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On the relationship between failure mechanism and compression after impact (CAI) strength in composites

M.R. Abir*, T.E. Tay[1], M. Ridha[1], H.P. Lee[1]

[a] Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore

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ABSTRACT

This work explores the relationship between different failure mechanisms and compression after impact (CAI) strength through an advanced finite element analysis. A Continuum Damage Mechanics (CDM) approach is used to model intra-laminar failure and Cohesive Zone Modelling (CZM) for inter-laminar failure. The FE progressive failure analysis is performed in two consecutive steps. The first is a low-velocity impact analysis in which the induced damage maps are obtained. In the second step, the boundary conditions are modified and an analysis of CAI is performed. The effect of change in ply layup sequence, sub-laminate scaling and ply blocking are investigated and a link between failure and CAI strength is established. Results suggest that changes in ply layup sequence affect delamination sizes, positions and shapes during impact, which in turn result in either global or sub-laminate buckling failure during compression. A global buckling mode results in higher CAI strength compared to failure by sub-laminate buckling for quasi-isotropic laminates of the same thickness. Ply-blocking increases tendency towards delamination, causing a decrease in CAI strength. Sub-laminate scaling causes a transition in failure mode from out-of-plane buckling to in-plane compressive fiber failure. These results suggest a strong correlation between failure mechanism and CAI strength.

1. Introduction

Composite structures in aircraft may be exposed to impact events by vaious foreign objects. Damage in composites due to impact may result in significant reduction of the compressive residual strength [1]. Under compression, impact damage can propagate rapidly. The design of damage tolerant structures are necessary so that they are able to resist damage and continue to function as designed.

During low velocity impact, the generation of high shearing stresses results in damage mostly in the form of delaminations that are embedded within the composite structure and cannot be easily detected visually. Aymerich et al. [2–4] used a combination of X-ray and ultrasonics technique to map the through-thickness impact damage for blocked and dispersed cross-ply laminates. Numerical models were also developed for predicting damage. The damage induced in blocked ply configurations were mostly concentrated within a few interfaces whereas dispersed ply sequence resulted in a more distributed damage. Consequently, other experimental work have also shown that ply clustering increases the projected delamination area [5,6]. The damage induced during impact is a function of the layup sequence. Quasi-isotropic specimens with no ply clustering can also show significant variation in damage when the ply stacking sequence is changed [7–9]. To optimize design against impact damage, dispersed and highly orientated stacking sequence is preferred for greater damage resistance [10,11].

The residual compressive strength is dependent on the position, geometry and the extent of damage induced during impact. Short et al. [12] studied the effect of delamination geometry and position on compressive strength by creating artificial delaminations using PTFE films as inserts at different through thickness position. The failure load was found to decrease with a decrease in delamination size and through-thickness position. Aslan et al. [13] investigated the effect of delamination size on the critical buckling load of E-glass/epoxy composites. Near-surface delamination was reported to exhibit the greatest reduction in compressive strength. To mimic the damage created during real impact situations, Wang et al. [14] carried out compression tests on specimens with multiple artificially programmed delaminations. The maximum reduction in compressive strength was obtained when delaminations divided the laminate into multiple sub-laminates. Although these studies indicate a clear link between damage size, position and geometry, actual impact damage states are inherently more complex. The interaction between different damage modes introduces additional

* Corresponding author at: Block EA, # 02-21, 9 Engineering Drive 1, Singapore 117575, Singapore.
E-mail address: abir@u.nus.edu (M.R. Abir).
[1] Block EA, # 02-21, 9 Engineering Drive 1, Singapore 117575, Singapore.

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complexity in the relationship between failure and residual strength after impact.

Dost et al. [15] carried out a series of impact and CAI experiments on quasi-isotropic laminates to conclude that the damage state created during impact plays a major role in determining CAI strength, and the damage state in turn is a strong function of the laminate stacking sequence. Hitchen et al. [16] found that the stacking sequence that minimizes overall delamination size maximizes CAI strength and vice versa. Rivallant et al. [17] investigated impact and CAI on quasi-isotropic and highly-oriented composite laminate and found that failure during CAI is through local buckling of delaminated sublaminates and crack growth from the impact damage zone. Sanchez et al. [18] carried out compression after impact tests on thin laminates and found that woven laminates have a greater normalized residual strength compared to quasi-isotropic and cross-ply layups. The fast nature of damage propagation means observing damage and its propagation is challenging. Abisset et al.[19] carried out a series of static indentation tests and used X-ray computed tomography and C-scan to understand the relationship between different damage mechanisms. Bull et al. [20] used microfocus computed tomography to scan for damage after impact and after application of near failure compression load. Observations revealed that multiple damage modes may contribute to damage tolerance. Results of advanced FE models, compared with experiments, can give a better understanding of damage mechanisms while reducing the time and cost of physical testing. Sepe et al. [21] carried out both numerical and experimental investigation of CAI for composite omega stiffened panel with a cut-out. Numerical predictions were accurate only up to the point where buckling occurs; post-buckling analysis was not performed because delamination was not modelled. Ridha et al. [22] performed experiments and modelling of omega stiffeners under impact and successive bending-after-impact. A comparison of damage sizes and bending-after-impact strength between experiment and simulation show that they are in good agreement. It was also shown that design modification by changing the orientation of some plies can help reduce damage size and improve bending-after-impact strength. Gonzalez et al. [23] developed a 3D finite element model by employing Continuum Damage Mechanics (CDM) for intra-laminar failure modelling (fiber and matrix damage) and cohesive elements to model delamination. Subsequently, other work on modelling of CAI have been reported [24,25,17]. Tan et al. [25] developed a high-fidelity FE model and used it to predict impact damage states and CAI strength accurately. Our previous work [24] analyzed damage initiation and growth during CAI of a quasi-isotropic laminate subjected to a range of impact energies. A parametric study showed that compressive strength, Mode I fiber compressive fracture toughness and Mode II interlaminar fracture toughness are key parameters that affect residual strength prediction. The capabilities of high-fidelity modelling can be further extended in two ways. Numerical models should be capable of capturing the distinct damage mechanisms undergone by different composite layup sequences. These damage mechanisms have to be quantitatively correlated with CAI strength and qualitatively compared with experimental observations to determine the critical failure modes. Ideally, this could be done across different material systems and layup sequences to validate the capability of numerical models and enable a better understanding of factors that affect residual strength in composites.

In this work, a relationship between failure mechanism and CAI strength is established for a range of layup sequences. Firstly, two different quasi-isotropic layups made of the same material system are studied. It is shown that, for the same impact energy, a change in layup sequence essentially changes the delamination position and geometry, which in turn causes compression failure through differing failure mechanisms (global buckling or sub-laminate buckling), resulting in significantly different CAI strength for the two laminates. Secondly, to understand how sub-laminate scaling and plyblocking (size effect) influence failure mechanism and CAI strength, further simulations and analysis are carried out for different sets of material system and layup sequence.

2. Modelling approach

Failure in composites is a combination of complex mechanisms of fiber breakage and pull-out, matrix cracks and delamination between plies. A simplified approach to modelling CAI is to consider the damage from impact as an equivalent circular hole or eplitical hole and then perform a compression test [26–28]. Such simplifications do not allow for capturing of the complex network of damage seen during impact and therefore in general, unable to predict CAI strength accurately. The modelling approach in this work involves the use of an integrated model that captures damage during impact and its propagation during CAI in a single FE model [24]. Details of damage such as: fiber fracture, matrix cracking and delamination are modelled but without over-simplifications. The use of improved techniques such as smeared crack model, energy-scaled cohesive elements and failure theories are used to predict residual strength and damage growth mechanisms. In this modelling approach, it is essential to ensure that the energy dissipated in the FE model is consistent with the experimentally determined critical energy release rates. The damage model is implemented in an Abaqus/Implicit UMAT user-subroutine.

2.1. Intra-laminar failure

Intra-laminar failure in composites is characterized by fiber failure and matrix cracking and a Continuum Damage Mechanics (CDM) approach is used to model it. The CDM approach models damage as distributed and diffused, which may be modelled through the material constitutive law. A combined maximum stress and Tsai-Wu criterion is used for damage initiation for fiber and matrix failures respectively as this has been shown to work well in previous progressive damage studies [24,29]. The propagation of damage is modelled by an energy-based evolution criterion.

2.1.1. Fiber damage

Fiber damage initiation in either tension or compression, is modelled using a max-stress criterion in the fiber direction given respectively by:

If $\sigma_{11} \geqslant 0$, then

$$\frac{\sigma_{11}}{X^t} = 1 \quad (1)$$

If $\sigma_{11} < 0$, then

$$\left|\frac{\sigma_{11}}{X^c}\right| = 1 \quad (2)$$

where σ_{11}, X^t, X^c are stress in the fiber direction, ply tensile strength and ply compressive strength respectively. After fiber damage is initiated, failure propagation is modelled using a linear softening law whereby the stiffness of the element as well as the Poisson's ratio is degraded linearly until the fiber damage variable, d_f, reaches 1. The degradation of the Poisson's ratio with damage progression is consistent with experimental observations [30,31]. The strain energy dissipated during this process is taken to be equal to the critical energy release rate, or the fracture toughness (G_{ft} and G_{fc} for tensile and compressive fracture toughness respectively) of the material. The strain energy released by the element can be determined by the area under the stress–strain curve, multiplied by the characteristic element length, l_c. This can be written as:

$$\int_0^\infty \sigma_{11} d(\epsilon_{11}\, l_c) = G_f \quad (3)$$

where G_f is the fracture toughness either in tension(G_{ft}) or compression (G_{fc}). Eq. (3) is used to model damage progression after initiation. From the fracture toughness, the final strain at failure, ϵ^f can be obtained by: