Important Issues in Modelling the Response and Failure of Fibre-Reinforced Composites

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Abstract

This presentation considers how to successfully model the response and failure of composites. Some of the key differences compared with metals are presented, including the orthotropic properties and non-linear response, the importance of delamination and capturing the correct failure mechanisms. Size effects and failure criteria are also discussed briefly.

1. Material Properties

Composite materials are orthotropic, and accurate specification of properties is clearly important. It is not always appreciated that carbon fibre composites show considerable nonlinearity in the fibre direction. Fig. 1 shows typical stress strain curves, with a stiffening response in tension and softening in compression. This can be fitted with a polynomial and the effective modulus determined. The differences are relatively small at low strains, but at high compressive strain the tangent modulus can be reduced by as much as 50%, which can make a large difference to buckling calculations [1]. Glass fibre composites are linear elastic in the fibre direction. Polymer fibres such as Kevlar or Zylon are highly non-linear in compression.

Polymer matrix composites are also highly nonlinear in shear. The response is visco-elastic and rate dependent, and can make a large difference in the response of unidirectional or cross-ply materials. However, where there are 45° plies such as in typical quasi-isotropic layups, the effect of shear non-linearity is small.

Through-thickness properties are required for 3D FEA, and often are not supplied by the manufacturer. Transverse isotropy is a reasonable assumption, whereby the properties in the through-thickness direction are assumed to be the same as the in-plane transverse properties.

Great care is needed in correctly defining the material orientations. This is done in different ways in different programs, and must be understood and checked, as it is a common source of errors.

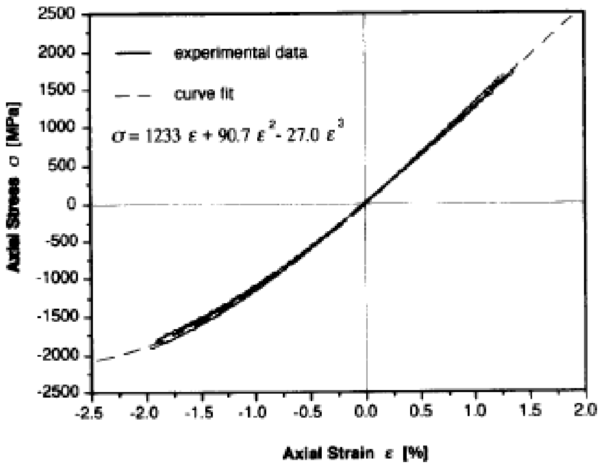

Figure 1: Nonlinear response of high strength carbon/epoxy [1]

Equivalent homogeneous properties may be calculated from ply properties by laminated plate theory, and can be useful, especially for large models with many plies. This generally gives good results for stiffness, displacements, natural frequencies, load paths and overall stresses, but the assumption is not always valid. Neglecting heterogeneity may miss crucial aspects of behaviour such as the effects of non-symmetry and coupling, residual stresses or discontinuities such as free edges and ply drops.

2. Delamination and Failure

Delamination is the Achilles heel of composite structures. Unexpected failures often occur due to out-of-plane stresses and low through-thickness strength. Delamination may be caused by out-of-plane loads, geometrical features such as tapers and curved sections and discontinuities such as free edges [2], and cannot be modelled with standard shell elements.

Delamination can also be crucial for in-plane failure. For example, a ±45° laminate loaded in tension usually fails not by fibre failure, but by transverse cracks linked up by delamination, as shown in Fig. 2. Standard shell models are unable to simulate this pull-out behaviour, and even complex 3D models will not give satisfactory results unless they include an energy-based delamination model.

There are many different failure criteria for composites, and there is no consensus about which is best, so results should be treated with caution. Composites also exhibit size effects where the strength tends to decrease with increasing volume of stressed material. Approaches based on Weibull statistics are available to model this phenomenon, e.g. [3], or it can be included by choosing appropriate strength values that take account of the size effect.

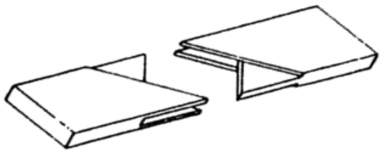

Figure 2: Failure of angle-ply laminate in tension by delamination and pull-out

3. Modelling Discrete Failures

Homogenised models and approaches based on continuum damage mechanics can be useful for analysing overall behaviour, but are not able to represent accurately the discrete failures due to splitting and delamination which are often important in controlling failure. Cohesive zone interface elements are a powerful way of modelling such behaviour, enabling good simulations of a wide range of different cases [4]. They can be thought of as non-linear springs between the plies, which have a stress criterion for failure initiation, and a fracture energy criterion for propagation. Cohesive elements can be included at every ply interface where delamination may occur, or at a subset of interfaces in a large model or where there are critical locations of interest.

Matrix cracks and splits may also be represented with interface elements in the plane of the model at critical locations or regularly placed throughout. There are now more sophisticated extended FE approaches to insert interface elements automatically where required during the analysis to reduce the size and complexity of the models.

Such simulations are able to model the detailed damage that occurs for example at a stress concentration. Fig. 3 shows the results of modelling a large number of open hole tension tests on quasi-isotropic laminates with different dimensions and ply thicknesses [5]. A large variation of strength was found experimentally, and the modelling was able to correctly capture the opposing trends of decreasing or increasing strength with increasing hole size depending the thickness.

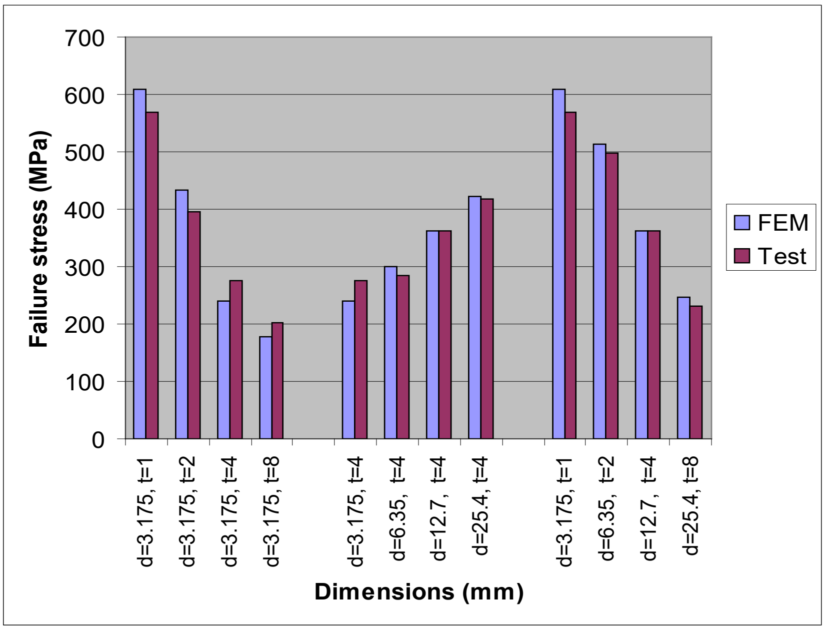

Figure 3: Correlation of predictions of open hole tensile strengths for IM7/8552 $(45_m/90_m/-45_m/0_m)_s$ laminates with different hole sizes and thicknesses [5]

4. References

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