DYNAMIC BEHAVIOR OF FML/ALUMINUM HONEYCOMB SANDWICH STRUCTURES USING VIBRATING BEAM TECHNIQUE

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ABSTRACT

For the current study, Fiber Metal Laminates (FML) in the form of Glass Laminate Aluminum Reinforced Epoxy (GLARE) and an aluminum honeycomb have been used to construct sandwich structures. Dynamic values of the structures have been measured using a non-contact vibrating beam test with free-free end conditions. A numerical modal analysis via the Altair Hyperworks 2019 Software has also been conducted. The results from the experimental and numerical works have been found in a good agreement. The effects of different fiber orientations of the laminates on the fundamental natural frequency, equivalent flexural modulus and especially damping values of the sandwich structures seem considerable.

Keywords: FML, GLARE, modal analysis, aluminum honeycomb, sandwich beam.
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1. INTRODUCTION

Use of aluminum materials in the construction of aerospace, automotive and ship industries is quite common due to their strong, lightweight, predictable and inexpensive features. One of their well-known applications is in the form of sandwich structures that include two stiff face sheets and a flexible core of honeycomb [1-4]. An aluminum honeycomb is bonded to the face sheets via an adhesive layer that leads to a compacted sandwich structure with high specific strength and weight ratios. Such aluminum sandwich structures are especially preferred in the applications where relatively high temperature and humidity environment exist. However, poor performance of these structure in terms of the vibration damping and the sound transmission makes their applications limited. On the other hand, use of fiber reinforced polymer matrix composites is a good option, being used as face sheets in the constructions of the sandwich structures [5-7]. Unfortunately, these materials too are not exempt from some disadvantageous such as being prone to deterring in high temperature and humidity environments, to fragile behavior resulting in cracks [8-9], delamination [10-11] and debonding [12-13]. In order to overcome the relevant disadvantages of these materials (aluminum and polymer composites), a concept of hybrid material system has been proposed; Fiber Metal Laminates (FMLs) interlacing fiber reinforced polymer (FRP) and metal sheets were initially designed for the aerospace industry. Although the hybrid systems can include some metals such as titanium [14-15] and magnesium [16-17], the main one is the aluminum-based FML in the form of different fibers; Aramid Fiber Reinforced Aluminum Laminate (ARALL) [18], Carbon

Reinforced Aluminum Laminate (CARALL) [19], and Glass Reinforced Aluminum Laminate (GLARE) [20-25].

Despite numerous aforementioned works at high stress levels to failure, there are only a few studies on the hybrid composite structures subjected to vibration tests at low stress levels. For example, Mohandes et al. [26] studied the free vibration of FML thin circular cylindrical shells with different boundary conditions. Strain–displacement relations were obtained according to Love's first approximation shell theory. The results showed that the influences of FML lay-up and volume fraction of composite on the frequencies of the shell were remarkable. In another theoretical work [27], the free vibration analysis of rotating and non-rotating FML beams, hybrid composite beams (HCB), and functionally graded beams (FGB) were investigated. The effects of different metal alloys, composite fibers, and different aspect ratios and angular velocities on the free vibration analysis of FML beams were studied. The effects of different angular velocities and different aspect ratios of rotating and non-rotating hybrid composite beams were also investigated. Other than similar theoretical works [28-30], the characterization of the elastic and damping properties of a traditional FML and an FML based on a self-reinforced polypropylene (SRPP) was carried out experimentally [31]. Both laminates were characterized in the frequency domain by means of a forced vibration test with a resonance technique where the Young's complex modulus was extracted. In addition to both FMLs, the aluminum employed in both laminates was characterized as reference material. The results showed that the FML based on a SRPP offers higher damping capacity than the traditional FML. Ameri et al. [32] investigated the fundamental frequency analysis of different types of materials, including isotropic, fiber-reinforced orthotropic composites, and FML hybrid composite in the presence and absence of honeycomb core, using the Rayleigh-Ritz method. To verify the obtained theoretical results, the FML beam with [Al/0^0/90^0/90^0/0^0/Al] lay-up pattern was fabricated by hand lay-up technique and subjected to clamped-free boundary condition. Accordingly, the free vibration experimental data confirmed the results which were obtained by the different theories.

In spite of many works related to the Fiber Metal Laminates (FMLs), it is believed that there is a lack of information about the FMLs being used as face sheets in the construction of sandwich structures. The purpose of this study is to investigate the dynamic performance of sandwich structures, composed of a FML used as face sheets and an aluminum honeycomb used as core material. The face sheets were manufactured from a Glass Laminate Aluminum Reinforced Epoxy (GLARE) that were composed of three thin layers of aluminum (Al) sheet and two layers of unidirectional fiberglass reinforced laminates. In this study, the main concentration is given to the dynamic values of the sandwich structures. A special emphasis has been made on the different fiber orientations of the glass laminate that is expected to contribute to damping performance of the structures. The dynamic values (damping and equivalent flexural modulus) of the sandwich structures have been measured using a non-contact vibrating beam technique with free-free end conditions. The experimental values measured at the fundamental natural frequency have been compared with the modal numerical analysis that was conducted using Finite Element Method via Altair Hyperworks 2019.

2. EXPERIMENTAL AND THEORETICAL WORKS

2.1 The Materials Used and Fabrication of the FMLs as Face Sheets

For the current work, three layers of Aluminum (Al) 2024-T3 sheets with 0.3 mm thickness were adhesively bonded to the glass fiber reinforced polymer matrix composite, Hexply 913/33%/UD280, produced by Hexcel, to construct the Fiber Metal Laminates (FMLs), in the form of Glass Laminate Aluminum Reinforced Epoxy (GLARE). Before the bonding process, the Al sheets were first chemically treated and then primer coated to get proper surface preparation for long term bond durability. After the surface preparation process, the laminates with different angles of fiber orientations were bonded to the Al sheets using an adhesive film (AF163-2K) produced by 3M. For the core material, an Al 5056 3/16" cell size and 0.0007" foil gauge honeycomb with a thickness of 25.42 mm thick was used. Due to the manufacture requirements, the honeycomb core contains continuous corrugated ribbons of relatively thin foil in the W direction. The foil ribbons are adhesively bonded to each other to form the honeycomb with a metal-to-metal bonding over all longitudinal walls that have the double thickness compared to the inclined walls of honeycomb cells. It is common to define the W direction and L direction as the longitudinal direction and transverse direction, respectively. It is well known that mechanical properties of the honeycomb as an orthotropic material are dependent on the W and L directions. For this study, the honeycomb was cut in the W direction to benefit from its low elastic property as it is likely to enhance the damping performance of the sandwich structure.

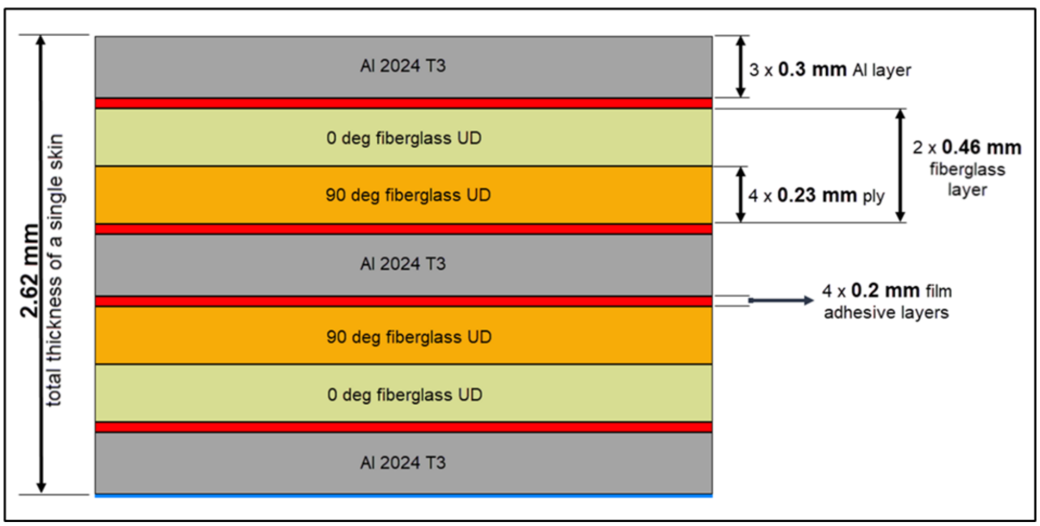


Fig. 1. A representative of the FML in the GLARE form that includes the materials used as the face sheets of the sandwich structure

To construct the sandwich beams, the core material was bonded to the FML face sheets using the same adhesive film (AF163-2K) that was cured at 125 ^{0}C for 60 minutes under a pressure of 2 bars. It is important to note that first the FMLs were vacuum bagged and cured in an autoclave at a temperature of 180 ^{0}C and pressure of 6.9 bars, and then bonded to the core material. The manufacturing process performed in a clean room was carried out under a controlled environment at room temperature and 50% relative humidity. In total, there were four different types of FML face sheets with different fiber orientations. The lay-ups of the FMLs in the form of GLARE consisting of 3 layers of aluminum 2024-T3 sheets and 2 layers of the glass fiber laminates were as follows; type1- [Al-$0^0/0^0$-Al-$0^0/0^0$-Al], type2- [Al-$90^0/90^0$-Al-$90^0/90^0$-Al], type3- [Al-$0^0/90^0$-Al-$90^0/0^0$-Al], and type4- [Al-$0^0/45^0$-Al-$45^0/90^0$-Al]. A representative example of the face sheet is shown Fig. 1 that is for the type3. Also, a detailed side view of the sandwich beam is indicated in Fig. 2 that consists of the constituent materials with their thicknesses. The dimensions and weight of the sandwich beams are shown in Table 1.

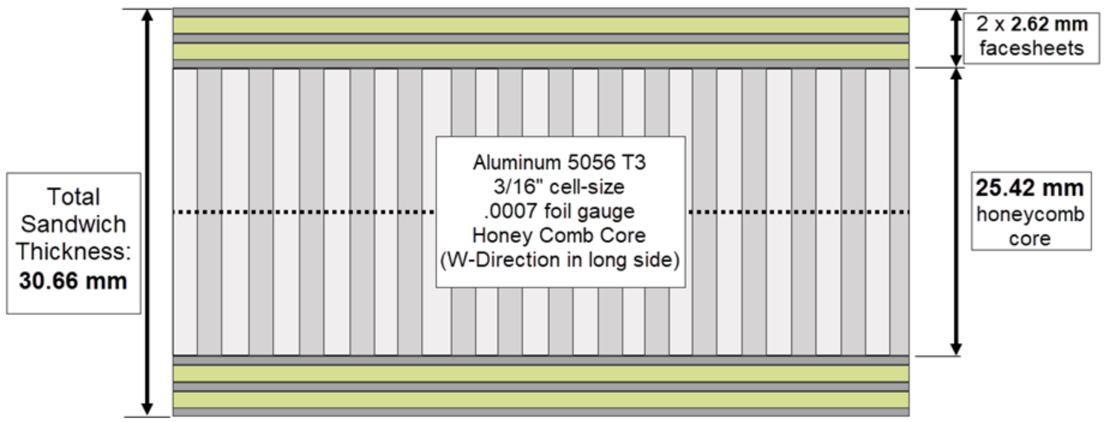


Fig. 2. A detailed side view of the sandwich structure that includes the FML face sheets and the aluminum honeycomb core

Table 1. The actual measurements of the sandwich beams

The sandwich beams	Width (mm)	Thickness (mm)	Length (mm)	Mass (g)	Density (kg/m^3)
type1- [Al-$0^0/0^0$-Al-$0^0/0^0$-Al]	60	30.66	520	383.75	401.00
type2- [Al-$90^0/90^0$-Al-$90^0/90^0$-Al]	60	30.66	520	372.87	389.79
type3- [Al-$0^0/90^0$-Al-$90^0/0^0$-Al]	60	30.66	520	378.15	395.30
type4- [Al-$0^0/45^0$-Al-$45^0/90^0$-Al]	60	30.66	520	381.35	398.65

2.2 The Experimental Set-up

To avoid any possible local damage of the sandwich beams in the test set-up during fixation procedure, all the beams were tested using free-free end conditions that allow the specimens to move freely without any restrains. The specimens under the test were also isolated from the measuring instruments that were an electromagnetic shaker and a laser doppler (laser head). For this purpose, the excitation of the specimens was produced by induced airflow and the response was picked up by the non-contact laser head shown in the experimental set-up in Fig. 3. In the test, the electromagnetic shaker connected to the power amplifier was used to produce sinusoidal movement of the beam. The response from the beam was detected via the laser head placed above. The input and output signals together connected to an oscilloscope to observe the resonant frequency and all measurements were made at resonance frequency. In vibrating the specimens, a non-contact mechanism was aimed as explained above. For this purpose, a thin plate with an area of 4 cm^2 was glued to the top of the shaker, and when it was vibrated, the plate was able to produce sinusoidal air flow and so to vibrate the specimen. It is believed that a true damping measurement of a material could be achieved by such a mechanism since there is no direct contact between the shaker and the specimen during the excitation, or between the specimen and the laser head during response pick-up (see Fig. 3).

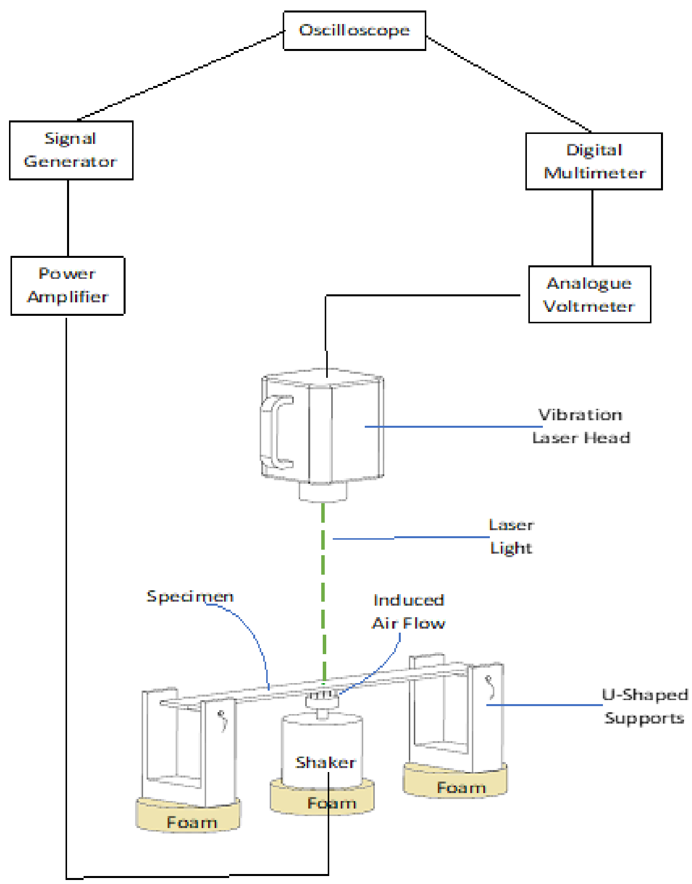


Fig. 3. Experimental set-up for vibrating beam technique with non-contact mechanisms

2.3 Measurement of the Equivalent Flexural Modulus of the Sandwich Beams

For every solid obeying Hook's Law, there is a specific natural frequency which is a function of its elastic modulus, geometry, density and the mode number. By using equation (1), the natural frequency of a beam is found as [33]:

$$f_n = \frac{1}{2\pi}(\frac{\lambda_n}{l})^2\sqrt{\frac{EI}{\rho t b}} \qquad (1)$$

where $\lambda_n = 4.730041$ is the 1st eigenvalue for free-free end conditions, n is the mode number, E is the equivalent flexural modulus, I is the second moment of area, l is the length, ρ is the equivalent mass density, t is the thickness, and b is the width of the beam. The flexural modulus of the specimen was measured using equation (1), and only the first (fundamental) natural frequency was taken into account for all the measurements.

2.4 Measurement of Damping

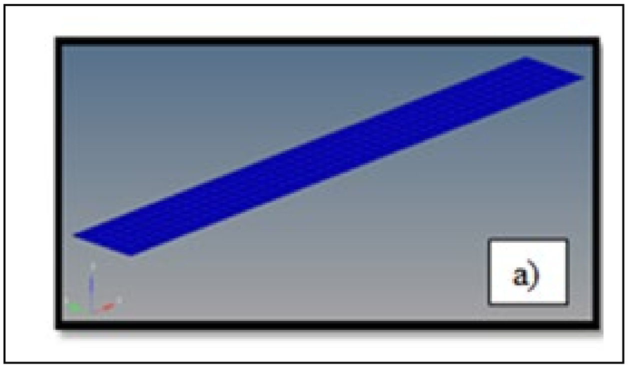
Since damping is the conversion of mechanical energy of a structure into thermal energy, it is defined in a number of different, yet related ways. Those commonly used are summarized by Singh [34]. For the current study, the half-power bandwidth method was used for measuring the damping value, formulated in equation (2).

$$\eta = \frac{f_2 - f_1}{f_n} \qquad (2)$$

where η is the loss factor which is one of the definitions of damping to explain energy dissipation in materials, and where f_2 and f_1 are the frequencies at which the displacement falls to $1/\sqrt{2}$ of its maximum value, which is reached at f_n, the resonant frequency.

2.5 Numerical Modal Analysis

Altair Hyperworks 2019 software has been used to conduct the Finite Element Analysis (FEA) for each specimen presented in Table 1. The specimens have been meshed with QUAD4 element type that is suitable for shell model as seen in Fig. 4a. In order to keep mesh related uncertainties to a minimum, the mesh model provides straightforward solutions. Analysis has been performed on the shell model, and the expansion of shell model image is presented in Fig. 4b that is a 3-D detailed expanded view. The specimens were modelled using free-free boundary conditions. The input data for the analysis for isotropic materials are shown in Table 2, where E denotes Young's modulus, G, shear modulus. For orthotropic materials, the data used in the analysis are presented in Table 3, where E_1 denotes modulus of elasticity in longitudinal direction, also defined as the fiber direction, E_2 for modulus of elasticity in lateral direction, G_{12} as in-plane shear modulus, G_{1Z}, transverse shear modulus for shear in 1-Z plane, G2Z transverse shear modulus for shear in 2-Z plane. NU denotes Poisson's ratio, and RHO, mass density for both isotropic and orthotropic materials. Note that, in the FEA, the in-plane shear modulus and both Young's moduli of honeycombs are kept very low and Poisson's ratio is given as zero.



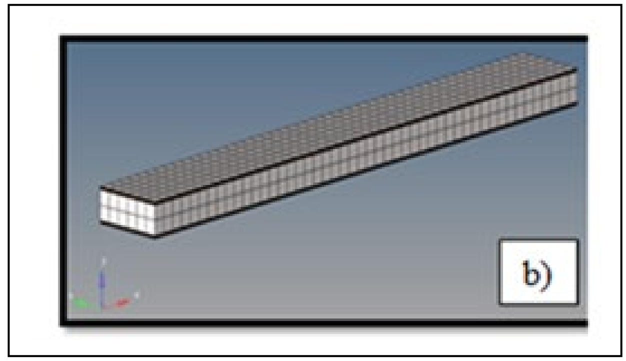


Fig. 4. a) 2-D meshed shell model, b) 3-D expanded view of the sandwich beam

Table 2. Input data used in the FEA for the isotropic materials

Material Properties	Al 2024-T3 Sheet Metal	AF-163-2K Epoxy Film Adhesive
E (MPa)	73100	1103
G (MPa)	28000	439
Nu	0.33	0.25
Rho (kg/m^3)	2780	1100

Table 3. Input data used in the FEA for the orthotropic materials

Material Properties	Al 5056-T3 3/16" Cell Size .0007 Foil Gage Honeycomb	Hex-Ply 913 S2 Glass Fiber Plies
E_1 (MPa)	1	45800
E_2 (MPa)	1	12950
G_{12} (MPa)	0.6	4810
G_{1Z} (MPa)	186.158	4810
G_{2Z} (MPa)	89.632	4981
Nu	0.0	0.30
Rho (kg/m^3)	16.02	1850

3. RESULTS AND DISCUSSION

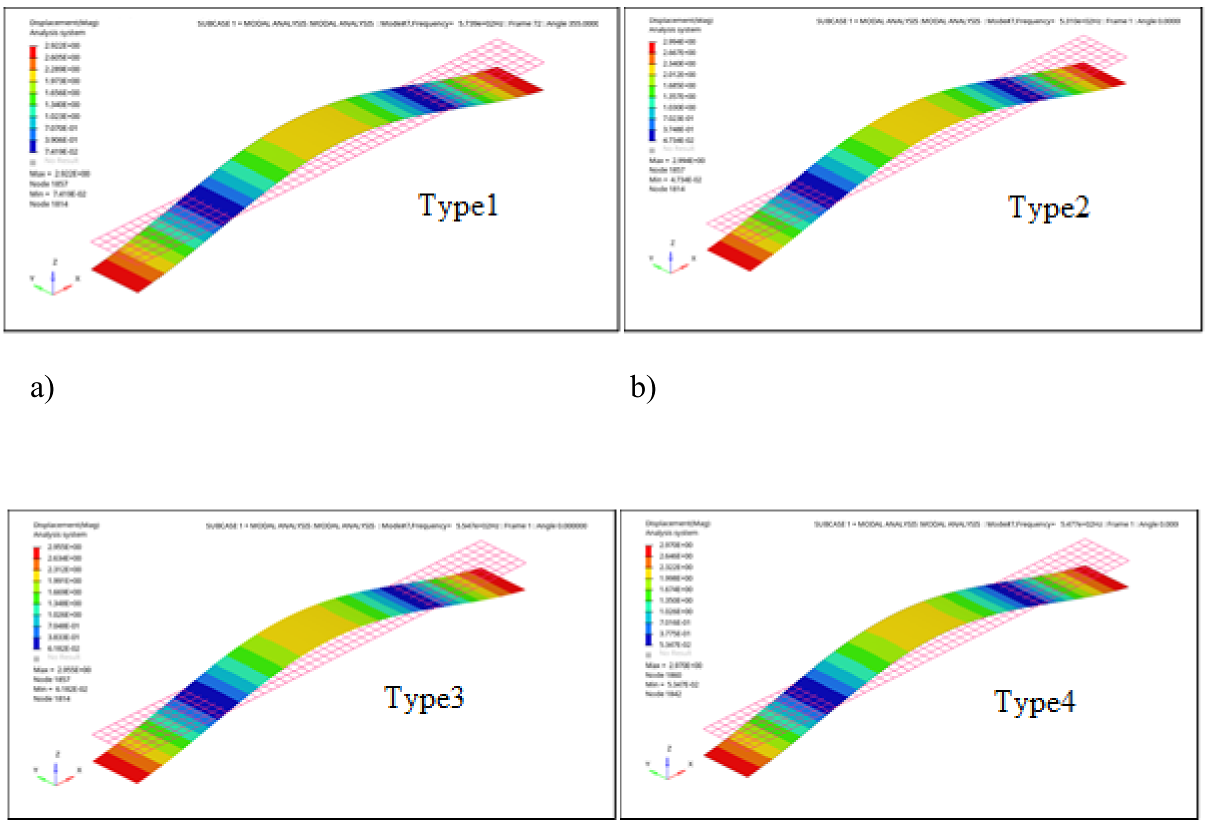
The results from the effects of different fiber orientations on the dynamic behavior of the sandwich specimens have been presented in Table 4. It is seen that the highest experimental value of the fundamental natural frequency is from the specimen with the [Al-0^0/0^0-Al-0^0/0^0-Al] face sheets, which is about 585.03 Hz. On the other hand, this specimen has the lowest damping (loss factor) value, about 0.0013. Opposite to these values, while the lowest natural frequency is about 531.84 Hz, the highest value of loss factor is about 0.0023 for the specimen with the [Al-90^0/90^0-Al-90^0/90^0-Al] face sheets. The values of experimental natural frequency and loss factor for those with the [Al-0^0/90^0-Al-90^0/0^0-Al] and [Al-0^0/45^0-Al-45^0/90^0-Al] are about 568.24 Hz and 546.68 Hz, and 0.0017 and 0.0020, respectively. By using equation (1), the equivalent flexural modulus of the sandwich beams, which is obtained from each constituent materials used, are about 10.10 GPa, 8.11 GPa, 9.39 GPa and 8.77 GPa for the type1, type2, type 3 and type4, respectively. The predicted results of the fundamental natural frequency and the equivalent modulus are shown in Table 4, too. It is seen that these results are in a good agreement with those from the experimental ones. The maximum deviation of the frequency is about 2.38% for the type3, and that of the modulus is about 3.76% between the numerical and experimental results. The predicted first mode shape of the beams are shown in Fig. 5 that is in 2-D shell models.

Table 4. A comparison of experimental (Exp.) and predicted (Pred.) dynamic results for the sandwich beams with different fiber orientations of the face sheets

The sandwich beams	Loss Factor	Natural Freq. (Hz)		Flex. Modulus (GPa)	
	Exp.	Exp.	Pred.	Exp.	Pred.
type1- [Al-0^0/0^0-Al-0^0/0^0-Al]	0.0013	585,03	573,90	10.10	9.72
type2- [Al-90^0/90^0-Al-90^0/90^0-Al]	0.0023	531,84	531,00	8.11	8.06
type3- [Al-0^0/90^0-Al-90^0/0^0-Al]	0.0017	568,24	554,70	9.39	8.95
type4- [Al-0^0/45^0-Al-45^0/90^0-Al]	0.0020	546,68	547,70	8.77	8.80

When the overall results are evaluated, the effects of different fiber orientations of the face sheets on the sandwich structures are considerable, especially in terms of damping values. Increase in the loss factor values are about 77%, 31% and 54% for the type2, type3 and type4 specimens, respectively, when compared with the type1 one. On the other hand, decrease in the experimental equivalent modulus are just about 19.67%, 6.99% and 13.19% for the same specimens. It is clear that the different fiber orientations of the FML face sheets contribute to the damping value of the sandwich structure, remarkably. The highest value is obtained from the type 2, the [Al-90^0/90^0-Al-90^0/90^0-Al] FML with about 77% increase in the loss factor. This is believed to be due to the mechanical behavior of the glass fiber ply with the 90^0 fiber orientation. It is mainly controlled by the matrix part of the composite that has high value of damping but low elastic modulus, which is totally opposite to the values from the ply with the 0^0 angle orientation controlled mainly by the high strength of the fibers that have high modulus but low damping values.

Finally, the current study shows that the damping, so acoustic, performance of the aluminum-based sandwich structures can be enhanced by using FMLs presented as hybrid material systems interlacing the aluminum metals and the glass fiber reinforced polymer plies. Such structures could also provide better dynamic performance at relatively high temperature and humidity environment, when compared to those with the only fiber reinforced polymer-based skins and Nomex honeycomb cores.



a) b)

c) d)

Fig. 5. The first modes of the sandwich beams with the **a)** [Al-0^0/0^0-Al-0^0/0^0-Al], **b)** [Al-90^0/90^0-Al-90^0/90^0-Al], **c)** [Al-0^0/90^0-Al-90^0/0^0-Al], and **d)** [Al-0^0/45^0-Al-45^0/90^0-Al] face sheets.

4. CONCLUSIONS

It has been shown that the damping, so acoustic, performance of an aluminum-based sandwich structures can be enhanced via the treatment of the FMLs. For this study, aluminum metal sheets with a 0.3 mm thickness and glass fiber reinforced polymer matrix laminates with different fiber orientations have been interlaced to construct the face sheets of the sandwich structures with an aluminum honeycomb core. The effects of the different fiber orientations on the dynamic behaviors (damping and equivalent elastic modulus) of the sandwich specimens have been found considerable. It has been shown that an increase of about 77%, 31% and 54% can be obtained in the damping values of the FML face sheets with the [Al-$90^0/90^0$-Al-$90^0/90^0$-Al], [Al-$0^0/90^0$-Al-$90^0/0^0$-Al], and [Al-$0^0/45^0$-Al-$45^0/90^0$-Al] fibers orientations, respectively, compared to the one with the [Al-$0^0/0^0$-Al-$0^0/0^0$-Al]. On the other hand, a decrease of just about 19.67%, 6.99% and 13.19% has been obtained in the flexural rigidity of the same specimens.

Acknowledgments

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5. REFERENCES

[1] Y.M. Jen and H.B. Lin, *Temperature-Dependent Monotonic and Fatigue Bending Strengths of Adhesively Bonded Aluminum Honeycomb Sandwich Beams*, Materials and Design, 45, 393–406, 2013.
[2] V. Crupi, G. Epasto and E. Guglielmino, *Collapse Modes in Aluminium Honeycomb Sandwich Panels under Bending and Impact Loading*, International Journal of Impact Engineering, 43, 6-15, 2012.
[3] Y.M. Jen and L.Y Chang, *Effect of Thickness of Face Sheet on the Bending Fatigue Strength of Aluminum Honeycomb Sandwich Beams*, Engineering Failure Analysis, 16, 1282–1293, 2009.
[4] Y.M. Jen and L.Y. Chang, *Evaluating Bending Fatigue Strength of Aluminum Honeycomb Sandwich Beams Using Local Parameters*, International Journal of Fatigue, 30, 1103–1114, 2008.
[5] G.D Xu, T. Zeng, S. Cheng, X.H Wang and K. Zhang, *Free Vibration of Composite Sandwich Beam with Graded Corrugated Lattice Core*, Composite Structures,229, 111466, 2019.
[6] E. Piollet, E.R. Fotsing, A. Ross and G. Michon, *High Damping and Nonlinear Vibration of Sandwich Beams with Entangled Cross-Linked Fibres as Core Material*, Composites Part B 168, 353–366, 2019.
[7] B. Freeman, E. Schwingler, M. Mahinfalah andK. Kellogg, *The Effect of Low-Velocity Impact on the Fatigue Life of Sandwich Composites*, Composite Structures, 70,374–381, 2005.
[8] K.C. Jung, M.G. Han and SH. Chang, *Impact Characterisation of Draped Composite Structures Made of Plain-Weave Carbon/Epoxy Prepregs Utilising Smart Grid Fabric Consisting of Ferroelectric Ribbon Sensors*, Composite Structures, vol. 238, p. 111940, 2020.
[9] Z. Yang, J. Liu, F. Wang, S. Li and X. Feng, *Effect of Fiber Hybridization on Mechanical Performances and Impact Behaviors of Basalt Fiber/UHMWPE Fiber Reinforced Epoxy Composites*, Composite Structures, 229, 111434, 2019.
[10] A.K. Barouni and H.N. Dhakal, *Damage Investigation and Assessment due to Low Velocity Impact on Flax/Glass Hybrid Composite Plates*, Composite Structures, 226, 111224, 2019.
[11] M. Moradi, B. Ameri and B. Mohammadi, *Post Buckling Behavior Analysis of Unidirectional Saddle Shaped Composite Panels Containing Delaminations Using Cohesive Zone Modeling*, Journal of Science and Technology of Composites, 6, (2), 255-264, 2019. doi: 10.22068/jstc.2018.85739.1442.

[12] M. Moradi and M.S. Safizadeh, *Edge Disbond Detection of Carbon/Epoxy Repair Patch on Aluminum Using Thermography*, Composites Science and Technology, 179, 41-53, 2019.
[13] M. Moradi and M. S. Safizadeh, *Experimental and Numerical Study of the Effect of Using Polyurethane Instead of Teflon Strip to Simulate Debonding Defect in Composite Patch Repairs Aluminum Plate Under Thermography Inspection*, Composites Part B: Engineering, 175, 107176, 2019.
[14] S. Bernhardt, M. Ramulu and A.S. Kobayashi, *Low-Velocity Impact Response Characterization of a Hybrid Titanium Composite Laminate*, Journal of Engineering Materials and Technology,129, 220–226, 2007.
[15] P. Cortes and W.J. Cantwell, *The Prediction of Tensile Failure in Titanium-Based Thermoplastic Fibre–Metal Laminates*, Composite Science and Technology, 66, 2306–2316, 2006.
[16] P. Cortes and W.J Cantwell, *Fracture Properties of a Fiber–Metal Laminates Based on Magnesium Alloy*, Journal of Materials Science, 39, 1081–3, 2004.
[17] P. Cortes and W.J. Cantwell, *The Fracture Properties of a Fibre–Metal Laminate Based on Magnesium Alloy*, Composites B, 37, 163–70, 2006.
[18] S.U. Khan, R.C. Alderliesten and R. Benedictus, *Post-Stretching Induced Stress Redistribution in Fibre Metal Laminates for Increased Fatigue Crack Growth Resistance*, Composite Science and Technology, 69, 396–405, 2009.
[19] C.T. Lin and P.W. Kao, *Fatigue Delamination Growth in Carbon Fibre-Reinforced Aluminium Laminates,* Composites A, 27A, 9–15, 1996.
[20] D.J. Shim, R.C. Alderliesten, S.M. Spearing and D.A. Burianek, *Fatigue Crack Growth Prediction in GLARE Hybrid Laminates*, Composite Science and Technology, 63, 1759–67, 2003.
[21] M. Kawai and A. Hachinohe, *Two-Stress Level Fatigue of Unidirectional Fiber–Metal Hybrid Composite: GLARE 2*, International Journal of Fatigue, 24, 567–80, 2002.
[22] E.M. Castrodeza, M.R.W.S. Abdala and F.L. Bastian, *Crack Resistance Curves of Glare Laminates by Elastic Compliance*, Engineering Fracture Mechanics 73, 2292–303, 2006.
[23] S.Y. Park, W.J. Choi and H.S. Choi, *The Effects of Void Contents on the Long-Term Hygrothermal Behaviors of Glass/Epoxy and GLARE Laminates*, Composite Structures, 92,18–24, 2010.
[24] S. Michelle, H. Fatt, C. Lin, J.D.M. Revilock and D.A. Hopkins, *Ballistic Impact of GLARE Fiber–Metal Laminates*, Composite Structures, 61, 73–88, 2003.
[25] A.S. Yaghoubi and B. Liaw, *Effect of Lay-Up Orientation on Ballistic Impact Behaviors of GLARE 5 FML Beams*, International Journal of Impact Engineering, 54, 138-148, 2013.
[26] M. Mohandes, A.R. Ghasemi, M. Irani-Rahagi, K. Torabi and F. Taheri-Behrooz, *Development of Beam Modal Function for Free Vibration Analysis of FML Circular Cylindrical Shells*, Journal of Vibration and Control, 24(14), 3026–3035, 2018.
[27] H. Ravishankar, R. Rengarajan, K. Devarajan and B. Kaimal, *Free Vibration Bahaviour of Fiber Metal Laminates, Hybrid Composites and Functionally Graded Beams using Finite Element Analysis*, International Journal of Acoustics and Vibration, 21, 4, 2016.
[28] A. Shooshtari and S. Razavi, *A Closed Form Solution for Linear and Nonlinear Free Vibrations of Composite and Fiber Metal Laminated Rectangular Plates*, Composite Structures, 92 (11), 2663-2675, 2010.
[29] G.H. Rahimi, M.S. Gazor, M. Hemmatnezhad and H. Toorani, *Free Vibration Analysis of Fiber Metal Laminate Annular Plate by State-Space Based Differential Quadrature Method*, Advances in Materials Science and Engineering, 2014. http://dx.doi.org/10.1155/2014/602708

[30] Y. Chen, Y. Fu, J. Zhong and C. Tao, *Nonlinear Dynamic Responses of Fiber-Metal Laminated Beam Subjected to Moving Harmonic Loads Resting on Tensionless Elastic Foundation*, Composites Part B: Engineering, 131, 253-259, 2017.
[31] J. Iriondo, L. Aretxabaleta and A. Aizpuru, *Characterisation of the Elastic and Damping Properties of Traditional FML and FML Based on a Self-Reinforced Polypropylene*, Composite Structures, 131, 47–54, 2015.
[32] B. Ameri, M. Moradi and R. Talebitooti, *Effect of Honeycomb Core on Free Vibration Analysis of Fiber Metal Laminate (FML) Beams compared to Conventional Composites*, https://doi.org/10.1016/j.compstruct.2020.113281

[33] J.P. Den Hartog, *Mechanical Vibrations*, McGraw-Hill Book Company Inc, New York, London, 1947.

[34] M.M. Singh, Ph.D. Thesis, *Dynamic Properties of Fibre Reinforced Polymers Exposed to Aqueous Conditions*, Department of Mechanical Engineering, University of Bristol, 1993.