

Damage prediction of carbon-epoxy composites under shear loads using the finite element method

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Abstract

Carbon fiber reinforced polymer composite (CFRP) laminates are used in many applications of the aerospace industry, particularly, in aircraft structural components due to their good stiffness to weight ratios compared to traditionally used aluminium. The ability of accurate prediction of the structural response of composites under complex loadings is crucially important for high-end designs and optimisation of composite structures. The accuracy and predictive capabilities of finite element models in the failure analysis of the carbon-epoxy (IM7/977-3) composite laminates have been evaluated. The cross ply composite laminate with the layup configuration [0,90]_{4S} was numerically modelled under shear loads, and the commercial finite element program ABAQUS was utilised. The failure due to shear loads were analysed using the Hashin's failure criterion. The numerical results were validated by comparing them against the carefully conducted experimental test data. The difference between the experimental and numerically predicted values of the stress and strain were compared to evaluate the accuracy of the finite element models.

Keywords: Composite materials, Carbon-epoxy, Failure criteria, Progressive damage.

Introduction

Composite laminates developed of fiber-reinforced plies are being progressively used in locomotive, aerospace, marine and defence industries as they acquire higher strength than those of metallic structures, and they can be engineered to attain optimum material properties in anticipated directions. A thought-provoking issue in designing composites is delineating numerous failure modes, such as matrix cracking, fiber breakage, fiber kinking, delamination, and fiber/matrix debonding, due to its anisotropic nature [Reifsnider 1980, Rotem 1998, Chen, Morozov et al. 2014]. The difficulty of the problem is supported by the fact that there are only few successfully theories of failure, such as Hashin's failure criterion [Hashin 1983], Tsai-Hill, Tsai-Wu, and Puck's failure criterion that are incorporated by the researchers to predict the damage and failure of the composite materials [Hinton, Kaddour et al. 2004, Kaddour, Hinton et al. 2004, Kaddour, Hinton et al. 2004]. Overall, the load carrying capability of a structure does not become extinct as soon as either damage or failure arises at a material point. The structure can support supplementary loads before it ultimately fails. Thus, it is significant to enumerate damage caused by the commencement of a failure mode and study its progression and the ultimate failure of a structure with an increase in the applied load.

Damage and failure in composite structures can be analysed by either using a micro-mechanics method that deliberates damage and failure at the constituent level or a continuum damage mechanics (CDM) method in which material properties of the composite have been standardised and damage and failure is studied at the ply/lamina level [Sun, Tan et al. 2011]. Damage studied at the constituent level is not only computationally expensive for a real time problem but also involves extensive investigational characterization to determine the values of material properties in the

damage modelling and analysis. Considering a specific case, a statistical approach can be adapted to study the micro-mechanical behaviour of the composite based on Weibull's distribution and the hypothesis that the inclusion or the reinforcements carries no load after it has debonded from the matrix; they thus included the effect of fiber/matrix debonding in Mori–Tanaka's micromechanics method of deriving effective properties [Benveniste 1986]. The effect of the micromechanics-approach of progressive debonding is considered by gradually reducing the elastic constants of the inclusions [Sun, Tan et al. 2011]. The debonding of the fiber and the matrix can be modelled by reducing strengths of the interface among the reinforcement and the matrix [Nguyen and Khaleel 2004]. Additionally, the micro-mechanics assists in analysing the combined effects of micro-cracks and debonding on the effective properties of a composite [Meraghni, Desrumaux et al. 2002]. Moreover, the micro-mechanics approach has a limitations, such as expensive for real time application and the modelling and simulation requires extensive experimental characterisation to determine the material properties.

One of the way to overcome the aforementioned limitation is to use damage mechanics approach and to study damage and failure at the lamina level. Damage mechanics is related with the illustration, or modelling, of damage of materials that is appropriate for obtaining engineering predictions about the fracture of materials, initiation, and propagation of damage and without resorting to a microscopic report that would be difficult for real-world engineering design and analysis [Krajcinovic and Mastilovic 1995]. Damage mechanics demonstrates the typical engineering methodology to model complex phenomena. One of the final task of engineering research is to deliver the insight of the examined phenomenon, and to provide a rational predictive tool applicable in design [Krajcinovic and Mastilovic 1995]. There is a need of failure criterion to predict the initiation of the damage and to analyse its propagation leading to failure.

Ladeveze and Dantec adapted damage mechanics based approach to degrade elastic properties of the composite due to matrix cracking, and fiber breakage and a plasticity theory considering permanent deformations induced under shear loading [Ladeveze and LeDantec 1992]. Hassan and Batra have used three internal variables, such as material properties, loads and ply stacking sequence to illustrate the behaviour of composite after initiation of damage due to matrix cracking, fiber breakage, and fiber/matrix debonding [Hassan and Batra 2008]. Puck and Schürmann have comprehended Hashin's [Hashin 1983] stress-based failure criterion, and proposed methods to degrade elastic parameters of the lamina consequent to the initiation of a damage [Puck and Schürmann 2004]. To predict the damage in three dimensional (3-D) composite structure Donadon et al. have used a smeared crack approach, developed on the basis of damage mechanics [Donadon, Iannucci et al. 2008]. Clegg et al. have considered plastic deformations of a composite material and have well-defined a damage surface in terms of stresses induced [Clegg, Horsfall et al. 1988]. The development of damage variables is articulated in terms of a fracture energy, critical strain, and fracture stress and a local characteristic dimension, which may help to decrease the reliance of computed results upon the finite element (FE) mesh used to analyse the problem numerically. To model and analyse the failure behaviour of composite laminates under shear loads, the Hashin's failure criterion has been used to analyse the failure of the composite laminate. The damage ensues at any point can be characterized by different modes of failure, such as fiber breakage in tension and compression, and matrix cracking in tension and compression. The internal variables used to characterise different modes of failure depends upon values of stresses in Hashin's failure criteria, which are expressed in terms of the strength parameters for the composite, longitudinal and transverse tensile strength, longitudinal and transverse compressive strength, and shear strengths.

In this paper, a load cases has been considered; the cross ply composite laminate with the layup configuration $[0,90]_{4s}$ was numerically modelled under shear loads. The failure has been

investigated using the Hashin's failure criterion. The numerical results were validated by comparing them against the wisely conducted experimental test data. The accuracy and the dependency of the finite element models have been discussed by analysing the difference between the experimental and numerically predicted stress and strain behaviour.

Finite Element Modelling

A finite element simulation was carried out using a commercial software ABAQUS/CAE, which is an engineering tool that is used to solve various engineering problems ranging from linear to non-linear problems that are complex. Finite element modelling of composites is liable on the requirement of the investigation. In ABAQUS, there are numerous methods for composite modelling, such as, macroscopic modelling, microscopic modelling, mixed modelling, discrete reinforcement modelling and sub-modelling. However, the commonly used in finite element simulations of composite material are layered-shells using conventional shell elements. A 16 ply composite laminate was analysed under shear loads.

Material and properties

The IM7/977-3 carbon epoxy composite materials are widely used in aerospace applications. Wide applications of this composite has resulted to analyse and predict the specific properties of the composite to obtain the long service life with minimum maintenance or repair of composites manufactured of IM7/977-3. Table 1 shows the properties of the composite used to numerically analyse the shear and three point bend loads.

Table 1. Properties of unidirectional IM7/977-3 carbon/epoxy composites [Clay 2014].

Property	Magnitude	Description
E_{1T} (GPa)	164.3	Modulus in fibre direction in tension
S_{11}^+ (MPa)	2905	Maximum stress in fibre direction in tension
ϵ_{1T}	0.01610	Maximum strain in fibre direction in tension
ν_{12}	0.3197	Poisson's ratio in fibre direction in tension
E_{2T} (GPa)	8.977	Modulus in 90-degree direction in tension
S_{22}^+ (MPa)	44.4	Maximum stress in 90-degree direction in tension
ϵ_{2T}	0.00499	Maximum strain in 90-degree direction in tension
ν_{21}	0.0175	Poisson's ratio in 90-degree direction in tension
E_{1C} (GPa)	137.4	Modulus in fibre direction in compression
S_{11}^- (MPa)	1274	Maximum stress in 0-degree direction in compression
E_{2C} (GPa)	8.694	Modulus in 90-degree fibre direction in compression
S_{22}^- (MPa)	247.6	Maximum stress in 90-degree direction in compression
G_{12} (GPa)	4.880	Shear modulus calculated from ± 45 -degree tension test
α_1 ($^{\circ}\text{C}$)	0.01e-06	Coefficient of thermal expansion in fibre direction [Tay, Liu et al. 2008]
$\alpha_2 = \alpha_3$ ($^{\circ}\text{C}$)	32.73-06	Coefficient of thermal expansion in transverse direction [Tay, Liu et al. 2008]

Failure criteria

Hashin [Hashin 1980] proposed three dimensional failure criterion of unidirectional fibre-reinforced composites. The criteria are established in terms of quadratic stress polynomials which are

articulated in terms of the transversely isotropic invariants of the applied average stress state. The four failure modes are: tensile fibre failure, compressive fibre failure, tensile matrix failure, and compressive matrix failure.

S_{11}^+ = Value of σ_{11} at longitudinal tensile failure

S_{11}^- = Value of σ_{11} at longitudinal compressive failure

S_{22}^+ = Value of σ_{22} at transverse tensile failure

S_{22}^- = Value of σ_{22} at transverse compressive failure

S_{12} = Complete value of σ_{12} at longitudinal shear failure

S_{23} = Absolute value of σ_{23} at transverse shear failure

If $\sigma_{11} \geq 0$, the Tensile Fibre Failure Criterion is:

$$F_f^+ = \left(\frac{\sigma_{11}}{S_{11}^+} \right)^2 + \alpha \left(\frac{\sigma_{12}}{S_{12}} \right)^2 \geq 1.0 \quad (1)$$

If $\sigma_{11} < 0$, the Compressive Fibre Failure Criterion is:

$$F_f^- = \left(\frac{\sigma_{11}}{S_{11}^-} \right)^2 \geq 1.0 \quad (2)$$

If $\sigma_{22} \geq 0$, the Tensile Matrix Failure Criterion is:

$$F_m^+ = \left(\frac{\sigma_{22}}{S_{22}^+} \right)^2 + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 \geq 1.0 \quad (3)$$

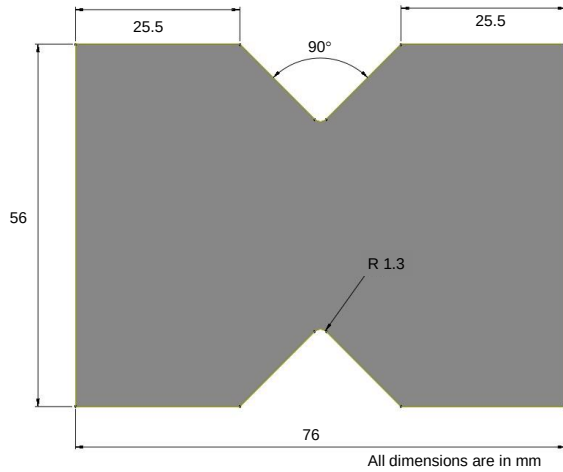
If $\sigma_{22} < 0$, the Compressive Matrix Failure Criterion is:

$$F_m^- = \left(\frac{\sigma_{22}}{2S_{23}} \right)^2 + \left[\left(\frac{S_{22}^-}{2S_{23}} \right)^2 - 1 \right] \frac{\sigma_{22}}{S_{22}^-} + \left(\frac{\sigma_{12}}{S_{12}} \right)^2 \geq 1.0 \quad (4)$$

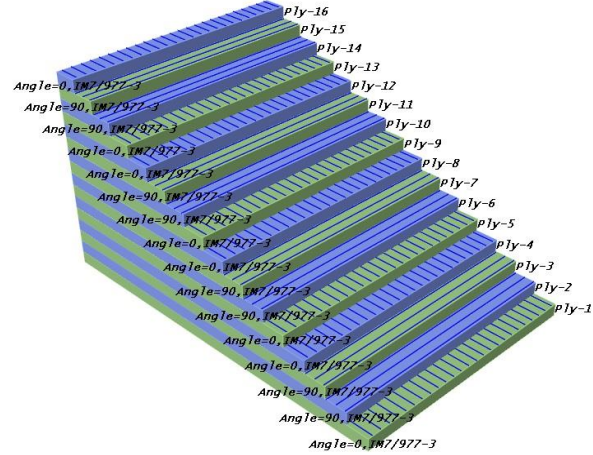
The Hashin's equations include two user-specified parameters: α and S_{23} . α is the user-specified coefficient that determines the contribution of the longitudinal shear stress to fibre tensile failure. Permissible range is $0.0 \leq \alpha \leq 1.0$, and the default value is $\alpha=0$. S_{23} is the transverse shear strength of the composite material. During modelling α is maintained 1 and S_{23} has been extracted from the literature [Tay, Liu et al. 2008]. α is a coefficient that determines the contribution of the shear stress to the fibre tensile initiation criterion. Based on Hashin's model proposed in 1980 [Hashin 1983] α is maintained as 1. The accuracy and predicative capability of the Hashin's failure criterion has been analysed, under shear loads, and the behaviour of the composite laminates are discussed below.

Model Geometry

A double-notched cross ply composite laminate is of 76 mm length and 56 mm width are analysed under shear loads, with a notch tip radius of 1.3 mm as shown in (Figure 1). The composite laminate is made of 16 ply of 2 mm thick, with equal number of 0 and 90 degree fiber oriented plies, hence the composite layup configuration is balanced and symmetric (Figure 1).



(a)



(b)

Figure 1: (a) Model geometry and (b) Layup configuration of the composite laminate

Meshing and Boundary Conditions

ABAQUS stress/displacement shell elements use a Lagrangian formulation, where the element relocates; bestowing to the behaviour of the constituent material. Guassian Quadrature is used to solve for static equilibrium at each integration point within the element. Shell elements are defined in ABAQUS using the *SHELL SECTION. This specifies the material, shell element thickness and number of through thickness integration points. The optional composite parameter permits the user to define separate layers and orientations. Using this type of section characterize a multiple layered, complex, laminate can be precisely described and allocated to shell elements.

A convergence study is conducted to determine the minimum number of triangular elements required to produce converged mechanical properties and failure patterns (Figure 2). This is achieved by starting with a small number of elements and continuously refining the mesh until a maximum of 5 % difference in the maximum principal stress is observed. The difference in the maximum principal stress between the 0.5 mm and 0.25 mm mesh size is 4.22%, which is less than 5%. It is preferred to select the mesh size 0.5 mm over 0.25 mm, because the convergence difference below 5% is acceptable and the choosing mesh size 0.5 mm saves the computational time and memory.

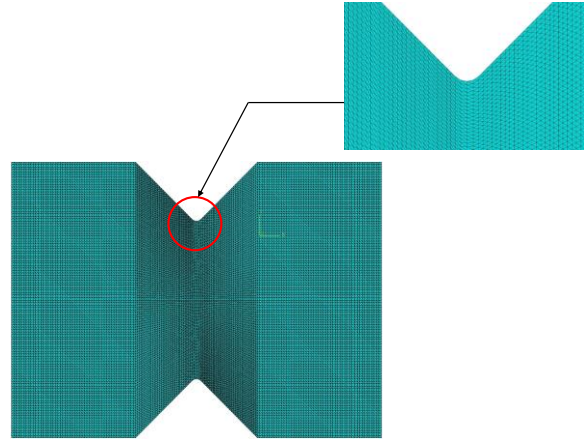


Figure 2: Finite element mesh of the composite laminate

The fiber reinforcement in the double-notch shear test modelled composite is apparently planar, and its principal axis is lateral to the model axis, planes of low shear strength will be existing, comprising the plane that is parallel to the bottoms of the two opposing notches. Under the shear loading, a shearing action is developed along the specimen centre-line between the notch roots, apparently leading to a failure on this shear plane. The loading and the boundary conditions are shown in (Figure 3). The fixture used in experimental test, has been designed to minimize the compressive, tensile and bending influence on the specimen under test. In the similar way the model developed has been constrained to bend and behaviour non-linearly.



Figure 3: Boundary and loading conditions

Results and Discussions

The fundamental problem with the Double-Notch Shear test models is that significant stress concentrations occur at the roots of the notches, resulting in premature failure. The below (Figure 4) shows the increased shear stress concentration in the roots of the notches of both fibers oriented in longitudinal and transverse direction.

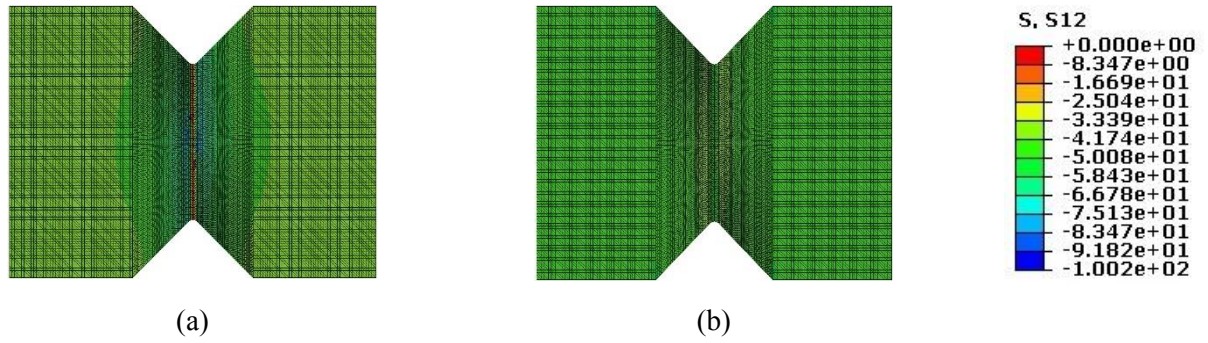


Figure 4: Stress distribution of [0,90]_{4s} composite laminate under shear loads (a) 0-degree ply and (b) 90-degree ply

The shear response is dependent on the fiber orientation in the composite laminate and it decreases from longitudinal direction (0-degree) to transverse direction (90-degree). The finite element model was developed to notice a simple shear state generated on the composite ply with double-notch. Since, the model's parallel faces are in opposite direction, under shear loads the model will develop horizontal cracks and delamination. But the model develop is based on the composite shell elements, hence the model cannot be used to predict delamination

The shear stress strain behaviour for [0/90]_{4s} model revealed, after a few increment of loading both the curves showed proportional behaviour at the commencement. Nevertheless, just beyond the comparative limit, they turn into nonlinear due to the build-up of matrix cracks. As stress was increased, the eccentricity from the linearity also increased due to the initiation and propagation of the cracks along the fiber direction and failure of some fibers by tension in the transverse loading direction. The materials exhibited first ply failure at the shear stress of 74 MPa, after which the model under goes series of damage in the elements of the adjacent plies, those are the elements which fail to carry loads. The maximum shear stress of 86 MPa and 81 MPa are observed under experimental and modelled results. The difference between the experimental and modelled results are 6% (Figure 5).

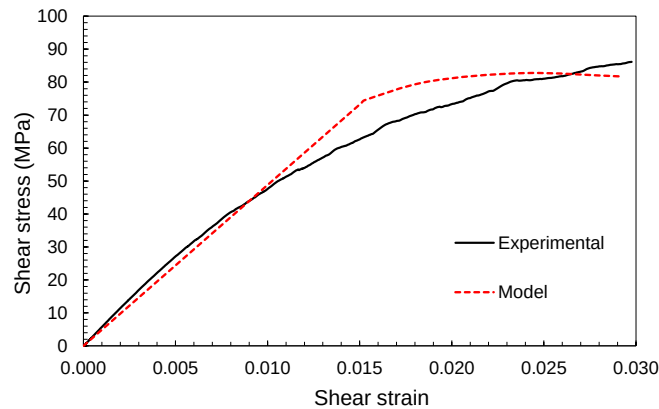


Figure 5: Stress strain behaviour of [0,90]_{4s} composite laminate under shear loads

Failure

The damage and failure prediction helps in knowing the failure pattern and critical elements that undergo more deformation, leading to catastrophic failure. Implementing Hashin's failure criterion the matrix and fiber failure modes are analysed and discussed below. The red coloured area represents the damaged portion.

Fiber compression

Under shear loads the developed model does not show any significant amount of damage in the fibers under compression. Because the fibers oriented in longitudinal and transverse direction has the potential to withstand compressive loads leading to failure (Figure 6).

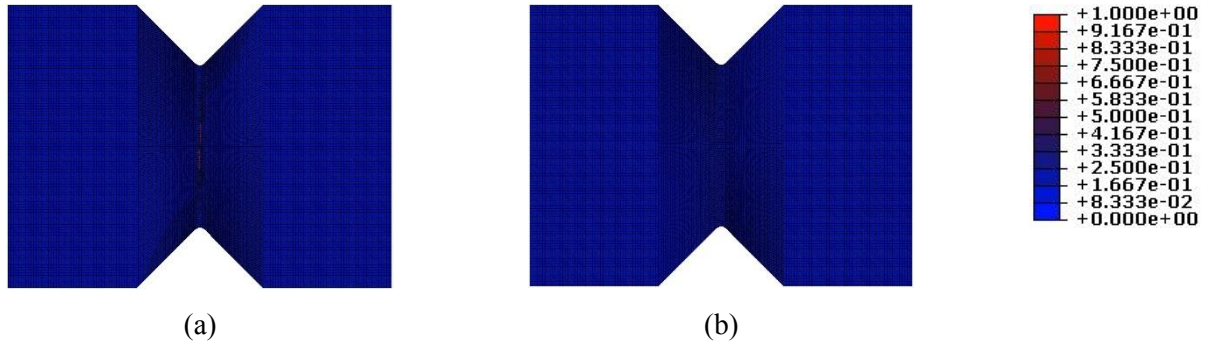


Figure 6: Comparison of Fiber compression failure pattern (a) 0-degree ply and (b) 90-degree ply

Fiber tension

A significant amount of damage is observed in both the plies (0-degree and 90-degree). The fibers oriented in longitudinal direction shows an initiation of the damage; in line with the notch tip. The damage propagates with the increase in load, and the direction of damage propagation is inclined at an angle of 45° to the orientation of fibers. Additionally the damaged areas shows the tensile failure zones in the model (Figure 7).

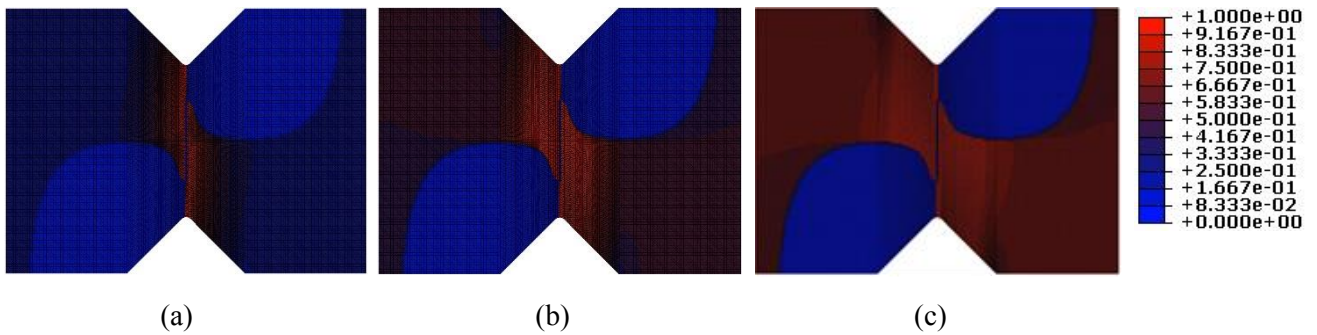


Figure 7: Fiber tension failure pattern of $[0,90]_{4s}$ composite laminate under shear loads

Comparatively, the damage initiation and propagation in 90-degree plies are less, with respect to 0-degree plies (Figure 8). It is mainly due to the shear response is dependent on the fiber orientation, the shear response is maximum in fibers oriented in longitudinal direction, and it decreases as the fibers are oriented in transverse direction. Hence, the use of computational model, and implementing the Hashin's failure criteria shows the dependence of shear failure upon the orientation of fibers.

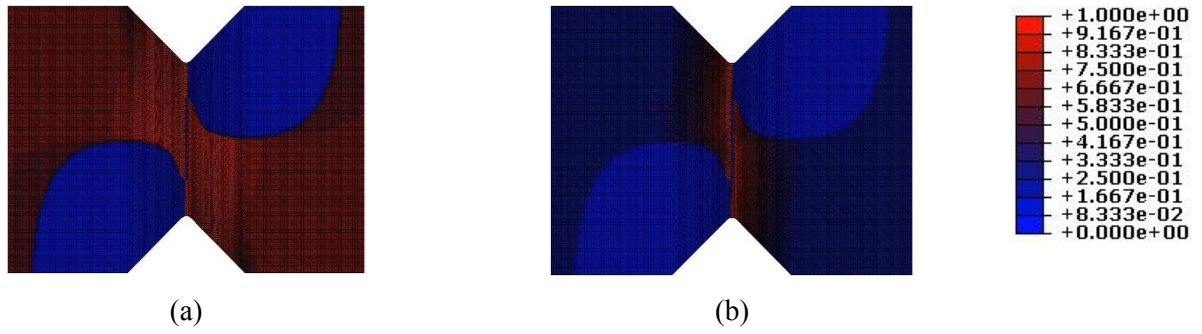


Figure 8: Comparison of Fiber tension failure pattern (a) 0-degree ply and (b) 90-degree ply

Matrix compression

The fiber reinforced polymer matrix composite laminate with v-notches suffers from loss in its stiffness, strength, and service life due to notch-enhanced stresses. The presence of notch results in prompting new modes of damage in the matrix of the composite laminate or by accelerating the growth of the existing damage. Figure 9 shows the initiation of the matrix damage at the centre of the composite in line with the notch root. A rapid increase in damage areas has been observed in the subsequent increment between the notch root tips. It is mainly due to global stiffness reduction and decrease in strength in the respective failure areas of the composite as shown in (Figure 9). However, the matrix damage developed by a double-notch is moderately small compared to the effects of a notch on the ultimate strength of the model.

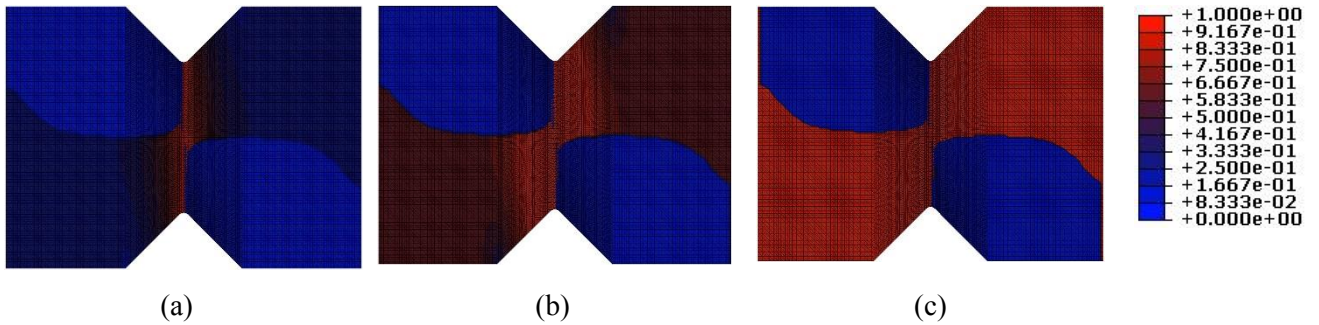


Figure 9: Matrix compression failure pattern of [0,90]_{4s} composite laminate under shear loads

Relatively the matrix damage is more dominantly observed in the fibers oriented in longitudinal direction, but the areas of damage are comparatively same (Figure 10). This conveys the fiber orientation doesn't play a vital role in the regions of the matrix damage.

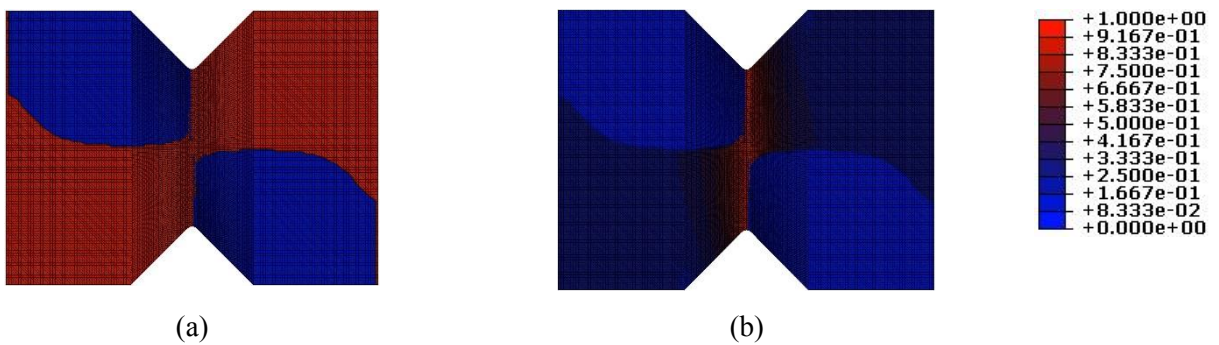


Figure 10: Comparison of matrix compression failure pattern (a) 0-degree ply and (b) 90-degree ply

Matrix tension

It has been observed from the experiments that the failure mechanisms leading to failure were the matrix cracks in transverse direction. Furthermore increase in loads will result in longitudinal cracks (splits) appearing and propagating in the longitudinal direction. A similar way of damage initiation and propagation has been observed in the finite element model, specifically in the matrix damage. The matrix which fails under tension also exhibits similar pattern of failure as matrix fail under compressive nature of the force, but the location of damage is opposite in nature (Figure 11). The region where matrix are damage is entirely dependent on the loading and the boundary conditions.

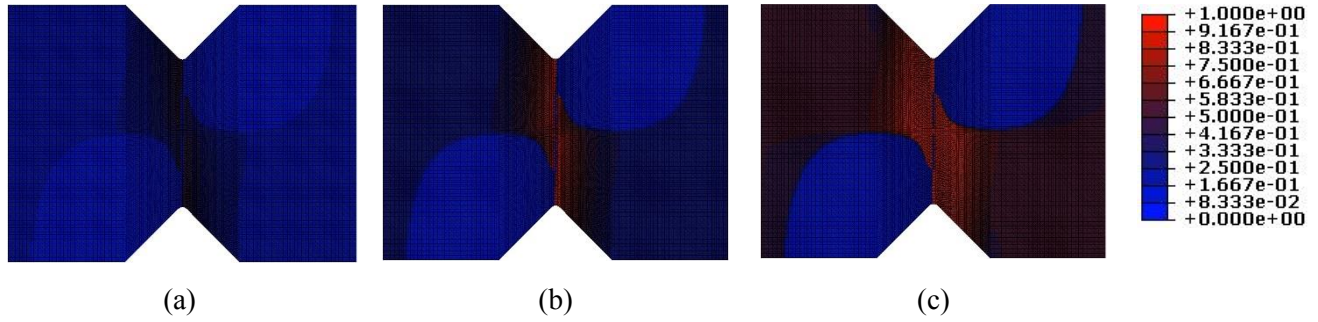


Figure 11: Matrix tension failure pattern of [0,90]_{4s} composite laminate under shear loads

When the matrix in the 0-degree laminate are fully damaged, the matrix in the 90-degree laminate are only 20% damaged. Additionally, it is evident that for both matrix tensile and matrix compressive damage are dominantly observed in 0-degree plies (Figure 12).

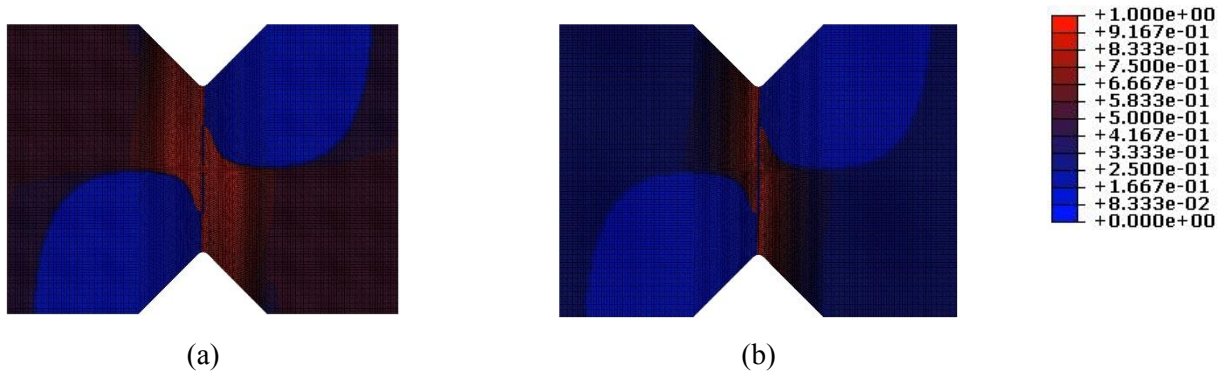


Figure 12: Comparison of matrix tension failure pattern (a) 0-degree ply and (b) 90-degree ply

The damage patterns observed in simulated results are comparable with the experimental results. Figure 13 shown below shows the failed test specimen. The visible damage pattern is of 0-degree ply, which is comparable with the simulated results (Figure 7, Figure 9 and Figure 11).



Figure 13: failure of carbon-epoxy specimen under shear loads

Conclusions

A progressive failure approach was applied to study the failure in terms of transverse and longitudinal fracture of cross-ply laminates with double-notch. The local matrix and fiber dominated failure was analysed by adapting the Hashin's failure criteria. The shear stress and strain behaviour of the model was analysed by a uniform stiffness reduction approximation. In the initial stages of loading the material behaved linearly, after reaching a yield shear stress of 75 MPa a non-linear behaviour has been observed with the development of damage in transverse direction. Furthermore increment of the load resulted in rapid development and propagation of damage in longitudinal direction. A difference of 6% between the experimental and modelled shear stress has been observed. Additionally, it has been evidently observed that a matrix dominated failure can be predicted in the double-v-notch composite specimen. It was found that the failure in shear model of $[0, 90]_{4S}$ was due to pure shear along the line between V-notches, where shear cracks were almost parallel to the loading direction, but in the off axis angle 45° , cracks were initiated at roots of notch and propagated in the direction of fibers.

Reference

- Benveniste, Y. (1986). "On the Mori-Tanaka's method in cracked bodies." *Mechanics Research Communications* 13(4): 193-201.
- Chen, J.-F., E. V. Morozov and K. Shankar (2014). "Simulating progressive failure of composite laminates including in-ply and delamination damage effects." *Composites Part A: Applied Science and Manufacturing* 61(0): 185-200.
- Clay, S. (2014). "Assess and Quantify the Benefits of Applying Damage Tolerant Design Principles to Advanced Composite Aircraft Structures.", FA8650-08-D-3858. U. S. A. F. R. Laboratory.
- Clegg, W. J., I. Horsfall, J. F. Mason and L. Edwards (1988). "The tensile deformation and fracture of Al-"Saffil" metal-matrix composites." *Acta Metallurgica* 36(8): 2151-2159.
- Donadon, M. V., L. Iannucci, B. G. Falzon, J. M. Hodgkinson and S. F. M. de Almeida (2008). "A progressive failure model for composite laminates subjected to low velocity impact damage." *Computers & Structures* 86(11-12): 1232-1252.
- Hashin, Z. (1980). "Failure criteria for unidirectional fiber composites." *Journal of applied mechanics* 47(2): 329-334.
- Hashin, Z. (1983). "Analysis of Composite Materials—A Survey." *Journal of Applied Mechanics* 50(3): 481-505.
- Hassan, N. M. and R. C. Batra (2008). "Modeling damage in polymeric composites." *Composites Part B: Engineering* 39(1): 66-82.
- Hinton, M. J., A. S. Kaddour and P. D. Soden (2004). "A further assessment of the predictive capabilities of current failure theories for composite laminates: comparison with experimental evidence." *Composites Science and Technology* 64(3-4): 549-588.

- Kaddour, A. S., M. J. Hinton and P. D. Soden (2004). Chapter 6.1 - Predictive capabilities of nineteen failure theories and design methodologies for polymer composite laminates. Part B: Comparison with experiments. Failure Criteria in Fibre-Reinforced-Polymer Composites. M. J. H. S. K. D. Soden. Oxford, Elsevier: 1073-1221.
- Kaddour, A. S., M. J. Hinton and P. D. Soden (2004). "A comparison of the predictive capabilities of current failure theories for composite laminates: additional contributions." *Composites Science and Technology* 64(3-4): 449-476.
- Krajcinovic, D. and S. Mastilovic (1995). "Some fundamental issues of damage mechanics." *Mechanics of Materials* 21(3): 217-230.
- Ladeveze, P. and E. LeDantec (1992). "Damage modelling of the elementary ply for laminated composites." *Composites Science and Technology* 43(3): 257-267.
- Meraghni, F., F. Desrumaux and M. L. Benzeggagh (2002). "Implementation of a constitutive micromechanical model for damage analysis in glass mat reinforced composite structures." *Composites Science and Technology* 62(16): 2087-2097.
- Nguyen, B. N. and M. A. Khaleel (2004). "A mechanistic approach to damage in short-fiber composites based on micromechanical and continuum damage mechanics descriptions." *Composites Science and Technology* 64(5): 607-617.
- Puck, A. and H. Schürmann (2004). Chapter 5.6 - Failure analysis of FRP laminates by means of physically based phenomenological models. Failure Criteria in Fibre-Reinforced-Polymer Composites. M. J. H. S. K. D. Soden. Oxford, Elsevier: 832-876.
- Reifsnider, K. (1980). "Fatigue behavior of composite materials." *International Journal of Fracture* 16(6): 563-583.
- Rotem, A. (1998). "Prediction of Laminate Failure with the Rotem Failure Criterion." *Composites Science and Technology* 58(7): 1083-1094.
- Sun, X. S., V. B. C. Tan and T. E. Tay (2011). "Micromechanics-based progressive failure analysis of fibre-reinforced composites with non-iterative element-failure method." *Computers & Structures* 89(11-12): 1103-1116.
- Tay, T., G. Liu, V. Tan, X. Sun and D. Pham (2008). "Progressive failure analysis of composites." *Journal of Composite Materials*.