

Research Article

Impact Response of Cantilever Fiber Metal Laminate (FML) Plates Using a Coupled Analytical-Numerical Method

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Abstract: In this study, dynamic response of cantilever Fiber Metal Laminate (FML) plates subjected to the impact of a large mass is studied. Aluminum (Al) sheets are placed instead of some Fiber Reinforced Plastic (FRP) layers. The effect of the Al layers on contact force and deflection of the plates is investigated by considering the interaction between the impactor and the target in the impact analysis. A two degrees-of-freedom system consisting of springs-masses and finite element modeling of the ABAQUS/Explicit software were employed to model the interaction between the impactor and the target. The results indicate that some parameters like the layer sequence, mass and velocity of the impactor, mass of the target are important factors which affect the impact response of the plates.

Keywords: Composite, contact force, Fiber Metal Laminate (FML), impact, plate

INTRODUCTION

Fiber Metal Laminates (FMLs) are hybrid structures consisting of different metal sheets and Fiber Reinforced Plastic (FRP) layers. One of the most important objects of their production is to combine good impact resistance of metals with better lightweight characteristic of FRPs (Vlot (1996) and Caprino *et al.* (2007)). The impact problems have received wide attention for many years. Dynamic response of the structures under impact loading is an important factor which should be considered in design.

Abrate (1994 and 2001) studied the impact behavior of composite laminates extensively. Olsson (2000, 2001 and 2003) classified low-velocity impact in two categories of small mass and large mass impact. This classification is based on the ratio of the impactor mass to the target (here, fiber metal laminates plate) mass. Small impactor masses cause a small mass response dominated by flexural and shear waves in which deflection, load and flexural strains are out of phase. When the mass of the impactor is larger than the target mass, there will be a 'quasi-static' large mass response, in which the peak load, stress and deflection are more or less in phase.

Many researchers have studied free vibration and have found frequency and mode shapes of isotropic and composite rectangular plates with simply support and fully clamped boundary conditions. Roy and Ganesan

(1993) studied the effects of different types of variations in profile and thickness of the amplitude of vibration and dynamic bending stresses of a square cantilever plate subjected to impact load. They observed that considerable reduction in amplitude and/or bending stresses can be achieved by proper selection of thicknesses variation. Chun and Lam (1996) analyzed the dynamic response of fully clamped laminated plates subjected to low-velocity impact of a mass by the Lagrange's principle and the Hertzian contact law. However, lack of reliable solutions still exists for the dynamic response of cantilever plates.

Christoforou and Swanson (1991) presented an analytical technique for the impact of laminated composite plates by a rigid impactor. Their solution was based on the Fourier series expansion for simply-supported plates combined with Laplace transform techniques for solving the impact problem. The solution gave the contact force, displacement of the plate and strain and stress as a function of time. Yung *et al.* (1989) calculated displacement, transient stress and strain distributions through the laminate thickness of composite plates during the impact using finite element method. They also studied the effect of initial velocity of the impactor on the contact force distribution, displacements and the transient stress and strain histories inside the plate during impact.

Abdullah and Cantwell (2006) studied the impact resistance of polypropylene-based fibre-metal

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laminates. They showed that these hybrid laminate systems offer potential for use in lightweight energy-absorbing structures. They also demonstrated that composite plies in the FMLs allow the aluminium layers to deform independently, absorbing significant energy through localised membrane stretching. In addition, the high strain to failure of the polypropylene fibres with the composite allow large amounts of energy to be absorbed in the failure process thereby enhancing the perforation resistance of these layered structures. It was observed that the highest specific perforation energy was offered by a simple sandwich construction based on a thick composite core and thin outer aluminium plies. An examination of the failed laminates showed that membrane stretching; plastic deformation and shear fracture in the aluminium layers as well as plastic drawing, delamination and ductile tearing in the composite plies were the primary energy-absorbing mechanisms in these laminates.

Caprino *et al.* (2007) presented a simple mechanistic model to predict the macroscopic response of fiberglass-aluminium laminates under low-velocity impact. They showed that the residual displacement after impact, mainly due to the plastic deformation of aluminium, is linearly dependent on the square root of the impact energy. Song *et al.* (2010) investigated on impact performance of carbon reinforced aluminum laminates experimentally and numerically. They showed that the specimen impacted by 2.35 J shows no critical damage behavior but the specimen impacted by 9.40 J shows fiber and matrix failures in CFRP layers and a shear crack on the aluminum surface. They also demonstrated that the specimen impacted by 2.35 J absorbed 64% of the impact energy and the specimen impacted by 9.40 J absorbed 83%. Therefore, the specimen impacted by 2.35 J shows less failure mechanism.

Payeganeh *et al.* (2010) studied the response of the FMLs subjected to low velocity impact and used the first-order deformation theory and Fourier series method to solve the system of governing equations of the plate analytically for the simply supported laminates. A system with two degrees of freedom consisting of springs-masses was used to model the interaction between the impactor and the plate. The results demonstrated that the use of the metal sheets inside the FRPs improved their global behavior against the impact. The plate with metal layers could damp the impact response more uniformly and rapidly. They showed that some of the parameters like layer sequence, mass and velocity of the impactor in a constant impact energy and aspect ratio of the target (a/b) were important factors which affect the dynamic response of the FMLs. They also demonstrated that metal layers affected the maximum contact force, maximum contact force time and contact time.

Rajkumar *et al.* (2012) investigated repeated low velocity impact behaviour of Glass Fibre/Epoxy-Al

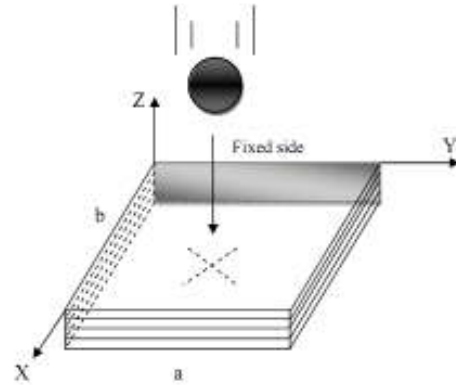


Fig. 1: Schematic view of the cantilever composite plate under the impact of a spherical mass

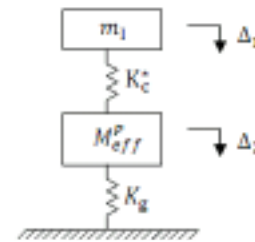


Fig. 2: A two degrees-of-freedom springs-masses model

Metal Laminates (GEAML) and Carbon Fibre/Epoxy-Al Metal Laminates (CEAML). They studied the effect of repeated impacts on peak load, absorbed energy, decelerated velocity and impact time with respect to deflection at impactor load of 5.2 kg under gravity fall. Their results showed that the Al plates, GEAML and CEAML exhibit different behaviour for both loading bearing capacity and damage pattern. They also demonstrated that maximum load bearing capacity was higher in case of monolithic aluminium but damage spread throughout the specimen, which contribute to the energy-absorbing capacity of these Al plates.

Hitherto, the phenomena of the impact on the cantilever plates have not been reported in the published literature. In this research, a model is represented to study the effect of some parameters on improving the large-mass impact behavior of the FMLs. The effect of using metal layers as well as some of the parameters such as stacking sequence, mass and velocity of the impactor on the impact response of the FML plates is also studied. The study of these parameters, which has not been presented in similar literatures, is useful for the designers as well.

- **Analysis of contact force and governing equations:** In the present research, a cantilever rectangular plate is chosen as shown in Fig. 1. A two degrees of freedom springs-masses model is proposed (Fig. 2).

In Fig. 1, m_I and M_{eff}^p represent the mass of the impactor and the effective mass of the plate,

respectively. Δ_1 and Δ_2 are the relative displacements of impactor and the plate masses, respectively. K_C^* and K_g also represent the improved contact stiffness and bending-shear stiffness of the plate respectively. Therefore:

$$m_i \ddot{\Delta}_1 + K_C^* (\Delta_1 - \Delta_2) = 0 \quad (1)$$

$$M_{eff}^p \ddot{\Delta}_2 + K_C^* (\Delta_2 - \Delta_1) + K_g \Delta_2 = 0 \quad (2)$$

$$\Delta_1 = A_1 \sin(\omega t + \varphi) \quad (3)$$

$$\Delta_2 = A_2 \sin(\omega t + \varphi)$$

$$\begin{bmatrix} -m_i \omega^2 + K_C^* & -K_C^* \\ -K_C^* & -M_{eff}^p \omega^2 + K_C^* + K_g \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = 0$$

$$\begin{Bmatrix} \Delta_1 \\ \Delta_2 \end{Bmatrix} = C_1 \bar{\varphi}^{(1)} \sin(\omega_{n1} t + \Psi_1) + C_2 \bar{\varphi}^{(2)} \sin(\omega_{n2} t + \Psi_2) \quad (3)$$

The values of C_1 , C_2 , Ψ_1 and Ψ_2 could be easily determined by the following initial conditions:

$$\begin{cases} \Delta_1(t=0) = 0 \\ \Delta_2(t=0) = 0 \end{cases} \& \begin{cases} \dot{\Delta}_1(t=0) = v_0 \\ \dot{\Delta}_2(t=0) = 0 \end{cases}$$

$$(m_i M_{eff}^p) \omega^4 + (-m_i K_C^* - m_i K_g - K_C^* M_{eff}^p) \omega^2 + K_C^* K_g = 0 \quad (4)$$

where ω is natural frequency, $\omega = \omega_n$:

$$C_1 = \frac{v_0 r_2}{\omega_{n1} (r_2 - r_1)}, C_2 = -\frac{r_1 \omega_{n1}}{r_2 \omega_{n2}} C_1 \quad (5)$$

$$r_1 = \frac{A_2^{(1)}}{A_1^{(1)}} = \frac{-m_i \omega_{n1}^2 + K_C^*}{K_C^*}, r_2 = \frac{A_2^{(2)}}{A_1^{(2)}} \quad (6)$$

$$= \frac{-m_i \omega_{n2}^2 + K_C^*}{K_C^*}$$

$$\bar{\varphi}^{(1)} = \begin{Bmatrix} A_1^{(1)} \\ A_2^{(1)} \end{Bmatrix} = \begin{Bmatrix} A_1^{(1)} \\ r_1 A_1^{(1)} \end{Bmatrix}, \bar{\varphi}^{(2)} \quad (7)$$

$$= \begin{Bmatrix} A_1^{(2)} \\ A_2^{(2)} \end{Bmatrix} = \begin{Bmatrix} A_1^{(2)} \\ r_2 A_1^{(2)} \end{Bmatrix}$$

$$F(t) = K_C^* (\Delta_1 - \Delta_2) \quad (8)$$

$$\delta = (\Delta_1 - \Delta_2) \quad (9)$$

where, $F(t)$ is the contact force and K_C^* can be calculated based on the following equation (Gong *et al.*, 1994):

$$K_C^* = \sqrt{\pi} \Gamma\left(\frac{p+1}{2}\right) \frac{2\Gamma\left(\frac{p}{2}+1\right) + \sqrt{\pi} \Gamma\left(\frac{p+1}{2}\right)}{4\Gamma^2\left(\frac{p}{2}+1\right) + \pi^2 \left(\frac{p+1}{2}\right)} \delta_m^{p-1} K_C, P = 1.5 \quad (10)$$

$$K_g = M_p \omega_{11}^2 \& K_C = \frac{4}{3} ER^{1/2} \quad (11)$$

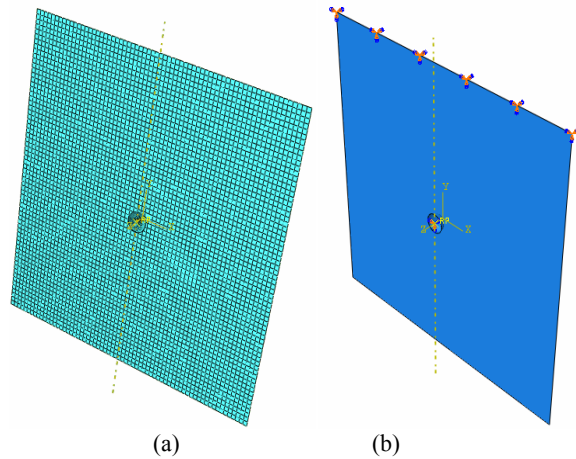


Fig. 3: A three-dimensional finite element model, a) meshing for a complete model, b) boundary conditions for a cantilever plate

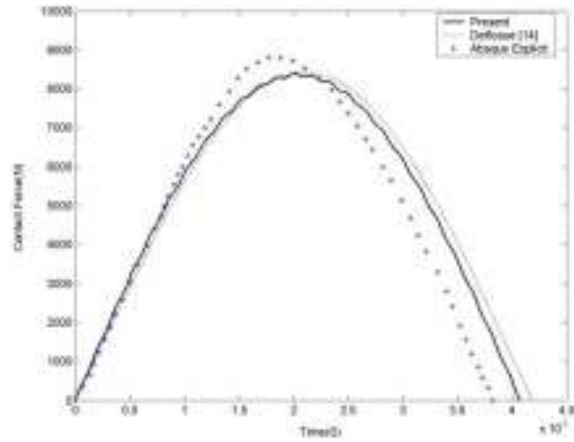


Fig. 4: Comparison of the contact force histories

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \& \frac{1}{E} = \frac{1-\nu_2^2}{E_2} + \frac{1-\nu_1^2}{E_1} \quad (12)$$

where, R_1 and R_2 are the curvature radius, ν_1 and ν_2 are the Poisson's ratio and E_1 and E_2 are the elastic modulus. Index 1 belongs to the target (plate) and index 2 indicates the impactor. ω_{11} is the first natural frequency of the plate and M_p is the total mass of the plate that can be calculated as follows:

$$M_i = \int_{V_i} \rho_i(z) dV_i = ab \int_{-h_i/2}^{h_i/2} \rho_i(z) dz, i = t \quad (13)$$

where, ρ and t are the density of the plate and some of the layers, respectively.

FINITE ELEMENT MODEL

A three-dimensional finite element model is also developed using ABAQUS/Explicit software (Fig. 4). Elements S4R and R3D4 are used for meshing the cantilever composite plate and the impactor respectively. Surface to surface contact with penalty

Table 1: Geometrical and material properties of the composite plate, FMLs and the impact or (Payeganeh *et al.*, 2010)

Geometrical properties of FML cantilever plate:
 Boundary conditions: Clamped-Free-Free-Free (CFFF) Lay-up: [0, 90, 0, 90, 0]_s
 Plate size: a = 200 mm; b = 200 mm
 Plate thickness: h = 2.69 mm (0.269 mm/layer)

Material properties of FRP layer (Glass-Polyester):
 $E_{11} = 24.51 \text{ GPa}$; $E_{22} = E_{33} = 7.7 \text{ GPa}$; $G_{12} = G_{13} = 3.34 \text{ GPa}$; $G_{23} = 1.34 \text{ GPa}$
 $\nu_{12} = \nu_{23} = 0.078$; $\rho = 1800 \text{ kg/m}^3$

Steel impact or properties:
 Tip diameter: 12.7 mm; $\rho = 7800 \text{ kg/m}^3$
 $m_i = 2 \text{ kgf}$; Impact velocity (v_0) = 3 m/s
 $E = 207 \text{ GPa}$, $\nu = 0.3$

Properties of Al layer (2024-T3):
 $E = 72.4 \text{ GPa}$, $G = 27.6 \text{ GPa}$, $\nu = 0.33$, $\rho = 2780 \text{ kg/m}^3$

contact formulation is used for defining the contact between the impactor and the plate. A three-dimensional finite element model showing: a) meshing for a complete model and b) boundary conditions for a cantilever plate is given in Fig. 3.

Model verification: To ensure the accuracy of the present model, the contact force determined from the springs-masses model is compared with the contact force determined from the experiment (Delfosse *et al.*, 1993) and ABAQUS software (Fig. 4). Figure 4 shows a good agreement in the results.

RESULTS AND DISCUSSION

The composite plate is symmetric and cross ply. The plate consists of 10 layers which are numbered from top to bottom (Table 1). Two layers of the Al 2027-T3 alloy are symmetrically placed instead of two glass-polyester layers in the FRP structures to observe their position effect on impact resistance of the structure; i.e., the Al layers are separately placed instead of these layers of the plate as: (1, 10), (2, 9), (3, 8), (4, 7) or (5, 6). The impactor is a spherical heavy object (impactor mass/plate mass>2). Geometrical and material properties of the composite plate as well as the impactor are presented in Table 1.

Effect of the layer sequence of the FMLs: Figure 5a demonstrates the time history of the transverse deflection of the plate. It can be seen that this value changes from 0.051 for the FRP plate (the composite without the Al layers, curve 6) to 0.0269 (curve 1), 0.0322 (curve 2), 0.0377 (curve 3), 0.0453 (curve 4) or 0.0495 (curve 5) which corresponds to composites when the Al layers are in (1, 10), (2, 9), (3, 8), (4, 7) or (5, 6) positions respectively. It can be observed that the closer the Al sheets to the impact zone (here, embedding the Al layers instead of the (1, 10) ones), the more reduction happens in reducing the composite deflection.

The second result is more interesting and it is reported in order to only simply support boundary conditions and not for cantilever plates (Payeganeh *et al.*, 2010). As evident in Fig. 5b, by replacing the

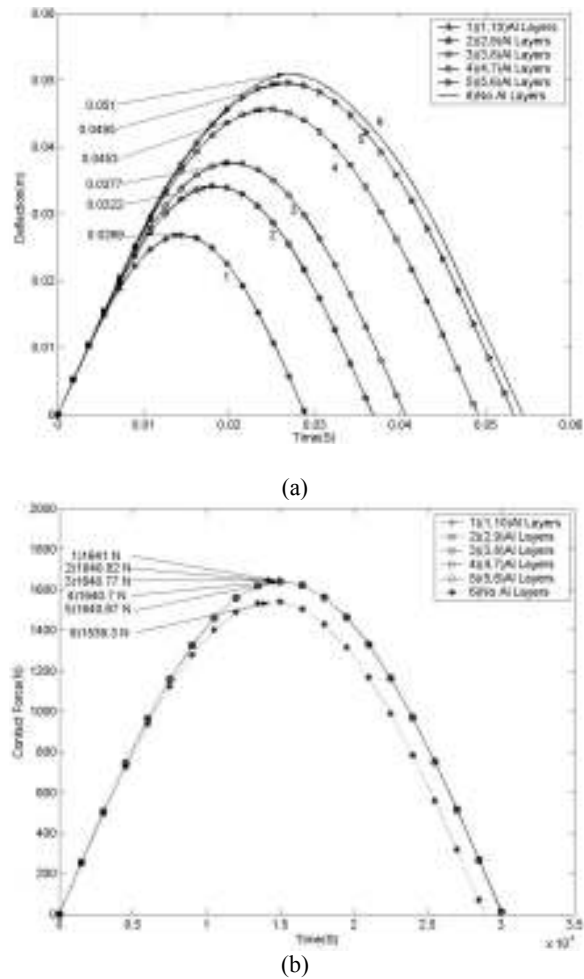
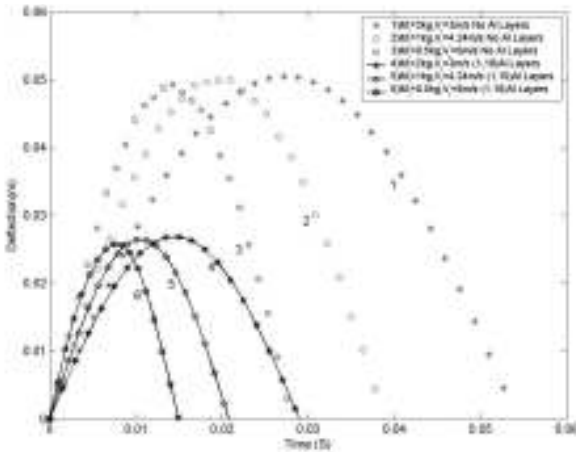


Fig. 5: Effect of the layer sequence of the Al layers on: (a) deflection history and (b) contact force history of the traditional and an Al embedded composite plates

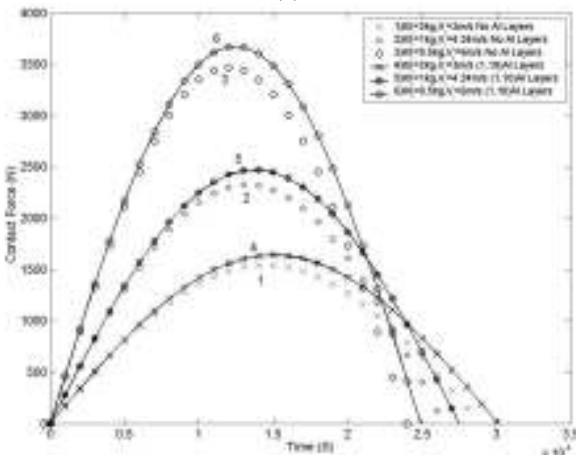
glass-polyester layers with the Al ones, the maximum contact force (hereinafter called MCF) increases from 1539.3 N in the case of the structure without the Al layers to 1641, 1640.82, 1640.77, 1640.7 and 1640.67 when the Al layers are positioned in the structure as (1, 10), (2, 9), (3, 8), (4, 7) or (5, 6) respectively. The maximum of MCF is seen in curve 1 (when the Al layers are placed instead of (1, 10) layers). This may be

Table 2: Effect of mass and velocity of the impact or at a constant impact energy level
Constant energy Level = 9 J, FML sheets are placed in (1,10) layers

Considered parameters different m and v	Maximum percent of deflection reduction	Maximum percent of MCF increase
• m = 0.5 kg, v = 6 m/s	47	6
• m = 1 kg, v = 4.24 m/s	47	6
• m = 2 kg, v = 3 m/s	47	6



(a)



(b)

Fig. 6: Effect of various masses and velocities of the impactor at a constant energy level on (a) contact force history and (b) deflection of the plate

due to the fact that when the Al layers are placed in the outer layers of the structure, the impactor hits a stiffer layer.

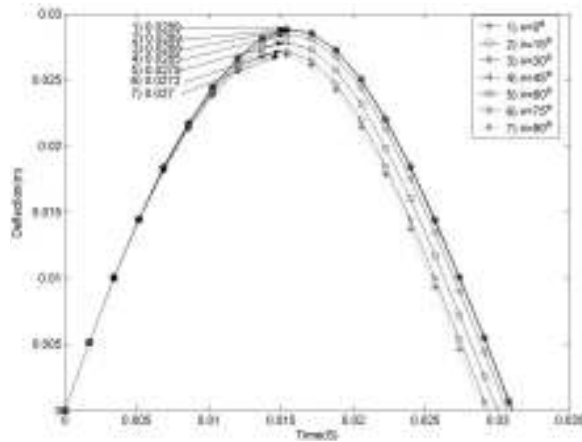
Similar to the results obtained by Khalili *et al.* (2007) for the smart structures, the MCF is also increased, while maximum contact force time (MCFT) tends to move to the right side of the diagram (Fig. 5b). Thus the shocking effect of the impact phenomena transferred to the plate decreases and a weaker impact is inflicted upon the structure. This is the reason that in other parts of this research the Al layers are embedded in the (1, 10) layers of the plate.

Effect of mass and velocity of the impactor in a constant impact energy level: Here, the effect of different masses and velocities of the impactor in a constant impact energy level equal to 9 J is studied. The mass and velocity of the impactor are chosen as:

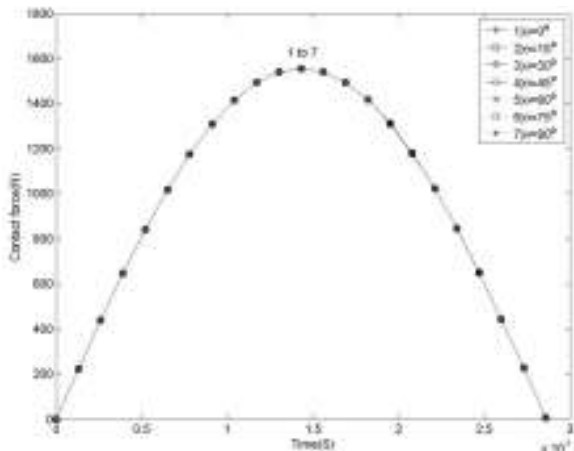
- m = 0.5 kg, v = 6 m/s
- m = 1 kg, v = 4.24 m/s
- m = 2 kg, v = 3 m/s

The Al layers are used in layers (1, 10) of the structure. The results obtained at a constant impact energy level, but, with different masses and velocities of the impactor are shown in Fig. 6. It can be found that:

- The maximum deflection (Fig. 6a) decreases by increasing the velocity and decreasing the mass of the impactor. Figure 6b also shows that irrespective of the position of Al layers in the structure (curves 4-6) or (curves 1-3), the minimum MCF increases a little with increasing the velocity and decreasing the mass of the impactor (from curves 1 to 3 when the Al layers are not placed in the structure and, from curves 4 to 6, when the Al layers are placed in the structure). It is also seen that, at a constant impact energy level, the impact velocity is a more effective parameter than the impactor mass to improve the impact response of the structure (Fig. 6a and b).
- Figure 6a shows that the maximum plate deflection decreases from curves 1 to 4, 2 to 5 and 3 to 6 respectively. When the Al layers are embedded in the structure, the period of the deflection histories also reduces to half (Fig. 6a). Therefore, the oscillation motion of the structure damps more rapidly. When the Al layers are placed instead of glass-polyester ones, the MCF increases (from curves 1 to 4, 2 to 5 and 3 to 6, respectively, in Fig. 6b). It can be concluded that at a constant impact energy level, the impactor velocity is a more effective parameter than the impactor mass for improving the impact response of the FMLs.
- The results obtained from Fig. 6 are classified in Table 2. As can be observed, the same reduction in the maximum deflection of the structure happens in all the cases, i.e., at a constant impact energy level, the amount of increase of the impact resistance of the structure is obtained by the Al layers (nearly independent from the value of mass or velocity of the impactor).



(a)



(b)

Fig. 7: Effect of orientation of composite fibers on (a) deflection of the plate and (b) contact force history

Table 3: Effect of a/b ratio on plate deflection

a/b ratio of composite plate	1	1.25	1.5	2
Maximum deflection of FRP plate	0.0510	0.0453	0.0414	0.0357
Maximum deflection of FML plate	0.0269	0.0240	0.0220	0.0183
Percent of increase	47	47	47	49

Effect of fibers orientation of the composite plate:

The effect of fibers orientation of the composite plate is also examined. To study the effect of fibers orientation of composite plate, the layup is chosen as $[0, \theta, 0, -\theta, 0]_s$ where $\theta = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ$ and 90° . As can be seen in Fig. 7a, increasing the fibers orientation of the composite layers results in a small decrease (about 7%) in the maximum of the plate deflection. Therefore, the impact resistance of the structures increases a little. Figure 7b also shows that changing the fibers orientation of the composite layers had nearly no effect on the contact forces.

Effect of the aspect ratio of the plate: The effect of aspect ratio (a/b ratio) is also studied. Again, the Al

layers are placed instead of the (1, 10) ones of the structure. The results of this section are presented in Table 3. According to this table, the following results are desired:

- The maximum plate deflection decreases by increasing of the a/b ratio irrespective of the presence or absence of the Al layers in the structure.
- Using Al layers has a positive effect on improving the impact response of the structure (about 47 to 49%), regardless of the value of a/b ratio.

CONCLUSION

In the present research, the dynamic response of a large-mass impact upon cantilever fiber metal laminates is studied using a coupled analytical numerical method. To model the interaction between the impactor and the plate, a system with two degrees of freedom which consists of springs-masses and ABAQUS/Explicit software are used. The results indicate that:

- The use of Al layers inside the traditional composite laminates improves their overall behavior against the impact, because the plates with the Al layers damp the impact phenomenon more uniformly and rapidly.
- The parameters like the layer sequence and impactor mass and velocity are important factors affecting the dynamic response of the FMLs.
- The location of Al layers is an important factor to change the behavior of the structure. Placing the Al layers near the impact zone can improve the impact resistance of the structure at the highest level.
- At a constant impact energy level, the amount of increase in the impact resistance of the structure obtained using the Al layers is nearly independent from the value of mass or velocity of the impactor.
- No matter what the fibers orientation of the composite laminate is, embedding the Al plates into the FRP plates results in a positive effect on improving of the impact resistance of these structures.

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