Composite Structures 168 (2017) 13–25

Contents lists available at ScienceDirect

Composite Structures

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

# Modelling damage growth in composites subjected to impact and compression after impact

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

*Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117575, Singapore*

A R T I C L E   I N F O

*Article history:*
Received 12 August 2016
Revised 18 January 2017
Accepted 3 February 2017
Available online 16 February 2017

*Keywords:*
CAI
Impact
Progressive damage
Damage growth
Residual strength

A B S T R A C T

Compression After Impact (CAI) tests are frequently performed to characterize the effect of impact damage on strength of composites. This paper presents an integrated single finite element model that enables analysis of impact damage and CAI without major simplifications and idealizations of damage in composites. When applied to a series of quasi-isotropic laminates, the results obtained from simulation correlate well with experiment with regards to damage shapes, sizes and CAI strength. Failure during CAI was found to be triggered by local buckling, causing fibre and delamination damage growth (during compression) that leads to rapid and sudden load drop. Compressive strength, Mode *I* fibre compressive fracture toughness and Mode *II* interlaminar fracture toughness were found to be the key parameters that affect residual strength of composites. Such models can lead to a better understanding of damage growth mechanisms necessary for development of damage tolerant structures, as well as promote virtual testing, with considerable cost and time savings.



## 1. Introduction

Composites are being used increasingly in the automotive and aerospace industry due to its high specific strength and stiffness. The use of composites has brought about greater fuel efficiency and fatigue and corrosion resistance of aircraft structures. However, they are prone to failure due to impact events, that can reduce the compressive residual strength of composites significantly [1]. Compressive residual strength after impact is a critical factor in design. In fact susceptibility to low velocity impact damage is believed to be one of the main factors that limit a more widespread use of composites, although the development of toughened composites have somewhat mitigated its effect. Low velocity impact can be more of a concern as compared to high velocity impact, as it gives rise to Barely Visible Impact Damage (BVID), which might reduce the compressive residual strength significantly without giving any visible signs of damage at the surface of the structure.

Damage tolerance is the ability of structures to continue to perform their intended functions with some tolerable level of damage. The design of damage tolerant structure is important to ensure that structures do not fail at least to the point of damage detectability, a process that requires rigorous experimentation which is costly. The development of reliable, robust material models that can simulate events such as compression after impact damage and CAI strength can reduce time and cost of testing. Both experimental studies and simulation models for low velocity impact have been investigated extensively by researchers [2–16]. These damage models are able to predict the size, shapes and location of delamination, matrix and fibre damage accurately, as well as maximum impact force and displacement. To develop such models, researchers exploited the use of cohesive elements to model delamination and continuum damage mechanics (CDM) to model fibre and matrix damage. Sun et al. [17] modelled interaction between delamination and matrix damage using cohesive interface elements for inter- and intra-laminar damage. A good correlation between experimental and simulation results were obtained, although the work did not consider fibre damage.

A number of experimental studies have been reported for Compression After Impact [18–22]. Compared to the number of experimental studies, very few studies are available on simulation of Compression After Impact(CAI) damage. Aminanda et al. [23] developed a numerical model for Compression After Impact (CAI) on sandwich structures made of metallic skins. Gonzalez et al. [24] used a 3D FE model to simulate intra-laminar and inter-laminar damage for CAI strength. The simulation results match well with that of experiments with some discrepancies (around 20%). Only CAI values are available and no force–displacement

* Corresponding author at: 9 Engineering Drive 1, EA # 02-21, Singapore 117575, Singapore.

*E-mail address:* abir@u.nus.edu (M.R. Abir).

http://dx.doi.org/10.1016/j.compstruct.2017.02.018
0263-8223/

curves were reported. Wang et al. [25] developed a FE model to predict CAI strength of impact damaged laminate as well as flush repaired laminate. The predicted CAI strength for impact damaged laminates agreed well with experiments, although the flush repaired model underpredicted the corresponding CAI strength. Esrail et al. [26] developed an efficient analytical model for predicting CAI strength. Damage size area from impact was first estimated, which was then sub-divided into concentric ellipses. Different strength and stiffness properties were assigned to each of these ellipses and a progressive damage analysis was carried out to determine CAI strength. Fairly reasonable agreement between experimental and analytical CAI strength was obtained for most of the cases studied. Recently, two interesting models for CAI have been developed. Firstly, Rivallant et al. [27] modelled both matrix cracks and delamination by using cohesive interface elements. CAI strength values are consistent with experiment. However, this model requires a specific meshing scheme. Every ply has to be modelled separately with each ply mesh orientation depending on the ply orientation. This is an inefficient process. Also, embedding cohesive elements in plies to model matrix crack is computationally very expensive, especially if we consider the number of cohesive layers that needs to be inserted in one ply to model matrix crack accurately. Sun et al. [17] have shown that at least 6 cohesive layers should be embedded in each ply to model matrix crack accurately. Tan et al. [28] used Continuum Damage Mechanics (CDM) to model inter-laminar damage (fibre and matrix damage) and cohesive elements to model delamination. A non-linear shear response for matrix crack was used to obtain permanent indentation from experimentally fitted data. The delamination shapes and areas obtained after impact correlates well with experiment. Both the work made use of an "artificially low" Mode *I* compressive fracture toughness ($G_{fc}$) value of 10 N/mm to achieve a good correlation between simulation and experiment, which was later experimentally and numerically proven to be around 40 N/mm [29]. Accurate determination and use of fracture toughness values is essential in predictive modelling of failure of composites. A parametric study carried out later would show the importance of compressive strength and fracture toughness values in determining residual strength of composites. Also, no damage growth mechanism during CAI was reported in any of the work.

To understand damage growth behavior in composites, Short et al. [30] experimentally studied the effect of delamination on compressive failure with the introduction of an artificial delamination geometry by inserting PTFE films into laminate during layup. It was concluded that delamination size and through thickness position affects compressive strength of composites. A smaller delamination size delays failure. The failure load decreases with an increase in delamination size and decrease in the through-thickness position of the delamination. Soutis et al. [31] analysed several experimental studies to conclude that compressive loading causes local buckling that spreads laterally from impact region accompanied by delamination propagation that grows in short discrete increments and then propagates rapidly during critical failure or load drop. A similar kind of failure is observed in open–hole compression. A fracture toughness model originally developed for open–hole compression was used to predict residual strength. Starnes et al. [32] used a number of inspection techniques to characterize the effect of impact damage and circular holes on compressive strength. It was found that during compression, the damage induced during impact propagated completely across the specimen width but only a small distance in the axial direction. One of the key challenges in CAI modelling is to be able to characterize damage growth during compression accurately in simulation models. Damage size along with its growth phenomenon are crucial in determining factors that affect residual strength in composites.

The compressive strength ($X_c$) and Mode *I* compressive fracture toughness ($G_{fc}$) can show significant variation in their values. This is because compression in composites is characterized by a complex mechanism. Several studies have indicated that compressive failure is initiated by microbuckling that develops into kink bands followed by subsequent crushing of fibres [33–36]. Compressive strength is far lower than tensile strength as a result of the microbuckling phenomena that sets in early in the compression process. The initiation of microbuckling is dependent on the fibre waviness of the composite. Fleck et al. [33] concluded that the average fibre waviness in composites is around 2–3 degrees. Wilkinson et al. [37] in an illuminating set of experiments inserted brass wires normal to the fibre direction into carbon-epoxy cloth to increase fibre waviness. They found that the compressive strength of T300/914 decreased from 1000 MPa to 200 MPa due to increase in fibre waviness. A small change in fibre waviness can cause significant variation in the compressive strength. Lee et al. [38] carried out compression tests on both thick and thin composites. Standard deviation of fibre misalignment (fibre waviness) in thick composites was found to almost double in comparison to thin ones. As a result, the variation of compressive strength in thick composites(>2 mm) is even more significant. For T700/M21, compressive strength values of 1015 [39],1250 [28] and 1465 MPa [40] were reported. In a similar manner, the determination of Mode *I* fracture toughness associated with compression ($G_{fc}$) has been a challenge, whereas the value of tensile fracture toughness ($G_{ft}$) can be easily determined and consistent results can be obtained [41]. Pinho et al. [42] used Compact Tension and Compact Compression tests to determine the Mode *I* tensile and compressive fracture toughness respectively. A compressive fracture toughness initiation value of 79.9 KJ/m$^2$ for material system T300/913 was obtained, no propagation value could be found. For IM7/8552 [43], the compressive fracture toughness initiation value was found to be 47 KJ/m$^2$, whereas for T800/924C [44], the compressive fracture toughness values varied between 21–39 KJ/m$^2$ depending on the layup sequence used. Lisle et al. [29] measured fracture toughness for compressive failure using infrared thermography while Hongkarnjanakul et al. [45] used finite element to conclude that the compressive fracture toughness of T700/M21 is around 40 KJ/m$^2$. Due to a large scatter, it is absolutely essential to understand how variation in compressive strength and fracture toughness affects residual compressive strength.

The aim of this paper is to implement a sufficiently general CAI model using Abaqus/Implicit that captures the physics and mechanisms of damage growth during CAI events enabling a greater understanding of damage growth mechanisms and factors that affect such growth, and also predict CAI strength. Thus, such a model would greatly improve our understanding of composite damage mechanisms and also enable development of component level simulation models in the future. The capabilities of the model are confirmed by comparing with experimental results obtained from literature. From the viewpoint of the understanding of damage growth, the role of fracture toughness and compressive strength in determining damage growth and the resulting residual strength of composites is then investigated.

## 2. Damage model

Failure in composites is a combination of complex mechanisms of fibre breakage and pull-out, matrix cracks and delamination between plies. To model such mechanisms, a CDM approach with stiffness degradation is used for intralaminar (fibre and matrix) failure, while interlaminar fracture (delamination) is modelled using cohesive interface elements. The damage model is implemented in an Abaqus/Implicit UMAT user-subroutine. A similar