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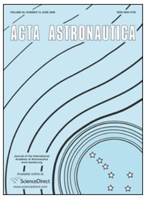

Ply level failure prediction of carbon fibre reinforced laminated composite panels subjected to low velocity drop-weight impact using adaptive meshing techniques

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ABSTRACT

This work is concerned with physical testing and numerical simulations of flat and round nose drop-weight impact of carbon fibre-reinforced laminate composite panels to predict ply level failure. Majority of the existing studies on impact of composites by spherical nose impactors are experimental, computational models are simplified, and based on classical laminated plate theories where contributions of through-thickness stresses are neglected. Present work considers flat nose impact and contributions from through-thickness stresses and is mainly simulation based. A computational model was developed in ABAQUS™ software using adaptive meshing techniques. Simulation produced (2D model) stresses were numerically integrated using MATALB™ code to predict through-thickness (3D) stresses. Through-the-thickness stresses were then utilised in advanced failure criteria coded in MATLAB™ software to predict ply level failures. Simulation produced results demonstrate that the computational model can efficiently and effectively predict ply-by-ply failure status of relatively thick laminates.

1. Introduction

Numerous failure theories have been proposed to identify the mode of failure, onset of yield, or fracture. The theories are mainly divided into two categories: interactive and non-interactive criteria [1,3]. Non-interactive criteria assume that the failure modes are decoupled and specific expressions are used to identify each failure mechanism. Failure/fracture is said to have occurred in the stress based criteria if each and every one of the stresses in the principal material coordinates greater than the respective strengths [5]. Similarly, the maximum strain failure criteria states that the failure occurs if one of the strains in the principal material coordinates exceed its respective failure strain [6,4].

The interactive criteria assume an interaction between two or more failure mechanisms and they describe the failure surface in the stress or strain space. Stress or strain polynomial expressions are used to describe the boundaries for the failure surface or envelope [5]. Any point inside the envelope shows no failure in the material. Shivakumar et al. [6] used the Tsai–Wu failure criterion and maximum stress criterion to model low-velocity impact damage in composites. Chang and Chang [7,8] proposed a progressive in-plane damage model for predicting the residual strength of notched laminated composites with property reduction based model. It was postulated that for fibre failure both the moduli were reduced to zero but shear modulus was degenerated according to the Weibull distribution. Choi et al. [9] investigated the low velocity impacts on composite plates

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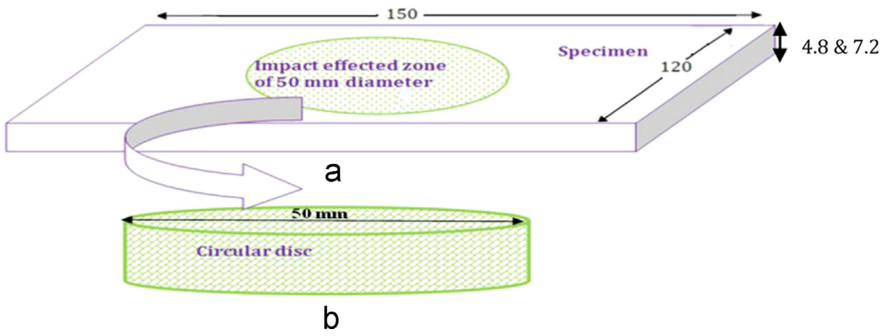

Fig. 1. Schematic of: (a) 16- and 24-Ply laminates and (b) testing cut-out.

using a line-nose impactor to detect the initiation of matrix cracking and delamination. Davies and Zhang [10] studied the low-velocity impact damage in carbon/epoxy composite plates impacted by hemispherical impactors using different impact energy levels, thickness, dimensions and boundary conditions. Kim and Soni [11] used through-thickness normal stresses along a ply thickness distance. They assumed that failure occurred when the average of the through-thickness stresses over the fixed distance reached the through-thickness tensile strength. Brewer and Lagace [12] proposed a quadratic stress criterion for initiation of delamination using the approach suggested in [11] and predicted that through-thickness stresses should be independent of the sign. A similar criterion was also proposed by Liu et al. [13] to predict matrix cracking and delamination in composite laminates. Disadvantage in using the interactive polynomial criteria is that they do not differentiate damage mechanisms. Hashin [14] proposed three-dimensional failure criteria for unidirectional composites. In his model four distinct failure modes associated with fibre failure in tension or compression and matrix cracking in tension or compression. Engblom and Havelka [15] proposed the use of a combination of the Hashin [14] and Lee [16] failure criteria. They used the Hashin [14] criterion to detect in-plane failure and the Lee [16] criteria to predict delaminations. Derivation and simulation of inter-laminar stresses are reported in [13–15]. The through-thickness stresses can have a considerable influence on the impact performance of composites reported in [17–19]. Particularly, high stress gradients in regions local to the round nose impact are reported in [20].

The solution of impact problems requires use of a large number of mesh points to accurately capture phenomena exhibiting high gradients variables appearing under impactor nose and inter-laminar layer boundaries [21,22]. Several approaches have been proposed for both structured and unstructured mesh adaptation in [23]. Numerical algorithms and adaptive meshing for simulation the effect of variation thickness are reported in [24,25].

During present work, flat and round nose physical tests were conducted on selected laminates for comparison against the simulation produced results. Computational models were developed using adaptive meshing schemes to discretise the domain and contributions from through-thickness stresses were considered. Impact response by flat and round nose impactors of sixteen and twenty-four ply laminates were investigated. Comparisons of the selected results demonstrated that the computational model developed herein can efficiently predict flat nose impact response of relatively thick laminates.

Table 1
Material properties.

Property	Units	Fibredux 914C-833-40
Tensile modulus (E_{11})	GPa	230
Tensile modulus ($E_{22}=E_{33}$)	GPa	23
Shear modulus ($G_{12}=G_{13}$)	GPa	88
Shear modulus (G_{13})	GPa	11
Poisson's ratio ($\nu_{12}=\nu_{13}$)		0.33
Longitudinal tensile strength	MPa	1453
Transverse tensile strength	MPa	32
Longitudinal compressive strength	MPa	650
Transverse tensile strength	MPa	15

2. Composite laminates and impactors

The European standard (equivalent to Boeing standard) laminates were considered. Test laminates consisted of 150 mm × 120 mm areas; 16-Ply of thickness 4.8 mm with lay-up code $[0/90/45/\text{-}45]_{2S}$; and 24-Ply of thickness 7.2 mm with lay-up code $[0/90/45/\text{-}45]_{3S}$ as shown in Fig. 1(a). The impact affected consists of circular cut-out of diameter 50 mm as shown in Fig. 1(b).

All tested laminates were made of aerospace grade carbon fibre-reinforced toughened epoxy code Fibredux 914C-833-40 of material properties given in Table 1.

The flat and round nose shape impactors used were made of harden stainless steel. Both impactors have shank of diameter 20 mm. The shank reduces to $10\pm(0.18)$ mm for the ground flat impact face. The round nose shape impactor has radius of $5\pm(0.15)$ mm.

No catastrophic failures or complete penetrations were assumed. The drop-weight models were investigated for range of velocity 1.6 to 4 ± 0.5 m/s selected on the basis of the experimental results proposed by James [4].

3. Drop-weight impact methodology

3.1. *Drop-weight impact testing*

The laminates were impacted in accordance with the accepted American standard testing method for measuring