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Finite element guidelines for simulation of fibre-tension dominated failures in composite materials validated by case studies

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ABSTRACT

This paper presents a finite element modelling methodology to predict the initiation and damage progression in notched composite laminated plates subjected to increasing in-plane tension load. An important feature of the methodology is it does not rely on customized user-subroutines but solely on the analysis capabilities of the general purpose software Abaqus; thus ensuring that the numerical results can be universally reproduced. The methodology presented copes with intralaminar failure modes and uses the Hashin failure criterion to predict the onset of failure (cracking). To account for damage progression after crack initiation there is a fracture energy calculated for each of four failure modes. Four open-hole laminated plates taken from the literature are used for benchmark examples. The predicted ultimate strength based on the analytically-obtained stress-displacement curve was found to be within 10% of the experimental observations. To study the influence of the interaction of having two or three holes across the mid-plane of a pultruded open-hole tension specimen, a parametric study was carried out. The paper ends giving guidelines for the generalized modelling methodology using Abaqus without user-subroutines.

1. Introduction

Composite structures of fibre reinforced laminae that are commonly found in aerospace, automotive and civil engineering applications exhibit a distinctively nonlinear behaviour when deformed to ultimate failure. This nonlinearity arises in various ways. The heterogeneous nature of the laminae, which consists of fibres of one material (usually carbon or glass) in a matrix of another (typically a polymer resin), makes the mechanical behaviour complex. The constitutive stress–strain response has directionally dependent properties and the failure behaviour is typically brittle in nature. In addition, since many composite structures consist of flat or curved thin plate elements, they are likely to undergo large deflections.

The description of real composite behaviour is a challenge, either using experimental procedures, or numerical methods. In this respect, virtual tests of composite materials carried out by means of numerical modelling are increasingly replacing some mechanical and physical tests to predict and substantiate structural performance and integrity. Computational advances in fracture modelling, especially the improvement of cohesive models of fracture and the formulation of hybrid stress–strain and traction-displacement models that combine continuum and discrete material damage representations in a single calculation, for example, make such a virtual approach realistic.

Finite element simulations can be performed at any scale level of the structural composite. Fig. 1 illustrates the cross-section of a laminate having unidirectional laminae (or plies, or layers) modelled at three different scales: (i) microscale (constitutive modelling of fibre and matrix), (ii) mesoscale (lamina level as a multiphase homogenized material), (iii) macroscale (laminate modelled as a series of stacked unidirectional laminae). In this paper, modelling is performed at the mesoscale at which the lamina is considered to be a homogeneous continuum. In other words, the material is homogenized by smearing the behaviour of the fibres and the matrix over a single lamina.

In order to obtain meaningful and reliable finite element simulations, analyses must account for different failure (or damage) processes and their progression and interaction. Cracking of the matrix parallel to the fibres may occur, as well as fracture of the fibres in tension and kinking or buckling of the fibres in compression, possibly accompanied by debonding at the fibre–matrix

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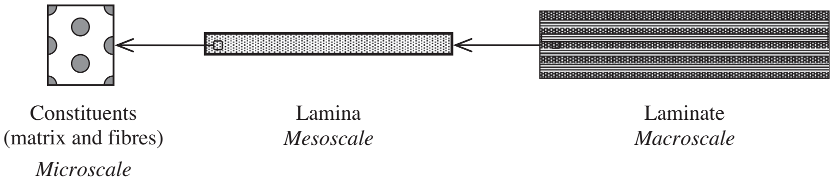

Fig. 1. Modelling scales for laminates.

interface. Matrix failure can be classified as delamination failure when it occurs between adjacent laminae. Early matrix cracks and delamination at free edges are mainly caused by the low transverse stiffness, and the mismatch of the Poisson's ratios between layers with different fibre orientations. Matrix-dominated processes correspond to the onset of damage in most composite designs, but do necessarily lead to loss of structural integrity. Further load can be accommodated due to stress redistribution in the laminate. This introduces the concept of progressive failure (or damage) of the composite material. In this framework, the numerical models presented here are based on critical stress and/or strain combinations that trigger damage initiation, and critical energy release rates or damage mechanics considerations that describe damage propagation. As this process progresses from meso- and macroscale to a large composite structure, the result is a continued weakening of the entire structure, up to the point where the structure can no longer carry additional load. This process is highly nonlinear as it degrades the ply and the laminate stiffness and extends beyond failure initiation.

Current state-of-the-art for computational modelling of progressive failure of composites is based almost exclusively on composite architectures found in aerospace and automotive applications (so-called *advanced composites*). This research work quantifies the state-of-the-art for materials produced by the pultrusion method, which are generally used in civil and infrastructural applications. The intent is therefore to enable and support the development of structural design guidelines. Pultruded shapes are different to thin-walled advanced composite structures in so far as they are typically prismatic, have relatively thicker component plates, and typically have lengths in the direction of pultrusion at least an order of magnitude greater than the section dimension. Indeed, Turvey and Wang [1] reported that methods of analysis appropriate for aerospace composites are "not suitable" for pultruded plates typical of infrastructure applications. They appear to attribute the inappropriateness of the methods to the more variable nature of infrastructure materials.

In civil applications, the matrix typically consists of a thermoset resin (e.g. polyester or vinylester) and additives (e.g., for colour, fire resistance, etc.). E-glass unidirectional rovings and continuous filament mats are used for the reinforcement, with an overall volume fraction typically between 30% and 50%. The fibres in the continuous filament mats are long, swirl and are randomly oriented in the plane. It is assumed the mats represent a layer with isotropic in-plane mechanical properties.

As the motivation increases to use pultruded shapes in construction, researchers are urged to investigate the sensitivity of these materials to damage, and to characterize the various mechanisms that govern the onset and progression of damage, leading to ultimate failure. There are a number of sources of initial damage, the most relevant being delamination and notches. Through-thickness holes – effectively notches – are drilled to mechanically fasten parts in the structure. The introduction of notches leads to stress concentrations in the composite material that cannot be redistributed by plastic flow, as would be the case if the material possessed inherent ductility. Designers need to know whether damage will develop and propagate under loading in the presence of the stress-raiser in order to assess structural integrity. There are a variety of theories and numerical implementations with respect to the modelling of progressive damage and failure in advanced composites. In the present research, the smeared crack approach will be adopted which, when properly implemented, ensures a large degree of objectivity with respect to finite element discretization and requires little or no modification to standard commercial finite element codes, such as Abaqus [2]. This latter aspect is particularly relevant to practising engineers concerned with virtual testing related to structural integrity and damage tolerance of fibre reinforced polymers for safety–critical structures.

2. Failure analysis in the context of the finite element method

The numerical modelling of composite structures in the elastic range is quite straightforward. However, the nature of failure initiation and progression to rupture, involving matrix, fibre and/or interface damage and fracture, makes full behaviour analysis rather complex. External loads are predominantly carried by axial forces in the fibres, and the failure process is driven by the energy released as these are unloaded after fracture. Matrix-dominated failure mechanisms, in the form of cracks and delaminations joining-up to produce a fracture surface, occur without necessarily having to break fibres.

Typical constitutive behaviour is characterized by an initial linear response followed by a second nonlinear response having reduced stiffness that results from the formation of micro-cracks in the vicinity of the crack tip. The strain energy accumulated in the material is released at the peak-load and a stable crack propagates progressively with a reduction in strength and stiffness until eventual failure. This is a typical quasi-brittle behaviour, although most polymer-based matrices can deform plastically before damage when subjected to shear loading. This progressive damage modelling is carried out in three steps [3]:

1. Stress analysis by finite element modelling and simulations: the geometry of the structure, load history and initial boundary conditions being known, the fields of stress and strain are calculated by means of strain constitutive equations and a numerical procedure.
2. Failure criterion or criteria: the most critical location(s) with regard to fracture is (are) determined and, the load corresponding to this macro-crack initiation is calculated by integration of damage constitutive equations for the history of local stress or strain.
3. Degradation of material/laminate properties based on damage progression models to calculate the evolution of the critical macro-crack(s) up to final rupture of the whole structure.

This section reviews the main features for the finite element modelling of intralaminar failure in a laminated plate. Some of the key concepts are considered first, including the element types and the material parameters. The mechanisms by which laminates may fail are then discussed. The different approaches for the