SIZE EFFECT ON THE DAMAGE EVOLUTION IN OPEN-HOLE COMPOSITE LAMINATES

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Abstract

Open holes are present in many composite structures, producing an increment of stress in its proximity and a strength reduction. The stress concentration factor in laminates depends on the material properties and laminate lay-up. Therefore, the influence of a hole has to be considered in the design of composite structures. In this work, the Discrete Damage Mechanics model of Barbero-Cortes is employed to study damage evolution in open-hole composite laminates subjected to uniaxial in-plane tensile loads. The model is validated with experimental and numerical data taken from the literature with different hole diameters and laminate widths. The influence of the stacking sequence on the evolution of crack density, stress-displacement, and notched strength of the laminate are analyzed.

1. Introduction

The increasing use of composite materials in the design of structural parts with high mechanical performance requires a better understanding, especially when it refers to stress concentration. Laminate damage usually appears at points of stress concentration, such as materials defects or zones near the edge of a hole. Many composite structures, such as aircraft frames, contain thousands of holes for joining purposes and open cut-outs for access. An open hole on a composite structure produces a stress gradient that increases the stress field in its proximity. The stress concentration factor depends on the material properties and the laminate stacking sequence. The strength, the stiffness and the service life of the notched structure suffers a considerable reduction compared with the unnotched structure. Hence, the study of the influence of a hole on composite structures is an important task for a successful design.

The influence of size effects on laminate strength have been previously analyzed in the literature. Several methodologies, from analytical models such as the as Whitney-Nuismer model, Continuum Damage Mechanics (CDM), and Stress Failure Criteria have been used to predict the global response of laminates containing holes [1-7,12,13]. An alternative to these methodologies is the Discrete Damage Mechanics (DDM). DDM can predict the appearance of the first crack, evolution of crack density, and redistribution of stresses in the laminate due to degradation of mechanical properties of the cracked lamina.

Among the models based on DDM, [9] is selected in this work because of its simplicity. Furthermore, it is modified in a previous work by the same authors to include tensile fiber failure [11]. In this work, a study of the effect of the stacking sequence on the behavior of notched carbon/epoxy laminates, subjected to uniaxial in-plane tensile loads, is carried out. The model is validated with experimental data and numerical results taken from the literature. This model has the advantage of requiring only the crack density of the laminate as a state variable and it is applicable to symmetric laminates under in plane loads.

2. Numerical Model

2.1. Model Description

The numerical model is implemented in Abaqus/Standard by programming a user subroutine UGENS (User General Section). A T300/1034-C carbon fiber reinforced epoxy laminate subjected to uniaxial tensile load is studied. The mechanical properties of the material are taken from the literature [8]. A total of 28 different stacking sequences are analyzed.

The meshing uses quadratic rectangular element (S8R) and triangular element (STRI165). To simulate the uniaxial tensile load, a horizontal displacement is applied. As it is demonstrated in [10], the DDM model is mesh independent.

2.2. Model Validation

The ultimate strength of a carbon fiber laminate with an open centered hole is calculated with the proposed model for plates with four different geometric ratios (radius/width). Experimental and numerical results are taken from [5] to compare with the present results. The laminate stacking sequence used to validate the model is $[0/\pm45/90_7]_s$.

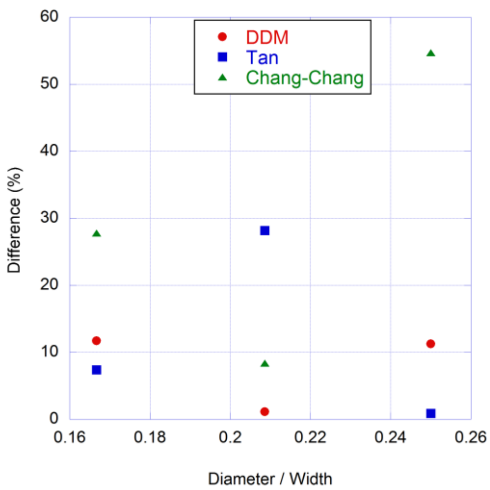


Figure 1. Difference on notched strength between experimental results and numerical models. Geometric ratios (Diameter/Width) = 0.17, 0.21 and 0.25.

The difference between predicted notched strength and experimental results is comparable to those achieve with other methodologies, even better in some cases. In view of the results of Figure 1 the model may considered to be validated.

3. Results

To study the influence of the stacking sequence over the damage evolution of a notched plate, 28 laminates with different stacking sequences are analyzed in this work. The geometry used for the plates correspond to a geometric ratio of 0.21 (hole diameter = 3.18 mm and plate width = 15.24 mm). Two different studies about the influence of the stacking sequence are reported.

3.1. Laminates with inverse stacking sequence

Laminates that have 0º and 90º laminae in opposite positions to the symmetry plane (from now called “inverse stacking sequences”) are studied. For example, $[0/90_4]_s$ compared to $[90_4/0]_s$. The following laminate stacking sequences and their inverses are analyzed:

- $[0/90_i]_s$ vs $[90_i/0]_s$ for i = 1 to 7
- $[0_i/90_i]_s$ vs $[90_i/0_i]_s$ for i = 1, 2 and 4
- $[0/90_i]_2$s vs $[90_i/0]_{2s}$ for i = 4, 5 and 7
- $[0_2/90_i]_s$ vs $[90_i/0_2]_s$ for i = 5 and 8

Crack density in the 90º laminae at the edge of the hole, longitudinal stress in the 0º laminae at the edge of the hole, applied load-displacement, and applied stress-displacement curves of the laminate are reported. The evolution of the variables with the displacement and the value of the notched strength, for a particular stacking sequence and its inverse, are equal for all cases studied.

Since the behavior of all laminates is similar, only the results for $[0/90_4]_s$ and $[0_2/90_2]_s$ stacking sequences and theirs inverses are shown in Figure 2. The evolution of crack density in the 90º laminae at the edge of the hole presents different trends as shown in Figure 2a. There is a threshold in the applied displacement for which crack density begins to grow quickly, and after that the curve displays a linear behavior until the notched strength is reached.

The applied stress-displacement curve of the laminate is shown in Figure 2b. As damage increases (for higher applied displacements), a decrease in the slope of the curve is perceived, due to stress softening. There are no differences between inverse stacking sequences in Figures 2, which can be explained as follows. It is well known that the propensity to damage of a 90º cluster on the surface is higher than that of the same cluster located in the interior of the laminate. But in Figure 2, when the clusters are placed inside the laminate, they are also double in thickness because of symmetry. Therefore, it can be concluded that symmetric 90º clusters (double thickness) have the same damage behavior (initiation and evolution rate) as cluster with half the thickness located on the surface.

In addition, the contour plots of crack density of 90º laminae and longitudinal stress of 0º laminae are reported for all level of applied loads. In Figure 3, the contour plots are shown for an applied load equal to the notched strength (displacement of 0.05mm approx.). The same contour plots can be observed for laminates with inverse stacking sequences. Similar behavior is found in all the cases studied.

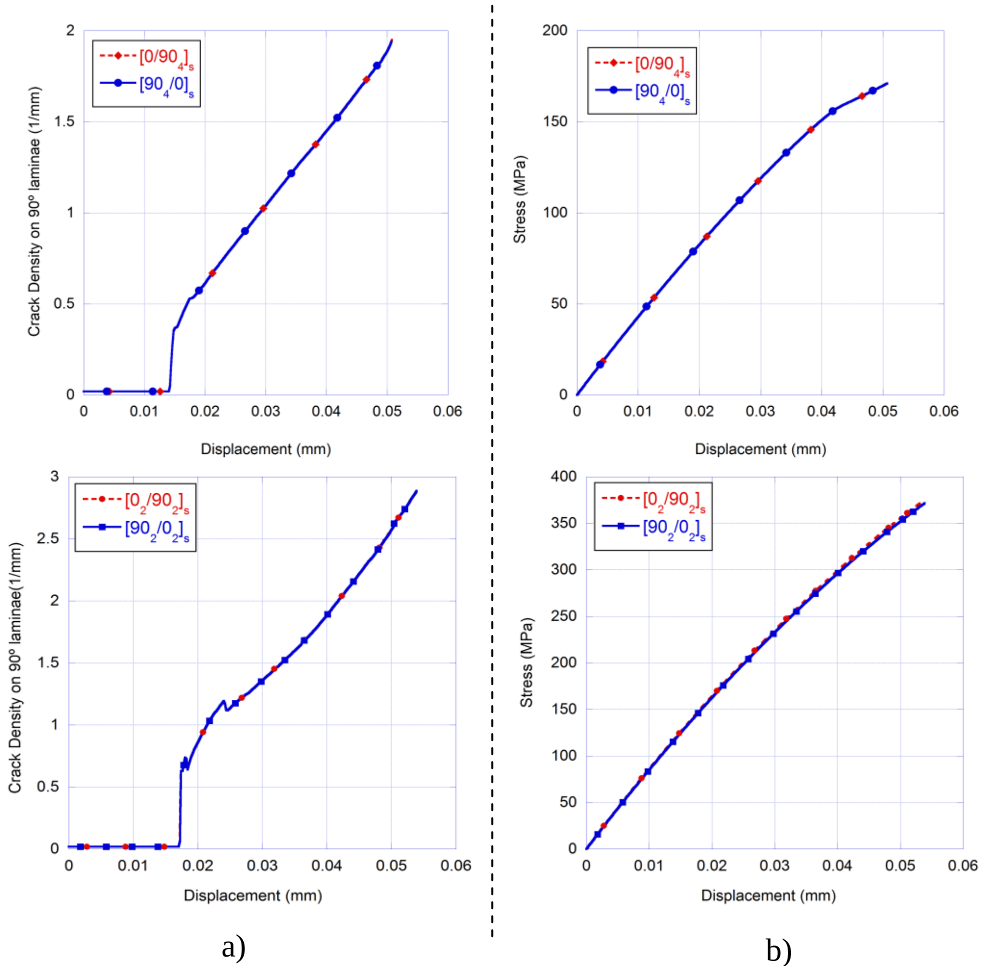


Figure 2. a) Crack density evolution on 90º laminae in the node situated at the edge of the hole and b) Applied stress evolution of the laminate, for $[0/90_4]s$ vs $[90_4/0]s$ and $[0_2/90_2]s$ vs $[90_2/0_2]s$ laminates.

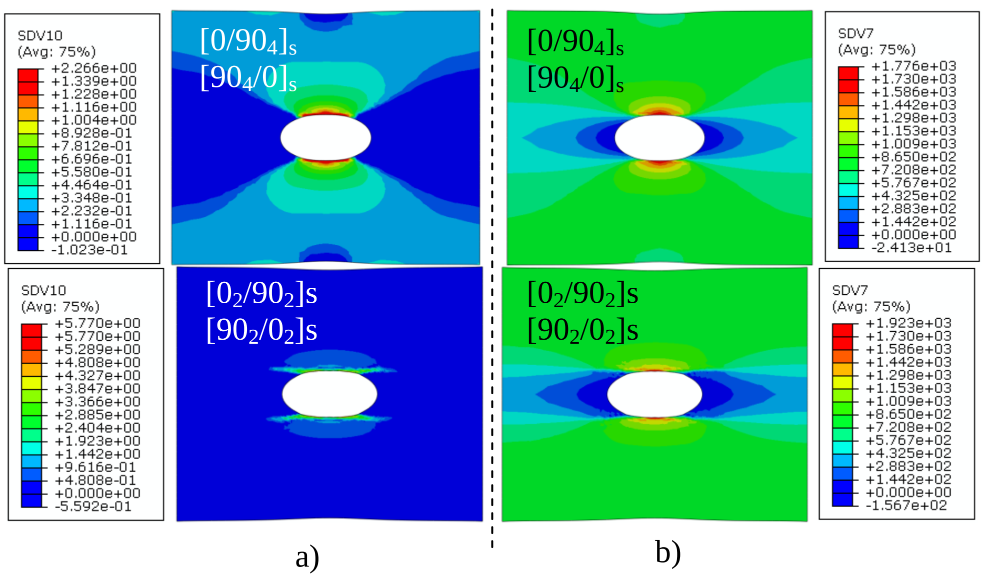


Figure 3. a) Crack density evolution on 90º laminae and b) Longitudinal stress on 0º laminae, for a displacement of 0.05mm approx. for $[0/90_4]s$ vs $[90_4/0]s$ and $[0_2/90_2]s$ vs $[90_2/0_2]s$ laminates.

As shown in Figure 3, the highest values of crack density and longitudinal stress are obtained at the edge of the hole perpendicular to the direction of load application. By contrast, the lowest values are found at the edge of the hole in the direction of the load application.

In view of the results shown in Figures 2 and 3, it can be concluded that all stacking sequences studied and their inverses behave similarly, in term of crack density evolution, longitudinal stress, applied load and its contour plots, and notched strength.

3.2. Laminates with the same overall number of plies but clustered differently

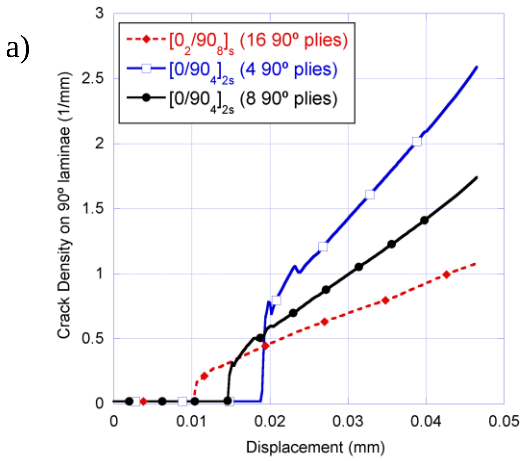
The following laminates have the same number of plies at 0° and 90°, but with stacking sequences that produce differents clusters of laminae:

$[0_2/90_8]_s$ vs $[0/90_4]_{2s}$ $\longrightarrow$ "$[0_2/\mathbf{90_{16}}/0_2]$ vs $[0/\mathbf{90_4}/0/\mathbf{90_8}/0/\mathbf{90_4}/0]$"
$[0_2/90_{10}]_s$ vs $[0/90_5]_{2s}$ $\longrightarrow$ "$[0_2/\mathbf{90_{20}}/0_2]$ vs $[0/\mathbf{90_5}/0/\mathbf{90_{10}}/0/\mathbf{90_5}/0]$"

The first pair of laminates have 16 laminae at 90º. While the $[0_2/90_8]_s$ stacking sequence has a cluster of 16 laminae, the $[0/90_4]_{2s}$ has three clusters of 90º laminae, one of 8 laminae and two of 4 laminae. The second pair of laminates has 20 laminae at 90º. While the $[0/90_4]_{2s}$ has two different clusters of 90º laminae, one of 10 laminae and another two of 5, the $[0_2/90_{10}]_s$ has a cluster of 20 laminae. For both pairs of laminates the behavior is similar. Therefore, only results for the comparison between $[0_2/90_8]_s$ and $[0/90_4]_{2s}$ laminates are shown.

In Figure 4.a significant differences on the crack density evolution, in the node situated at the edge of the hole, are observed. As the clustering of plies at 90º increases, the evolution of crack density starts at a lower displacement (as expected) and its growth rate is slower, reaching lower values for the same applied load. Namely, the slope of the curve of crack density decreases as the clustering at 90º is thicker (16_90º plies > 8_90º plies > 4_90º plies).

As far as the global response of the laminate are concerned, curves of the applied stress-displacement of the laminate are represented in Figure 4b. For both stacking sequences the initial behavior is the same (linear behavior) up to an applied displacement of 0.027 mm. From this point on, it is observed that the laminate with a higher number of 90º plies in the cluster ($[0_2/90_8]_s$) changes its slope (i.e., stress softening), and notably the notched strength reaches a smaller value compared with $[0/90_4]_{2s}$ laminate. This is consistent with practical experience that indicates that thicker laminates are not desirable.



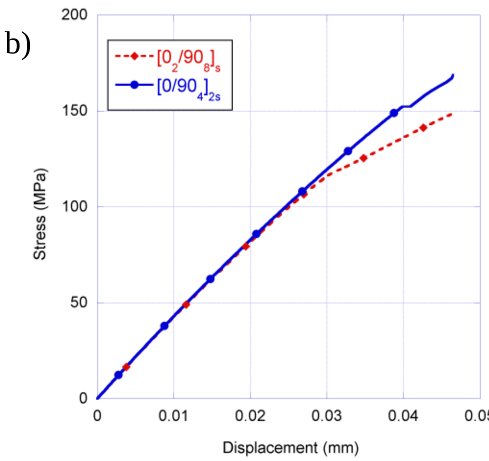


Figure 4. Comparison of: a) crack density evolution on 90º laminae in the node situated at the edge of the hole for three different clusters of 90º laminae for $[0/90_4]_{2s}$ and $[0_2/90_8]_s$ stacking sequences, and b) Curve applied stress-displacement of the laminate between $[0/90_4]_{2s}$ and $[0_2/90_8]_s$ stacking sequences.

In Figure 5a the contour plot of crack density of the 90º laminae for a displacement of 0.046 mm is shown. As the number of 90º plies in the cluster decreases (from left to right), the crack density value around the edge of the hole in perpendicular direction to load application increases. However, its evolution is slower. While in clusters with 16_90º plies and 8_90º plies the damage reaches the edge of the plate, in the cluster with 4_90º plies the damage is concentrated around the edge of the hole.

The contour plot of longitudinal stress in the 0º laminae are presented in Figure 5b. In this case the differences between $[0_2/90_8]_s$ and $[0/90_4]_{2s}$ are minor. For the laminate with the larger cluster at 90º plies ($[0_2/90_8]_s$), the area where the maximum value of longitudinal stress is reached (on the edge of the hole in perpendicular direction to the load application), is lower in extension and value compared with $[0/90_4]_{2s}$ laminate. In both cases, the lowest longitudinal stresses are located in the direction of the load application.

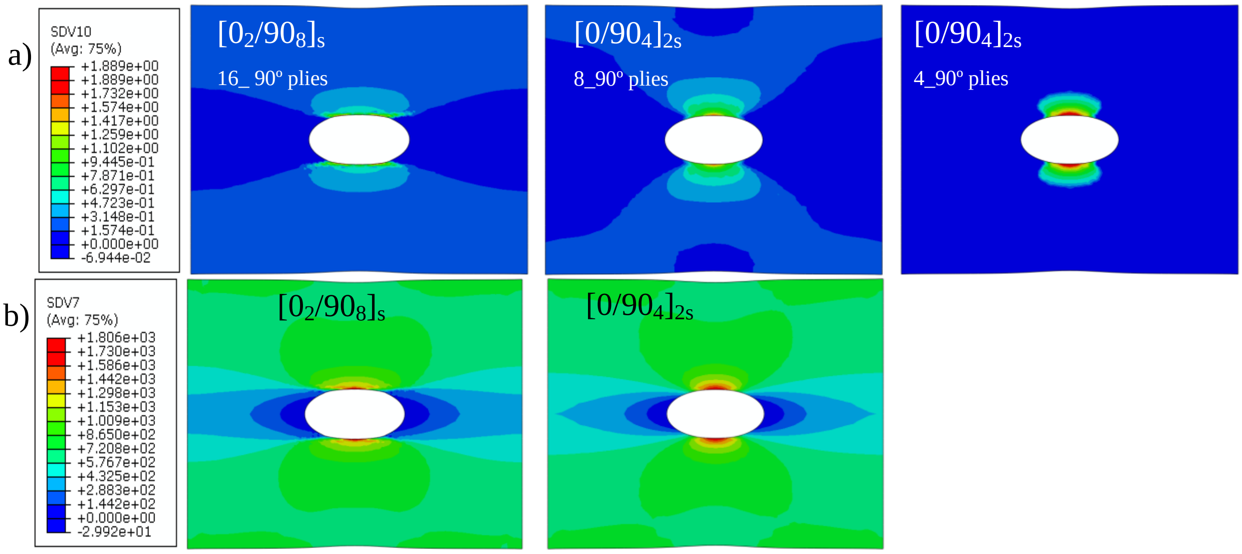


Figure 5. For a displacement of 0.046 mm a) contour plot of crack density evolution on 90º laminaes and b) contour plotof longitudinal stress on 0º laminaes, between $[0/90_4]_{2s}$ and $[0_2/90_8]_s$ stacking sequences.

4. Conclusions

For a laminates with inverse stacking sequences, no differences are observed in terms of crack density evolution, longitudinal stress, applied load, and their contour plots, as well as notched strength. All stacking sequences studied and their inverses behave similarly. Several differences are observed for laminates with the same number of plies but clustered differently. As the clustering of plies at 90º increases, the onset of the damage starts for a lower applied load, the slope of the curve is lower, the extension of damage evolution is larger reaching the edge of the plate, and the maximum value reached at the edge of the hole is lower compared to the clustering with less 90º plies. For the applied stress-displacement evolution, the laminates present similar behavior up to a specific value of displacement, and from this point on, the laminate with more 90º plies in the cluster changes its slope, with notched strength lower than the other laminate. Additionally, the maximum values of stresses are reached at the edge of the hole in perpendicular direction to the load application, and the lowest values are registered in the direction of the applied load near the edge of the hole. The model results display the expected behavior regarding surface cracks, cracks in constrained clusters, and cracks in thicker constrained clusters. Furthermore, evidence suggests that thicker clustering of plies in not desirable.

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