Original Article

Fracture toughness and notch sensitivity of jute fiber mats reinforced unsaturated polyester matrix composites based on the characteristic distance

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Abstract

Recycled needle punched natural jute fiber mats were used to reinforce unsaturated polyester matrix composites via modifying the hand lay-up technique with resin pre-impregnation into the jute fiber mats in vacuum. The notch sensitivity of these composites was investigated by using the characteristic distance d_o calculated by Finite Element Method (FEM) according to Whitney and Nuismer model definition. In this work, the concept of the characteristic distance was discussed from the point view of fracture mechanics, therefore the aim of this study is to investigate and reconfirm the physical meaning of d_o by investigation the fracture toughness (K_{Ic}) of jute mat composites (JMC) based on d_o calculated by Finite Element Method (FEM) with width, W, to the hole diameter (D = 10 mm) ratio (W/D = 3) with 25 wt% fiber weight content. The results showed that JMC composites in terms of residual tensile strength (σ_n/σ_o) (the ratio of notched to unnotched strength) that there is only 16 % loss in the tensile strength due to the presence of the hole. Moreover, the experimental maximum load during tension test with hole is almost near to the maximum load calculated using K_{Ic} and d_o which validates the physical meaning of d_o which represents the distance from the hole boundary at which the brittle fracture starts to occur.

Key words
characteristic distance, FEM, fracture toughness, jute mat, unsaturated polyester

1. Introduction

The terms "notch sensitivity" and the "notched shape sensitivity" are classified based on experimental studies. If the performance of a laminate is affected by the stress concentrations, it is notch sensitive. If it is affected by the change of opening shape with a same opening length, the laminate is defined as notched shape sensitive. In general most of the laminates are found to be notched shape sensitive (Potti et al., 2000).

Mechanical joints are widely used as a reliable and practical method to assemble the composite parts that constitute a mechanical structure; they offer the advantage of assembly and disassembly for accessibility and maintenance, and reliability at various environmental conditions. However, a significant drawback when using the mechanical joint is that it always requires joint holes, which can be a source of stress concentration and thereby weakens the intended strength for the structures (Camanho and Lambert, 2006; Green et al., 2007).

The problem of the stress distribution around a circular hole in a composite plate and the associated failure criteria have been the subject of extensive research. (Shembekar and Naik, 1992) reported that the stacking sequence has a significant effect on the notched and unnotched tensile strength of woven fabric composite laminates and the fabric structure governs the failure modes of woven fabric composites. (Feraboli, 2008; Feraboli et al., 2009) investigated the notched failure response of oriented strand board (OSB) in the form of wood composite and carbon fiber/epoxy composites. They concluded that OSB and carbon fiber/epoxy composites are notch insensitive due to the internal stress concentration arising from the heterogeneous nature of the substructure.

It is known that fractures of engineering material are categorized as ductile or brittle fractures. Ductile fractures absorb more energy, while brittle fractures absorb little energy, and are generally characterized by fracture with flat surfaces. Moreover, the fracture toughness is a material property which is related to the amount of energy required to create fracture surfaces and is a quantitative way of expressing a material's resistance to brittle fracture when a crack is present.

Most methods currently used for predicting tensile strength of composite laminates containing holes and cracks adopt a characteristic distance approach are such as the point stress criterion (PSC) and the average stress criterion (ASC) developed by (Whitney and Nuismer, 1974) which they were based on the assumption that fracture would occur when the stress at a specific distance (the characteristic distance, do) away from the discontinuity reached the unnotched strength level. This dimension represents distance over which the material must be critically stressed in order to find a sufficient flaw size to initiate failure.

The limitation of such approaches, however, is that do is not a physical parameter but is an empirically determined constant depends on the geometry of the specimen among other factors. In this work, the concept of the characteristic distance was discussed from the point view of fracture mechanics, therefore the aim of this study is to investigate and reconfirm the physical meaning of do by investigation the fracture toughness of jute mat composites based on do calculated by Finite Element Method (FEM) with width, W, to the hole diameter (D = 10 mm) ratio (W/D = 3) with 25 wt% fiber weight content.

2. Experimental procedure

2.1 Materials and composites preparation

Jute fiber mats consisting of 50 % jute slivers and 50 % recycled jute were prepared by Yano Co.LTD, Japan. Unsaturated polyester, Rigorac™ was obtained from Showa Denko K.K., Japan and the curing agent is Methyl ethyl ketone peroxide (PERMEK® N) obtained from NOF Corporation, Japan. Composites were fabricated using pre-impregnation of jute fiber mats in unsaturated polyester in vacuum conditions and they were cured under a pressure of about 50 kg/cm^2 at room temperature for 24 h and details were mentioned in (Elbadry and Hamada, 2012). The abbreviation for jute mat composites can be called JMC.

2.2 Mechanical characterization

Tensile test of unnotched specimens were determined according to ASTM D 3093/D3039 M standard with sample dimensions of 250 × 25 × 6 mm using aluminum taps of 1 mm thickness to prevent gripping damage. For the circular hole notched specimens, the hole diameter was D = 10 mm as shown in Figure 1 with W/D = 3 with gage length of 100 mm and the drilling was carried out on wooden plates to avoid delamination during the drilling. Three specimens were tested and the measurements were done using a universal Instron testing machine (Model 55 R 4206, Japan) at a crosshead speed of 1 mm/min. at room temperature.

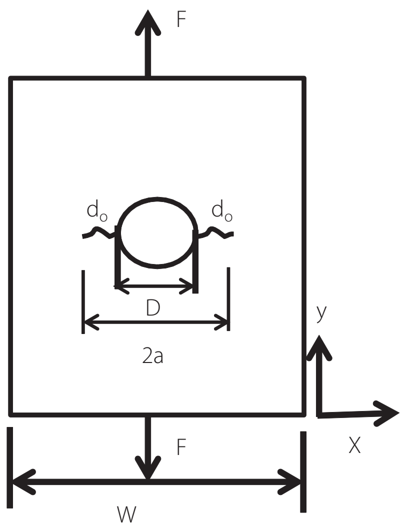

Figure 1: Dimension of the notched specimen

Moreover, the fracture toughness test was carried out using tension testing of eccentrically loaded, single-edge-notch specimen, ESE(T), specimens in open mode loading according to ASTM E 1922-97 with specimen dimension of 250 × 25 × 6 mm with specimen width to crack length ratio (W/a = 2,3). Five specimens were tested for each and the measurements were carried out using a universal Instron testing machine (Model 55 R 4206, Japan) at a crosshead speed of 1 mm/min. at room temperature.

2.3 Finite Element Method (FEM)

The characteristic distance d_o was obtained according the point stress (Whitney and Nuismer, 1974). In this criterion d_o is the distance which the failure occurs when the stress σ_y over some distance d_o away from the discontinuity is equal to than the strength of the unnotched material σ_o and FEM stress analysis was performed to obtain tensile stress distribution σ_y around the hole as shown in Figure 2.

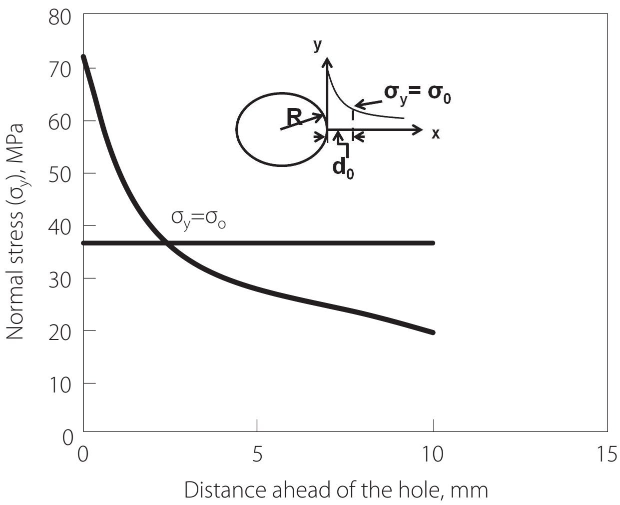

Figure 2: Stress distribution at failure around the hole for JMC composites for W/D = 3

This stress distribution was obtained using the maximum load and the material constant i.e. the modulus by using 2D plane element (Marc) for analysis the stress distribution around the circular hole assuming the materials are isotropic with Poisson's ratio is equal to 0.3. The meshing process were modeled with boundary condition with displacement equals zero in x direction and the displacement equal 1 mm in y direction which is the direction of the tensile loading as shown in Figure 1 and the element type is mechanical as plain strain solid and entirely elastic.

3. Results and discussion

The tensile strength of notched composites σ_n can be determined from the following equation:

$$\sigma_n = \frac{P_{max}}{(W\text{-}D) \times t} \quad (1)$$

where P_{max} is the experimental maximum load (N), W is the specimen width (mm), D is the notch diameter and t is the specimen thickness (mm) as shown in Figure 1. Figure 2 shows FEM average stress distribution around the hole of JMC at 25 wt% for W/D = 3, from which d_o represents the distance at which the failure occurs when the stress σ_y over d_o away from the hole boundary is equal to the strength of the unnotched material σ_o.

The fracture toughness K_{Ic} of JMC was calculated according to according to the following equation:

$$K_{Ic} = [P_{mzx}/BW^{1/2}]\ \alpha^{1/2}\ [1.4 + \alpha]\ [3.97 - 10.88\ \alpha + 26.25\ \alpha^2 - 38.9\ \alpha^3 + 30.15\ \alpha^4 - 9.27\ \alpha^5]\ /[1\text{-}\alpha]^{3/2} \quad (2)$$

where K_{Ic} is the critical stress intensity factor (the fracture toughness), MPa.m$^{1/2}$, P_{max} is the maximum applied load, MN, α is a/W (dimensionless), a is the crack length, m, B is the specimen thickness, m and W is the specimen width, m. The fracture toughness of JMC is almost constant value and was calculated for W/a equal to 2 and 3 and was found to be 3.07 and 2.95 MPa.m$^{1/2}$, respectively. It is known that K_{Ic} is a material constant property and so the average value can be taken as 3.01 MPa.m$^{1/2}$. The critical stress intensity factor K_{Ic} (the fracture toughness) for a wide tensile specimen having center crack with the maximum stress of notched specimen (σ_o) and the crack length (2a) can be correlated through the following equation (4):

$$K_{Ic} = Y\sigma_o\sqrt{\Pi a} \quad (3)$$

where Y is the geometry factor dimensionless parameter or function that depends on both crack and specimen sizes and geometries, as well as the manner of load application. For planar specimens containing cracks that are much shorter than the specimen width, Y has a value of approximately unity i.e. for a plate of infinite width having a through-thickness crack Y = 1 (Callister, 2001), and because W/D = 3 Y value is assumed to be unity.

The crack length (2a) is considered as the length at which the crack starts to occur and so the crack length is correlated to the diameter of hole (D) and d_o as shown in Figure 1 through the following equation:

$$2a = D + 2d_o \quad (4)$$

where a is the half length of the crack and can be determined through the following equation:

$$a = R + d_o \quad (5)$$

where R is the radius of the hole from equations 3 and 5 the average of K_{Ic} is known as 3.01 MPa.m$^{1/2}$ and R and do are known so the maximum stress (σ_o) can be calculated through the following equation.

$$\sigma_o = \frac{K_{Ic}}{\sqrt{\Pi \times (R + d_o)}} \quad (6)$$

And therefore, the maximum load (P_{max}) can be calculated through the following equation:

$$P_{max} = \frac{\sigma_o}{W \times t} \quad (7)$$

The experimental and calculations results of notched tensile specimens for W/D = 3 is shown in Table 1. The ratio of σ_n/σ_o can be used to as a measure the notch sensitivity; the higher σ_n/σ_o indicated lower notch sensitivity and if σ_n/σ_o ratio equals unity the composites will be insensitive to the notch. It can be observed from Table 1 that JMC composites in terms of residual tensile strength (σ_n/σ_o) are sensitive to the notch but the degree of sensitivity is not high as can be seen that the average residual tensile strength (σ_n/σ_o) is 0.84 which means that there is only 16 % loss in the tensile strength due to the presence of the hole.

The limitation of the most previous characteristic distance approaches such as in (Whitney and Nuismer, 1974), however, is that the physical meaning of do has not been approved. Table 1 shows that the experimental maximum load during tension test with hole is almost near to the maximum load calculated using the value of fracture toughness and the characteristic distance at W/D = 3. The equality of the calculated and experimental maximum load values validates

Table 1: The experimental and calculations results of notched tensile test of JMC for W/D = 3.

Specimen No.	Residual tensile strength σ_n/σ_o	Characteristic distance, d_o, mm	Half crack length, a, mm	Calculated P_{max}, KN	Experimental P_{max}, KN
1	0.95	3.304	8.304	3.21	3.99
2	0.82	2.258	7.258	3.40	3.41
3	0.74	1.773	6.773	3.54	3.10
Average	0.84	2.445	7.445	3.38	3.50

and reconfirms the physical meaning of the characteristic distance which represents the distance from the hole boundary at which the brittle fracture starts to occur.

4. Conclusion

The fracture toughness of jute mat composites was investigated based on the characteristic distance d_o to validate the physical meaning of d_o. The experimental maximum load during tension test with hole is almost near to the maximum load calculated which validates the physical meaning of d_o which represents the distance from the hole boundary at which the brittle fracture starts to occur.

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