SIMULATION OF DAMAGE ON CARBON FIBRE LAMINATES USING THE LADEVÈZE MATERIAL MODEL

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Abstract
This paper focuses on the development of a numerical model based on the Ladevèze material model for the design of purposely introduced weak points/defects and the prediction and manipulation of its failure response. To identify mechanical properties and damage parameters mechanical testing on carbon prepreg coupons was carried out. The experimental work involved tensile testing at 0°, compression testing at 0°, cyclic in-plane shear testing at ±45°,+45° and ±67.5° fibre orientation. The cyclic tests involved five load-unload cycles with increasing load levels for the identification of the elastic damaging behaviour and furthermore the inelastic behaviour of the system. Mode I and Mode II samples were also manufactured for the characterisation of fracture toughness and the description of delamination. Out of these tests the identified material parameters, damage and coupling factors were introduced on the model. The model which was implemented in the Pam-Crash™ [1] finite element solver was verified for fibre damage under tension and compression. The case of shear loading was also studied and verified taking into account matrix shear and transverse damage evolution, which are coupled through the implementation of a factor.

1. Introduction

Composites have been increasingly utilised in high performance operations as vital parts for the Oil & Gas, Offshore Marine, Aerospace, Automotive, Chemistry and Nuclear industries. Numerous research investigations have focused on the damaging phenomena taking place in these materials under loading. Analytical and Finite Element methods have been developed for the prediction of damage mechanisms that can deteriorate the integrity of composite structures. Modelling is carried out in a design context where damage and failure are evaluated against loads and tolerance dictated by the application. Among these methods, the Ladevèze material model [2] was developed based on continuum damage mechanics theory for the description of fibre rupture, matrix microckracking and fibre/matrix debonding. The Ladevèze material model is dedicated to the simulation of unidirectional continuous fibre reinforced composite materials treating the ply using homogeneous continuum mechanics.

This research work focuses on the development and validation of a numerical model that simulates the influence of defect on the damage response of composite structures. The Finite Element Analysis is performed on a single element of a fibrous composite laminate. The ultimate aim is to utilise the developed constitutive model for targeted introduction of artificial defects in order to manipulate the failure response of the structure.

2. Methodology

The methodology followed for the development of this model involved the preparation of carbon fibre plates using carbon prepreg SE84LV, a qualified material by Lloyd's Register. The plates consisted by 8 layers which were laid up. Subsequently, they were cured at 120°C and prepared into coupons. Material characterisation tests were carried out to define the in-plane and out-of-plane damage evolution based on the Ladevèze material model. The coupons were prepared for tensile testing at 0°, compression testing at 0°, cyclic in-plane shear testing at ±45°,+45° and ±67.5° fibre orientation (Figure 1).

Figure 1. Tensile testing (left hand side) and Mode I delamination testing (right hand side) on Instron machine.

The fibre damage evolution was calculated through the results from tensile and compression testing at 0° fibre orientation [1-3]. Through the tensile testing, the damage parameter "d" was defined. This parameter reduces the value of the Young's modulus depending on the region of the fibre damage threshold strain which might be characterised as subcritical, critical or post critical. Equations 1-3 describe how the damage parameter and Young's moduli are calculated throughout the test. When the damage reaches its ultimate value (equals to 1), the structure has failed completely.

Subcritical: $$E_1=E_1^{0t}\left(1\text{-}d^{ft}\right) \qquad d^{ft}=0 \qquad \text{if } \varepsilon_{11}<\varepsilon_i^{ft} \tag{1}$$

Critical: $$E_1=E_1^{0t}\left(1\text{-}d^{ft}\right) \qquad d^{ft}=d_u^{ft}\frac{\varepsilon_{11}\text{-}\varepsilon_i^{ft}}{\varepsilon_u^{ft}\text{-}\varepsilon_i^{ft}} \qquad \text{if } \varepsilon_i^{ft}\leq\varepsilon_{11}<\varepsilon_u^{ft} \tag{2}$$

Post critical: $$E_1=E_1^{0t}\left(1\text{-}d^{ft}\right) \qquad d^{ft}=1\text{-}(1\text{-}d_u^{ft})\frac{\varepsilon_{11}}{\varepsilon_u^{ft}} \qquad \text{if } \varepsilon_u^{ft}\leq\varepsilon_{11}<\infty \tag{3}$$

The investigation of fibre damage evolution through compression testing followed the principals of fibre damage due to tension. In addition to this, a factor "γ" was identified, responsible for fibre misalignment and fibre microbuckling phenomena taking place during testing. Equations 4-7 were used for the identification of the required parameters for the development of the model. The stress-strain curves for fibre tensile and compression damage are presented in Figure 2. The initial and ultimate strain thresholds are associated with modulus degradation due to damage increase.

$$E_1^{\gamma}=\frac{E_1^{0c}}{1+\gamma E_1^{0c}|\varepsilon_{11}|} \tag{4}$$

Subcritical: $$E_1^c=E_1^{\gamma}\left(1\text{-}d^{fc}\right) \qquad d^{fc}=0 \qquad \text{if } |\varepsilon_{11}|<\varepsilon_i^{fc} \tag{5}$$

Critical: $$E_1^c=E_1^{\gamma}\left(1\text{-}d^{fc}\right) \qquad d^{fc}=d_u^{fc}\frac{|\varepsilon_{11}|\text{-}\varepsilon_i^{fc}}{\varepsilon_u^{fc}\text{-}\varepsilon_i^{fc}} \qquad \text{if } \varepsilon_i^{fc}\leq|\varepsilon_{11}|\leq\varepsilon_u^{fc} \tag{6}$$

Post critical: $$E_1^c=E_1^{\gamma}\left(1\text{-}d^{fc}\right) \qquad d^{fc}=1\text{-}\left(1\text{-}d_u^{fc}\right)\frac{|\varepsilon_{11}|}{\varepsilon_u^{fc}} \qquad \text{if } \varepsilon_u^{fc}\leq|\varepsilon_{11}|<\infty \tag{7}$$

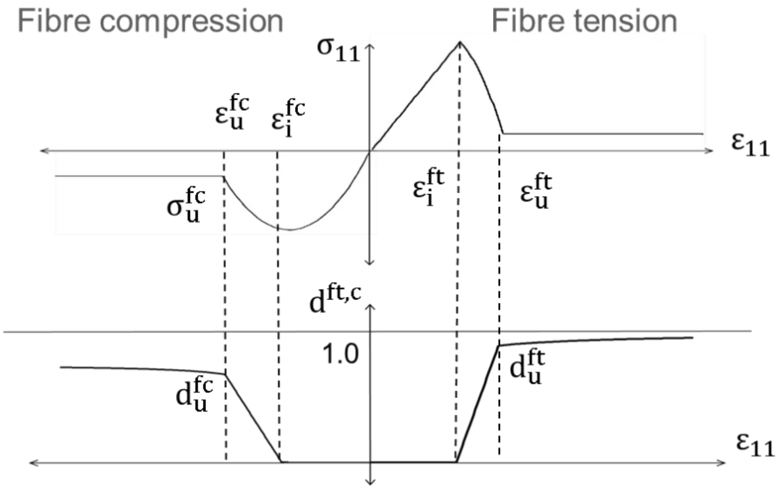

Figure 2. Fibre tensile and compressive damage.

The cyclic shear testing required five load-unload cycles with increasing loading levels. Out of these cyclic shear tests the shear and transverse damage behaviour was studied. Additionally, the inelastic behaviour of the system was identified through the ±45° cyclic in-plane shear test taking into account the reduction of the Young's moduli at the beginning of each cycle and hence calculating the damage that has occurred in the composite structure due to inelastic phenomena. Equations 8-14 were used to extract the damage factors and material properties from the ±45° shear test and were introduced in the model. Factor d_{12} is related to damage occurring during debonding between fibres and matrix, whilst Y^C_{12} , Y^0_{12} , and Y^U_{12} represent the critical, initial and ultimate shear damage limits. For the inelastic behaviour, parameter R_0 represents the initial inelastic stress and β and m are hardening coefficients.

$$d^i_{12}=1-\frac{G^i_{12}}{G^0_{12}} \tag{8}$$

$$Y^i_{12}=\sqrt{\frac{1}{2}G^0_{12}(2\varepsilon^{ei}_{12})^2} \tag{9}$$

$$Y_{12}(t)=Y^c_{12}d^i_{12}+Y^0_{12} \tag{10}$$

$$Y^U_{12}=\max(Y^i_{12}) \tag{11}$$

$$R_i=\frac{\sigma^{pi}_{12}}{1-d^i_{12}}-R_0 \tag{12}$$

$$\varepsilon^{pi}_{12}=\int_{\varepsilon^{p(i-1)}_{12}}^{\varepsilon^{pi}_{12}}(1-d^i_{12})\,d\varepsilon^{pi}_{12}=\sum_{i=1}^{i}\varepsilon^{pi}_{12} \tag{13}$$

$$R_i=\beta(\varepsilon^{pi}_{12})^m \tag{14}$$

The out-of-plane damage evolution was studied through delamination tests. This involved Mode I (double cantilever beam, DCB) and Mode II (end notched flexure, ENF) testing. From these tests the critical strain energy release rates were calculated for the initiation and propagation of the delamination crack for each case of out of plane test. This parameters were included in the Pam-Crash™ finite element solver and used to simulate the delamination propagation through cohesive, tied interfaces [4-5]. These interfaces are associated with degrees of freedom of nodes on opposite sides of an interface and are dictated by a force-displacement law.

3. Experimental and simulation results

Material parameters, damage and coupling factors that were estimated based on in-plane and out-of-plane tests were introduced in the model. The model consisted of one element in which the fibre direction and loading conditions were being changed depending on the test under study. The element model was verified for fibre damage under tension (Figure 3) and compression (Figure 4) showing that experimental and modelling results were in agreement. Also, analytical investigation was carried out to further explain the damage evolution mechanics taking place.

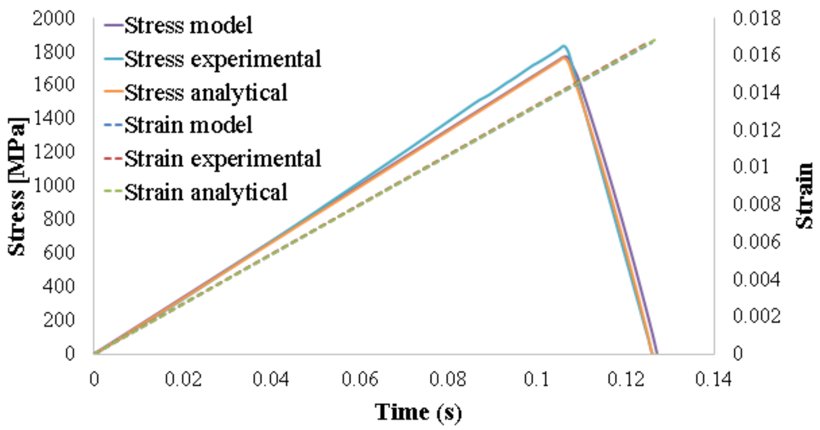

Figure 3. Stress-strain results for tensile fibre damage evolution.

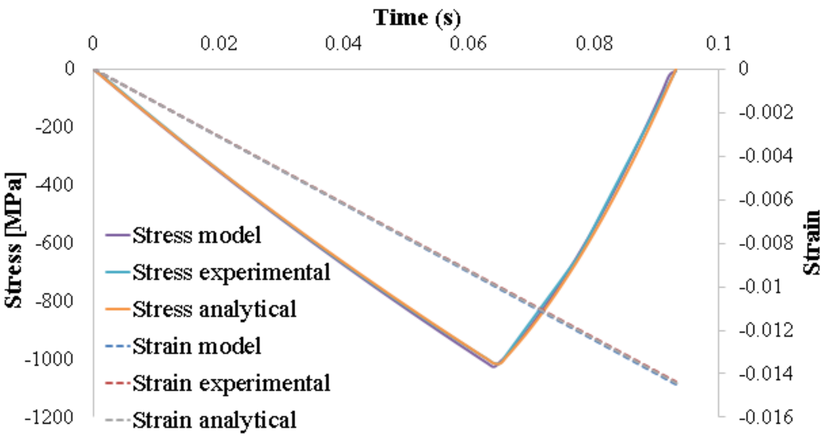

Figure 4. Stress-strain results for compressive fibre damage evolution.

Similarly to the 0° tests, the element model was prepared for loading cases [Figure 5] similar to the cyclic shear testing of ±45°, ±67.5° and +45° fibre orientation [Figure 6]. The element model was verified and the damage parameters for shear and transverse damage evolution were proved to match the experimental results.

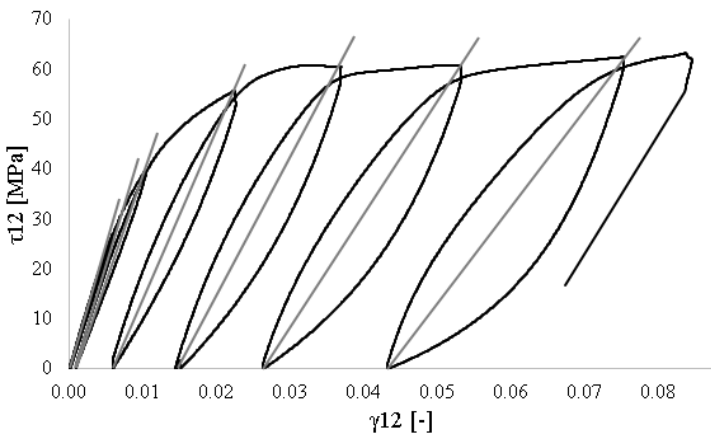

Figure 5. Shear stress-strain curves for ±45° fibre orientation

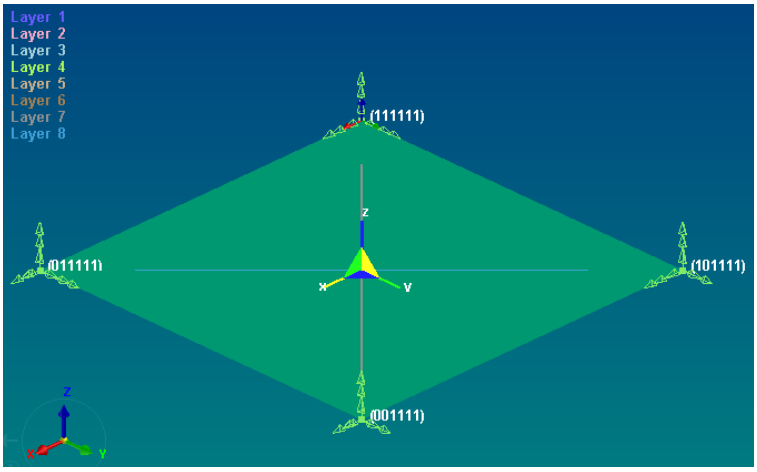

Figure 6. Subscaled in-plane shear coupon of ±45° fibre orientation.

The out-of-plane damage model implementation was carried out through the design of a Mode I double cantilever beam (DCB). The model [Figure 7] was comprised of the delamination initiation and propagation strain energy release rates. Figure 8 demonstrates the DCB model and the location of the tied interfaces; the master segment is presented in dark red colour whilst the slave nodes are the ones in between the two composite parts in bright blue colour. The results of the model matched the experimental results verifying the case of out of plane damage evolution.

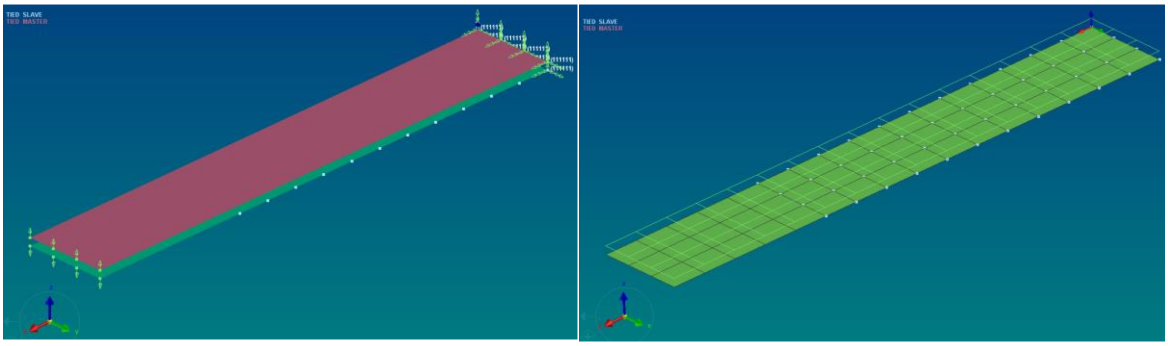

Figure 7. Tied interfaces described by the master segment and slave nodes.

4. Conclusions

Investigation of in-plane damage and out-of-plane damage was performed through the use of the Ladevèze material model. Experimental, analytical and modelling results were in agreement for the cases of in-plane damage evolution. The out-of-plane damage evolution for the case of delamination was also in agreement to the experimental results for the calculation of the strain energy release rate during Mode I and Mode II loading.

5. Future work

The developed constitutive model will be used for the manufacturing of coupons with introduced weak points/defects at prearranged patterns indicated through the developed constitutive model. The experimental results will be compared to the results from modelling to validate the model. The validated model will be also used on composite pipes for the manipulation of its failure response.

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