EFFECTS OF DIFFERENT FIBER ORIENTATIONS ON THE DYNAMIC RESPONSE OF THE GLARE FML BEAMS

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ABSTRACT

Owing to their high fatigue life and energy absorption capabilities, Glass Reinforced Aluminum Laminate (GLARE) hybrid systems are the most preferred type of the Fiber Metal Laminate (FMLs) that have been the focal point of many works conducted at high stress levels. In this study, dynamic performance of a GLARE was investigated at low stress levels using a vibrating beam technique with fixed-free end conditions. Effects of different glass fiber angles of plies on the GLARE material were evaluated with a special emphasis on the damping values. Values of equivalent flexural modulus of the specimens were measured experimentally and compared with the predicted ones that were obtained via a numerical modal analysis. The results from both methods are reasonably in a good agreement.

Keywords: FMLs (Fiber Metal Laminates), GLARE (Glass Laminate Aluminum Reinforced Epoxy), Vibrating Beam Technique, Numerical Modal Analysis
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1. INTRODUCTION

Aluminum with is strong, lightweight, predictable and inexpensive features is one of the most common materials used in the construction of airplanes. On the other hand, fiber-reinforced polymer matrix composites have gained a great attention thanks to their advantages such as strength to weight ratio, damping properties, impact performance, fatigue life and resistance to corrosion etc. Applications of these composites in aircraft structures are increasing year by year in a wider spectrum. Fiber Metal Laminates (FMLs) are hybrid structures built from thin layers of metal sheets and plies of fiber reinforced polymeric materials [1]. The fiber/metal composite technology combines the advantages of metallic materials and fiber reinforced polymer matrix composites. The most commercially available FMLs are aramid fiber reinforced aluminum laminate (ARALL) [2], glass fiber reinforced aluminum laminate (GLARE) [3-8], and carbon fiber reinforced aluminum laminate (CARALL) [9]. FMLs are being used in various components of aerospace vehicles thanks to their advantages of high specific strength/stiffness, good fatigue resistance, better damage tolerance, fire resistance, blunt notch strength, formability and re-workability [10]. For instance, FMLs are being used as fuselage skin and lower wing structures of the next-generation commercial aircrafts, owing to their excellent features.

The GLARE hybrid system is the most preferred type of these hybrid systems used in the aerospace applications, which consists of a few layers of high strength aluminum alloy sheets and glass fiber reinforced laminates. These materials are considered to be a good choice for their high fatigue life and energy absorption capabilities. For example, Shim et al. [3] investigated the crack growth rates in three different types of GLARE laminates with center-cracked tension configurations under cyclic loads that were predicted and compared with experimental results. The approach predicted that the crack growth rate remained approximately constant with crack length, which was consistent with experimental observations. In another work, Kawai and Hachinohe [4] studied effects of the change in amplitude on the off-axis fatigue strength of a unidirectional hybrid laminate (GLARE2). Tension–tension fatigue tests with a single change in stress amplitude were performed at room temperature for step-down and step-up sequences, respectively. History-dependence of the fatigue strength of GLARE2 under two-stress level cycling conditions was examined through comparisons with the results of constant amplitude fatigue tests. It was found that the two-stress level fatigue strength was affected in a complicated manner by the sequence of fatigue load, the number of prior cycles and the off-axis angle of specimen. The subsequent fatigue life for the step-down sequence was governed by the decrease in stress amplitude, while for the step-up sequence it was done by both an increase in stress amplitude and the number of prior cycles. To predict the ballistic limit and energy absorption of fully clamped GLARE panels subjected to ballistic impact by a blunt cylinder, analytical solutions were derived [7], based on test results from NASA Glenn. Predictions of the ballistic limit from the resulting non-linear differential equation were within 13% of the test data. The deformation energy due to bending and membrane accounted for most of the total energy absorbed (84–92%), with the thinner panels absorbing a higher percentage of deformation energy than the thicker panels. Yaghoubi and Liaw [8] studied experimental and numerical investigations on ballistic impact behaviors of GLARE 5

(3/2) fiber-metal laminated (FML) beams of various stacking sequences. The results showed that when subjected to ballistic impact, the specimen with [0^0/90^0]s lay-up orientation dissipated more energy compared to the other lay-up orientations.

Viscoelastic behavior of the polymer matrix composites leads to higher damping performance, thus, energy is dissipated more in such composites than metallic materials under vibration conditions [11]. Wang et al [12] investigated vibration reduction characteristics of laminated composite panels to see the effect of different fiber orientations on damping performance. They found that the damping ratio of fiber curve ply laminates was affected considerably depending on the fiber angles. As to the FMLs at low stress levels, Merzuki et al. [13] studied the vibration behavior of a GLARE material system by using different manufacturing methods such as vacuum bagging and compression molding. It was shown that with an increase of the thickness plate, the natural frequency also increased. Fiber metal laminates fabricated by the vacuum bagging indicated higher natural frequency values compared to those by compression molding, due to the increased thickness resulted in higher volume fraction of the fiber and matrix. In another work, Saini et el. [14] modeled fiber laminate beam using ANSYS package program, which enabled to investigate the effect of fiber orientation angles on the natural frequency. The results showed that the highest frequency values were at 0^0 fiber orientation while the minimum values were at the 60^0.

From the literatures given above, there are only a few works related to the FML hybrid systems under vibratory conditions at low stresses, and there is a lack of motivation about the dynamic performance (damping and flexural modulus) of these materials. The aim of this study is to find out the effects of different angle orientations of glass fiber reinforced plies on the dynamic behavior of a GLARE that consists of three layers of aluminum sheets and two laminates of glass fiber reinforced plies. To measure damping and equivalent flexural modulus of the GLARE manufactured in the beam configuration, a vibrating beam test setup with fixed-free ends conditions was used. The measurements were conducted at the fundamental natural frequency and compared with the predicted results that were obtained using numerical modal analysis.

2. EXPERIMENTATION

2.1 Materials and Fabrication

For manufacturing process of the specimens, a panel of aluminum (Al) 2024-T3 alloy sheet with a thickness of 0.4 mm was cut into dimensions of 250 mm x 25 mm. The Al sheets were first chemically treated and then primer coated to obtain proper surface preparation for long term bond endurance. Three layers of the Al sheets and two of glass fiber reinforced laminates were interlaced to construct the FML in the form of a GLARE 3/2. An epoxy adhesive, FM 94K Modified Epoxy Film (Cytec Engineered Materials, Inc., Havre de Grace, MD), was used between the Al sheets and the laminates for bonding and stabilization of the FML beams. The lay-ups were as follows; 1- (Al-0^0/0^0-Al-0^0/0^0-Al), 2- (Al-90^0/90^0-Al-90^0/90^0-Al), 3- (Al-0^0/90^0-Al-90^0/0^0-Al), and 4- (Al-0^0/45^0-Al-45^0/90^0-Al). All the specimens were manufactured in a clean room under controlled environment at 23 ^{0}C temperature and 50% relative humidity. They were located on a plate, then bagged and vacuumed before the curing process that was performed at a temperature of 180 ^{0}C and pressure of 6.5 bars. Some manufactured specimens and their constituents are shown Figure 1a and 1b, respectively. The details about the dimensions and weight of the specimens are indicated in Table 1.

Table 1. The actual measurements of the composite specimens

The specimen types	**Width [mm]**	**Thickness [mm]**	**Length [mm]**	**Mass [g]**	**Density [kg/m^3]**
(Al-0^0/0^0-Al-0^0/0^0-Al)	24.43	2.25	249	29.61	2163.38
(Al-90^0/90^0-Al-90^0/90^0-Al	24.52	2.25	249	29.71	2163.60
(Al-0^0/90^0-Al-90^0/0^0-Al)	24.24	2.19	249	28.68	2169.71
(Al-0^0/45^0-Al-45^0/90^0-Al)	24.45	2.12	249	27.71	2146.95

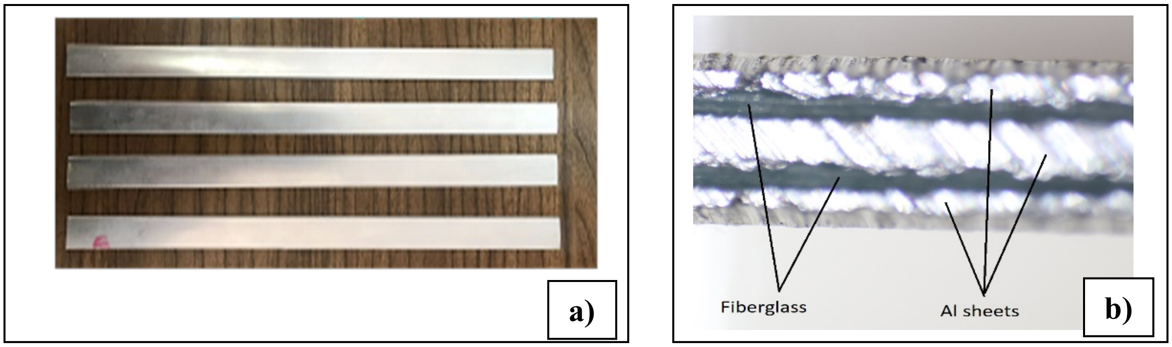

Figure 1. a) Fabricated specimens, **b)** A representative cross section of the GLARE FML

2.2. Numerical Modal Analysis

To predict mode shapes and natural frequencies of the GLARE FML specimens, a numerical modal analysis was conducted using the commercial ANSYS package program. Solid shell SOLSH190, suitable for both two-dimensional (2d) and three-dimensional (3d) modelling, was chosen as an element type due to its advantages of flexibility and proper usage on layered structures. The element has 8 nodes and each node have three degrees of freedom that are translational motions in x, y & z directions. The specimens with the fixed-free boundary conditions were modelled, and their fundamental natural frequencies and mode shapes were predicted. A three-dimensional (3-D) meshed model of the specimen is shown in Figure 2. The data of each constituent material used for the numerical modal analysis are shown in Table 2.

Table 2. The input data used for the numerical modal analysis

Materials	**Elastic Modulus [Pa]**	**Density [kg/m^3]**	**Poisson's Ratio**
Al2024-T3	7.31×10^{10}	2780	0.33
Glass Fiber Ply*	4.5×10^{10}, 2×10^9, 2×10^9	2160	0.28, 0.28, 0.28
Film Adhesive	1.7×10^9	392	0.3

*Elastic modulus and Poisson's ratios in x, y and z directions, respectively.

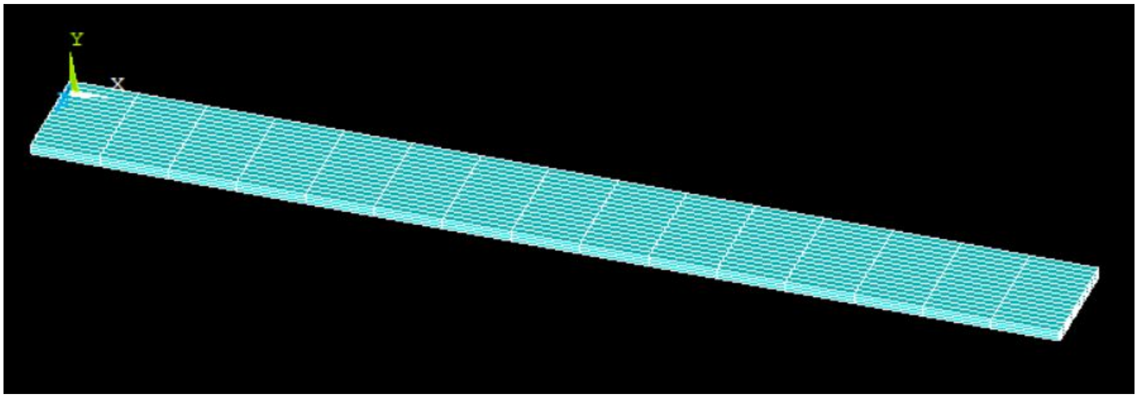

Figure 2. A 3-D meshed model of the specimen used

2.3. The experimental test set-up

For the dynamic measurements of the specimens, a vibrating beam test set-up shown in Figure 3 was used. The experimental set-up includes an instrumented impact hammer, 8206 Bruel & Kjaer, to generate impulse and a non-contact microphone, Type 1706/8206 Bruel & Kjaer, to pick up the response from the specimen. The impacted specimen is aimed to give its natural frequencies within a required frequency domain, via some distinguished peak values of the amplitude, depending on the mode shapes. A sophisticated data acquisition card, HBM QuantumX MX410B, was used to collect the digital values of the hammer and microphone. The set-up is supported by a software, HBM Catman data acquisition software (DAQ), to process the data according to the required output format for visualization and analysis. The natural frequency, equivalent flexural modulus and damping values of the specimens were measured easily via the technique. For the damping values, the half power bandwidth method was used via the following equation; $\eta = \frac{f_2 - f_1}{f_n}$, 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/√2 of its maximum value, which is reached at f_n , the resonant frequency.

The natural frequency of a beam is found as [15]: $f_n = \frac{1}{2\pi}(\frac{\lambda_n}{l})^2 \sqrt{\frac{EI}{\rho t b}}$, where $\lambda_n = 1.875$ is the 1st eigenvalue for fixed-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 equivalent flexural modulus of the specimen was measured using this equation, and only the first (fundamental) mode was considered for all the measurements.

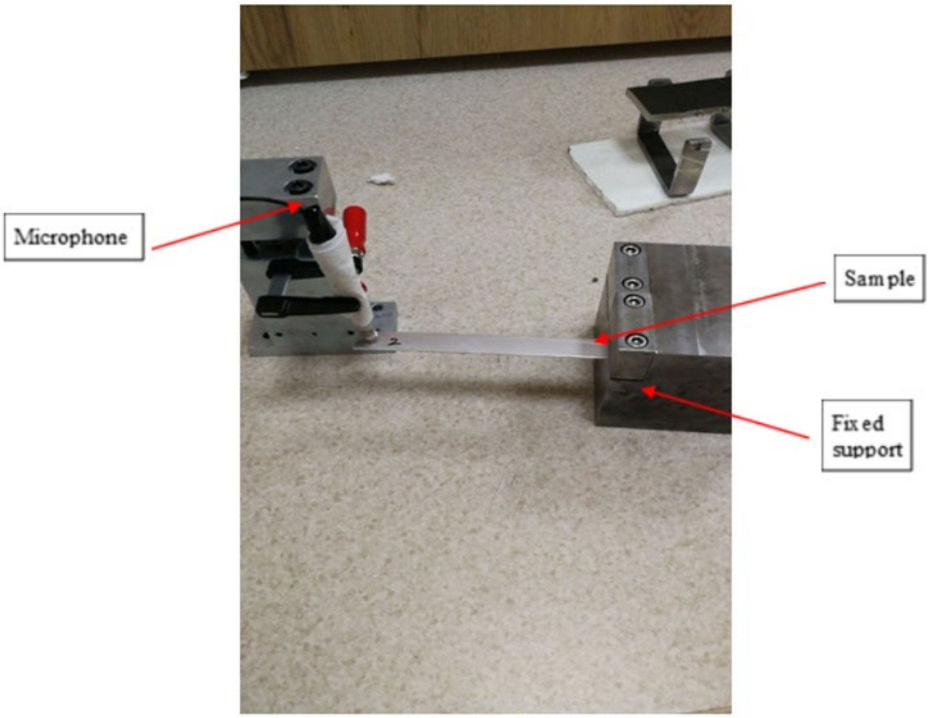

Figure 3. The experimental set-up for the vibrating beam tests

3. RESULTS AND DISCUSSION

The experimental values from the effects of different fiber orientations on the dynamic response of the GLARE as a member of FMLs are presented in Table 3. While the frequency values were obtained using the experimental setup shown in Figure 3, the values of the equivalent flexural modulus were calculated from the above equation [15] that takes the values presented in Table 1. The second moment of area, *I*, used in the formula is obtained from the thickness and width of the specimens. The equivalent density is obtained from the mass and volume of the specimens. For example, the calculations of the second moment area and the density for the specimen (Al-0^0/0^0-Al-0^0/0^0-Al) are (24.43×2.25^3)/12 and 29.61/(24.43x2.25x249), respectively. All the values are converted to meter and kilogram units.

The results indicate that the specimen with the (Al-0^0/0^0-Al-0^0/0^0-Al) fiber orientation has the highest natural frequency and the equivalent flexural modulus but the lowest damping values, 37.35 Hz, 55.96 GPa and 0.005, respectively. On the other hand, opposite is the case for the one with the (Al-90^0/90^0-Al-90^0/90^0-Al) that has the highest value of damping (0.008) but lowest values of the frequency (34.63 Hz) and the modulus (47.71 GPa). These values for the (Al-0^0/90^0-Al-90^0/0^0-Al) specimen are 0.06, 35.84 Hz and 54.10 GPa, and for the (Al-0^0/45^0-Al-45^0/90^0-Al) specimen are 0.07, 35.22 Hz and 55.16 GPa, respectively. The predicted values of the fundamental natural frequency are also presented in Table 3, which seem in agreement with the experimental ones. A representative 1st and 2nd mode shapes of the specimens with fixed-free boundary conditions are shown in Figure 4 that is predicted from the numerical modal analysis.

While a maximum of increase is about 60% for the damping value, only a decrease of about 14.74% in the equivalent flexural modulus of the (Al-90^0/90^0-Al-90^0/90^0-Al) specimen is obtained, compared to the (Al-0^0/0^0-Al-0^0/0^0-Al) one. The decrement in the modulus of the (Al-0^0/90^0-Al-90^0/0^0-Al) and (Al-0^0/45^0-Al-45^0/90^0-Al) specimens is much less, about 3.32% and 1.43%, while an substantial increment of the damping occurs, about 20% and 40%, respectively. It is important to note that while the fibers of a ply provide high strength and modulus, its matrix mainly introduces high damping values and a medium for load transfer. In line with this, the fibers with the 0^0 angle are oriented in line with the applied axial direction, hence controlled the flexural rigidity leading to a relatively high value of the modulus. On the other hand, for the fibers with the 90^0 angles, the matrix with its relatively low value of modulus rules the deformation in the plies, and hence in the GLARE, resulting in a relatively a high damping performance but low equivalent modulus. This implies that when proper fiber alignment is applied to the FML beams, a remarkable contribution of damping value can be added to the hybrid system, with a very small loss of the flexural rigidity. It is well known that a high damping value of structures is especially demanded by the designers working in the aerospace and automotive sectors as it helps to dissipate energy under vibratory conditions and thus prevent high amplitude of displacements. The current work shows that among their many advantages such as high fatigue life and energy absorption at high stress levels [3-8], a GLARE material is also able to be useful at low stress levels, too.

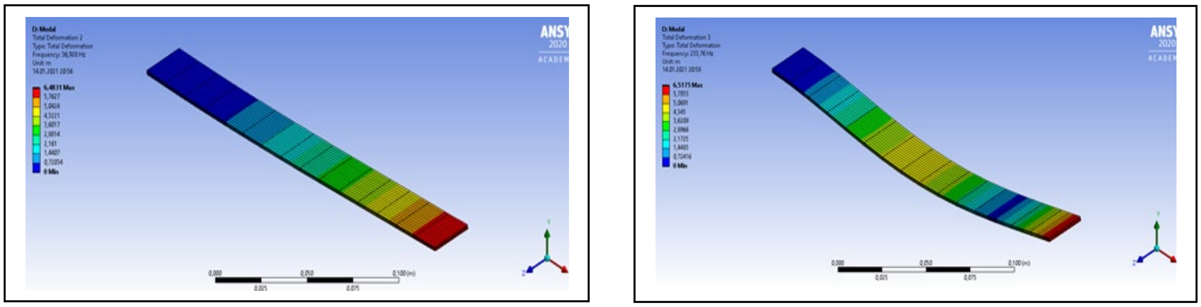

Figure 4. The predicted 1st and 2nd mode shapes of the FML using the numerical modal analysis

Table 3. Experimental results of the specimens with fixed-free boundary conditions

The specimen types	Natural Freq. [Hz]		Flex. Modulus [GPa]		Loss Factor -
	Exp.	Pred.	Exp.	Pred.	Exp.
(Al-0^0/0^0-Al-0^0/0^0-Al)	37.35	36.63	55.96	63.3	0.005
(Al-90^0/90^0-Al-90^0/90^0-Al)	34.63	33.52	47.71	51.3	0.008
(Al-0^0/90^0-Al-90^0/0^0-Al)	35.84	35.15	54.10	57.8	0.006
(Al-0^0/45^0-Al-45^0/90^0-Al)	35.22	34.75	55.16	55.3	0.007

4. CONCLUSIONS

The effects of different glass fiber orientations of the plies on the Fiber Metal Laminate (FML) in the form of Glass Reinforced Aluminum Laminate (GLARE) have been found remarkable. Despite high increase in the damping values, only a small amount of decrease was obtained in the value of the equivalent flexural modulus. Compared to the (Al-0^0/0^0-Al-0^0/0^0-Al) specimen, the highest increase was found in the damping value of (Al-90^0/90^0-Al-90^0/90^0-Al), about 60%, with a decrease of about 14.74% in the modulus. Along with satisfactory performance of the GLARE hybrid materials under dynamic loading at high stress levels, this study has proved that they could also be good damping materials under vibratory conditions at low stress levels.

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