Composite Structures 108 (2014) 161–171

Contents lists available at ScienceDirect

Composite Structures

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

Finite element modelling of damage induced by low-velocity impact on composite laminates

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A R T I C L E   I N F O

Article history:
Available online 17 September 2013

Keywords:
Impact behaviour
Delamination
Finite element analysis (FEA)
Cohesive elements

A B S T R A C T

Progressive damage models based on continuum damage mechanics were used in combination with cohesive interface elements to predict the structural response and the failure mechanisms of composite laminates subjected to low-velocity impact. The potential of this simulation approach for correctly predicting the through-thickness distribution of internal damage was specifically examined in the study. The constitutive models for intralaminar and interlaminar damage modes were incorporated into the ABAQUS/Explicit FE code by user-defined VUMAT material subroutines. The results of numerical simulations were compared with experimental data obtained by drop-weight impact testing and stereoscopic X-radiography. The developed FE model provided a correct prediction of the structural impact response of laminated samples over the range of impact energies examined and successfully simulated the temporal sequence of the major damage mechanisms. A reasonably good agreement was also achieved between numerical predictions and experimental observations in terms of shapes, orientations and sizes of individual delaminations induced by impact at the different interfaces. Additional numerical analyses were also conducted to investigate the influence of simulated intralaminar damage modes on the prediction of interface delaminations. The analyses show that implementation of intralaminar damage modes may be required for accurate simulation of the three dimensional delamination pattern induced by impact.

1. Introduction

Composite laminates are being increasingly used in lightweight structural components for a variety of engineering fields – such as the aerospace, automotive, marine and wind turbine sectors – because of their high strength and stiffness to weight ratios, good fatigue performance and excellent corrosion resistance. A more widespread use of composites in primary structures is, however, still restrained by their high susceptibility to internal damage caused by foreign object impact events, which can be reasonably expected during the whole life of a structure [1]. Typical damage occurring in impacted laminates consists of a combination of intralaminar damage mechanisms (such as matrix cracking or plasticity, fibre/matrix debonding and fibre fracture) and interlaminar failure, which develops at the interface between adjacent plies in the form of debonding between layers (delamination). Interface delaminations are probably the most critical and insidious failure mechanisms, since they may severely degrade the strength and the integrity of the structure [2,3], and may propagate undetected during service, leading to unexpected collapse of the component.

For these reasons, there is a strong need for models and simulation procedures capable of predicting the structural performance and the damage resistance of laminated structures subjected to impact. A large number of predictive methods have been proposed in the literature to model initiation and growth of delaminations in impacted laminates [4]. Although stress-based continuum damage mechanics has been used in the past to study delamination in composites [5,6], this approach is not particularly suited to model discrete failure phenomena characterized by highly localized stresses at geometrical or material discontinuities [7] and fracture mechanics is now more widely adopted to analyze the progression of interlaminar cracks by means of FE-based procedures such as the Virtual Crack Closure technique (VCC) or cohesive zone models [4,7–9]. The VCC approach is however very sensitive to mesh geometry and density, and requires both the assumption of a pre-existing crack and the application of adaptive re-meshing techniques in order to adjust the mesh to changes in the shape of the delamination front. The use of cohesive zone models, which combine strength-based criteria to predict damage initiation with fracture mechanics energy criteria to simulate damage propagation

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http://dx.doi.org/10.1016/j.compstruct.2013.09.004

and subsequent fracture, allows to overcome the main limitations of VCC analyses and cohesive interface elements have gained special interest for the simulation of discrete failure modes in impacted laminates.

Cohesive elements placed at the interface between layers were for example successfully used in various studies to model delaminations induced by low-velocity impact in cross-ply composite laminates [10,11]. The combined effect of intralaminar and interlaminar damage was investigated in further analyses, where cohesive [12–15] or special spring elements [16,17] were used for modelling both delaminations at the interfaces between layers and major matrix cracks (such as bending cracks on the bottom layer and shear matrix cracks in the middle layers) developing in impacted laminates.

However, while cohesive elements are especially suitable for modelling cracks that are constrained to propagate along well defined fracture surfaces (such as delaminations at the interface between layers), their use may be problematic for simulation of intralaminar matrix cracking in cases where the site of crack initiation is not known in advance, such as for damage generated by transverse impact loads. Even when placing cohesive interface elements along all interelement boundaries (which would likely result in extremely long computation times), the geometry of the FE mesh would restrict the direction of crack propagation to the orientations of the element sides, and the presence of the cohesive surfaces would inevitably introduce a spurious artificial compliance to the undamaged structure [18].

In order to overcome these limitations, various strategies for progressive damage modelling based on a smeared crack approach, which considers the fracture energy distributed over the element volume, have been developed and extensively used in the last decade to simulate intralaminar damage in composite laminates [19–24]. Typical progressive damage models integrate the use of failure criteria with the application of material degradation procedures, to simulate, respectively, the initiation of damage and the reduction of elastic properties due to the degradation of the material [25].

Modelling schemes based on the combined use of continuum damage mechanics (CDM) models and cohesive surface elements has been adopted, in the past few years, to represent distributed intralaminar damage (such as matrix cracking and fibre fracture) and interlaminar damage developing in laminates under impact loading. In plane CDM degradation models controlled by energy dissipation constants and accounting for shear nonlinearity were for example implemented in [26,27] into the explicit dynamic DYNA3D FE code for predicting, in association with interface cohesive elements, the impact damage resistance of woven composite laminates. Good agreement between numerical predictions and experimental results was obtained in terms of force time history, general damage features and envelope of overall planar damage. Impacts on multidirectional laminates with various stacking sequences were simulated in [28,29] using constitutive material models formulated in the framework of continuum damage mechanics for in-ply damage (matrix cracking and fibre breakage damage mechanisms) and cohesive surface models for progressive interface delamination under variable mixed-mode loading conditions. Good correlation was achieved between experimental and calculated impact force histories and projected damage areas for various impact energies. In particular, a detailed comparison between delaminations predicted at each interface and experimental data obtained using fluorescent penetrant inspection was carried out in [28]; all major delaminations, including their orientations, were generally correctly predicted by the model, even though shapes and absolute sizes of individual delaminations were not properly captured for some laminate lay-ups. In-ply damage models (implementing stress-based criteria for damage initiation and energy-based evolution laws for degradation of elastic properties, as well as shear nonlinearity) and cohesive interface elements (for capturing interlaminar failure) were also used in [30,31] to simulate the structural and damage response of stiffened quasi-isotropic panels [30] and of cross-ply laminates [31] to low-velocity impact. Numerical predictions were in good agreement with experimental data with respect to absorbed energy, impactor force versus time and global damage extent, even though the correctness of sizes and shapes of delaminations predicted at each interface could not be assessed because no experimental information was available on the through-thickness distribution of damage.

The findings of the studies briefly summarized above indicate that the predictive capabilities of damage modelling strategies integrating CDM and cohesive zone models have yet to be specifically tested with regard to their accuracy in simulating the full three dimensional distribution of internal damage. In particular, because of the limitations of ultrasonic or conventional radiographic inspection techniques in the presence of overlapping delaminations, there is an almost total lack of quantitative comparisons between experiments and simulations in terms of shape and size of delaminations developing at each interface in laminates with multiple delaminations, with only a few investigation [16,17,28], to the best of our knowledge, specifically attempting to compare numerically predicted and experimentally measured delaminations on a full interface-by-interface basis.

Motivated by this background, the specific objective of this paper is twofold. First, to evaluate the capability of simulation approaches based on the combined use of cohesive interface elements and continuum ply damage models to correctly capture not just the planar extent but also the detailed through-thickness distribution of damage induced by impact in composite laminates. Second, to assess the importance of accounting for in-ply damage in the estimation of shape and extent of individual delaminations at different depths.

To this aim, progressive failure models based on continuum damage mechanics were used in combination with cohesive interface elements to model structural response and internal failure mechanisms of composite laminates subjected to low-velocity impact. Constitutive laws for damage models were implemented into the FE code ABAQUS/Explicit through user-written VUMAT subroutines; the FE model was applied to simulate the damage processes occurring in $[0_3/+45/-45]_S$ graphite/epoxy laminated plates for various impact energies ranging between 1 J and 8 J.

The results obtained by the FE analyses are illustrated and compared with experimental data obtained by drop-weight impact tests followed by stereoscopic X-radiography, which was used for detailed reconstruction of the through-thickness distributions of delaminated areas induced by impact. The quality of numerical predictions is illustrated in terms of global structural response (force–time and force–displacement curves; dissipated energy) and of extent of damage developing within the laminate at different depths. In particular, shape and size of individual delaminations predicted at each interface over a wide range of impact energies are qualitatively and quantitatively compared with those characterized through X-ray stereoscopy, thus providing novel data and additional information for assessing the accuracy of this class of models for future use in damage tolerant design of composite structures.

The importance of modelling in-ply damage for a correct simulation of individual delaminations is also examined by carrying out additional numerical analyses based on the same FE model but without implementation of intralaminar damage models in the code.