Composite Structures 130 (2015) 85–94

Contents lists available at ScienceDirect

Composite Structures

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

An efficient approach for predicting low-velocity impact force and damage in composite laminates

Jikui Zhang[a], Xiang Zhang[b,*]

[a] Department of Aircraft Design, Beihang University, Beijing 100191, PR China
[b] Faculty of Engineering and Computing, Coventry University, Coventry CV1 2JH, UK

ARTICLE INFO

Article history:
Available online 24 April 2015

Keywords:
Low-velocity impact
Finite element
Delamination
Cohesive zone model
Critical impact force

ABSTRACT

An efficient approach is presented to predict the critical impact force and corresponding damage in composite laminates subjected to low-velocity impact. In developing such approach, stress analysis was conducted first for a 4 mm thick quasi-isotropic laminate to determine the potential failure modes and locations under the critical impact force. Three finite element models were subsequently built to simulate the damage in the upper, middle and lower interfaces and investigate the effect of each damage mode on the laminate stiffness. It is found that delamination adjacent to the impact point is suppressed by the high compressive through-thickness stress resulting in negligible reduction of the laminate stiffness. Both the delamination in interfaces adjacent to the mid-thickness plane and matrix fracture on the lower face can cause the first load drop, which corresponds to the critical impact force. The former is the main causative mechanism for the laminate studied in this paper. A simplified and efficient finite element model, which takes account of the delamination damage adjacent to the mid-thickness plane and the lower face, is developed that is computationally affordable and delivers acceptable prediction of the critical impact force, damage shape and size, by both quasi-static load and dynamic impact analyses.

1. Introduction

Advanced carbon fibre reinforced plastics (CFRP) have been increasingly used in the airframe primary structures due to their excellent mechanical properties and low specific weight. However poor properties in the through-thickness direction make CFRP particularly susceptible to the low velocity impact. Composite laminates exhibit a relatively brittle behaviour and can undergo internal damage in forms of matrix cracks, fibre breakage and delamination when they are subjected to foreign object impacts. These damages (in particular delamination) may propagate undetected during the service resulting in unexpected failure of the component, especially for the primary structures loaded in compression. Therefore, it is essential to develop a computer-based design tool to predict the damage onset and evolution in composite structures under impact.

The cohesive zone model (CZM), which combines strength-based criteria with fracture mechanics energy criteria, has attracted considerable interests in recent years. Cohesive elements placed at the interface between layers have been successfully used in various studies to model the delamination induced by low velocity impact in composite laminates with cross-ply [1–3] and clustered layers [4–6]. Several CZMs have achieved acceptable prediction for simulating the impact damage initiation and propagation in multi-direction composites [7–9], e.g. $[0_3/+45/45]_S$, $[0_2/45_2/90_2/-45_2]_S$, and $[45/-45/90/0]_S$ laminates. However, these laminates consisted of fewer than 7 interfaces that need to be modelled by cohesive elements. Lopes et al. [10] developed a finite element (FE) model to simulate the damage of a 24 ply laminate $[\pm 45/90/0/45/0_4/-45/0_2]_S$ under low-velocity impact. Cohesive elements were inserted in each interface to simulate the delamination initiation and propagation. It took 4–5 days to complete a simulation using a cluster 32 CPU’s workstation. Therefore, it is not yet possible to use the CZM as a design tool for realistic structures.

As pointed out in the open literature [11–15], there are two different phases in the impact response during the damage process. First, the impact force reaches a threshold value, also defined as the critical force that results from the delamination onset causing a sudden loss of the laminate stiffness and drop of the impact force in the response. Second, the damage size increases with the force until the force reaches its maximum, defined as the peak force.

---

* Corresponding author. Tel.: +44 24 77658599.
E-mail addresses: zjk@buaa.edu.cn (J. Zhang), xiang.zhang@coventry.ac.uk (X. Zhang).

http://dx.doi.org/10.1016/j.compstruct.2015.04.023
0263-8223/

The difficulty to predict the peak force of thick multi-direction laminates under impact loading is mainly due to the complexity of the physical phenomena involved during the damage propagation, which require accurate modelling of the dynamics response, contact formulation, interlaminar friction, interaction of various failure modes, including matrix cracking, delamination and fibre breakage. Current computer models will take days to simulate a simple test coupon, which are not yet regarded as design tools. However, it is feasible to develop an efficient FE model to predict the critical impact force that is also defined as the Delamination Threshold Load (DTL) [13,16,17], which is a measurement of the damage resistance of a composite material [18]. The critical force can be related to critical impact energy for design purpose. Extensive experimental tests have shown that the critical force is independent of the specimen size, boundary condition and impact energy [12,16,18,19]. Therefore, it can aid the design process by relating the coupon test data with realistic structural elements as long as the thickness and the stacking sequence are the same.

The prediction of critical impact force has been attempted by many researchers. Sjoblom [20] predicted that the critical damage initiation load is related to $t^{3/2}$, where t is the laminate thickness. Davies et al. [21,22] developed an equation based on the mode II fracture to determine the onset of the delamination based on the simple beam theory and assumption of quasi-isotropic property with one delamination in the mid thickness. This equation also indicates that the critical force is proportional to $t^{3/2}$, which has been supported by a number of tests [23–25] and provides an estimate of the critical force for a given quasi-isotropic laminate. Independent experiment by Olsson [26] also shows the correlation of critical force with $t^{3/2}$.

To summarise, critical impact force is a key parameter to characterise the damage resistance of composite materials. Although the equation developed by Davies et al. [21,22] gives acceptable results for quasi-isotropic laminates, it cannot be applied to more complex laminates or realistic structures, e.g. non-quasi-isotropic layups, multiple delamination and delamination that is triggered by early matrix cracking (bending mode dominated thin or larger plate or weaker resin properties). Therefore, an FE-based design tool is still needed to predict the critical impact force of realistic structures.

The aim of the work presented in this paper is to develop an efficient approach for predicting the critical impact force under low velocity impact. First, three FE models have been developed to simulate the damage located in the top and middle interfaces, and also the laminate's back face, and their effects on the stiffness degradation. Second, based on these models, a computationally efficient model is established and the prediction results are compared with the experimental tests in terms of the critical force, force–displacement relation, and damage shape and size.

2. Strategy of modelling approach

In this paper, a previously conducted low velocity impact test [19,27] is modelled. The material is unidirectional pre-preg IM7/977-3. Ply mechanical properties obtained from [19,27] are given in Table 1, where E_{xx}, E_{yy} and E_{zz} are respectively the Young's modulus of the fibre, transverse to the fibre and normal directions, G_{xy}, G_{xz} and G_{yz} the shear moduli, ν_{xy}, ν_{xz} and ν_{yz} the Poisson's ratios. The interface stiffness values in the normal and two shear directions, K_n, K_s, and K_t, are derived and shown in Table 1.

Standard test coupons are of 150 × 100 mm nominal size with quasi isotropic stacking sequence $[-45/0/45/90]_{4S}$, with a nominal ply thickness of 0.125 mm, 32 plies resulted in a panel of 4 mm nominal thickness. Impact test was conducted using a Rosand instrumented falling weight Type 5 impact tester comprising a load cell detecting the force applied to the impact target. The diameter of the hemispherical impactor was 15.75 mm. The impact support fixture was a 20 mm thick steel plate with a 125 × 75 mm cut out. Four clamps were used to restrain the test coupon during the impact. Coupons were impacted at 5, 10, 15, 20 and 30 J. Filtered impact force vs. time history of five individual tests is shown in Fig. 1. A critical impact force of about 5400 N can be clearly observed, that is the first load drop point. Following the impact test, the damage extent in the test coupons was measured using an immersion ultrasound scanner (C-scan).

Table 1
Mechanical properties of IM7/977-3 laminate [27].

Lamina ply	Cohesive interface
Elastic modulus (GPa)	Stiffness (GPa/m)
E_{xx} = 162, $E_{yy} = E_{zz}$ = 8.34, $G_{xy} = G_{xz} = G_{yz}$ = 4.96	K_N = 240,000, $K_s = K_t$ = 86,000
Poisson's ratio $\nu_{xy} = \nu_{xz} = \nu_{yz}$ = 0.27	
Longitude tension and compression strength (MPa)	Normal strength N = 64 MPa
X_T = 2275, X_C = 1680	Shear strength $S = T$ = 121 MPa
Transverse tension and compression strength (MPa)	Critical strain energy release rate (J/m^2)
Y_T = 64, Y_C = 186	G_{IC} = 320 $G_{IIC} = G_{IIIC}$ = 580
Shear strength (MPa) S_{xy} = 121, $S_{xz} = S_{yz}$ = 127	

Although several different failure modes can occur under the low velocity impact load, major efforts have been focused on the modelling of delamination. The CZM, which places the cohesive elements in the interfaces of laminate to calculate the interlaminar cohesive forces, is the most common approach used in the literature. However, it should be pointed out that the CZM relies on predefined interfaces that constrain the interlaminar crack paths. When the crack path is unknown, cohesive elements must be placed in all the interfaces of the laminate layers, which is computationally expensive for the thick and multi-direction laminates.

To reduce the number of interfaces where the cohesive elements need to be defined, stress analysis was conducted first to determine the potential failure modes and location under the critical force. As shown in Fig. 2a, the laminate is modelled by continuum solid element (designated as C3D8R in ABAQUS). The smallest element size in the impact zone is 0.44 × 0.44 mm. Each element layer represents one lamina ply. The zero-thickness cohesive elements (COH3D8) are inserted in all the interfaces. The reason to have the cohesive elements in the stress analysis model is to facilitate a direct comparison with the fracture analysis models presented in Section 3. Fig. 2b shows a fracture analysis model

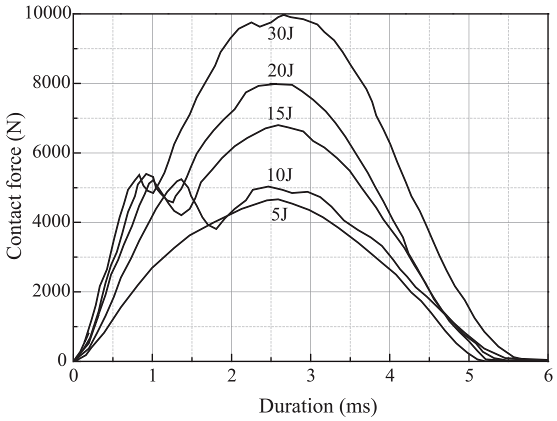

Fig. 1. Filtered impact force vs. time history of low velocity impact test [19,27] (test specimen size 150 × 100 mm; inside the support fixture 125 × 75 mm).