FAILURE STRENGTH OF FABRIC COMPOSITES WITH DRILLED AND MOULDED-IN HOLES

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ABSTRACT

The effect of drilled and moulded-in circular holes of woven fabric composites on failure strength have been examined in flexural test. Three types of woven fabric-reinforced composite systems were used: glass fiber (E glass), Kevlar fiber, and glass- Kevlar hybrid in polyester matrix. All these types are of (30%) volume fraction, and hole diameter of (1, 2, 3, 4 and 5 mm) for each type. ISO standard flexural specimens were tested and repeated three times.

It is noticed that the specimens with moulded-in holes exhibit failure strengths higher than those of drilled specimens by (7- 24%). Also the values of stress concentration factors (K_t) increase with increasing the hole size for all types of laminates, and they were arranged in an ascending order as follows: Kevlar/ polyester, glass-kevlar hybrid/ polyester, and glass/ polyester.

Key words: strength, composite, failure, moulded-in hole, drilled holes

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الخلاصه

في هذا البحث تم دراسة تاثير قطر الثقوب قبل الصب وبعد الصب على إجهاد الكسر لحصائر المواد المركبة بتسليط احمال انحناء عليها٠ تم استخدام ثلاثة انواع من المواد المركبة المقواة بالالياف وهي الالياف الزجاجية (نــوع E)، اليــاف الكفلر ومادة هجينة من الالياف الزجاجية والياف الكفلر في راتنج البوليستر وبنسبة كسر حجمي مقداره (٣٠%)، وبقطر ثقب (١، ٢، ٣، ٤ و٥ ملم) لكل نوع، حيث استخدمت المواصــفات العالميــة (ISO Standard) لاختبــار الانحنــاء وتحضير العينات وإجراء الاختباروالتكرار لثلاث مرات.

لوحظ ان قيم اجهاد الكسر للعينات المتقوبة قبل الصب اعلى مقارنة بالعينات المتقوبة بعد الصب بمقدار (٧- ٢٤%). كذلك فان قيم معاملات تركز الاجهاد تزداد بزيادة قطر الثقوب لجميع الانواع، وان قيمها مرتبة تصاعديا كمــايلي: الياف الكفلر، الالياف الهجينة من الكفلر والالياف الزجاجية واخيرا الالياف الزجاجية في راتنج البوليستر٠

INTRODUCTION

A composite material can be defined as a macroscopic combination of two or more distinct materials, having a recognizable interface between them **(Theodore and Linda, 1987)**.

The term "hybrid" is used to describe composites containing more than one type of fiber material in a common matrix. Hybrid composites have several advantages as compared with conventional composites. For example, the freedom in tailoring material properties increases; the cost of fiber can be reduced by using fewer amounts of expensive fibers **(Fukuda and Chou, 1983)**. Researches on hybrid composites have grown rapidly since the eighties of the recent century as reviewed by **(Chou and Kelly, 1980)**, and **(Renton, 1981)**. In recent years, the utilization of hybrid composite materials in many engineering fields has increased tremendously. **(Mohamed et al, 2009)** studied fabric-reinforced hybrid composite laminates with different volume fractions of the constituent materials.

Woven fabric reinforcements for composites offer advantages such as dimensional stability, deep-draw shape ability and enhanced toughness **(Curtis and Bishop, 1984)**.

The main functions of the fibers in a composite are to carry most of the load applied to the composite and provide stiffness. For this reason, fiber materials have high tensile strength and high elastic modulus **(Bolton, 1998)**.

Composite materials notches analysis becomes very important subject due to the wide expansion in the use of these materials in all fields of industry, and the possibility of notched parts failure at these regions. It is very important for the engineer to be aware of the effects of stress raisers such as notches, holes or sharp corners in the design work. Stress concentration effects in machine parts and structures can arise from internal holes or voids created in the casting or forging process **(Theodore and Linda, 1987)**.

The stress concentration due to the hole will cause substantial reduction in strength and stability of notched composite laminates. The magnitude of this reduction varies considerably with a multitude of factors. All composite materials that exhibit a linear elastic stress-strain relationship to failure will be very sensitive to notches. Unlike metallic materials, the effects of the notch on strength will vary with the size of the notch but are relatively independent of notch geometry **(Mohamed et al, 2009)**.

(Arola and McCain, 2003) studied the influence of hole quality on the mechanical behavior of fiber reinforced laminates.

The use of flexural tests to determine the mechanical properties of resins and laminated fiber composite materials is widespread throughout industry owing to the relative simplicity of the test method, instrumentation and equipment required. Although, it is frequently found, that flexure tests give results which are very similar to those form other tests (tension and compression, for example) **(Hodgkinson, 2000)**.

Glass fiber (E glass) and Aromatic polyamide (Kevlar 49) are the fibers used in this work. E-glass is the most commonly used glass because it draws well and has good tensile strength of (1.4–2.5 Gpa) and young's modulus of (76 Gpa), also has good stiffness, electrical and weathering properties. Kevlar has a higher tensile strength of (2.8–3.6 Gpa) and young's modulus of (125 Gpa) **(Hull, 1981)**.

In this paper, an experimental data base of notched strength of Kevlar, glass and glass-kevlar hybrid woven fabric composites with polyester matrix is established. Strength characterizations in bending are performed. Specimens with drilled and moulded-in holes of diameter (1, 2, 3, 4 and 5 mm) are studied. Fiber volume fraction of all specimens assumed to be 30%.

There is an obvious enhancement in notch strength by replacing drilled holes with moulded-in holes, and the failure strength of laminates with moulded-in holes are higher than those of laminates with drilled holes by (7- 24%).

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 fracturing point. Then the maximum stress without notch is determined and another specimen with notch is subjected to flexure load to get (σ_{max}), as follows **(Mccrum et al, 1997)**:

$$\sigma_{max} = \frac{M\,C}{I} \quad (1)$$

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 quations 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 static stress concentration factor (K_t) is calculated as follows (**Caprino et al,1979)**:

$$K_t = \frac{Unnotched\ Stress}{Notched\ Stress} \quad (2)$$

This method is widely used because it is easy and can be carried out with minimum expenses with generally acceptable errors.

Although most calculations on composite materials are based on the volume fraction of the various constituents, it is sometimes important, particularly when calculating the density of the composite to use weight fractions. The appropriate conversion equations are **(Hull, 1981)**.

$$V_1 = \frac{\frac{W_1}{\rho_1}}{\frac{W_1}{\rho_1} + \frac{W_2}{\rho_2} + \frac{W_3}{\rho_3} ....} \quad (3)$$

And

$$W_1 = \frac{\rho_1 V_1}{\rho_1 V_1 + \rho_2 V_2 + \rho_3 V_3 .....} \quad (4)$$

Where:

V_1 , V_2 , V_3 etc. are the volume fractions of the constituents.

W_1, W_2, W_3 etc. are the weight fractions of the constituents.

ρ_1, ρ_2, ρ_3 etc. are the densities of the constituents.

EXPERIMENTAL PROCEDURE

Three types of woven fabrics are utilized in this study: Glass fiber, kevlar fiber and glass-kevlar hybrid in polyester resin. All types are of 30% volume fraction (V_f = 30%) and of three layers. Each group has the same various hole diameters of (1, 2, 3, 4 and 5 mm). The densities of E-glass fiber, Kevlar and polyester resin are (2.56) g/cm^3 **(Suhad, 2002)**, (1.45) g/cm^3 and (1.2) g/cm^3 **(Hayat, 2002)** respectively.

The geometry and dimensions of the flexure specimens with a hole in the middle are according to **ISO** standards **(Handbook, 1984)** as shown in **Figure (1)**. The thickness and length (L_c) of the specimens are (1.5 and 24 mm) respectively.

Where the relation is:

L_c = 15h to 17h. L= L_c+20 mm for every end. W = 15 mm ± 0.5 for 1mm < h <10 mm.

A circular hole was machined by initially drilling a starter hole of small diameter, and carefully enlarging it to its final dimensions by incremental drilling.

Moulded-in holes were formed in the prepreg sheets after they were cut in to the 30×30 mm size and before curing. A steel punch with a pointed end was used gradually to open a circular space between the fibers up to the desired diameter. In order to control the size of the holes precisely, a pin was inserted into the hole formed in the prepregs. An additional aluminum plate was placed on top of the lay-up to ensure a smooth specimen surface, especially at areas near the moulded-in holes. **Figure (2)** shows a moulded-in hole of glass, Kevlar, and glass- Kevlar hybrid specimens.

It should be mentioned that a period of (8) days is required by the composite material setting to the material being ready for sample preparation.

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

RESULTS AND DISCUSSION

The purpose of moulding-in holes is to increase the strength of the laminate. The experimental results for the three composite types are shown in **Tables (1 and 2)**. These results show that the failure strength of specimens with moulded-in holes are higher than those with drilled holes by (7- 24%), due to reinforcing the area in the vicinity of the hole, and maintaining fiber continuity. For glass/polyester and glass-kevlar/ polyester hybrid laminates, the notched strength ratios (moulded-in to drilled) are greater than unity and tend to increase as the hole size increased. In the case of Kevlar/polyester laminates, the notched strength ratios are greater than unity and tend to decrease for larger hole sizes.

Table (3) shows the values of stress concentration factors for drilled and moulded-in holes. When comparing the results of stress concentration factor for glass/polyester, kevlar/ polyester and glass-Kevlar/ polyester laminates, it has been noticed that the stress concentration factor for kevlar/ polyester is lower than hybrid/ polyester, and the stress concentration factor for hybrid/ polyester is lower than glass/polyester. This is because of the Kevlar/ polyester specimens fail at a slightly higher stress than the hybrid/ polyester and the last fails at a slightly higher stress than glass/polyester. This is due to the flexural strength for Kevlar fiber is higher than for glass fiber. Also **Table (3)** shows that the results of stress concentration factors of moulded laminates are lower than those of drilled laminates, due to increasing local fiber volume fraction, and maintaining fiber continuity. These results show a good agreement when compared with those corresponding results obtained by **(CHANG et al, 1987)**. In addition to the above it can be shown that the stress concentration factor increases with increasing hole size, due to the decrease in the failure strength.

Figure (3) shows the failure mode of the glass laminate of moulded-in and drilled hole. The brittle fracture process consisted of some delamination. Each half of the fractured specimens was attached to part of the edge of the hole from the matching half. For drilled hole specimens, the fractured halves had no extended hole edge attached, but showed brittle fracture across the entire fracture surface.

Kevlar composites showed several different failure modes. The ductile fracture process consisted. For moulded-in and drilled hole as shown in **Figure (4)**, each half of the fractured specimens was attached to part of the edge of the hole from the matching half. The development of failure started near the hole and propagated towards the end until the specimen broke, mostly due to delamination.

The failure modes of the hybrid laminates more closely resembled those of the Kevlar laminates than those of the glass laminates. The fracture of the laminate was ragged, and the brittle type of fracture mode observed in the glass laminates was not distinctive in this case as shown in **Figure (5)**. Also the hole shape was again distorted during the failure process.

CONCLUSIONS

The main conclusions are listed below:

- The failure strengths of specimens with moulded-in holes are higher than those with drilled holes by (7- 24 %).
- The notched strength ratio (moulded-in to drilled) for glass/polyester and glass-kevlar/polyester hybrid laminates are greater than unity and tend to increase as the hole size become bigger.
- The notched strength ratio (moulded-in to drilled) Kevlar/polyester laminates are greater than unity and tend to decrease for larger hole sizes.
- The values of stress concentration factor for the laminates are arranged in an ascending order as follows: Kevlar/ polyester, hybrid/ polyester, and Glass/polyester.
- The results of stress concentration factor of moulded laminates are lower than the results of drilled laminates.
- The values of stress concentration factors increase with the increase in the hole size for all types.

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Table (1) failure strength of woven fabric laminates with drilled holes.

Hole size (mm)	glass/polyester		kevlar/polyester		glass-kevlar/polyester	
	Unnotched strength σ_o (Mpa)	Failure strength σ_N (Mpa)	Unnotched strength σ_o (Mpa)	Failure strength σ_N (Mpa)	Unnotched strength σ_o (Mpa)	Failure strength σ_N (Mpa)
1	357.3	253.2	501.3	443.6	405.3	332.2
2		232		401		302.4
3		211.4		374.1		273.8
4		196.3		353		254.9
5		182.3		332		237

Table (2) failure strength of woven fabric laminates with moulded-in holes.

Hole size (mm)	glass/polyester		kevlar/polyester		glass-kevlar/polyester	
	Unnotched strength σ_o (Mpa)	Failure strength σ_N (Mpa)	Unnotched strength σ_o (Mpa)	Failure strength σ_N (Mpa)	Unnotched strength σ_o (Mpa)	Failure strength σ_N (Mpa)
1	357.3	271.1	501.3	479.1	405.3	374.1
2		258.9		447.6		340.2
3		248.1		420.9		331.3
4		235		385.6		302.4
5		226.1		362.2		287.4

Table (3) values of stress concentration factor for drilled and moulded-in holes.

Hole size (mm)	glass/polyester		Kevlar/polyester		glass-kevlar/polyester	
	Moulded-in holes	Drilled holes	Moulded-in holes	Drilled holes	Moulded-in holes	Drilled holes
1	1.318	1.41	1.046	1.13	1.083	1.22
2	1.38	1.54	1.12	1.25	1.191	1.34
3	1.44	1.69	1.191	1.34	1.223	1.48
4	1.52	1.82	1.3	1.42	1.34	1.59
5	1.58	1.96	1.384	1.51	1.41	1.71

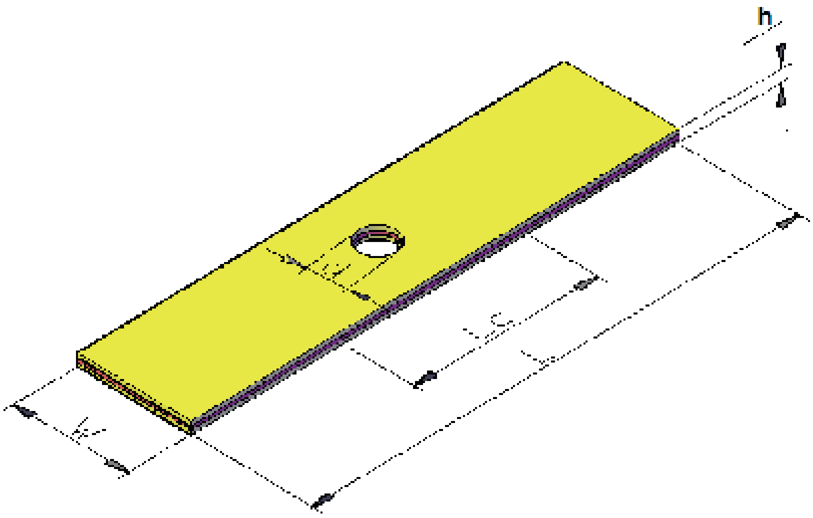
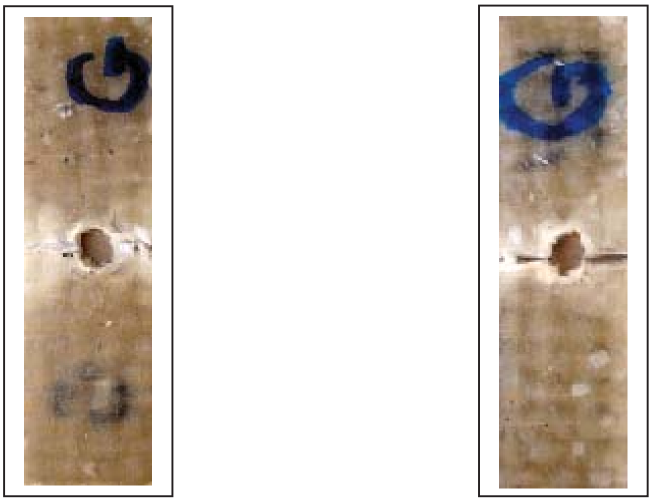


Figure (1) test specimen showing dimensions

(a) (b) (c)

Figure (2) moulded- in holes of (a- glass, b- kevlar, and c- glass- kevlar hybrid) laminates

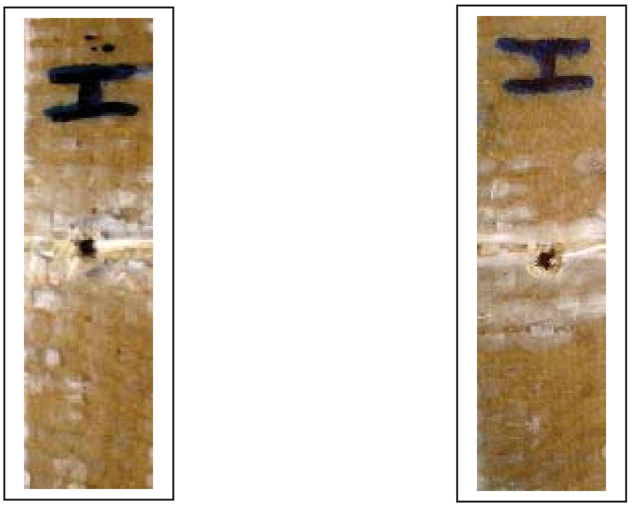


(a) (b)

Figure (3) fracture modes of (glass/ polyester) a- moulded-in hole, b- drilled hole

(a) (b)

Figure (4) fracture modes of (kevlar/ polyester) a- moulded-in hole, b- drilled hole



(a) (b)

Figure (5) fracture modes of (hybrid/ polyester) a- moulded-in hole, b- drilled hole