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Approach to Dynamic Fracture Toughness of GFRP from Aspect of Viscoelastic and Debonding Behaviors

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Abstract: Debonding tensile test of single fiber bundle is carried out for static and intermediate loading rates. Based on the Young Modulus test, the viscoelastic property of interface layer and polyester matrix are identified. Then using those viscoelastic parameters, the criterion for the initiation of debonding which is independent with the loading rate is identified. One single fiber bundle model will be extended to the three-point bend model to calculate the fracture toughness of randomly oriented fiber.

Keywords: Dynamic Fracture Toughness, Viscoelastic, Debonding, Glass Fiber Reinforced Polymer, Interface layer, Polyester matrix, Damage

1. Introduction

The mechanical properties of GFRP such as Young's Modulus and fracture toughness are dependent with the loading rate. In the machine component and structural application, the GFRP component not only sustains the constant load but also in most case sustains dynamic load. The knowledge on the fracture toughness is important to maintain the integrity of the structural and machine component.

Other researcher investigates the debonding between the inclusion and the matrix near a crack tip in three-point bend specimen. The debonding occurs when the radial stress reaches the interfacial strength. The effects of parameters such as the distance between the crack tip and inclusion center, the inclusion diameter, Young's modulus ratio of the inclusion and the matrix and also the interface stiffness are analyzed[1]. However, the specimen was monotonically loaded. In other research, the loading rate effect on the debonding of GFRP was carried out[2] but the properties of GFRP were assumed to be elastic.

Numerical analysis of the damage model in FEM code are implemented systematically using the so-called zero-thickness interface elements with double nodes [3-4], after the cracking criterion is satisfied, a fracture-based interface constitutive law is activated i.e. cohesive crack models. However, this implementation requires a large number of nodes. The other way is to use only double nodes without interface elements along those lines where cracking is anticipated [3].

The effects of the interface are usually considered by introducing a linear or non-linear relationship (interface bond). The complete debonding occurs when the interface bond vanishes. The hard inter-phase enhances the reinforcement, but the soft inter-phase worsens the strengthening effect of PMMC significantly[5].

In previous paper by recent author[6], the numerical analysis of the fracture toughness of GFRP take into account the viscoelastic effect can not explain the loading rate effect completely. Stress and strain intensity factors were calculated without taking into account the damage zone effect on the stress and strain distribution ahead of the crack tip. Whole region of the model was considered as isotropic material.

In this paper, the fracture toughness of GFRP is discussed from debonding aspect. The random glass fibers in all orientations must be considered to represent the actual damage zone ahead of the crack tip in three-point bend specimen. However, for simplicity, one single fiber bundle model will be extended to the three-point bend model to calculate the fracture toughness of randomly oriented fiber.

2. Debonding Experiment

To identify debonding criterion of GFRP, The debonding experiment was carried out. The specimen is loaded in tensile for two loading conditions, static and intermediate. Debonding test under dynamic loading is available in literature[2]. The loading rate at the debonding is loaded in certain rate so that the stress intensity rate is the same with the one applied to the TPB specimen for the fracture toughness test. Later the fracture toughness is modeled using a single fiber bundle at the crack tip.

2.1 Experiment Method

A specimen for the debonding test is a round bar polyester matrix specimen containing a glass fiber bundle of an around 1.0 mm diameter as shown in Fig. 1. The diameter of fiber bundle is 1 mm, Elastic modulus, E, 6.18 Kg/m^3, Poisson's ratio,ν, 0.32 and density, ρ is 1180 Kg/m^3.

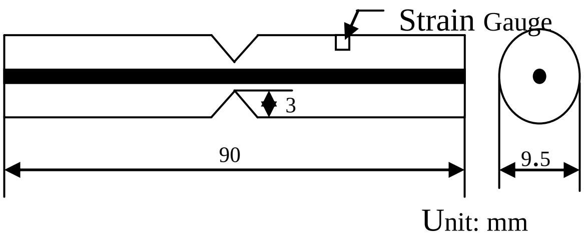


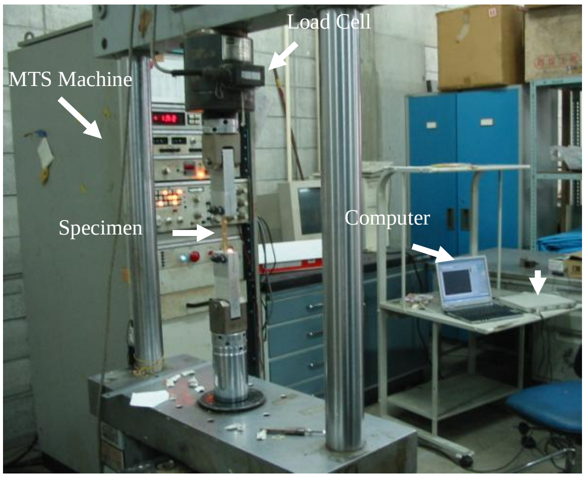
Fig.1 Specimen Geometry for Debonding Test

The analysis result of the stress intensity factor at the crack tip of TPB specimen for static and intermediate loadings were 1 and 1000 MPa$\sqrt{m}$/s, respectively. Hence in debonding test, to create the same stress intensity rate, the loading rate is 0.0614 and 61.4 KN/s for static and intermediate loadings, respectively. The debonding test apparatus is shown in Fig. 2.

The debonding test was carried out by appling the load with associate loading rate. When load is applied, the specimen is observed whether the debonding occurs. The load magnitude and duration is maintained to get an appropriate loading rate for the debonding to take place.

2.2 Experiment Result

The debonding occurs in the following sequence, the matrix facture initiates from the notch root i.e. at high stress concentration region of the single fiber bundle specimen. Then, the matrix crack propagates perpendicularly to the specimen longitudinal axis until reach the fiber bundle. When matrix /fiber interfacial stress reaches a critical value, the debonding starts and the crack turns and grows along the interface as



shown in Fig. 3.

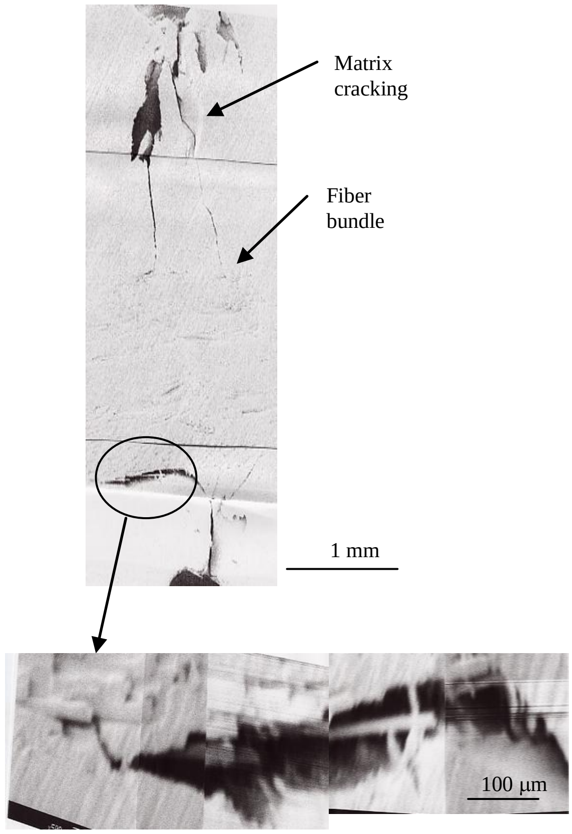
Fig.2 Debonding Test Apparatus

Debonding length is plotted against strain in Fig. 4. As seen in this figure, the load necessary to initiate debonding under static loading and intermediate loading is the same. Debonding is initiated when the load exceeds 4.7 MPa under static and intermediate loadings, respectively.

In this chapter, the debonding initiation load for static and intermediate loading is the same, around 4.7 MPa. It indicated that single fiber bundle bonding strength is less affected by the change of the loading rate, i.e. static and intermediate loading. On the other hand, the single fiber bundle bonding strength under dynamic loading is significantly affected by the loading rate[2].

If one assumed the equation of static is valid, the strain under static and intermediate loadings can be calculated as a ratio of stress to E. The initiation debonding strains for static and intermediate cases are approximately 360$\mu\varepsilon$ which are much lower than the dynamic debonding initiation strain of 3500 $\mu\varepsilon$[2].

This result is similar with the numerical analysis result in TPB specimen[10] where the strain intensity factor at the crack tip is less affected by the loading rate. The strain intensity factor at the crack tip under static loading was approximately the same with the one under intermediate loading. In reverse, the strain intensity factor under dynamic loading is twice of the static one which is



highly affected by the loading rate.

Fig.3 Matrix Crack Initiate from the Notch across the Specimen Thickness

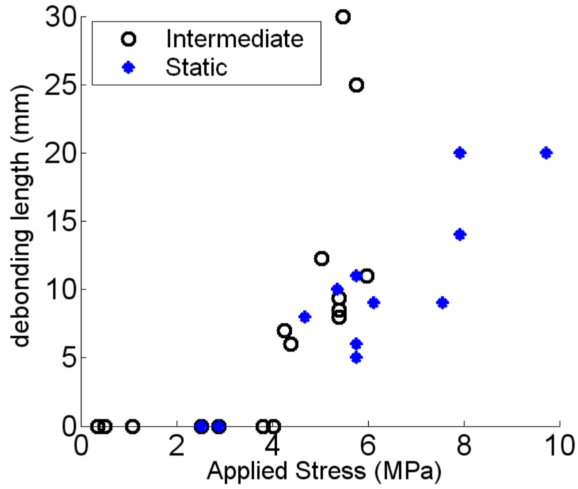


Fig.4 Debonding Length as a Function of the Applied Load

This result suggests that debonding play a significant role in the determination of the fracture toughness of randomly oriented GFRP composite.

3. Numerical Analysis

The debonding criterion is identified by numerical analysis. To get similar model with the real material the viscoelastic parameter is identified by combination of experiment and numerical analysis of Young's Modulus Test.

3.1 Young's Modulus Test

In the previous paper by recent author, randomly oriented glass fibre in polyester matrix for Young's modulus test is modelled as isotropic material[10]. However, the result can not fully explain the loading rate completely. In this paper, randomly oriented glass fibre is modelled as one single fibre embedded in polyester matrix in order to identify the viscoelastic layer between matrix and fibre. This layer with thickness of 0.1 mm is considered to behave as a strong viscoelastic layer since fiber is elastic.

Young's modulus tests are carried out numerically using commercial FEM code, Ansys90 and Ansys90/LS-DYNA. Viscoelastic material is modeled with the Maxwell model as shown in Fig.5.

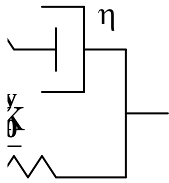


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Fig.5 Three Parameter of Maxwell Model

Young's modulus tests of GFRP and polyester matrix are simulated by numerical analysis using the same specimen geometry and loading condition. The FEM model for Young's modulus test is shown in Fig.6.

In Young's modulus test, the change in strain rate is obtained by changing displacement magnitude. The three viscoelastic parameters are changed systematically to obtain the best agreement between the simulation and the experimental results. Young's modulus is defined as stress divided by the strain of the surface element. Finally Young's modulus is plotted as function of the strain rate.

Appropriate sets of long-time shear modulus G~, short-time shear modulus Go and relaxation time τ, will provide the best fit between the numerical and experimental results.

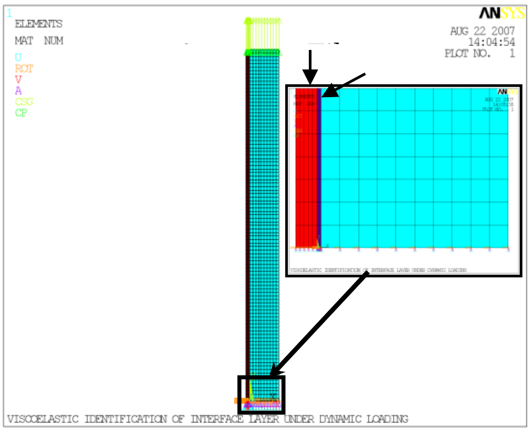
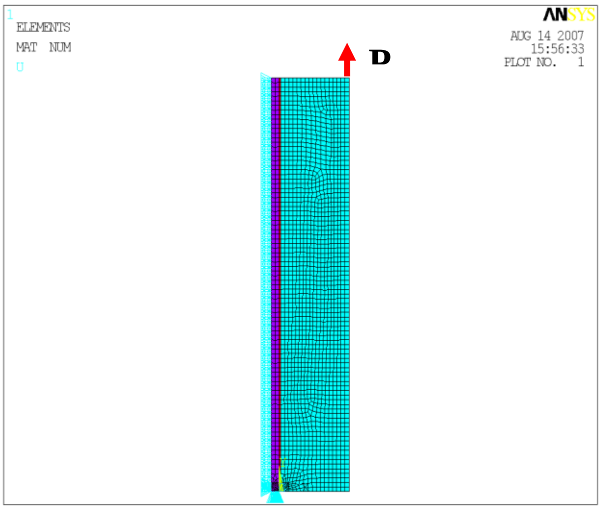


Fig.6 One Single Fiber Model for Viscoelastic Parameter Identification of GFRP

3.2. Debonding Criterion

The debonding single fiber bundle test is modeled as single fiber bundle with the viscoelastic interface layer of 0.1 mm thickness.



In Fig.7 FE Model for Debonding Test under Static and Intermediate Loadings

In the analysis the fiber is considered as an elastic material while the polyester matrix and the interface are considered as viscoelastic material. Hence the input data in the analysis for fiber is fiber's elastic property[7], i.e. Young's modulus of 76 GPa and Poisson's ratio of 0.33. For the interface layer and polyester matrix the inputs data are the viscoelastic parameters identified by Young's modulus test in previous section. The loading models are shown in Figs. 7and 8.

In the experiment, the SEM observation of the debonding specimen shows that the debonding initiates along the interface i.e. between the interfacial layer and the fiber bundle as seen in Fig. 3.

This region is regarded as the interface layer between matrix and fiber. Hence, in the simulation of the debonding test, it is assumed for a crack to propagate along the interface between an elastic fiber as shown in Fig.9.

In previous paper[6], the fracture toughness of GFRP is controlled by the strain rather than the stress. It is because the fracture in GFRP is preceded by the damage zone formation which consists of matrix cracking, debonding and fiber break.

In the experiment, the debonding initiation load for static and intermediate loadings were almost the same, around 0.3 KN. In work by Homma.et.al.[2], under dynamic loading, debonding initiation strain from strain gauge output was 3500$\mu\varepsilon$. Thus in the analysis, static and intermediate debonding test were carried out by applying the tensile load of 0.3 KN at the specimen end and for dynamic test the strain applied is 3500$\mu\varepsilon$. Then, the strain components are calculated at the debonding tip for all loading rate. For the validation of the FEM code used in this study under dynamic loading, the calculated strain history is plotted to get the best fit with the one from the strain gauge output.

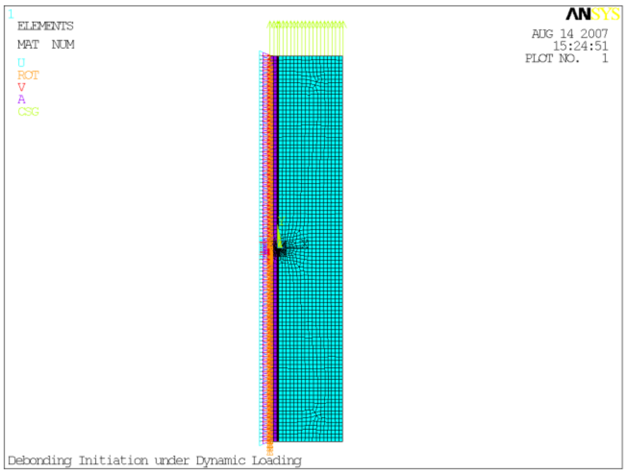


Fig.8 FE Model for Debonding Test under Dynamic Loading

3.3 Fracture Toughness

The experiment result outline that the dominant failure mechanism for all loading rates is the debonding between fiber and matrix. Hence to represent damage zone ahead of the crack tip simply, only the dominant failure mechanism will be modeled.

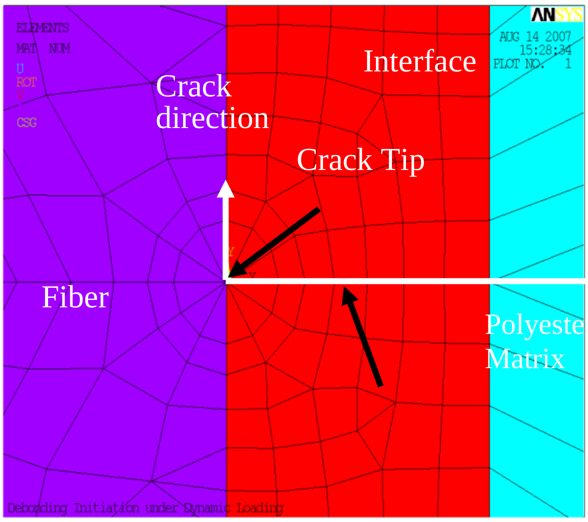


Fig.9 Debonding Model at the Crack Tip under Dynamic Loading

As can be seen in Fig.10 the damage zone ahead of the crack tip of the three-point bend specimen is modeled using one perpendicular fiber. The fiber is considered as elastic material. Then, the idea is to use the constant fiber strength to obtain fracture toughness value of GFRP which is independent with the loading rate.

3.3.1. Mesh Model for Debonding of fracture toughness specimen

To represent the debonding process ahead of the crack tip in the numerical analysis, an area consisting of a single fiber bundle, viscoelastic interface layer and the polyester matrix are modeled and installed ahead of the crack tip in the FEM mesh model. The finite element code ANSYS 9.0/ LS DYNA is used to solve the problem.

The FEM model of the three point bend specimen is consisted of 15702 elements and 16136 nodes. The smallest element size at the crack tip is 20 μm.

The three point bend model for the FEM analysis is shown in Fig.11. The damage zone that consists of a fiber bundle, interface and polyester matrix is surrounded by the isotropic, viscoelastic material model of GFRP. The viscoelatic data in FEM code for the isotropic part are the viscoelastic parameters that are used for entire model in previous paper[6].

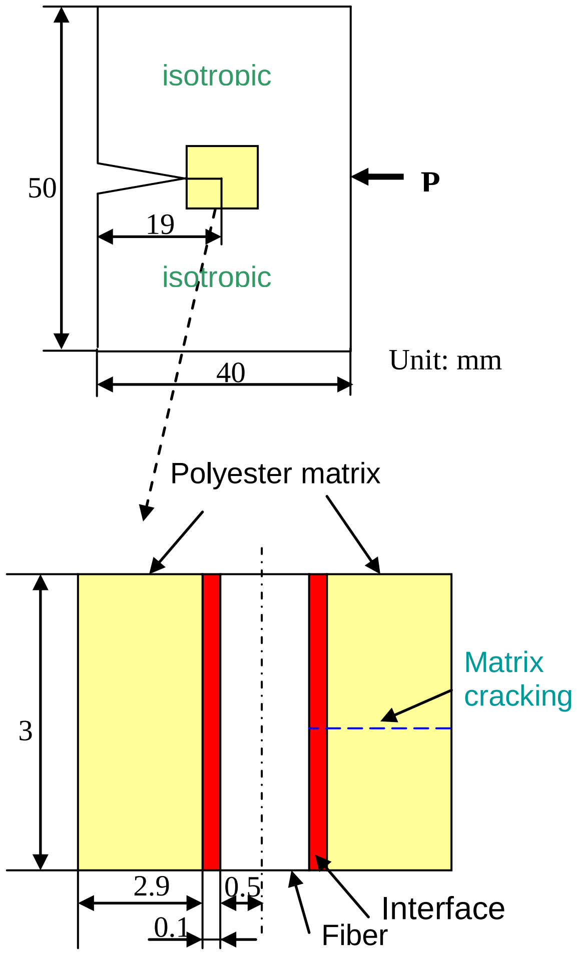


Fig. 10 Damage Zone ahead of the Crack Tip of the Three-point Bend Specimen

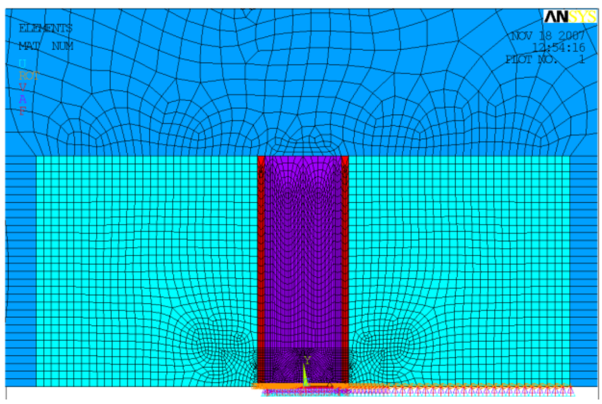


Fig. 11 Damage Zone Consists of Fiber, Interface and Polyester Matrix

The meshing at the crack tip is shown in Fig.12. The crack tip is located between the viscoelastic interface and the fiber. Hence this boundary consists of two nodes, of which one belongs to the element of the viscoelastic interface and the other belongs to the element of the elastic fiber. In this boundary the duplicate node is jointed or released to simulate the debonding process.

3.3.2. Numerical Procedure

The fracture mechanism of GFRP is proposed[6]. In this model, the matrix cracking process is neglected; it is assumed that the matrix cracking already reaches the fiber i.e. the crack tip is located at the boundary of the viscoelastic interface and the fiber.

The numerical procedures for the simulation of the fracture process for all loading rates are as follows: first, at the static test, the load of arbitrary magnitude is applied, then the strain component at the crack tip or debonding tip is calculated.

The criterion for debonding initiation and propagation is the strain component at debonding tip which is independent of the loading rate. If after the first calculation, strain component is less than the critical value i.e. debonding cirterion, the applied load is increased. When the criterion is satisfied, the debonding tip is advanced by 0.1 mm.

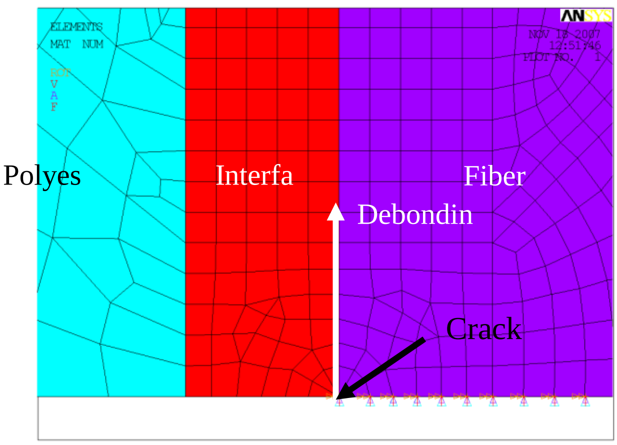


Fig. 12 Mesh at the Crack Tip

The propagation of the debonding is simulated by separating the joint node between the fiber element and the interface element. For every step the principle stress in the fiber is calculated. The debonding length increases whenever the criterion of the initiation/propagation of the debonding is satisfied.

The iteration is stop when the strain at the strain gauge location in the experiment is equal to the value corresponding to the static fracture toughness obtained by the experiment, i.e. 7 MPa√m. In this step, the fiber is considered to be broken because in the experiment, the crack is initiated in the specimen at this stress intensity level. The principle stress is calculated and defined as the fiber strength. The fiber strength is considered to be independent of the loading rate.

The same procedure is applied to the intermediate and the dynamic fracture toughness test, but the iteration is stopped when the principle stress in the fiber exceeded the fiber strength. Then the stress intensity is calculated from the strain value at the strain gauge location in the model and compared with the experimental one.

4. Results and Analysis

4.1. Viscoelastic Property

Young's modulus of pure polyester is plotted against the strain rate in Fig.13. Young's modulus value only changes from 5 to 6 GPa.

This little change indicates that the polyester matrix does not behave as a strong viscoelastic material.

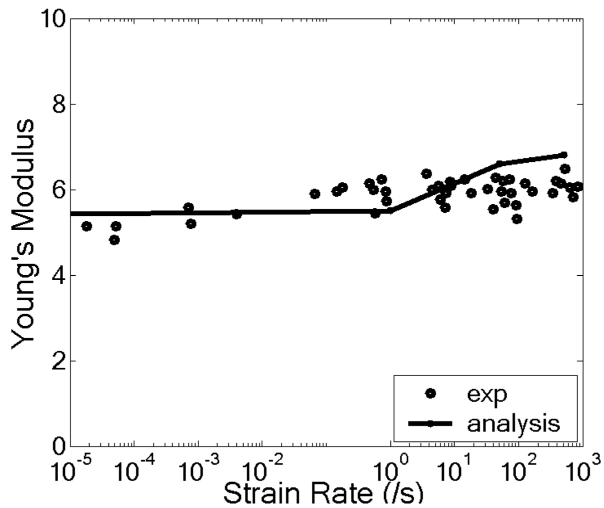


Fig.13. Comparison of the Young's Modulus of Polyester Matrix

The best fit can be seen between the experiment and the analytical result. The appropriate set of G~, Go,τ for polyester matrix is listed in Table 1. In contrast, Young's modulus of GFRP is highly affected by the strain rate.

The best fit of the analysis to the experiment result is shown in Fig.14. Randomly oriented fiber in GFRP is successfully represented by a single fiber bundle model. The appropriate set of G~, Go,τ of GFRP is listed in Table 1.

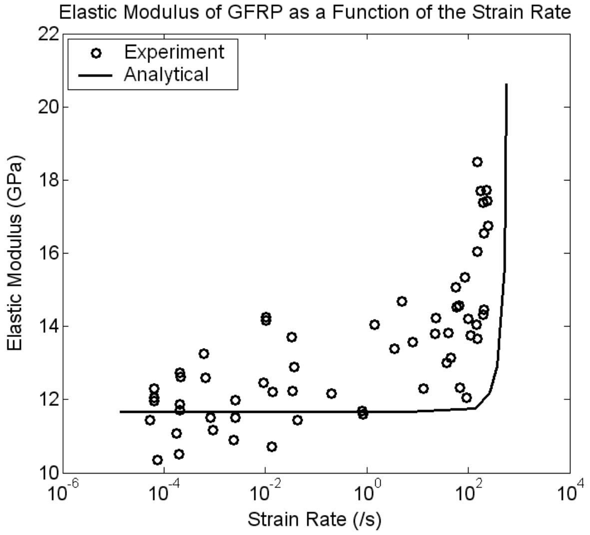


Fig.14. Comparison of the Young's Modulus of GFRP

Table 1 Viscoelatic Parameter of Interface Layer

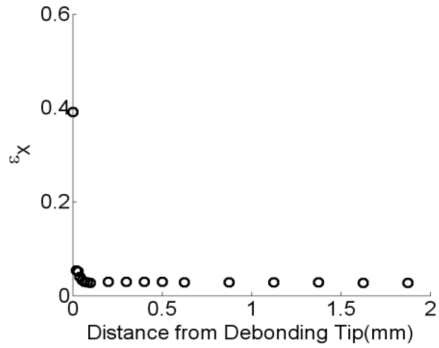
Viscoelastic Parameter	Polyester Matrix	Interface Layer
Short-time Shear Modulus (GPa) Long-time Shear Modulus (GPa)	4.92 3.67	3.26×10^{-5} 1.00×10^{-6}
Bulk Modulus(GPa)	12.00	7.96×10^{-5}
3 Maxwell Elements for Shear Relaxation Coefficient	-	0.42 0.42 0.16
Relaxation Times for Shear Relaxation	0.97	0.69×10^{-1} 0.65×10^{-2} 0.10×10^{-3}

4.2. Debonding Criterion

The result from debonding test shows that for all loading rates the strain component is tensile. The strain component in x direction, ε_x, of 0.4 is unaffected by loading rates. Whereas the strain component in y direction ε_y, and the shear strain ε_{xy}, depend on the loading rates. Hence the debonding of GFRP material is controlled by the strain component in x direction, ε_x. Strain component in x direction for all loading rates are shown in Fig. 15.

4.3. Fracture Toughness

The debonding stage for all loading rates is as follow; the load is increased gradually to get the strain, ε_x, of 0.4 at debonding tip. When the strain, ε_x, equals or exceeds the critical value for debonding initiation i.e. ε_x = 0.4, the debonding tip moves forward 0.1 mm. For every step the fiber stress and the stress intensity are calculated.



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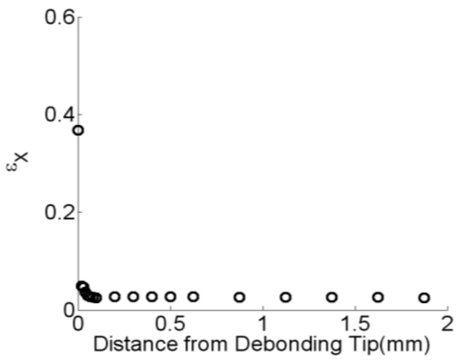

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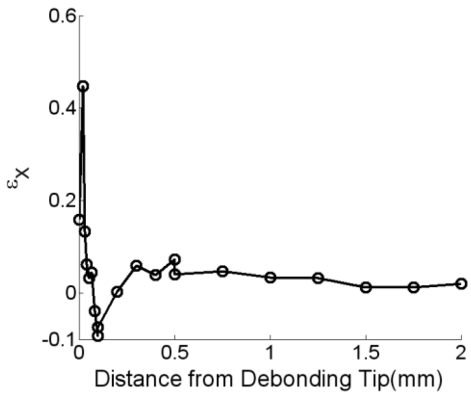

(c)

Fig.15. Strain Component in x Direction, ε_x,

(a) Static (b) Intermediate (c) Dynamic

Under static loading the increase in load is linear with the strain at the debonding tip, hence it is easy to get the strain equal to the critical value. For intermediate loading, which displays the close behavior to elastic material, the strain is linearly related to the load. On the other hand, under dynamic loading the strain is not linearly related to the load because the viscoelastic property of GFRP is dominant at high loading rate.

For static case, the numerical analysis is done to get the fiber strength. In the experiment of the fracture toughness[7], the crack is initiated when the stress intensity factor measured by the strain gauge method equals 7 MPa√m. In the numerical analysis, the stress intensity factor calculated by the same method as the strain gage method in the experiment, the fiber stress reaches its tensile strength. Based on this idea, the fiber strength under static loading is calculated.

The fiber strength for intermediate and dynamic loadings is considered to be the same with the static fiber strength because in GFRP material, the fiber is considered as linear elastic and brittle material, i.e. independent of the loading rate. Then in the numerical analysis the calculation is done to get the fiber stress that exceeded the static fiber strength. After the fiber stress under intermediate and dynamic loadings exceeded the static fiber strength, the stress intensity factor at the strain gauge location in the model is calculated and compared with the experimental one. The fracture toughness values for all loading rates obtained are listed in Table 2.

Table 2 Stress Intensity Factor of GFRP for Three Loading Rates

Loading Rates	Numerical			Experiment
	Debonding Length (mm)	Fiber Stress (MPa)	K1c (MPa √m)	K1c by Strain Gauge (MPa√m)
Static	0.50	1464	7.0	7.0
Inter-mediate	0.46		7.7	8.3
Dynamic	0.22		11.8	12.0

As shown in table 2, the numerical results fit with the experimental ones. Hence using this FEM model, the fracture toughness of GFRP under a wide range of loading rate can be predicted if the static fracture toughness is known.

5. Conclusions and Future Works

To explain the loading rate effect on fracture toughness of GFRP, viscoelastic parameters of the interfacial layer and polyester matrix are identified. In Young's modulus test, GFRP with randomly oriented fiber is successfully represented by a single fiber bundle model.

The debonding and fracture toughness tests are numerically simulated for a wide range of loading rate. The debonding propagates between the fiber and the interface layer according to the debonding criterion. If the static fracture toughness is known, the FEM model developed in this study can be used to predict the fracture toughness value under a wide range of loading rates.

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References

[1] Savalia, P., C., Tippur, H., V., Kirugulige, M., S., *"A Numerical Study of Inclusion-matrix Debonding in the Presence of a Nearby Crack"*, Engineering Fracture Mechanics, Article In Press, 2007

[2] Homma, H., Gunawan, F., Yamauchi, M., and Fenny, K., *"Interfacial strength of glass fiber composite"*, Key Engineering Materials, Vols.243–244 (2003), pp.81-86

[3] Daniela Ciancio, Ignacio Carol, Massimo Cuomo, "*Crack opening conditions at 'corner nodes in FE analysis with cracking along mesh lines"*, Engineering Fracture Mechanics 74 (2007) 1963-1982

[4] Caporale, A., Luciano, R., Sacco., E, *"Micromechanical analysis of interfacial debonding in unidirectional fiber-reinforced composites"*, Computers and Structures 84 (2006) 2200-2211

[5] Zhang,W.,X.,Li,L.,X.,Wang,T.,J., *Interphase effect on the strengthening behaviour of particle-reinforced metal matrix composites"*, Computational Material Science (2007), doi:10.1016/j.commatsci.2007.03.011

[6] Shirley Savet Lana and Hiroomi Homma, *"Approach to dynamic fracture toughness of GFRP from aspect of viscoelastic and debonding behaviors"*, Journal of Solid Mechanics and Materials Engineering, Vol. 1, No. 3, pp.275-286, February 2007

[7] Shirley Savet Lana, Hiroomi Homma, and Kohji Nakazato, *"Viscoelastic effect on the fracture toughness of GFRP: Experimental*

Approach", Key Engineering Materials, Vols. 306-308, pp. 745-750, March 2006

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