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Investigation of modal analysis on glass fiber laminate aluminium reinforced polymer: An experimental study

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Abstract. The present analysis deals with experimental investigation on the vibration behaviour of fiber metal laminates (FMLs) plate. FMLs offer good mechanical properties such as high specific properties in term of strength to weight and stiffness to weight ratio. However, it is observed that very few studies are available on the dynamic behaviour of FMLs. In this experiment, the dynamical behaviour of glass fiber/epoxy and fiber metal laminates was carried out. The specimens have been manufactured using different manufacturing process which is compression mould and vacuum bagging. Free vibration analysis by exciting an impact hammer at the cantilever plate were conducted to determine the dynamical characteristic of the specimens. The stiffness of the material increases, which contributes to the natural frequency increase.

1. Introduction

The evolutions in the field of manufacturing and materials have led to forward new kinds of materials. New class of composite materials which is laminate materials have been developed recently. Fiber metal laminate (FMLs) is a family of hybrid composite that combination of fiber-reinforced polymer layer and metal layers. Aluminium, titanium and magnesium are currently used and fiber-reinforced layer is either carbon, glass, and kevlar fiber[1]. FMLs shows better mechanical characteristics such as higher fracture toughness, compressive strength, and yield stress when compared to conventional fiber reinforced polymers (FRPs). Resistance to impact, high strength and stiffness to weight ratio another advantages of FMLs. The CARALL, ARALL and GLARE laminates are now being incorporated as structural materials in aircrafts. Metallic and FRPs layer are joined using mechanical or adhesive bonding. For instance, FMLs materials have been successfully in building the structural in the building the aircraft structure (in the fuselage skin) of the Airbus A380 [2-4]. Another application have been considered on FMLs tubes for chemical and nuclear industry, cargo floor, and blast resistant containers[5].

In service, many structures like automotive and aerospace are frequently subjected to both dynamic and static loads. Effect of the situation, it is required to deeply understand about the deformation and vibration of FMLs structural. For ensure correct and efficient use of composite materials as FMLs need more the latest analysis techniques and experimental system to estimate the dynamic behaviour[6]. Most researchers investigated on the FMLs on static analysis and a few study on low velocity impact. But, the researcher did not focus more on the vibration behaviour of FMLs structure. Based on Roebroeks studies [7] the fatigue crack initiation and evolution response of FMLs subjected to realistic loading conditions. Botelho et al.[8] investigated the effect of hygrothermal conditioning on mechanical

properties of the FMLs under tensile loading. In Gonzalez [9] investigated the tensile properties of FMLs based on aluminium alloy and aramid fiber reinforced polymer composites. The result shows that FMLs exhibit a more ductile behaviour than its constituents. Sharma et al.[10] are studied about the tensile behaviour of the FMLs under uniaxial loading in order to detect into damage evaluation. Further, commercial FE simulation ABAQUS software was used to perform the simulation. Beside, Sadighi et al.[11] presented the experiments on low velocity impact behaviour of FMLs plates under drop weight test. Bikakis [12] investigated the static response of circular FMLs plates, subjected to oblique indentation using FEM-based ANSYS software and analytical methods. All above studies are focus more to determination the tensile test, elastic and inelastic properties, ballistic impact response, low and high velocity impact of the FMLs.

Based on the literature above, it is observed that very few studies are available on the dynamic behaviour of FMLs. The experimental studies on the dynamic behaviour of FMLs are hardly in the literature. The main study in this experiment is to investigate the dynamical behaviour of glass fiber/epoxy and fiber metal laminates with different manufacturing process which is using compression mould and vacuum bagging. Free vibration dynamical mechanical tests by excited impact hammer are used to obtain the natural frequency and mode shapes.

2. Mathematical model

Here, an FMLs plate is considered of length 'a', width 'b', and thickness 'h' consisting of n number of thin layers, θ is represented for oriented at an angle with lamina system, as shows in Figure 1. The displacement function in shear deformation theory is

$$
\begin{aligned}
u(x,y,z) &= u_0(x,y) + z\theta_x(xy), \\
v(x,y,z) &= v_0(x,y) + z\theta_y(xy), \\
w(x,y,z) &= w_0(x,y),
\end{aligned}
\tag{1}
$$

where u, v, and w are the displacements in X, Y and Z directions, u_0, v_0 and w_0 are displacements. θ_x, and θ_y are the rotations of the cross-section perpendicular to X and Y axes. The Green-Lagrange strain relations is where $\varepsilon_{xx}, \varepsilon_{yy}$, and γ_{xy} are the bending strains and γ_{xz}, γ_{yz} are the transverse shear strains.

$$
\begin{Bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\gamma_{xy} \\
\gamma_{xz} \\
\gamma_{yz}
\end{Bmatrix}
=
\begin{Bmatrix}
\dfrac{\partial u}{\partial x} \\[2mm]
\dfrac{\partial v}{\partial y} \\[2mm]
\dfrac{\partial u}{\partial y} + \dfrac{\partial v}{\partial x} \\[2mm]
\dfrac{\partial u}{\partial z} + \dfrac{\partial w}{\partial x} \\[2mm]
\dfrac{\partial v}{\partial z} + \dfrac{\partial w}{\partial y}
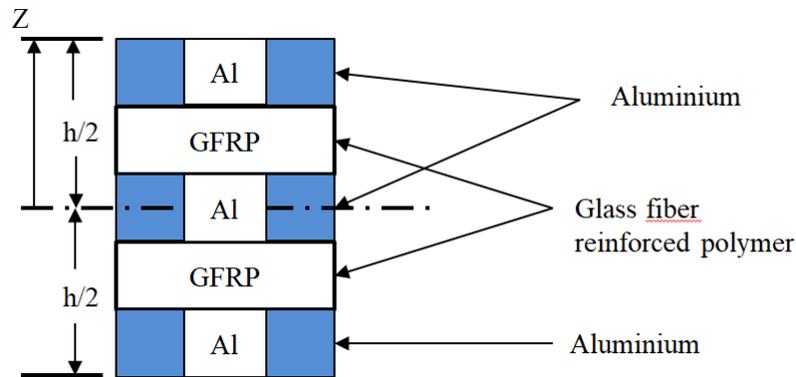\end{Bmatrix},
\tag{2}
$$

Figure 1. The details layer of FMLs

From the study Rath [13], the constitutive equations for plate are

$$\{F\} = [D]\{\varepsilon\}, \tag{3}$$

$$\{F\} = \{N_x, N_y, N_{xy}, M_x, M_y, M_{xy}, Q_x, Q_y\}^T,$$

$$\{\varepsilon\} = \{\varepsilon_x, \varepsilon_y, \gamma_{xy}, \kappa_x, \kappa_y, \kappa_{xy}, \varphi_x, \varphi_y\}^T,$$

$$[D] = \begin{bmatrix} A_{ij} & B_{ij} & 0 \\ B_{ij} & D_{ij} & 0 \\ 0 & 0 & S_{ij} \end{bmatrix}, \tag{4}$$

where N_x, N_y, and N_{xy} are in-plane stress resultants, M_x, M_y, and M_{xy}, are moment resultants, Q_x, Q_y, are transverse shear stress resultants. A_{ij}, B_{ij}, D_{ij}, are extensional, bending-strectching coupling, bending and S_{ij}, are transverse shear stiffness.

$$(A_{ij}, B_{ij}, D_{ij}) = \sum_{k=1}^{n} \int_{z_{k-1}}^{k} \left[\bar{Q}_{ij} \right]_k (1, z, z^2) dz \quad (i, j = 1, 2, 6),$$

$$(S_{ij}) = \alpha \sum_{k=1}^{n} \int_{z_{k-1}}^{k} \left[\bar{Q}_{ij} \right]_k (1, z, z^2) dz \quad (i, j = 4, 5), \tag{5}$$

where $\left[\bar{Q}_{ij} \right]$ is the off-axis elastic constant matrix and 'α' is the shear correction factor where (5/6) is adopted. $\left[\bar{Q}_{ij} \right]$ in Eq. (5) is defined as

$$\left(\bar{Q}_{ij} \right)_k = [T_1]^T [Q_{ij}]_k [T_1] \quad (i, j = 1, 2, 6),$$

$$\left(\bar{Q}_{ij} \right)_k = [T_2]^T [Q_{ij}]_k [T_2] \quad (i, j = 4, 5), \tag{6}$$

$$[T_1] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & \sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -\sin\theta\cos\theta \\ -2\sin\theta\cos\theta & 2\sin\theta\cos\theta & \sin^2\theta - \cos^2\theta \end{bmatrix}, \quad [T_2] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}, \tag{7}$$

where the $[T_1]$ and $[T_2]$ are transformation matrices, $[\bar{Q}_{ij}]$ is on axis elastic constant matrix and defined as

$$[\bar{Q}_{ij}]_k = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \quad (i,j = 1,2,6),$$

$$[Q_{ik}]_k = \begin{bmatrix} Q_{44} & 0 \\ 0 & Q_{55} \end{bmatrix} \quad (i,j = 4,5),$$

(8)

in which

$$Q_{11} = E_{11} / (1 - v_{12}v_{21}), \quad Q_{12} = v_{12}E_{22} / (1 - v_{12}v_{21}),$$
$$Q_{22} = E_{22} / (1 - v_{12}v_{21}), \quad Q_{44} = G_{13,} \quad Q_{55} = G_{23,}$$

where E_{11}, E_{22} are Young's moduli of lamina along and cross the fibers, $G_{12}, G_{13,}$ and G_{23} are shear moduli of lamina, v_{12}, v_{21} are Poisson rations along and across the fibers. The element mass matrix $[M_e]$ as

$$[M_e] = \int_{-1}^{+1} [N]^T [P][N][J] d\xi d\eta,$$

(9)

where $[N]$ is shape function matrix an $[P]$ is the inertia matrix and can expressed as

$$[N] = \sum_{i=1}^{4} \begin{bmatrix} N_i & 0 & 0 & 0 & 0 \\ 0 & N_i & 0 & 0 & 0 \\ 0 & 0 & N_i & 0 & 0 \\ 0 & 0 & 0 & N_i & 0 \\ 0 & 0 & 0 & 0 & Ni \end{bmatrix} \text{ and } [P] = \begin{bmatrix} P_1 & 0 & 0 & 0 & 0 \\ 0 & P_1 & 0 & 0 & 0 \\ 0 & 0 & P_1 & 0 & 0 \\ 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & I \end{bmatrix}$$

in which

$$P_1 = \sum_{K=1}^{n} \int_{z_{k-1}}^{z_k} (\rho)_k \, dz \text{ and } I_1 = \sum_{K=1}^{n} \int_{z_{k-1}}^{z_k} (\rho)_k z^2 \, dz,$$

(10)

where $(\rho)_k$ is the mass density of kth layer from the bottom surface. The element stiffness matrix is

$$[K_e] = \int_{-1}^{+1} \int_{-1}^{+1} [B]^T [D][B][J] d\xi d\eta,$$

(11)

where $[B]$ is the strain displacement matrix, stress strain $[D]$ and Jacobian determinant $[J]$. The natural frequency of FML plates are determined by

$$\left| [K] - \omega^2 [M] \right| = 0$$

(12)

where $[K]$ is the global stiffness matrix, $[M]$ is the global mass matrix and ω is the natural frequency.

3. Materials and method

Glass fiber/epoxy (GF-E) and aluminium 2024-T0 (AL) were used in this study. The aluminium surface were prepared for adhesive bonding by using sand blasting for generate micro-rough surface, which can improve bonding with GF-E [14]. The Table 1 showed glass fiber/epoxy and aluminium mechanical properties.

Table 1. Mechanical properties used to produce fiber metal laminates, (a) glass fiber/epoxy

Property	GF-E
Longitudinal elastic modulus, E_1 (GPa)	7
Transverse elastic modulus, E_2 (GPa)	7
Thickness elastic modulus, E_3 (GPa)	1
In-plane Poisson's ratio, v_{12}	0.22
Thickness Poisson's ratio, v_{13} , v_{23}	0.22
In-plane shear modulus, G_{12} (GPa)	1
Thickness shear modulus, G_{13} , G_{23} (GPa)	2.5

(b) Mechanical properties of aluminium 2024-T0 (AL)

Property	Value
Density, ρ (kg/m^3)	2780
Young's modulus, E (GPa)	70.6
Poisson ratio, v	0.3

The composite materials (GF-E) were produced 4 layers. Furthermore, the glass fiber laminates aluminium reinforced polymers were prepared by stacking laminae of the glass fiber/epoxy and aluminium sheet. The lay-up sequence of the FMLs was 2/1 and 3/2 as follows in Table 2. In the production composite materials and hybrid composites, two different methods are used which is compression mould (CM) and vacuum bagging (VB). In the compression mould process, 0.4 MPa pressure is applied under room temperature, shown in Figure 2. For vacuum bagging, the air under the bag is extracted by a vacuum pump and thus up to one atmosphere of pressure can be applied to the laminate to consolidate it.

In the production process, glass fiber was cut in dimension of 300 x 80, laminated fabric were manufactured by the applied the epoxy resin to the fiber layers by layer. For hybrid materials, glass fibers were cut in dimension 300 x 40 mm and aluminium in dimension 250 x 25 mm. The total length of each vibration test specimens has 250 mm span and 25 mm width. However, free beam length is kept on 213 mm.

Table 2. Stacking sequence of the fiber metal laminates composite (FMLs)

Naming	Stacking sequence
A2G1	AL/GF/AL
A3G2	AL/GF/AL/GF/AL

AL: Aluminium; GF: Glass fiber; CF: Carbon fiber

(a) Vacuum bagging   (b) Compression mould
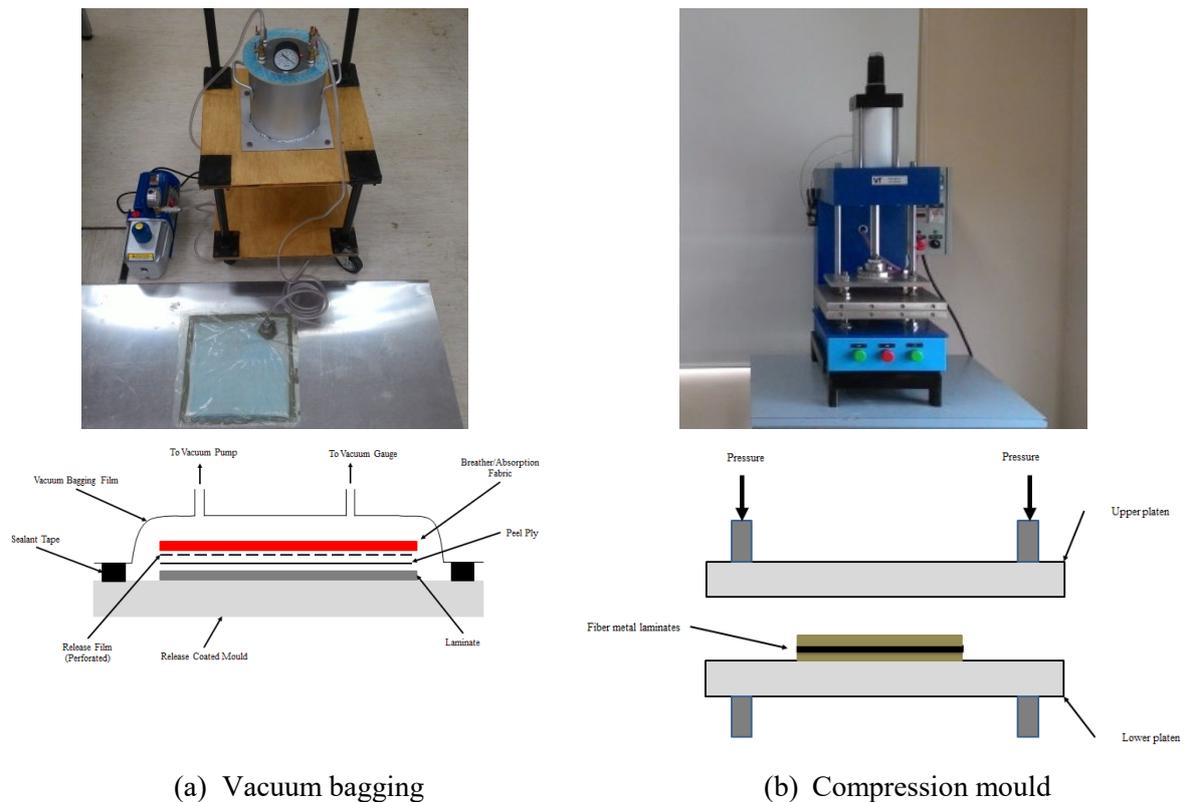
Figure 2. Fabrication of fiber metal laminates by using two different methods; (a) vacuum bagging, (b) compression mould

In Figure 3 shows the process to check flattened of the surface composite plate using dial gauge. The reading in Table 3 showed the surface flattened of GF-E almost similar after manufacturing using vacuum bagging. Six points were taken to get average of the surface flattened reading. Atmospheric pressure was applied during manufacturing GF-E using vacuum bagging to ensure good surface flattened.
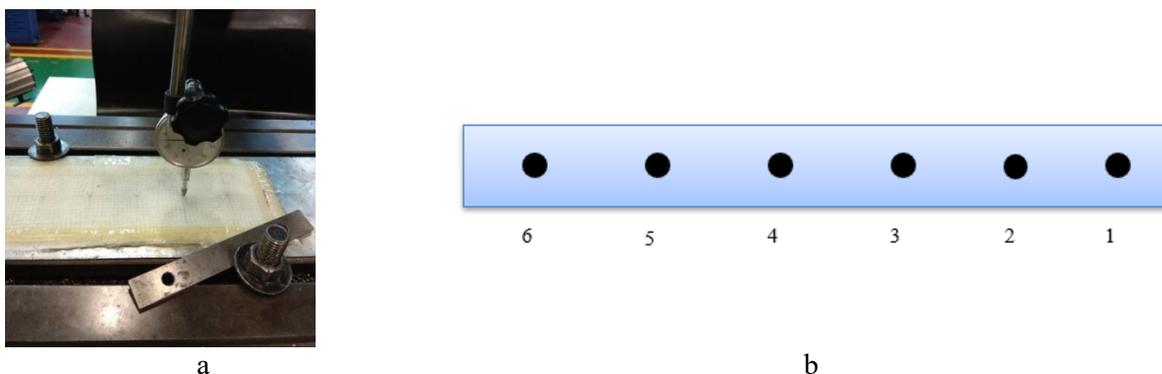

a   b

Figure 3. Check surface flattened using; (a) dial gauge, (b) schematic diagram

Table 3. Reading surface flattened of GF-E

| Point	1	2	3	4	5	6
Reading (mm)	2.15	2.14	2.15	2.14	2.15	2.16

3.1   Vibration test

A series of vibration tests were carried out on fiber metal laminates (FMLs) (250 x 25 x 15mm) with fixed-free boundary condition. Dynamic characteristic of fiber metal composites laminates were measured using the free vibration method as per the ASTM standard E756. Figure 4 shows experiment setup for free vibration test set up. In this experiment, uniaxial ICP® accelerometer, PCB 086C03 general purpose modal impact hammer, National Instrument NI9234 and ME'ScopeVES software were used for output signal acquisition, stimulus forces signal and data acquisition. Every five points, the FMLs plate was excited with help of modal impact hammer, and then subsequent vibrations of the plate were received by the accelerometer, which was attached to the plate using wax.

Frequency response properties of the samples were recorded during the dynamic modal analysis test a function of amplitude and frequency (Hz) by using Fast Fourier Transforms (FFT) in order to determine natural frequencies and damping factors. Frequency response only extracted within frequency range from 0 to 1000 Hz

Table 4. Dimension of specimens used in experiment

Specimen	Length (mm)	Width (mm)	Thickness (mm)		Weight (g)	
			CM	VB	CM	VB
GF-E	250	25	2.56	2.94	27.0639	33.9162
A2G1	250	25	2.32	2.38	33.4350	33.7431
A3G2	250	25	3.50	4.20	53.5684	58.2130

CM: Compression mould, VB: Vacuum bagging
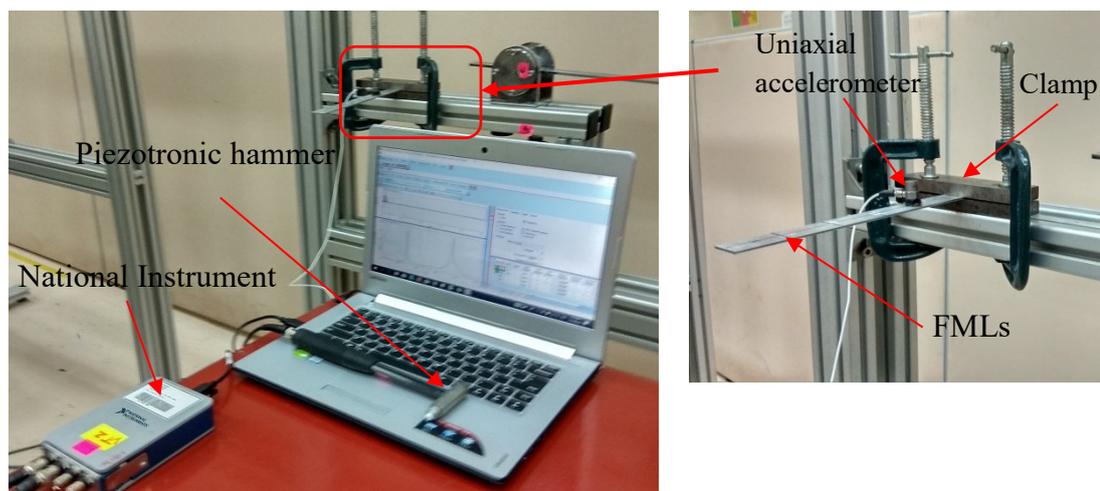
Figure 4. Experimental setup for free vibration by using impact hammer tests

In this experiment, the uniaxial accelerometer will move to every point while impact hammer will only impact at one point only. The process called roving accelerometer. Fifteen averages data which are obtained from excited location are taken during acquisition for each specimen to prevent experimental errors.

4. Results and discussion

Based on results in Table 5 shows influence of different manufacturing on natural frequency of composite laminates, two types manufacturing of composite laminates which is compression mould and vacuum bagging. The variation of natural frequency with respect to different manufacturing process is presented for the fixed-free boundary condition. It is noticed that the natural frequency of GF-E and FMLs plate with manufacturing process using vacuum bagging is increased by 28.1% for GF-E for 1st mode, 2nd mode is 33.3% and 3rd mode is 14.5%. It shows that with increase the thickness of plate, the natural frequency also increases. Composite materials produced by using vacuum bagging shows better natural frequency values due to better volume fraction between matrix and fibers.

Table 5. Variation of natural frequency for fixed-free boundary condition

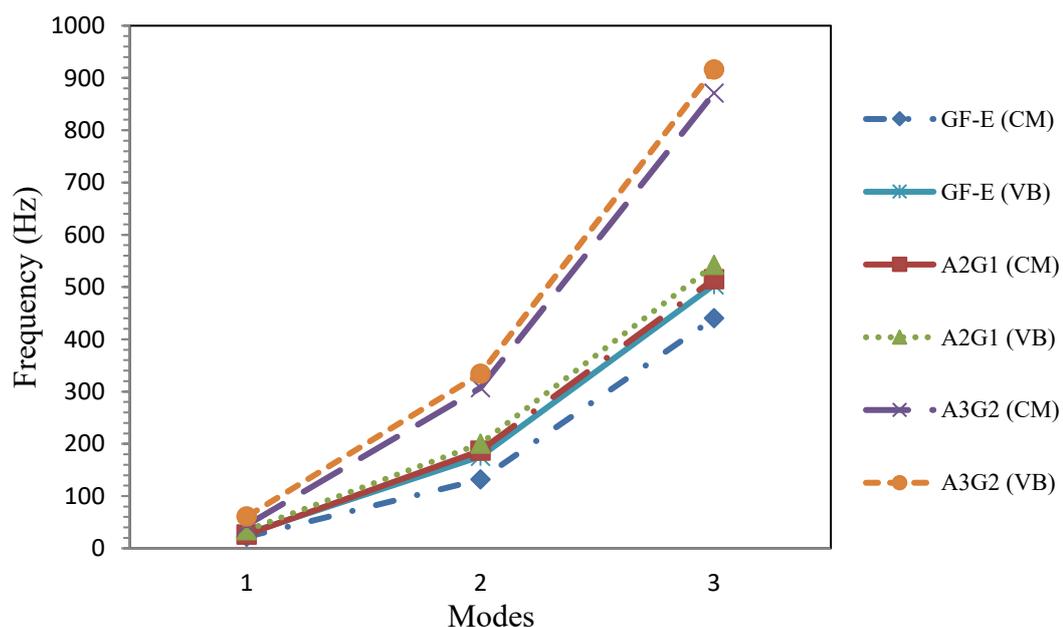| No. Mode (Hz)	1st Frequency		Improvement (%)	2nd Frequency		Improvement (%)	3rd Frequency		Improvement (%)
	CM	VB		CM	VB		CM	VB	
GF-E	22.0	28.2	28.1	132.0	176	33.3	440	504	14.5
A2G1	26.2	34.5	31.7	187.0	200	6.9	515	542	5.2
A3G2	44.3	60.7	37.0	307.0	334	8.8	871	916	5.1

Figure 5. Effect of different manufacturing process on natural frequency of composite materials and FMLs

Once again, for A2G1 and A3G2 materials also shows natural frequency is increasing with manufacturing process by vacuum bagging. For A2G1, the natural frequency increase from 26.2 to 34.5 Hz for 1st mode, 2nd mode is 187.0 to 200.0 Hz and 3rd mode is 515 to 542 Hz. This is fact that when the thickness of plate increases lead to an increase plate stiffness and the natural frequency value. Furthermore, it was observed that values increased by using the AL layer. The lateral elastic modulus of the AL layer was greater than glass fiber, with increase the number of the AL layers, the values natural frequency increased. The density of AL layers with respects to GF-E layer, also resulted in the increase at moment of inertia in the plates. It must be also noted that the stiffness and strength of the plate and also natural frequency of the plate increased with to the case the AL layers were embedded in the middle

layers of the structures. Figure 5 shows effect of different manufacturing process on natural frequency of composite materials and FMLs.

5. Conclusions

Vibration characteristic of glass fiber/epoxy and fiber metal laminates were determined and the effect of manufacturing process was evaluated. Natural frequency and mode shape of all samples were determining by free vibration analysis using exciting impact hammer on the specimen. The main conclusions from this experiment can be summarized as follows:

- Vibration characteristic of the glass fiber/epoxy and fiber metal laminates plate are strongly affected by the different manufacturing process which is compression mould and vacuum bagging.
- The increase in thickness of the specimens had higher natural frequency. The different thickness happened due to different pressure applied during cure process of the composite materials. Furthermore, the different thickness occurred due to different volume fraction between matrix and fibers.

Finally, the free vibration results can be utilized as a technique for health monitoring of structures testing.

Acknowledgements

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