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Subtle features of delamination in cross-ply laminates due to low speed impact

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A B S T R A C T

In cross-ply laminates, the shape of delamination areas, which form due to low velocity impact, have two subtle features, which have been observed consistently in numerous experiments. Those are the pointed delamination tips and the intact zone between the lobes of delamination. However, there have not been any account available in the literature how they can be consistently captured through numerical modelling, and hence these features in published modelling results were often absent. It is the objective of this paper to identify the underlying modelling considerations so that these features can be captured with confidence. A key and unique reason has been identified in each case. Namely, inclusion of intra-laminar damage allows to reproduce the pointed delamination tips, while the gap between the lobes of delamination can be captured by models with sufficiently refined mesh, where friction between the laminas is taken into account. The capability of capturing these subtle features helps to raise the level of fidelity on the simulation of delamination due to impact.

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1. Introduction

Delamination in laminated composites caused by low speed lateral impact has been subjected to countless investigations from various perspectives [1], to such an extent that standards [2] have been drawn, as the problem has been considered as one of the key aspects in material selection, in particular, for aerospace applications.

Cross-ply laminates are one of the simplest types of laminates, which is not of much practical significances in terms of their engineering applications. However, their simplicity makes them an ideal case of verifications and validations of theoretical models. They have indeed been employed frequently as one of the benchmarking cases [3]. Experimental results based on different materials are found highly reproducible and consistent [4–6]. Most of the prominent features of delamination are captured well through carefully conducted numerical simulations. Reasonable agreement between the experimentally observed and numerically predicted delamination, both qualitative and quantitative, has been reported by many [5,7–10]. More research outcomes are still being reported [11–16], which suggests the need of better understanding before composites can be applied with higher level of fidelity, the lack of which in relation to the extensive use of composites in Boeing 787 was clearly identified in the report from a US government public enquiry [17].

In order to improve modelling of the delamination predictions under low velocity impact, different considerations are taken into account. Some researchers seek to improve the formulation of the constitutive behaviour of the cohesive layers, proposing modifications to the existing models [18] or devising models of their own [15]. Specifically, in their recent review, Abrate et al. [19] surveyed a great variety of cohesive zone models available to-date.

Accounting for the intra-laminar damage is yet another aspect which is commonly included into the formulations of the models. Again, both the material models available in commercial finite element codes [11,13] and the user-defined models [5,16] have been used for the purpose.

Another consideration, which is sometimes included in the formulation of the models, is the effect of friction on contact surfaces between the adjacent delaminated laminae following the failure of the interface [4,5,13–16].

Though a reasonable agreement between the experiment and modelling is usually reported, there is still lack of understanding as to what effect the various factors included in modelling have on

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delamination predictions. Another closely associated and even more important issue is the inability to comprehensively explain two subtle features of delamination as will be defined below, which are observed consistently in impact tests of cross ply laminates, but are not captured in many accounts exploring the subject.

Consider the relatively best known case of cross-ply laminates of a layup $[0°_m/90°_n/0°_m]$ subjected to impact, as defined by ASTM standard [2]. It can be easily predicted, as well as experimentally observed, that little delamination occurs on the 0°/90° interface closer to the impactor, and the observed delamination is dominated by the one on the 90°/0° interface farther from the impactor. The delamination area and dimensions are always measured from the dominant delamination. Schematic drawing of the delamination outline as typically observed experimentally is shown in Fig. 1. The following two subtle features as marked have never been understood appropriately and captured consistently through modelling.

(1) The tips of delamination at both ends tend to be pointed;
(2) The intact zone between the two lobes of the delamination. The so-called intact zone is usually not entirely damage free. In fact, complicated damage patterns can usually be observed there as a result of localised indentation due to the impact. However, as far as the interface under consideration is concerned, the delamination does not propagate into this zone.

Researchers tend to turn a blind eye to them when producing their theoretical predictions, hence even when captured in some way [15,16,20], the comprehensive explanation of the definitive factors in the modelling responsible for those subtle features has never been given. There is no lack of interest in capturing these features as they are so characteristic and experimentally reproducible, but the fact is that there has been not yet a conclusive statement about their being and the reason behind such distinctive features of delamination. Although such subtle features are not as significant as the delamination area and dimensions in representing the effects of the delamination, the inability to capture them does cast doubts on the fidelity of predictions, even if one has managed to estimate the area and the dimensions reasonably accurately. Without capturing such consistently observable features, the authors would find it hard to be content with the existing simulation capability.

The objective of this paper is to address these subtleties. The discussion is restricted to $[0_3/90_3]_s$ layup, in which the two subtle features as discussed are always present, as confirmed by numerous experimental studies. It has been revealed that they result from definitive reasons and, once these reasons have been taken into account properly, these subtle features can be captured consistently in numerical simulations. The authors have been inspired by available results and considerations in the literature, such as generic mesh sensitivity of the problem and contributions from the effects of transverse matric cracking and the delaminated interfacial friction. However, there has been no account available in the literature, to the best of the authors' knowledge, where such considerations have been associated specifically with the features under investigation in this paper. Through the specific considerations introduced to the model as presented in this paper, these subtle features will be reproduced vividly and reasons responsible for these features will be identified.

2. Modelling cross-ply laminates subjected to impact

In the present investigation, delamination due to low velocity impact on cross-ply laminate of $[0_3/90_3]_s$ lay-up is studied via finite element modelling conducted with Abaqus/Explicit [21]. The finite element model was generated in order to compare directly with the laminated panel impact experiments [6,10]. The model takes into account effects of both the intra-laminar cracking, through a user-defined material subroutine for the composite laminas, and the delamination at the interfaces, which is modelled using conventional cohesive elements as available in Abaqus.

2.1. Finite element model

In the experiments [6], the $[0_3/90_3]_s$ laminate was 2 mm thick, with 65 mm × 87.5 mm in-plane dimensions. The laminate panel was simply supported. The simple support conditions in the experiments were obtained by resting the specimen on a rigid steel frame with a rectangular opening of dimensions 45 mm × 67.5 mm with all four corners of the specimen clamped to the frame. The clamps were to ensure zero deflection at the corners. The specimen was impacted at the centre by a hemispherical impactor 12.5 mm in diameter, which was considered as a rigid body. Impacts of different energies were simulated by assigning appropriate velocity values to the impactor at the instant of contact. The mass of the impactor in the tests was 2.3 kg.

To reduce the computational costs, only a quarter of the specimen was modelled, with appropriate symmetry conditions being imposed, as specified in Fig. 2(a). The composite laminate was idealised into a layup of three laminae, each consisting of plies having a common orientation as shown in Fig. 2(b). The interfaces between the composite layers were modelled using cohesive elements COH3D8. The unidirectional composite layers were meshed with continuum shell elements, SC8R. The surface-to-surface contact interactions were defined between the plate and the indenter. The same were also pre-planted on the faces of neighbouring laminae, which would be activated upon the deletion of the cohesive elements following interface failure to prevent the interpenetration between the neighbouring laminae. Since the analysis was conducted with a quarter of the panel, the mass of the impactor was also reduced to a quarter in the model.

Given the mesh sensitivity of delamination problems in general, a study has been conducted to determine the mesh convergence, which was reached when both the composite and the cohesive layers were meshed with elements of 0.25 mm × 0.25 mm in-plane

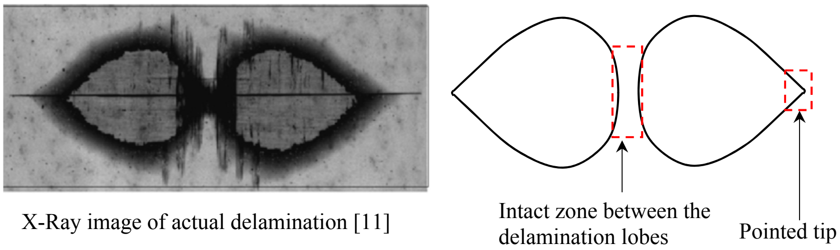
X-Ray image of actual delamination [11]

Fig. 1. X-Ray image of actual delamination and a schematic drawing of the delamination pattern typically observed experimentally.

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