Strength degradation of E-glass plates with circular and square notches

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***Abstract*— In the current investigation, our objective is to determine experimentally the stress concentration in multilayered perforated composite plates subjected to uniaxial tensile loading. The stress concentration factors (SCFs) around circular and square notches are calculated using Digital Image Correlation (DIC) technique. On the other hand, the Finite Element Method (FEM) using FreeFem++ software is employed to validate numerically the experimental findings. The tensile strength degradation of E-glass laminated plates with both circular and square holes is also addressed in the present work through a combination of experimental and numerical studies. The DIC technique is used to obtain full-field surface strain measurements in notched specimens with different hole shapes and sizes, in order to show their effects on SCF and failure strength and failure mechanism.**

Keywords*— Stress concentration, strength, digital image correlation, composite material, notch

I. INTRODUCTION

Laminated composite plates with various notch sizes are being extensively used in different aircraft structural elements to facilitate joining of structural parts or to provide access to the interior of the structure. When these structures are subjected to various load conditions, undesirable high stress concentration, which affect their performance, is produced around these notches. Over last decades, the development of stress concentration has always been of major concern, and great efforts have been conducted to investigate the effect of the presence of holes on laminate strength.

Many efforts have been made during the past two decades to evaluate the stress distribution around cutouts in isotropic and anisotropic structures. A variety of methods have been used to estimate the 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 the literature, there are three analytical methods for the determination of the stress field: Lekhnitskii Formalism [2, 3], Stroh Formalism [4, 5] and approximate analytical methods [6, 7]. During the sixties and seventies, Lekhnitskii [2] and Savin [3] provided the basis for what is now called “Lekhnitskii Formalism”. They presented solutions for circular, elliptical, triangular and square holes in, mainly, infinite orthotropic plates. This method essentially generalizes Muskhelivshili’s approach [8]. Although Savin [8] uses Schwarz-Christoffel integral mapping, while Lekhnitskii [7] derived the stress functions by using Fourier series, their solutions are the same. On the other hand, while these methods are powerful in solving a wide variety of elasticity problems, they are complicated and must be reformulated for each type of far-field load.

The other main class of mathematical methods for evaluating the stress distribution in perforated plates is based on the Finite Element Method (FEM). The FEM is a numerical method used for solving various problems of engineering. For complex problems, involving complicated geometries and material properties, it is generally difficult to get the analytical solutions. Hence engineers need to rely on the numerical methods to get acceptable solutions. Examples of researchers who investigated the stress distribution around various shaped holes using special finite elements are Chen [9], who developed a special finite element for efficient evaluation of stress concentration around circular cutout and the complex variable formulation is used to derive a special set of stress functions which embody the stress concentration effects of a hole, Piltner [10], who developed special finite elements with circular and elliptic holes and internal cracks. Wang et al. [11] recently developed a special hole element using a special fundamental solution for an infinite isotropic domain containing a single elliptical hole, which is derived based on complex conformal mapping and Cauchy integrals. These special elements are used at the hole locations at the region near the hole boundary to resolve the stress concentrations while regular elements are used at other locations.

Experimentally, few experimental studies using Digital Image Correlation (DIC) technique have been performed to study the global response (stress distribution, strength failure and damage) of open-hole plates subjected to in-plane loadings, especially for different notch diameters.

In the current work, series of tensile tests on laminates with various hole shapes and specimens with different circular notch diameter/width (*D*/*W*) ratios are designed and tested to determine the SCF and fracture mechanisms for unnotched and notched specimens. DIC technique is used to obtain full-field surface strain measurements in notched specimens strain measurements in notched specimens with different hole shapes and sizes, in order to show their effects on SCF, failure strength and mechanisms. The strain concentration that allowed damage initiation and failure propagation in the notched laminated plates is obtained experimentally and compared with the simulation details.

II. METHODS

A. Experimental study

During this experimental work, specimens with different notch sizes and shapes (circular and square holes) were fabricated by hand lay-up method. The specimens were made of 4-layers unidirectional E-glass/epoxy lamina. The in-plane mechanical properties were measured by following ASTM D3039 [12] and ASTM D3518 [13] for tensile and shear properties, respectively. Four identical specimens were used in each material characterization test. To create circular holes at the center of specimens, different sizes of drill (0 'unnotched', 2.5, 5, 7.5, 10, 12.5 mm) were used to obtain different diameter to width (*D/W*) ratios. On the other hand, the following procedure is followed to create various sizes of square (4 × 4, 6 × 6, 8 × 8 and 10 × 10 mm^2) notches at the center of laminated specimens. The first step is to make a transparent paper and fixing it onto the laminated plate using adhesive tape. The transparent paper shows the 4 corners as well as the center of the square hole. A needle is used to mark the center locations on the laminated plates. A straight edge and the needle are used to connect the 4 points. Initially, 1 mm diameter drill is used for creating the initial holes at the 4 points and the center. Starting with a small diameter drill improves the accuracy of the location of the hole. Then, using a drill of sufficient diameter, a bigger hole centered at the initial hole is created just to reach the edges of the square. The small drill is also used to remove the extra material inside the square and to get the edges of the hole closer to the drawing lines. The finishing work will be done using a flat file to get straight edges. The specimen surfaces were scrubbed and were cleaned thoroughly to remove the dirt.

Before the testing, and in order to determine the strain pattern, the DIC specimens were prepared and covered using a black paint and sprayed with a white aerosol to create a random speckle pattern, which was used for the DIC analysis (see Fig. 1). These specimens have to be prepared carefully, in order to obtain a suitable spackle pattem.

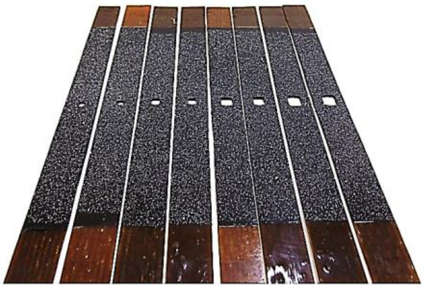

Fig.1: Plates with different open hole sizes.

A universal testing machine (INSTRON-5969) was used to conduct the tests on the laminate specimens (see Fig. 2). The testing machine is connected with a computer to record the stress/strain curve during the tensile process.

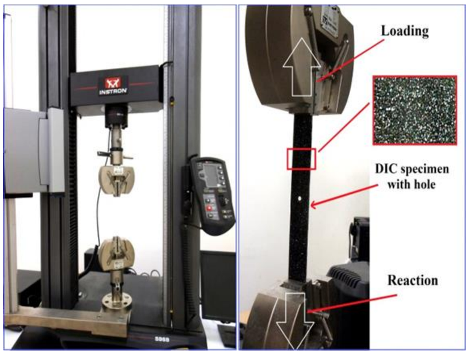

Fig.2: Experimental setup for DIC testing.

The specimen was illuminated by ordinary white light during the experiment. High resolution images during the loading event were taken using a digital camera using an appropriate speckle pattern. The experimental data obtained in this study were processed with open source 2D-DIC software [14].

B. Finite element study

A 2D finite element analysis (FEA) was developed using the open source FE software Freefem++ [15]. Freefem++ is a software to solve partial differential equations numerically. As its name implies, it is a free software based on the FEM; it is not a package, it is an integrated product with its own high level programming language. Freefem++ has an advanced automatic mesh generator, capable of a posteriori mesh adaptation; it has a general purpose elliptic solver interfaced with fast algorithms such as the multi-frontal method UMFPACK, SuperLU. The FE model of all groups of specimens is created and the stress distribution around circular and square notches is obtained. Furthermore, in view of the rapid change in the stress field near the hole, a higher mesh density with smaller elements is adopted and coarse meshes far from the notch region (see Fig.3).

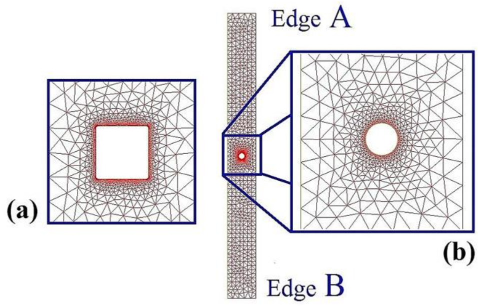

Fig.3: Finite element mesh. (a) Square hole, (b) Circular hole.

A convergence study is carried out to obtain initial appropriate fine mesh in the open hole zone, then automatic parametric program was developed changing the open hole size and the mesh refinement, because if we keep the same element number around the cutout boundary, the stress distribution will be affected changing the hole size.

III. RESULTS AND DISCUSSION

The performed experimental tests aimed to evaluate the tensile strength of unnotched and notched specimens as well as the strain distribution in laminated plates containing different notch sizes and shapes in order to calculate the stress state. The results obtained from the longitudinal tension tests are summarized in Table 1.

TABLE I. MATERIAL PROPERTIES.

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

Fig. 4, 5 and 6 show typical stress/strain curves for four unnotched laminated specimens $[0]_4$, $[45]_4$ and $[90]_4$ used for material characterization. It can be seen from the figures that the curves have identical behavior and the curves overlap each other. The curves also show an elbow at the end of the elastic region which can be related to an earlier fiber damage initiation.

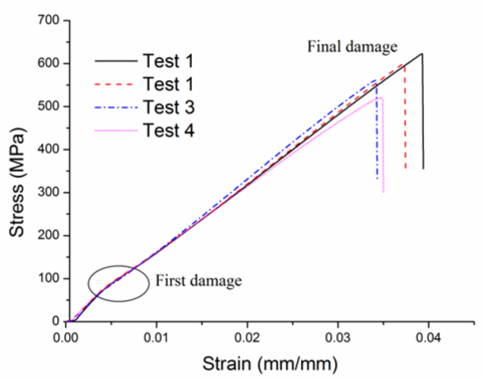

Fig.4: Typical stress/strain curves for $[0]_4$ laminated specimens.

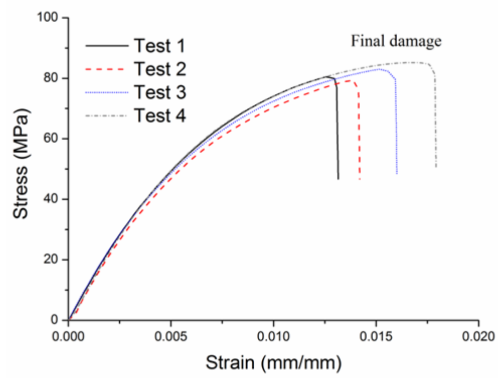

Fig.5: Typical stress/strain curves for $[45]_4$ laminated specimens.

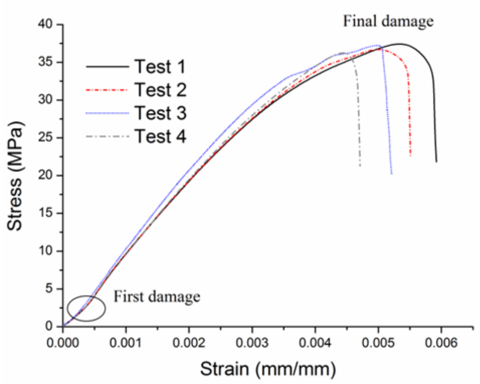

Fig.6: Typical stress/strain curves for $[90]_4$ laminates.

The tensile strength results for the unnotched/notched longitudinal [0]4 laminated specimens are shown in Figs. 7 and 8. Figs. 7 and 8 show the stress/stain curves and one can clearly see that the degradation of strength values was related to the notch shape and size.

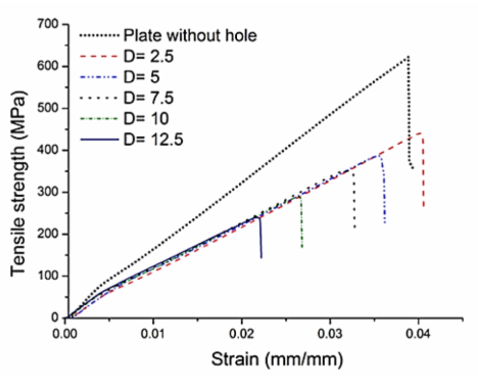

Fig.7: Comparison of the stress/strain curve for unnotched/notched specimens with various hole diameter.

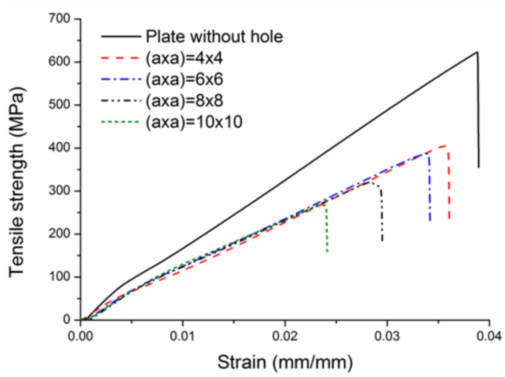

Fig.8: Comparison of the stress/strain curve for unnotched and notched specimens with various square holes.

As discussed earlier, the DIC technique was used to obtain the strain fields developed in composite specimens with various shapes as well as in specimens with different notch sizes loaded in tension at a rate of 0.5 mm/min. In order to calculate the SCF around the zone of discontinuities, we used the stress/strain relationship for planar composite structures. The SCF results tabulated, in Tables 2 and 3, are actually the average of three values obtained for each specimen.

TABLE II. SCF RESULTS FOR COMPOSITE MATERIAL WITH DIFFERENT CIRCULAR HOLE SIZES.

Circular holes			
2R/W	Anal.	FEM	Test
0.1	3.981	3.756	4.114
0.2	4.122	3.937	4.025
0.3	4.384	4.194	4.799
0.4	4.801	4.601	5.072
0.5	5.428	5.213	5.122

TABLE III. SCF RESULTS FOR COMPOSITE MATERIAL WITH DIFFERENT SQUARE HOLE SIZES.

Square holes		
a x a (mm2)	FEM	Test
4 x 4	4.682	5.721
6 x 6	5.313	5.956
8 x 8	5.917	7.032
10 x 10	6.551	7.229
-	-	-

Remark: For DIC measurements only one surface of the specimen is painted. The thickness of the paint must be very small compared to the thickness of the specimens; otherwise the paint later will have effect on overall deformation pattern of the laminate (due to unsymmetry) being tested. Thus, ideally both surfaces must be painted. However, in the present study only one surface is painted with very thin layer and therefore, its effect on overall deformation is neglected.

Remark: Delamination is one of the main defects that we can observe during the drilling of laminated plates and can be an important limiting factor for the use of composite materials. This is because the drilling process causes micro-cracks and these cracks are the origin of the high stress concentrations. It has been observed that the lower cutting speed can minimize delamination and lead to a better notched surface. Also, wood en plate under the specimens is used in order to limit the effects of delamination around the openings caused by the drilling process.

It can be seen that the FE outputs are in good argument with both approximate analytical [6] and experimental results, and the difference between them is considered insignificant (see Tables 2 and 3, Figs. 9 and 10).

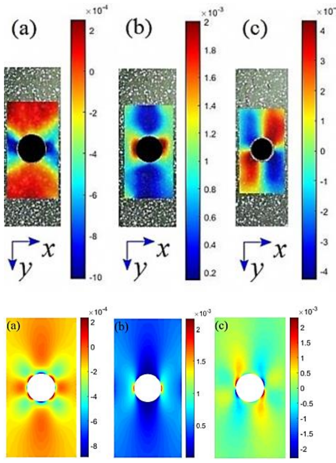

Fig.9: DIC and FEA strain fields for $[0]_4$ laminate with circular hole (D=10 mm); (a) ε_{xx} , (c) ε_{yy} and (d) ε_{yx} distributions.

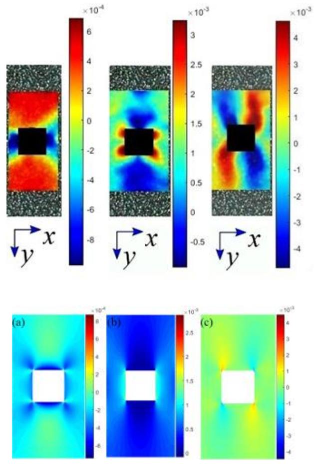

Fig.10: DIC and FEA strain fields for $[0]_4$ laminate with square notch (a x a=10x10 mm^2); (a) ε_{xx} , (c) ε_{yy} and (d) ε_{yx} distributions.

On the other hand, it can be seen from the results given in Tables 2 and 3 that the SCFs increase with the increase in the notch size. It can be concluded that the stress concentration phenomena explains the strength degradation in notched specimens. It turned out that the strength degradation decreases as the stress concentration increases.

IV. Conclusion

In the present work, DIC technique was used to the assessment of stress distribution taking place in laminated plates with various notch sizes and shapes loaded in tension. In addition, approximate analytical solution and finite element method were also used to validate the experimental results and investigate the tensile strength degradation in these laminated. It has been shown that tensile strength degradation and final damage mechanism that appear after final failure are depending of open hole size, shape and stress distribution. It can be seen that the SCF and the damage zone increase and the notched strength decreases with increase in the notch size.

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