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Modelling the interaction between matrix cracks and delamination damage in scaled quasi-isotropic specimens

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Abstract

A series of tensile tests on scaled quasi-isotropic laminates have been carried out and modelled using finite element analysis to predict failure. Observations during testing and examination of the failed test specimens showed significant influence of matrix cracking and delamination on the final failure. Initially the virtual crack closure technique (VCCT) was used to determine the applied load that would cause free edge delamination. Experimental results showed that failure occurred at loads lower than those predicted. Matrix cracks, observed in the testing, were introduced into the model and interface elements were used to model the delamination development. This approach gave good correlation to the behaviour observed in the tests. Even in the specimens apparently dominated by fibre failure, delamination was shown to be significant.

Keywords: B. Strength; C. Delamination; C. Transverse cracking; C. Finite element analysis

1. Introduction

The question of damage and failure in composites is one which has received considerable attention in the literature. The world wide failure exercise of Hinton, Kaddour and Soden [1] has collated and benchmarked many of the failure criteria which are in common use. Stress based criteria are however generally not able to predict failure taking into account specimen layup and size. In addition to the many laminate based criteria there exist other techniques for the prediction of individual failure modes, taking account of their progressive effects on the laminate behaviour. One of the most significant single failure modes is delamination since its presence can cause a reduction in the compressive strength of a laminate. Techniques for predicting delamination failure include the virtual crack closure technique (VCCT) [2] and the cohesive zone or interface element technique. The use of interface elements is growing in acceptance as shown for example by the implementation of the formulation of Camanho et al. [3] in version 6.5 of the commercial finite element software ABAQUS and that of Hellweg [4] in the LUSAS finite element software. Many other formulations have also been presented in the literature (e.g. Allix and Ladeveze [5] and Borg et al. [6]). Both VCCT and interface elements have successfully been applied to the case of delaminations arising from a free edge in composite materials [7,8].

The failure process is further complicated by the presence of matrix cracks which often occur at stress levels below those which cause delamination. There is some consideration of the effects of interaction between matrix cracks and delamination in the literature but this is generally limited to that occurring at the micro or meso scale. Ladeveze et al. [9] take account of the effect of matrix cracking on delamination by modifying the respective damage parameters in a model in which the matrix cracking is considered as distributed throughout the continuum. Salpekar et al. [10] have considered delamination growing at the intersection of a matrix crack and a free edge in an

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angle ply laminate using VCCT. This more closely resembles the situation observed experimentally here but concentrates on the growth of the delamination rather than its overall effect on the laminate. Work by Noh and Whitcomb [11] also examines the interaction between matrix cracks and delaminations using VCCT. Another study which combines the effect of matrix cracks and delaminations is that of Akoi et al. [12] which uses interface elements to predict delaminations arising from matrix cracks during out of plane impact to flat plates.

Here a series of tensile tests on carbon/epoxy specimens manufactured from uni-directional pre-preg tape are presented. The layup was selected after analysis using VCCT so as to minimise edge delamination. In order to examine the already well documented size effect [13] for this particular layup and material, tensile tests on specimens with dimensions scaled in all directions were carried out. In all cases the specimens failed at strains below that predicted by the VCCT analysis leading one to expect that the failures would not show any delaminations. This however was not the case, especially for the larger specimens which showed extensive delamination back to the grips before fibre failure. Observation of the specimens during the test and examination of the failed specimens showed the existence of matrix cracks and progressive delamination development. It was felt necessary to include this in the analysis in order to achieve good correlation. The interface element formulation presented by Jiang et al. [14] was adopted to model the progressive delamination and investigate its interaction with matrix cracks which were included in the model from experimental observations.

2. Experimental programme

An experimental programme has been carried out on unnotched carbon/epoxy composite specimens (Hexply IM7/8552) scaled in all dimensions by up to a factor of 8 and tested in tension at quasi-static rates of strain. Scaling in the thickness direction has been achieved by increasing the ply thickness as opposed to sublaminate level scaling which is perhaps more commonly used. This gives layups of $[45_m/90_m/-45_m/0_m]_s$ where m is number of plies blocked together and also the scaling factor. The stacking sequence was chosen such that it gave the quasi-isotropic laminate least likely to delaminate from the free edge whilst still maintaining a 45° ply on the surface as is consistent with industrial practice. This was calculated prior to the experimental programme using the virtual crack closure technique (VCCT) as described in the following section. Table 1 gives specimen dimensions for each of the scaling factors tested as well as mean stress levels (calculated from nominal thickness) for the different failure mechanisms observed.

In the baseline or $m = 1$ case no matrix cracking or delamination could be observed during the loading of the specimens before ultimate failure occurred by fibre fracture at a mean stress of 842 MPa for the 11 specimens tested. Fig. 1a shows a typical failed specimen. Post failure examination by dye penetrant testing (Ardrox 9812) of the specimen in a region away from the fracture location revealed the existence of matrix cracks in the 45° surface ply and delamination at the 45/90 interface (Fig. 1b) which is believed to have occurred during specimen loading. It is difficult to present this as incontrovertible evidence that

Table 1
Different failure events in ply level scaled specimens (failure stress shown in bold)

Case	Lay-up	No. of tests	Gauge length (mm)	Width (mm)	45°/90° delam. stress (MPa)	C.V. (%)	−45°/0° delam stress (MPa)	C.V.(%)	Fibre failure stress (MPa)	C.V. (%)
$m = 1$	$(45/90/-45/0)_S$	11	30	8	–		–		**842**	7.6
$m = 2$	$(45_2/90_2/-45_2/0_2)_S$	8	60	16	418	13.8	–		**660**	3.3
$m = 4$	$(45_4/90_4/-45_4/0_4)_S$	11	120	32	316	11.4	**458**	5.8	541	5.2
$m = 8$	$(45_8/90_8/-45_8/0_8)_S$	10	240	64	222	10.3	**321**	2.9	458	7.2

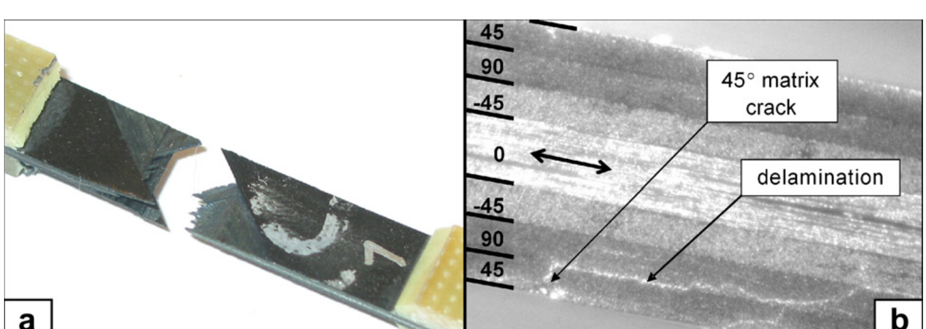

Fig. 1. (a) Failed specimen (scaling factor, $m = 1$) and (b) detail of failed specimen edge.