INTERFACIAL STRENGTH EVALUATION IN A GLASS FIBER REINFORCED COMPOSITE USING CRUCIFORM SPECIMEN METHOD

Shinji Ogihara [1], Yoriaki Sakamoto [2], Hajime Kato [2], Satoshi Kobayashi[3] and Ichiro Ueno [1]

[1] Dept. of Mechanical Engineering, Tokyo University of Science, 2641 Yamasaki Noda, Chiba 278-8510, JAPAN Chiba, Japan
[2] Graduate student, Department of Mechanical Engineering, Tokyo University of Science, Chiba, Japan
[3]Tokyo Metropolitan University
ogihara@rs.noda.tus.ac.jp

ABSTRACT

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

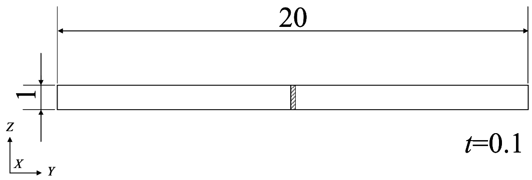
In fiber reinforced composite materials, the interface between the fiber and the matrix plays a key role in mechanical properties of composite materials. Therefore, a more accurate evaluation method of the interface is necessary to develop better fiber reinforced composite materials. The fragmentation 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.

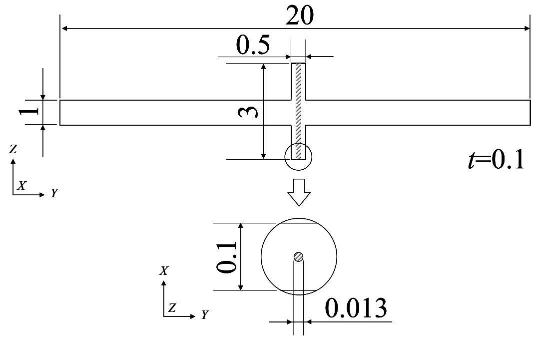
2. EXPERIMENT AND ANALYTICAL METHODS

2.1 Single fiber reinforced composite materials tensile test

In experiment, a single fiber composite that has a fiber perpendicular to the loading direction is used. In the present study, a glass fiber (GF, 13μm 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 straight specimen and the cruciform specimen were prepared. Fig. 1 shows the specimen geometry. In each specimen, tension test was conducted with a small loading machine installed on the stage of the digital microscope. During loading, interfacial debonding initiation and the progress was observed with the digital microscope. To emphasize the light, which is reflected from the fiber, light was vertically applied from both sides. The crosshead speed was 0.05mm/min.



a) Straight specimen



b) Cruciform specimen

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

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.2 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.

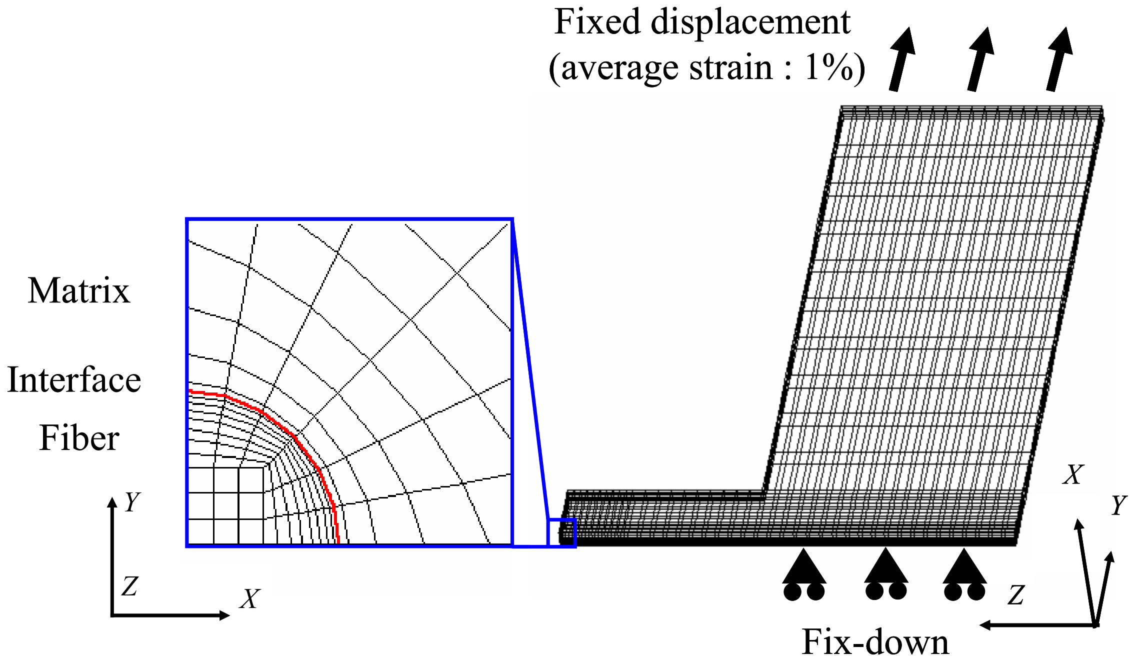


Fig.2 Schematic of a finite element analysis models

Table 1 Material properties and number of elements

	Young's moduls	Poisson's ratio	Number of elements	
	E (GPa)	ν	Straight-GF	Cruciform-GF
GF	70	0.2	1026	1995
Epoxy	4.28	0.42	3510	5325

3. RESULTS AND DISCUSSIONS

3.1 Tensile test

Figs.3 and 4 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. Fig.5 shows the relation between the average stress and observed debonding length. It was 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.

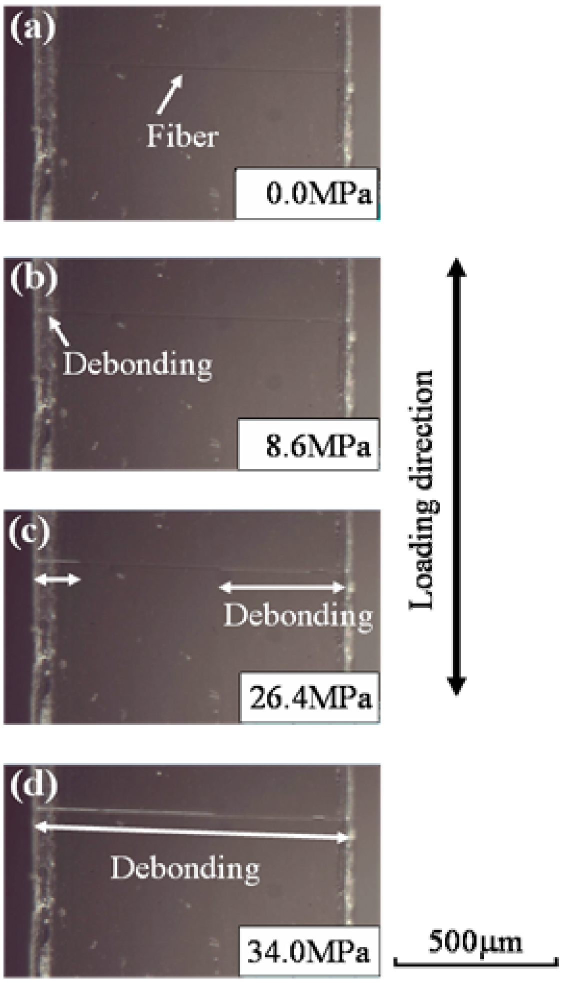


Fig.3 Debonding initiation and progress in a straight specimen

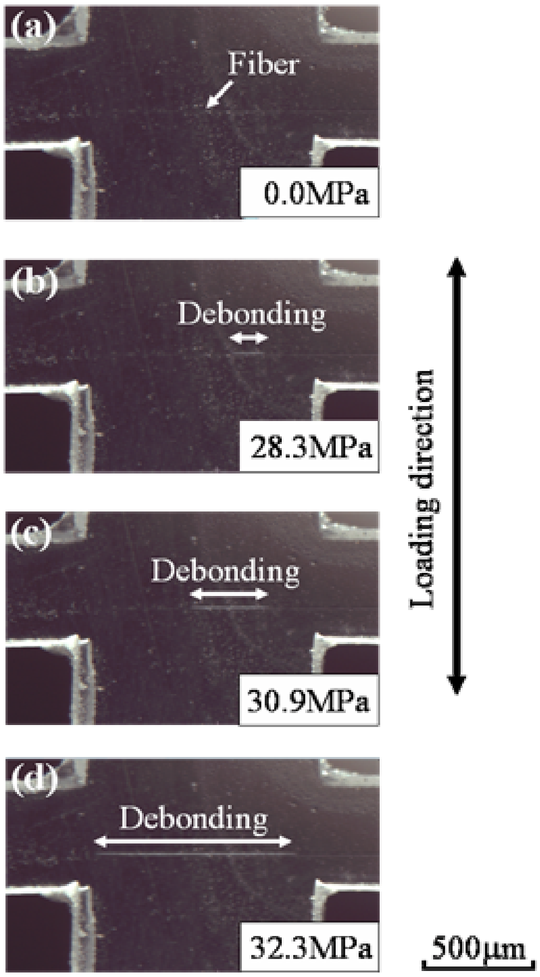


Fig.4 Debonding initiation and progress in a cruciform specimen

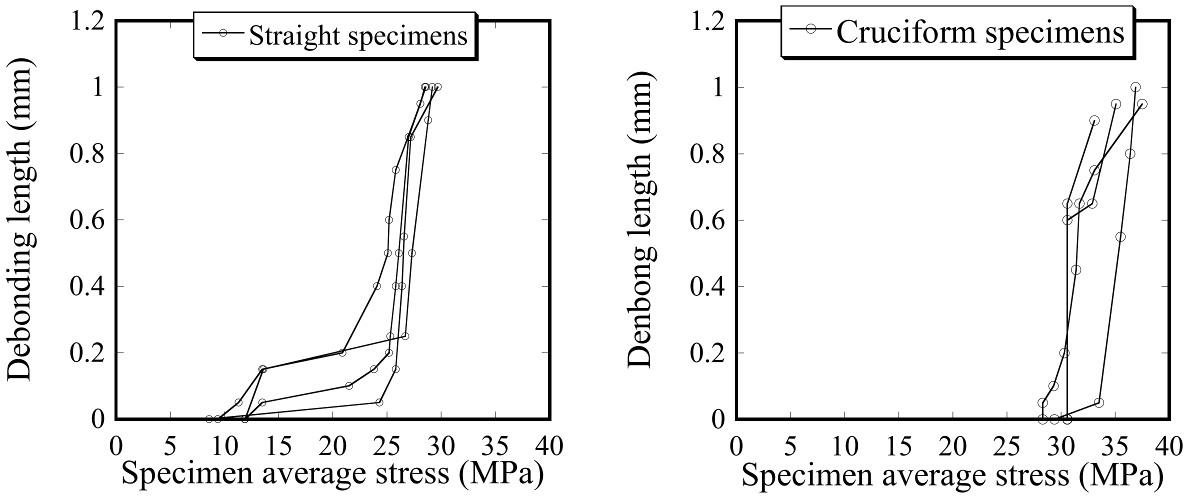


Fig.5 Relation between debonding length and specimen average stress in a) straight specimen and b) cruciform specimen

3.2 Evaluation of interfacial strength

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.6 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.7 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).

$$S_n = \frac{\sigma_{y'y'}}{\sigma} \quad (1)$$

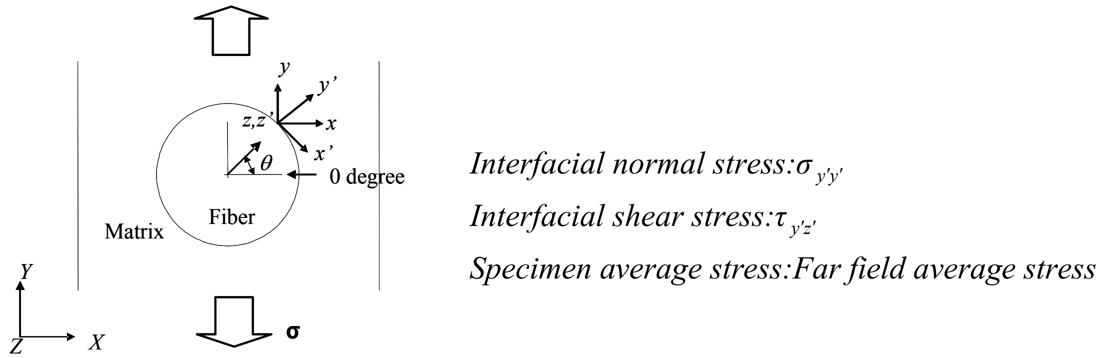
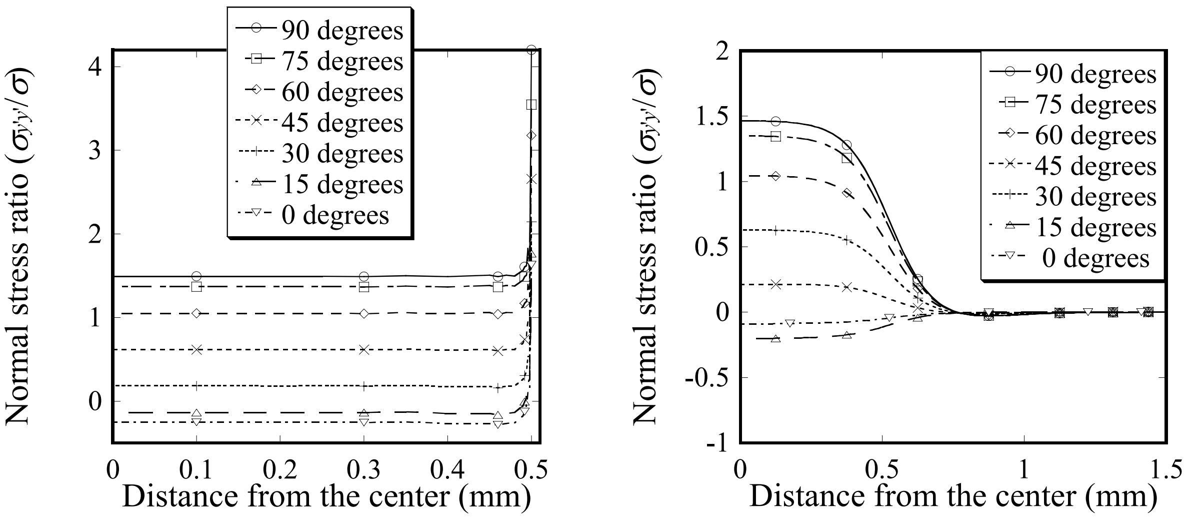


Fig.6 Stress evaluation sites



a) Straight specimens b) Cruciform specimens

Fig.7 Relation between interfacial normal stress ratio and distance from the edge along fiber in a) straight specimen and b) cruciform specimen

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.

The evaluated interfacial normal stresses are shown in Fig.8. Each average values of debonding stress (far field stress at debonding) in the straight specimens, debonding 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.

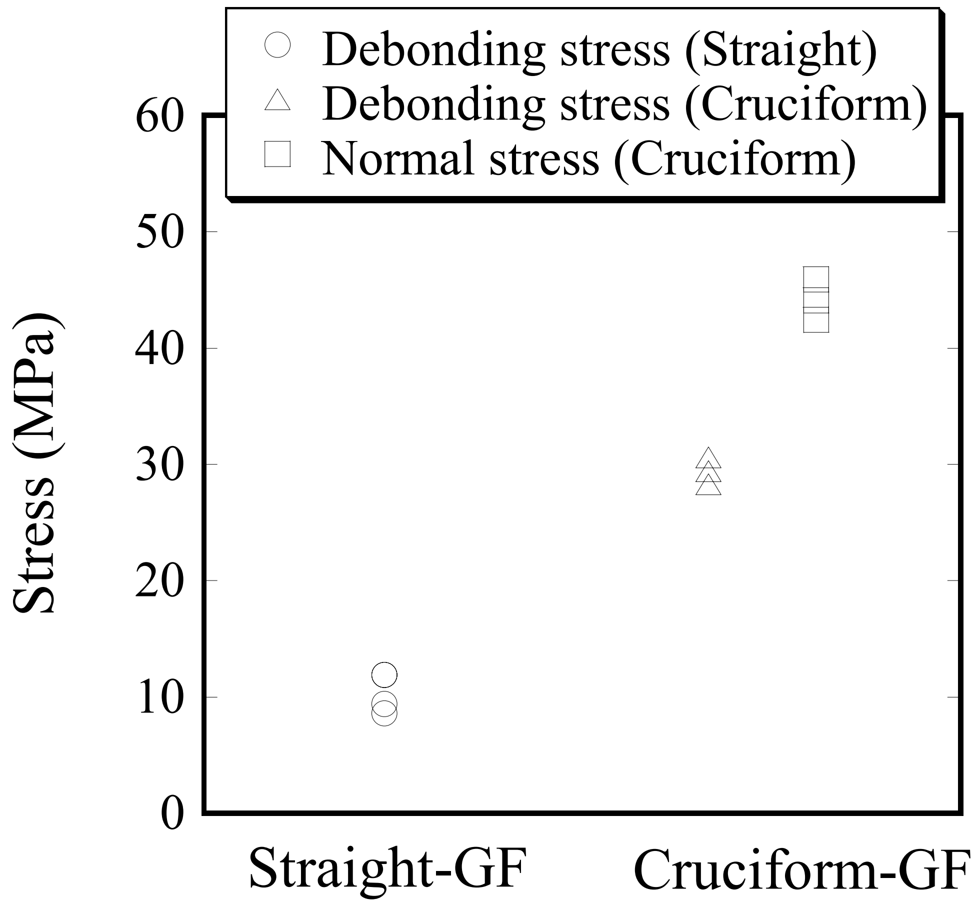


Fig.8 Debonding initiation stress and modified stress values by the stress ratio

4. CONCLUSION

The initiation of the interfacial debonding and the progress behavior were observed by using the model composite materials of GF/epoxy, and the differences in the straight specimen and the cruciform specimen were clarified experimentally. Moreover, using finite element analysis results for the cruciform specimen, it was shown that the stress singularity influence on the free edge in the straight specimen diminished, and that there is a possibility that the interfacial normal strength can be accurately evaluated by using this method.

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