NON-LOCALIZED FAILURE CRITERION FOR OPEN-HOLE AND PINNED JOINT COMPOSITE STRUCTURE USING CHARACTERISTIC VOLUME APPROACH

Arruck Tragangoon, Baramee Patamaprohm and Jacques Renard

Centre des Matériaux, Mines ParisTech, CNRS UMR 7633, BP 87, 91003 Evry, France
Email: arruck.tragangoon@mines-paristech.fr, Web Page: http://www.mat.mines-paristech.fr

Keywords: woven composite, non-localized failure criterion, characteristic area/volume

Abstract

This study proposed a non-localized failure criterion to predict the failure of composite laminate structure induced by local stress concentration. The twill glass/polyamide6 composite specimens with an open-hole as well as a bolted joint have been investigated. Based on the classical characteristic distance approach, the proposed method predicts the structure failure using the characteristic volume identified by the aide of experimental results and numerical simulations. The average values of failure criteria indices over this characteristic volume were used to determine the failure. The numerical simulations were carried out by taking into account anisotropic and non-linear behaviors of composite. By post-processing, the failures of specimens with different geometries were predicted and showed a good agreement with the experimental results.

1. Introduction

Currently, automotive industrials are focusing on the weight reduction replacing several metallic parts with composites due to their favorable high mechanical properties to weight ratio. In particular for the woven composites, a good resistant to delamination is an additional advantage. In many structural applications, the composites with open holes or mechanical joint are very common. In order to predict the strength of composite laminates with stress concentration due to the presences of holes, many approaches have been proposed. Each of them has its own advantages. The well-known point stress and average stress proposed by Whitney and Nuismer [1] are the characteristic distance approach which is widely used in the industry due to its simplicity. Based on this classic method, many authors proposed modifications, for example, effective stress fracture models which utilize a characteristic length [2], a characteristic length based on FEM with progressive damage approach [3]. Recently, some authors proposed a characteristic volume approach [4, 5] which is practical to apply due to its less geometry-dependence. Moreover, this characteristic volume approach has been also proposed for the bearing failure onset of pin-contact in composite laminates [6], while some author has been proposed failure area index method [7] predicting failure from an average value of failure indices of damaged elements.

In this work, we proposed a non-localized failure criterion for composites with an open hole or a bolted joint. The mechanical properties of composite laminate were first determined experimentally. Then, experimental tests were conducted on open-hole specimens and bolted composite joints as validations. The identification of characteristic volume and criterion's validation has been carried out using FEM simulations with additional post-processing.

Excerpt from ISBN 978-3-00-053387-7

2. Non-localized approach

For composite materials, it is well known that when the stress field is non-uniform induced by any stress concentrations, the failure criteria locally applied on the structure would result in an underestimation of the failure load. As pointed out by many authors, the structure failure does not occur immediately after minor failure but sufficient volume. Due to this fact, the failure prediction using characteristic length is proposed, in which the characteristic length needs to be determined experimentally. However, since the characteristic length is sensitive to geometry variation, the method proposed in this work uses a characteristic volume to determine the failure of the structure under consideration. The shape of characteristic volume was chosen to be cylindrical which reduces the effect of stress singularity at a holed edge and has only diameter and thickness to identify.

The failure of structure is obtained when an average value of interested quantity over the characteristic volume is satisfied. The calculated average value might be the stresses or the failure criteria. In this work, the failure criteria used to predict the structure failure were the maximum stress criterion and Hashin failure criteria which is originally proposed for unidirectional composites. Some failure modes of Hashin were chosen to use with woven composites as described in the following section. The failure indices of these failure criteria are determined at every material points in a characteristic volume, and then averaged over this volume in the following manner

$$\overline{\boldsymbol{FI}} = \frac{\mathbf{1}}{\boldsymbol{V}} \int_{\boldsymbol{V}} \boldsymbol{FI} \cdot \boldsymbol{dv} \tag{1}$$

where $\boldsymbol{FI}$ stands for local failure index, $\overline{\boldsymbol{FI}}$ is the average failure index over characteristic volume.

3. Modeling of material behavior

Material investigated in this work is a twill glass/polyamide 6 composite balanced in warp and weft with volume fraction of 45%. The laminates have a thickness of 2 mm (4 plies in total). In order to characterize a material behavior, series of tensile and compressive tests have been carried out according to ASTM D3039, and ASTM D6641, respectively. Furthermore, the bending tests (ISO 14125) were also carried out to determine non-linear behavior parameters as described in the following paragraph. The results are shown in the Table 1, where $\boldsymbol{X}$ is the strength in the warp direction, $\boldsymbol{Y}$ is the strength in the weft direction, and subscripts $\boldsymbol{T}$ and $\boldsymbol{C}$ stand for tensile and compressive, respectively.

Table 1. Results of tensile and compressive tests.

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C* (MPa)	S_{12} (MPa)	S_{13} (MPa)	S_{23} (MPa)
20.65	22.14	2.96	0.07	447.65	360.94	434.19	360.94	119.83	43.3	41.21

* Y_C is assumed to be equal to X_C due to material availability

Excerpt from ISBN 978-3-00-053387-7

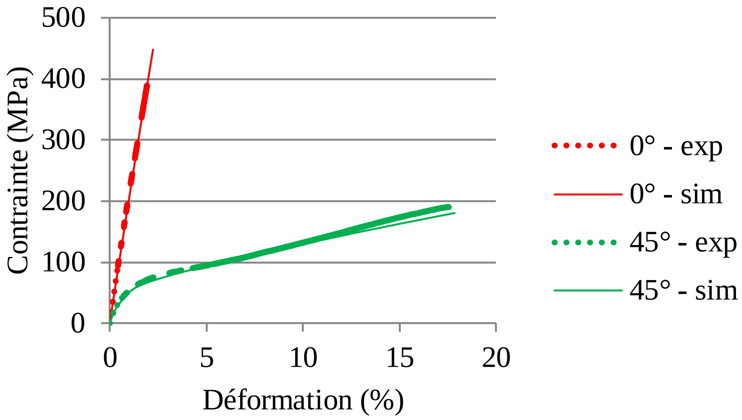


Figure 1. Comparison of numerical and experimental results in fiber and off-axis directions for tensile tests.

As shown in Fig. 1, the composite show a linear response in the fiber direction up to failure, while in 45° direction, it presents high degree of non-linear response. This non-linear behavior results from a combination of several degradations including plasticity of matrix, micro damages, and fiber reorientations toward loading direction, and exists only in the off-axis directions, which is contributed by the in-plane shear stress. Therefore, we adopted the classical plasticity theory of anisotropic material to model the non-linear behavior, called "pseudo-plasticity". Hill's yield criterion was modified in this work to yield only in the off-axis directions. Indeed, non-linear behavior is only contributed by the in-plane shear stress.

$$F(\sigma_{22}-\sigma_{33})^2+G(\sigma_{33}-\sigma_{11})^2+H(\sigma_{11}-\sigma_{22})^2+2L\sigma_{23}^2+2M\sigma_{31}^2+2N\sigma_{12}^2=1 \quad (2)$$

Generally, the parameters of Hill's yield criterion are determined from yield strengths of each stress components. Thus, the yield strengths of all stress components except the in-plane shear stress were assumed to be equal to the corresponding failure strengths to ensure that there is no plasticity contributed by these components. For the in-plane shear stress component, the yield strength was determined experimentally from the tensile tests in 45° direction. The resulting Hill's yield criterion parameters are F = 1.169×10^{-3}, G = 1.099×10^{-3}, H = 2.43×10^{-5},L = 0.198, M = 0.18, N = 1.5. Furthermore, the plastic flow was also determined from tensile tests in 45° direction and modeled by non-linear isotropic hardening model in which its monotonic loading response can be expressed by

$$\sigma_{eq,y}=\sigma_{eq,y}^0+H\varepsilon_{eq}^P+Q\left(1-e^{-b\varepsilon_{eq}^P}\right) \quad (3)$$

where $\sigma_{eq,y}^0$ = 15, H = 880, Q = 37, b = 300. The 2D numerical simulations were conducted on Abaqus in the fiber direction (0°) and off-axis direction (45°), and the results are compared with the experiments as also shown in Fig. 1.

4. Open-hole specimen

In this section the prediction of failure loading on open-hole composite is presented. As mentioned in the earlier section that a non-uniform stress distribution caused by stress concentration leads to the underestimation of failure load predicted by local failure criteria and we present here the non-localized approach to carry it out. The experimental tests were first conducted to determine the characteristic volume by the aide of numerical simulation, and then the failure loads of other specimens with different configurations were numerically predicted and compared to experimental results.

Excerpt from ISBN 978-3-00-053387-7

4.1 Experiments

The test procedure was guided by ASTM D5766. All open-hole specimens used in this work have the same width of 50 mm. but different in hole diameter and material orientation as summarized in Table 2. Tensile tests on open-hole specimens were carried out by Instron universal testing machine. The extensometer and video extensometer were used as observation methods.

Table 2. Geometries of open-hole specimen.

Configuration	W50D3	W50D6.8	W50D6.8-15	W50D6.8-30	W50D6.8-45	W50D10
Width (mm)	50	50	50	50	50	50
Diameter (mm)	3	6.8	6.8	6.8	6.8	10
D/W	0.06	0.14	0.14	0.14	0.14	0.2
Orientation	0°	0°	15°	30°	45°	0°

4.2 Numerical simulations

The 2D numerical simulations of open-hole specimen were conducted on Abaqus with introduction of plasticity mentioned in the section 3. Meshes of all specimen configurations were created and loaded up to failure loads of each configuration. Fig. 2 shows the comparison of numerical and experimental results of the configuration W50D6.8 with 4 different material orientations; 0°, 15°, 30°, and 45°.

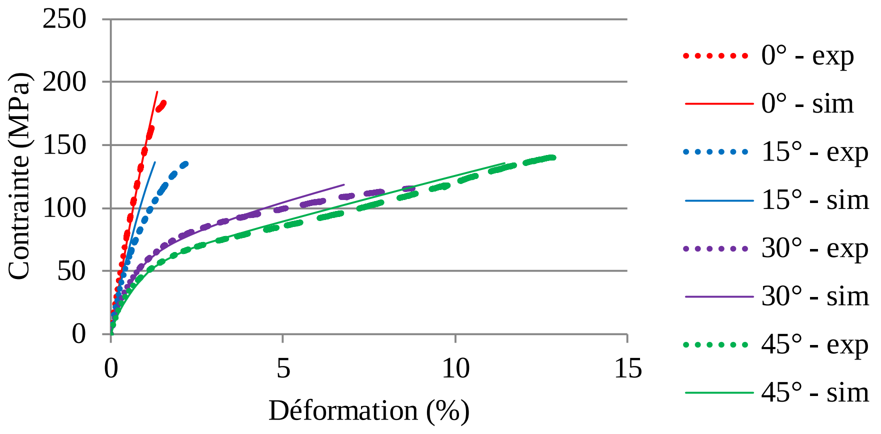


Figure 2. Numerical simulations of W50D6.8 with different material orientations against experiments.

From the results shown in Fig. 2, the simulations have a good agreement with experiments except in the direction 15°. This is due to the fact that the non-linear behavior described by classical plasticity theory cannot take into account all of non-linear sources, especially the fiber reorientations of composite loaded in off-axis direction, which is more severe in the direction 15°. As shown in Fig. 3, the fibers in weft direction tried to reorient toward loading direction.

Excerpt from ISBN 978-3-00-053387-7

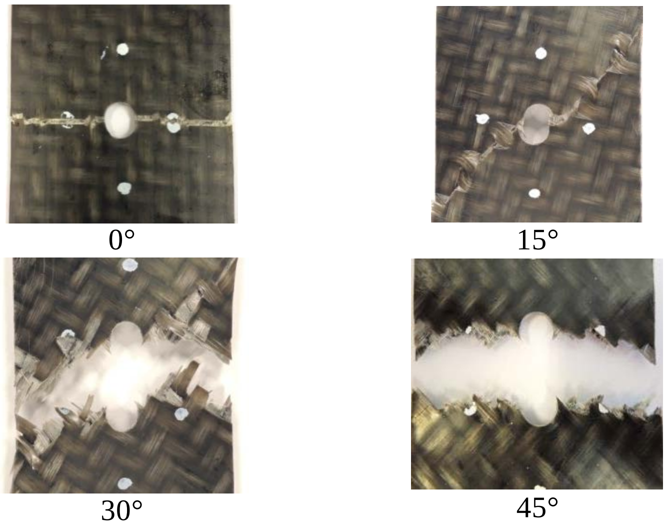


Figure 3. W50D6.8 specimens with different material orientations at failure.

4.3 Post-processing for failure prediction

To predict the specimen failure, the stress fields around the hole of each configuration were exported from Abaqus using Abaqus Scripting Interface for post-processing in Matlab. A python script was written to create the zone of interest around the hole, and then write all stress components at the interpolation points situated in the zone of interest as a function of spatial coordinates in a text file.

The failure criteria used in this work are Maximum stress criterion (Eq. 4) and Hashin failure criteria, which is used to predict the failure of unidirectional composites. Thus, for woven composites, only tensile and compressive fiber failures are applied to the warp and the weft directions (the failures in all direction 0°, 15°, 30°, 45° were clearly due to the fiber breaks, Fig 3), as stated in Eq. 5-6 for the warp direction.

Maximum stress criterion, $MSTRS$

$$\boldsymbol{MSTRS = max\left(\frac{\sigma_{11}}{S_{11}}, \frac{\sigma_{22}}{S_{22}}, \frac{\sigma_{12}}{S_{12}}\right)} \tag{4}$$

Hashin tensile fiber failure criterion, $HSNFTCRT$ $(\sigma_{11} \geq 0)$

$$\boldsymbol{HSNFTCRT = \left(\frac{\sigma_{11}}{X_T}\right)^2 + \left(\frac{\tau_{12}^2}{S_{12}^2}\right)^2} \tag{5}$$

Hashin compressive fiber failure criterion, $HSNFCCRT$ $(\sigma_{11} < 0)$

$$\boldsymbol{HSNFCCRT = \left(\frac{\sigma_{11}}{X_C}\right)^2} \tag{6}$$

where X_T , X_C : tensile and compressive strength in the warp direction
Y_T , Y_C : tensile and compressive strength in the weft direction
S_{12} : the in-plane shear strength
S_{11} equals X_T for $\sigma_{11} \geq 0$ and equals X_C for $\sigma_{11} < 0$
S_{22} equals Y_T for $\sigma_{22} \geq 0$ and equals Y_C for $\sigma_{22} < 0$

Excerpt from ISBN 978-3-00-053387-7

In Matlab, all stress components were imported as well as their coordinates to determine failure indices of Maximum stress and Hashin failure criteria at each point. Then, an average value of failure indices inside the characteristic volume which is reduced from a cylinder to a circle for 2D problem can be determined by Eq. 1 with area, A instead of volume, V. This characteristic circle sweeps around the hole edge to determine and locate the maximum average value of failure indices, as shown in Fig 4. Finally, the diameter of characteristic circle, D_c was determined from the diameter resulting in the average failure index, $\overline{FI}$ = 1.

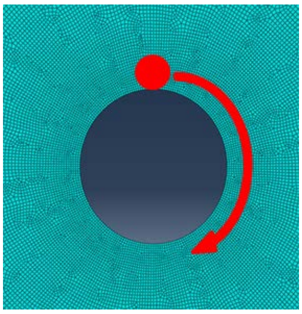


Figure 4. Maximum average failure indices are determined by sweeping the characteristic circle around the hole edge.

4.4 Results and discussions

The characteristic diameters, D_c for Maximum stress criterion (MSTRS) and Hashin failure criteria (HSNCRT) were first determined from the specimen configuration W50D6.8 which is 0° orientation, and equaled 0.61 mm. and 0.68 mm, respectively. Then, $D_{c,MSTRS}$ = 0.61 and $D_{c,HSNCRT}$ = 0.68 were used to predict failure of other configurations. The simulated stress fields around the hole at failure of other configurations were then exported for post-processing purpose. The resulting average failure indices, $\overline{FI}_{MSTRS}$ and $\overline{FI}_{HSNCRT}$, determined by $D_{c,MSTRS}$ and $D_{c,HSNCRT}$, are shown in the Table 3 below.

Table 3. Resulting average failure indices of each specimen configuration.

Configuration	Maximum stress criterion		Hashin failure criteria	
	$\overline{FI}_{MSTRS}$	% error	$\overline{FI}_{HSNCRT}$	% error
W50D3	1.10	10	1.27	27
W50D6.8*	1.00	0	1.00	0
W50D6.8-15	0.95	5	0.98	2
W50D6.8-30	0.98	2	1.44	44
W50D6.8-45	0.97	3	1.29	29
W50D10	1.02	2	1.04	4

* W50D6.8 is the reference geometry used to determine the characteristic diameter.

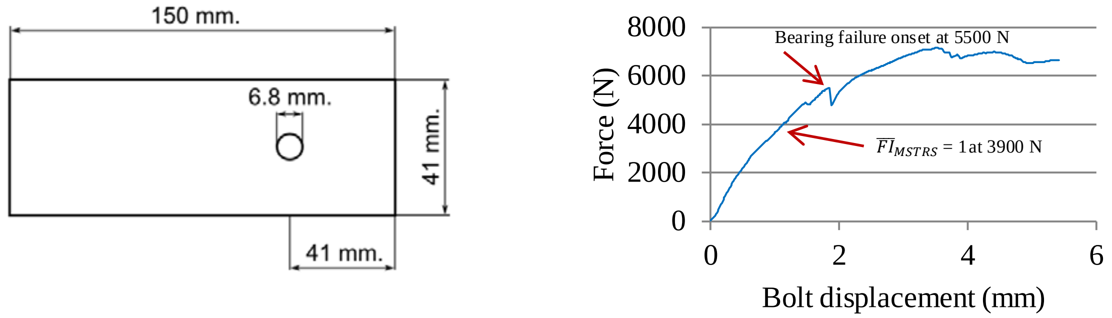
From the results shown in Table 3, the Maximum failure criterion is more suitable to predict the failure using the Non-localized approach with maximum error of 10%, while the Hashin failure criteria resulted in maximum error of 44%. This can be explained by, for material direction 0° where the shear stress does not exist, the squared term in the mathematical expressions of Hashin failure criteria. The $D_{c,HSNCRT}$ was identified from the W50D6.8 configuration, so that it resulted in no errors but, for other configurations, the errors increase exponentially due to the squared term of normal stress component.

Excerpt from ISBN 978-3-00-053387-7

For other material directions where the shear stress is more elevated, the failure index is the combination of normal and shear components which results in overestimation up to 44% error.

5. Application on bolted composite joint

The Non-localized approach was also applied on the bolted composite joint. The specimens had the width of 41 mm, a hole diameter of 6.8 mm, and the distance between the hole and the end edge of 41 mm, as shown in Fig. 5A. The geometry of specimens was chosen in order to obtain the bearing failure mode as proposed by Collings [8]. The test procedure was guided by ASTM D5961 with hand tight as clamping force and the bolt displacement was measured by digital image correlation. The experimental curve of force vs. displacement of pin is shown Fig. 5B.



A) B)

Figure 5. A) Bolted composite joint geometry. B) Experimental result of bolted composite joint test.

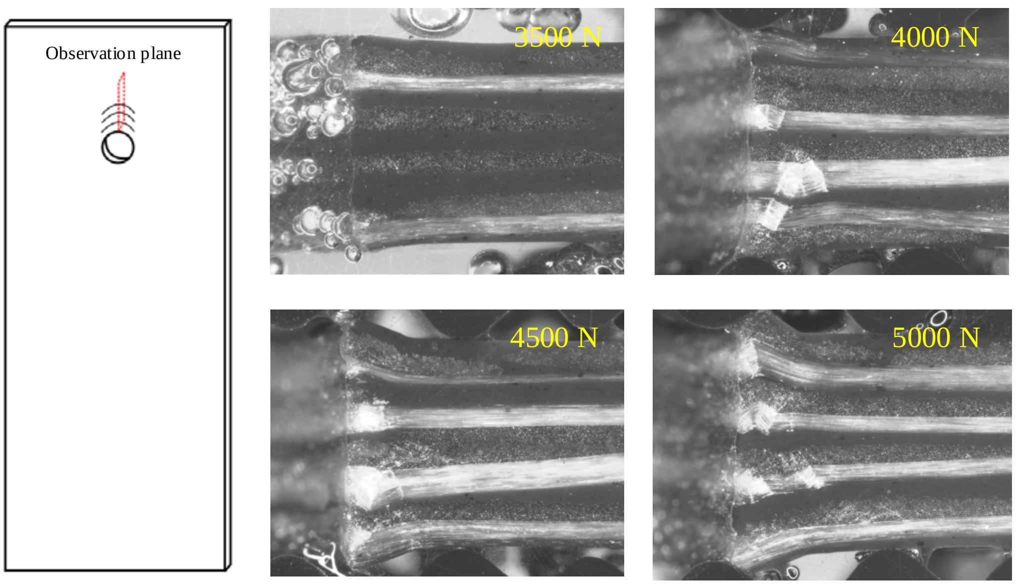


Figure 6. Observations through a microscope of bolted composite specimens (10-time magnification).

The numerical simulations were also conducted on Abaqus to determine the failure of the test specimen by the same procedure proposed in the section 4. Since the results from Maximum stress criterion were better, only this failure criterion was applied. As also shown in Fig. 5B, the predicted failure load is 3900 N where $\overline{FI}_{MSTRS}$ = 1, while the experimental results showed the visible initiation

Excerpt from ISBN 978-3-00-053387-7

of bearing failure at 5500 N. Did the proposed method underestimate the failure load compared to the experimental results?

The failure of composite mechanical joint is well-known as a complicated damage due to the accumulation of various phenomenons such as damage on the contact surface, fiber kink bands, and delamination. Modeling of these phenomenons needs a hard work on progressive damage. Since our work was dedicated to industrial application, the local damage initiation is more important for conceptual design. What does the predicted load signify?

The further investigations were carried out by loading the specimen to various levels to determine the local failure initiation. The loaded specimens were polished and observed through a microscope, as shown in Fig 6.

From the microscope observations the fiber breaks due to the compressive load were observed at 4000 N where its initiation is between 3500-4000 N. This is in agreement with the failure load predicted by the proposed method using Maximum stress criterion ($\overline{FI}_{MSTRS}$ = 1 at 3900 N), which was principally contributed by the failure indices based on compressive strength of material.

6. Conclusions

In this work, the twill glass/polyamide6 composite was modeled using Hill's yield criterion in combination with the non-linear isotropic hardening model to describe the non-linear behavior of the material when loaded in off-axis direction. The characteristic diameter was first determined experimentally from the tensile tests on open-hole specimens with the reference geometry. Then, the numerical simulations were conducted to predict the failure of specimens with smaller and bigger hole diameters and with different material orientations. The results show good agreement with the experiments using Maximum stress criterion. Furthermore, the proposed method was applied to the bolted composite joint to predict its failure. The proposed criterion is able to predict a local failure initiation confirmed by the microscopic observations. The material was damaged on its fibers at predicted load by proposed method. This satisfies the industrial requirement that the damage is not supposed to exist in the material.

References

[1] J.M. Whitney, and R.J. Nuismer. Stress fracture criteria for laminated composites containing stress concentrations. *Journal of Composite Materials*, 8:253-265, 1974.
[2] S.C. Tan. Effective stress fracture models for unnotched and notched multidirectional laminates. *Journal of Composite materials*, 22:322-340, 1988.
[3] J. Wang, P.J. Callus, and M.K. Bannister. Experimental and numerical investigation of the tension and compression strength of un-notched and notched quasi-isotropic laminates. *Composite Structures*, 64:297-306, 2004.
[4] Ch. Hochard, N. Lahellec, and C. Bordreuil. A ply scale non-local fiber rupture criterion for CFRP woven ply laminated structures. *Composite Structures*, 80:321-326, 2007.
[5] S. Miot, Ch. Hochard, and N. Lahellec. A non-local criterion for modeling unbalanced woven ply laminates with stress concentrations. *Composite Structures*, 92:1574-1580, 2010.
[6] P.S. Wu, and C.T. Sun. Modeling bearing failure initiation in pin-contact of composite laminates. *Mechanics of Materials*, 29:325-335, 1998.
[7] J.H. Choi, and Y.J. Chun. Failure load prediction of mechanically fastened composite joints. *Journal of Composite Materials*, 37:2163-2177, 2003.
[8] T.A. Collings. *The strength of bolted joints in multi-directional CFRP laminates*. Her Majesty's Stationary Office, 1977.

Excerpt from ISBN 978-3-00-053387-7