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Predicting the effect of through-thickness compressive stress on delamination using interface elements

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Abstract

The failure of interface elements is typically based on interactive mixed mode criteria for both initiation and propagation of damage. The effect of tensile through-thickness stress is normally taken into account in combination with interlaminar shear stress. When the through-thickness stress is compressive, however, its effect is usually ignored and the failure of interface elements is considered to be pure mode II. Experiments on single-lap, cut-ply and dropped-ply specimens however show that the compressive through-thickness stress can greatly increase the delamination failure stress and cannot be simply neglected.

The influence of compressive stress on mode II damage evolution is investigated numerically based on the cut-ply and dropped-ply experiments. A new interfacial failure model with modified failure initiation and propagation criteria is proposed to take the effect of compression on matrix shear strength and mode II critical fracture energy, G_{IIC}, into account. The new model uses one independently determined parameter to relate the compression to the increase in interlaminar shear strength and G_{IIC}. With the new failure criterion applied, two types of cut-ply models and two types of dropped-ply models, using the same input parameter, all produce excellent correlation with experimental delamination stresses. As a validation case the single-lap model was run with the new criterion and the same input parameters and this also achieves very good correlation with the experimental failure stress.

Keywords: B. Mechanical properties; B. Delamination; B. Fracture; C. Finite element analysis (FEA); Interface elements

1. Introduction

The through-thickness properties of composite materials are typically lower than their in-plane properties and represent a weakness and potential failure mechanism, particularly in impact loading scenarios. It is therefore important to be able to characterise these properties and have numerical models to predict failure. The interlaminar shear strength is one such property and a number of different tests exist to determine its value. Dong and Harding [1] developed a single-lap shear specimen for use at high strain rate to characterise the through-thickness shear strength of carbon/epoxy laminates. Finite element analysis was undertaken to predict the delamination failure [2]. It was found that local stress concentrations existed in both shear and direct stress components and this caused significant differences between the test result and the finite element predictions. As a result of this highly localized stress concentration, results are further dependent on the mesh refinement in the area of high stress gradients [3].

Interlaminar failure in laminated composites is often localized in the resin rich layer between plies. The thickness of these layers is generally very small and they can therefore be modelled as interfaces where displacement discontinuities can take place in a mathematical model. This is a basic assumption of the widely-used interface element models, which are then characterised by suitable constitutive relationships between the stresses acting on the interface and the displacement discontinuities. Interface elements can be either continuous (line, plane and shell interfaces [4–7]) or discrete (nodal or point interfaces [8–10]), and

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typically use maximum stress levels as input for damage onset and critical energy release rates, i.e. G_{IC}, G_{IIC} and/or G_{IIIC}, for damage propagation. The critical energy release rates specify the amount of energy dissipation per unit area, which does not expose the interface elements to any pathological mesh dependency.

One such discrete interface element formulation has been implemented in the explicit finite element code LS-Dyna [11,12] and used for predicting delamination. This avoids the problem of the local stress concentration since failure is located at the interface between plies and failure is initiated (but not completed) once a critical stress has been reached. The interface elements are automatically generated between potential delamination interfaces using a purpose written pre-processing program. To overcome some of the difficulties in pre- and post-processing the discrete interface elements, a new solid interface element formulation, which can also be automatically generated with a similar pre-processing program, has been developed and implemented in LS-Dyna. The new interface element has been validated by simulating single mode tests such as the mode I double cantilever beam (DCB) and mode II end notched flexure (ENF) tests and is used in all the numerical simulations in this paper. Similar solid element formulations have also been successfully implemented in LS-Dyna by other authors [13,14] but for different applications.

The single-lap test in Ref. [1] has been re-analysed using interface elements to predict the delamination failure, obtaining a consistent mesh independent result. The predicted failure stress was still significantly below the experimental value. Unlike the single-lap debonding problems in some other publications [15–18] where failure occurs under combined tensile through-thickness stress and interlaminar shear stress, the single-lap failure here initiated at a point with a highly localized compressive through-thickness stress. When the failure criterion neglects the influence of compressive stresses at the failure initiation points, the failure stress of the model is underestimated.

Evidence has been presented in the literature that through-thickness compression can improve the interlaminar shear strength of laminates. Some researchers such as Deteresa et al. [19,20] take this strengthening effect of compression on shear strength into account by modifying the stress interaction criterion as below

$$\frac{\sigma_{33}}{Z_f} + \frac{\sigma_{13}^2 + \sigma_{23}^2}{S_{shear}^2} \leqslant 1 \qquad (1)$$

where Z_f is the maximum through-thickness stress and S_{shear} is the maximum interlaminar shear stress. Other investigations such as those by Hart-Smith [21–23], Sun and Tao [24] and Rotem [25] suggest it is the result of in situ effects in laminates. Work by Cui et al. [26] reveals that the through-thickness compression can suppress delamination in terms of increasing the critical Mode II fracture energy (G_{IIC}) which was expressed as a linear function of average through-thickness normal stress.

A parametric study on the influence of increased maximum shear stress (S_{shear}) and G_{IIC} on the single-lap model showed that the strengthening effect of compressive stress on both S_{shear} and G_{IIC} should be taken into account in order to improve the correlation between numerical and experiment results [3]. To further investigate the relation between through-thickness compressive stress and the increase of S_{shear} and G_{IIC}, two types of cut-ply models and two types of dropped-ply models, based on the work of Cui et al. [26], are used in this paper to generate different levels of through-thickness compressive stress. Three possible Mode II damage evolution laws under compression are proposed to explain the increase of S_{shear} and G_{IIC}. The interface failure criteria based on these assumptions have been implemented in LS-Dyna and are used to simulate the delamination in the cut-ply and dropped-ply experiments. By comparing the results of the three failure criteria in the cut-ply and dropped-ply models, it is found that the increases of S_{shear} and G_{IIC} are not independent. The increase of G_{IIC} can be predicted with a knowledge of the increase in S_{shear} and an appropriate assumption of the Mode II traction behaviour under compression. The increase of S_{shear} is determined by an analogous internal friction factor. Excellent correlation for the delamination stresses for all the four cut-ply and dropped-ply models was achieved. As an independent validation the single-lap model was rerun with the new formulation and again correlation was very good.

2. Introduction of interface elements for delamination modelling

The failure stress predicted by finite element analysis in the presence of stress concentrations is often dependant on the mesh refinement used. To be able to investigate predictive models of delamination behaviour and failure criteria it is required to reduce or eliminate such mesh dependence. Previous work has shown that analysis of a single-lap shear test resulted in the maximum stress localizing in a single element [2]. Further investigation of this phenomenon is carried out here and the use of interface elements proposed to remove the observed mesh size effect. This then allows a more detailed investigation of the failure criteria used to model the delamination failure.

2.1. Experimental results

The full test results on which the analysis is based have been published in Ref. [2] and are only briefly summarised here.

A single-lap shear specimen design, optimised to achieve a uniform shear stress over the central failure plane and minimal normal stresses under dynamic loading [1] was tested in a compressive split Hopkinson bar apparatus.

Fig. 1 shows a schematic of the specimen design and loading. Inset is a photograph of the failure plane obtained