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

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ABSTRACT

The failure of a quasi-isotropic composite laminate containing an embedded out-of-plane fibre wrinkle defect was investigated under tension loading. Laboratory test specimens with controlled severity of fibre waviness were manufactured. Along with recording load–displacement data, high resolution camera images were taken at regular intervals which monitored the initiation and interaction of different damage mechanisms during test. Three-dimensional FE models were built following the geometry of actual test specimens. The information obtained from the tests was used to develop user material subroutines, implemented in Abaqus/Explicit as continuum damage and cohesive zone models for intra- and inter-ply failure respectively. The results of the simulations showed very good correlation with test observations in terms of failure load, location of damage initiation and interaction between different damage mechanisms for a range of waviness cases tested.

1. Introduction

Composite materials are increasingly being used to manufacture structural parts in the aerospace and automotive sectors for the advantages they provide in terms of weight saving, ability to tailor stiffness in safety-critical regions, good energy absorption capacity etc. One key challenge that limits their use is the presence of various process-induced defects [1]. These defects typically act as sites of potential failure initiation in composite laminates and reduce their load bearing capacity. Out-of-plane fibre waviness or 'wrinkling' is one such defect which typically is found in thick section composite structures. Wrinkles are identified by the fibre-misalignment through-the-thickness of the laminate resulting in localised wavy regions (Fig. 1(a)). Following [2], the geometry of a typical wrinkle is described by three parameters δ, λ and θ which are respectively the amplitude, wavelength and waviness angle of the defect (Fig. 1(b)) The reasons behind wrinkle formation is still an active area of research as the mechanisms are many and varied. For example, the wrapping of pre-preg tapes around drums for storage causes a difference in path-length between the outside and inside surface of the pre-preg, promoting fibre wrinkling [1], or Automated Fibre Placement (AFP) laying heads turning on small radii will cause fibres to buckle out-of-plane [3]. Recently Lightfoot et al. [4] suggested a new mechanism of wrinkle generation in multidirectional laminates laid on curved radii, due to generation of relative shear forces between the stiff and compliant ply orientations during consolidation.

Tensile failure of composite laminates containing wrinkle has been previously studied by El-Hajjar and Petersen, Bloom et al. and Makeev et al. [5–7]. Steel rods of different diameter were used by El-Hajjar and Petersen [5] to artificially induce waviness in unidirectional and multidirectional carbon–epoxy tests. In multidirectional laminates, they noted delamination and internal ply failures caused a small drop in load–displacement response much earlier than the final failure by tensile fibre fracture. Intermittent images were taken to observe damage evolution at the gauge section. Analytically, the axial stiffness of the specimens was predicted using lamination theory and by approximating the waviness using a Gaussian function. Bloom et al. [6] used the technique of fitting slightly oversized plies to a mould to generate artificial wrinkling in unidirectional and woven glass–epoxy composites. The strain distribution on the surface of the specimens near the wrinkle was measured using Digital Image Correlation (DIC) and video gauge techniques. In both composite systems, the final failure was found to be fibre fracture due to high tensile strain concentration in the wrinkle, which also caused subsequent delamination between plies. Simple design guidelines, which related the failure stress to the volume of wrinkled plies in the laminate, gave a significant over prediction of the knockdown levels. They concluded that a detailed 3D finite element analysis might be necessary for this problem due to the complex failure mechanisms and their

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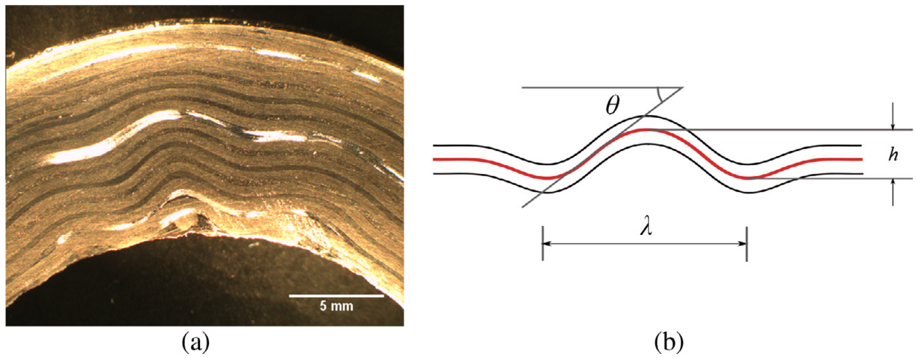

Fig. 1. (a) Wrinkled plies in a curved composite part. (b) Geometric parameters associated with a wrinkle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

interaction. Makeev et al. [7] tested thick-section carbon–epoxy multidirectional tape laminates with different grades of wrinkle severity. DIC was used to measure strain in components during loading until complete failure. Plane stress Finite Element (FE) models were built with nonlinearity in the interlaminar shear stress–strain relationship incorporated in the model. Failure initiation was predicted using maximum interlaminar tensile stress criteria and Hashin mixed-mode criteria. They found that including the nonlinear shear behaviour in the model was essential to get correct prediction of failure load. They were also able to predict delamination initiation in the location of the wrinkle, which was experimentally confirmed. The flexural strength of carbon–epoxy unidirectional laminates containing a wrinkle was studied by Potter et al. [8]. Under four point bend loading a strength reduction of as much as 70% of pristine value was reported for samples appearing to fail on the tensile surface.

The work presented in this paper builds on previous work to be found in the literature and offers an improved predictive capability for failure of wrinkled laminates under tension, by particularly taking into account both intra and inter-laminar damage modes and their interaction in a 3D finite element framework. The organization is as follows: In Section 2 the experimental methods for manufacturing and testing wrinkle specimens are described. In Section 3 the FE modelling strategy is introduced, which also outlines the formulations of different damage models used. In Section 4, the results of the test and model are presented along with a detailed comparison between the two. Finally in Section 5, conclusions are drawn based on the above study.

2. Experimental procedures

2.1. Wrinkle specimen manufacture

Commercially available (Hexcel Composites Ltd) IM7/8552 pre-preg tapes with 0.125 mm nominal cured ply thickness were laid up by hand to make a quasi-isotropic ($[+45_2/90_2/-45_2/0_2]_{3s}$) laminate. The test specimen dimensions were 250 mm × 30 mm × 6 mm with a gauge length of 150 mm after tabbing. Wrinkle-free baseline specimens with the same dimensions were also manufactured for comparison of failure load. Out-of-plane fibre waviness was created in the central region by inserting thin 90° ply strips adjacent to the full-length 90° plies in certain locations through the thickness of the laminate (Fig. 2(a) and (b)). Although during the natural process of wrinkle defect formation, usually neat resin fills the gap around the wavy fibres, it was difficult to recreate the same effect when inducing a wrinkle artificially. In place of neat resin, the use of 90° strip plies can be justified by the fact that, these plies being completely orthogonal to the loading direction, their behaviour was

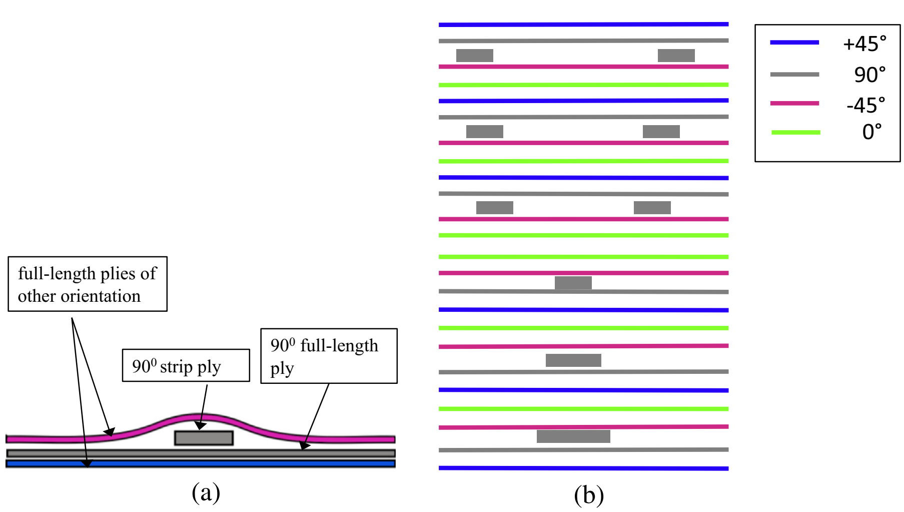

Fig. 2. (a) Artificially inducing waviness using the strip-insertion method. (b) Lay-up profile of the laminate showing the location of inserted strips. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)