Notched strength prediction of glass fiber reinforced composite based on fracture toughness analysis

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Abstract

The notched strength prediction of normal glass mat composite and needle punched glass mat composite based on fracture mechanics was carried out in this study. The prediction constitutes of three parts including establishing the relation between characteristic distance and notch strength ratio (a ratio of notch strength to unnotched strength), modulus calculation in thickness direction and fracture toughness measurement. The characteristic distance was determined by point stress criterion and calculated from finite element analysis. After contrastive analysis from a mass of tensile results on notched specimens with an open hole, a relation between characteristic distance and notch sensitivity was established. Modulus calculation was calculated according to the classic theory of "Rule of Mixtures" and "Reuss Model". After that, the results of modulus calculation together with fracture toughness results were employed to establish the relation between notch strength and characteristic distance according to elastic fracture mechanics. The characteristic distance was used in this part as a parameter of a crack. Finally, from the two equations between notch strength and characteristic distance, the notched strength of composite with an open hole can be predicted. The predicting results were compared and analyzed with experiment results.

Key words

needle punching process, fracture toughness, characteristic distance, notched strength, finite element method

1. Introduction

The prediction of composite materials is a vital part for composite structure designing, especially in the aerospace industry which strives for accurate physically-based and fast strength prediction methods for composite laminates with stress concentration (Camanho et al., 2012). The stress concentration is very common in the case of assembly of structure of composite materials which cannot avoid the presence of a hole or cut out. This stress concentration can cause the reduction of the strength (Martin et al., 2012). It is a typical stress concentration problem of open hole tension that has been used thoroughly since a strength estimation has been offered for a wide range of engineering situations which go from fasteners to defects (Maini et al., 2012).

The strength of a notched specimen with an open hole is a function of many factors, including the varying orientations, stiffness, coefficients of thermal expansion, the amount of absorbed moisture, the dimension of the specimen including the hole size and width, the progressive failure and the fracture form of the specimen and so on. The investigation of notch strength prediction has been performed by researchers.

The characteristic distance approach which was proposed from well-known point-stress and average-stress failure criteria by Whitney and Nuismer is used extensively throughout the industry because of its simplicity and accuracy (provided that the relations can be correlated with test data for the subject laminate) (Whitney et al., 1974). In the point-stress failure criteria, the characteristic distance (d_0) is the length from the hole edge to the point where the stress equals to unnotched strength when the notched material carries a maximum load. For average-stress failure criteria, the characteristic distance (d'_0) is the length from the edge of the hole to the point where the average stress equals to unnotched strength. It was further assumed that the characteristic distance is a material property and is independent of the hole size or geometry of the plate. To determine the characteristic distance, two dimensional elasticity solutions which can be conveniently expressed as closed-form equations were available. Moreover the finite element method (FEM) can also be used to calculate this value. In the FEM calculation, the geometry and stress field near the hole may be arbitrary that is the advantage compared to the closed-form solutions.

If the failure prediction of the open hole specimens was investigated, two situations can be expected including brittle failure and ductile failure. The nominal strength for brittle failure is predicted by the elastic limit analysis. On the other hand, if ductile failure is expected the plastic limit analysis is used (Bazant et al., 1998). Several model named theories of critical distance have been developed to predict the nominal strength of quasi-brittle structures. These models share the common features of using an elastic analysis together with a material characteristic length that defines the transition from ductile to brittle failure and have been used with remarkable success through adjusting experimental results for various kinds of materials, especially with composite laminates (Camanho et al., 2007; Tan, 1987; Green et al., 1987).

In this study, the glass fiber chopped strand mat (GM) and needle punched glass fiber chopped strand mat (NGM) were used to fabricate composite with unsaturated polyester resin. Normal tensile test, central hole tensile test and single-edge-notched tensile test were conducted to obtain the experiment data for prediction. The notched strength of the specimen with an open hole was tested on glass mat composite (GMC) with different width to diameter (w/d) ratio together with needle punched glass mat composite (NGMC). In the prediction, the composite was considered as quasi-brittle material according to its mechanical property and fracture behavior. The prediction based on fracture mechanics can be divided into three parts, including establishing correlation between characteristic distance and notch sensitivity, calculation of modulus in thickness direction and measurement of fracture toughness. The predicting results were compared with experiment results finally.

2. Materials and experimental procedure

2.1 Materials

GM fabric (Nitto Glasstex Co., Ltd.) with the gram weight of 450 g/m^2 was used as reinforcement. The fabric was made of continuous glass fiber bundle which was chopped into 50 mm in length. The chopped glass bundles were distributed in random directions. The same GM fabric was used to produce NGM fabric. One ply of NGM contained 5 layers of GM. Unsaturated polyester resin (Showa: RIGORAC 150HRBQNTNW) was used as a matrix. The resin was mixed with the hardener MEKPO (PERMEK N; NOF Corporation) in a ratio of 100:0.7. Five layers of GM and 1 ply of NGM were used to fabricate GMC and NGMC via hand lay-up method. After curing the composite in room temperature for 24 hours, they were heated in an oven at 100 °C (for 2 hours) as post-cure.

2.2 Specimen preparation and tensile test

After fabrication, the composite plate was cut into testing specimens. The dimension of the specimens is shown in Table 1. For GMC, notched specimens were used with 3 types in order to get different w/d ratio. Tensile test was performed by using an Instron Universal Testing machine with a speed of 1 mm/min. Additionally, strain gauges (KYOWA KFG-10-120-C1-11) were employed to measure the strain of the unnotched specimens during testing process.

Table 1: Dimension of testing specimens

Unit: mm	Normal tension	Open hole tension	Single-edge-notched tension
Width	20	20/30/50	30
Length	200	200	200
Span	100	100	100
Hole diameter	/	10	/
Crack length	/	/	10

2.3 Finite element method (FEM)

To calculate the characteristic distance, the stress distribution around the open hole was calculated by FEM. The finite element analysis software MSC.Marc was employed here. In the simulation, a triangle element of three points (Element_type 6) was used. In order to obtain more accurate results around the hole, finer elements were meshed near the open hole

2.4 Calculation of modulus in thickness direction

After needle punching process, thickness direction fibers were introduced in NGM which reinforced the thickness direction in NGMC. The modulus in thickness direction is the main difference between GMC and NGMC. This difference affects the progressive failure and then effects the notch strength. In GMC, the glass fiber was 90 degree in thickness direction. This situation is suitable for Reuss Model which is shown in equation (1)

$$E_2 = \left[\frac{f}{E_f} + \frac{1-f}{E_m}\right]^{-1} \qquad (1)$$

Where, the E_2 is the modulus of materials with 90 degree fiber only; f is the volume fraction of fibers; E_f is modulus of fibers and Em is modulus of matrix. In NGMC, the glass fiber included 90 degree and 0 degree in thickness direction due to the needle punching process. The calculation of modulus includes Rule of Mixtures and Reuss Model shown in equation (2)

$$E'_2 = \left[\frac{f_2}{E_f} + \frac{1-f_2}{E_m}\right]^{-1} + f_1 E_f \qquad (2)$$

Where E'_2 is modulus in thickness direction of NGMC; f_1 is fiber volume fraction in 0 degree and f_2 is fiber volume fraction in 90 degree. The volume fraction of 90 degree was obtained from a burning method. To calculate 0 degree (thickness direction) fibers of NGMC, the optical observation was conducted and the fibers were counted by Photoshop software. Then the cross section area of fibers can be calculated in ImageJ software.

3. Results and discussion

3.1 Relation between notch sensitivity and characteristic distance based on FEM

Tensile test was conducted on unnotched and notched GMC specimens with volume fraction in the range of 20 %-40 % of glass fibers. The relation between notch strength ratio and characteristic distance calculated from FEM are shown in Figure 1. Three types of specimens including 2, 3 and 5 of *w/d* ratio were used here.

From the results, it was found that the correlation between characteristic distance and each type specimens according to w/d ratio is obvious. However, if the different types of specimens are put together, the correlation is unsatisfactory.

In order to get better correlation with notch sensitivity, a parameter was introduced which included the factors of

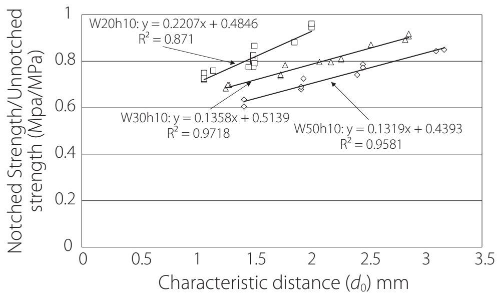

Figure 1: Relation between characteristic distance and notch sensitivity of GMC

width and diameter. The modified relation between characteristic distance and notch strength ratio of GMC are shown in Figure 2. The results show a satisfied correlation.

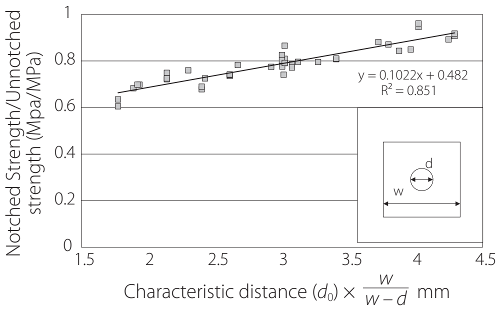

Figure 2: Modified relation between characteristic distance and notch sensitivity of GMC

Considering the case in NGMC, it also shows a good correlation in Figure 3. Compared with Figure 2, it was found that the notch sensitivity was higher in NGMC than GMC which means that the NGMC has better resistance to an open hole. It was considered that the fibers in thickness direction introduced from needle punching process prevented the fracture of delamination in NGMC. From these results, the equation between notch strength and characteristic distance was established and illustrated in equation (3).

$$\frac{\sigma_n}{\sigma_0} = A \times (d_0 \times \frac{w}{w-d}) + B \tag{3}$$

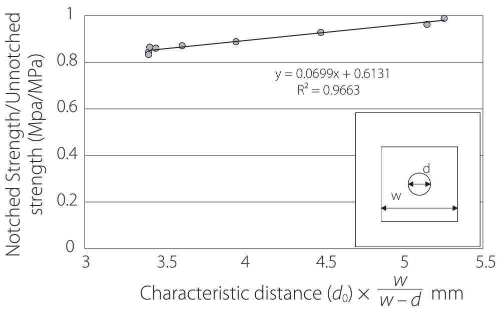

Figure 3. Modified relation between characteristic distance and notch sensitivity of NGMC

Where, A and B are constant which was considered to have relation with reinforcement and can be determined from experiments.

3.2 Calculation of modulus in thickness direction

The modulus of GMC in thickness direction can be calculated by equation (1). The modulus of NGMC in thickness was calculated with equation (2). The optical observation was conducted in thickness direction of NGMC. The photo from optical observation is shown in Figure 4. In this figure, the fiber in thickness direction was introduced from needle punching process. After observation, the number of glass fibers in thickness direction was counted in Photoshop software and the cross section area of glass fibers can be calculated. The observed area was calculated through ImageJ software. Together with glass fiber cross section area, the volume fraction of glass fiber in thickness direction can be obtained. In this study, the volume fraction of glass fibers in thickness direction was 1.827 %. It has a direct relation with needle punching density.

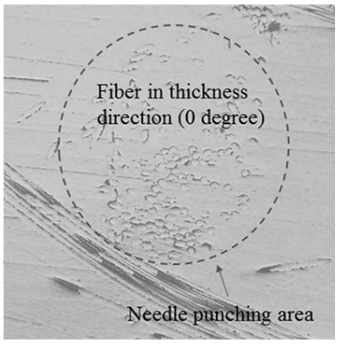

Figure 4: Optical observation of NGMC in thickness direction

3.3 Fracture toughness results from single-edge-notched tension (SENT)

The single-edge-notched tension was carried out on both GMC and NGMC specimens to obtain the fracture toughness. The fracture toughness calculation was according to stress Intensity Factor and Limit Load Handbook of Ainsworth (1998). The calculation results are shown in Figure 5.

From Figure 5, it was found that the fracture toughness values were close between GMC and NGMC under the same volume fracture of glass fibers. However in higher volume fraction, the fracture toughness of NMGC was lower.

3.4 Relation between notched strength and characteristic distance based on fracture mechanics

During a tensile test of notched specimen, the initial damage occurred at the edge of the open hole and extended to the outside. During this process, the remote stress σ kept growing until the crack reached some point at which the specimens reached maximum load and the failure happened rapidly. The size of the new crack has relations with charac-

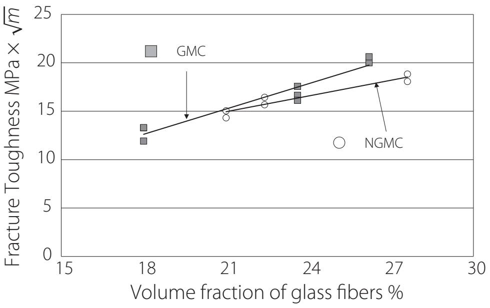

Figure 5: Fracture comparison between GMC and NGMC

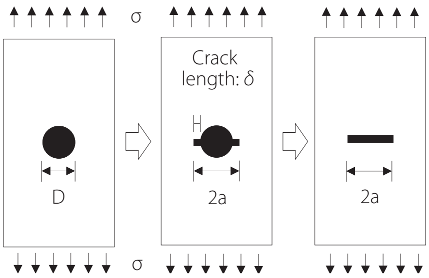

Figure 6: Mold transferring from open hole to central crack

teristic distance which has a big influence on notch strength. The mold transferring from the open hole to central crack method is shown in Figure 6. In this figure, the crack length is defined as following equation (4)

$$\delta = ln\frac{E_1}{E_2}\times d_0 \qquad (4)$$

Where E_1 is the modulus in plane; E_2 is the modulus in thickness direction and d_0 is characteristic distance. Therefore the crack in the new mold can be expressed in equation (5).

$$a = \frac{D}{2} + ln\frac{E_1}{E_2}\times d_0 \qquad (5)$$

Then the notch strength can be expressed as equation (6)

$$\sigma_n = \frac{W}{W-D}\times\sigma = \frac{W}{W-D}\times\frac{K_1 C}{\beta\times\sqrt{\pi\left(\frac{D}{2}+ln\frac{E_1}{E_2}d_0\right)}} \qquad (6)$$

Where σ is remote stress of notched specimens, K_1 is fracture toughness, β is function of specimen dimension, d_0 is characteristic distance, C is a correction factor which can be calculated from experiment (Here the value was 0.8).

Combining equation (3) and equation (6), the notch strength of specimens with an open hole can be predicted. The prediction results are shown in Table 2.

In this table, the d_0 is characteristic distance calculated by finite element analysis. σ_n is notch strength obtained from tensile test, σ_{cal} is the prediction results. In GMC, the three kinds of dimension were used according to w/d ratio with high volume fraction and low volume fraction. In NGMC, one kind of dimension was used. The results show good consistency between prediction and experiment data.

Table 2: Results of prediction of notched strength

Type	V_f %	w/d	d_0 mm	σ_n MPa	σ_{cal} MPa	Difference %
GMC	26.8	2	1.63	150	145	3.33
		3	2.09	139	136	2.16
		5	2.09	124	130	4.84
	23.7	3	1.85	119	121	1.68
NGMC	20.0	3	3.32	106	107	0.94
	27.8	3	2.45	140	132	5.71

4. Conclusion

In this research, the two equations were established between characteristic distance and notch strength based on the FEM results and fracture mechanics analysis. From the two equations, the notch strength of GMC and NGMC can be predicted. This prediction can be suitable for different dimensions of specimen with an open hole. It also can be used for composite reinforced with needle punched fabrics. The prediction results show good consistency with experiment data.

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