Mathematical, Numerical and Experimental investigation of low energy impact on Glass Fiber Reinforced Aluminum Laminates

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Abstract

GLARE belongs to a family of fiber-metal laminates composed of alternate layers of prefabricated reinforced composites with unidimensional glass fibers and Aluminum 2024 sheets first invented for aeronautical applications. The dynamic response of structures, which are subjected to impact loading can be studied by employing equivalent mechanical systems consisting of springs and masses. It is then possible to derive the differential equations of motion using the equilibrium of forces, which are applied on the masses. In this research, a mathematical model of low velocity impact loading on Glass Fiber Reinforced Aluminum Laminates was derived and simulated, as well as the dynamic effect of low energy impact with the simulation of finite element method (FEM) of on 4 types of GLARE were performed. Low velocity impact tests were conducted with drop-weight impact tower and the central plate’s deflection, force-time history, velocity-time history and energy-time diagrams obtained from the mathematical model and simulation of finite element analysis were compared with the experimental data obtained from the drop weight impact tower. The comparison of the results shows that the results of simulation of finite element are 4% and the results of the 8% mathematical model differ with experimental results and mathematical model can use for low velocity impact modelings.
Keywords: Glare, low velocity impact, mathematical model, experimental tests, finite element model

List of Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$M_0$</td>
<td>mass of the impactor</td>
</tr>
<tr>
<td>$m_e$</td>
<td>the effective plate mass</td>
</tr>
<tr>
<td>$w_0$</td>
<td>central plate’s deflection</td>
</tr>
<tr>
<td>$f$</td>
<td>the force due to the global deflection of the plate</td>
</tr>
<tr>
<td>$\rho_{ave}$</td>
<td>average mass density</td>
</tr>
<tr>
<td>$r$</td>
<td>radius of circular plate</td>
</tr>
<tr>
<td>$t$</td>
<td>thickness of circular plate</td>
</tr>
<tr>
<td>$N_x$</td>
<td>in-plane force in x direction of aluminum layers</td>
</tr>
<tr>
<td>$N_y$</td>
<td>in-plane force in y direction of aluminum layers</td>
</tr>
<tr>
<td>$N_{xy}$</td>
<td>in-plane force in xy plane of aluminum layers</td>
</tr>
<tr>
<td>$A_{ij}$</td>
<td>extensional stiffnesses of the laminate</td>
</tr>
<tr>
<td>$\vartheta$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$E_{mean}$</td>
<td>average stiffness of the panel</td>
</tr>
<tr>
<td>$G_{IIc}$</td>
<td>the mode II interlaminar shear fracture toughness of the glass–epoxy</td>
</tr>
<tr>
<td>ILLS</td>
<td>interlaminar shear strength of the glass–epoxy</td>
</tr>
</tbody>
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I. Introduction

A fiber metal laminate (FML) such as GLARE is a hybrid composite consisting of thin aluminum layer and fiber-reinforced epoxy composite layer. The combination of the diverse metal having different strength and the composite layer with different orientation can achieve to lead improvement of aircraft structure design. The most widely used metal for FML is aluminum, and the fibers are Kevlar or glass. FMLs with glass fiber (GLARE) and Kevlar fibers (ARALL) are used in aircraft structures [XIII], [II], [XII], [IX], [XV] since they have many advantages such as weight saving, good impact resistance, and damage tolerance. Furthermore, the maintenance of metallic aircraft structure such as easy machining, forming, and mechanical fastening ability and damage inspection can apply on FMLs [XIV]. GLARE laminate could be identified as good candidate material for a lot of applications in future aircraft structure, i.e. the fuselage, pressure bulkhead, tails and wings etc. This outstanding of GLARE laminate has been already approved by the commercial aircraft Airbus A380 [III] Impact damage is a one of the concentration topics for aerospace structures. The inability to visually detect interior damage to composite layers, sometimes extending well beyond the impacted area, remains an important safety issue. Therefore, it is necessary to accurately predict internal impact damage to FMLs. Due to out of-plane loads, such as impacts, FMLs may suffer damage in the form of different mechanisms such as: (i) plastic deformation of the metal layers; (ii) matrix cracking and fiber failure; (iii) delamination between composite plies; and (iv) debonding of the metal and composite layer. Numerous researchers have reported results of low-velocity impact tests on FMLs as...
summarized in Table 1. This table also lists the types and configurations of the tests. Also listed is the size of the test specimen and size of the test area. A detailed summary of these methods is provided in [XVIII]. The abbreviations in the table are CARALL (CARbon Reinforced ALuminum Laminate), CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass fiber reinforced Polymer) and AFRP (Aramid Fiber Reinforced Polymer). In general, these results showed that GLARE will outperform aluminum under impact loading in terms of absorbed energy [XI], [XVI]. GLARE will also develop a visible dent, similar to monolithic alloys, when subjected to impact. This dent provides clear visual evidence that an impact has taken place. Traditional composites will develop significant internal damage with little surface indications when subjected to the same impact energy levels [XI], [I]. Impact tests are typically time consuming and because of scatter in the results, require large sample sizes. Therefore, some efforts have been undertaken to model the response of FMLs. Delamination was only incorporated into the FEA models to model damage from in-plane and out-of-plane peel loads. Some analytical techniques have been developed for impact loading [XII], [XVI]. Wu et al. [VI] was studied experimentally. Caprino et al. [IV], [V] developed a mechanistic model to predict the response of square fiber glass–aluminum laminates under low velocity impact, which requires the implementation of several experimental tests. Hoo Fatt et al. [X] employed a spring-mass model in order to predict the ballistic response of clamped square GLARE panels. In this study a spring-mass mathematical method and finite element method simulation were developed to analysis and prediction of dynamical response of circular clamped GLARE under low energy impact.

Problem definition

Glare 2, 3, 4 and 5 2/1 consists of two layers of Al 2024-T3 aluminum alloy sheet and one layer of [0/0], [0/90], [0/90/0] and [0/90/90/0] glass/epoxy composite respectively. Fig. 1 shows the Glare 5 2/1 lay-up configuration used. A 30 × 30 mm2 square test FML specimen was clamped between two steel plates exposing a circular central impact region with a diameter of 50 mm. A steel spherical impactor of 10 mm diameter with a mass of 6.29 kg was used with kinetic energy 10.8 J. Fig 2 shows Schematic of the drop-weight impact test.

Fig 1. Glare 5 2/1 lay-up configuration
Impact test

Low velocity impact tests were conducted on a PSh 1120 drop-weight impact tower at impact velocity 1/85 m/s. The data during an impacting testing were collected by a PC based data acquisition system. After the initial impact, the pneumatic brake system is activated and prevents the kickback of the impactor. The GLARE plate was clamped between two 115 mm square steel plates. The center of these two steel plates had a circular hole 30 mm in diameter. The impactor was a 10 mm diameter spherical steel alloy with a weight of 6.29 kg.
II. Mathematical modeling

The dynamic response of structures, which are subjected to impact loading can be studied by employing equivalent mechanical systems consisting of springs and masses. It is then possible to derive the differential equations of motion using the equilibrium of forces, which are applied on the masses. The results from the solution of these differential equations predict the time history response of the structure due to impact with satisfactory accuracy. Mechanical spring-mass systems with a single degree of freedom have been employed in order to study the dynamic response of square GLARE plates due to ballistic impacts. For our analysis, we also consider a spring-mass system consisting of one spring and an equivalent mass in order to model the movement of the circular GLARE plate along with the impactor. The spring force represents the impact load due to the global deflection of the GLARE plate, while the equivalent mass represents the masses of both the plate and the impactor. The corresponding differential equation of motion of this mechanical system is given by:

\[
(M_0 + m_e) \ddot{w}_0 + f_L(w_0) = 0
\]

\[
m_e = \frac{r^3(3\pi^2 - 28)\rho_{ave} t}{2\pi}
\]

This equation is applicable for the prediction of the dynamic response of plates in loading stage before delamination (stage 1), which are subjected to low velocity impacts [VI].

\[
f_L(w_0) = C_{plate} w_0 + C_{elastic} \dot{w}_0^2
\]

Where

\[
C_{plate} = 24.5N_x + 24.5N_y + 32.2N_{xy}
\]

\[
C_{elastic} = \frac{1}{r^2}[8.63(A_{11} + A_{22}) + 5.73(A_{12} + 2A_{66})]
\]
Initial conditions for equation of stage 1 are:

\[ w_0(0) = 0 \quad \text{and} \quad \dot{w}_0(0) = v \]  
(6)

The Equation suitable for loading stage after delamination (stage2) is:

\[ (M_0 + m_j)\ddot{w}_0 + f_L(w_0) = 0 \]  
(7)

Initial conditions for equation of stage 2 are:

\[ w_0(0) = w_{01} \quad \text{and} \quad \dot{w}_0(0) = \dot{w}_{01} \]  
(8)

The Equation suitable for unloading stage (stage 3) is:

\[ (M_0 + m_j)\ddot{w}_0 + f_U(w_0) = 0 \]  
(9)

Where

\[ f_U(w) = C_{\text{plate}}(2w_0 - w_0^{\text{max}}) + C_{\text{elastic}}w_0^2 \]  
(10)

Initial conditions for equation of stage 3 are:

\[ w_0(0) = w_0^{\text{max}} \quad \text{and} \quad \dot{w}_0(0) = 0 \]

The in-plane forces of aluminum layers are:

\[ N_x = N_y = n\sigma_{\text{yield}} t_{Al} \]  
(11)

\[ N_{xy} = \frac{1}{\sqrt{3}} n\sigma_{\text{yield}} t_{Al} \]  
(12)

\[ A_{ij} = \begin{bmatrix} E_{11} & \frac{\gamma_{12}E_{22}}{1 - \gamma_{12}\gamma_{21}} & 0 \\ \frac{\gamma_{12}E_{22}}{1 - \gamma_{12}\gamma_{21}} & 1 - \gamma_{12}\gamma_{21} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \]  
(13)

when impact loading on the plate equals to \( F_{\text{del}} \) Delamination of glass – epoxy layers occurs.

\[ F_{\text{del}} = \sqrt{\frac{8\pi^2 E_{\text{mean}} t^3 G_{\text{fmc}}}{9(1 - \gamma^2)}} \]  
(14)

Delamination radius and delamination energy respectively are:
\[ R_{del} = \frac{F_{del}}{t\pi^2 ILSS} \] (15)

\[ E_{del} = \pi R_{del}^2 G_{Ilc} \] (16)

Conflation of equation (12) and (13) attains:

\[ E_{del} = \frac{2t\pi E_{\text{mean}} G_{Ilc}^2}{9(1 - G^2)ILS^2} \] (17)

Effect of delamination on the velocities of system and relationship between velocities in stage 1 and 2 is:

\[ \frac{1}{2}(M_0 + m_{eq})\dot{w}_{01} - E_{del} = \frac{1}{2}(M_0 + m_{eq})\dot{w}_{02} \] (18)

The following equation gives impactor kinetic energy:

\[ E_k = \frac{1}{2}M_0(\dot{w}(t))^2 \] (19)

This equation holds for all three stages.

### III. Results

In order to predict impact response of circular plate of GLARE 2 2/1, GLARE 3 2/1, GLARE 4 2/1 and GLARE 5 2/1, the differential equations of motion and FEM modeling was applied. Figures 3 to 9 shows the final outcomes.

Fig 5. FEM predicted von mises stress contours of GLARE 5 2/1
Fig 6. Comparison FE simulation and mathematical model results for predicting dynamic response curves of GLARE 5 2/1

Fig 7. Comparison FE simulation and mathematical model results for predicting dynamic response curves of GLARE 2 2/1

Fig 8. Comparison FE simulation and mathematical model results for predicting dynamic response curves of GLARE 3 2/1
Fig 9. Comparison FE simulation and mathematical model results for predicting dynamic response curves of GLARE 4 2/1

Fig 10. Comparison FE simulation and mathematical model force-time history with experimental results for GLARE 5 2/1

Fig 11. Comparison FE simulation and mathematical model force-time history with experimental results for GLARE 4 2/1
Figures 6 to 9 shows mathematical model results for GLARE 2 2/1, 3 2/1, 4 2/1 and 5 2/1 in the following charts: the center of circular plate’s deflection–time (w0–t) In terms of units of measurement (mm–ms), velocity-time (v0-t) In terms of units of measurement (m/s–ms), kinetic energy-time (Ek-t) In terms of units of measurement (J–ms) and load-time history (F-t) In terms of units of measurement (kN–ms) and FEM model results in in the following charts: the center of circular plate’s deflection–time (w0–t) In terms of units of measurement (mm–ms) and kinetic energy-time (Ek-t) In terms of units of measurement (J–ms) and comparison of them. The comparison between the deflection–time (w0–t) kinetic energy-time (Ek-t) graphs in mathematical modeling and finite element shows the results of both methods are close. Therefore, to determine the accuracy of mathematical models and finite element simulation, it is necessary to compare their results with experimental results.

Figures 10 and 11 shows the Comparison FEM simulation and mathematical model force-time history with experimental results for GLARE 5 2/1 and 4 3/2 respectively. Comparison of mathematical model results, finite element simulation with experimental results show that numerical simulation and then mathematical model are very accurate and very well simulate the phenomenon of very low velocity impact.

IV. Conclusion

In this research, the dynamic response of 4 type of circular GLARE plates under low velocity impact was analyzed by mathematical modeling and FEM simulation. For mathematical analysis of the problem, a mechanical system of nonlinear mass-spring model was considered first and then the differential equations of the system were extracted. Also, a finite element model of low-velocity impact at circular GLARE was prepared and the results of the simulation were determined. Finally, the results of the mathematical model and finite element simulation were compared with the experimental results obtained from the drop weight impact tower. The comparison of the results shows that the results of simulation of finite element are 4% and the results of the 8% mathematical model differ with experimental results.

References


