Chapter

Strength Improvement and Stress Analysis of E-Glass Laminated Plates with Circular Notches Using Digital Image Correlation

Abdelhak Khechai, Preetamkumar Marutrao Mohite, Abdelouahab Tati and Mohamed-Ouejdi Belarbi

Abstract

In the current work, the stress concentration and tensile strength degradation of E-glass/epoxy laminates are addressed in the present investigation through a combination of both experimental and numerical studies. The numerical study is performed using finite element method (FEM). The main aim of this work is to improve the ultimate strength of perforated composite plates, by using defense hole system (DHS) technique. The samples are manufactured from commercially available unidirectional (UD) E-glass and clear 1070 resin epoxy. Digital image correlation (DIC) technique is also used to get the full-field surface strain measurements in perforated samples with various open hole diameters and DHS configurations, in order to show their effects on failure strength. Based on the experimental results, the ultimate strength can be improved by introducing two circular auxiliary holes along with the principal stress directions.

Keywords: stress concentration, strength, digital image correlation, notches and defense hole system

1. Introduction

Composite structures have found widespread applications in aerospace and other major industries where weight reduction and directional properties are the main criteria. Circular cutouts are unavoidable in these structures to satisfy the design requirements. However, these cutouts change the mechanical behavior of these structures and produce a high undesirable stress concentration located at the vicinity of these notches. If the material strength is not high enough, failure will undoubtedly occur, usually from the region near the cutout. Therefore, it is mandatory to well identify the stress-strain distributions around the cutout.

Many studies have been done during the past two decades to determine the stress-strain distributions at the circumferential of notches in isotropic and anisotropic structures. A variety of methods have been used to estimate the stress concentration factor (SCF) values, such as exact and approximate analytical analysis. A brief review on current analytical methods for the determination of stress distribution around holes has been given by Sevenois [1].

In structural design field, engineers try to optimize various objectives, such as strength and structural weight, depending upon some requirements. Within the context of optimization, the weight or the strength is the objective function. The structural dimensions such as the thickness, length, or width are the design variables that can be controlled to achieve the best configuration [2]. In the case of composite laminated plates with cutouts, various response mechanisms of these structures are not fully understood and are still topics for continuing research.

Based on Sevenois [1] work, most of the research works to solve the stress concentration problem focus on the stress distributions in orthotropic plates subjected to different loads with different material properties. However, these investigations do not address the problem of whether the stress concentration degree is acceptable for a certain material strength and how one can improve the stress-strain distributions and the strength for these types of structures.

From a design point of view, if there is more than one cutout, the stress concentration at the vicinity of the original notch can be reduced, if one determines the optimum locations of other corresponding holes. This is known as the defense hole theory (DHT). It relies on the following rationale. By introducing small notches (auxiliary holes) on both sides of the main hole, it is possible to smooth the flow of the principal stress paths past the main notch, and this will reduce the SCF around the main notch [3].

This idea is very powerful for reducing the stress concentration. In this context, Erickson and Riley [4] were one of the first investigators to reduce the stress concentration around circular notch in isotropic plates under uniaxial loading. Durelli et al. [5] tried to obtain an ideal boundary of a discontinuity in perforated rectangular plate. They defined this boundary as that boundary along which there is no stress concentration. The ideal design of the boundary of the hole in the rectangular plate reduces the maximum stresses by 26%. On the other hand, the response of orthotropic laminated plates with circular notches has been also studied by Jain [6]. In this study, a FE study was made for reduction of SCF around circular notch in infinite isotropic and orthotropic laminates subjected to uniaxial tension. The SCF was reduced up to 24.4% in isotropic plates and 31% in orthotropic laminates by introducing four auxiliary notches on both sides of the original cutout.

Here, the current investigation addresses the research in the domain of optimization of composites for stress concentration and strength. The main goal of the present experimental and numerical studies is to obtain the best optimal size and position of defense holes for perforated laminates when they are subjected to uniaxial loading condition. For practical industrial applications, the most important characteristic to improve is the strength of the particular structure. Thereby, one of the aims of this study is to contribute to the minimization of the stress concentration and know if there can be a significant improvement in the strength of particular perforated composite laminates. Experimental studies investigated using E-glass/epoxy laminates to validate the improvement of the behavior of perforated laminates with auxiliary holes. Material and specimen preparation steps and different material characterization tests are dealt in detail.

2. Materials and sample preparation

During the present work, samples with different opening diameters were fabricated by the hand lay-up method. A mold release agent is first applied to the mold for getting a high-quality surface finish and facilitates the release of the laminated plates from the metallic mold. When the release agent has cured sufficiently, the UD E-glass fibers are manually placed on the metallic mold. After putting the fibers properly, the resin is applied by brushing. A paint roller is used, in order to distribute the resin uniformly on the metallic mold surface and also to consolidate the lamina, thoroughly wetting the reinforcement and removing the entrapped air. Subsequent layers of the UD glass fibers are added to build the required laminate thickness. The samples were made of four-ply UD E-glass/epoxy lamina. The thickness of each layer is 0.5 mm. The initial materials, E-glass fiber 400 g/m^2 and clear 1070 resin epoxy with a density of 1.15 g/cm^3 and a hardener with a density of 1.02 g/cm^3, were purchased from SF Composites (France).

The completed specimens have been checked to ensure that the final laminates are in good quality without defects and then cut into samples with a length of L = 250 mm and a width of W = 25 mm. These specimens have been cut using a dedicated cutting machine with a diamond-coated blade. Four-layered laminated plates, all in the same direction $[0]_4$, were fabricated in this experimental investigation as perforated specimens.

In order to create circular notches at the center of samples, different sizes of drills were used. On the other hand, to limit the delamination effects at the vicinity of the holes, caused by the drilling process, wooden plates under the samples and a drill machine with a speed of 2300 rad/min were used. Various diameters of drill (2.5, 5, 7.5, and 10 mm) were used in order to obtain various diameter-to-width (D/W) ratios. The main notch is machined by drilling initially a hole of a small diameter and then carefully enlarging it to its final dimension by incremental drill size.

In addition, the following procedure is followed to create different diameters of auxiliary holes in various locations at the vicinity of the main one. The first step is to make transparent papers and fix them onto the laminates using adhesive tape. These papers show the centers of the auxiliary holes. A needle is used in order to mark the center locations of the auxiliary holes on the laminates. Initially, 1 mm diameter drill is used for creating the initial holes. Starting with a small size of a drill improves the accuracy of the locations of the notches. Then, using a drill of sufficient size, a bigger hole centered at the initial hole is created.

Before the testing, the DIC samples were cleaned to remove dirt, and then they were prepared and covered using a black paint and sprayed with a white aerosol to create a random speckle pattern. The samples tested for the present experimental investigation are shown in **Figure 1**.

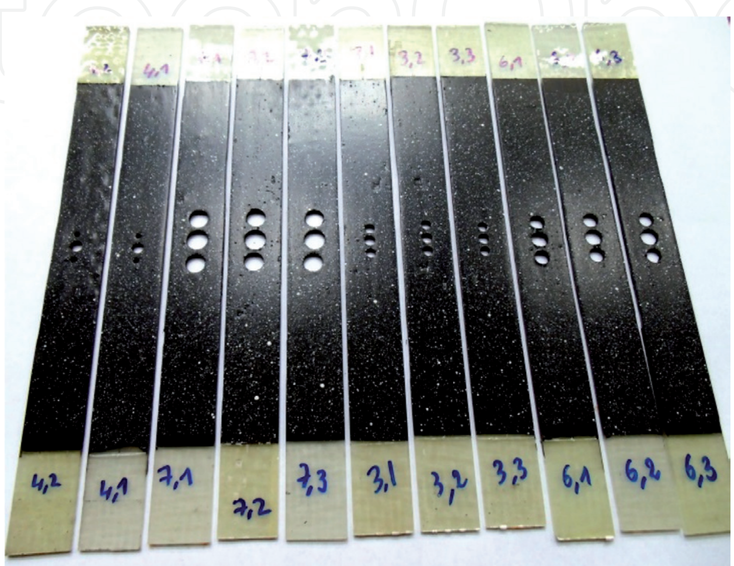

Figure 1.
UD laminated plates with various DHS configurations.

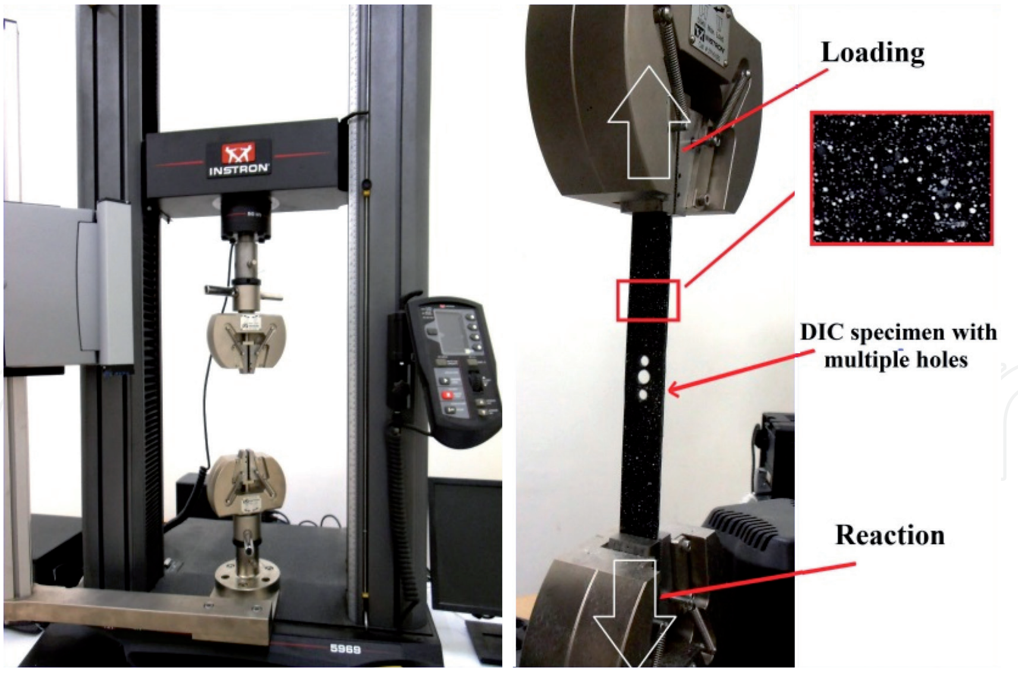

Figure 2.
Experimental setup for the DIC analysis.

In order to obtain the in-plane mechanical properties of the present material, the following ASTM D3039 [7] and ASTM D3518 [8] for tensile and shear properties, respectively, have been used.

The tensile properties of the unnotched samples, such as the laminate Young's modulus E_1 and E_2, Poisson's ratio v_{12}, and ultimate strength, were measured by static tension testing of longitudinal $[0]_4$ and transverse $[90]_4$ UD samples. The shear modulus of the samples was measured by loading the specimens whose principal axes are on 45°. Four samples were used in the characterization tests.

The INSTRON-5969 testing machine was used in the present study in order to conduct the experimental tests on laminated samples (see **Figure 2**).

The testing machine is connected with a computer in order to record the stress-strain curves during the tensile tests. As shown in **Figure 2**, the samples were illuminated by ordinary white light during the experiments. During the loading process, high-resolution images were taken using a digital camera. The experimental results obtained in the present study were processed with a 2D-DIC MATLAB code [9]. In order to perform the DIC tests, we replicate three experiments for each sample, and the results are averaged. This procedure was repeated for all samples to obtain correct stress distributions and reduce the errors that can be related to the speckle pattern.

Remark: The DHS technique is based on the idea of introducing smaller holes (auxiliary holes) on both sides of the main notch, in order to smooth the flow of the principal stress paths past the main notch, and this will reduce the stress concentration developed around the original notch. This process is similar to the topology optimization technique which is based on logic of "material should be removed from the regions that are less essential for carrying the loads."

Remark: The DIC is one of the powerful noncontact techniques used for measuring the deformations. The DIC technique uses images in order to track the relative displacements of a random speckle pattern point. These displacements are calculated between an undeformed image (reference image) and the current one (the deformed image). In the present work, the authors obtained the full-field strain distributions using a 2D-DIC MATLAB code [9].

3. Finite element modeling

2D finite element models were developed using the open-source FE software FreeFem++ [10]. The models were developed using a linear triangular element (three nodes with 2 degrees of freedom per node), because these elements are more adaptable for meshing plates with circular notches. In order to validate the experimental results, the dimensions and the mechanical properties of the numerical models are chosen to be the same as the experimental specimens (a total length of L = 250 mm and a width of W = 25 mm). In addition, various sizes of hole diameters (2.5, 5, 7.5, and 10 mm) are used in order to obtain different diameter-to-width (D/W) ratios. The length and width of the plates are divided into 70 and 5 elements, respectively.

The FE models of all groups of samples are created, and the stress-strain distributions at the vicinity of notches are obtained. Furthermore, in view of the rapid change in the stress-strain fields around the holes, a higher mesh density with smaller finite elements is adopted and a coarse mesh far from the hole region.

A convergence study is carried out to obtain initial appropriate fine mesh in the open hole zone (the initial mesh size was 30 elements around a hole diameter of 2.5 mm), and then automatic parametric program was developed in order to change the notch size and the mesh refinement automatically, because if one keeps the same element number at the vicinity of the notch boundary, the stress-strain distributions will be affected by changing the notch diameter (see **Figure 3a**). All the numerical models are subjected to a tensile load.

On the other hand, the introduction of the DHS is dependent on the logic of adding auxiliary holes in the areas of low stress near the main cutout. The number of the auxiliary holes in this study is two circular holes (see **Figure 3b**). Various finite element models are also developed for different DHS configurations.

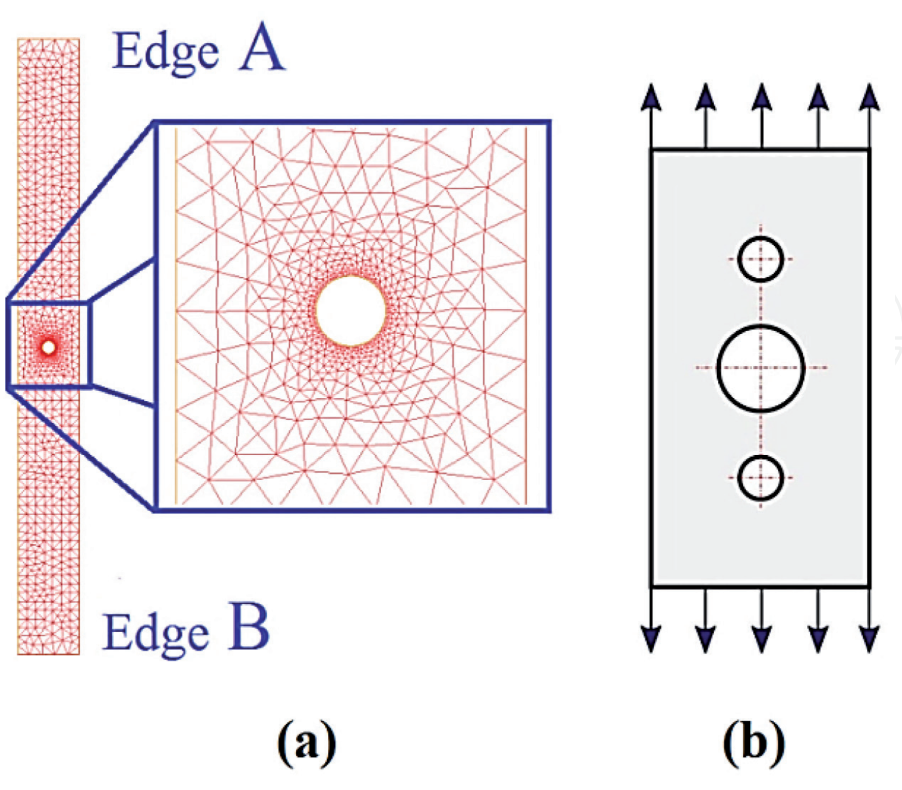

Figure 3.
Finite element models of laminated plates under a tensile loading. (a) A plate with a single hole and (b) a plate with DHS.

4. Results and discussion

In this section, the stress concentration factors and the tensile strengths of laminated plates with different notch diameters are analyzed. The results will be given first for plates with a single hole, and then the same analysis will be done for plates with different DHS configurations.

4.1 Stress concentration and strength of specimens with a single hole (SH)

The performed experimental study aimed to determine the ultimate tensile strength of unnotched/notched samples as well as the stress-strain distributions in laminates weakened by various notch diameters in order to evaluate the stress state. The obtained results from the characterization tests are summarized in **Table 1**.

Table 2 presents the stress concentration and the strength (ultimate stress) obtained experimentally for specimens without notches (unnotched plates) and with a single hole. It can be clearly seen that the SCF and the degradation in strength values are related to the notch dimension. The ultimate strength values vary greatly with the notch size, and the laminate strength decreases as the hole size increases. It turned out that as the notch diameters increased from 2.5 to 10.0 mm, the strength values steadily decreased from 427.57 to 274.86 and the SCF increased from 4.114 to 5.072.

The SCF findings presented in **Table 2** are the average of three values obtained for each sample. One can see that the numerical results are in good agreement compared to the experimental data and the difference between them is considered insignificant.

4.2 Stress concentration and strength of specimens with various DHS configurations

The experimental tensile strength results for the unnotched and notched longitudinal $[0]_4$ laminated specimens with different DHS configurations are shown in **Table 3** and schematically in **Figure 4**. The present DHS configuration is given as $(D/(A, A)/(d, d))$ where D is the main hole diameter, A is the auxiliary hole diameter, and d is the distance between the centers of the main and the auxiliary holes.

Material	Elastic properties			
	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	v_{12}
E-glass/epoxy	22.54	10.94	3.54	0.30

Table 1.
E-glass/epoxy laminate properties.

Material	Ultimate strength	Stress concentration values	
	(MPa)	FEM	Experimental results
Unnotched	527.04	—	—
2.5	427.57	3.756	4.114
5.0	353.54	3.937	4.025
7.5	314.93	4.194	4.799
10.0	274.86	4.601	5.072

Table 2.
Strength and SCF values of unnotched and notched specimens with various notch diameters.

Case		Strength load (MPa)			Improvement
		Unnotched plate	With SH	With DHS	%
Case 1-a	5/(4.5,4.5)/(6,6)	527.04	353.54	413.17	16.87
Case 2-a	5/(4.5,4.5)/(7,7)	527.04	353.54	412.39	16.65
Case 3-a	5/(4,4)/(6,6)	527.04	353.54	386.34	09.27
Case 4-a	5/(2.5,2.5)/(6,6)	527.04	353.54	348.57	−1.41

Table 3.
Experimental strength loads for $[0]_4$ laminates with different DHS configurations.

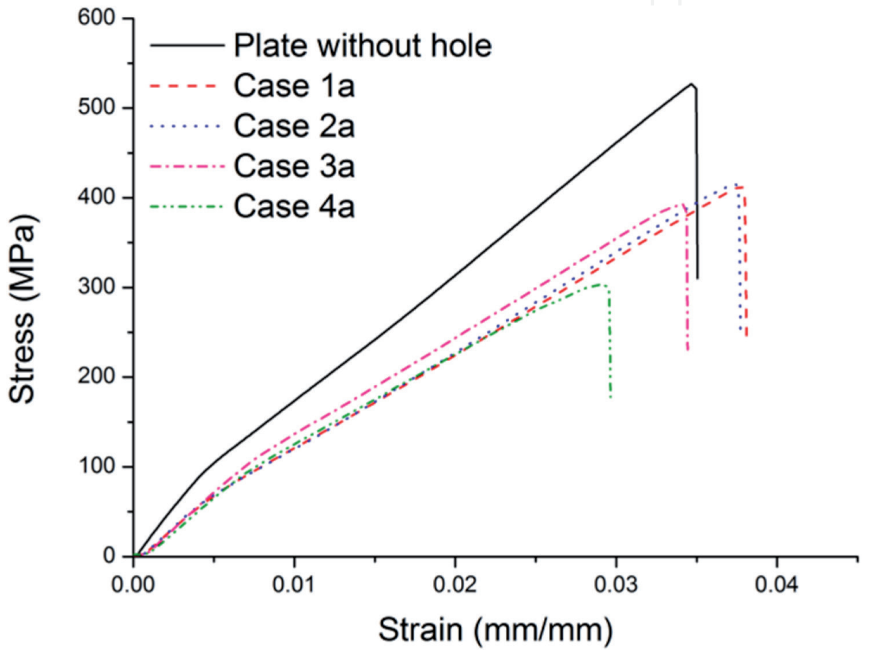

Figure 4.
Typical stress-strain curves for (D = 5 mm) laminated plates with different DHS configurations.

In this experimental investigation, the obtained strength values were compared to plate with a single hole, and the main hole diameter in this case is 5.0 mm.

Figure 4 shows the experimental stress-strain curves, and it can be clearly seen that the strength values were related not only to the main notch diameter but also the auxiliary notch diameters and their locations. The ultimate strength value varies greatly with the auxiliary hole sizes and locations, and the laminate strength increases as the auxiliary notch size increases and is located too near to the main one (see **Table 3**).

4.3 Strain distributions using DIC

As discussed earlier, the DIC technique was used in order to get the strain fields developed in composite samples with different open hole configurations loaded in tension at a rate of 0.5 mm/min. It is shown that the technique provides quantitative information that can be used to identify the strain distribution. A speckle pattern was applied manually on the specimen surface, and the quality of the speckle pattern affects the strain distribution; so it needs to be carefully dropped. The correlation subset size was large enough to ensure that there was a sufficiently distinctive pattern contained in the area used for correlation. In order to calculate the SCF around the

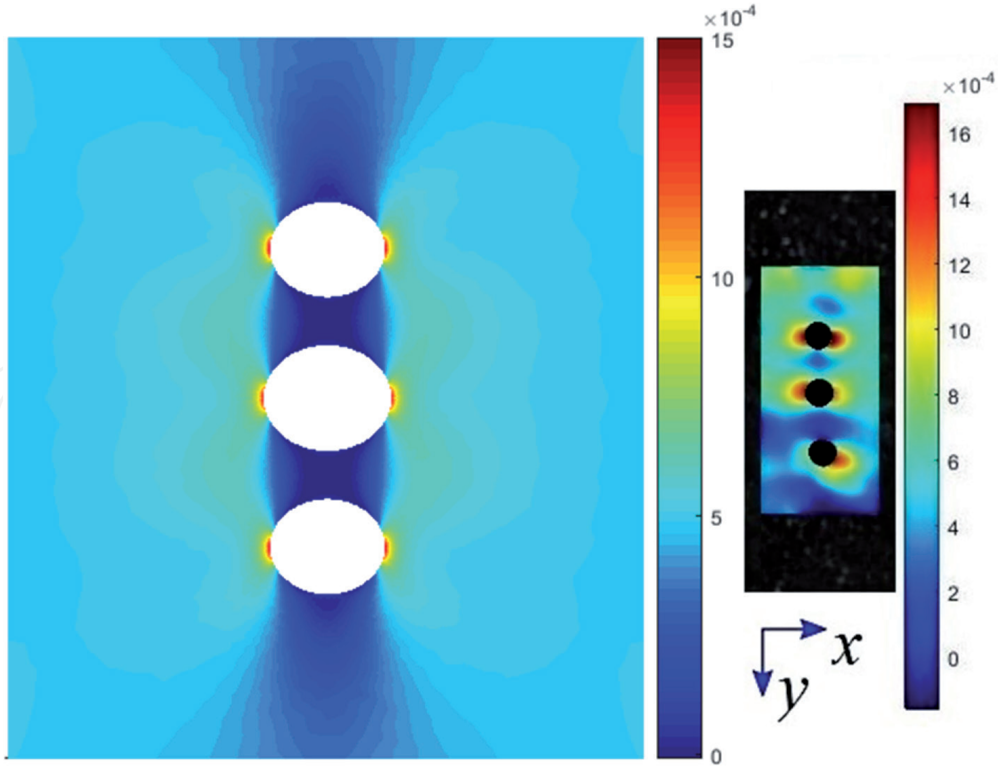

Figure 5.
Finite element and DIC engineering strain fields for $[0]_4$ *notched laminated plate with a 5/(4.5, 4.5)/(7, 7) DHS configuration.*

zone of discontinuities, the stress-strain relationship for planar composite structures was used. DIC technique measurements were carried out in all the samples.

The SCF results tabulated in **Table 2** are actually the average of three values obtained for each specimen. One can see that the experimental results are in good agreement with finite element outputs and the difference between them is insignificant. In addition, one can clearly see that the stress concentration near circular cutouts can be reduced using two auxiliary holes (see **Figure 5**). So, it can be concluded that the stress concentration reduction explains the tensile strength load improvement in specimens with DHS.

5. Conclusion

Notches with different forms and sizes are unavoidable in composite laminates to satisfy the needs of some design requirements. The stress developed around these notches reduces the load-bearing capacity of these composite structures. The accuracy of the analysis of these kinds of structures is based on the choice of an appropriate strategy. In the present investigation, DIC technique was used to the assessment of stress distribution taking place in laminates with different notch sizes loaded in tension. In addition, FEM is also used to validate the distribution of stresses obtained experimentally and investigate the tensile strength degradation in these laminated plates. It has been shown that the ultimate strength degradation and final damage mechanism that appear after the final failure are depending on the open hole size and strain distribution. One can see that the SCF and the damage zones increase and the perforated plate strength decreases with the increase in the hole size. Moreover, to improve the ultimate strength values, the DHS technique was used. DHS is introduced to these structures as a strategy to increase the ultimate strength as well as the weight of the structures. Based on the experimental results, the ultimate strength can be improved by introducing two circular auxiliary holes along the principal stress directions.

Conflict of interest

The authors declare no conflict of interest.

Author details

Abdelhak Khechai[1]*, Preetamkumar Marutrao Mohite[2], Abdelouahab Tati[3] and Mohamed-Ouejdi Belarbi[3]

1 Civil Engineering Laboratory, University of Biskra, Algeria

2 Department of Aerospace Engineering, Indian Institute of Technology, Kanpur, India

3 Energy Engineering and Materials Laboratory, University of Biskra, Algeria

*Address all correspondence to: a.khechai@univ-biskra.dz

References

[1] Sevenois R, Koussios S. Analytic methods for stress analysis of two-dimensional flat anisotropic plates with notches: An overview. Applied Mechanics Reviews. 2014;**66**(6):060802. DOI: 10.1115/1.4027562

[2] Gürdal Z, Hafta RT, Hajela P. Design and optimization of laminated composite materials. 1st ed. New York: Wiley & Sons Inc.; 1999

[3] Akour SN, Nayfeh JF, Nicholson DW. Defense hole design for a shear dominant loaded plate. International Journal of Applied Mechanics. 2010;**2**(02):381-398. DOI: 10.1142/S1758825110000548

[4] Erickson PE, Riley WF. Minimizing stress concentrations around circular holes in uniaxially loaded plates. Experimental Mechanics. 1978;**18**(3): 97-100. DOI: 10.1007/BF02325003

[5] Durelli AJ, Brown K, Yee P. Optimization of geometric discontinuities in stress fields. Experimental Mechanics. 1978;**18**(8):303-308. DOI: 10.1007/BF02324161

[6] Jain N. The reduction of stress concentration in a uni-axially loaded infinite width rectangular isotropic/orthotropic plate with central circular hole by coaxial auxiliary holes. International Islamic University Malaysia Engineering Journal. 2012;**12**(6):141-150. DOI: 10.31436/iiumej.v12i6.228

[7] ASTM Committee. Standard test method for tensile properties of polymer matrix composite materials. ASTM D3039/D M; 3039; 2008

[8] ASTM Committee. Standard test method for in-plane shear response of polymer matrix composite materials by tensile test of a ±45 laminate. ASTM D 3518/D; 3518; 2001; (94)

[9] Blaber J, Adair B, Antoniou A. Ncorr: Open-source 2D digital image correlation matlab software. Experimental Mechanics. 2015;**55**(6):1105-1122. DOI: 10.1007/s11340-015-0009-1

[10] Hecht F. New development in Freefem++. Journal of Numerical Mathematics. 2012;**20**(3-4):251-266. DOI: 10.1515/jnum-2012-0013