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Notch Sensitivity of Glass/Polyester Laminates

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Abstract

The effect of the hole size on the fracture behavior of glass/polyester fabric laminates are experimentally studied in flexural test. An "ANSYS" program is employed for the purpose of comparison, and for computation of the maximum stress and its concentration factors. Four groups of composite materials are used, one layer; two layers; three layers and four layers. All these groups are of 35% volume fraction, 450 g/m^2 areal weight, and hole diameter of (1, 2, 3, 4 and 5) mm for each group. ISO standard flexural specimens are tested and repeated three times.

It is noticed that values of stress concentration factors (K_t) decrease with the increase in hole diameter. Also, the fracture load and the stress concentration factors increase with increased number of layers. The present Theoretical results show a good agreement with the experimental results.

الخلاصــــــة

في هذا البحث تم دراسة تأثير تغيير قطر الثقوب على سلوك الكسر لعدد من الطبقات لراتنج البوليستر المقوى بالألياف الزجاجية بتسليط أحمال انحناء عليها، وحساب إجهاد الكسر ثم بعد ذلك حساب معامل تركيز الاجهادات. أستخدم نظام ANSYS لغرض مقارنة نتائجه مع النتائج المستحصلة من الاختبار العملي. تم استخدام أربع مجامع من المواد المركبة بعدد طبقات (١،٢،٣و٤) وبنسبة كسر حجمي مقداره ٣٥% لنوع ٤٥٠ غم/م^٢، وبقطر ثقب (١،٢،٣،٤ و٥) ملم لكل مجموعة، حيث استخدمت المواصفات العالمية (ISO Standard) لاختبار الانحناء وتحضير العينات وإجراء الاختبار والتكرار لثلاث مرات.

لوحظ أن قيم معاملات تركز الإجهاد تقل بزيادة قطر الثقوب. كذلك فأن حمل الكسر يزداد بزيادة عدد طبقات المادة المركبة، أما معاملات تركز الإجهاد فقد ازدادت عند زيادة عدد الطبقات، وقد أظهرت النتائج العملية والنظرية تطابق جيد.

1. Introduction

Composite materials with holes are being used more frequently as primary load-bearing structural component. It is well-known that holes introduce stress concentrations which significantly reduce the fracture strength of components. However, the problems of the strength reduction and the unstable fracture criterion are not completely understood [1].

The use of high stiffness fibers in a low stiffness (or a ductile) matrix approaches an ideal from the notch sensitivity point of view. When fracture of fibers occurs the load is transmitted to neighboring fibers by the matrix. So the load over a small volume has been diffused, thus avoiding stress concentrations [2]. The notch sensitivity of materials is closely related to their resistance to fracture. For design purposes it is necessary to predict the overall loads which can be applied to a structure without catastrophic propagation of pre-existing flaws or flaws generated during service [3].

When a laminated material is subjected to bending or flexure, the corresponding stresses are proportional to the elastic properties of the respective lamina and their position with in the laminate. Differences in properties between lamina can result in crack initiation within the laminate beam rather than at the extreme outer surface as one would expect in an isotropic material. Furthermore, bending a laminate in one direction may produce different bending in other directions, consequently warping the structure [4].

Several models have been developed to predict the effect of notches, either circular holes or slits. One model, developed by Waddoups et. al. [5], employs the principle of linear elastic fracture mechanics. The other model for predicting the effect of notches of composites was developed by Whitney et. al. [6]. In these models, it is assumed that the characteristic dimension has the same values for all notch sizes. But, this assumption has been shown to be invalid [7].

The current study is concerned with determining the stress concentration factors of laminates fabricated from fabric prepreg subjected to a flexure load. A number of specific items were addressed. These include comparisons between laminates (one layer, two layers, three layers and four layers) of similar random glass fiber and with the same various diameter (1, 2, 3, 4 and 5) mm for each laminates. The basic Load-Deflection behavior, maximum stress, failure modes and stress concentration factors were computed. To achieve the above objectives, experimental study and "**ANSYS**" program was utilized so that full picture of stress concentration factors can be illustrated.

2. Theoretical Analysis

The analysis of flexure test includes the measurement of the maximum stress (σ_{max}) by applying a flexure load using a flexural test apparatus. The specimen is subjected to a flexure load till its fracture. Then the maximum stress without notch is determined and another specimen with notch is subjected to flexure load to get (σ_{max}), as follows [8].

$$\sigma_{max} = \frac{MC}{I} \qquad \text{......(1)}$$

where:

σ_{max} : The maximum bending stress in the member which occurs at a point on the cross-sectional area farthest array from the neutral axis.

M: The resultant internal moment, determined from the method of sections and the equations of equilibrium, and computed about the neutral axis of the cross section.

I: The moment of inertia of the cross-sectional area computed about the neutral axis.

C: The perpendicular distance from the neutral axis to a point farther away from the neutral axis, where σ_{max} acts.

The theoretical stress concentration factor is the ratio of the maximum stress in the notch to the nominal stress [9], assuming that the material possesses a linear stress.

$$K_t = \frac{\text{Maximum Stress in Notch}}{\text{Nominal Stress based on Minimum Area}} \qquad \text{......(2)}$$

The value of the theoretical stress concentration factor is a function of the geometry of the part and loading; it does not depend on the mechanical properties of the material (assumed to be elastic and isotropic). The static stress concentration factor (K_t) is calculated as follows [10].

$$K_t = \frac{\text{Unnotched Stress}}{\text{Notched Stress}} \qquad \text{......(3)}$$

This method is widely used because it is easy and can be carried out with minimum expenses and the error associated with this method is generally acceptable.

With regards to volume fraction which is very important, the properties of composite materials depend especially on the volume of each constituent in the specimens. In an ideal two-component composite, the fiber and matrix volume fractions are given as [11]:

$$V_f + V_m = 1 \qquad \text{......(4)}$$

Assuming no porosity, the volume fraction (V_f) can be computed experimentally by the following equations [12].

$$V_f = \frac{1}{1+\left(\frac{1-\psi}{\psi}\right)\frac{\rho_f}{\rho_m}} \qquad \text{......(5)}$$

$$\Psi = \frac{W_f}{W_c} \qquad \text{......(6)}$$

where:

Ψ *: Weight fraction.*

W_f , W_c*: Fibers and composite material weights respectively.*

ρ_f , ρ_m *: Fibers and matrix material density respectively.*

2-1 Numerical Solution

Finite element procedures are one of the methods in solving composite materials problems. They are very widely used in engineering analysis and its application has increased significantly in the last years due to the increase in computer capacities [13].

The procedures are employed extensively in the analysis of solids and of heat transfer and fluids and indeed, finite element methods are useful in virtually every field of engineering analysis. The finite element method is used to solve physical problems is engineering analysis and design. The physical problem typically involves an actual structure or structural component subjected to certain loads.

The idealization of the physical problem to a mathematical model requires certain assumptions that together lead to differential equations governing the mathematical model. It is necessary to assess the solution accuracy. If the criteria accuracy are not met, the numerical (i.e. finite element) solution has to be repeated with refined solution parameters (such as finder meshes) until a sufficient accuracy is reached [9]. The finite element meshes used for this work is shown in **Fig.(1)**.

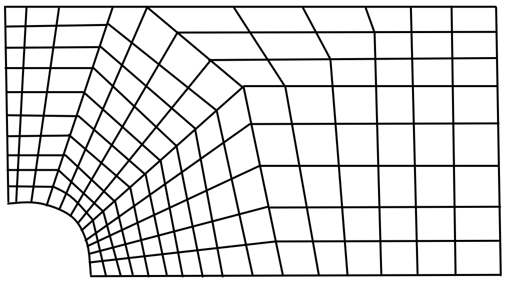


Figure (1) Finite element meshes

One of the best package employing of the finite element methods is the "**ANSYS**" program, which is used for solving design problems. A random fiber orientation means that the moduli will be quasi-isotropic in the plane of the lamina. Therefore the material properties of random (fiber glass-polyester resin) lamina are calculated using (Halpin-Tsai) equation [14]. With regard to materials properties of E-glass/polyester resin, the results of calculation are summarized as follows: Modulus of elasticity (E=13.5 Gpa); Shear modulus (G=4.7056 Gpa); Poisson's ratio (υ =0.4352), and then fed to the program.

The **"ANSYS"** program is used to model composite materials by specialized elements called **"SHELL 99"** layered elements.

2-2 Boundary Conditions

The specimens are subjected to a flexure load. Let x, y and z represent the axes of symmetry. A quarter of the plate is modeled due to symmetry in geometry, material, and orientation. The boundary conditions can be on displacements as in **Fig.(2)**.

UY = 0, UZ = 0, ROTY = 0, ROTZ = 0 along line BC

UX = 0, ROTX = 0 along line AB

UY = 0, ROTY = 0 along line DE

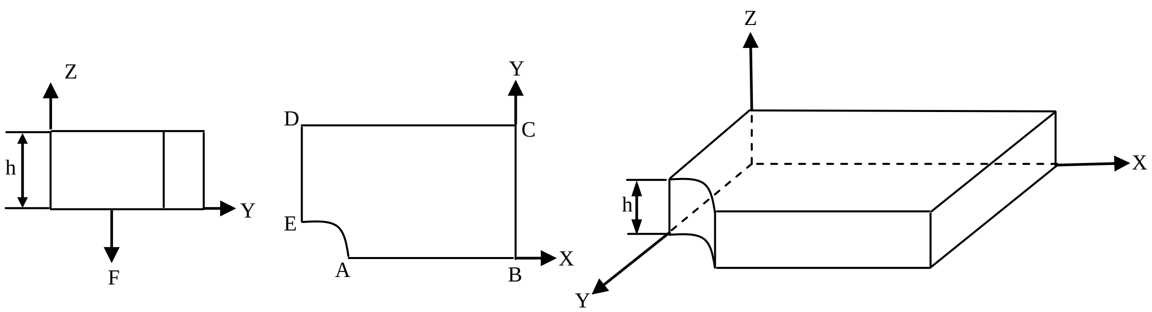


Figure (2) Boundary conditions

3. Experimental Procedure

Four groups of composite materials are experimentally investigated: (one layer, two layers, three layers and four layers). All groups are of 35% volume fraction (V_f = 35%). Each group has the same various holes diameters which are (1, 2, 3, 4 and 5) mm.

The geometry and the dimension of the flexure specimens with a hole in the middle are according to ISO standard [15] as shown in **Fig.(3)**. A circular hole is machined by initially drilling a starter hole of small diameter, and carefully enlarging it to its final dimensions by incremental drilling. The thickness and length (L_c) of the (one layer, two layers, three layers and four layers) plates are (0.5 mm, 8 mm), (1 mm, 16 mm), (1.5 mm, 24 mm) and (2 mm, 32 mm) respectively. The density of E-glass fiber and polyester resin are (2.56 and 1.2) g/cm^3 respectively [16].

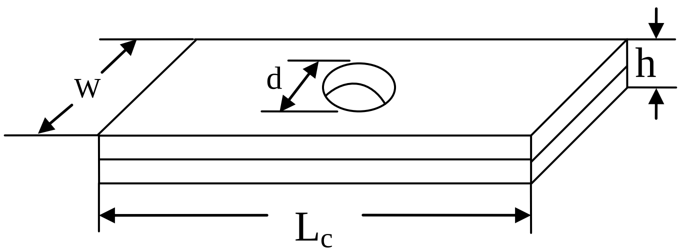


Figure (3) Test specimen showing dimensions

where the relation is:

L_c = 15h-17h. L= L_c+20 mm for every end., W = 15 mm $\pm$0.5 for 1mm < h <10 mm.

All the static tests are conducted on the bending apparatus, and at room temperature. For each test, three identical specimens are tested and the average results are taken into account.

4. Results and Discussion

Composite materials are expected to behave linearly in bending tests within the elastic range and non-linearly in the plastic range. These are shown experimentally in **Figs.(4, 5, 6 and 7)**. It can be shown that the values of failure load of specimens decrease with the increase in the hole size, but the maximum flexure stress increase. This is due to the increase in the missing material volume with the increase in hole size. Thus, the stress concentration factors will decrease, as shown in **Fig.(8)** for all laminates.

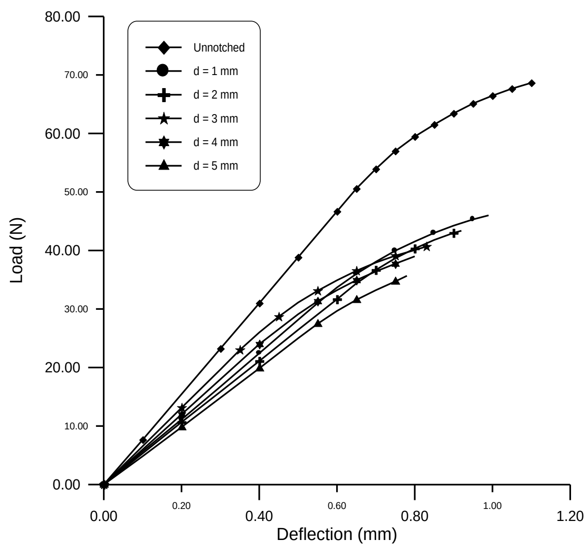


Figure (4) Flexure curves of one Layer

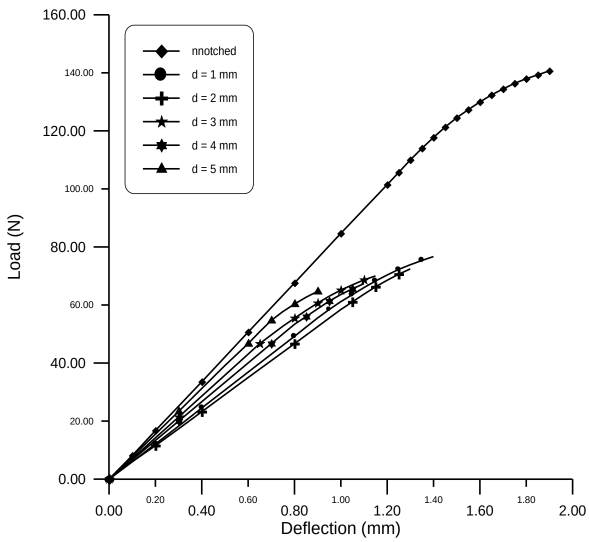


Figure (5) Flexure curves of two Layers

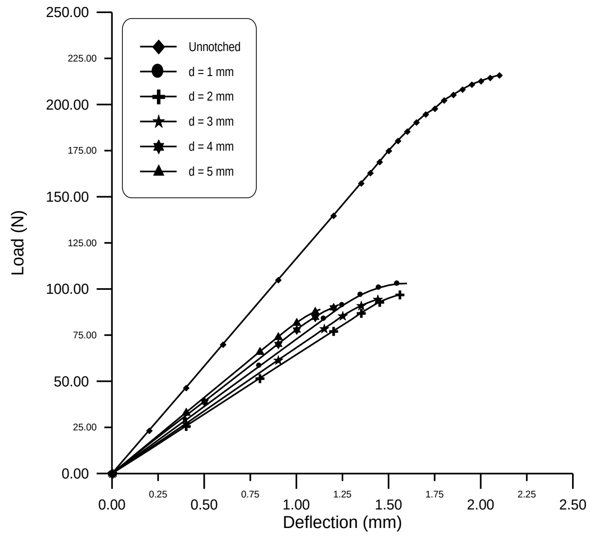


Figure (6) Flexure curves of three Layers

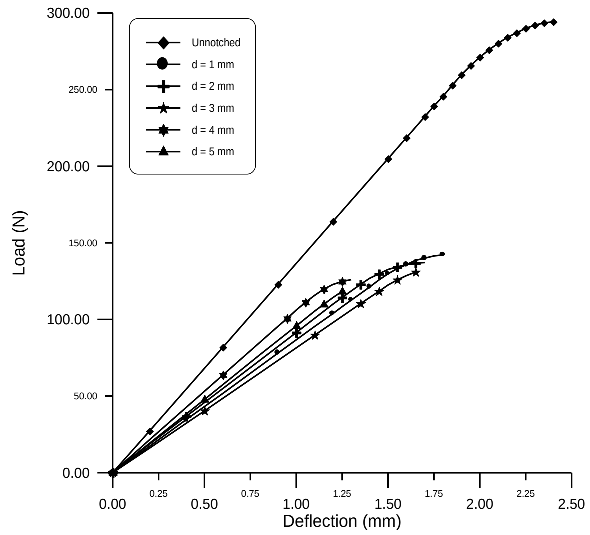


Figure (7) Flexure curves of four Layers

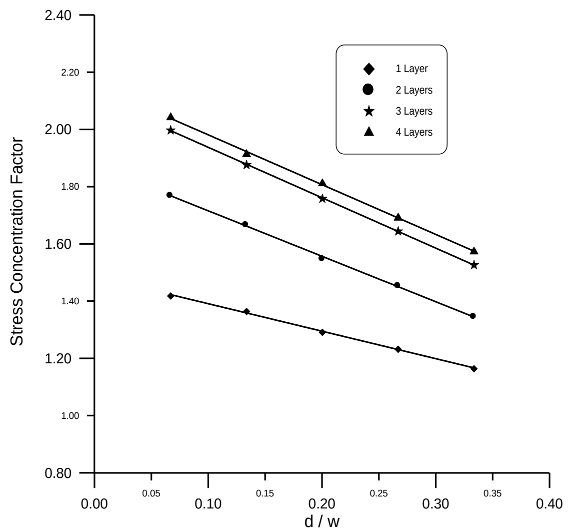
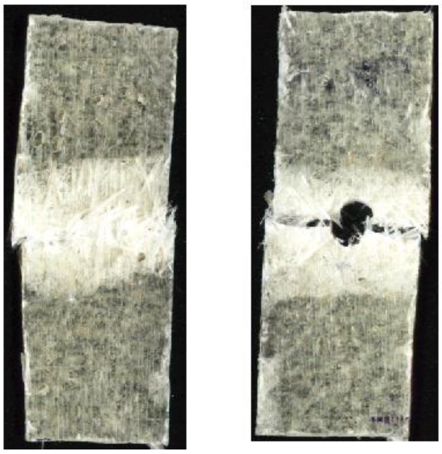


Figure (8) Experimental stress concentration factor for a circular hole as diameter to width varies

When comparing the results of stress concentration factor for (one, two, three and four) layers laminate, It has been noticed that (K_t) increase with an increase number of layers. This is because of the four layers specimens' failure at a slightly higher stress than the three layers. The three layers specimens fail at higher stress than the two layers one. The two layers do fail at higher stress than the one layer. This is due to the increase in thickness of the specimens which increase the cross sectional area, and, thus the flexure stress will increase slightly.

The failure modes of these specimens shown in **Fig.(9)** give some indication as to the reason why the results for the notched specimens fall below the data for the other unnotched specimens. In the case of unnotched specimens, all the laminates showed some edge delamination, but the predominate failure mode was a break across the entire width of the specimen. However, the notched specimens had relatively clean crack through the notch with virtually no delamination.



(a) **(b)**

Figure (9) Fracture modes of specimens: (a) Unnotched; (b) Notched

The numerical results are presented in **Figs.(10, 11, 12 and 13)**. They show the relation between the maximum stress ($\sigma_{\max}$) with the distance from notch (x). It is shown that the higher level of stress occurs at the tip of the notch (x =0). Then it falls off to an average value near the edge of the specimen. The reason for this behavior is due to missing material volume in the notch. Also, it is noticed that stress decrease with an increase hole size, The reason for this behavior is that with the increasing of the hole size, the volume of the missing material is increased. Thus the stress induced at this volume and transferred to the notch region is also decreased. The distribution of stresses contours for notched specimen is shown in **Fig.(14)**.

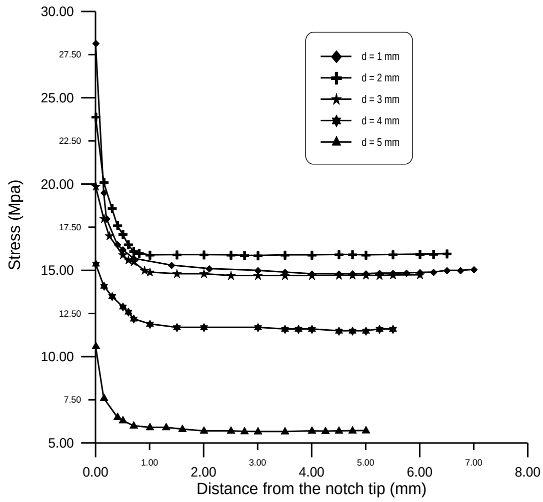


Figure (10) Variation of maximum stress with distance from the notch tip for one layer

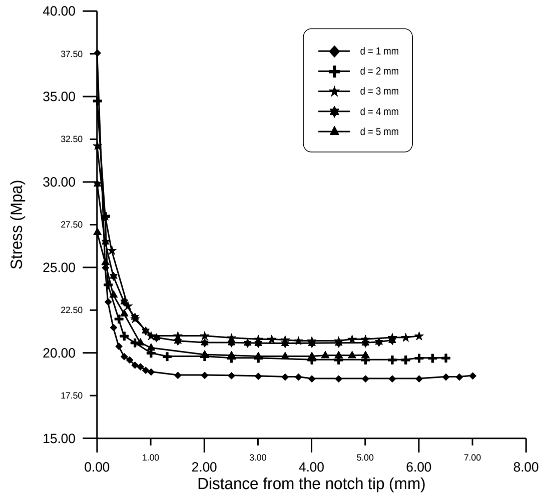


Figure (11) Variation of maximum stress with distance from the notch tip for two layers

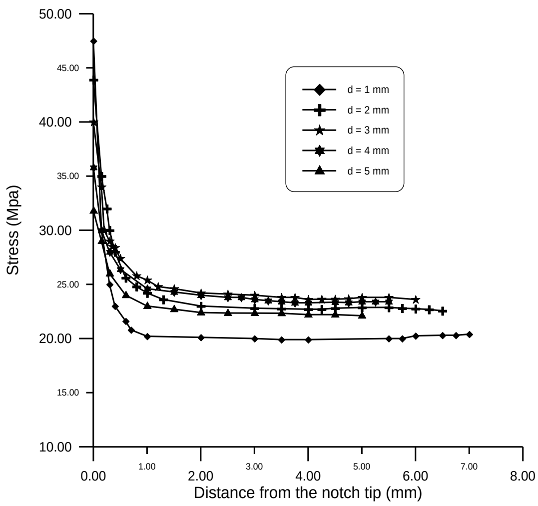


Figure (12) Variation of maximum stress with distance from the notch tip for three layers

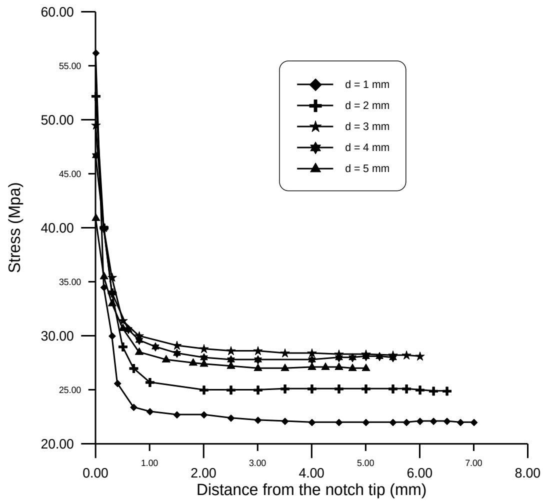


Figure (13) Variation of maximum stress with distance from the notch tip for four layers

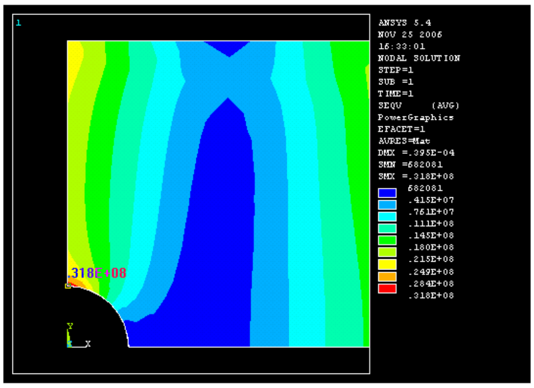


Figure (14) Distribution of stresses contours for notched specimen

Finally, the theoretical results of stress concentration factors for a circular hole are presented in **Fig.(15)**. The general behavior of these curves shows that the values of stress concentration factor decrease with the increase in the hole size. Again, the reason for this behavior was explained before which is similar to that of **Fig.(8)**.

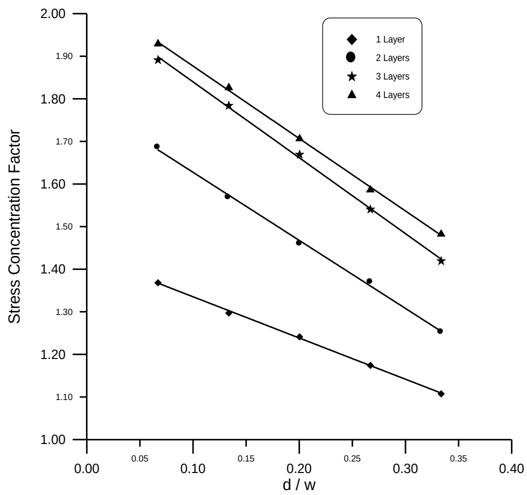


Figure (15) Theoretical stress concentration factor for a circular hole as diameter to width varies

The differences between the theoretical and experimental results are shown in **Tables (1, 2, 3, and 4)** for one, two, three, and four layers respectively. These tables show little differences between the two sets of results. In all cases the theoretical results were lower than the experimental results. This is due to two sets of error sources. The first set is due to the error which caused by using the finite element techniques which is an approximation method. The second set of error is generated in the experimental results due to using equation (3). This equation involved two values of the ultimate flexural strength. Some error is inherited in using the volume constancy equation in calculating the area for the section.

It is obvious that the experimental results show a relatively good agreement with the theoretical results with arrange of error ranging from (3.52 to 4.908%) for one layer, (4.69 to 6.91%) for two layers, while in the three layers the ranging of error was (4.9 to 7.007%), and (4.54 to 6.205%) for four layers.

Table (1) The difference between theoretical and experimental (K_t) for 1 layer

Hole size (mm)	Theoretical K_t	Experimental K_t	Difference %
1	1.369	1.419	3.52
2	1.298	1.365	4.908
3	1.242	1.292	3.87
4	1.175	1.233	4.703
5	1.108	1.165	4.89

Table (2) The difference between theoretical and experimental (Kt) for2 layers

Hole size (mm)	Theoretical K_t	Experimental K_t	Difference %
1	1.686	1.769	4.69
2	1.569	1.667	5.87
3	1.46	1.547	5.62
4	1.37	1.454	5.77
5	1.253	1.346	6.91

Table (3) The difference between theoretical and experimental (K_t) for3 layers

Hole size (mm)	Theoretical K_t	Experimental K_t	Difference %
1	1.892	1.998	5.305
2	1.785	1.877	4.9
3	1.67	1.759	5.06
4	1.541	1.645	6.32
5	1.42	1.527	7.007

Table (4) the difference between theoretical and experimental (K_t) for4 layers

Hole size (mm)	Theoretical K_t	Experimental K_t	Difference %
1	1.93	2.043	5.53
2	1.827	1.914	4.54
3	1.707	1.812	5.8
4	1.587	1.692	6.205
5	1.483	1.574	5.78

5. Conclusions

The main conclusions of this work are listed below:

1. The behavior of the composite beam under flexural load can be separated into two portions: Linear and non-linear.
2. The number of layers (N) in the laminated beams affects the laminated beam stiffness. Increasing (N), increase failure load and stress concentration factors.
3. The values of stress concentration factors decrease with the increase in the hole size for all layers.
4. The stress distribution induced in the composite notches was non-linear. The maximum value of the stress occurred near the tip of the notch.
5. The application of the finite element techniques yielded acceptable results compared to the experimental results.

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