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Low velocity impact of carbon fiber aluminum laminates

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This paper investigates the low velocity impact behavior of the carbon fiber aluminum laminates (CARALL). The purpose of the research is to study the applicability of carbon fiber in FMLs and the effect of the properties of aluminum alloy on the low velocity impact response of CARALL. A user-defined material subroutine (VUMAT) is used to define Hashin's 3D damage constitutive model of composite. The numerical simulations using the progressive damage model have a good agreement with the test results of Glare in the impact incident. Simulation results reveal that CARALL represents the better impact resistance property than Glare due to the high strength and stiffness carbon fiber reinforced plastic (CFRP). The numerical simulations using the proposed damage model successfully predict the impact mechanical behavior of CARALL. In addition, finite element models are developed to investigate the effect of the impact resistant of CARALL panels with different aluminum alloys, namely 1060-O, 2024-T3, 6061-T6 and 7075-T6. It is shown that the impact resistance of CARALL is improved by increasing the yield strength of aluminum alloy.

1. Introduction

Fiber metal laminates (FMLs) are a kind of metal-like hybrid composite materials consisting of metal and composite, typically aluminum alloy and glass fiber reinforced epoxy. Currently, glass fiber aluminum laminates (GLARE) have been widely applied to the aircraft structure. Examples for the application of FMLs are ARALL in the cargo door of the American C-17 aircraft and GLARE in significant parts of the fuselage of the Airbus A380 as a new structural material [1,2]. GLARE is also reported to be used as a surface material in Boeing 777 cargo floor panels due to its excellent impact properties [3]. Several articles have shown that FMLs possess both the wonderful impact resistance characteristics of metals and the attractive mechanical properties of fiber reinforced composite materials [3–6].

In recent years, the low and high velocity impact behaviors of fiber metal laminates [7,8] have been investigated. Abdullah and Cantwell [7] studied the impact behavior of a glass fiber reinforced polypropylene FML and found that the FML offered an excellent impact resistance to low and high velocity impact loading. The results showed that FMLs absorbed energy through plastic deformation in the aluminum and micro-cracking in the composite layers. Some scholars have tried to simulate the impact response of FMLs using numerical techniques [9–12]. Karagiozova et al. [9] modeled the blast response of FML panels with various stacking configurations using ABAQUS/Explicit and predicted the influence of the loading parameters and structural characteristics on their overall behavior. Although ABAQUS has a number of failure criteria for composite materials, they are used with 2D elements, such as plane stress and continuum shell elements. Therefore, it is necessary to develop a constitutive model with failure criteria and simulate a composite material using 3D solid elements. Recently, Vo et al. [10] developed FE models which were validated with experimental data of FMLs based on a 2024-O aluminum alloy and a woven glass–fiber polypropylene composite. The constitutive model and failure criteria were then implemented in ABAQUS/Explicit using the VUMAT subroutine. Vo et al. [12] also used the VUMAT subroutine to analyze the blast resistance of FML panels based on the four aluminum alloys.

Carbon fiber reinforced plastic (CFRP) as high strength-to-weight and stiffness-to-weight ratio materials have been widely used in many fields such as aircraft, aerospace, ship and so on. Since the CFRP has more advantages than aramid fiber reinforced plastic (AFRP) and glass fiber reinforced plastic (GFRP) as a potential composite layers to fabricate CARALL. High stiffness of carbon fiber can provide more efficient crack bridging to aluminum layers than aramid fiber and glass fiber and the presence of aluminum layer provides good impact resistance. This combination of high stiffness and strength with good impact resistance give CARALL a great advantage for application to structures of aircraft, space, helicopter, robot, laminated pipe, drive shaft and so on [13–16]. Xue et al. [14] studied the reduction of thermal residual stress in carbon fiber aluminum laminates using a thermal expansion clamp.

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Lawcock et al. [16] characterized the influence of fiber/metal adhesion on the impact properties of carbon fiber reinforced metal laminates. However, few scholars research the applicability of carbon fiber in FMLs and the role of the metal layers on the impact behavior of the CARALL structure.

To characterize the role of fiber and metal layers in FMLs, this paper investigate the influence of fiber in FMLs and the role of properties with the aluminum alloy on the low velocity impact response of CARALL. In addition, three dimensional (3D) finite element (FE) models are used to analyze the influence of the properties of different aluminum alloys, namely 1060-O, 2024-T3, 6061-T6 and 7075-T6 aluminum alloys, on the low velocity impact behavior of CARALL. A vectored user material subroutine (VUMAT) is developed to define the mechanical constitutive behavior and Hashin's 3D failure criteria in the CFRP. The subroutine is introduced in the commercial finite element code ABAQUS/Explicit to simulate the deformation and failure process in CARALL.

2. Finite element modeling

2.1. Aluminum layers

The aluminum alloy is considered as an elastic–plastic material with the rate-dependent behavior. The Johnson–Cook model is used in this paper:

$$\sigma = \left[A + B(\bar{\varepsilon}_{pl})^n\right]\left[1 + C\ln\left(\frac{\dot{\bar{\varepsilon}}_{pl}}{\dot{\bar{\varepsilon}}_0}\right)\right] \tag{1}$$

where ε_{pl} is the equivalent plastic strain, $\dot{\bar{\varepsilon}}_0$ and $\dot{\bar{\varepsilon}}_{pl}$ are the reference strain rate and equivalent plastic strain rate and A, B, n, C are material parameters. The temperature effect in the aluminum alloy is not taken into account.

Failure is assumed to occur when the damage parameter $D = 1$. Material damage in the Johnson–Cook model is predicted using the following law:

$$D = \sum\left(\frac{\Delta\bar{\varepsilon}_{pl}}{(\bar{\varepsilon}_{pl})_f}\right) \tag{2}$$

where

$$(\bar{\varepsilon}_{pl})_f = \left[D_1 + D_2 e^{(D_3\sigma^*)}\right]\left[1 + D_4\ln\left(\frac{\dot{\bar{\varepsilon}}_{pl}}{\dot{\bar{\varepsilon}}_0}\right)\right] \tag{3}$$

Here, $\Delta\bar{\varepsilon}_{pl}$ is the increment of equivalent plastic strain during an increment of loading and σ^* is the mean stress normalized by the equivalent stress. Hence the current failure strain $(\bar{\varepsilon}_{pl})_f$ and the damage degree D is a function of the mean stress and strain rate. The constants in the Johnson–Cook model for the aluminum alloy used in this study are given in Table 1.

Young's modulus, Poisson's ratio and density of the aluminum alloy are taken as $E = 70$ GPa, $\upsilon = 0.33$ and $\rho = 2700$ kg/m^3, respectively.

2.2. Fiber reinforced composite layers

The carbon and glass fiber composite is modeled as an orthotropic material. The material properties are shown in Table 2.

Damage initiation is modeled using the modified 3D Hashin's failure criterion. Hashin criteria have been used widely to predict the damage of CFRP [20,22], GFRP [10,28] and KFRP [29]. The criterion involves five damage modes, namely fiber tension, fiber compression, matrix tension, matrix compression and delamination [22]. The failure criteria may be expressed as follows:

Fiber tension:

$$R_{ft}^2 = \left(\frac{\varepsilon_{11}}{X_T^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{12}}{S_{12}^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{13}}{S_{13}^\varepsilon}\right)^2, \quad \varepsilon_{11} > 0 \tag{4}$$

Fiber compression:

$$R_{fc}^2 = \left(\frac{\varepsilon_{11}}{X_C^\varepsilon}\right)^2, \quad \varepsilon_{11} \leqslant 0 \tag{5}$$

Matrix tension:

$$R_{mt}^2 = \left(\frac{\varepsilon_{11} + \varepsilon_{33}}{Y_T^\varepsilon}\right)^2 + \left(\frac{1}{S_{23}^\varepsilon}\right)^2\left(\varepsilon_{23}^2 - \frac{E_{22}E_{33}}{G_{23}^2}\varepsilon_{22}\varepsilon_{33}\right) + \left(\frac{\varepsilon_{12}}{S_{12}^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{13}}{S_{13}^\varepsilon}\right)^2, \quad \varepsilon_{22} + \varepsilon_{33} \geqslant 0 \tag{6}$$

Matrix compression:

$$R_{mc}^2 = \left(\frac{E_{22}\varepsilon_{22} + E_{33}\varepsilon_{33}}{2G_{12}S_{12}^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{22} + \varepsilon_{33}}{Y_C^{\varepsilon 2}}\right)\left[\left(\frac{E_{22}Y_C^\varepsilon}{2G_{12}S_{12}^\varepsilon}\right)^2 - 1\right] + \left(\frac{1}{S_{23}^\varepsilon}\right)^2\left(\varepsilon_{23}^2 - \frac{E_{22}E_{33}}{G_{23}^2}\varepsilon_{22}\varepsilon_{33}\right) + \left(\frac{\varepsilon_{12}}{S_{12}^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{13}}{S_{13}^\varepsilon}\right)^2, \quad \varepsilon_{22} + \varepsilon_{33} < 0 \tag{7}$$

Tensile delamination:

$$R_{ld}^2 = \left(\frac{\varepsilon_{33}}{Z_T^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{13}}{S_{13}^\varepsilon}\right)^2 + \left(\frac{\varepsilon_{23}}{S_{23}^\varepsilon}\right)^2, \quad \varepsilon_{33} \geqslant 0 \tag{8}$$

where $X_T^\varepsilon, X_C^\varepsilon$ are the tensile and compressive ultimate strains in the longitudinal direction, Y_T^ε, Y_C^ε are the tensile and compressive ultimate strains in the transverse direction, S_{23}^ε, S_{12}^ε and S_{13}^ε are the in-plane and out-of-plane shear ultimate strains, Z_T^ε are the tensile delamination ultimate strain of composite laminate. The failure factor R_i ($i = ft, fc, mt, mc, ld$) represents the levels of failure. These ultimate strain components are defined as follows:

$$X_T^\varepsilon = X_T/E_{11}, \quad X_C^\varepsilon = X_C/E_{11} \tag{9}$$

$$Y_T^\varepsilon = Y_T/E_{11}, \quad Y_C^\varepsilon = Y_C/E_{22}, \quad Z_T^\varepsilon = Z_T/E_{33} \tag{10}$$

$$S_{12}^\varepsilon = S_{12}/G_{12}, \quad S_{13}^\varepsilon = S_{13}/G_{13}, \quad S_{23}^\varepsilon = S_{23}/G_{23} \tag{11}$$

After the damage initiation is satisfied, the stiffness of material is degraded. Scholars show different failure degradation models. Based on the different damage criteria, different degradation schemes of the material stiffness were chosen in this article according to reference [22]. Once the equation $R_i \geqslant 1$ is satisfied, the corresponding damage variable d_i evolves according to the following equation:

$$d_i = 1 - 1/R_i^n \quad (R_i \geqslant 1, n \geqslant 1; i = ft, fc, mt, mc, ld) \tag{12}$$

Table 1
Johnson–Cook constants and static tensile strength for aluminum alloys.

Aluminum type	A (MPa)	B (MPa)	n	C	D_1	D_2	D_3	D_4	Tensile strength (MPa)
1060-O	34.5	56.5	0.183	0.001	0.13	0.13	−1.5	0.011	63
2024-T3[17]	369	684	0.73	0.0083	0.130	0.130	−1.50	0.011	483
6061-T6[18]	324	114	0.42	0.002	−0.77	1.450	−0.47	0.000	310
7075-T6[19]	546	678	0.71	0.024	−0.068	0.451	−0.952	0.036	572