International Journal of Impact Engineering 119 (2018) 14–25

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Effect of metal layer placement on the damage and energy absorption mechanisms in aluminium/glass fibre laminates

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ARTICLE INFO

Keywords:
GLARE
Low velocity impact
Delamination
Abaqus
VUMAT

ABSTRACT

This study focuses on the effect of metal layer distribution in glass fibre reinforced aluminium laminates (GLARE) subjected to low velocity impact. Four GLARE variants specimens were considered in which the metal layers of different thicknesses were placed at various positions in the layup while keeping the same total metal layer thickness. Experiments and Finite element (FE) analysis were performed to understand the behaviour of the GLARE specimens. A user written material subroutine VUMAT which incorporates Hashin failure criteria along with Puck's action plane concept were used to predict the response of the composite layers. The damage was evolved for each failure mode using the exponential damage evolution law. Interface delamination between the layers was initiated by cohesive surface behaviour which includes the friction effect between the plies. It was found that placement of thinner metal layer on top of the laminate and its distribution inside the layup lowers the impact resistance of GLARE. Moreover, the patterns of delamination are also affected by the placement of metal layer within the laminates. It was further shown that the propagation direction of delamination is governed by the fibre direction of lower ply of the interface.

1. Introduction

Fibre metal laminates (FMLs) are high performance hybrid structures that are composed of stacked arrangements of fibre-reinforced matrix composite plies and metal alloy layers. They combine the durability and toughness offered by metals with the outstanding fatigue and strength properties of composites [1,2]. Also they provide improved fracture and fatigue resistance, superior damage threshold energy and enhanced tensile properties as recognized in several experimental studies [3–5]. Moreover, during a loading scenario they can dissipate a significant amount of energy through their constituent's failure mode(s) such as shear failure in metal plies or localized fibre fracture in composite plies. They have been used successfully in many aircrafts including Boeing 777 and Airbus A380 [6]. Although FMLs possess many useful properties their failure mechanism is rather complex as the hybrid solution is inhomogeneous. The complexity is elevated further as the failure is accompanied with the interaction of different failure mode(s) and redistribution of stress among the unfailed plies [7]. Several mechanisms, including plastic deformation and shear failure of the metal plies, fibre fracture, matrix cracking and delamination between adjacent load-carrying plies, may contribute to the failure of the FMLs. Some studies have concluded that the metal dominates the dynamic response of an FMLs [8,9] while the failure modes of its constituents vary with ductility [10]. The failure patterns in FMLs are greatly affected by their stacking sequence or placement of metal layer in the layup configurations [9,11]. Although the failure modes of composite laminates and metal are identified separately the authors could find only few studies in the literature [12] that discloses the interaction between the FML constituents.

It has been reported that delamination is one of the dominant failure mechanism in FMLs and mostly initiates in the vicinity of holes in notched specimens [13]. As initiation of delamination in the lay-up postpones fibre failure and increases its notched strength [14] modelling methods that do not account for delamination may result in overestimation of results [15].

Due to the time and cost of laboratory testing of the FMLs and laborious manufacturing process involved in making them, finite element (FE) technique offers a good alternative to analyze these hybrid materials efficiently. Moreover, a closer look can be obtained into the complex internal damages and redistribution of stress during failure in a relatively short time. To ensure that the physics of the problem is not compromised and to capture their behaviour accurately, sophisticated constitutive material models are required and correct modelling methodology should be followed. Earlier, an integrated and elaborative

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https://doi.org/10.1016/j.ijimpeng.2018.04.011
Received 18 November 2017; Received in revised form 21 April 2018; Accepted 21 April 2018

Table 1

Details of GLAREs considered in this study.

GLARE	Configuration#
GLARE-1	$[A6/0/90]_s$
GLARE-2	[A4/0/90/A4/90/0/A4]
GLARE-3	[A3/0/90/A6/90/0/A3]
GLARE-4	$[A3/0/A3/90]_s$

Here A6, A4 and A3 represent aluminium layers of thickness 0.6 mm, 0.4 mm and 0.3 mm, respectively.

numerical model was developed by Li et al. [16] to predict the various internal damages occurring due to low velocity impact. However, nowadays continuum damage mechanics (CMD) is being used to model composites. Lately, some of the studies have used these models on FMLs to predict the damage occurring owing to low velocity impact [17–20]. These models use an built-in Hashin 2D failure criteria [21] available in Abaqus material library [22]. This built-in failure criteria can be implemented through continuum shell elements in applications related to in plane loading only. To correctly capture the through thickness stresses and its distribution during ply failure, a full 3D failure model with solid continuum elements is required [23]. Moreover, the energy based damage evolution laws used in the built-in Abaqus model were given by Lapczyk and Hurtado [17] and require fracture energies in all failure modes. These values are difficult to obtain experimentally for all four failure modes and hence are mostly assumed [19,24,25].

In this study, E-glass fibre layers were reinforced with aluminium 2024-T3 plies of different thickness at different positions of layup to make four different GLARE specimen as shown in Table 1. These laminates were subjected to low velocity impact loading at different impact energy levels to see the influence of placement of metal layers in the laminate. Experiments were done on the GLARE specimens using the drop weight impact machine. To gain insight into the failure and stress distribution within the laminates, detailed FE study was performed. A user defined material subroutine (VUMAT) based on Hashin 3D failure criteria for fibre failure modes and matrix tension mode while Puck's action plane concept [26] for matrix compression failure mode were implemented in Abaqus Explicit. Moreover, exponential damage evolution was used to degrade material stiffness once the failure criterion is initiated. A more sophisticated surface based cohesive methodology that includes the friction effects was used to initiate the delamination between the plies of the GLARE specimen. A penalty based general contact algorithm was used to initiate the contact between impactor and GLARE top surface and between the plies. The numerical results after the simulation were compared with the experimental results to demonstrate the ability of proposed damage model to predict the damage occurring within the laminates when subjected to low velocity impact.

The current study focuses on the interaction occurring between middle metal/composite layers of GLARE specimens subjected to impact loading through numerical simulation. GLARE layups having different number of metal layers resulting in different number of metal/composite interfaces inside the FML are considered to bring out the affect of adding such interfaces inside the FMLs on their impact response. We believe that the findings from present study will be useful in making careful choice of FML layups in accordance with a particular requirement.

2. Constitutive material model

Hashin [21] proposed a quadratic stress based failure criteria which is popular in the industry and categorized the failure of composite into four failure modes. These failure modes are tensile and compressive fibre/matrix failure. The failure in these modes is initiated as per the following equations.

Fibre tension ($\hat{\sigma}_{11} \geq 0$)

$$F_f^t = \left(\frac{\hat{\sigma}_{11}}{X^t}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S_{12}}\right)^2 + \left(\frac{\hat{\sigma}_{13}}{S_{13}}\right)^2. \tag{1}$$

Fibre compression ($\hat{\sigma}_{11} < 0$)

$$F_f^c = \left(\frac{\hat{\sigma}_{11}}{X^c}\right)^2. \tag{2}$$

Matrix tension ($\hat{\sigma}_{22} + \hat{\sigma}_{33} \geq 0$)

$$F_m^t = \left(\frac{\hat{\sigma}_{22} + \hat{\sigma}_{33}}{Y^t}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S_{12}}\right)^2 + \left(\frac{\hat{\sigma}_{23}}{S_{23}}\right)^2. \tag{3}$$

In Eqs. (1)–(3) $\hat{\sigma}_{ij}\,(i, j = 1, 2, 3)$ is the effective stress tensor, X^t *and* X^c are longitudinal tensile and compressive strengths whereas Y^t represents the tensile strength in transverse direction, and $S_{ij}\ (i, j = 1, 2, 3)$ represent in plane and out of plane shear strengths of composite respectively.

Matrix compression failure used to occur in shear mode for unidirectional laminates at a fracture plane orientation of $53^o \pm 2^o$ with respect to the compressive loading direction [27]. A stress based failure criteria for transverse compression is suggested by Puck and Schurmann [26] which evaluates the failure on the oriented fracture plane.

Matrix compression ($\hat{\sigma}_{22} + \hat{\sigma}_{33} < 0$)

$$F_m^c = \left(\frac{\sigma_{tn}}{S_{23}^A + \mu_{tn}\sigma_{nn}}\right)^2 + \left(\frac{\sigma_{ln}}{S_{12} + \mu_{ln}\sigma_{nn}}\right)^2. \tag{4}$$

Where the subscripts *n, l* and *t* refer to the normal, longitudinal and tangential direction with respect to the fracture plane. The stress components present in Eq. (4) are obtained by rotating the stress tensor $\hat{\sigma}_{ij}$ with respect to the fracture plane (θ) by using standard matrix transformation as follows:

$$\begin{aligned}
\sigma_{nn} &= \hat{\sigma}_{22}\cos^2\theta + \hat{\sigma}_{33}\sin^2\theta + 2\hat{\sigma}_{23}\cos\theta\sin\theta \\
\sigma_{tn} &= -\hat{\sigma}_{22}\cos\theta\sin\theta + \hat{\sigma}_{33}\cos\theta\sin\theta + 2\hat{\sigma}_{23}(2\cos^2\theta - 1) \\
\sigma_{ln} &= \hat{\sigma}_{12}\cos\theta + \hat{\sigma}_{13}\sin\theta
\end{aligned} \tag{5}$$

where S_{23}^A is the transverse shear strength in the potential fracture plane (action plane), which is given by $S_{23}^A = \frac{Y_c}{2\,tan\,(\theta)}$ where Y_c represents the compressive strength in transverse direction. The transverse friction coefficients based on Mohr-coulomb theory are given as $\mu_{tn} = \frac{-1}{tan\,(2\theta)}$ and $\mu_{ln} = \frac{S_{12}}{S_{23}^A}\mu_{tn}$.

Hence these damage initiation threshold Eqs. (1)–(4) create the size and shape of the damage surface in the effective stress space. If any of these failure indices $F_j^i(i = t, c\ and\ j = f, m)$ reaches the damage surface ($F_j^i = 1$) then failure is assumed to have been initiated in the plies as shown in Fig. 1. Further the growth of damage surface is controlled by exponential damage evolution law proposed by Matzenmiller et al. [28] and further modified by Batra et al. [29] as shown below

$$d_j^i = 1 - exp\left(\frac{1}{m_j^i}(1 - F_j^i)^{m_j^i}\right) \tag{6}$$

where the material softening parameter m_j^i, $i = t, c\ and\ j = f, m$ controls the rate of degradation for each mode. Singh and Mahajan [30] have done a mesh sensitivity analysis and proposed values for *m* in each failure mode in relation to the element size. Based on the mesh size of $0.25 \times 0.25 \times 0.25\ \text{mm}^3$, values of m_f^t, m_f^c, m_m^t and m_m^c were chosen as 0.2, 0.07, 1.15 and 3 respectively. These values were found to give good results in this study.

The damage failure initiation and evolution criterias were executed through a user written subroutine VUMAT which was implemented in the commercial FE software package, Abaqus Explicit. As the strains were supplied by the software, the damage initiation is checked at each material point of the element by the subroutine. If the damage is initiated at the material point then subroutine further evaluates the level of damage and degrades the new stresses by the damage variable (d_j^i) and provides them back to the software. During this at any point if d_f^t