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Interaction of inter- and intralaminar damage in scaled quasi-static indentation tests: Part 2 – Numerical simulation

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ABSTRACT

A numerical study, accompanied by the experimental data from Part 1 of this paper, provides a clear picture of the global damage behaviour and local response of four scaled Carbon Fibre Reinforced Polymer (CFRP) laminates under quasi-static transverse loading. Interface elements with a cohesive formulation are employed to model delamination, matrix cracks and their interaction. The predictive damage from different numerical simulations with different levels of detail is presented, and the validity is illustrated both qualitatively and quantitatively. Specifically the number of inserted potential intralaminar crack paths is varied from no cracks, through single, then double, to multiple cracks. It is shown that the models with the capability to simulate multiple matrix cracks best predict the key aspects of barely visible damage of composite laminate during quasi-static loading.

1. Introduction

Low-velocity impact of carbon-fibre reinforced laminated composites is one of the most critical loading conditions of aerospace structural components, because the mechanical properties of laminated composites are considerably weaker in the matrix-dominated directions. Two types of damage can be readily induced by such loading. They are delamination accompanied by matrix cracks, and back-face fibre breakage, which are called Barely Visible Impact Damage (BVID) in aerospace structural applications. This damage takes place inside the laminate and may not be easily inspected. Delaminations arising at the ply interfaces induced by transverse loading are apt to propagate during in-plane compressive loading, which is the one of the most common loading conditions for composite panels in today's aircraft primary structural components. The presence of delamination can lead to significant compressive strength reduction even without the presence of fibre breakage [1–8]. For this reason, delamination and associated matrix cracks and their interaction are important mechanisms to be understood. The damage behaviour and damage mitigation of composites have thus been extensively studied and reviewed by both experimental and numerical approaches e.g. [9–14].

During an impact event, the laminate is subject to a complex loading condition, which causes compression at the top, tension at the bottom of the laminate, interlaminar shear stress inside the laminate and contact stress immediately under the impactor. Matrix cracking is recognised as an early damage mechanism before delamination, after which the stress is redistributed and causes stress concentrations at the locations where the matrix cracks intersect with resin-rich region at the adjacent ply interfaces. Because of the developed interlaminar shear stresses and the relatively weak mechanical properties of the matrix, delamination initiates from these matrix cracks. Since the matrix cracks are not able to penetrate adjacent plies with a different fibre orientation, the cracks tend to migrate from one ply to another by joining up via delaminations at the interfaces [15,16]. As the load increases, delamination growth at pre-existing locations and the occurrence of fibre breakage at surfaces result in the load-bearing capability of the laminate being completely disrupted. Therefore, non-critical damage mechanisms and coupling phenomena between matrix cracks and delamination before critical failure become extremely important for the study of both impact damage resistance and damage tolerance.

Owing to the strong demand for advanced, well-validated and robust numerical models for virtual testing in academia and industry, many efforts in studying, characterising and predicting the failure behaviours and damage mechanisms of laminated composite using the Finite Element Method (FEM) are reported in the literature. Numerical prediction of impact-induced damage can be modelled by continuum and discrete approaches. Both approaches usually rely on stress-based criteria for damage initiation and fracture mechanics for damage evolution. Material models for low-velocity impact damage prediction based on these two

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approaches, Continuum Damage Mechanics (CDM) and Cohesive Zone Modelling (CZM), have been studied in the literature in recent years e.g. [17–20]. Lopes et al. [21] used a three-dimensional progressive failure model to simulate intralaminar damage. A physically-based failure criterion [22] for damage initiation, and a mesh-independent evolution law adopted from Maimí [23] were employed. The delamination prediction was modelled using CZM, and a good correlation with experimental results was obtained. Likewise, Shi et al. [19] have used a stress and energy-based damage model for fibre failure and matrix cracks, as well as taking nonlinear shear behaviour into account, and using cohesive elements at the interface of plies to model delamination, to predict damage in a cross-ply laminate under low-velocity impact. Improvements to these models have been made later by adding strips of interface elements at the intralaminar level for discretely simulating the matrix crack, and by this method the accuracy of predicted energy absorption and the splitting damage at the bottom ply was significantly improved [24].

The interest in implementing interface elements with CZM formulations into potential damage regions at the interlaminar level has increased, and the approach has become a standard feature in most commercial FEA software packages. The development and applications of deploying interface elements to predict discrete matrix-dominated failure has been reviewed by Wisnom [25]. Hallett et al. [26] have showed the advantages of using interface elements with a CZM formulation to simulate intra and interlaminar damage in tension loaded scaled laminates with damage arising from the free edge, giving results that agreed with experimental observations very well. Aymerich et al. [27], Lammerant and Verpoest [28], Moura and Gonçalves [29] and Zhang et al. [30] all have simulated delamination and single matrix cracks at predefined locations using the CZM approach and studied the effect of matrix cracks and neighbouring fibre orientations on the behaviour of delamination propagation during low-velocity impact in cross-ply laminates. All delamination prediction was much improved compared to models without matrix cracks being modelled.

Bouvet et al. [14] in contrast to these single crack models proposed a distinct formulation with a unique model architecture to take account of the effect of global matrix cracks on delamination of quasi-isotropic composite plates under impact loading. Each ply was meshed into small parallel strips along the fibre direction with one volumetric element. A zero length spring element was used to connect a group of four adjacent ply elements between parallel strips for simulating matrix cracking through a stress-based quadratic criterion. Delamination was also modelled in a similar manner using four individual spring elements to link the four nodes between each of the two consecutive plies. The predicted individual delamination shape and overall response of the plate correlated with experimental observation extremely well.

CDM, on the other hand, has been considered as an accurate and less expensive modelling method than the CZM approach for complex structures. However, model size in CDM analysis is usually gradually increased as more plies are being modelled because continuum elements with a small characteristic length have to be placed over large potential damage regions to overcome such shortcomings as mesh-dependency and strain localisation [22]. This could lead to substantial increase in the computational cost if thin layers of cohesive elements between plies are globally deployed. Moreover, because the matrix-dominated damage (delaminations and matrix cracks) takes place at different locations, CDM may not allow intralaminar crack tips to capture the physical interaction with the interlaminar region.

Despite the large amount of information in the literature and numerous existing numerical studies, there has not yet been a systematic study on the level of detail with which the matrix cracking needs to be included in a model to achieve accurate results. Also there is a lack of highly detailed experimental data needed for correlation of such numerical studies across a sufficiently wide range of cases to validate the models. This has been addressed through a series of scaled indentation tests on specimens with different thicknesses and in-plane dimensions in Part 1 of this paper [31] and here an equivalently detailed study of the numerical modelling of such tests is presented. Cohesive elements were inserted in both inter and intralaminar levels systematically at potential damaged regions. Each ply was modelled as an orthotropic elastic material, and fibre failure has not been considered here since the priority of this study was to investigate the interaction between matrix cracks and delamination before the fibre failure initiation, which usually occurs after the formation of BVID. It has been noted that scaled tests provide a particularly rigorous case for model validation, especially when there is variation in the level of damage and failure response [32,33]. This approach has been followed in this study with both in-plane and full 3D scaling undertaken [33] to rigorously assess the models presented here.

The loading was undertaken at quasi-static rates in the experiments since it is advantageous, over low-velocity impact, to control the level of damage achieved. Many studies have shown the high degree of equivalence between quasi-static indentation and low-velocity impact damage in laminated composites [34–39] and this was also confirmed here [31]. To distinguish the various impact events and static indentation processes, Olsson [39] has used a mass criterion to characterise different responses of composite plates under low-, intermediate- and high-velocity impact with small and large mass of impactor. This was shown to be an easy procedure to define the limit to approximate transverse impact response using quasi-static solutions such as that developed by Swanson [38]. Both authors suggested that a large-mass impactor, whose mass is at least ten times larger than the target plate and travels at a few m/s, and impacting a composite plate in the transverse direction is deemed to be a quasi-static process. The response of the substrate is a static deformation mode, and consequently the relation of the contact force and plate transverse displacement should match with that in the static indentation process. Aoki et al. [34] and Nettles et al. [40] have compared the damage behaviours of CFRP laminates under low-velocity impact and static indentation tests using various post damage inspection techniques. Regardless of minor dynamic and local effects, a high degree of equivalence between both test results in terms of load–displacement histories, damage mechanism and damage size was found. Numerical models in this study and experimental results in Part 1 of this paper based on static analysis are therefore considered to be reliable to model and replicate the damage behaviour of composite plates under large-mass, low-velocity impact.

2. Experiment

The experimental results used for validation of the numerical models are presented in detail in Part 1 of this paper [31], and pertinent information will not be repeated here except for the description of some key features of the specimens, damage mechanisms and test setup. Four types of scaled quasi-isotropic laminates were subjected to quasi-static indentation test, based on the ASTM standard for measuring the damage resistance of CFRP plates to drop-weight impact events [41]. During static indentation, several load drops and recoveries before complete penetration of the laminate by the indenter can be found in the load–displacement plot, and each load drop is reflected by the damage extent and mechanisms. The load level before the first significant load drop, referred to as the critical load or delamination threshold load, indicates the elastic limit of the laminate, which is one of the most important factors