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Experimental and Numerical Investigation on the High Velocity Impact Response of GLARE with Different Thickness Ratio

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Abstract

GLARE is a fiber metal laminate that is a novel hybrid composite, consisting of thin aluminum and glass/epoxy layers. The main advantage of GLARE is its high fatigue and impact loading resistance. Also its areal density is lower than metals or composites when they are used alone. In fact, it has benefits of metals and composites simultaneously. In this paper some 2/1 GLARE laminates are manufactured and impacted by 8.7 mm diameter blunt cylinder projectiles at energies up to that required to achieve complete perforation of the target using a helium gas gun. Aluminum and composite layers in these laminates have different thicknesses so the effect of changing thickness of aluminum or composite layers on the ballistic performance of GLARE, ie. Ballistic limit velocity and specific perforation energy, can be investigated. The efficient thickness ratio to maximize the specific perforation energy is obtained, too. The same tests are analyzed numerically by LS-DYNA and the results show good agreement with experimental data. The results are discussed and commented upon.

Keywords: GLARE, ballistic limit, specific perforation energy, layer thickness, LS-DYNA.

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1. Introduction

Light weight composite materials are currently finding extensive use in a wide range of load bearing engineering applications. Fiber metal laminates (FMLs) are a family of highly fatigue and impact resistant laminated composite materials. They offer the structural designer a damage tolerant, light-weight and cost-effective replacement for conventional aluminum alloy sheets or composites in advanced transport structural applications. GLARE is the well known member of the FMLs, consists of alternating thin layers of aluminum sheets and unidirectional glass/epoxy composite plies [1], and has been selected for the upper fuselage skin structures of airbus A380.

The impact performance of the structures is one of the important safety issues. It has been known that GLARE enhances energy absorption and increases the ballistic limit than metal or composite from which it is made [2-5].

Nomenclature

| Symbol | Description                  |
|--------|------------------------------|
| \( \rho \) | Density (kg/m\(^3\)) |
| \( E \)  | Elastic modulus (GPa)         |
| \( \nu \) | Poisson’s ratio               |
| \( S_y \) | Yield strength (MPa)          |
| \( E_t \) | Tangent modulus (MPa)         |
| \( \varepsilon_a \) | Ultimate tensile strain      |
| \( E_1 \) | Elastic modulus in longitudinal direction (GPa) |
| \( E_2 \) | Elastic modulus in transverse direction (GPa) |
| \( E_3 \) | Elastic modulus in thickness direction (GPa) |
| \( G_{12} \) | Shear modulus 1-2 plane (GPa) |
| \( G_{13} \) | Shear modulus 1-3 plane (GPa) |
| \( G_{23} \) | Shear modulus 2-3 plane (GPa) |
| \( \nu_{12} \) | Poisson’s ratio in 1-2 plane |
| \( \nu_{31} \) | Poisson’s ratio in 3-1 plane |
| \( \nu_{32} \) | Poisson’s ratio in 3-2 plane |
| \( X_t \) | Longitudal tensile strength (MPa) |
| \( Y_t \) | Transverse tensile strength (MPa) |
| \( Y_c \) | Transverse compressive strength (MPa) |
| \( S \)  | In plane shear strength (MPa)  |
| \( \varepsilon_f \) | Ultimate tensile strain      |
| \( \gamma_f \) | Ultimate shear strain        |
Vlot tested bare aluminum layers and GLARE laminates in low and high velocity impact and showed that GLARE laminates have better impact resistance than aluminum sheets [2]. Also, he expanded the results of his research to ballistic limit, absorbed energy, central deflection and radius of delaminated area [3]. In addition, he used a non-linear elastic impact model to calculate the transient deflection and impact force under low velocity conditions [4], but did not address anything about ballistic limit. There are too many numerical or analytical researches that have been done about ballistic limit of aluminum layers or composite laminates individually, but there is little about GLARE [6-9]. Hoo Fatt et al. [10] presented analytical solutions to predict the ballistic limit and energy absorption of fully clamped GLARE 5 panels subjected to ballistic impact.

With increasing researches about many aspects of GLARE, the full potential of GLARE has not been fully explored yet. The aim of this research is to answer the question that if GLARE is more ballistic resistant than its constituents (aluminum or glass/epoxy), so what is the optimum content of each material in a GLARE panel? To answer this question some 2/1 GLARE specimens with various thickness ratios (constant aluminum thickness layer and variable glass/epoxy ply numbers) are fabricated and impacted with high velocity projectiles. The ballistic limit velocity and specific perforation energy (The specific perforation energy is defined as the energy absorbed by panel divided by areal density) of each panel is obtained and compared to each other. Also, the same tests are analyzed numerically by LS-DYNA and the results show good agreement with experimental data.

2. Specimen preparation and experimentation

2.1. Materials and fabrication

The GLARE laminates consists of thin high-strength aluminum alloy sheets bonded together with glass/epoxy adhesive layers. The aluminum layers are of 2024-T3 type that using for the airplane fuselage. Glass fiber reinforced polymer layers are made by E-glass unidirectional fiber layers and CY219 Huntsman epoxy resin. The mechanical properties of materials are obtained according to ASTM E8M and ASTM D3039 listed in table 1 and 2.

Table 1. Mechanical properties of aluminum sheet

| \( \rho \) | \( E \) | \( v \) | \( S_y \) | \( E_t \) | \( e_u \) |
|---|---|---|---|---|---|
| 2700 | 72 | 0.32 | 350 | 1.3 | 0.18 |

Table 2: Mechanical properties of glass/epoxy ply

| \( \rho \) | \( E_1 \) | \( E_2 \) | \( G_{12} \) | \( G_{13} \) | \( G_{23} \) | \( v_{12} \) | \( v_{13} \) | \( v_{23} \) | \( X_t \) | \( Y_t \) | \( Y_c \) | \( S \) | \( \nu \) | \( \gamma \) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1540 | 36 | 5 | 5 | 2.7 | 2.7 | 1.92 | 0.25 | 0.301 | 0.25 | 465 | 5.6 | 5.6 | 19.2 | 0.013 | 0.12 |

Specimens were fabricated by hand lay-up method and pressed under 1.5 bar pressure for 8 hours (curing time of resin). For better adhesion between aluminum and resin, surface preparation for aluminum layers was performed by initial removing oil, abrading and cleaning by high-pressure water according to the ASTM D2651. The aluminum and glass/epoxy thicknesses are 0.5 mm and 0.35 mm respectively. All specimens have 2 aluminum layers for front and rear of the panels and between them the glass/epoxy
layers are in 0° and 90° orientations. For reducing the effect of unknown factors only one change is perform between orientations in the mid plane of the panel. The base of orientation is the rolling direction of aluminum layers. The difference of specimens is of the ratio of the thickness of aluminum layers to glass/epoxy layers. The specimens that are tested is shown in table 3.

Table 3. Tested specimens

| lay-up            | Weight (gr) | overall thickness (mm) | thickness ratio of glass/epoxy plies to aluminum layers |
|-------------------|-------------|------------------------|--------------------------------------------------------|
| (AL/0/90/AL)      | 101.2       | 1.75                   | 0.75                                                   |
| (AL/0/2/90/AL)    | 125.9       | 2.45                   | 1.45                                                   |
| (AL/0/8/90/AL)    | 310.8       | 7.25                   | 6.25                                                   |

2.2. Experimental procedures

The impact tests were conducted at room temperature using a helium gas gun shown in Fig. 1. The gas gun consisted of a pressure vessel of 50 bar capacity, a high speed solenoid valve and a stainless steel hollow barrel with 2.5 m long. The inside diameter of barrel was 8.7 mm. The projectile was blunt cylinder with 14.1 gr. weight. The projectile is hardened so the impact has negligible effects and cannot deform it.

Fig. 1. Schematic illustration of gas gun

The specimens are squared flat panels of 15cm×15cm and were clamped on all sides in a fixture with a 13cm×13cm opening. As shown in Fig. 1 the projectile’s velocity before impact was measured with a chronograph. The ballistic limit was achieved by impacting panels at different velocities to narrow the range between perforation and no perforation. Generally the difference between the velocities of perforation and no perforation is very small, so the average of those two velocities is considered as ballistic limit.
3. Numerical analysis

Numerical analysis was carried out by a nonlinear explicit finite element code, LS-DYNA [11]. Due to symmetry, a quarter of the panel and projectile was modeled. The target and projectile were modeled with 8 node solid elements. Material model 20 (*MAT_RIGID) was chosen for projectile. Aluminum layers of the panel and composite plies were modeled with material model 3 (*MAT_PLASTIC_KINEMATIC) and Material model 22 (*MAT_COMPOSITE_DAMAGE) respectively. Material model 3 is based on Cowper-Symonds strain rate hardening model and isotropic hardening effect was considered. Chang-Chang progressive failure model is the basis of material model 22. In order to delete failed composite elements, material model 0 (MAT_ADD_EROSION) was appended to material model 22. The erosion criterion was maximum principle and shear strain. *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE algorithm was applied between each pair of the panel. Also, *CONTACT_ERODING_SURFACE_TO_SURFACE was applied between projectile and each target layers. The numerical results were in good agreement with experimental data.

Fig. 2. penetration and deformation pattern of GLARE 2/1 target

4. Results and discussion

A plot of the ballistic limit as a function of thickness ratio is given in Fig. 3. It is shown that by increasing the overall thickness of the target, the ballistic limit is increasing, too. It means that, with more glass/epoxy layers, the target absorbs more energy during perforation.

Fig. 3. Ballistic limit velocity versus thickness ratio

The results show one thing more that the slope of the plot becomes less by more increasing the glass/epoxy layers. In the first step the number of glass/epoxy layers becomes double and the ballistic limit becomes 1.47 times. In the second step, the number of glass/epoxy layers becomes 16 But the ballistic limit becomes 1.37 times. It can be resulted from accounting the mechanisms of energy
During perforation of projectile into GLARE targets, the kinetic energy of the projectile can be dissipated in global deformation, including panel bending and membrane stretching; extensive delamination within the glass/epoxy layers; and tensile fracture of the glass/epoxy and aluminum. So if the thickness of the panel becomes more, the panel becomes stiffer and the global deformation becomes less but shear deformation, fiber fracture and friction between the projectile and the target becomes more. On the other hand if the number of glass/epoxy plies becomes less, the thickness of the panel decreases then the global deformation becomes more, i.e. the panel bends more and the distal layer stretched more, too. So adding the glass/epoxy plies to thick panels have less effect on energy absorbed than thin panels.

Increasing the thickness of the panel in most targets of any material can enhance the ballistic limit but for aerospace application, it means heavy structure and a disadvantage. One of the outstanding benefits of the GLARE is having the same ballistic strength like aluminum layers with less weight. According to this, in comparing the strength of GLARE laminates, the weight of the panel should be considered. Fig. 4 shows the specific perforation energy as a function of thickness ratio. The advantageous of GLARE against bare aluminum (thickness ratio → 0) or glass/epoxy (thickness ratio → ∞) is obvious. The results show that for improving the ballistic limit, there is an optimum thickness ratio that should be obtained. In this research the thickness ratio of 1.45 is better than others.

![Fig. 4. Specific perforation energy versus thickness ratio](image)

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