A DISCRETE-CONTINUOUS FINITE ELEMENT MODEL TO PREDICT DAMAGE PROGRESSION IN NON-CRIMP FABRIC CFRP COMPOSITES UNDER TENSILE LOADING

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ABSTRACT

The application of a modified version of the continuum damage model CODAM2 together with the discrete cohesive zone method (CZM) enables the simulation of intra-laminar damage modes combined with delamination. We use this discrete-continuous approach in the explicit finite element software, LS-DYNA, to predict the structural response of non-crimp fabric CFRP composites under tensile loading. Damage parameters for CODAM2 and CZM are calibrated using over-height compact tension (OCT) tests in the two principal directions of the orthotropic material. The proposed method is then applied to the simulation of an off-axis OCT coupon with respect to the loading direction in order to assess whether the model captures the expected overall response and off-axis damage propagation in this general loading configuration.

KEYWORDS: *non-crimp fabric composites, damage modelling, finite element analysis*

1 INTRODUCTION

To reliably simulate the damage response of composites the interactions of various failure modes including intra-laminar failure (fibre and matrix failure) and inter-laminar failure (delamination) should be considered while maintaining the computational efficiency of the model. Various approaches have been employed to model damage ranging from discrete models to continuum damage models at different scales.

The UBC COmposite DAmage Model (CODAM) introduced by Williams et al. (2003) is a continuum damage mechanics based model at the macro-scale that takes the sub-laminate as its basic building block. The second generation of this model (CODAM2) developed by Forghani et al. (2013) employs an orthotropic non-local averaging scheme to tackle the localization issue and improve the predicted damage patterns. A built-in form of this material model is available in the commercial finite element software package, LS-DYNA, as MAT219. The inputs for damage parameters in CODAM2 are the initiation and saturation values of the equivalent strains that drive each mode of damage. These values are extracted from the strain-softening response of the laminate that could be experimentally characterized using the approach proposed by Zobeiry et al. (2015).

When damage is dominated by large splits and delamination, continuum damage models are not able to accurately predict the nonlinear response of the structure and lead to erroneous prediction of damage propagation. In this study, a modified version of CODAM2 applied at the mesoscopic scale and combined with discrete modelling of the interface, as proposed by Shahbazi (2017), is adopted to capture the interacting intra-laminar and inter-laminar damage mechanisms in orthotropic non-crimp fabric (NCF) CFRP laminates subjected to tensile loading. NCF composites in the recent past have proven to be a very valuable addition to the group of textile composite materials. They are used mostly in the automotive industry and there is a need for a thorough understanding of their behaviour under different loading conditions.

2 METHODOLOGY

In the modified version of CODAM2 developed by Shahbazi (2017) and implemented as a user-defined material model (UMAT) in LS-DYNA, the original CODAM2 is enhanced and used in a mesoscopic context which takes the individual plies of the laminate as the basic building block. In other words, the intra-laminar damage modes are modelled using an enhanced ply-based and nonlocal representation of CODAM2. Damage initiation in the matrix is based on Hashin's interactive stress-based failure theory that facilitates consideration of the matrix in-situ strength. Using shear lag theory the in-situ strength in this model is allowed to vary in order to account for the effect of ply thickness and constraints imposed by the neighbouring plies on the initiation of matrix cracking. Proper estimation of the onset of matrix cracking in turn influences the prediction of delamination that is induced by the inter-laminar stresses operating at the tip of matrix cracks. The progression of the intra-laminar damage is governed by the fracture energy values for the fibre and matrix damage modes.

The elastic moduli and strength properties of the individual plies as inputs for enhanced CODAM2 are extracted from standard tests on unidirectional laminas. To calibrate the intra-laminar damage saturation strains and in-situ fracture energies associated with each of the fibre and matrix damage modes, over-height compact tension (OCT) tests are carried out.

Delamination is explicitly modelled as a macro crack between the dissimilar plies allowing the independent damage propagation in the separated plies. Therefore, a mixed mode cohesive-based tie-break contact formulation available in LS-DYNA is used for simulation of delamination. This interface follows a bilinear traction-separation law with quadratic mixed-mode delamination criterion.

For calibration of the inter-laminar strength properties, a 3D stress analysis on the laminate is conducted while inhibiting delamination between the plies. At the instant when intra-laminar matrix damage in adjacent plies initiates, the inter-laminar stresses close to the notch are taken to be equal to the inter-laminar normal and shear strengths. Inter-laminar fracture energies are obtained using the standard double cantilever beam (DCB) and end-notched flexure (ENF) tests.

3 MATERIALS AND EXPERIMENTS

The materials used in this study are NCF CFRP laminates with the layup sequence of $[0_3/60/\text{-}60]_{3s}$. Unidirectional elastic and strength properties for an equivalent single ply of this laminate are computed (back-calculated) from the standard (tension and shear) tests conducted on the laminate in the principal orthotropic directions and are listed in Table 1 (the materials and standard test results were provided by Ford Motor Company, 2017). The in-situ transverse tensile strength and shear strength, for each ply is also calculated using the procedure described in Shahbazi (2017).

Table 1 Unidirectional elastic and strength properties of the equivalent single ply of the NCF CFRP laminate

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	v_{12}	X_T (MPa)	Y_T (MPa)	S_L (MPa)
111.8	7.6	3	0.3	1919	61	75

Mesoscopic CODAM2 assumes linear strain-softening curves for progression of damage in the fibre and transverse (matrix dominated) directions, 1- and 2-directions, respectively. Given the orthotropic nature of the NCF laminates, calibration of their strain softening curves and fracture energies is carried out using OCT tests conducted in the two principal directions of the laminates (longitudinal and transverse). Figure 1 (a) shows the geometry and dimensions of the OCT specimen.

The damage pattern and mechanisms in the transverse testing direction i.e. $[90_3/30/\text{-}30]_{3s}$ are distinctly different from those of the longitudinal testing direction i.e. $[0_3/60/\text{-}60]_{3s}$. While the damage in OCT tests on $[90_3/30/\text{-}30]_{3s}$ layup is mainly driven by stable progression of fibre breakage with minor delamination, the damage in OCT tests on $[0_3/60/\text{-}60]_{3s}$ layup is mostly dominated by delamination and matrix cracking in the form of splits running parallel to the loading direction. The former test provides an estimate of the fibre fracture energy density (area under the strain-softening curve), g_1^f, whereas the latter contributes to calibration of the matrix fracture energy density, g_2^f.

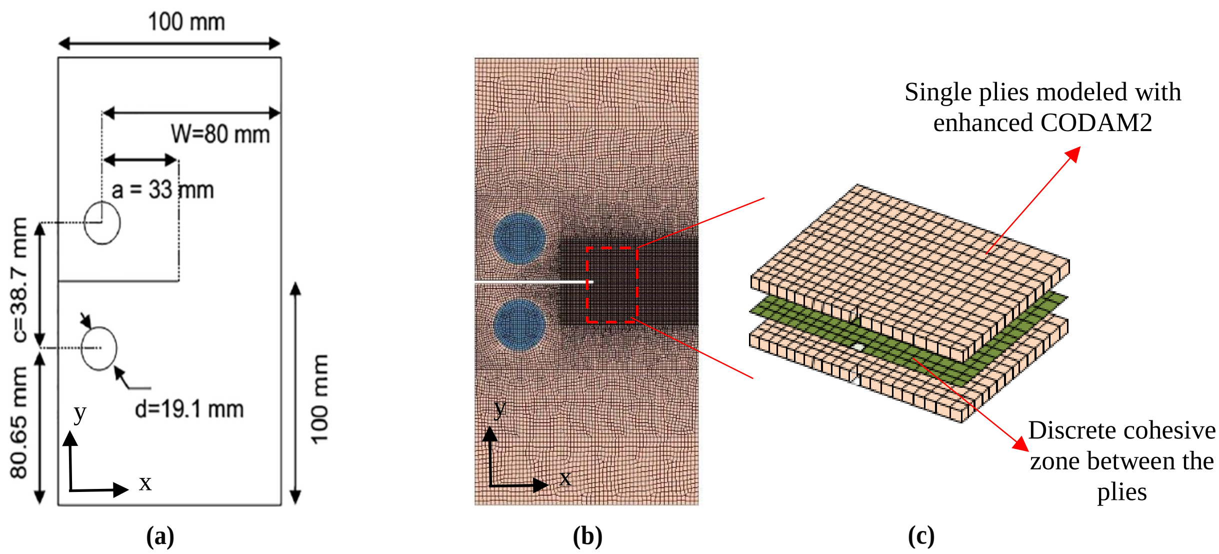


Figure 1: (a) OCT geometry and dimensions, (b) FE mesh for the OCT coupon, (c) Exploded through-thickness view of the region close to the notch tip of OCT specimen showing contact interface between adjacent dissimilar plies (Shahbazi, 2017)

The parameters required as input in the cohesive-based tie-break contact in LS-DYNA are summarized in Table 2. The inter-laminar shear and normal strength values are adjusted using the 3D stress analysis as described in Section 2. The mode I and mode II inter-laminar fracture energies, G_{Ic} and G_{IIc}, are determined from DCB (ASTM-D5528) and ENF tests (ASTM-D7905) conducted on the NCF laminate with a non-adhesive Teflon layer inserted at the mid-plane (between adjacent 0° layers) to define a starter crack.

Table 2 Inter-laminar damage properties

Layup	Maximum inter-laminar normal stress, $t_{\max}^N$ (MPa)	Maximum inter-laminar shear stress, $t_{\max}^S$ (MPa)	Mode I fracture energy, G_{Ic} (kJ/m^2)	Mode II fracture energy, G_{IIc} (kJ/m^2)
$[90_3/30/\text{-}30]_{3s}$	9.2	12	0.564	2.028
$[0_3/60/\text{-}60]_{3s}$	4	5.2	0.564	2.028

4 NUMERICAL SIMULATIONS

Figure 1 (b) shows the FE model used for simulation of the OCT tests. Each single ply is modelled with under-integrated thick shell elements (ELFORM=5 in LS-DYNA). The enhanced CODAM2 material model developed by Shahbazi (2017) is assigned to each layer with its specific ply orientation. A discrete delamination interface is inserted between the dissimilar plies as shown in Figure 1 (c). The element size in the expected fracture process zone close to the notch is 0.5 mm. Displacement in the vertical direction is applied to the loading pins, shown in blue in Figure 2 (b).

Each of the fibre and matrix fracture energy densities, g_1^f and g_2^f, respectively, determines the area under the associated stress-strain curve. Therefore, fibre and matrix damage saturation strains, ε_1^s and ε_2^s, respectively, that are used as input in enhanced CODAM2, can be calculated based on the fracture energy densities.

The OCT tests on $[90_3/30/\text{-}30]_{3s}$ layup are modeled using a local approach, given that in this case fibre damage localizes into a self-similar and stable fracture process zone with a fairly constant height. Therefore, the fibre fracture energy density g_1^f is related to the fibre fracture energy, G_1^f governed by the Bazant's crack-band relationship given below:

$$g_1^f = \frac{G_1^f}{l_e} \qquad (1)$$

where l_e is the characteristic element length in the model.

In the nonlocal averaging approach that is used for modelling the OCT tests on $[0_3/60/\text{-}60]_{3s}$ layup, g_2^f can be related to the experimental intra-laminar matrix fracture energy, G_2^f through an effective length scale $h_c^{\text{effective}}$ such that:

$$g_2^f = \frac{G_2^f}{h_c^{\text{effective}}} \qquad (2)$$

where $h_c^{\text{effective}}$ is related to the nonlocal averaging radius and the mesh size. Approximate evaluation of this relationship is provided in Shahabzi (2017).

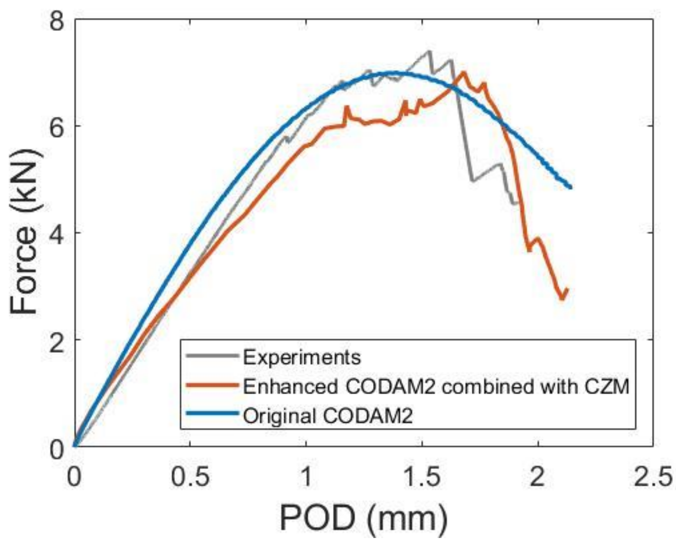
In order to estimate fiber fracture energy density, g_1^f, OCT tests on $[90_3/30/\text{-}30]_{3s}$ layup are simulated. Matrix fracture energy density, g_2^f is assumed to have an insignificant impact on the global response due to the dominance of fiber damage mode in this case. Comparing the numerical and experimental load-displacement curves for $[90_3/30/\text{-}30]_{3s}$ laminates, the fibre fracture energy density is approximated as g_1^f= 210 N/mm^2. Once the fibre fracture energy is obtained, this value is used as input in the simulation of the OCT tests on $[0_3/60/\text{-}60]_{3s}$ layup in order to calibrate the matrix fracture energy density, g_2^f. The numerical analyses are performed using a range of values for g_2^f while keeping all the other damage parameters constant. Based on comparisons of the numerical global behavior (force-displacement curve) and damage mechanisms against the experimental results, g_2^f was found to be in the range of g_2^f = 2 to 5 N/mm^2. The experimental and numerical force vs pin opening displacement (POD) curves for these two layups are shown in Figure 2. Figure 2(b) also displays the numerical force-POD curve for the $[0_3/60/\text{-}60]_{3s}$ layup when the plies are tied together (i.e. cohesive interfaces are not introduced between the plies). It is evident that without incorporation of delamination, the response of this layup cannot be captured properly.

The application of the original sublaminate-based CODAM2 to capture the response of the OCT tests with $[90_3/30/\text{-}30]_{3s}$ layup is also investigated. The laminates's elastic properties and damage initiation strain are derived from standard tensile tests on this laminate layup (load is applied along the *y*-direction, see Figure 1). Damage saturation strain of the laminate for this layup which is associated with fibre breakage in the ±30° layers, is determined using the measured laminate's fracture energy from the OCT tests. The input parameters are listed in Table 3. The predicted force-displacement response using this approach is overlaid in Figure 2(a). It is seen that the original CODAM2 can also provide a reasonable prediction of the overall response for cases where delamination plays a minor role. However, a fully continuum approach cannot be used for simulating the response of the $[0_3/60/\text{-}60]_{3s}$ layup where delamination is significant.

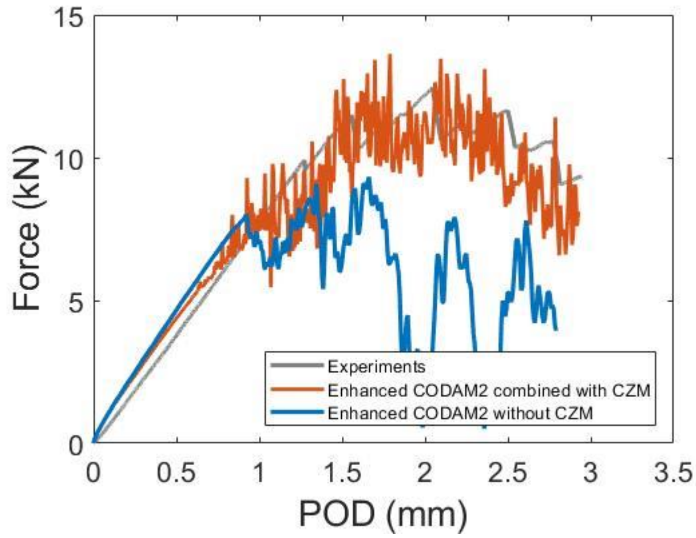
Table 3 Elastic properties and damage parameters of the $[90_3/30/\text{-}30]_{3s}$ laminate used as input to the original sublaminate-based CODAM2

E_x (GPa)	E_y (GPa)	G_{xy} (GPa)	ν_{xy}	Damage initiation strain in y-direction, ε_y^i	Damage saturation strain in y-direction, ε_y^s	Laminate's fracture energy, G_f (kJ/m^2)
73	35	14	0.3	0.008	0.58	86

To verify the calibration methodology for different layups of the same material system, off-axis OCT tests such as $[45_3/15/\text{-}105]_{3s}$ are simulated. The numerical predictions of the force-displacement curve for this layup is shown in Figure 3 and, as expected intuitively, the response lies between the results for the two bounding principal testing directions. This predicted response will be validated with detailed experimental results in the near future in order to instill confidence in the model and its calibration procedure.



(a)



(b)

Figure 2 Comparison of the numerical and experimental force vs POD in OCT tests on NCF laminates: (a) $[90_3/30/\text{-}30]_{3s}$ (b) $[0_3/60/\text{-}60]_{3s}$

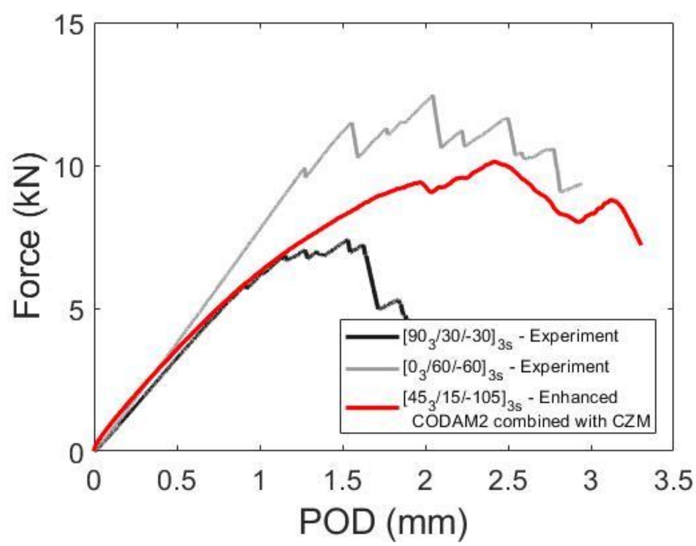


Figure 3 Numerical prediction of the force vs POD curve for $[45_3/15/\text{-}105]_{3s}$ layup superposed on the experimentally obtained curves in the two principal directions

5 CONCLUSION

This work presents the application of a methodology, which combines an enhanced version of the continuum damage model CODAM2 in a mesoscopic context with a discrete approach, to orthotropic NCF laminates in order to predict their general nonlinear response to tensile loading where damage initiation and progression can either be dominated by fibre damage or delamination or combination thereof depending on the orientation of the laminate with respect to the loading direction. A systematic procedure is used to calibrate the required damage parameters. Compact tension tests on notched specimens are carried out in the two principal directions each isolating the two distinct fibre-dominated and matrix/delamination-dominated damage modes. This calibration framework is used to predict the response of other layup sequences which will be validated by further OCT tests in the future.

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