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Application of the Experimental Planning Design to the Notched Precracked Tensile Fracture of Composite

N. Mahmoudi

***Abstract*—**Composite materials have important assets compared to traditional materials. They bring many functional advantages: lightness, mechanical resistance and chemical, etc. In the present study we examine the effect of a circular central notch and a precrack on the tensile fracture of two woven composite materials. The tensile tests were applied to a standardized specimen, notched and a precarcked (orientation of the crack 0°, 45° and 90°). These tensile tests were elaborated according to an experimental planning design of the type 23.31 requiring 24 experiments with three repetitions. By the analysis of regression, we obtained a mathematical model describing the maximum load according to the influential parameters (hole diameter, precrack length, angle of a precrack orientation). The specimens precracked at 90° have a better behavior than those having a precrack at 45° and still better than those having of the precracks oriented at 0°. In addition the maximum load is inversely proportional to the notch size.

***Keywords*—**Polymer matrix, Glasses, Fracture.

I. Introduction

FRACTURE mechanics finds extensive applications in damage analysis of composite laminates. In all materials, brittle or ductile, homogeneous or composites, fracture is governed more or less by microscopic discontinuities and imperfections, such as cracks, inclusions, or dispersed phases. The material strength may be correlated with its fracture energy, elastic modulus, and the size of the crack initiating the fracture. The importance of estimating the fracture load of notched plates is more or less established while influence of related parameters like notch geometry, thickness of specimen, notch angle, and notch dept are widely studied [1]. One of the most important parameters in the application of fracture mechanics in composite structures is the energy release rate. Composite materials offer some exciting advantages over more traditional metallic materials. Applications range from ski sticks, tennis rackets and reinforcement of highway bridges to advanced aircraft and space vehicles. More widely, diverse applications suffer from difficulties in recycling to questions of long term durability and the inability to predict their life accurately.

In order to predict the life of the structural integrity of composite components, designers must possess a good understanding of the effect of stress concentrations around design features. The problem of predicting the notched strength of composite materials is one that has attracted a great deal of research over a period of around 30 years. There are a few studies concerning failure of notched woven fabric composite in literature. Naik et al. [2], Xiao et al. [3] and Kim et al. [4] demonstrated the applicability of the Whitney-Nuismer models. Damage development and fracture in notched woven fabric composites is affected by the range of variables, in particular notch size and shape, laminate lay-up and thickness. In the fracture field, Ashbee et al. [5] have verified, in an experimental way, the micromechanical damage due to cracking between inter-phase and matrix in composite. The present paper is concerned with the experimental characterization of the notched tensile fracture of two woven fabric composite materials. The notched and precracked specimens were subjected to the tensile tests in order to obtain the maximum fracture loads. A precrack was realised for a different length and orientation (0º, 45º and 90º). Applying the experimental design planning, a model describing the effect of all parameters was obtained.

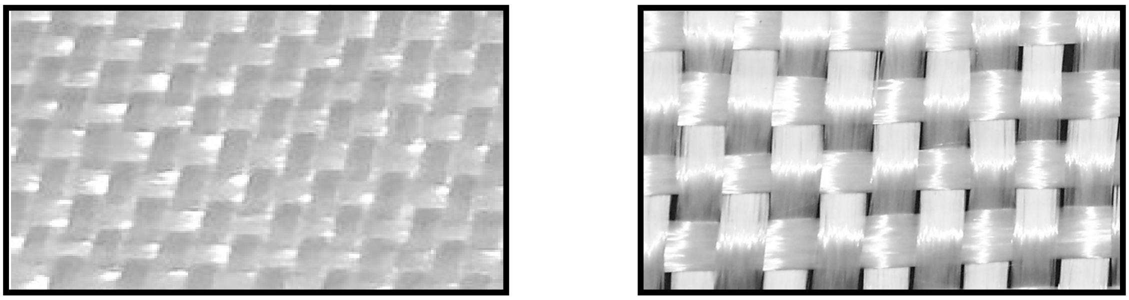
II. Materials

Two woven fabric composite materials were investigated. They were made of two panels of 350mm x 350mm, with a nominal thickness of 2 mm. The commercial denominations for these materials are RT270 and RT440. The panels were made of a bidirectional woven RT270 and RT440 glass fibre see Fig. 1 (with an unsaturated polyester thermoplastic matrix). The weight fraction of matrix considered was 30% for both materials. The laminates were made of 7 layers for RT270 and 4 layers for RT440.

III. Preparation of Specimens

The specimens were moulded first at 2 Bar and 315°C for 20 min and then at 20 Bar and 140°C for 10 min. The specimens were cut according to ASTM D3039 [6], and Tab aluminium end tabs were stuck on both sides of the specimens using 3M adhesive. The dimensions of the specimens were 125 x 20 x 2mm. Circular central holes with 2, and 4mm diameters were drilled. For each diameter, artificial precracks with length 1, 2 and 3mm were realized. The precracks orientation angles were 0°, 45° and 90° for each length and diameter. The precracks were perpendicular to the loading axis and carried out on one side of the circumference.

N. Mahmoudi is with the Laboratoire genie industiel et développemnt durable, Centre Universitaire Relizane. Algeria (phone:+213561557999; e-mail: mahmoudi.nord@gmail.com).



RT270 **RT440**

Fig. 1 Woven fabrics

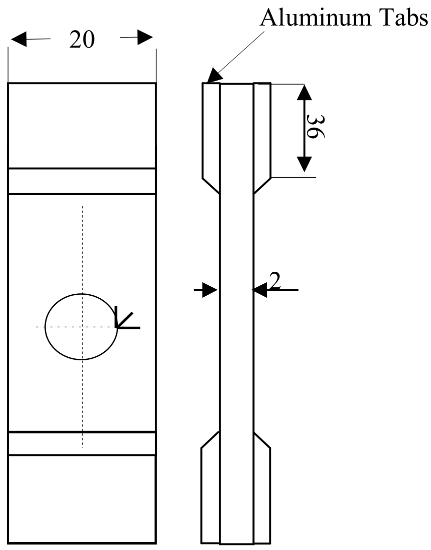


Fig. 2 Tensile specimen

IV. Tensile Fracture Test

For the tensile fracture test, five specimens of each material were tested according to ASTM D3039 using an Instron machine at a constant loading rate of 0.5 mm/min.

Fig. 3 shows the specimen after the test. Table I presents the real limit and a coded value of the influents parameters.

Taking into account of all influent parameters, the experiment of type $2^3.3^1$ was chosen. Because of the units diversity, values were coded by the relation [7]:

$$Xi = (xi\text{-}xio)/\Delta xi \quad (1)$$

Table II shows the coded influent parameters.

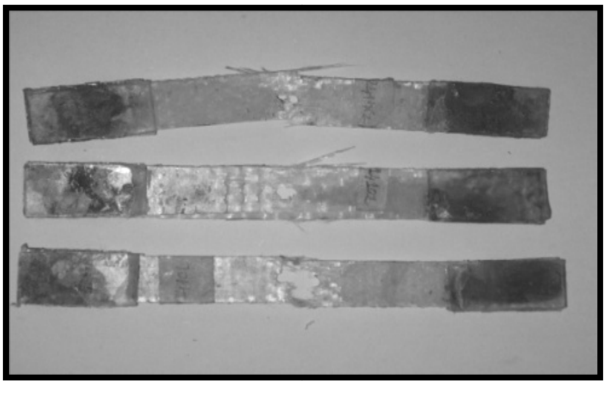


Fig. 3 Photograph showing the critical damage zone formed on laminated specimen

TABLE I
PARAMETERS VARIATIONS

Independent variables		Unit	Superior Level	Intermediate Level	Inferior Level
Materials (Weaving Types)	X1 (X1)		RT440 (+1)		RT270 (-1)
Notch Diameter	X2 (X2)	[Mm]	4 (+1)	3 (0)	2 (-1)
Precrack Length	X3 (X3)	[Mm]	3 (+1)	2 (0)	1 (-1)
Precrack Orientation Angle	X4 (X4)	[°]	90 (+1)	45 (0)	0 (-1)
Maximum Tensile Load	Y (Xi,βi)	[N]		Output Parameters	

TABLE II
EXPERIMENTAL DESIGN OF THE TYPE $2^3.3^1$

N°	X1	X2	X3	X4	X1 X2	X1 X3	X1 X4	X2 X3	X2 X4	X3 X4	X1 X2 X3	X1 X2 X4	X1 X3 X4	X2 X3 X4	X4*	$\overline{Y}$
1	-	-	-	-	+	+	+	+	+	+	-	-	-	-	1/3	7885
2	+	-	-	0	-	-	0	+	0	0	+	0	0	0	-2/3	8595
3	-	+	-	+	-	+	-	-	+	-	+	-	+	-	1/3	9085
4	+	+	-	-	+	-	-	-	-	+	-	-	+	+	1/3	7785
5	-	-	+	0	+	-	0	-	0	0	+	0	0	0	-2/3	8090
6	+	-	+	+	-	+	+	-	-	+	-	-	+	-	1/3	9960
7	-	+	+	-	-	-	+	+	-	-	-	+	+	-	1/3	7725
8	+	+	+	0	+	+	0	+	0	0	+	0	0	0	-2/3	7865
9	-	-	-	+	+	+	-	+	-	-	-	+	+	+	1/3	9545
10	+	-	-	-	-	-	-	+	+	+	+	+	+	-	1/3	8390
11	-	+	-	0	-	+	0	-	0	0	+	0	0	0	-2/3	7785
12	+	+	-	+	+	-	+	-	+	-	-	+	-	-	1/3	9335
13	-	-	+	-	+	-	+	-	+	-	+	-	+	+	1/3	7780
14	+	-	+	0	-	+	0	-	0	0	-	0	0	0	-2/3	8350
15	-	+	+	+	-	-	-	+	+	+	-	-	-	+	1/3	8955
16	+	+	+	-	+	+	-	+	-	-	+	-	-	-	1/3	7765
17	-	-	-	0	+	+	0	+	0	0	-	0	0	0	-2/3	8635
18	+	-	-	+	-	-	+	+	-	-	+	-	-	+	1/3	10040
19	-	+	-	-	-	+	+	-	-	+	+	+	-	+	1/3	7750
20	+	+	-	0	+	-	0	-	0	0	-	0	0	0	-2/3	8025
21	-	-	+	+	+	-	-	-	-	+	+	+	-	-	1/3	9300
22	+	-	+	-	-	+	-	-	+	-	-	+	-	+	1/3	8060
23	-	+	+	0	-	-	0	+	0	0	-	0	0	0	-2/3	7735
24	+	+	+	+	+	+	0	+	+	+	+	+	+	+	1/3	9030

V. RESULTS AND INTERPRETATIONS

Using the regression analysis of [7]-[10], we obtain the regression coefficients:

$$\overline{\overline{Y}} = \sum_{1}^{N} X_0 Y \Big/ \sum_{1}^{N} X_0^2 \tag{2}$$

$$\beta_{tt} = \sum_{1}^{N} X_i^* \overline{Y} \Big/ \sum_{1}^{N} X_i^{*2} \tag{3}$$

$$\beta o = \overline{\overline{Y}} - \left(1/C^*\right) \sum_{1}^{k} \beta_{tt} \tag{4}$$

$$X_4^* = X_4^2 - \left(2/3\right) \tag{5}$$

$\beta 0$ = 8134.87; $\beta 1$ = 122.08; $\beta 2$ = 241.25; $\beta 3$ = 93.33; $\beta 4$ = 756.87; $\beta 12$ = -57.92; $\beta 13$ = -1.67; $\beta 14$= 38.75; $\beta 23$ = 35.83; $\beta 24$= -84.37; $\beta 34$= -17.5; $\beta 123$ = -21.66; $\beta 124$ = -7.5; $\beta 134$ = 13.13; $\beta 234$ = -31.25; $\beta 44$ = 514.69

The confidence interval ($|\Delta\beta i|$ = S(bi).tα, fy) of the regression coefficients obtained with α= 0.05 and 24 experiments is equal to 51.21 [8].

With: t(0.05, 24) = 1.711 and S(bi) = 29.93

Taking only the significant coefficients, the model can be written as follows:

Y(Xi, βi) = 7791.74 +122.08X1 +241.25X2 +93.33X3 +756.87X4 -57.92X1X2 -84.37X2X4 + 514.69X42 (6)

The model presented by (6) describes the phenomenon adequately by the fact that Fexp. = 1.287 is lower than Fth. = 2.11 [7].

In order to obtain the graphical representation of (2), we maintain the type of weaving fibers (X1) and the notch diameter (X2= 3mm average value), the mathematical model presented in (2) has the form:

Y(Xi, βi) = 7791.74+ 93.33X3 + 756.87X4 +514.69X42 (7)

The graphical representation of (7) is given in Fig. 4.

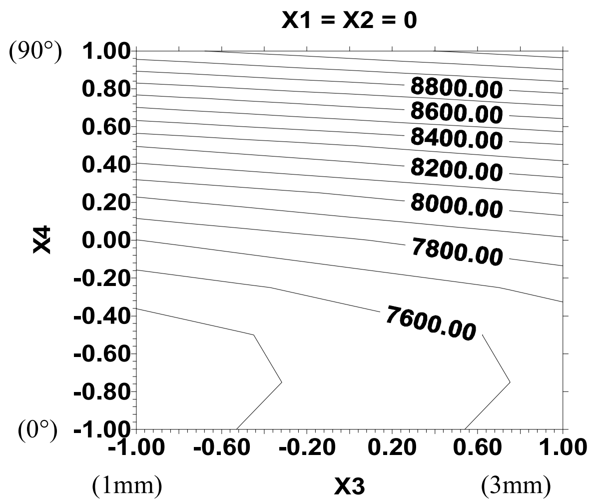


Fig. 4 Effect of the precrack lenght and the angle of orientation on the maximum load

For an increase in a precrack length, the maximum tensile load does not increases linearly with respect to the angle of orientation from 0 to 10.8° because the direction of the traction charge is perpendicular with respect to the length axis of the crack whish provides a weak resistance against the breakdown of break [11]. Up to this value, the load does not increase linearly from 10.8 to 45° because the structure of fibers that stop the progress of fracture [12], and then increases linearly and break rapidly from 45 to 90° because the crack axis is parallel to the charge axis [13].

The angle 10.8º was calculated from (1):

$$x_i = X_i * \Delta x + x_{i0} \ ;$$

(where Δx = xi - xi0) = 0.76 * 45 + 45

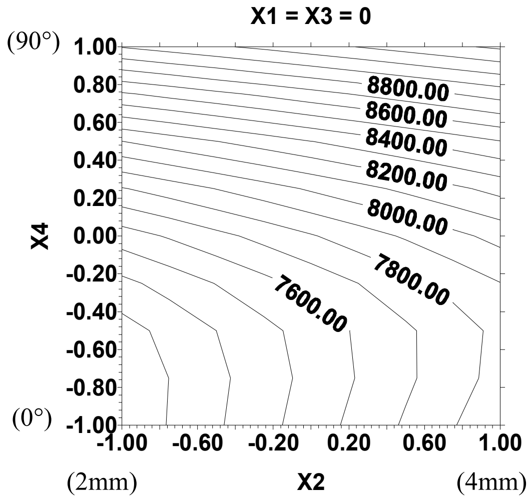


Fig. 5 Effect of the notch diameter and the angle of orientation on the maximum loading

From Fig. 4, the maximum load 9650 N was reached for an orientation angle of 90º and a precrack length of 3mm for a central notch diameter of 3mm.

In the second stage, we maintain the type of weaving X1 and the precrack length X3 (2mm average value), the model described in (2) takes the form:

Y(Xi, βi) = 7791.74+241.25X2+756.87X4-84.37X2X4 +514.69X42 (8)

Equation (4) is represented in Fig. 5. With an increase in the notch diameter, the maximum tensile fracture does not decrease linearly but slowly with the growth of the angle of orientation from 0 to 21.6°. The load increases in a non-linear way and slowly for an angle ranging from 21.6º to 66.6°. Beyond this value, it increases linearly and rapidly (Fig. 5), because the material is insensitive to the notch effect. It even shows the opposite effect, namely that the ligament is much stronger resistant then the depth of cut is large. This can be explained by the mechanisms of damage at the mesoscopic scale of oblique folds [14], [15].

In the third stage, we maintain the type of weaving X1 and the angle of orientation X4 (45º average value), the model presented in (6) becomes:

Y(Xi, βi) = 7791.74+ 241.25X2 + 93.33X3 (9)

Equation (9) is represented in Fig. 6.

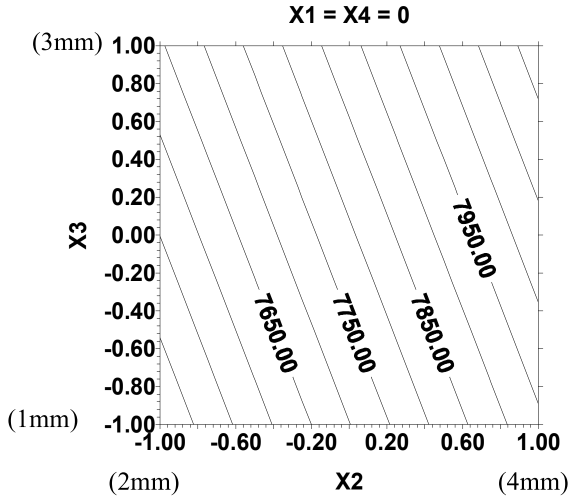


Fig. 6 Effect of the notch diameter and the precrack length on the maximum load

From Fig. 6, we note that the simultaneous increase of the notch diameter (X2) and the precrack length (X3) generate a linear growth of the maximum loading tensile [16]-[18].

For the fourth stage, we maintain the notch diameter X2 (3mm average value) and X3 (2mm average value), (6) takes the form:

Y(Xi, βi) = 7791.74+ 122.08X1 + 756.87X4 +514.69X42 (10)

Fig. 7 shows the mathematical representation of (10).

From Fig. 7, the change in the type of weaving fibers generates no linear decrease in the maximum load with the variation in the angle of orientation from 0º to 10.8°. The load increases in a non linear way and slowly for an angle ranging from 10.8º to 59.4°, then linearly and rapidly for an angle ranging from 59.4º to 90° [19]-[21].

In the fifth stage, the notch diameter and the angle of orientation are maintained to their average values X2 = 3mm and X4 = 45º, (6) takes the form:

Y(Xi, βi) = 7791.74+ 122.08X1 + 93.33X3 (11)

The maximum load given by (11) is represented in Fig. 8. It is noted that the maximum load increases linearly with the variation of the type of weaving and the precrack length [22].

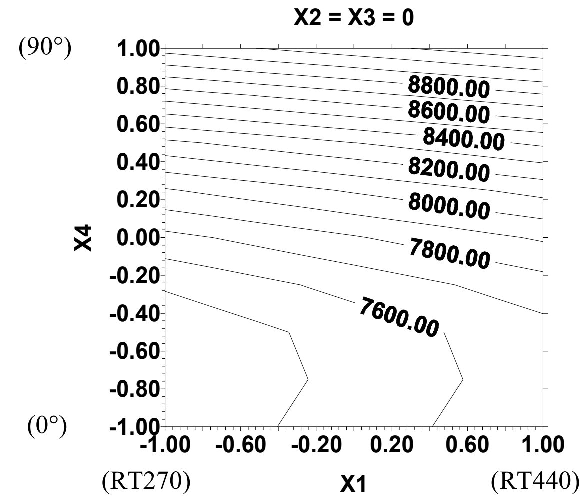


Fig. 7 Effect of the weaving type and the angle of orientation on the maximum load

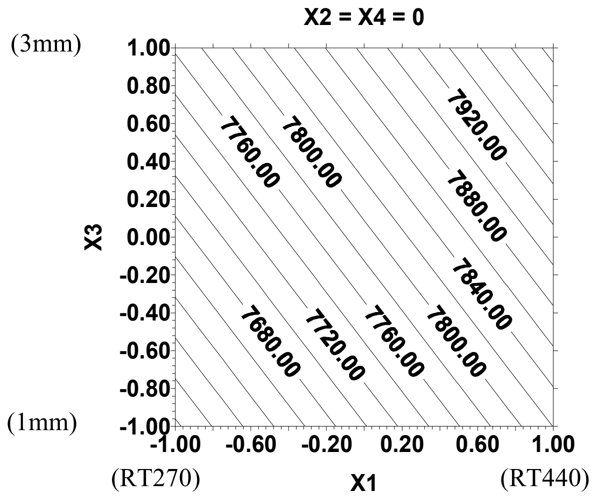


Fig. 8 Effect of material and the crack length on the maximum loading

In the last stage, we maintain the precrack length (X3 = 2mm) and the angle of orientation X4 = 45º to their avrage values, (6) becomes:

$$Y(Xi, \beta i) = 7791.74+ 122.08X1 + 241.25X2 -57.92X1X2 \quad (12)$$

Fig. 9 shows the mathematical representation of (12).

Fig. 9 shows that the maximal load in the case of RT440 is higher than that of RT270 because the resistance of the former (1,100 N/cm) is higher than that of the latter (360 N/cm) in traction [23], [24].

The same figure also shows that the load increases with the notch diameter growth [25], [26].

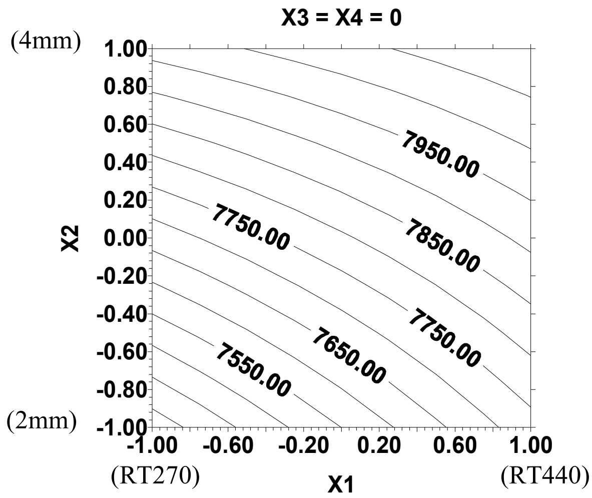


Fig. 9 Effect of the weaving type and the notch diameter on the maximum loading

VI. CONCLUSION

The tensile fracture test is carried out in order to determine the maximum fracture load of two woven fabric unsatured poly-esther matrix reinforced with glass fibers. The circular central notches of different diameters are drilled. For each diameter the artificial precracks are made. The precracks have different orientations. By applying the planning experimental design, a mathematical model giver the maximum tensile load is obtained. It takes in account into of the different parameters like notch diameter, the precrack length, the angle of orientation and the type of weaving. From the obtained results, the tensile load for a material RT270 is lower than that of material RT440. The load increases linearly with the simultaneous increase of the notch diameter and the precrack length. On the other hand it decreases with the increase of the orientation angle of the precrack and the notch diameter.

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