MODELLING DAMAGE DEVELOPMENT IN CARBON/EPOXY OVERHEIGHT COMPACT TENSION (OCT) SPECIMENS

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SUMMARY: A continuum damage mechanics (CDM) approach to modelling the damage accumulation in composite laminates has been developed. This model, CODAM, is used in this instance to predict the force-displacement curve and the region of damage developed in several quasi-statically loaded overheight compact tension (OCT) specimens. Carbon/epoxy laminates with three different layups are simulated. The predictions of the overall stiffness, peak force, displacement at ultimate load and the general shape of the load-displacement curve agree very well with the corresponding experimental data. Furthermore, predicted damage development progresses according to the manner observed in the experiments.

KEYWORDS: Damage; strain-softening; constitutive model; OCT test; crack growth; continuum damage mechanics

INTRODUCTION

Understanding damage development in composite materials is an important requirement of the aerospace industry for the continued adoption of composites in commercial aircraft. Damage, especially delamination damage, is difficult to detect without extensive inspection. Developing damage tolerant materials and understanding the amount of damage caused by commonplace events such as tool drops or hail strikes are therefore high priorities. One of these materials is stitched resin film infused (S/RFI) carbon/epoxy laminates, in which the stitching yarns are run perpendicular to the plane of the laminates and are intended to limit the spread of delamination damage. This study details some of the efforts involved in modelling the damage growth in S/RFI laminates.

OVERHEIGHT COMPACT TENSION TEST

The overheight compact tension test (OCT) is an experimental methodology developed by Kongshavn and Poursartip (1999) to investigate the damage growth behaviour in notched specimens. The OCT specimen is a geometry in which stable damage growth can be developed and measured in a simple test. The specimen is edge-notched, and loaded in tension using displacement control through two off-centre loading pins. Lines are inscribed on the specimen surface, parallel to the notch, at fixed distances above and below the notch mid-plane. These lines are used to determine the local displacements in front of the notch tip as damage develops during the test. Further, a CMOD gauge is used to measure the crack opening.

Photographs taken during the loading can be used in conjunction with the lines scribed onto the surface of the specimen to determine the location of the crack tip at any time during the test. Additionally, the pin load and CMOD are recorded throughout the test. Destructive techniques such as deplying, cross-sectioning, and the testing of mini-tensile specimens cut from the damaged regions are used to determine the extent of damage in the specimen after the test is complete.

The OCT test procedure involves loading the specimen into a universal testing machine and quasi-statically loading it through the load pins with a displacement-controlled rate of 0.02 inches per minute (0.508 mm/min). To inhibit out-of-plane twisting of the specimen during testing, two narrow steel stiffeners were used at the compression edge of the specimen. The guides were coated with a layer of Teflon to reduce friction and to prevent damage during the test. A schematic and photograph of the test are shown in Figure 1.

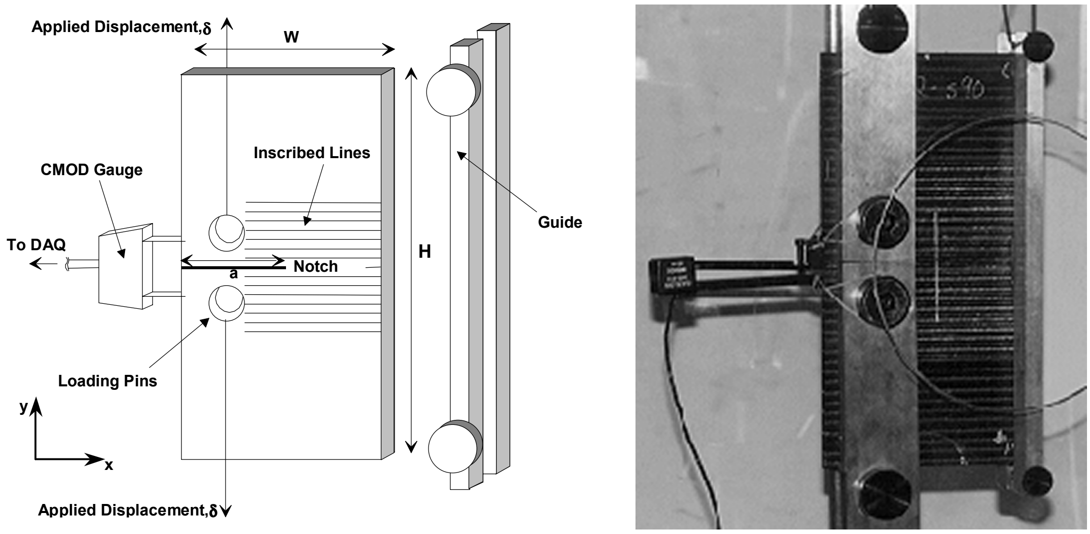


Figure 1. Schematic and photograph of OCT test setup. Note that the 0° layers are aligned in the y-direction (load direction).

For this investigation three specimens of S/RFI carbon/epoxy laminates with common overall geometries (W= 106mm, H= 208mm, a =32.2mm) but three different thicknesses resulting from stacking sequences of $[+45/-45/0_2/90/0_2/-45/+45]_n$ sub-laminates with n = 4,5 and 6 were examined. In the course of the investigation, experimentation showed that the 5-sublaminate specimen behaved significantly different from the 4- and 6-sublamiante specimens. The reasons for this anomalous behaviour have yet to be determined, but the simulation inputs have been modified to accommodate for this difference in behaviour.

CODAM CONSTITUTIVE MODEL

A constitutive model for composite laminates called CODAM (*<u>CO</u>mposite <u>DA</u>mage <u>M</u>odel*) has been developed at the University of British Columbia (Williams et al., 1999). CODAM is a continuum damage mechanics model with a level of abstraction that is based on sub-laminate rather than lamina response. The sub-laminate formulation implicitly accounts for the effects of ply interactions in the generalized laminate response. The model uses two sets of curves; a damage parameter versus effective strain curve and a modulus reduction versus damage parameter curve for normal loading in each principal material direction and shear loading.

Damage Parameters

Consistent with traditional CDM models, the CODAM model associates damage parameters with cracking in the principal directions, and separates damage growth into matrix and fibre dominated stages. A damage parameter in a particular direction is defined as the projection of crack density within a representative volume element normalized with respect to the saturation crack density. As a result, the damage parameter, ω, ranges from 0 to 1. In the plane-stress formulation of the CODAM model considered here, two principal material directions exist. Therefore, two damage parameters, namely, ω_x and ω_y are sufficient to describe the effect of damage on the direct moduli in each of the principal material directions. The formulation does not include a separate damage parameter to degrade shear resistance. Rather, the resulting effect of damage on shear modulus is determined by combining the damage parameters in the principal directions into a shear damage parameter, ω_s, defined as:

$$\omega_s = \sqrt{\omega_x^2 + \omega_y^2 - \omega_x \omega_y} \tag{1}$$

Damage Potential

CODAM determines the damage potential based on the current strain state (ε_x, ε_y, γ_{xy}) according to Equation 2:

$$F = \sqrt{\left(\frac{\varepsilon_x}{K_{t,c}}\right)^2 - \left(\frac{\varepsilon_x}{K_{t,c}}\right)\left(\frac{\varepsilon_y}{L_{t,c}}\right) + \left(\frac{\varepsilon_y}{L_{t,c}}\right)^2 + \left(\frac{\gamma_{xy}}{S}\right)} \tag{2}$$

The constants in Equation 2 (K, L, S) are not used as measures of strength, rather they are scalars used to provide a mechanism to control the contribution of each strain component to the damage potential function. Different constants can be used for tension or compression loading, as indicated by the subscripts t and c. Due to the orthotropic properties of the composite and the directional nature of damage, two damage potential functions, F_x and F_y, are employed.

Damage Growth

The key to the CODAM model is the interaction between the three variables: damage potential, damage parameter, modulus reduction (normalized modulus). To determine the shape and values for the relationships between the variables one considers the physics of the problem. Firstly, only two types of damage are assumed, fibre damage and matrix damage. Matrix damage consists of all types of matrix damage including microcracking, fibre/matrix debonding and delamination. With these damage modes in mind, the independent influences of damage growth for a uniaxial "thought-experiment" are assumed as follows:

- Damage parameter at the saturation of matrix damage: ω'_m
- Damage potential at the onset of matrix damage: F_{mi}
- Damage potential at the saturation of matrix damage: F_{ms}
- Damage potential at the onset of fibre damage: F_{fi}
- Damage potential at the saturation of fibre damage: F_{fs}
- Normalized modulus attributed to matrix damage at damage saturation: RE'_m

Note that two more related quantities can be computed, the damage parameter at the saturation of fibre damage ($\omega'_f = 1-\omega'_m$), and the normalized modulus attributed to fibre damage at damage saturation ($RE'_f = 1-RE'_m$). Here RE denotes the ratio of damaged (reduced) modulus and undamaged (initial) modulus.

Once these quantities have been determined, the relationship between them is assumed to be linear. For example, as the damage potential increases from F_{mi} to F_{ms}, the corresponding damage growth from 0 to ω'_m is assumed to be linear. Figure 2 demonstrates these relationships.

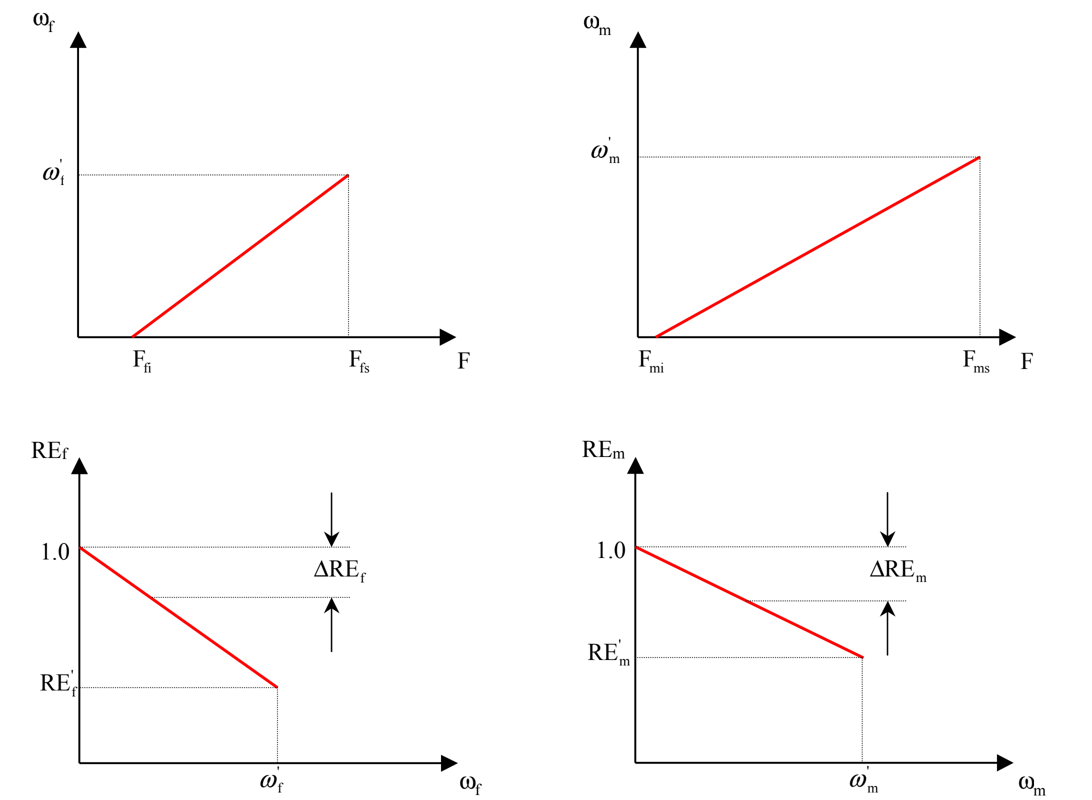
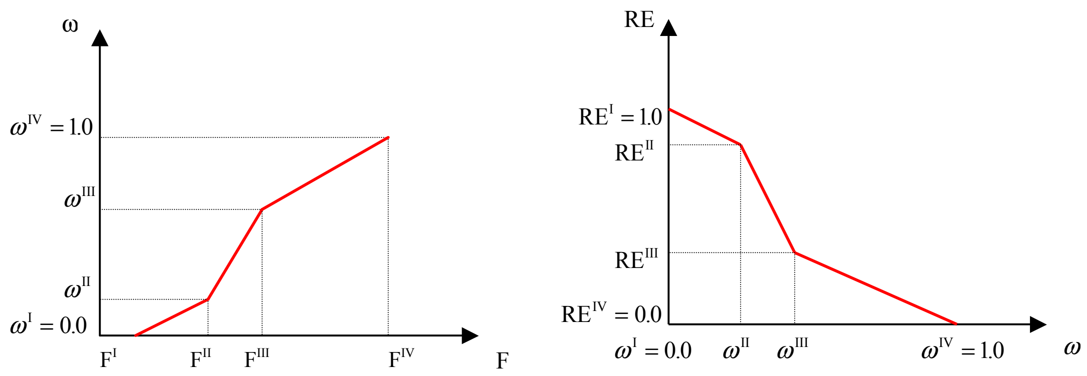


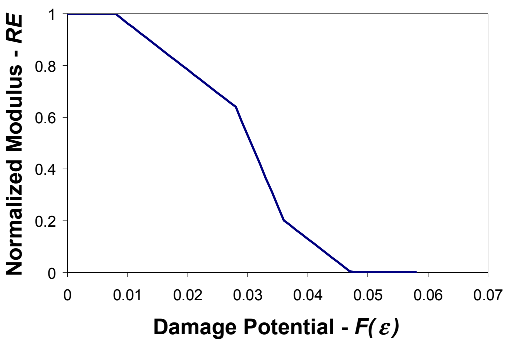
Figure 2. Input parameters that define the initiation and saturation of fibre and matrix damage and the associated modulus reduction curves.

Once the parameters have been defined for each of the damage modes, the corresponding curves can be combined to describe the overall sub-laminate constitutive response. The schematics of the resulting damage growth and modulus reduction curves are shown in Figure 3. The resulting stress-strain curve exhibits a softening behaviour, as shown in Figure 4.

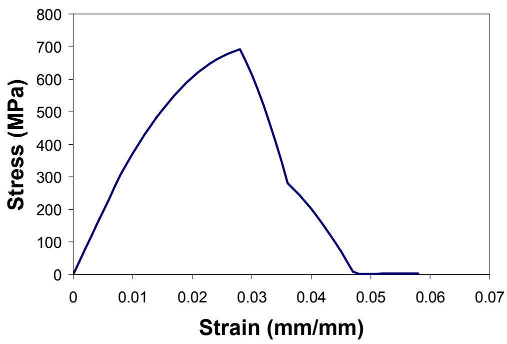


(a) (b)

Figure 3. Schematic of the damage growth curve (a), and the modulus reduction curve (b).



(a)



(b)

Figure 4. Modulus reduction curve as a function of damage potential (a) and stress-strain curve (b) for the inputs shown in Figure 3.

Note that shear stiffness degradation has not been addressed in this exercise. As noted previously, the shear damage parameter is a calculated value, based on the damage parameters in each of the principal material directions *x* and *y*. However, the shear modulus reduction curve must still be defined. Currently, for simplicity a linear degradation of shear modulus with respect to the associated damage parameter is assumed (i.e. $RG_{xy} = 1\text{-}\omega_s$).

Implementation

The CODAM model has been incorporated into the explicit finite element package LS-DYNA (LSTC, 1997) as a user model for both shell and brick elements. For the OCT simulations, plane-stress shell elements with single-point quadrature for both in-plane and through-thickness integrations are used. The CODAM algorithm is strain-driven, receiving the strain increments in the local material coordinate system. Based on the strain increments, CODAM determines the total strain at the integration point, computes the damage potential for each direction, and then determines the corresponding damage parameter for each direction from the damage growth curve. From the damage growth curve, the corresponding modulus reduction is determined from the modulus reduction curve. It can be shown that, in order to maintain symmetry and positive definiteness of the material stiffness tensor, the normalized modulus functions for E_x and E_y uniquely define the degradation of Poisson's ratio ν_{xy}. The stiffness tensor is updated, the stresses are determined and passed back to the main LS-DYNA routine, and the simulation marches forward in time.

SIMULATIONS

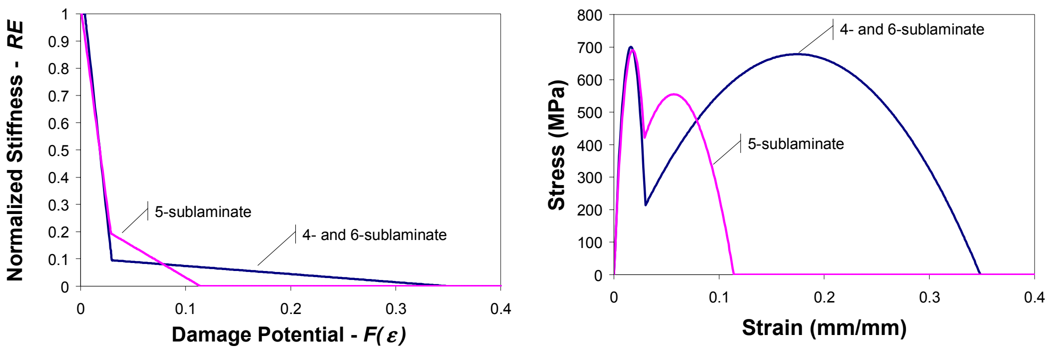
The elastic properties of this material used in the simulations were obtained from standard quasi-static tests and are listed in Table 1. The baseline input parameters required for CODAM were determined by matching the resulting stress-strain curves generated by the CODAM inputs to stress-strain curves determined from four-point bending tests of the material. Further modifications to the input parameters were made to create a better fit between the experiments and numerical simulations of OCT specimens. Table 2 lists the CODAM inputs used for the simulations. Figure 5 shows the modulus reduction curve and the stress-strain curve for the inputs.

Table 1. Elastic properties used in the simulations. Note that *y*-direction coincides with the direction of loading and the fibre direction in the 0° plies.

$\mathbf{E_x}$	30 GPa
$\mathbf{E_y}$	75 GPa
$\mathbf{G_{xy}}$	17.1 GPa
$\boldsymbol{\nu_{xy}}$	0.161

Table 2. CODAM model inputs for the simulations.

4 and 6 sublaminates				5 sublaminates		
	x	y			x	y
ω'_m	0.4400	0.5600		ω'_m	0.4400	0.5600
F_{mi}	0.0190	0.0128		F_{mi}	0.0190	0.0043
F_{ms}	0.0650	0.3485		F_{ms}	0.0650	0.1140
F_{fi}	0.0130	0.0042		F_{fi}	0.0130	0.0010
F_{fs}	0.0320	0.0298		F_{fs}	0.0320	0.0289
RE'_m	0.7200	0.9000		RE'_m	0.7200	0.7500



(a) (b)

Figure 5. Modulus reduction curve as a function of damage potential (a) and stress-strain curve (b) for the y-direction inputs shown in Table 1 and Table 2. The odd double-hump shape of the stress-strain curve is a result of the combination of 3 parabolas.

Note that two different behaviours were observed in the experiments. The four and six sublaminate specimens exhibited cracking in the direction of the load (i.e. splitting) whereas the five sublaminate specimen showed cracking perpendicular to the load. To simulate the two behaviours, two sets of CODAM inputs were required. The difference between the two sets of inputs was in the y-direction (load direction) behaviour. The four and six sublaminate specimens needed a strain-softening curve that maintained stiffness at strains much higher than the five sublaminate specimens. The four and six sublaminate specimens maintain small stiffness in the y-direction at strains roughly three times larger than the five sublaminate specimen. Figure 5 demonstrates these differences. Note that the odd double-hump shape of the stress-strain curve is a result of the model formulation. As the model assumes linear stiffness reduction with strain, the resulting stress-strain curve is the envelope of intersecting parabolas. The lack of smoothness does not cause any numerical difficulties since the model is used in an explicit finite element formulation.

The OCT mesh is shown in Figure 6. Only half of the specimen is modelled, taking advantage of the symmetry of the problem.

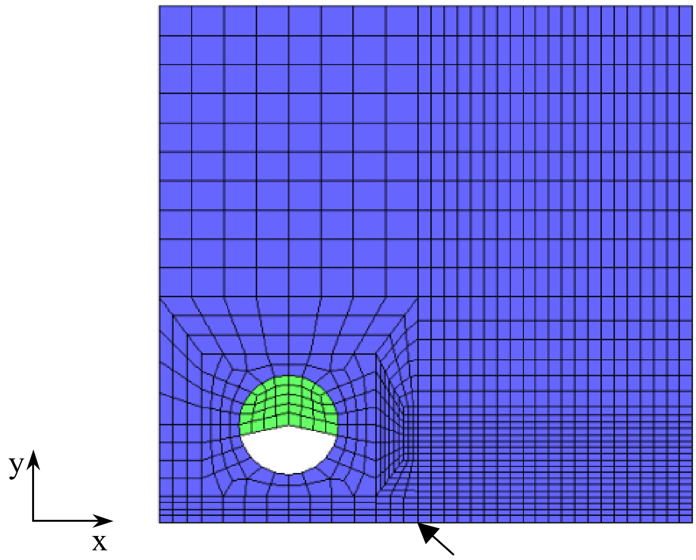


Figure 6. Finite element mesh used to model half of the OCT geometry. The notch runs from the lower left-hand edge to the arrow tip.

The load-displacement curves are shown in Figure 7 and Figure 8. Figure 9 shows the damage in the specimens and highlights the differences in behaviour between the 4- and 6-sublaminate specimens and the 5-sublaminate specimen. Figure 9 also shows that changing the y-direction input for the 4 and 6 sublaminate specimens changed the damage mode from a predominately y-direction damage mode (like the 5-sublaminate result) to a predominately x-direction damage mode. This provides some insight that minor changes in the softening behaviour of the material completely changes the damage mode in the specimen.

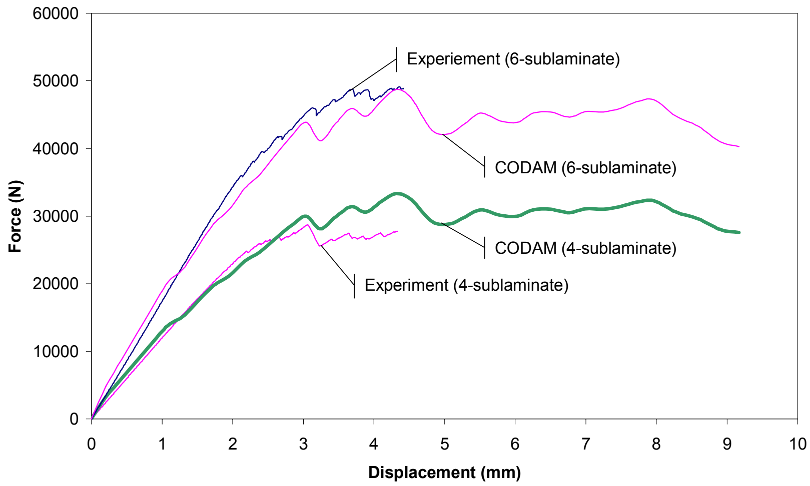


Figure 7. Load-displacement curves for the 4- and 6-sublaminate specimens and the corresponding CODAM simulation results.

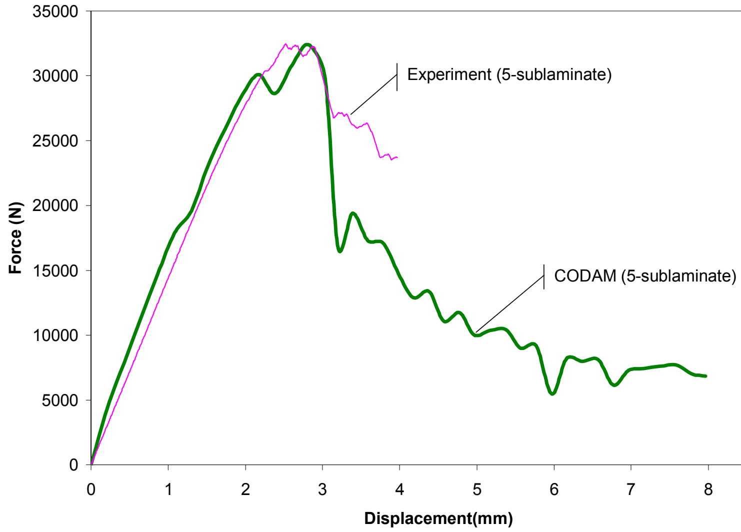


Figure 8. Load-displacement curve and simulation results for the 5-sublaminate specimen.

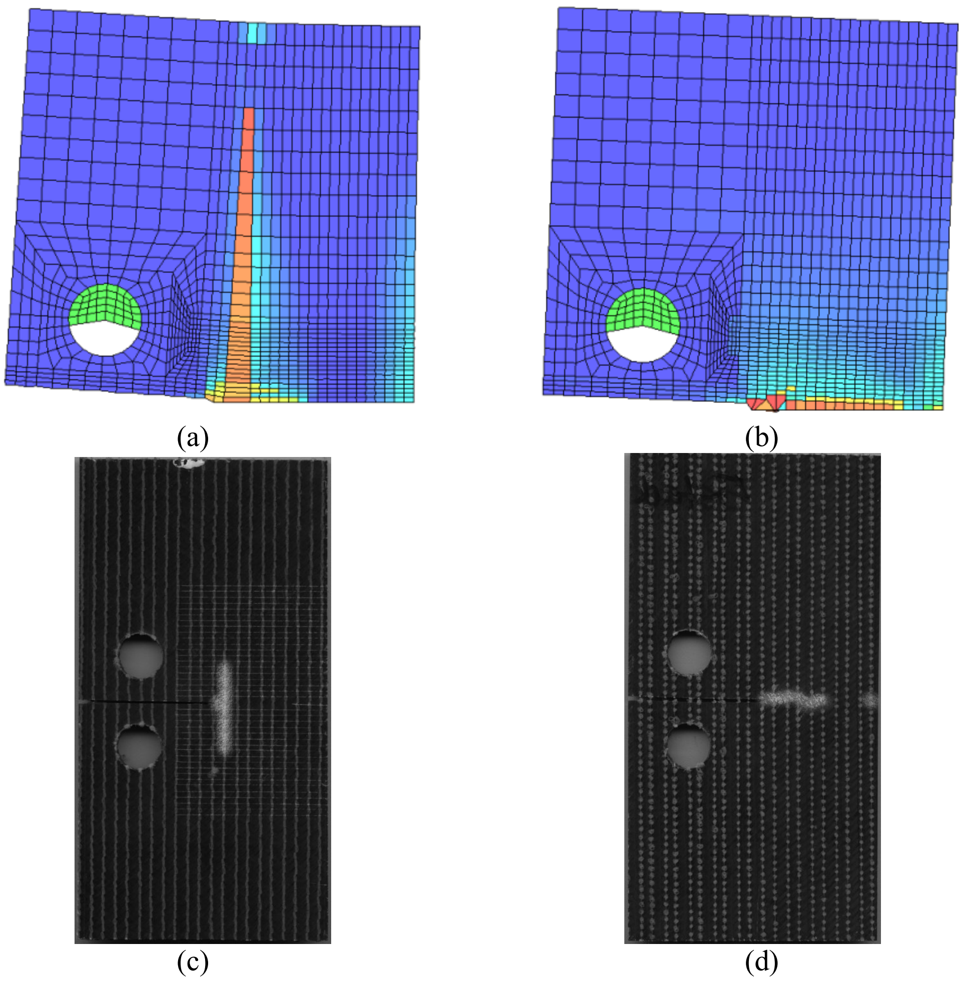


Figure 9. Fringes of shear damage for the 4- and 6-sublaminate simulation (a) and the 5-sublaminate simulation (b). Also shown are photos of the unloaded specimens with the cracking highlighted in (c) and (d).

CONCLUSIONS

The CODAM simulations do a good job of modelling the behaviour of the S/RFI OCT specimens. The simulations capture the essence of the experimentally measured load-displacement curves as well as the observed damage patterns and crack growth. The differences in the experimental tests were recreated by only changing the softening parameters, resulting in the complete change of damage mode in the numerical results.

Research is continuing in the development of the CODAM model. More robust techniques are being developed for determining the input parameters. Other material systems, and loading cases are being examined and the model has been extended to a full three-dimensional brick implementation for applications involving out-of-plane loading. CODAM has shown itself to be a viable, physically-based laminated composite damage model.

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