EVALUATION OF GLASS FIBER/EPOXY INTERFACIAL STRENGTH USING A CRUCIFORM SPECIMEN

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Keywords: *interfacial strength, cruciform specimen, straight specimen, finite element analysis, interfacial debonding, glass fiber, stress singularity*

Abstract

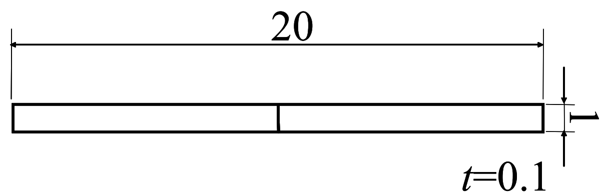
The In fiber reinforced composite materials, the interface between the fiber and the matrix plays a key role in mechanical properties of composite materials. Therefore, a more accurate evaluation method of the interface is necessary to develop better fiber reinforced composite materials. Many techniques are used for evaluating the interfacial properties. An interfacial strength evaluation method using cruciform specimens has a feature that it can avoid the influence of the stress singularity at the free edge. The purpose of the present study is to verify the validity of the cruciform specimen experimentally and analytically. A GF/Epoxy model composite is used. The initiation and propagation of interfacial debonding in both cruciform specimen and straight specimens are experimentally clarified. Moreover, stress analysis using finite element method (FEM) is conducted.

1 Introduction

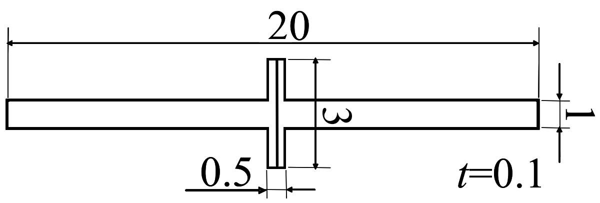
In fiber reinforced composite materials, the interface between the fiber and the matrix plays a key role in mechanical properties of composite materials. Therefore, a more accurate evaluation method of the interface is necessary to develop better fiber reinforced composite materials. The fragmentation test and the microbond test, etc. exist as a technique for evaluating the interfacial properties [1]. These are used to investigate interfacial shear strength mainly and methods of investigating interfacial tensile strength are not well established. The simplest way to evaluate the interfacial tensile strength is to use a tensile specimen with parallel straight edges in which a through-the-width embedded fiber whose direction is perpendicular to the loading direction. However, if the fiber end appears on the free surface, stress singularity arises because the bimaterial interface is on the free surface. Even if the fiber is embedded in the matrix, the fiber end serves as the corner bimaterial interface which results in stress singularity. Therefore, it may be very difficult to evaluate the interfacial tensile strength accurately using this type of specimen configuration because debonding initiation is influenced by the stress singularity.

Recently, an experimental method of evaluating interfacial tensile strength that uses a cruciform shape specimen is proposed from such a viewpoint [2～5]. In the cruciform specimen, a single fiber whose direction is perpendicular to the loading direction is embedded in the specimen central region where the specimen width is enlarged. This method can avoid the influence of interfacial stress singularity at the specimen edge on the debonding initiation. Although there are some studies on this method and it may be very useful in evaluating the interfacial tensile strength, it is not well established as an evaluation method and is not widely used yet.

The purpose of the present study is to discuss the validity of the cruciform specimen method experimentally and analytically. In this study, a glass fiber (13μm in diameter) actually used as composite materials was used for the experiment, and the single fiber reinforced model composite materials whose matrix was the epoxy were made. The difference between the debonding initiation and the progress behavior of a cruciform specimen and a straight specimen (specimen without width enlargement part) was observed, and the validity of the cruciform specimen was confirmed. Moreover, the stress analysis using finite element method (FEM) is conducted to determine an effective cruciform specimen geometry.



(a) Straight specimen



(b) Cruciform specimen
Fig.1 Schematic of specimens
(a) Straight specimen and (b) Cruciform specimen

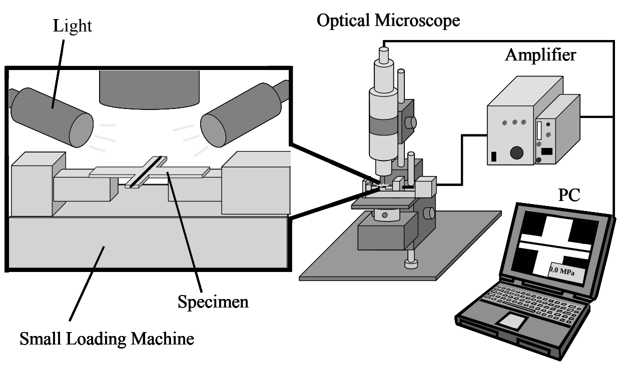


Fig.2 Schematic illustration of the observation system

2 Experiment and analytical methods

2.1 Single fiber reinforced model composite materials tensile test

The single fiber reinforced model composite materials were used for the experiment. Figure 1 shows the specimen geometry used in the experiment. A specimen has an embedded single fiber perpendicular to the loading direction at the center. Fig.1 (a) shows a schematic of a parallel straight edged specimen (straight specimen) and Fig.1 (b) shows a cruciform specimen, respectively. The specimen geometry was determined based on the FEM result of the following section. In the present study, a glass fiber (GF, 13□m in the diameter) was used for the fiber. Epoxy resin (Epikote 828) was used for the matrix material with TETA (Triethylenetetramine) as a hardener. The glass fiber was washed with acetone and the fiber was embedded in the resin. A teflon sheet (0.05mm in thickness) which has a specimen shape cutout was used for a mold. The glass fiber was fixed with a tension of 10mN to prevent bending of the fiber. Epikote 828 and TETA were mixed at a rate of 100:11, and it was poured into the mold and cured at the room temperature. Epikote 828 resin was defoamed for 30 min. before mixture with TETA. 6 min defoaming procedure was followed by the mixture with TETA. Awatorirentaro (Thinky, LTD.) was used in the defoaming process.

In each specimen, tension test was conducted with a small loading machine installed on the stage of an optical microscope. Fig.2 shows the overall experimental apparatus. During loading, interfacial debonding initiation and the progress was observed with the optical microscope. To obtain the image of the debonding clearly, light was vertically applied from both sides. The crosshead speed was 0.05mm/min. A tensile test on the epoxy matrix material was done, and the results were used in the FEM analysis.

2.2 Finite elements analysis

The stress distribution in the specimen geometry used in the experiment was examined by finite element analysis (MSC.Marc). Effective specimen geometry was discussed for the material system used. Fig.3 shows the model of the cruciform specimen. As shown in the figure, the direction of the specimen thickness was set to be the x-direction, and the loading direction the y-direction, and the direction of the specimen width the z-direction, respectively. Due to symmetry, 1/8 of the model is considered. The eight node solid elements are used. The analysis was conducted as a linear elasticity problem. The uniform fixed displacement was applied on the upper edge of the model. The average strain in y-direction was 1%. The material property and the number of elements used for the analysis are shown in Table 1. In near edge region and interface neighborhood, finer elements were used because stress gradient may be large.

Preliminary FEM analysis was conducted to determine the specimen geometry for experiment. In this paper, main results are shown to explain the process. For the cruciform specimens, geometry as shown in Fig.4 is considered. The difference in the stress distribution around the fiber is considered in the following two cases. First, as shown in Fig.4 (a), to discuss the effect of specimen width at the width-enlargement part, four cases, that is, $2l$ = 1.00mm, 1.25mm, 1.50mm and 1.75mm, are considered. Second, as shown in Fig.4 (b), to discuss the effect of the length of the width-enlargement part, four cases, that is $2w$ = 0.10mm, 0.25mm, 0.50mm and 1.00mm, are considered.

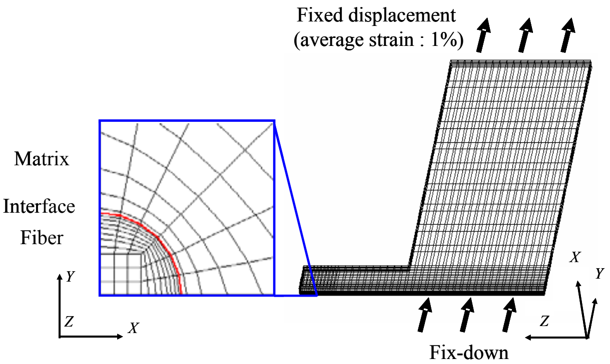


Fig.3 Schematic of a finite element analysis models

Table 1 Material properties and number of elements

	Young's moduls	Poisson's ratio	Number of elements	
	E (GPa)	ν	Straight	Cruciform
GF	70	0.2	1,026	1,995
Epoxy	4.28	0.42	3,510	5,325

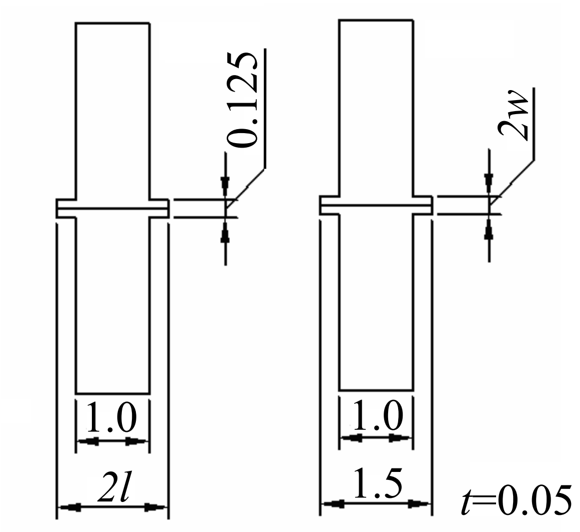


Fig.4 Schematics of FEM models to design specimen shape (a) analytical examination of $2l$ and (b) analytical examination of $2w$

3 Results and discussions

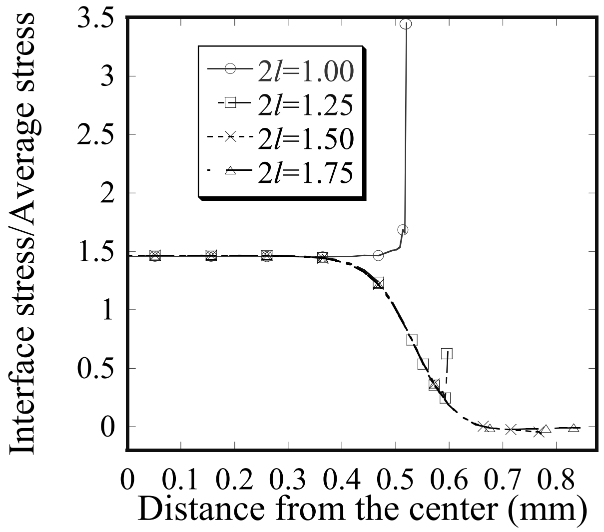
3.1 Determination of specimen geometry by FEM analysis

Fig.5 shows the FEM results of the cruciform specimen shown in Fig.4. Figure shows the change in the normal stress at the fiber/matrix interface along specimen width. The vertical axis shows the interfacial normal stress σ_{yy} normalized by the average stress (far field stress). The transverse axis is the distance from the center of the specimen. The evaluation point of the stress is a point on the intersecting line of a specimen central place and the interface. Neither shear stress τ_{xy} nor τ_{yz} are generated from symmetry on this line.

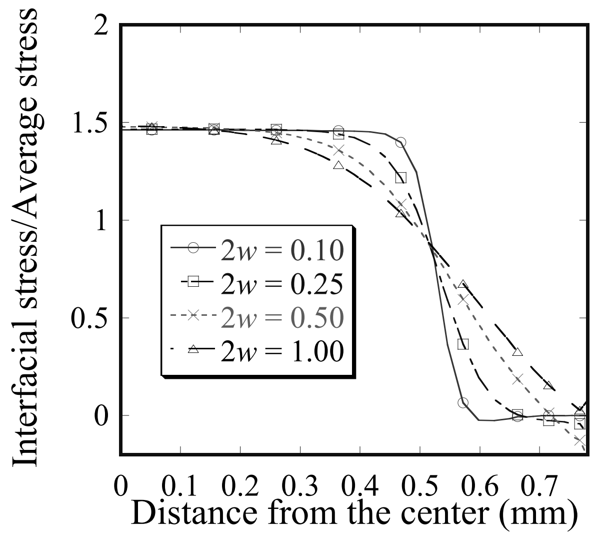
Fig.5 (a) shows the difference in the stress distribution for the cases $2l$ = 1.00mm, 1.25mm, 1.50mm and 1.75mm. In the case of $2l$=1.25mm, it is observed that the stress still rises at the edge. In the case of $2l$=1.50mm and $2l$=1.75mm, the stress singularity at the edge disappears and the stress in the wide part is almost 0. Moreover, it is observed that there is a region where the normal stress is uniform at the centre of the specimen regardless of the length of $2l$. Therefore, it is expected that a debonding can be generated in this region. If the specimen average stress can be evaluated, an interfacial tensile stress when debonding is generated can be calculated.

Fig.5 (b) shows the difference in the stress distribution for the cases $2w$ = 0.10mm, 0.25mm, 0.50mm and 1.00mm. In the case of $2w$=1.00mm, it is observed that the stress rises on the edge. In the case of $2w$=0.50mm or shorter, it is seen the stress at the free edge disappears. Moreover, the shorter $2w$, the more rapidly the stress decreases, thus, the region of uniform stress is expected to be longer.

Therefore, it is expected that the cruciform specimen efficiently avoids the stress singularity at the free edge by shortening the width of $2w$ and taking the length of $2l$ long enough, and has longer region of uniform stress in the specimen. The specimen geometry shown in Fig.1 was determined by considering the convenience of the observation with the microscope in addition to the above-mentioned FEM results.



(a) Effect of 2*l*



(b) Effect of 2*w*

Fig.5 Results of finite element analysis to design specimen shape. (a) Effect of 2*l* and (b) Effect of 2*w*

3.2 Evaluation of interfacial strength

Figs.6 and 7 show the initiation and progress of the interfacial debonding observed in a straight specimen and a cruciform specimen, respectively. Each stress value shows the average stress of the specimen. In the straight specimen, debonding initiated from the free edge at a lower stress compared to the cruciform specimen. It was also observed that the debonding propagates gradually as the load increased. In the cruciform specimen, debonding initiated at a higher stress compared to the straight specimen. In cruciform specimens, no debonding initiation at the free edge was observed. It was also observed that the debonding propagation after initiation was much faster than in the straight specimens. As a result, it was experimentally shown that the cruciform specimen is able to remove the influence of the stress singularity at the edge of the specimen, and able to evaluate the interfacial strength.

Fig.8 shows the relation between the average stress and observed debonding length. In the straight specimens, it is observed that debonding initiated at a lower stress compared with the cruciform specimens. The debonding progress rate after debonding is initiated is low. The debonding progress rapidly when the stress becomes between 25MPa and 30MPa. This stress corresponds to the stress level where debonding is initiated and progressed in the cruciform specimens.

The stress analysis result by FEM of the specimen used in experiment is shown. First of all, the normal stresses at fiber/matrix interface in the straight specimen and the cruciform specimen are considered. The stresses at the point shown in Fig.9 are evaluated. Consider the local coordinate system *x*'-*y*'-*z*' where the tangent of the fiber surface is set to be the *x*'-direction and the radial direction is set to be the *y*'-direction (*z*'-direction coincides with *z*-direction) and $\sigma_{y'y'}$ is considered as the interfacial normal stress.

Fig.10 shows change in the interfacial normal stress along the fiber in the straight and cruciform specimens. The interfacial normal stress $\sigma_{y'y'}$ is normalized by the average specimen stress σ in the loading direction. That is, it is shown by the following equation (1).

$$S_n = \frac{\sigma_{y'y'}}{\sigma} \tag{1}$$

The value is called “normal stress ratio” in the present study. In the straight specimen, it is seen that the influence of the stress singularity at free edge exists, and the interfacial normal stress is very high in the vicinity of the free edge. In the cruciform specimen, it is seen that the interfacial normal stress is vanishing in the vicinity of the free edge. This corresponds to the debonding initiation behavior obtained from the experiment. The stress ratio is 1.465 in the central part of the cruciform specimen. Therefore, it is expected that the interfacial normal stress at debonding initiation (interfacial normal strength) can be evaluated by using the specimen average stress at debonding initiation and the stress ratio.

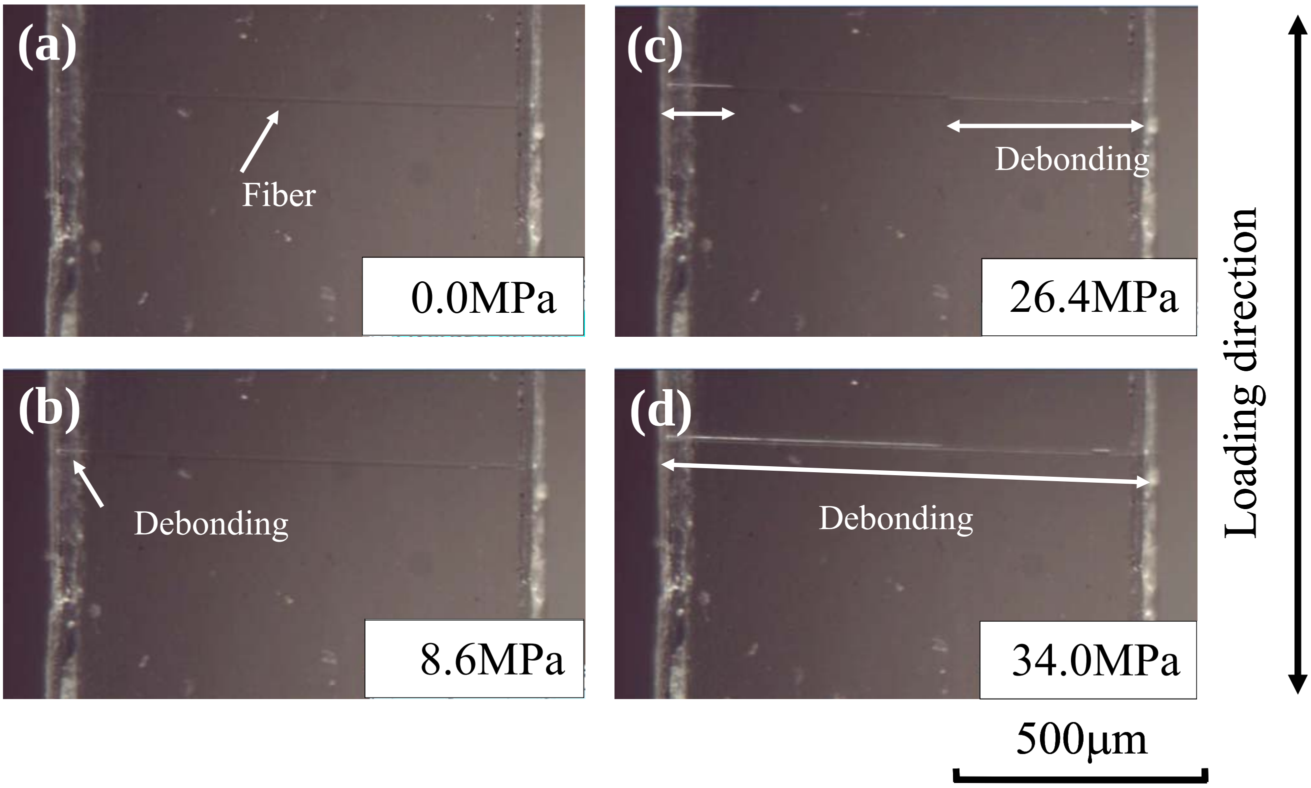


Fig.6 Debonding initiaion and progress in a straight specimen

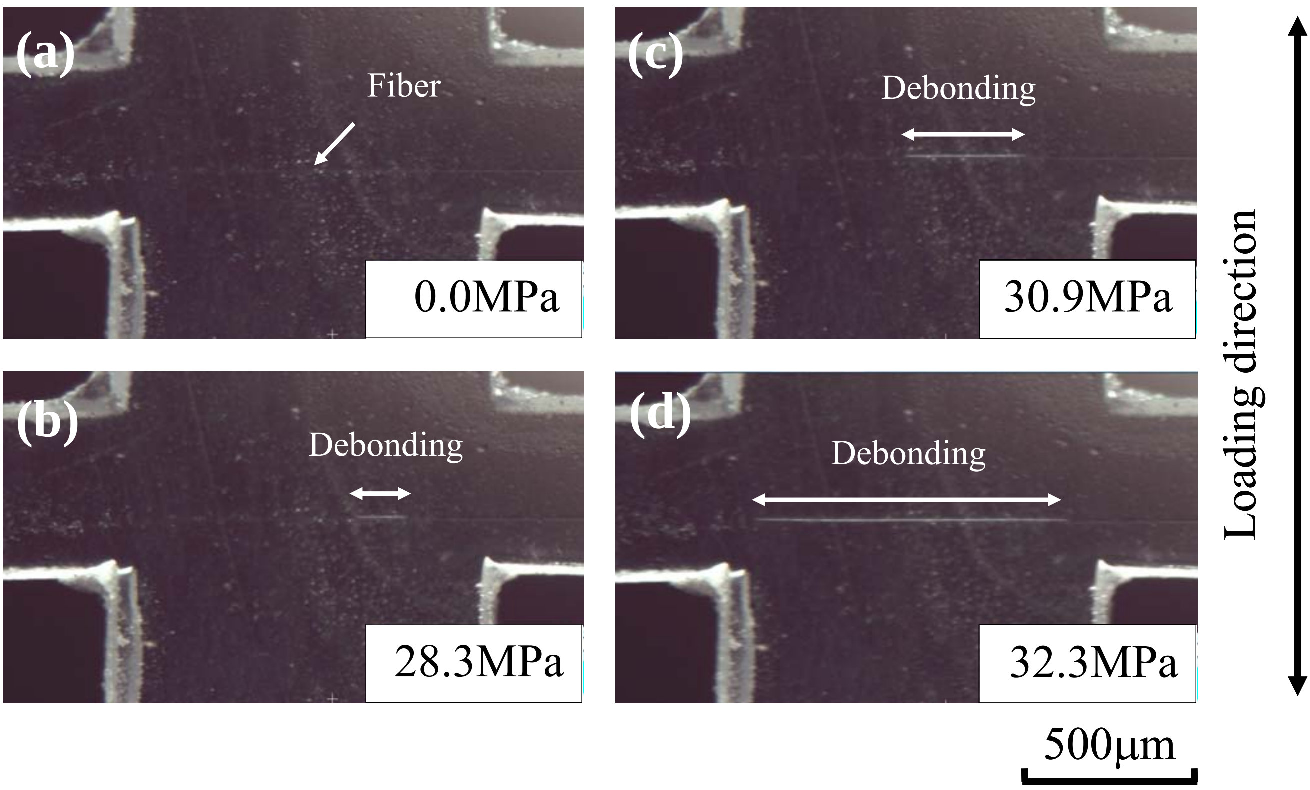
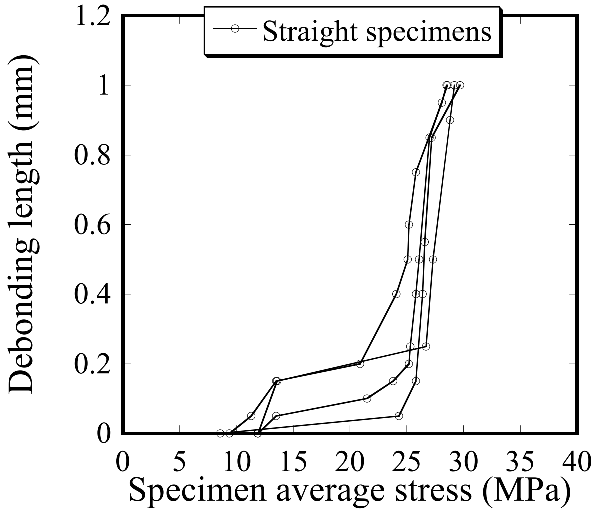
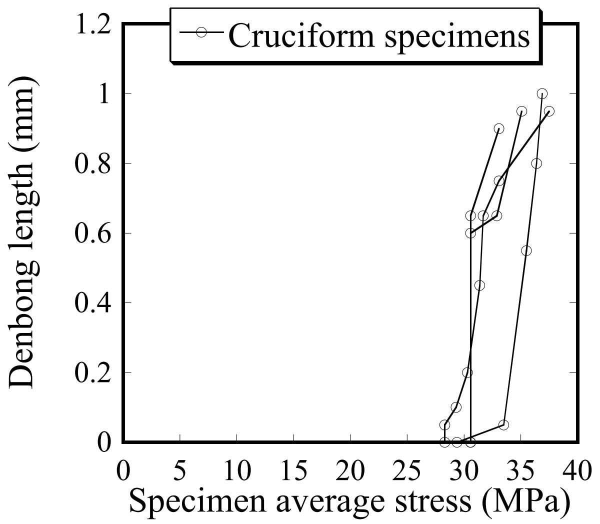


Fig.7 Debonding initiation and progress in a cruciform specimen



(a) Straight specimens



(b) Cruciform specimens

Fig.8 Relation between debonding length and specimen average stress in (a) straight specimen and (b) cruciform specimen

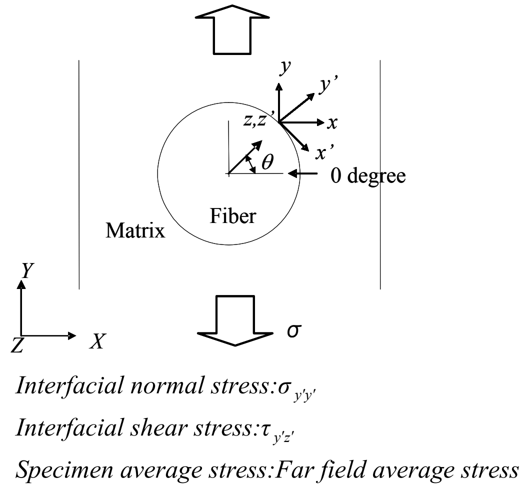
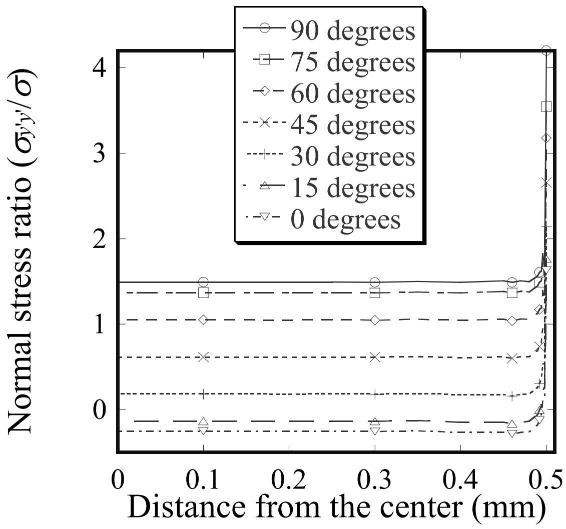
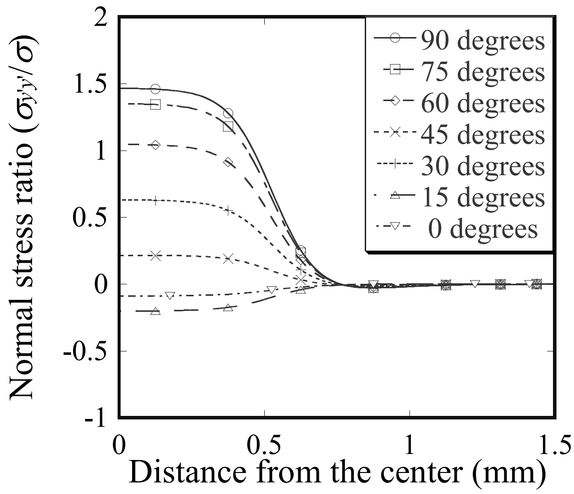


Fig.9 Stress evaluation sites



(a) Straight specimens



(b) Cruciform specimens

Fig.10 Relation between interfacial normal stress ratio and distance from the edge along fiber in (a) straight specimen and (b) cruciform specimen

The evaluated interfacial normal stresses are shown in Fig.11. Each average values of debonding initiation stress in the straight specimens, debonding initiation stress in the cruciform specimens and the estimated normal stress at debonding initiation in the cruciform specimens were 10.9MPa, 30.8MPa and 45.5MPa, respectively. Thus, the interfacial normal strength in this system is estimated to be 45.5MPa.

In the future, we will conduct a experiment that where the load angle is changed. It is expected that the debonding condition when both the normal and shear stresses are applied can be clarified.

3 Conclusions

In the present study, interfacial strength in a glass fiber reinforced composite using a cruciform specimen is evaluated experimentally and analytically.

(1) The initiation and progress behavior of a interfacial debonding were observed by using a glass fiber/epoxy model composite for both the straight and the cruciform specimens. The validity of the cruciform specimen method is experimentally confirmed.

(2) Stress analysis using FEM for both the straight and cruciform specimens showed that the stress singularity at the free edge vanishes in the cruciform specimens.

(3) Using the debonding initiation observation and FEM stress analysis results, the interfacial normal strength in a GF/epoxy composite is experimentally evaluated.

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