution map. It can be observed the maximum stress concentrated on the loading point of the top face sheet. The bending experiment was simulated by keeping the lower two supports are fixed, and the displacement was given from the top. The support plates were marked as frictionless contact. As similar to the bending, in compressive simulation, the top and bottom support plates are in frictionless contact, and compression was given from the top.

Similarly, the other stress distribution maps are also concentrated on the top face sheets’ loading point. An identical deformation is also noted with the experimental cases. Further, all the tested samples are fractured at the lower face sheets, and the first bending is initiated at the top face sheet.

Figure 7 shows the axial compression response of the sandwich composites as a function of core thickness. Figure 7(a) illustrates the force elongation relationships. Like bending performance, in compression, the increase in core thickness requires more force during the contraction. At the same time, the stress produced linearly increases with the increase in strain. Figures 7(c), (d) shows the sandwich composite before and after compression. The compression is uniform across the volume (figure 7(c)), and the same is also observed with the simulated results (figure 7(d)).

Table 3 presents a comparison between the experimental and numerical values of the sandwich studied. A good agreement between the results was found, which confirms the validation of the sandwich fabricated’s mechanical properties.

### 3.2. Vibration analysis

Free vibration characteristics of fabricated AA3003/CFRP composites are studied using the Kistler model 9722A500 kit. The sample length and width are kept uniform for all the three thicknesses of the core as 250 × 50 mm. A sharp hardened impact hammer has been used in exciting the fabricated composite. The displacement signals are acquired by an accelerometer glued at the end of the composite by wax, and they are...
recorded using a data acquisition system. Two separate adaptors have been used for capturing the output signal. One is attached with the impact hammer, and the other is fixed at the sandwich composite’s free end. In this study, the natural frequency and damping have been measured and calculated using the impact hammer technique, as shown in figure 3.

Figure 8(a) illustrates the signal obtained from the DEWE software during the impact excitation of the sandwich composites. The same has been further processed with Fast Fourier Transformation (FFT) to discrete the signal to get various modes’ natural frequencies. In the present case, the impact excitation can excite only three modes in the sandwich composite, as marked in figure 8(b).

Table 3. Comparison of the experimental and numerical results of sandwich composites.

| Sample code | Experimental bending strength (MPa) | Bending strength simulated (MPa) | Experimental compressive strength (MPa) | Compressive strength simulated (MPa) |
|-------------|-----------------------------------|---------------------------------|---------------------------------------|-----------------------------------|
| 15c         | 2318                               | 2538                            | 3807                                  | 3699                              |
| 25c         | 2467                               | 2590                            | 3885                                  | 4643                              |
| 35c         | 2666                               | 2244                            | 3367                                  | 3130                              |
Further, in free vibration, the energy dissipation is expressed in mechanical vibration, which ends with the motion amplitude decay. The free vibration can be obtained for each mode directly from the acquired data. The damping would be calculated by employing the half-power bandwidth method; the resonant peak’s sharpness will measure the damping. Figure 9 illustrated the technique used in damping calculation, and equation (1) shows the expression followed in obtaining the damping factor from the acquired signal.

$$\zeta = \frac{\Delta \omega}{2\omega_n}$$

Where, $\Delta \omega$ is the bandwidth at the $n$th mode’s resonant peak at the half-power points, and $\omega_n$ is the resonant frequency.

Table 4 presents the effect of core thickness on the vibrational properties of the sandwich composites. The natural frequency is high in all the three exciting modes in a 15 mm core sandwich. On the other hand, an intermediate response in the 25 mm core sandwich’s natural frequency is recorded. Further, the natural frequency of the 35 mm core composite is found the lowest among the experimented composites. The excitation is given by keeping the sandwich as a cantilever beam in flatwise. On excitation, any one of the natural frequencies with the excitation frequency results in a deformation pattern. As fabricated sandwich composites, it is noted that three modes of deformation pattern have excited during the excitation. The first mode is simple bending, when excited, dwells with the first frequency, which is 473.63 Hz for the 15C sandwich composite. The second mode of deformation is twisted and during the excitation, it is at a higher frequency (1005.86 Hz) for 15C sandwich composites. The third dwell excites the mode three deformations, second bending, and a higher frequency (1499.02 Hz).

Table 4. Variation in natural frequencies and modes concerning core thickness.

| Sandwich code | Mode 1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) |
|---------------|-------------|-------------|-------------|
| 15C           | 473.63      | 1005.86     | 1499.02     |
| 25C           | 345.46      | 675.50      | 968.15      |
| 35C           | 217.29      | 346.68      | 437.01      |

Further, in free vibration, the energy dissipation is expressed in mechanical vibration, which ends with the motion amplitude decay. The free vibration can be obtained for each mode directly from the acquired data. The damping would be calculated by employing the half-power bandwidth method; the resonant peak’s sharpness will measure the damping. Figure 9 illustrated the technique used in damping calculation, and equation (1) shows the expression followed in obtaining the damping factor from the acquired signal.

$$\zeta = \frac{\Delta \omega}{2\omega_n}$$

Where, $\Delta \omega$ is the bandwidth at the $n$th mode’s resonant peak at the half-power points, and $\omega_n$ is the resonant frequency.

Table 4 presents the effect of core thickness on the vibrational properties of the sandwich composites. The natural frequency is high in all the three exciting modes in a 15 mm core sandwich. On the other hand, an intermediate response in the 25 mm core sandwich’s natural frequency is recorded. Further, the natural frequency of the 35 mm core composite is found the lowest among the experimented composites. The excitation is given by keeping the sandwich as a cantilever beam in flatwise. On excitation, any one of the natural frequencies with the excitation frequency results in a deformation pattern. As fabricated sandwich composites, it is noted that three modes of deformation pattern have excited during the excitation. The first mode is simple bending, when excited, dwells with the first frequency, which is 473.63 Hz for the 15C sandwich composite. The second mode of deformation is twisted and during the excitation, it is at a higher frequency (1005.86 Hz) for 15C sandwich composites. The third dwell excites the mode three deformations, second bending, and a higher frequency (1499.02 Hz).

Figure 10 illustrates the variation in the damping ratio of sandwich composites. The damping factor is calculated from the acquired and processed signals. It is expected that higher core thickness intends to absorb more vibration during excitation. The results support the anticipations. At first, the bending deformation mode exists, and the damping is 0.47, which is lower among all the tested experiments. Further, a 13% increase in damping is noted with the increase in core thickness, and also, when the core thickness is increased to 35 mm, the damping hikes by 39% of 15 mm core values. The increase in core thickness offers porosity to the entire structure, and it enhances the damping properties.
4. Conclusion

In this study, aluminum honeycomb sandwich panels are produced through a simple compression route. An experimental study of the AA3003/CFRP sandwich structure produced by epoxy resin has been presented. Based on the results of the study, the following conclusion is drawn.

- The bending performance of the sandwich composite is found increasing with an increase in the core thickness. The honeycomb members' buckling during bending is expected, but the intender’s compression has made the honeycomb member deflect instead of buckling. This attribute slips in the honeycomb-face sheet interface. Hence, further research on adhesion is motivated here.
- The analytical model developed and simulated shows a good deal with the experimental observations.
- In vibrational properties and significantly damping in concern, higher core thickness has offered more vibration absorption. The obtained results encourage the application of studied materials for the automotive and aviation applications.

ORCID iDs

Ragavan R @ https://orcid.org/0000-0002-9339-7806
Pitchipoo P @ https://orcid.org/0000-0002-2850-6084

References

[1] Mirazo J M and Spearing S M 2001 Damage modeling of notched graphite/epoxy sandwich panels in compression Appl. Compos. Mater. 8 191–216
[2] Meo M, Morris A J, Vignjevic R and Marengo G 2003 Numerical simulations of low-velocity impact on an aircraft sandwich panel Compos. Struct. 62 355–60
[3] Giglio M, Gilioli A and Manes A 2012 Numerical investigation of a three point bending test on sandwich panels with aluminum skins and NomexTM honeycomb core Comput. Mater. Sci. 56 69–78
[4] Wang J, Shi C, Yang N, Sun H, Liu Y and Song B 2018 Strength, stiffness, and panel peeling strength of carbon fiber-reinforced composite sandwich structures with aluminum honeycomb cores for vehicle body Compos. Struct. 184 1189–96
[5] Eschen H, Harnisch M and Schüppstuhl T 2018 Flexible and automated production of sandwich panels for aircraft interior Procedia Manuf. (Elsevier BV) pp 35–42
[6] Wu Y, Liu Q, Fu J, Li Q and Hui D 2017 Dynamic crash responses of bio-inspired aluminum honeycomb sandwich structures with CFRP panels Compos. Part B Eng. 121 122–33
[7] Qiu K, Ming W, Shen L, An Q and Chen M 2017 Study on the cutting force in machining of aluminum honeycomb core material Compos. Struct. 164 58–67
[8] Xiao Y, Hu Y, Zhang J, Song C, Liu Z and Yu J 2018 Dynamic bending responses of CFRP thin-walled square beams filled with aluminum honeycomb Thin-Walled Struct. 132 494–503
[9] Potluri R and Syam Dheeraj R 2018 GVNGV Vital, Effect of stacking sequence on the mechanical & thermal properties of hybrid laminates Mater. Today Proc. (Elsevier Ltd) pp 5876–85
[10] Ashab A M, Ruan D, Lu G, Xu S and Wen C 2015 Experimental investigation of the mechanical behavior of aluminum honeycombs under quasi-static and dynamic indentation Mater. Des. 74 138–49
[11] Wu X, Yu H, Guo L, Zhang L, Sun X and Chai Z 2019 Experimental and numerical investigation of static and fatigue behaviors of composites honeycomb sandwich structure Compos. Struct. 213 165–72
[12] Liu Q, Lin Y, Zong Z, Sun G and Li Q 2013 Lightweight design of carbon twill weave fabric composite body structure for electric vehicle Compos. Struct. 97 231–8
[13] Koricho E G and Belingardi G 2015 An experimental and finite element study of the transverse bending behaviour of CFRP composite T-joints in vehicle structures Compos. Part B Eng. 79 430–43
[14] Liu Q, Mo Z, Wu Y, Ma J, Pong Tsui G C and Hui D 2016 Crush response of CFRP square tube filled with aluminum honeycomb Compos. Part B Eng. 98 406–14
[15] Thomsen O T and Banks W M 2004 An improved model for the prediction of intra-cell buckling in CFRP sandwich panels under in-plane compressive loading Compos. Struct. 65 259–68
[16] Yahaya M A, Ruan D, Lu G and Dargusch M S 2015 Response of aluminium honeycomb sandwich panels subjected to foam projectile impact—an experimental study Int. J. Impact Eng. 75 100–9
[17] Rao K K, Rao K J, Sarwade A G and Madhava Varma B 2012 Bending Behavior of Aluminum Honey Comb Sandwich Panels International Journal of Engineering and Advanced Technology 1 268–72 https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.678.3714&rep=rep1&type=pdf
[18] Kee Paik J, Thayamballi A K and Sung Kim G 1999 Strength characteristics of aluminum honeycomb sandwich panels Thin-Walled Struct. 35 205–31
[19] Abbadi A, Koutsawa Y, Carmasol A, Belouettar Sand Azari Z 2009 Experimental and numerical characterization of honeycomb sandwich composite panels Stain. Model. Pract. Theory. 17 1533–47
[20] Zhang J and Ashby M F 1992 The out-of-plane properties of honeycombs Int. J. Mech. Sci. 34 475–89
[21] Rajini N, Winowlin Jappes J T, Siva I, Varada Rajulu A and Rajakarunakaran S 2017 Fire and thermal resistance properties of chemically treated ligno-cellulosic coconut fabric–reinforced polymer eco-nanocomposites J. Ind. Text. 47 104–24
[22] Rajini N, Jappes J W, Rajakarunakaran S and Siva I 2012 Tensile and Flexural Properties of MMT-Clay/Unsaturated Polyester Using Robust Design Concept 2 87–101
[23] Senthil Kumar K, Siva I, Jeyaraj P, Winowlin Jappes J T, Amico S C and Rajini N 2014 Synergy of fiber length and content on free vibration and damping behavior of natural fiber reinforced polyester composite beams Mater. Des. 56 379–86
[24] Murali Mohan Rao K, Mohana Rao K and Ratna A V 2010 Prasad, Fabrication and testing of natural fibre composites: vakkka, sisal, bamboo and banana Mater. Des. 31 508–13
[25] Berthelot J M 2006 Damping analysis of laminated beams and plates using the Ritz method Compos. Struct. 74 186–201
[26] Rajini N, Jappes J W, Rajakarunakaran S and Jeyaraj P 2013 Dynamic mechanical analysis and free vibration behavior in chemical modifications of coconut sheath/nano-clay reinforced hybrid polyester composite J. Compos. Mater. 47 3105–21
[27] Jeyaraj P, Ganesan N and Padmanabhan C 2009 Vibration and acoustic response of a composite plate with inherent material damping in a thermal environment J. Sound Vib. 320 322–38
[28] Berthelot J M 2006 Damping analysis of orthotropic composites with interleaved viscoelastic layers: modeling J. Compos. Mater. 40 1889–909