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Compressive failure of laminates containing an embedded wrinkle; experimental and numerical study

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ABSTRACT

An experimental and numerical study has been carried out to understand and predict the compressive failure performance of quasi-isotropic carbon–epoxy laminates with out-of-plane wrinkle defects. Test coupons with artificially induced fibre-wrinkling of varied severity were manufactured and tested. The wrinkles were seen to significantly reduce the pristine compressive strength of the laminates. High-speed video of the gauge section was taken during the test, which showed extensive damage localisation in the wrinkle region. 3D finite element (FE) simulations were carried out in Abaqus/Explicit with continuum damage and cohesive zone models incorporated to predict failure. The FE analyses captured the locations of damage and failure stress levels very well for a range of different wrinkle configurations. At lower wrinkle severities, the analyses predicted a failure mode of compressive fibre-failure, which changed to delamination at higher wrinkle angles. This was confirmed by the tests.

1. Introduction

The influence of manufacturing defects in laminated composites is an active area of research ([1,2]) due to their detrimental effect of final part quality. The most commonly found defects include voidage/porosity, in and out-of-plane fibre misalignment, local variations in fibre-volume fraction, fibre-resin debonds, etc. Under mechanical loading, the overall failure of a structure is significantly influenced by the presence of such defects. Hence, it is crucial to accurately estimate the role of defects on the mechanical performance of composite structures in order to have a damage tolerant design. Out-of-plane misalignment of fibres is a type of defect also known as “wrinkling” [3]. Wrinkles are very commonly found in thick section components or curved composite parts as localised band of wavy fibres through-the-thickness. Geometric parameters such as amplitude, wavelength and waviness angle [4] are used to quantify the severity of the wrinkle. An example of a wrinkle defect occurring in a curved composite part is shown in Fig. 1(a).

The presence of wrinkles is known to reduce the compressive strength of composites [4–8]. Adams and Hyer [4] performed static compression tests on symmetric cross-ply laminates containing artificially produced embedded wrinkles of varied severity. For high-severity wrinkles, failure was found to be localised in the region of the wave. They found a reduction of compressive strength as high as 36% compared to pristine laminates. Post-test visual inspection revealed extensive through-the-thickness matrix cracking and delamination between plies in the failed specimens. Wisnom and Atkinson [9] carried out tests and FE analysis of compressive failure of unidirectional laminates with artificially induced waviness. They found from the analysis that fibre failure was triggered in the region of maximum misalignment and this was due to shear instability rather than the well-known classical compressive instability. It was also noticed that the shear instability was essentially due to the shear non-linearity in the material response. Bradley et al. [5] studied interlaminar strain localisation and compressive failure in two different types of wrinkle formation, namely a single wavy layer and three nested wavy layers located along the middle of cross-ply laminates. High normal and shear strains in the region of wrinkles were found using optical interferometry. The nested layer waves were seen to be approximately three times more severe in causing failure compared to the single layer wave. The predicted failures from FE models were less accurate when compared with test results. The authors concluded that simple stress based failure criteria may not be accurate in this case and identified the need for an improved formulation for failure prediction. Following the experimental work by Wang et al. [8] to assess compressive failure in laminates containing waviness induced by ply-drops, Lemanski et al. [6] did a numerical study with the same test configurations. The damage in the plies was approximated by a perfectly-plastic response while delamination between plies was modelled using cohesive elements in a 2D plane-stress framework. The test failure loads and the locations

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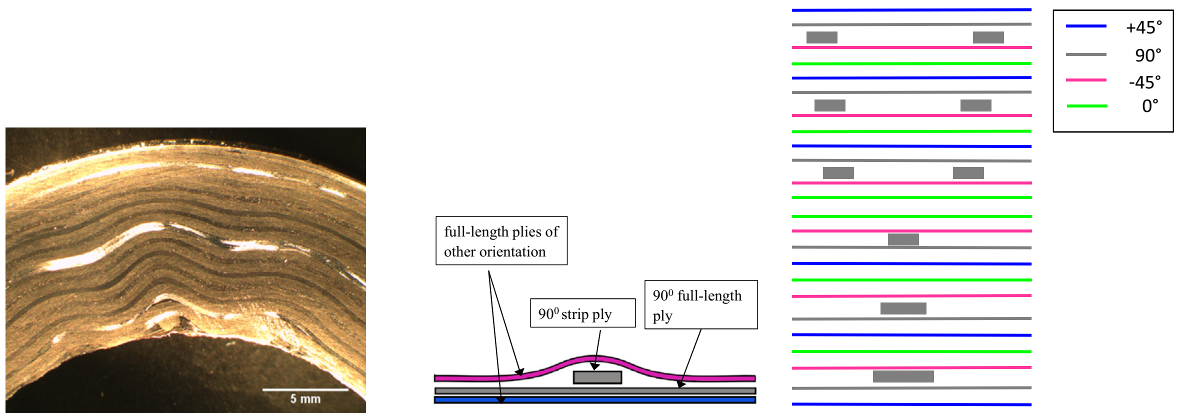

(a) (b)

Fig. 1. (a) Wrinkle formation in a curved composite part. (b) Lay-up profile of the laminate showing the location of inserted strips. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of damage in the failed test specimen compared well with the model results. However, it was acknowledged that 3D failure criteria for CFRP instead of a simple elastic–plastic material model may provide more accurate predictions in a general loading scenario. Leong et al. [7] investigated compression failure in GFRP sandwich structures with wrinkles present in the face-sheet of sandwich panels. The damage initiated as a debonding between the face-sheet and core, localised at the wrinkle, which was followed by delamination in the face-sheet. The DIC strain contours near the wrinkle compared well with their FE analysis. The local failure initiation stresses predicted in the model by the Northwestern University (NU) criterion [10] correlated well with the tests. However, in absence of a progressive failure criterion, the global failure could not be successfully captured.

In the present work, a quasi-isotropic layup was chosen for study as this was more representative of layups used in industrial practice. Compared to uni-directional and cross-ply laminates, the compression failure behaviour in this case was more complex due to multiple active damage mechanisms and their interaction. Instead of visually inspecting the failed specimens to find out the failure modes, the progressive damage in the laminates was monitored by recording images at a very high frame rate during tests using a high-speed video camera. The information obtained from the tests was used to implement three-dimensional failure criteria at the inter-ply and intra-ply levels in a finite element framework. The FE results successfully captured the initiation of multiple interacting damage modes near the wrinkle and the progressive failure behaviour, which resulted in accurate prediction of failure stress levels. Previous work by the authors has looked at tensile loading of similar specimens [11] and here the experiments and models have been extended to compressive loading and predictions. The organisation of the paper is as follows: In Section 2, techniques for manufacturing and testing laminates containing artificially induced wrinkles of controlled severity are briefly described. The three dimensional FE models with the damage formulations are presented in Section 3. Section 4 discusses the findings from the tests and the results obtained from the models drawing a comparison between the two. Finally, in Section 5 conclusions are drawn based on the above study.

2. Experimental techniques

2.1. Wrinkle coupon manufacture

Hexcel's IM7/8552 pre-preg tape with a nominal cured ply thickness 0.125 mm was hand-laid to make quasi-isotropic ($[+45_2/90_2/-45_2/0_2]_{3s}$) compression test specimens with embedded wrinkles. The specimen dimensions were 110 mm × 3 0 mm × 6 mm with a 30 mm gauge length after tabbing. Test specimens of the same dimensions, free of any wrinkle, were also manufactured to serve as a reference against which the wrinkle containing coupons were compared for compressive strength reduction. During the lay-up process, narrow 90° ply strips were introduced on already laid-up full-length 90° plies in certain locations which intentionally induced out-of-plane fibre wrinkle formation [8,11]. The severity of the wrinkle can be controlled by varying the width and thickness of the inserted strips (see Fig. 1(b)). Three distinct levels of wrinkle severities were produced by this method. Those were named level#1, level#2 and level#3 respectively, with a higher number representing a higher wrinkle angle. Eight test coupons for each of the three severity levels were manufactured. The wrinkle severities were estimated by taking images of the wavy-sections in the coupons and measuring the angle that a tangent drawn at a wavy ply made with a straight reference ply (see Fig. 2(a)). The average of the measured waviness angles for the level#1, 2 and 3 specimens were 5.6°, 9.9° and 11.4° respectively.

2.2. Compression testing

Uniaxial compression tests were performed on the coupons using the Imperial College compression test fixture [12] (see Fig. 2(b)) in a servo-hydraulic machine of 250 kN capacity at a constant loading rate of 0.25 mm/min. Although no anti-buckling guides were used during the tests, preliminary FE analyses were carried out to confirm that the cross-sectional stress required to initiate buckling was higher than the mean compressive strength of the wrinkle-free baseline specimens. Because compressive failure is sudden and catastrophic in nature, a Photron SA-1 high-speed video camera was used to better understand the sequence of failure events. The camera was aimed at the edge of the gauge section during the test and used to take pictures at a frame rate of ~70,000 frames/s. The load–displacement response as well as the data obtained from the video camera were later analysed to identify the initiation and interaction of different damage mechanisms.

3. Finite element modelling

3.1. Mesh generation

3D FE models of the laminates were built in Abaqus/Explicit [13]. Progressive failure behaviour was included in the models