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Ballistic impact response of fiber–metal laminates and monolithic metal plates consisting of different aluminum alloys

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ABSTRACT

In this article, the ballistic impact response of square clamped fiber–metal laminates and monolithic plates consisting of different aluminum alloys is investigated using the ANSYS LS-DYNA explicit nonlinear analysis software. The panels are subjected to central normal high velocity ballistic impact by a cylindrical projectile. The implemented finite element models have been validated by comparison with published experimental data concerning GLARE 5 and monolithic 2024-T3 aluminum plates. Using the validated models, the influence of the mechanical properties of the constituent aluminum alloy on the ballistic resistance of the fiber–metal laminates and the monolithic plates is studied. Apart from 2024-T3, the aluminum alloys 2024-T351, 2024-O, 6061-T6, 7039 and 7075-T6 are considered. It is found that the ballistic limits of the panels can be substantially affected by the constituent aluminum alloy. The 7075-T6 aluminum alloy offers the highest ballistic resistance whereas 2024-O aluminum alloy offers the lowest ballistic resistance.

1. Introduction

Fiber–metal laminates are hybrid composite materials, consisting of alternating metal layers bonded to fiber-reinforced prepreg layers. ARALL (Aramid Reinforced ALuminum Laminates), CARALL (CArbon Reinforced ALuminum Laminates) and GLARE (GLAss REinforced) are representative hybrid composites which belong to this new family of materials. The unidirectional fibers in ARALL, CARALL and GLARE consist of aramid, carbon and glass, respectively. Although the material of the fibers is different, the metal layers of these fiber–metal laminates are manufactured using aluminum alloys. Consequently, aluminum alloys are of primary importance for the construction of fiber–metal laminates.

GLARE is the most successful fiber–metal laminate up to now and is currently being used for the construction of primary aerospace structures, such as the fuselage of the Airbus A380 air plane. Further applications have also been considered: aircraft cargo floors of Boeing 777, aircraft engine cowlings, bonded GLARE patch repair, aircraft stiffeners with a wide variety of shapes, cargo containers, seamless GLARE tubes [1–4].

Impact properties are very important in aerospace structures, since impact damage is caused by various sources, such as maintenance damage from dropped tools, collision between service cars or cargo and the structure, bird strikes and hail [3,5–8]. Much work has been published on the subject of impact, concerning monolithic materials, composite materials and fiber–metal laminates, which are frequently used in aerospace structures. Analytical, numerical and experimental impact studies have been considered [9–26]. In these impact studies, the static indentation, the low and high velocity impact, and the ballistic impact response of conventional and hybrid composite materials, like GLARE, are analyzed.

In the study of Hoo Fat et al. [10], the ballistic impact of GLARE 5 panels is investigated. Pertinent experimental results concerning the ballistic limit of GLARE 5 and monolithic 2024-T3 aluminum plates are reported there. Yaghoubi and Liaw studied the ballistic response of GLARE 5 beams [17,21]. They presented experimental and theoretical results of the transient beam response. For their theoretical results they used the LS-DYNA finite element code. In two other articles [11,12], the same authors studied the ballistic response of GLARE 5 plates and presented corresponding experimental and FEM results. Both experimental and numerical results in the aforementioned articles are closely related with the response of 2024-T3 aluminum alloy, which is used for the construction of the examined panels. In a recent article [18], the ballistic response of fiber–metal laminates based on 1050 aluminum alloy is investigated.

In this article, extensive research has been implemented in order to investigate and compare the influence of the mechanical properties of different aluminum alloys on the ballistic re-

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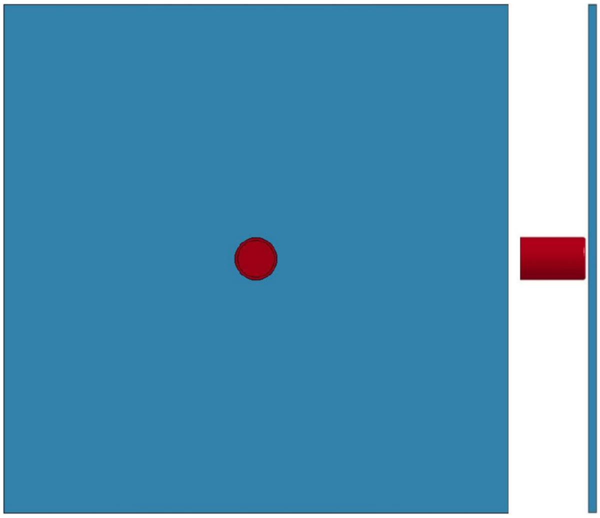

Fig. 1. Top view and side view of a monolithic aluminum square plate with 3.2 mm thickness along with the cylindrical projectile.

sistance of glass-reinforced fiber–metal laminates and monolithic metal plates consisting of these alloys. ANSYS LS-DYNA finite element software is employed for this purpose. A total of 30 different ballistic impact cases have been simulated. To the authors' knowledge, there is not any published literature with comparative ballistic impact evaluation of unidirectional glass-reinforced fiber–metal laminates consisting of different metal alloys. The presented results shed light to the ballistic impact response of aluminum plates and aluminum based fiber–metal laminates and will help engineers and researchers to understand the behavior of the examined materials along with the effect of using different aluminum alloy for their manufacturing.

2. Problem definition

For the evaluation of the ballistic performance of the fiber–metal laminates and aluminum plates examined in this article, we consider the same structural arrangement which is employed for the ballistic experiments presented in reference [10]. Namely, we consider square clamped panels with dimensions equal to 152.4 mm × 152.4 mm. The panels consist of either fiber–metal laminated material or monolithic aluminum alloy. The fiber–metal laminates consist of alternating layers of aluminum and glass-epoxy. Each panel is struck at its center by a rigid projectile with known initial high velocity. The projectile's initial velocity vector is normal to the panel. As in the experiments of reference [10], the mass of the projectile is equal to 14.125 g. The projectile is flat-faced, cylindrical, 25.4 mm long with a diameter equal to 12.7 mm. The impacting face of the projectile has a small radius equal to 0.8 mm. A representative solid model illustrating the geometry of the problem is shown in Fig. 1.

The ballistic limit of a tested material is defined as the lowest velocity for complete perforation of the corresponding panel. As the projectile strikes on the panel, its initial ballistic velocity and kinetic energy drop abruptly. The initial ballistic kinetic energy is consumed for the perforation of the panel. As analyzed in [10], there are several basic mechanisms contributing to the ballistic impact energy absorption in fiber–metal laminates: global panel deformation, delamination among glass-epoxy layers, tensile fracture of glass-epoxy layers, petaling of aluminum layers. The global panel deformation includes bending and stretching of the aluminum and prepreg layers of the laminate.

The examined ballistic impact phenomenon is a transient nonlinear problem involving contact interaction and geometric and material nonlinearities. ANSYS LS-DYNA explicit nonlinear finite element analysis software is used in order to simulate the ballistic impact. The ballistic limit along with the transient response of the projectile-panel system will be determined numerically. Different layup configurations, panel thicknesses and aluminum alloys are evaluated.

3. Finite element modeling

In this article, we implement a three-dimensional finite element modeling procedure in order to predict the transient ballistic impact response of square clamped panels consisting of fiber–metal laminates or monolithic aluminum alloys, when subjected to central normal ballistic impact by a cylindrical rigid projectile. ANSYS LS-DYNA explicit finite element analysis software is used for this purpose.

The projectile is modeled with SOLID164 elements. These hexahedral-shaped elements have eight nodes with nine degrees of freedom per node, corresponding to the translations, velocities and accelerations in the three nodal directions. The monolithic aluminum plate is also modeled with SOLID164 elements with two solid elements along its thickness. The fiber–metal laminate is modeled using SOLID164 elements as well. Two solid elements are used along the thickness of each aluminum metal layer. One solid element is used along the thickness of each glass-epoxy prepreg layer. It is noted that the same mesh density along the thickness of fiber–metal laminates is employed in references [12,17,21].

In order to simulate the contact between the projectile and the panel we use the surface-to-surface contact type with the eroding contact option. The eroding contact option is needed in order to erode those elements of the panel which satisfy predetermined failure criteria.

In order to simulate the contact between adjacent layers of the fiber–metal laminate we use the surface-to-surface contact type with the tiebreak contact option. The tiebreak contact option is needed in order to allow delamination/debonding between adjacent layers. With this option, the delamination/debonding is governed by the failure criterion proposed by Chang and Springer [27,28]:

$$\left(\frac{\sigma}{\sigma_c}\right)^2 + \left(\frac{\tau}{\tau_c}\right)^2 \geq 1 \tag{1}$$

where σ, τ are the normal and shear stresses acting in the interface of two adjacent layers and σ_c, τ_c are the normal and shear strength of the interface, respectively. It is assumed that delamination/debonding is taking place due to the interfacial shear stresses between the contacting layers. For this reason, an increased value of the normal interfacial strength is employed, yielding a shear-driven delamination/debonding failure, as in references [12,17,18,21].

The projectile is considered rigid. This consideration is valid for projectiles made of materials with adequate strength and hardness, and is also employed in references [10,18]. For this reason, a rigid material model is used for the projectile.

The material of monolithic aluminum plates and of the aluminum metal layers in the fiber–metal laminates is modeled with the simplified Johnson–Cook plasticity material model [28,29]:

$$\sigma_y = \left(A + B\varepsilon^n\right)\left(1 + C\ln\dot{\varepsilon}^*\right) \tag{2}$$

where σ_y is the flow stress, A, B, C, n are material constants, ε is the equivalent plastic strain and $\dot{\varepsilon}^*$ is the dimensionless plastic strain rate. This material model does not include temperature variations and cumulative damage of the metal. It is however a