NUMERICAL MODELLING OF THE PSEUDO-DUCTILITY EFFECT IN ±45° ANGLE-PLY LAMINATES UNDER BIAXIAL LOADING

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Abstract
The pseudo-ductility phenomenon has been extensively studied analytically and experimentally in different configurations of angle-ply laminates, due to its ability to suppress damage when fibre rotation appears permitted by the matrix plasticity. The studies carried out to date have focused on characterizing their behaviour by means of tensile tests and recently in bending testing. However, no reference has been found describing pseudo-ductility in angle-ply laminates under biaxial loading conditions.

This work aims to reproduce numerically the complex pseudo-ductile response of ±45° angle-ply laminates in uniaxial and cruciform specimens utilised for obtaining biaxial stress states. The numerical model is based on Hashin's failure theory and its results are contrasted with the experimental data obtained from tensile uniaxial tests and, once the uniaxial data are accurately modelled, with the results of tensile-tensile biaxial testing.

In the biaxial case the complexity of the non-linear material problem is increased by the geometry of the cruciform specimen, in which the pseudo-ductile effects are strong in the uniaxially loaded arms while the damage accumulation and the fibre rotation should be minimised in the central region biaxially loaded. The strong influence of the arms non-linear response on the central region observations are pointed out.

1. Introduction

The fibre-reinforced composite materials have represented a significant step forward in the design of structures with high requirements in stiffness and specific resistance. In particular, laminates composed of layers with unidirectional fibre allow to optimize the mechanical properties in certain directions by the appropriate choice of the stacking sequence. The laminae generally present a linear elastic brittle behaviour, whereas in previous studies [1,2] it has been demonstrated that the angle-ply laminates shown an effect called pseudo-ductility, which allows to reach large strains. This phenomenon is produced by the yielding of the matrix, which simultaneously allows a reorientation of the fibres towards the loading directions.

Recently, the studies of Wisnom and Fuller [1-3] have deeply collected this pseudo-ductile behaviour in angle-ply laminates with multiple configurations and under quasi-static tensile loading. One of the conclusions drawn from these works is the greater relevance of the effect of pseudo-ductility and rotation of fibres in laminates $[\pm 45]_{ns}$.

On the other hand, Serna Moreno et al. [4] carried out a study on the effect of pseudo-ductility presence in $[\pm 45]_{ns}$ laminates under bending. However, to the authors' knowledge a study of this effect under multiaxial loads has not been performed. Therefore, the experimental observation of pseudo-ductile behaviour under biaxial tensile loads and its numerical modeling is proposed in this work. The numerical analysis is achieved by means of a material modelling based on the idea of accumulation of damage in the matrix, following an approach similar to other authors [5]. This is accomplished through a damage model currently implemented in a commercial Finite Element (FEM) software, which is based on the Hashin's failure criteria [6].

2. Material and equipment

To carry out this work a pre-impregnated epoxy matrix reinforced with unidirectional carbon fibre from the company Hexcel has been used. Specifically, the commercial designation of the prepeg is M21E/34%/UD268/IMA-12K.

With regard to the test facility, a machine with triaxial testing capacity has been used, with six pneumatic actuators force-controlled up to 50kN. The acquisition of data from the testing machine is complemented by an extensometer MTS and strain gauges from the company KYOWA.

The numerical simulations have been performed using the FEM software ABAQUS [7]. In order to model the orthotropic properties of the lamina, the values of elastic modulus, Poisson's ratios and tensile strength in the principal directions of the ply have been used. These values were obtained in a previous work [4] through standardized uniaxial testing.

3. Procedure

The Hashin's failure criteria takes into account four different failure modes, assigning a damage initiation criterion to each one. The matrix and fibre tensile modes are described repectively in Eqs. 1 and 2, where X_t and Y_t represent the longitudinal and transverse tensile strengths and S^L is the longitudinal shear strength. The parameter α is a coefficient which defines the contribution of the shear stress to the fibre tensile criterion.

$$f_m^t = \left(\frac{\hat{\sigma}_{22}}{Y_t}\right)^2 + \left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 \tag{1}$$

$$f_f^t = \left(\frac{\hat{\sigma}_{11}}{X_t}\right)^2 + \alpha\left(\frac{\hat{\sigma}_{12}}{S^L}\right)^2 \tag{2}$$

Up to the point of damage initiation (point A in Fig. 1) the model requires that the behaviour of the undamaged material is linearly elastic. Once the damage has begun, the evolution of the damage is represented as a loss of stiffness, measured through the damage variable D (Eq. 3). This groups the evolution of the damage in the fibre and matrix modes, symbolized by the variables d_f and d_m (note that each of these modal damage variables are associated either to tension or to compression, in our case they are both under tension). This work is proposed on developing this idea, in such a way that it has been thought that the damage of the matrix generates the highly gradual loss of stiffness associated with pseudo-ductility (the instantaneous stiffness of the damaged material is shown with the orange-dashed line in Fig.1), which leads to a highly energetic damage evolution process.

$$D = 1-(1-d_f)(1-d_m)\ \nu_{12}\nu_{21} \tag{3}$$

The damage variables d_f and d_m, are calculated as a relation of equivalent displacements. The maximum equivalent displacement, i.e. the one asociated to maximum damage (δ_{eq}^{u} in Fig. 1), is calculated as the equivalent displacement that produces an energy dissipated to failure (integral of the equivalent stress-displacement curve) equal to the G^c defined in each studied mode. Additionaly, the ultimate point of the damage evolution (represented as point B in Fig. 1) can be numerically set by establishing a limit in the degradation of the stiffness, through the maximum degradation D^{max}.

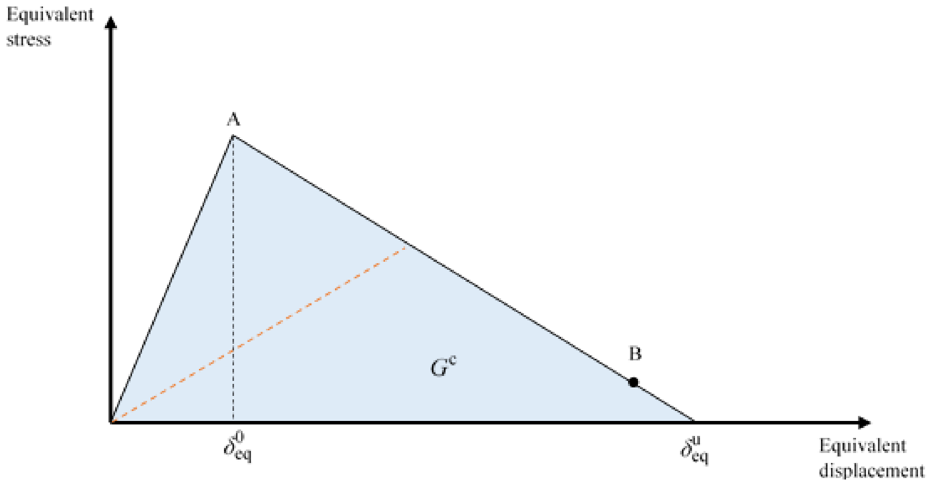

Figure 1. Stiffness degradation model associated to damage evolution.

The matrix damage variable d_m strongly depends on the fracture toughness associated to the matrix tensile mode G_m^c (corresponding to the case of a laminate subjected to tensile stress in transverse direction). In this study, this property is estimated through a mathematical optimization, which seeks to reflect the great damage absorption capacity existing in the case of angle-ply laminates due to the pseudo-ductility effect, which is unrelated to the brittle linear elastic behaviour of the lamina in principal directions.

Therefore, the values of the numerical parameters (α, G_m^c and D^{max}) necessary to generate the damage model are proposed to be calculated based on the experimental results obtained for the $[\pm 45]_{2s}$ stacking sequence under uniaxial tensile testing. This process of obtaining parameters has been carried out using a non-linear multivariate optimization based on the trust-region reflective algorithm [8]. Once these parameters are optimized, the material model is applied to a more complex stress state: the biaxial tensile testing.

Regarding the experimental study, uniaxial specimens of the $[\pm 45]_{2s}$ laminate are manufactured and tested following the procedure described in the ASTM D3039 standard. In these tests the strain state is acquired by combination of an MTS extensometer in the direction of loading and rosette of strain gauges.

The biaxial tensile-tensile tests are carried out on cruciform specimens manufactured from a $[\pm 45]_{2s}$ laminate, which are machined to obtain a $[\pm 45]_s$ laminate in the gauge zone. The specimen's design follows the geometry used in previous studies to obtain the same level of loads in both directions [9-10]. The testing procedure and the results obtained with this cruciform specimen have been detailed in previous works by the authors [11].

3. Results

As previously mentioned, the phenomenon of pseudo-ductility is associated with an accumulation of damage in the form of the matrix yielding. Due to this plasticity of the matrix, in the case of our material being uniaxially loaded, a plateau is observed experimentally in the stress-strain curve of the material, measuring a stiffness drop. Subsecuently a third stage in the stress-strain curve characterized by a stiffening favored by the scissoring effect is observed experimentally, whereby an even greater modulus would be expected as the angle of the fibers decreases with respect to the loading direction. However, the value of apparent elastic modulus in this area is lower than expected due to the accumulated damage in the material close to the failure.

This accumulation of damage has also presence in the FEM simulation, since the variable *D* accumulates the damage in the matrix produced during the plateau stage. Afterwards, a linear evolution is predicted, in which there is an increase of damage in the fibre direction until the final failure of the laminate.

The first two stages have been reflected in the numerical model with a perfect agreement, while the third stage, having an experimental non-linearity, presents a certain difference. This is explained because the numerical model does not include the gradual increase in stiffness associated with the fibre reorientation, but it only collects the degradation of mechanical properties of the yielded matrix.

It should also be noted that from the two terms that form the tensile-matrix damage criterion (Eq. 1), the most relevant is the one associated with the shear stress σ_{12}, as observed in the numerical results. The rest of failure modes remain in values much lower than the limit of initiation of damage during the linear region and the plateau associated with the pseudo-ductility, as it would be expected.

With regard to the results of the biaxial simulations, it is verified that the initiation of the damage occurs firstly in the area of the arms next to the gauge zone, and that this damage advances along the entire specimen's arm tensile-uniaxially loaded. The laminate under biaxial loads, that is, the one of the central zone in the cruciform-shape specimen, does not reach in any point of the simulation values of damage criterion close to 1, reason why it is verified that the laminate subjected to biaxial tension in two perpendicular directions does not suffer from the large-strain related to pseudo-ductility.

Experimentally, a difference in stress-strain behaviour in the gauge zone is recorded at the level of applied load which triggers the plateau of the pseudo-ductility in the arms. This variation with regard to the numerical model is explained by the stress-measuring method in the central area. That is, the stress in the gauge zone is obtained through the numerical linear ratio between the force applied at the ends of the specimen and the force suffered by the central section, as explained in a previous biaxial testing work [9]. Then, it has been constated that it should be taken into account the influence of the pseudo-ductility in the arms on the numerical ratio in order to find accurate measurements in the region biaxially tested.

4. Conclusions

The feasibility of modelling the pseudo-ductility effect in [±45º] laminates under tensile load has been proved. This model has been successfully applied to assest the stress/strain behaviour of a biaxially tensile-loaded cruciform specimen, which agree with the experimental results and allow to draw several conclusions:

- The damage model based on Hashin criteria and already implemented in a Finite Element commercial software can be successfully applied to model the non-linearity produced by the pseudo-ductility. This is performed under the assumption of damage suppression through high shear strain energy absorption, adapting the parameters of the model to a reference test.

- It has been proved that the previous model correctly assest the non-linear initation and evolution of the pseudo-ductility in the biaxial tensile-tensile test, in the regions submitted either to uniaxial load or to the biaxial stress state.
- The effects of the pseudo-ductility in the tensile-tensile biaxial testing of [±45º] angle-ply laminates has been described experimentally. Through the numerical model and the experimental data it has been observed the shear-strain dominated process started and developed in the tensile uniaxially-loaded arm, while the pure biaxial stress state is obtained in the specimen without reaching the conditions that lead to the pseudo-ductility.

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