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New criteria for simulating failure under multiple impacts of the same total energy on glass fiber reinforced aluminum alloy laminates

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ABSTRACT

The low-velocity impact behavior of glass-fiber-reinforced aluminum alloy laminates (GLARE) is analyzed under single and multiple impacts of the same total energy. A new failure-judgment method is proposed by modifying previous failure criteria. This method is combined with a materials performance gradual degradation method and is employed by writing the LS-DYNA user subroutine for the impact simulation and testing of GLARE. The established finite-element model is proved reliable by comparing test results. Analyzing the simulated single and multiple impacts of the same total energy reveals that, GLARE sustains greatest internal damages under single impact. However, repeated impacts induce the largest deformation. If the impact frequency is maintained constant, the GLARE's damaged area widens as the initial impact energy increases.

1. Introduction

Low-velocity impact incidents often occur on the structure of a spacecraft in service or under maintenance [1–3]. As a newly laminated structural material, glass-fiber-reinforced aluminum alloy laminates (GLARE) were first applied on the cabin in 1987 [4], after their wide engineering application [5–6]. During impact of GLARE, various failure modes may occur, such as metal/plastic deformation and cracking, composite matrix cracking, fiber breakage, delamination, and debonding [7]. According to the failure mechanism, impact energy is partly absorbed and the composites are internally damaged; however, GLARE may externally have only a dent, though the effect on the laminate structure's safety performance may be severe. These damages of the composite laminates could be measured with an apparatus [8–9]. However, the aluminum alloy sheets covering GLARE make internal damage detection difficulty. Therefore, a numerical-analysis method is recommended, and numerous research achievements have been reported [10–11].

Numerous studies were conducted on the single-impact properties of fiber-metal laminates [12–15]. However, there are few studies concerning multiple impacts, and they are mainly focused on experiments. For example, Mouritz [16] discovered that matrix cracking, delamination, and fiber breakage occur in glass-fiber-reinforced laminates after repeated impacts. They inferred that after each impact, interfacial shear strength significantly reduces, resulting in matrix cracking, debonding, and delamination. Therefore, they proposed shear strength as the main parameter for impact analysis. Whrick [17] suggested that the main damage in carbon/epoxy composites occurs during the initial impact, and subsequent impacts lead to fewer damages. Ho [18] indicated that the main failure mode of carbon-fiber-reinforced polymer laminates after repeated impacts is fiber failure. Hosur [19] discovered that the peak load does not significantly change after multiple low-energy impacts. Icten [20] indicated that, after the fourth impact, the maximum contact force and the energy absorption value of a carbon-fiber-reinforced polymer decreases as the number of impacts increases. Yarmohammad [21] performed tests of repeated low-velocity impact on GLARE 5 using a drop impact tower. The damage evolution was evaluated using visual inspection, ultrasonic C-scan, scanning electron microscope (SEM), and mechanical sectioning techniques. Rajkumar [22] investigated the effect of repeated low-velocity impacts on the tensile strength of the fiber metal laminates via a drop weight impact tester. Results indicated that ultimate tensile strength, failure strain, and ductility of all specimens initially decrease and then remain constant with increasing number of impacts. Morinière [23] conducted an experimental study on the multiple low-velocity-impact behaviors of GLARE 5-2/1-0.3 and discovered that the aluminum layers prevent the penetration of the projectile and the expansion of delamination; the glass/epoxy plies can withstand several impacts until perforation. This efficient mechanism preserves the structural integrity of GLARE until the first aluminum sheet cracking at the non-impacted side. Jakubczak [24] analyzed the multiple impact resistance of fiber metal laminates (FMLs) experimentally and indicated that they have good resistance to multiple impacts. The results revealed that the damage to the FMLs considerably increases stably after each impact; after multiple impacts, the damage is characterized by delamination in the composite layers and the metal–composite interface, and deformation of the aluminum sheet. Kashani [25] compared a single impact with two impacts of the same total energy through an experiment, and obtained the failure

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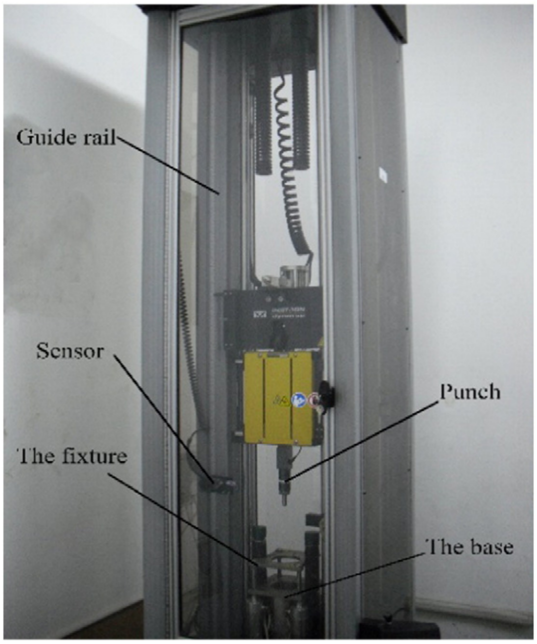

Fig. 1. Drop-hammer low-velocity impact testing machine.

modes and impact parameters influenced by this impact-energy sequence.

Previous studies about the behavior of FMLs after repeated impacts mainly focused on experiments. Although a few studies employed numerical simulations to establish the analytical model, the shear stress influence of the neighboring layers on the interface delamination was not focused on. Therefore, this paper aims to establish an adaptive model to analyze the influence on GLARE of different multiple impact with the same total impact energy. The same total impact energy of 30 J is adopted herein, and the impact energy combinations are 30 J, (10 + 20) J, (20 + 10) J, and (10 + 10 + 10) J. Among them, (10 + 20) J total impact energy produces two successive impacts with 10 J and 20 J, respectively. Tests are combined with numerical simulation herein. The drop-hammer low-velocity impact-testing machine is employed to verify the model's reliability, and the numerical simulation is based on the user subroutine of the LS-DYNA software. The influence of multiple impacts on GLARE is successfully explained by test and the computational results.

2. Material and methods

2.1. Test specimen preparation and impact test

To obtain the deformation and internal damage of GLARE during the multiple impacts, (10 + 10) J and 20 J impact tests were conducted on prepared GLARE specimens. The (10 + 10) J impact test refers to two impacts on the same location of the GLARE specimen with 10 J impact energy each, whereas the 20 J impact test refers to a single impact on the GLARE specimen with 20 J impact energy. To ensure test data accuracy, the same impact test was performed five times, during which any changes in the punch contact force and displacement were recorded.

Table 1
Aluminum alloy sheet performance parameters [26].

Elastic parameters	Yield parameters	Failure parameters
$E = 724\text{GPa}$	$A = 265\text{MPa}$	$d_1 = 0.112$
$\nu = 0.33$	$B = 426\text{MPa}$	$d_2 = 0.123$
$\rho = 2770\text{kg/m}^3$	$c = 0.0083$	$d_3 = 1.5$
	$m = 1.7$	$d_4 = 0.007$
	$n = 0.73$	$d_5 = 0$

The meaning of the parameters in this table is explained in Section 2.2.

The drop-hammer low-velocity impact testing machine was employed (Fig. 1); in the testing machine, the fixture could drop on the specimen. The impact zone was circular with a 76 mm diameter. The punch head of the machine was hemispherical with an 8 mm diameter and a punch mass of 11 kg. The base was fixed. When the impact test began, the specimen was clamped by the falling fixture, then the punch fell on the exposed specimen, and the sensor acquired the test data.

The preparation method of GLARE specimens included the following steps: 1) decontaminating the aluminum alloy sheet in acetone solution, 2) degreasing aluminum alloy sheet in a mixture of 25–30 g/L sodium hydroxide and 25–30 g/L sodium bicarbonate solution for 1 min, 3) deoxidizing the aluminum alloy sheet in a 300–500 g/L nitric acid solution for 5 min, 4) anodizing the aluminum alloy sheet in 120–140 g/L phosphoric acid solution for 20 min, 5) cleaning and drying the aluminum alloy sheet in an oven for 15 min, 6) laying the glass-fiber-reinforced prepreg layers between two aluminum alloy sheets, 7) curing the specimen into a vacuum tank for two hours with 180 °C and 0.9 million atmospheres, and 8) cooling down the specimens to ambient temperature for testing. In this study, four prepreg layers were included in the GLARE specimen and the glass-fiber-reinforced prepreg stacking sequences were 0/90/90/0; the zero refers to the crushing direction of the aluminum alloy, as shown in Fig. 2. The 2024-T3 Al aluminum alloy sheet was adopted for GLARE, the performance parameters were taken from the literature [26] (Table 1), and the single-layer glass-fiber-reinforced composite laminates were provided by the manufacturer (Table 2). The specimen dimensions are shown in Table 3.

2.2. The finite element model

2.2.1. Finite element model

To obtain an adaptive analytical model to simulate experimental phenomena, the commercial finite-element software LS-DYNA is adopted. The analytical procedure is presented in Fig. 3. Herein, in

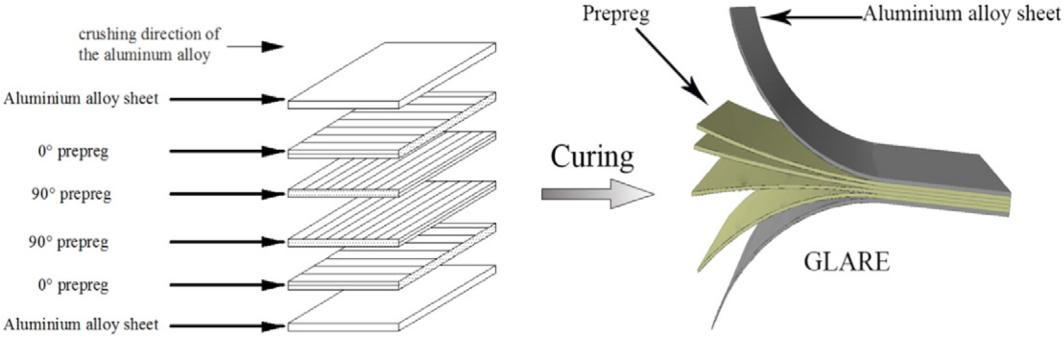

Fig. 2. GLARE and internal prepreg stacking sequences.