Research Article

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Free Vibration Analysis of Fiber Metal Laminated Straight Beam

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Abstract: In recent years, studies on the development of new and advanced composite materials have been increasing. Among these new technological products, Fiber Metal Laminates (FML), and hybrid structures made of aluminium, carbon, glass or aramid fiber, are preferred especially in the aircraft industry due to their high performance. Therefore, free vibration analysis is necessary for the design process of such structures. In this study, the vibration characteristics of FML for clamped-free boundary conditions were investigated experimentally and numerically. Firstly, numerical results were obtained using Finite Element Method (FEM) and then these results were compared with the experimental results. It was seen that the numerical results were in good agreement with the experimental results. As the theoretical model was justified, the effects of various parameters such as number of layers, fiber orientations, and aluminium layer thickness on the in-plane vibration characteristics of the FML straight beam were analysed using FEM. Thus, most important parameters affecting the vibration characteristics of the hybrid structures were determined.

Keywords: Fiber Metal Laminates; Laminated Composite Straight Beam; Vibration Analysis; Finite Element Method; Hybrid Structures.

1 Introduction

Composite materials are widely used in aircraft, defense industry and similar areas because of their high strength, high rigidity, high fatigue strength,

high wear resistance and good corrosion resistance. Materials such as aluminium alloys and fiber reinforced composites used in such structures have advantages and disadvantages relative to each other. Thanks to the developing technology, these two materials have been combined to form a hybrid structure. Fiber metal laminates (FML) are hybrid structures consisting of fiber-reinforced polymer matrix composite and different sheet metals. This combination of materials provides good properties of metals and fiber reinforced composite materials [1]. There are some studies on composites and FML materials in the open literature. The determination of the mechanical and dynamic properties of structures made of composite materials is of great importance [2,3]. Considering the studies of fiber-metal laminated composite beams, the damping ratio with the Young's modulus is experimentally determined for the forced vibration condition [4]. The effects of the transverse shear deformation of the beams on the vibration characteristics were investigated by the Rayleigh-Ritz method. Effects of sheet thickness, fiber orientation, and plate aspect ratio on vibrational behavior were observed [5]. Based on the Timoshenko theory, the effects of length, depth, temperature field, geometric nonlinearity and transverse shear deformation on the nonlinear dynamic response of the beam were investigated [6]. Free vibration analysis of circular fiber metal composite plate with a central hole was studied depending on the theory of elasticity [7]. Some studies were performed on the free vibration of the FML circular cylindrical shells subjected to different boundary conditions [8-9]. Numerical and experimental vibration analysis of FML plates were examined. The effects of aspect ratio and boundary conditions on the natural frequencies of fiber metal laminated plates were investigated using the Finite Element Method (FEM) for numerical analysis [10]. Nonlinear vibration behaviour of fiber metal composite beams subjected to moving loads was carried out [11]. Free and forced vibrations of cracked FML carrying moving loads were studied. Numerical analysis was carried out using the modal expansion theory and Newmark method [12]. Dynamic progressive failure properties of glass fiber composite/aluminium hybrid

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laminates under low-velocity impact was investigated by FEM [13]. It was also seen that there are limited research studies in the literature on the vibrational analysis of FML straight beams numerically and experimentally. In the present study, numerical results were obtained using FEM and compared with the achieved experimental results to demonstrate the accuracy of the proposed model. The beam was modelled with the ANSYS simulation software. Natural frequency values and mode shapes were given in the graphical form.

2 Experimental Verification of the Numerical Model

In order to validate the accuracy and applicability of the proposed model, numerical results were compared with experimental results. The layered composites were produced by hot pressing at 120°C and under 3.92 kN forces which was applied to the sample for two hours. FML composites were produced with 6 and 8 layers. In addition, lower and upper layers of the composites were made of aluminium sheet while inner layers were composed of carbon prepregs. Experimental results were obtained with the PULSE vibration measurement system, which is a computer-based multichannel analysis system. The material properties of carbon-fiber prepregs were chosen to be as follows: modulus of elasticity (longitudinal and transverse respectively): $E_1 = E_2 = 65.7$ GPa, modulus of elasticity (transverse): $E_3 = 39.42$ GPa, shear modulus: $G_{12} = G_{23} = G_{13} = 31.55$ GPa, poisson ratios: $\nu_{12} = \nu_{23} = \nu_{13} = 0.041$, density: $\rho = 1600$ kg/m³. The material properties of Al2024-T3 were taken as: modulus of elasticity: $E = 53$ GPa, shear modulus: $G = 27.6$ GPa, poisson ratio: $\nu = 0.33$ and density: $\rho = 2850$ kg/m³. Geometrically, length and width of the beam are 165 mm, 25 mm, respectively. Thickness of aluminium sheets and carbon fiber prepregs are 0.3 mm and 0.275 mm, respectively. The beams have clamped-free boundary conditions. The natural frequencies (Nf) were obtained from the ANSYS program. It can be seen from Table 1 that, the present results are in good agreement with the results of experiments obtained with PULSE vibration measurement system.

3 Numerical Analysis

To study the vibration characteristics of FML straight beams the finite element technique was used. After the theoretical model was justified, for which the numerical

Figure 1: FML composite beam sample.

Table 1: Comparison of Natural Frequencies of FML Straight Beam.

Number of layers	Experimental Analysis		Numerical Analysis	
	First mode (Hz)	Second mode (Hz)	First mode (Hz)	Second mode (Hz)
6	<i>Nf</i> 56.5	343.5	53.8	336.75
8	<i>Nf</i> 73.5	452.6	74.17	464.14

results and mode shapes were given in Table 1 and Figure 4 respectively. The effects of various parameters such as number of layers, fiber orientations, and aluminium layer thickness on the in-plane vibration characteristics of the FML straight beam were analysed by using FEM. The beam was modelled as 12 layers consisting of Aluminium layer and Carbon / epoxy layers.

Ethical approval: The conducted research is not related to either human or animal use.

4 Results and Discussion

In this study, four different groups depending on the number and location of Aluminium (Al) and carbon prepreg (C) have been produced and presented in Table 2. For the given lamination in group **A**, as the number of aluminium layers increases, the natural frequencies decrease which is contrary to expectations: as the number of aluminium layers increases, the real frequency is expected to decrease (Figure 2 a). The reason is that as the number of aluminium layers increases, the effective stiffness and density of the composite beam increase. However, both the increment in density and the mass moment of inertia are more dominant than increment in the stiffness of the system.

Considering the operating frequency was near the real frequency of the aluminium-free beam; increasing the number of Aluminium layers would result in a safer design since the difference between the natural and operating frequency increases. In the group **B**, the natural frequencies increase when the position of Al

Table 2: The Configurations of FML composite beam having different layer sequences.

Case	Configuration	Description	Case	Configuration	Description
A ₁	(C ₀ –C ₉₀ –C ₀ –C ₉₀ –C ₀ –C ₉₀)s	In group A , the effect of the number of Al layer on the vibration behavior of the FML composite beam	C ₁	(Al ₅ C ₀)s	In group C , the Al layers were placed on the outer surface of the laminated composite and the orientation of fibers were changed
A ₂	(Al ₁ –C ₉₀ –C ₀ –C ₉₀ –C ₀ –C ₉₀)s		C ₂	(Al ₅ C ₁₅)s	
A ₃	(Al ₁ –Al ₁ –C ₀ –C ₉₀ –C ₀ –C ₉₀)s		C ₃	(Al ₅ C ₃₀)s	
A ₄	(Al ₁ –Al ₁ –Al ₁ –C ₉₀ –C ₀ –C ₉₀)s		C ₄	(Al ₅ C ₄₅)s	
A ₅	(Al ₁ –Al ₁ –Al ₁ –Al ₁ –C ₀ –C ₉₀)s				
A ₆	(Al ₁ –Al ₁ –Al ₁ –Al ₁ –Al ₁ –C ₉₀)s				
A ₇	(Al ₁ –Al ₁ –Al ₁ –Al ₁ –Al ₁ –Al ₁)s				
B ₁	(Al ₁ –C ₃₀ –C ₆₀ –C ₉₀ –C ₁₂₀ –C ₁₅₀)s	In group B , Al one layer was moved from the outer surface to the center of the composite step one step and change in the vibration behavior of the composite beam was analyzed	D ₁	(C ₄₅ –Al ₁ –Al ₁ –Al ₁ –Al ₁)s	Group D is similar to group B however, in group D carbon fiber layer with 45° degrees orientation was moved from outer surface to the center of the composite instead of Aluminum.
B ₂	(C ₃₀ –Al ₁ –C ₆₀ –C ₉₀ –C ₁₂₀ –C ₁₅₀)s		D ₂	(Al ₁ –C ₄₅ –Al ₁ –Al ₁ –Al ₁)s	
B ₃	(C ₃₀ –C ₆₀ –Al ₁ –C ₉₀ –C ₁₂₀ –C ₁₅₀)s		D ₃	(Al ₁ –Al ₁ –C ₄₅ –Al ₁ –Al ₁)s	
B ₄	(C ₃₀ –C ₆₀ –C ₉₀ –Al ₁ –C ₁₂₀ –C ₁₅₀)s		D ₄	(Al ₁ –Al ₁ –Al ₁ –C ₄₅ –Al ₁)s	
B ₅	(C ₃₀ –C ₆₀ –C ₉₀ –C ₁₂₀ –Al ₁ –C ₁₅₀)s		D ₅	(Al ₁ –Al ₁ –Al ₁ –Al ₁ –C ₄₅ –Al ₁)s	
B ₆	(C ₃₀ –C ₆₀ –C ₉₀ –C ₁₂₀ –C ₁₅₀ –Al ₁)s		D ₆	(Al ₁ –Al ₁ –Al ₁ –Al ₁ –Al ₁ –C ₄₅)s	
Al: Aluminium / C _α : Carbon prepreg / α: Fiber orientation angle					

Figure 2: Effect of (a) the number of aluminum layers (b) placing the aluminium layer from the outer layer to the inner layer on the natural frequencies of the composite beam.

layers change from surface towards mid-plane, due to the increase in effective thickness (Figure 2b). This was due to the fact that the lateral stiffness of the carbon-fiber prepreps was greater than the Al layers, and their effect on the natural frequency of the structure was increased by being embedded in the inner layers of the structure of aluminium layer. Another reason is that the Al layers have high density compared to carbon prepreps causing an increase in moment of inertia on the beam. The cases (C₁, C₂, C₃, C₄) have been investigated in order to compare the frequencies by changing the fiber orientation angle of prepreps between first and last Al plies (Figure 3a). It was also observed that, the natural frequencies change related with the variation in orientation angle of fibers.

The values of natural frequency increase more and more by increasing fiber orientation angle from 0° to 45° with an increment of 15° due to the rise of the stiffness of the structure. Besides, as the carbon/epoxy layer is placed from the surface towards the middle plane, natural frequency values decrease.

The highest natural frequency value was obtained with the composite beam having a fiber orientation angle of 45° which was another important finding of the present study. In group D, the natural frequencies decrease when the position of prepreg layers change from surface towards mid-plane, due to the increase in effective thickness causing an increase in moment of inertia on the beam (Figure 3b).

Figure 3.: Effect of (a) carbon fiber orientation angle (b) position of carbon/epoxy layer on natural frequencies of the composite beam.

Figure 4: Mode shapes and their corresponding frequencies of the composite beam for the case A₂.

5 Conclusion

The vibration properties of FML composite beam subjected to fixed-free boundary condition were studied numerically. In this investigation, four cases depending on the number and location of Al and prepreg have been investigated.

1. It was seen that, the natural frequencies decrease when the number of Al layers increase.
2. The natural frequencies increase when the position of Al layers changing from surface towards mid-plane.
3. It was also observed that, the natural frequencies change with a change in orientation angle of fibers.

4. The change in the position of prepreg layers from surface towards mid-plane result in the decrease in natural frequencies.

Conflict of interest: Authors state no conflict of interest.

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