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Finite element model for compression after impact behaviour of stitched composites

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ABSTRACT

A finite element (FE) model using coupling continuum shell elements and cohesive elements is proposed to simulate the compression after impact (CAI) behaviour and predict the CAI strength of stitched composites. Continuum shell elements with Hashin failure criterion exhibit the composite laminate damage behaviour; whilst cohesive elements using traction-separation law characterise the laminate interfaces. Impact-induced delamination is explicitly modelled by reducing material properties of damaged cohesive elements. Computational results have demonstrated the trend of increasing CAI strength with decreasing impact-induced delamination area. Spring elements are introduced into the model to represent through-thickness stitch thread in the composite laminates. Results in this study validate experimental finding that CAI strength is improved when stitching is incorporated into the composite structure. The proposed FE model reveals good CAI strength predictions and indicates good agreement with experimental results, making it a valuable tool for CAI strength prediction of stitched composites.

1. Introduction

Carbon Fibre Reinforced Plastics (CFRP) have gained prominence as high performance structural materials in aerospace industries due to their high strength-to-weight ratio. This makes CFRP hugely employed in modern aircraft structures, with the aim to improve fuel economy and extend flight range [1]. One major milestone that has gained tremendous world-wide attention is the use of 50% CFRP composite materials as primary structural materials in the Boeing 787 Dreamliner. This trend is deemed to continue. However, one of the challenges with CFRP structure is that its performance degrades once subjected to impact of even modest magnitudes [2]. It is well known that the compressive strength of CFRP structure reduces significantly after an impact event, such as tool drop, runway debris impact, bird strikes, and ballistic projectiles [3]. The impact event results in matrix cracking, fibre breakage and delamination within the CFRP structure [4,5]. Under further compressive loading, these failure mechanisms trigger subsequent damage and impact-induced damage propagates to failure at significantly lower load levels compared to the undamaged state.

Over the last two decades, research work on the damage tolerance and compression after impact (CAI) behaviour of CFRP has progressed at tremendous pace. Experimental investigations result in better characterization of CAI damage and sharper correlation of CAI strength to impact-induced damage phenomena [6–10]. Numerical studies offer to understand CAI behaviour and predict CAI strength for reliable design purposes [11–15]. The predicted CAI strength should be reasonably conservative within design limits, but not overly protective that inhibits structural weight reduction. Very few references discuss the efficient use of continuum shell models in combination with cohesive elements for modelling of CAI behaviour. Continuum shell elements are expected to be more efficient in modelling compared to solid elements, thus enabling savings in time and computational costs.

3D composites made by textile processing techniques like weaving, knitting, braiding and stitching, have proven to be more superior in terms of out-of-plane interlaminar strength compared to 2D laminated composites. Numerical and computational studies on textile and woven composites are used to model mechanical behaviour [16–20], impact and CAI behaviour [21,22]. However, there are currently no studies on modelling the CAI behaviour of

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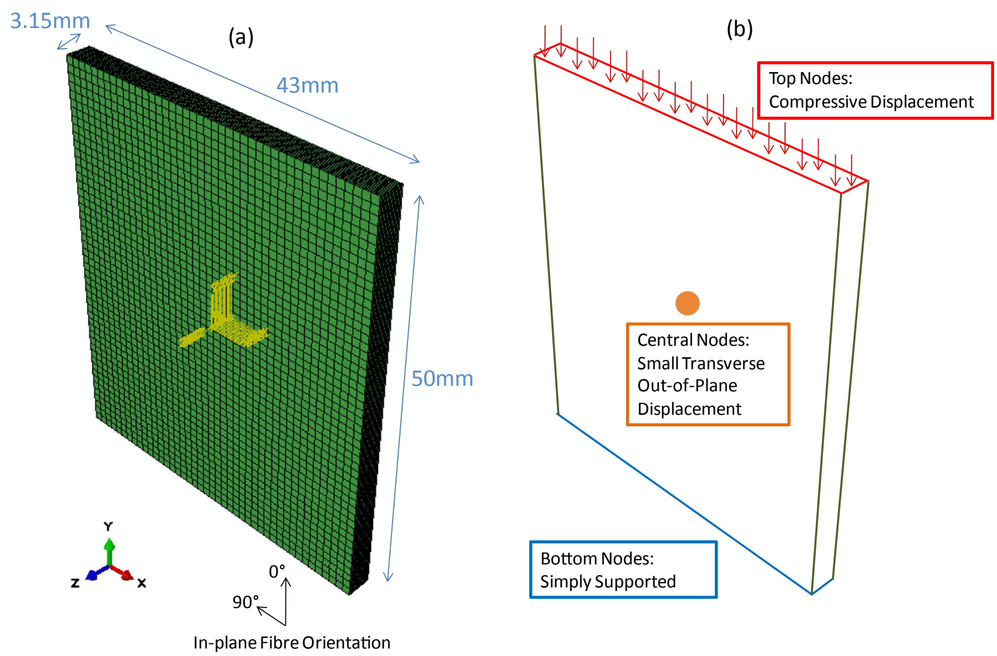

Fig. 1. Composite laminate FE model (a) finite element geometry and discretization; (b) loading and boundary conditions.

stitched composites using computational methods. Moreover, experimental testing of stitched composites to understand CAI behaviour and to obtain CAI strength is costly.

This study aims to provide reliable simulation of CAI behaviour and accurate prediction of CAI strength for stitched composites. This work employs the use of coupling continuum shell elements and cohesive elements in the finite element (FE) model. Continuum shell elements are used to model composite plies and by employing Hashin damage failure criterion to predict composite damage; whilst cohesive elements are used to represent the cohesive interfaces between composite plies and by using traction-separation law to characterise delamination and interlaminar damage behaviour. The modelling strategies for impact damaged composites by explicitly defining delamination interfaces are presented and discussed. The use of spring elements to represent stitches in the FE model and the prediction of CAI strength for stitched composites are also illustrated and demonstrated. Simulation results of stitched and unstitched CFRP laminates are reported and validated by comparing with experimental test data.

2. Modelling methodology

2.1. Coupling continuum shell-cohesive elements for composite laminate FE model

The finite element (FE) model of the composite laminate is created using commercial FE modelling software, ABAQUS. The geometry and finite element discretization of the composite laminate FE model are illustrated in Fig. 1a. The mesh is uniformly generated with in-plane element size of 1 mm × 1 mm, so that stitch elements can be subsequently incorporated with even spacing to study the effect of stitching.

An 8-node quadrilateral in-plane general purpose Continuum Shell element (SC8R), of reduced integration with hourglass control and finite membrane strains is used to model the composite plies, while 8-node linear 3D cohesive elements are employed to model the cohesive interfaces. Each ply contains a single element through its thickness. Tie constraints are defined between adjacent surfaces to ensure behaviour of the entire model as a single part. Surface-to-surface contact of finite tangential frictionless sliding is also defined on adjacent composite plies to prevent interpenetration during local buckling.

In this study, shell elements are used for the composite plies because they are more efficient for modelling thin laminate structures than 3D solid elements. Shell models can retain many of the necessary predictive attributes of much more complex 3D models while providing the computational efficiency that is necessary for design [23]. Moreover, solid elements are not good in bending as they experience the shear locking effect. If solid elements are used, each layer should consist of a few elements in the through thickness direction. However, using shell elements allow the use of one element through the thickness per ply.

Continuum shell elements, in particular, discretize an entire 3D body, unlike conventional shells which discretize a reference surface. The thickness is determined from the element nodal geometry. Continuum shell elements have only displacement degrees of freedom. From a modelling point of view, continuum shell elements look like 3D continuum solids, but their kinematic and constitutive behaviour is similar to conventional shell elements. Continuum shell elements employ first-order layer-wise composite theory [24]. Unlike conventional shells, continuum shell elements can be stacked to provide more refined through-thickness response. Stacking continuum shell elements allows for a richer transverse shear stress and force prediction and allows for the prediction of through-thickness pinching force. Continuum shell elements are more accurate in contact modelling than conventional shells, since they employ two-sided contact taking into account changes in thickness no matter how thick the elements are compared to other element dimensions. On the whole, continuum shell elements have similar behaviour as shell elements and, therefore, can be used effectively for modelling slender structures dominated by bending behaviour. The elastic constants used in the continuum shell elements for the composite plies are summarised in Table 1.

The composite in-plane carbon fibre layup is a typical quasi-isotropic laminate configuration of $(+45/0/-45/90)_{2S}$. Each