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Eccentric low-velocity impact on fiber-metal laminates under in-plane loading using unified zigzag theory

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ABSTRACT

This paper investigates the eccentric low-velocity impact of Fiber metal laminates (FMLs) subjected to spherical projectile using a unified Zig-Zag plate theory. The presented zig-zag plate theory enforces transverse shear stress continuity through the thickness and can be reduced to conventional plate theories using appropriate shape function. The governing equations and suitable boundary conditions are obtained using the principle of minimum total potential energy. Runge-Kutta method is employed to solve initial value problem resulted by the method of Ritz. The present model is validated by comparison and good agreement between its results and those of reports in open literature. Influence of various specifications of impact phenomenon such as laminate thickness, projectile radius, projectile velocity, in-plane load and eccentricity parameter is examined on deflection and contact force time history. The obtained results indicate that continuity of transverse shear stress is required to achieve accurate contact force even for moderately thin FMLs.

1. Introduction

With a growing demand for lightweight structures in aerospace industry, an enormous amount of current researches targeted in development of new composite structures. The recent works focused on Fiber metal laminates (FMLs) which are built up of thin metallic sheets and fiber reinforced composites (Fig. 1) [1,2]. FMLs combine impact resistance and easy repair of metals and superior strength of stiffness of composites [3,4].

Fokker Aerostructure of Netherlands discovered that bonded laminates prevent the rapid crack growth compared to the monolithic materials in 1950 [5]. However, after the second worldwide war, the first mechanical test was performed around 1970. The first optimized FML called ARALL (Aramid Reinforced ALuminium Laminate) manufactured by Delft University in 1982 [6]. ARALL was employed in C17 cargo doors. GLARE (GLAss REinforced aluminum laminate) was developed in 1987 because ARALLs suffers from inadequate compression properties. Utilizing GLARE in upper fuselage structure of Airbus A380 caused saving nearly 794 kg gross weight [5].

Primary structure requires an accurate prediction of stress field which can be achieved by considering the non-classical effects such as transverse shear and normal deflection [7]. Equivalent Single Layers (ESL) theories such as First-order Shear Deformation Theory (FSDT), High-order Shear Deformation Theory (HSDT) and Advanced High Order Theories offer a simple solution to thin and moderately thick laminates [8]. However, these theories suffer from some drawbacks in modeling high transverse anisotropic laminate. On the other hand, Layer-Wise theory (LWT) provides high accurate predictions, whereas it becomes computationally expensive in case of laminates with a large number of layers [9].

Zig-Zag Theories (ZZT) offer a simple way to consider shear deformation in the framework of ESL theories. Due to capture transverse anisotropy, slope of in-plane displacement through the thickness varies as shown in Fig. 2 which is called Zig-Zag phenomenon [10]. Carrera developed a unified theory including ESL, LW and ZZ effects as a special case. The finite element matrices derived in a unified manner and vast numerical examples have been given [11,12]. Brischetto et al. employed Murakami's ZZ function (MZZF) to analysis sandwich panels [13]. Gherlone et al. [10] examined the mixed formulation of MZZF in comparison with displacement-based MZZF, RZT and Timoshenko beam. They showed RZT is more accurate for arbitrary lay-ups by considering the ZZ effects. Groh and Weaver [7] presented displacement-based and mixed formulation based on Reddy shape- function and MZZF. Also, they developed a unified general theory through Hellinger–Reissner mixed formulation to consider non-classical effect in analysis of highly heterogeneous multilayers [14,15].

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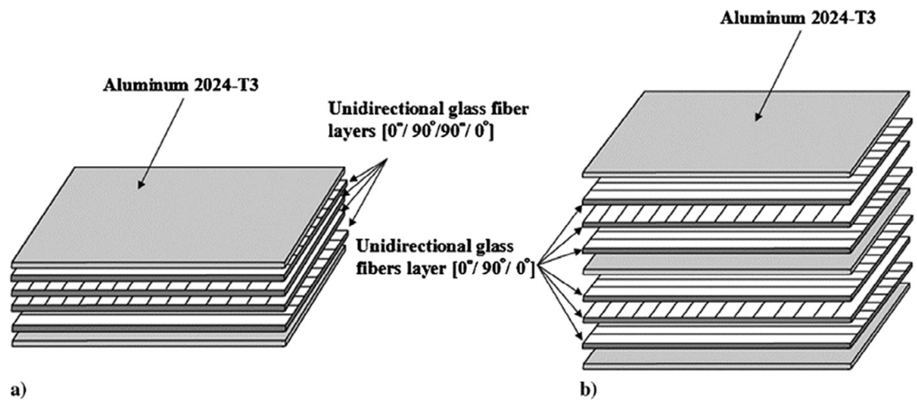

Fig. 1. Arrangement of GALRE laminate (a) GALRE 5-2/1 (b) GLARE 4-3/2 [2]

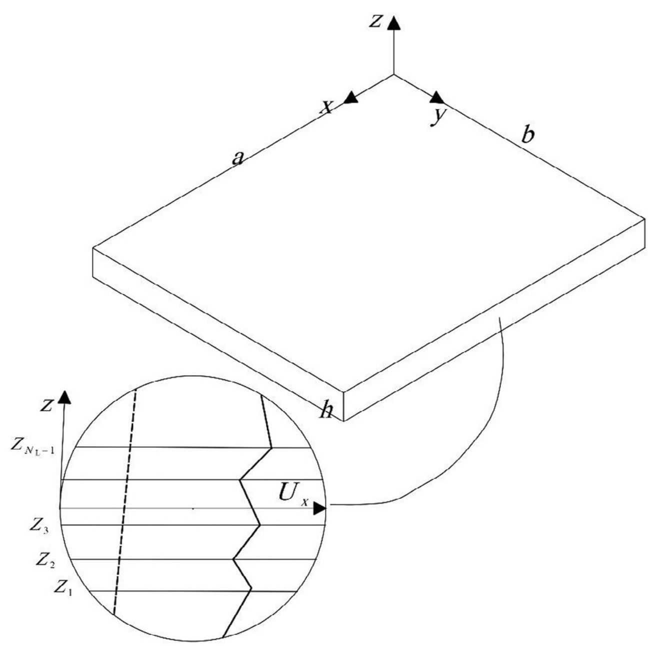

Fig. 2. The piece-wise continuous displacement field and change of slope through the thickness (ZZ phenomenon) due to transverse shear stress continuity.

Aerospace structures may encounter low-velocity impact caused by sources such as tool drop, runway stones, etc. According to the literature, the analytical modeling procedure of impact can be classified into three types [16]: spring-mass models [17,18], energy balance models [19,20], structural models based on plate theories(including 1-tem Ritz method [21] and N-term Ritz method [22]).

To the best of our knowledge, most researchers investigated FMLs numerically or experimentally. A few research works focused on analytical models to predict impact response of FMLs. Vlot indicated that the impact model required depends on the impact regime [23]. Tsamasphyros and Bikakis studied the low-velocity response circular GLARE FML using 1-term Ritz method. They predicted the first failure (fiber fracture) for studied circular plates [24]. Bikakis investigated the low-velocity impact of circular GLARE FMLs using linearized spring-mass model. He presented an analytical expression to predict the impact load, position and velocity time history and compared the predicted results with those of experiments [25]. Morinière et al. developed a progressive quasi-static model to predict dynamic response of GLARE subjected to low-velocity impact. They indicated aluminum layers absorbed 90% of the total energy absorbed by the FMLs during impact [26]. Zarei et al. investigated dynamic response of FMLs subjected to low-velocity impact based on HSDT. The effect of projectile velocity, projectile radius and thermal environment was studied in detail [27].

In the present work, the eccentric low-velocity impact of FMLs subject to spherical projectile is investigated. Hertz law of contact is employed to consider the nonlinear phenomena of contact. A ZZ plate theory is presented based on Groh and Weaver's [7] theory for the beam structure. Governing equations and suitable boundary conditions are obtained using the principle of minim total energy. Runge-Kutta method is employed to solve initial value problem resulted by the method of Ritz. Influence of various specifications of impact phenomenon is examined on deflection and contact force time history.

2. Governing equations

In the present study, a rectangular FML plate is formulated within the framework of Zig-Zag theory (ZZT) as shown in Fig. 3. According to ZZT, transverse shear stresses of kth layer at any point (x,y,z) for a symmetric laminate can be expressed as based on [7]

$$\tau_{xz}^{(k)}(x,y,z)=\left[G_x\left\{A_x^{(k)}+m_x^{(k)}\left(\frac{d\varnothing(z)}{dz}-1\right)\right)\right\}\right]\overline{\gamma}_{xz}(x,y) \tag{1}$$

and

$$\tau_{yz}^{(k)}(x,y,z)=\left[G_y\left\{A_y^{(k)}+m_y^{(k)}\left(\frac{d\varnothing(z)}{dz}-1\right)\right)\right\}\overline{\gamma}_{yz}\right](x,y) \tag{2}$$

where $\overline{\gamma}_{xz}(x,y)$ and $\overline{\gamma}_{yz}(x,y)$ are transverse shear stress in xz-plane and transverse shear stress in yz-plane, respectively. A posteriori shape function $\varnothing(z)$ is considered to include shear stress variation through the thickness within framework of the various plate deformation theories (See Table 1).

In Eq. (1), the modification factors, $m_x^{(k)}$ and $m_y^{(k)}$ can be expressed

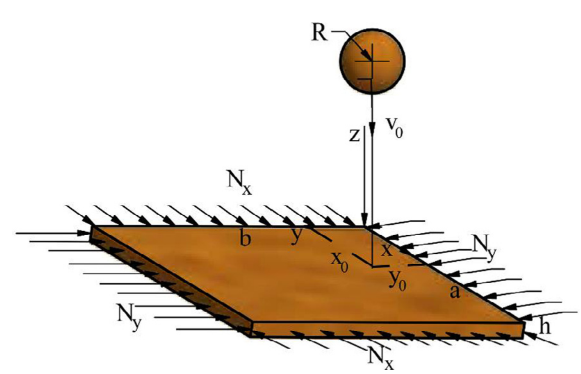

Fig. 3. A rectangular FML plate subjected to transverse impact and its geometry.