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Finite element simulation of carbon fibre-reinforced composite laminates subjected to low velocity impact using damage induced static load-deflection methodology

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ABSTRACT

This work is concerned with the prediction of low velocity impact damage resistance of carbon fibre-reinforced laminated composite laminates. Pre-assumed damage induced laminates were simulated to correlate damage corresponding to impactor nose profiles. Majority of the existing studies conducted on the topic are experimental, based on three-dimensional stresses and failure theories that cannot readily predict ply level impact damage. Hence efficient computational models are required. The present study was conducted to efficiently predict ply level impact response of composite laminates. Static load-deflection based computational model was developed in the commercial software ABAQUS^{TM}. Eight, 16, and 24 ply laminates impacted by point, small, medium, and flat nose impactors were considered with emphasis on flat nose impacts. Loading areas under the impactor nose profiles were partitioned to investigate effects from variations in applied loading. Pre-assumed damage zones consisting of degraded material properties equivalent to the impactor nose profiles were inserted across thickness of the laminates to predict ply-by-ply damage. Impactor nose profiles and pre-assumed damage zones (size, type, and location) were correlated to the simulation produced deflection quantities to predict the ply level damage. Selected results were compared against the data available in the literature and also against the intra-simulation results and found in good agreement.

1. Introduction

Fibre-reinforced composites are being extensively used in aerospace industry because of their high specific strength and stiffness. A challenging issue in designing composites is their vulnerability to localised drop-weight impacts such as tool and tool box on wing and fuselage during maintenance of an aircraft. The impacts could create internal damage that goes undetected during routine inspections nonetheless it might result in un-expected catastrophic failure during later operations. That is a major cause of concern for aircraft industry and requires detailed investigations. Extensive studies are being carried out on various aspects of the topic. Most of the studies found in the literature are devoted to use the static load-deflection data in place of more costly impact testing for early damage detection in relation to maintenance, structural design improvements, safety and reliability. As damage initiation and propagation can be easily detected, measured with greater accuracy and correlated between deflection and visible damage size (dent or crack length). The deflection can also be directly measured in tension or compression to achieve elastic failure due to low shear strength [1]. The methodology also greatly simplifies theoretical analysis as time-dependent terms in the governing equations do not appear and much more data can be obtained [2,3]. The data can be used to correlate various loading parameters to the internal damage modes such as: matrix cracking, delamination, and fibre failures. Experimental studies were conducted to correlate pre-assumed damaged zone of known position, size and shape to applied load [4]. Ghasemi Nehjad and Parvizi-Majidi have reported strong correlation between damaged area to the residual compressive strength in [4]; and concluded that smaller damage areas give smaller reductions in residual strength. Analytical models were suggested for prediction of impact damage initiation and growth during quasi-static response caused by large impactors [5,6]. Experiments and analysis of laminates with artificial damage for simplified studies are reported in [7]. Impact response of composite laminates and corresponding reduction in stiffness, internal damage, and elastic failure are described in [8]. Starnes et al. [9] studied effects of impact induced damage and circular hole on the compressive strengths of carbon

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fibre/epoxy laminates. Subsequently, Cairns and Lagace [2] validated the model and proved a relation between the damage zone and critical buckling load. Impact damage initiation and damage propagation are reported in [10], damage characterisation and progression methods in [11,12], failure in [13], and damage tolerance studies were reported in [14]. Influence of impactor nose shapes on the impact response of composite laminates is presented in [15,16]. Low-velocity impacts on pre-loaded of fibre reinforced laminates with various impactor shapes are reported in [17]. Damage mechanisms in composite laminates impacted by a flat-ended impactor are reported in [18]. Studies on prediction of critical thresholds and experimental investigation on the multilayered plates against hemispherical-nosed projectiles is reported in [19]. Static indentation response of an in-plane pre-stressed composite sandwich plate subjected to a rigid blunted impactor is reported in [20]. Finite element studies on low velocity impact of composite plates are presented in [21–23]. Effects of energy dissipation capacities induced different failure mechanisms by different impactor types: cone, flat, hemi-sphere, and semi-cylinder impactors are reported in [24]. Investigation of the effect of impact damage locations arising from central, near edge, and on edge impact events are reported in [23]. The damage distribution as summation of individual shapes of the delaminated layers at various through-thickness positions is reported in [10]. The damage shape was roughly approximated by a circular or an elliptic shape. Cantwell et al. in [25] reported that increasing impact energy results in extensive surface cracks due to the compressive bending stresses and fractures of the fibres mainly at the surfaces and impact point of the laminate. Kim and Goo in [26] modelled the effects of altering the ratios between impactor nose lengths to impactor radius: 0, 1, up to 10 and found that as ratio decreases the nose becomes blunt, the peak force increases and the impact duration decreases. Delamination and matrix cracking were investigated by introducing pre-assumed crack across thickness and delamination at the ply interfaces. Indentation was calculated as the difference between the centres of the topmost and bottom plies for orthotropic beams. Different material degradation coefficients were observed in different failure modes ranging from 0 to 0.4 [24]. In order to avoid numerical problems, the coefficients contained in matrix were not equated to zero but to a very small numbers, the procedure is described in [25,26]. Pre-assumed matrix, fibre, and fibre-matrix shearing failure modes were introduced by the loss of corresponding material properties and Poisson's effects [1]. For delamination, the material loss and Poisson's effect are pre-assumed in the thickness direction. Laminate could not carry shear loads while elastic constants in fibre and lateral directions remain intact. For the matrix and fibre failure, elastic constant in lateral direction and major Poisson's ratios reduced near to zero while elastic constant in fibre direction remain unaltered. The matrix failure and shear constants were reduced for fibre failure based on an exponential decaying [23]. Literature search revealed that majority of the studies on the topic are on spherical nose impactor, experimental, time and resource consuming, and produce limited data. Efficient prediction of the flat nose impact damage resistance of laminates is needed to investigate flat type impactor response that inflicts invisible (internal) damage. In recognition of the need, the static load-deflection computational model was developed in ABAQUS^{TM} software. Laminates embedded with pre-assumed damage zones corresponding to the impactors' nose profiles were simulated and results were compared to the data available in the literature and also to the intra-simulations dada and found to have good agreements up to 90%. Based on comparisons of results it is confirmed that the model is capable of efficiently predicting ply-by-ply damage corresponding to impactor nose profiles without resorting to residual strength predictions and three-dimensional stress and failure theories.

2. Materials and methods

2.1. Composite laminates, material properties, and impactors

The industry made and provided samples of eight-, 16-, and 24 ply laminates were cut by diamond saw into 150 (mm) × 120 (mm) × 2.88 (mm) dimensions. Thickness of an individual ply in 8-Ply laminate was 0.36 (mm), in 16-ply laminate 0.18 (mm), and in 24-Ply laminate it was 0.12 (mm). The lay-up code of 8-Ply laminate was $[45/0/\text{-}45/90]_S$, 16-Ply laminate $[45/0/\text{-}45/90]_{2S}$, and 24-Ply laminate $[45/0/\text{-}45/90]_{3S}$. Fibre orientations in laminates is shown in Fig. 1(a); a schematic of the laminates is shown in Fig. 1 (b), and enlarged view of the impact affected area of consisting of circular cut-outs of diameter 100 (mm) is shown in Fig. 1(c).

Material properties assigned to the plies are given in Table 1

The results presented in Table 1 are gained from property testing detailed in [8].

Accidental foreign object impact on laminates could be of any shape. Nonetheless, four possible nose shapes of harden stainless steel considered herein are shown in Fig. 2. Small, medium, and flat nose impactors have shank of diameter 20 (mm). The shank reduces to: 2.1 ± (0.1) mm for small; 4.2 ± (0.15) mm for medium; and 6.3 ± (0.18) mm for flat nose impactors.

2.2. Static load-deflection testing

Quasi-static tests were performed to verify accuracy of the simulated results. Numerical and experimental studies were carried out under the same conditions. Generally, the indentation tests

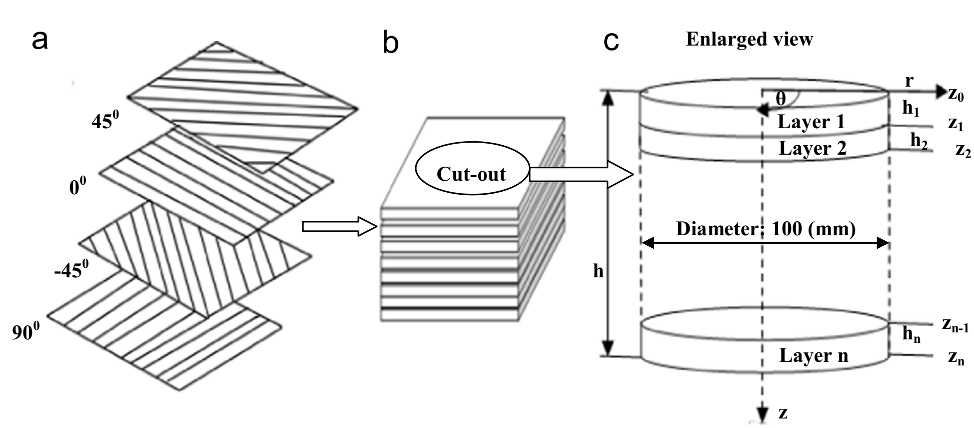

Fig. 1. Schematics: (a) Quasi-isotropic lay-up, (b) 8-Ply laminate, and (c) ply sequence.