Determination of Damage Zone Size Ahead of Stable Crack in FRP by FE Analysis

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ABSTRACT

In this paper, the stable crack growth was examined in both experimental and analytical ways to establish a test method to evaluate the fracture toughness of FRP. A mechanism of the stable crack growth was considered from observations of vicinity of the crack tip. A damage zone was found by debonding between the fibers and the matrix ahead of the crack tip and became larger as an applied load increased. Stress distribution near the crack tip was calculated by linear elastic finite element analysis on the assumption that the fibers in the damage zone could only carry tensile stress to be compared with the observed damage zone size in the experiment. So we supposed membrane model for damage zone and simulated the process of damage zone formation.

1 INTRODUCTION

Much attention has recently been attracted on fiber reinforced plastics (FRP) as industrial materials because of their high ratio of strength and stiffness to weight. They have been applied to aircraft and other structural components. However the fracture behavior of these materials has not been completely understood yet. Recently, strength of FRP is often evaluated on the basis of fracture mechanics concepts (Grag and Trotman 1980). In general, the FRP has a significant stable crack growth between the initiation of crack and unstable crack growth. However, many kinds of FRP are produced to use and their fracture behavior significantly changes from one FRP to the other. For example, the crack initiation toughness is considered as a material constant like for metal material (Kageyama et al. 1985), on the other hand the unstable fracture toughness after the stable crack propagation is also considered as a material constant (Yanada and Homma 1983). Usually a long stable crack propagation process exists in fracture test of a FRP specimen with a crack. In GFRP (Glass Fiber Reinforced Plastics), the unstable crack growth takes place at more than twice of the crack initiation load. If we can evaluate the fracture toughness at maximum load : P_{max} which was initiation at unstable crack growth, the evaluation method is of great value from viewpoint of saving weight and resources. In order to establish the method of a reasonable fracture toughness test for FRP, the stable crack propagation mechanism should be examined in more detail. In this paper, the fracture toughness test for GFRP was made to observe damage near the crack tip and the finite element analysis was made to determinate of damage zone size.

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2 FRACTURE EXPERIMENTS

2.1 Experimental procedure

Compact tension (CT) specimens were cut from unsaturated polyester plates reinforced by chopped strand mat made of glass fibers. Its dimensions are 60mm in width, 63mm in height and 1.1mm in thickness. A saw cut (t=0.3mm) was introduced in each specimen instead of the pre-crack, because it is very difficult to produce a well-defined fatigue crack in FRP. At the fracture test, the applied load P and the crack mouth opening displacement delta were recorded. The tensile speed of actuator was 0.01 mm / sec.

Table 1 Constituents of the FRP laminates

FRP laminate	Mat
Glass fiber	EM 600
Matrix	UP
Glass content	33 wt %

2.2 Experimental results

Near the tip of the crack propagating in a stable manner, a lot of microcracks were initiated in the matrix and debonding between matrix and fiber took place. It is called the damage zone. In GFRP, the damage zone was whitened and could be detected easily. The model of damage zone is shown in Fig.1. The relations between the vertical size of damage zone (Rp) and the stress intensity factor (K_R) can be expressed by

$$R_P = 0.013 K_R^{1.9} \tag{1}$$

3 ANALYSIS OF THE TENSILE STRESS OF FIBER

There is always a damage zone ahead of the crack tip, and in this area fibers are debonding from the matrix. Therefore, in the damage zone, the applied load is carried by only fibers. The crack propagation is caused by breaking the fiber, when the stress carried by the fiber at the crack tip is beyond the tensile strength of the fiber. For the examination of the stable crack propagation, it is very important to analyze the tensile stress of fiber at crack tip. For this analysis, the model shown in Fig. 2 was used together with the damage zone size measured in fracture experiments of FRP. The analytical results showed that the tensile stress carried by the fibers in the damage zone became maximum at crack tip, and decreased with the approaching the boundary of the damage zone. In the stable crack propagation, the tensile stress of the fiber at the crack tip was uniform and was equal to the strength of glass fiber.

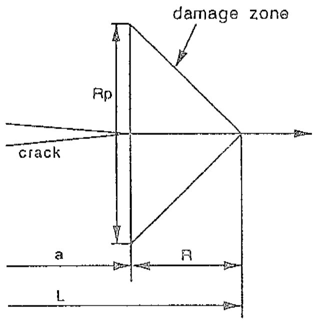

Fig. 1 The model of damage zone.

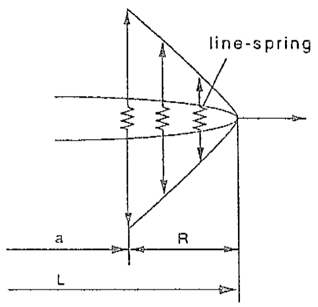

Fig. 2 The line-spring model of damage done.

4 DETERMINATION OF DEBONDING CRITERION

The damage zone size is also very important to examine the stable crack growth. First, we consider the determination of debonding between fibers and matrix. Recently, much research have been done about the debonding and pull-out in fibrous composites (Wells and Beaumont 1985). But, in that research the material used was considered to be the composite of continuous fibers aligned parallel to an applied load and the debonding criterion was determinated by microscopic observation. Because in our research the mat used randomly directed fibers in it considered the debonding criterion in a broader perspective. And we tried the determination of debonding criterion by stress distribution.

The stress distribution analysis was made by finite element method (FEM). 8-nodes isoparametric element were used. There were 323 elements and 1045 nodes used in this analysis. The results are shown in Fig. 3. Stress distribution is shown for the maximum principal stress in the vicinity of crack tip. The triangle in the figure is the damage zone size observed in the experiment. In the left figure, applied load is 118.7MPa, and in the other figure, applied load is 147.1MPa. The principal stresses at vertically farthest boundary of the damage zone are almost same. So, in this research , we regard the debonding criterion as maximum principal stress. And non-linear analysis is required to determine the accurate damage zone size.

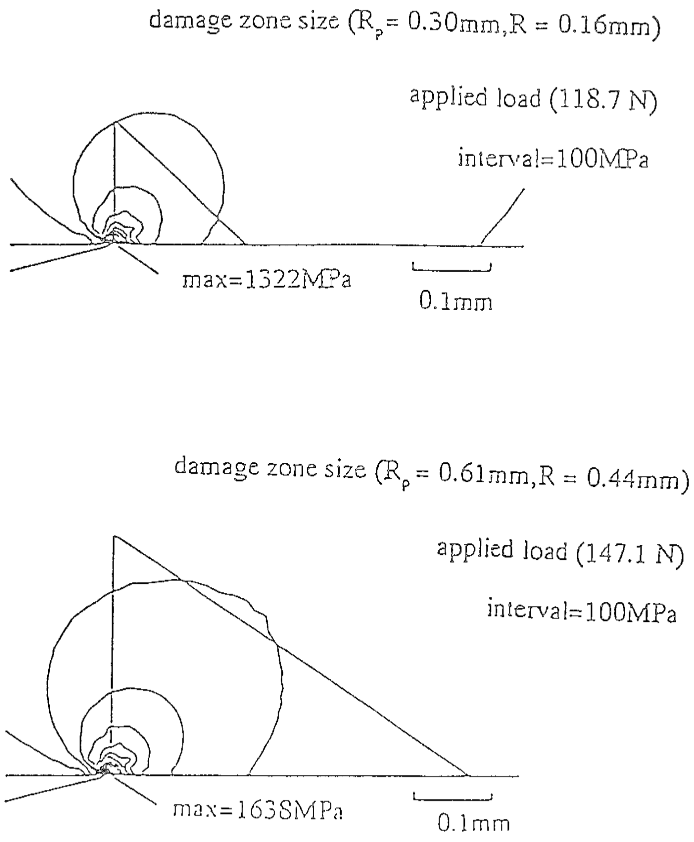

Fig. 3 The stress distribution of maximum principal stress in the crack tip vicinity.

5 DAMAGE ZONE MODEL

A model for non-linear analysis was assumed as follows. The fibers were considered to be the membrane, since the fibers' directions were at random. In the damage zone, the membrane carries only the tensile stress, but it can't carry the compressive stress. The Poisson's ratio is equal to zero, and then the relation between stress and strain is expressed by,

$$\begin{aligned} \sigma_1 &= E\,\varepsilon_1 \quad (\varepsilon_1 > 0), \qquad \sigma_1 = 0 \quad (\varepsilon_1 < 0) \\ \sigma_2 &= E\,\varepsilon_2 \quad (\varepsilon_2 > 0), \qquad \sigma_2 = 0 \quad (\varepsilon_2 < 0) \end{aligned} \tag{2}$$

E is given by,

$$Ed = Ef \times Vf \times Zf \tag{3}$$

where Ef is the Young's modulus of fiber, Vf is the volume fraction of fiber, Zf is the ratio of fibers direction, and Zf is

$$Z_f = \frac{2}{\pi}\int_0^{\frac{\pi}{2}} \cos\theta \, d\theta \tag{4}$$

This relation for stress-strain matrix becomes as follows.

$$D_d = \begin{bmatrix} E_d & 0 & 0 \\ 0 & E_d & 0 \\ 0 & 0 & G \end{bmatrix} \qquad (\sigma_1 \geq 0\ ,\ \sigma_2 \geq 0) \tag{5}$$

We used three kinds of the shearing modulus of elasticity (G = 0, G = E / 10000, G = E / 2), in order to examine the effect of shearing stress.

And because this matrix is thought to be the matrix principal stress's direction, so it is multiplied with the matrix of coordinate transformation on both sides.

6 ANALYSIS METHOD

Fig. 4 shows the method of our analysis. First, it is assumed that the process which subtract the damage zone occurrence load (Pin) from applied load (P). It is called the process of damage zone formation. Second, this process is divided into several stages and we made calculations repeatedly for each stage.

1) Elastic analysis is calculated at the damage zone occurrence load Pin.

2) Every element is calculated principal stress based on the stress of analysis result. If the principal stress is larger than the stress of damage zone occurrence, that element uses the Dd-matrix with the membrane model. In the other case, the element uses the elastic D-matrix.

3) The displacement of each new element is compared with the last one. And the difference of two is judged with convergence. If the calculation is converged, a load is added to dP.

4) If the load is smaller than the applied load, the calculation is repeated from 2) to 3).

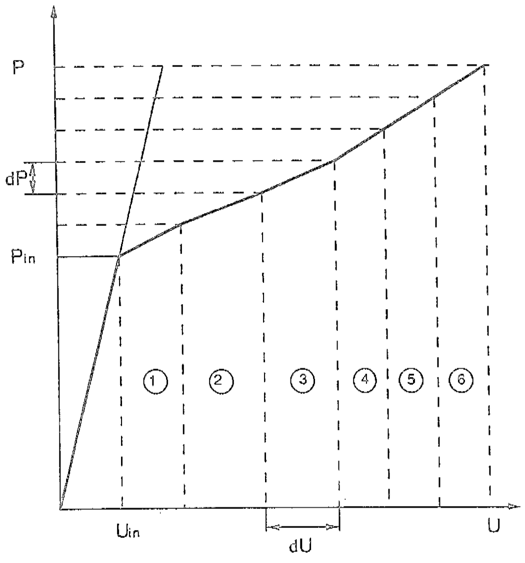

Fig.4 The analysis method

7 ANALYSIS RESULT

The simulation of damage zone was performed using the membrane model. FEM analysis was carried out using 3 node elements with a total number of 829 elements with 456 nodes. Specimen dimension for this analysis was same as that of the experimental specimen. Because of the symmetrical shape of CT specimen, the analysis was carried out on only one half of specimen. The simulation of damage zone formation process is shown in Fig. 5. Numbers shown with every figure indicate the stage and total number of elements damaged in that stage. It is noticed that the damage zone formation takes place gradually from the crack tip.

In figure 6, the damage zone size calculated analytically is compared with the experimental result. This figure shows that, when load is small, sizes Rp and R are similar for both analytical and experimental procedures. But as the load grows larger there is a significant difference between two result. From the damage zone model we assume that the fibers and matrix were perfectly debonded in the damage zone, but in fact, all the fibers did not debond, that is why we observe a large gap in R.

We can see the effect of the modulus of shearing elasticity (G) in Fig. 6. In the figure, the normal triangular marks represent values for G = 2 and the inverted triangular marks represent the values for E = 0 respectively. Normal triangular marks show a similarity when compared to experimental results which are represented with circular marks. Because this analysis used chopped strand mat which has no directions, this FRP is regarded as homogeneous, and if Poisson's ratio is equal to zero, the modulus of shearing elasticity (G) is equals to E / 2.

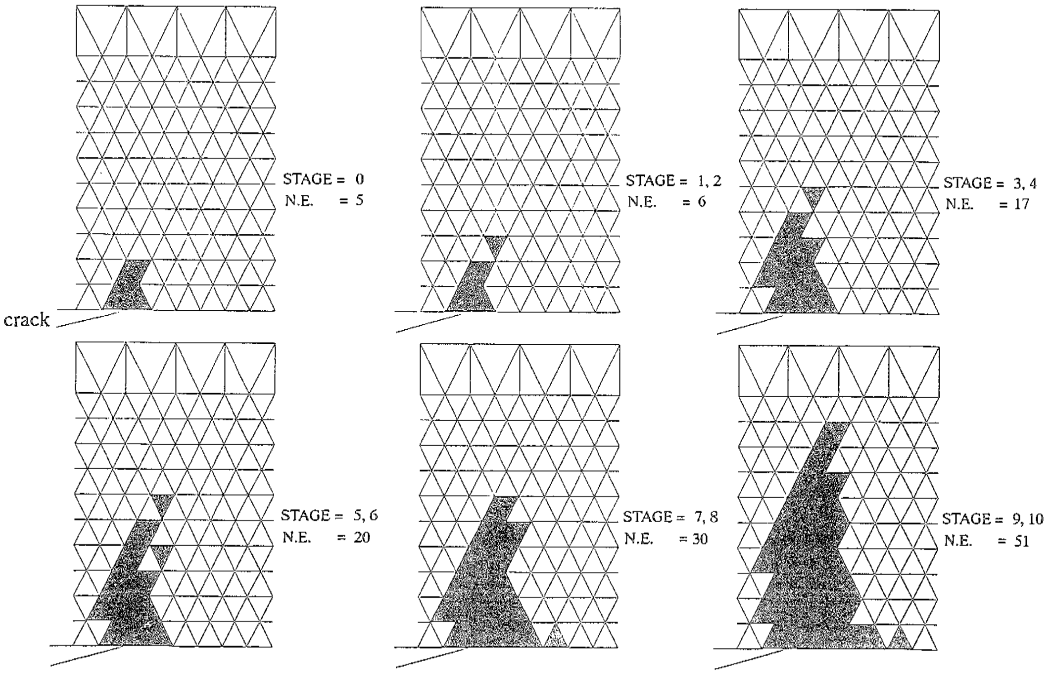

Fig. 5 The simulation of damage zone formation process

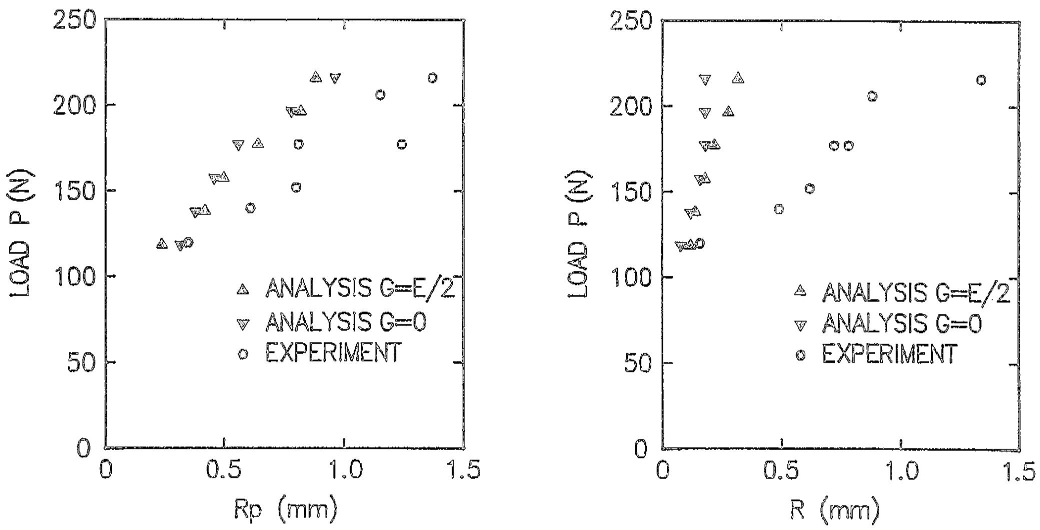

Fig. 6 The comparison between analytical and experimental result.

8 CONCLUSION

In order to clear the stable crack propagation mechanism, the process of damage zone formation at crack tip was simulated by finite element analysis. We can conclude as follows.

Because the applied load in the damage zone is carried only by the fibers, so the damage zone is assumed to be the membrane model. Using this model, we can simulate the formation of damage zone. Consequently, the maximum principal stress is one of the criterion of damage zone and the membrane model is useful for finite element analysis.

Further investigation is necessary to improve the criterion of damage zone and the damage zone model for analysis.

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