Composite Structures 203 (2018) 50–59

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Finite element analysis of initial imperfection effects on kinking failure of unidirectional glass fiber-reinforced polymer composites

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ARTICLE INFO

Keywords:
Kinking failure
Birth-and-death method
Finite element
Fiber microbuckling
Initial imperfections

ABSTRACT

The compressive kinking behavior of non-slender unidirectional glass fiber-reinforced polymer (GFRP) specimens has been analyzed by finite element (FE) models. The experimentally observed imperfections, including the initial fiber waviness throughout the entire specimen volume and the scattered resin/interface defects, were taken into account in the FE models. The birth-and-death method was employed to simulate the progressive damage to the material. The consideration of the coexistence of initial fiber waviness and initial resin/interface defects was found to be essential for accurate modeling of the kinking failure process. Kinking was initiated due to the disproportional increase of the fiber microbuckling at the locations of initial defects. The numerically obtained peak load, fiber microbuckling amplitudes, kink band angle and width, and compressive strain concentrations at the kink band edges were well predicted compared to the experimental results. The number of defects was less significant than the fact that defects existed that served as initiation points of the kink band formation.

1. Introduction

The kinking failure of unidirectional glass fiber-reinforced polymer (GFRP) composites is primarily caused by disproportional fiber microbuckling, as for instance experimentally observed in Ref. [1], to which this paper refers to. Finite element (FE) analysis can increase the understanding of such complex failure mechanisms since the individual composite components (fibers, resin and interfaces) can be modeled and their deformation on the micro-scale can be obtained, something that cannot be easily observed during experiments.

For the prediction of compressive failure mechanisms, i.e. kinking or delamination, FE models have been proposed in the literature on the macro-scale (multilayer models) and micro-scale (micromechanical models). Multilayer approaches [2–9] model each lamina of the laminate as a separate layer consisting of specific categories of elements, such as shell [2], brick [3,4] solid [5] or truss elements [8]. Individual fibers, resin, interfaces, and initial imperfections, such as initial fiber waviness or resin/interface defects caused by voids for example, existing in each lamina, are normally not modeled separately. Additional layers to take into account the interface material with a user-defined strength were however implemented for the simulation of delamination failures, e.g. in [6]. Element failure detection was based on a user-defined failure criterion, and when failure occurred the stiffness of the failed elements was reduced to a certain extent, e.g. 10% of the original value [3]. The models were then updated by assuming the deteriorated element properties, and an iterative process was followed until the compressive failure of the whole laminate occurred [6]. These models have been applied for the prediction of the compressive failure of various composites, such as notched multidirectional carbon fiber-reinforced epoxy laminated panels [2], carbon fiber-reinforced composite laminates with an open hole in the center [3], and laminates without any initial artificially drilled holes or cracks [6,7]. The success of the multilayer models mainly laid in the prediction of the failure load, initial slopes on the load-displacement curve, and the failure area. The mechanisms behind the compressive failure, such as the disproportional fiber deformation, or the failure modes affected by the initial imperfections, were beyond the prediction capacity of these models.

Micromechanical models were established based on the assumption that the global behavior of a composite specimen can be simulated by a representative volume element (RVE), comprising in this case a fraction of the fibers and resin surrounding these fibers. According to the micromechanical models, deformation and failure of the volume element are representative of the deformation and failure of the entire composite [10–18]. For unidirectional fiber composites, periodic boundary conditions can be applied [11] assuming that all fibers throughout the specimen volume deform proportionally to the fibers of the representative volume element. Different numbers of fibers were used for the definition of the RVEs in different models, as few as two to four

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https://doi.org/10.1016/j.compstruct.2018.07.010
Received 9 March 2018; Received in revised form 28 June 2018; Accepted 2 July 2018
Available online 04 July 2018
0263-8223/

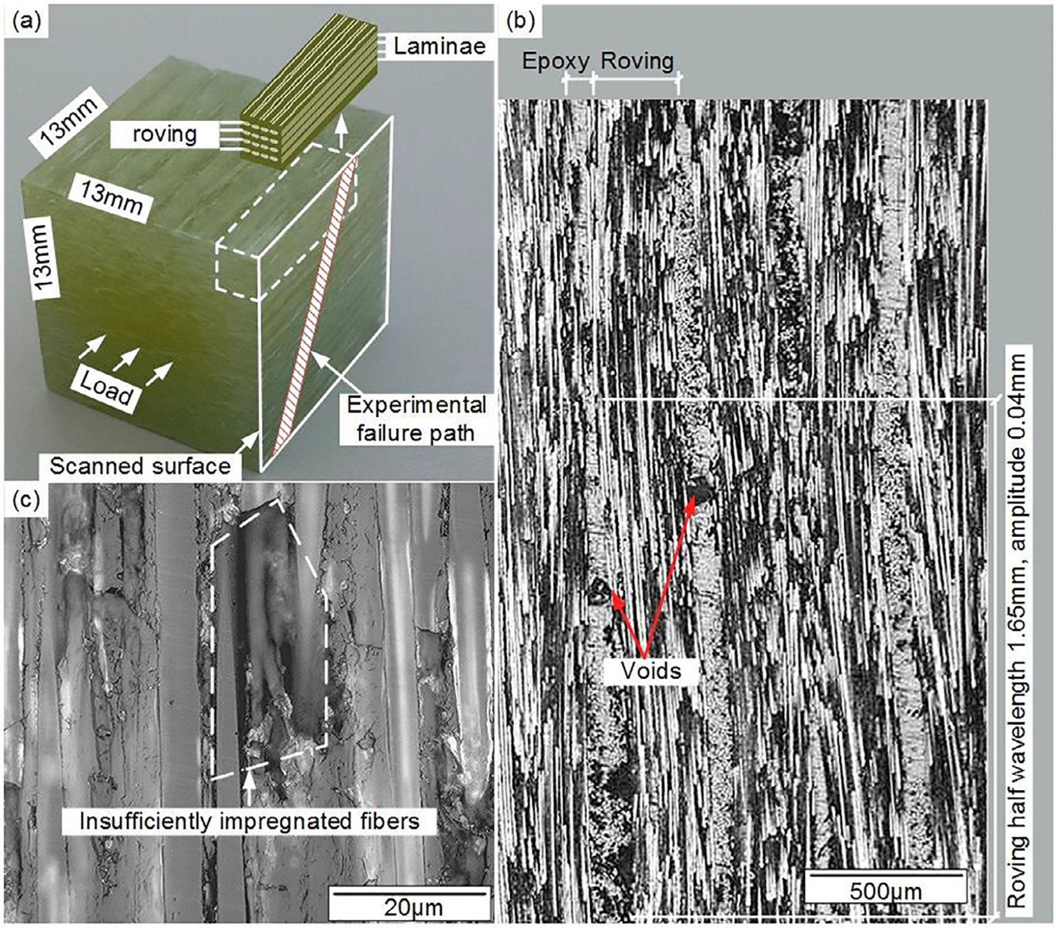

Fig. 1. (a) Specimen for optical microscopy, (b) fiber waviness and voids between rovings, (c) voids inside roving [1].

single fibers [11,12], and up to as many as 40 e.g. [13]. The micromechanical models were established in either two dimensions [11,14] or three dimensions [12,13]. 2-D models with periodic boundary conditions could only be used for the prediction of the failure of specimens demonstrating uniform fiber deformation across the cross section, such as buckling failure. 3-D model predictions can theoretically predict the failure of materials showing non-uniform deformation [16]. However, the prediction, limited by the scale of the RVE, could provide an assessment of the global failure propagation path across the entire width/height of the composite concerned [13]. Moreover, experimental validation of the micromechanical model predictions is lacking in several works in the literature [13,17,18].

The above-mentioned literature review shows that both multilayer and micromechanical models comprise inherent drawbacks due to their basic assumptions. The multilayer models are not capable of considering initial imperfections, including initial fiber waviness and defects and therefore cannot predict the failure modes related to these imperfections. The micromechanical models, due to the limited size of the RVE, cannot predict the failure propagation on a macroscopic scale. New FE models are thus presented in this work for simulation of the kinking failure of glass fiber-reinforced polymer composites. The new models were established in such a way that they incorporate both the simplicity of the multilayer models and the precision of the micromechanical models. Initial imperfections, including fiber waviness and initial defects (e.g. voids) are implemented in the models. The numerically estimated failure mode, peak load, fiber microbuckling development and strain fields are compared to the experimental results obtained in Ref. [1]. The effect of initial imperfections on the kinking failure formation is thoroughly investigated.

2. Finite element models

2.1. Experimental results summary

Prismatic non-slender specimens with nominal dimensions of $12.7 \times 12.7 \times 50\,mm^3$ according to ASTM D695-10 [19] were cut from a fully cured GFRP unidirectional laminate and subjected to axial compression [1]. The quasi-static experiments were performed at different temperatures at a displacement rate of 0.5 mm/min. The specimen displacements were recorded by monitoring the movement of the machine loading head and by a digital image correlation (DIC) system. At a temperature of 90 °C (still below the glass transition temperature), a clear and typical kinking failure occurred.

The microstructure of the laminate was examined using an optical scanning microscope with a specimen of dimensions $13 \times 13 \times 13\,mm^3$, see Fig. 1(a). The scanned surface, on which the experimental kinking failure path was observed, was perpendicular to the lamina plane and its microstructure is shown in Fig. 1(b) and (c). As shown in Fig. 1(b), the fiber bundles were not perfectly straight and exhibited initial imperfections with average wavelengths and amplitudes of 3.23 ± 0.17 mm and 0.036 ± 0.003 mm respectively [1]. Voids, created by trapped air and insufficient impregnation of individual fibers during the hand lay-up fabrication, were also observed in the epoxy resin near the rovings, see Fig. 1(c). Both the fiber waviness and the voids inside and between the fiber bundles may represent locations for failure initiation under the applied compressive load.