

# EVALUATION OF DEBONDING ENERGY RELEASE RATE OF EXTERNALLY BONDED FRP SHEETS FOR REHABILITATION OF INFRASTRUCTURES

Koji YAMAGUCHI<sup>1</sup>, Isao KIMPARA<sup>1</sup>, and Kazuro KAGEYAMA<sup>1</sup>

<sup>1</sup> *Department of Environmental & Ocean Engineering, The University of Tokyo  
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

**SUMMARY:** A new peeling test method of FRP sheets bonded on mortar and concrete was proposed to characterize the peeling strength in term of the debonding energy release rate. In addition to this, the two methods of data reduction for this test method were proposed from the viewpoint of fracture mechanics and theory of elastic thin membrane. The application and the limitation of the proposed data reduction methods were examined by the experiments and the FEM analysis. It was shown that the mode II energy release rate in this test method always makes up over 80% of the total energy release rate based on the FEM analysis. The effects of different surface treatments and different base materials on the peeling strength of FRP sheets were successfully evaluated based on the proposed data reduction.

**KEYWORDS:** Energy release rate, Debonding, Peeling test, Bonding strength, Externally bonded FRP sheets, Rehabilitation of infrastructure, Elastic membrane

## INTRODUCTION

Much attention has recently been paid to rehabilitation such as repair and preservation of infrastructure with the use of fiber reinforced plastics (FRP) sheets. A widespread use of carbon fiber sheets has already been found in Japan with hundreds of field applications including repairs of bridge beams, retaining walls, utility poles, slabs, chimneys, tunnels and other structures requiring strengthening, stabilization or seismic upgrade. The social demands to consider the effective counter-measures for seismic retrofitting of damaged structures and seismic upgrading for existing structures have been rapidly increasing in Japan since the Big Earthquake in Kobe in 1995.

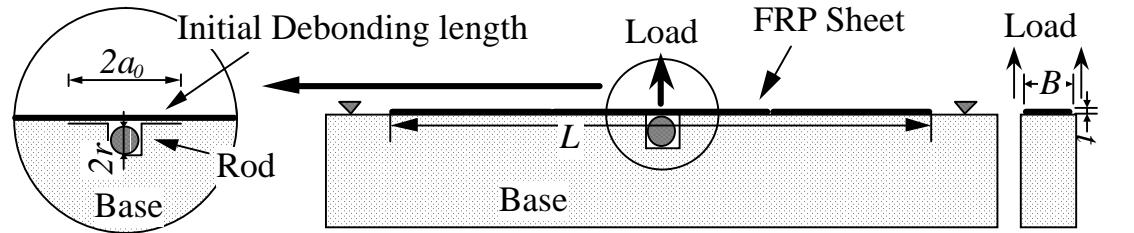
The use of externally bonded FRP sheets as reinforcement in mortar or concrete members has been investigated both theoretically and experimentally [1-4], showing a good promise of effective strengthening in view of the simplicity of application relative to the bonding of steel plates. The strength of structural members reinforced by bonded FRP sheets depends naturally on the bonding or peeling strength between FRP sheets and structures. Various test methods have been proposed to evaluate the bonding strength. The bonding strength is

generally evaluated based on the average strength by those test methods [5-7], that give apparent strengths depending on the geometrical configurations. Some test methods have also been proposed to evaluate the critical energy release rate of debonding or peeling based on the methods [8, 9]. It has, however, been difficult to evaluate the inherent bonding strength in practical constructions due to actual spot process by means of a simple data reduction.

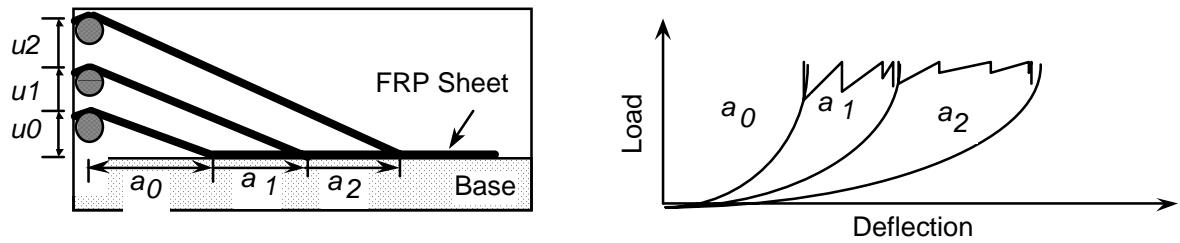
In this study, A new peeling test method of FRP sheets bonded on mortar and concrete was proposed to characterize the peeling strength in term of the debonding energy release rate. In this test method, it was shown that the load and the energy release rate due to peeling are functions of deflection-to-debonding-length ratio from the geometrical consideration and equilibrium condition of thin elastic membrane. This formula gives the basis for a simple data reduction method for the critical energy release rate. The effects of different surface treatments of concrete and different base materials on the peeling strength of FRP were evaluated based on the proposed data reduction method.

### PROPOSAL OF MEMBRANE PEELING TEST

Consider a test specimen and a testing method as shown in Fig. 1(a), in which a peeling load is applied with a loading rod of radius  $r$  on a FRP sheet of width  $B$ , thickness  $t$  and initial debonding length  $2a_0$ , bonded on base material (mortar or concrete), as shown in Fig. 1(a). The resulting non-linear load-deflection curves due to the extension of debonding are schematically shown in Fig. 1(b). Though this loading method is apparently similar to the one proposed by Lin Ye et al. [10], it is quite different in the assumption that FRP sheet is regarded as an elastic membrane in the present testing method. This assumption made it possible to make a useful simple data reduction as described later. Hence this method is hereafter referred to "Membrane Peeling (MP) Test".



(a) Specimen and testing method



(b) Load-deflection-curves due to extension of debonding

Fig. 1: Proposed testing method for evaluating debonding energy release rate  
DATA REDUCTIONS

Because a load-deflection curve in this test method is not linear, the conventional "Compliance Method" is not appropriate to be applied to evaluate the energy release rate. The

two methods of data reduction are proposed for evaluating the energy release rate. The first is referred to "Area Method" and the second is referred to "Membrane Peeling (MP) Method".

## AREA METHOD

The energy release rate can be evaluated based on the area encircled by load-deflection curve, dissipated energy,  $\Delta A$ , divided by the area of crack extension,  $B\Delta a$ :

$$G = \frac{\Delta A}{2B \cdot \Delta a} \quad (1)$$

In this method, however, the debonding length should be measured accurately by means of repeated loading unloading.

## MEMBRANE PEELING METHOD

A modification of the compliance method is proposed for evaluating the energy release rate. It is assumed that the FRP sheet is a linear elastic membrane, and that the out-of-plane load is applied to the sheet with a loading rod with equal right and left debonding length, as shown in Fig. 2.

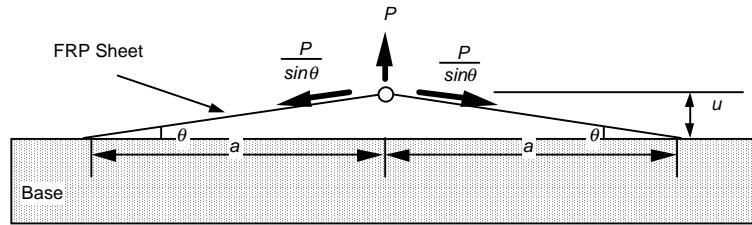


Fig. 2: Equilibrium of forces between sheet and rod under a given deflection,  $u$

Considering the equilibrium of forces between sheet and rod, the relation between deflection,  $u$ , of the sheet and load,  $P$ , is expressed by:

$$P = 2 \cdot EtB \cdot x \left( 1 - \frac{1}{\sqrt{1+x^2}} \right) \quad (2)$$

where  $x = u/a$

Integration of Eqn 2 with respect to  $u$  under the condition that debonding length,  $a$ , is constant and the initial condition of  $U=0$  at  $x=0$  gives the strain energy stored. And differentiation of the strain energy with respect to  $a$ , under the condition that sheet deflection,  $u$ , is constant, gives:

$$G = Et \left( \frac{x^2}{2} + \frac{1}{\sqrt{1+x^2}} - 1 \right) \quad (3)$$

From the Eqn 3, it is noteworthy that the energy release rate is given as a function of  $x=u/a$ , and independent of debonding length,  $a$ . This formula gives the basis for a simple data reduction method for critical energy release rate to be calculated from extensional rigidity and deflection-to-debonding-length-ratio. When bonding strength is evaluate based on energy

release rate in this data reduction, measurement of debonding length is not required and neither is repeated loading and unloading, so that a continuous R-curve of critical energy release rate due to crack extension can be obtained.

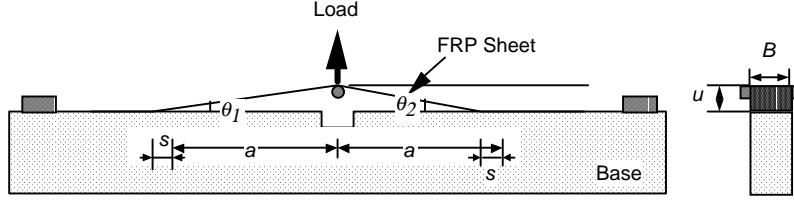


Fig. 3: Debonding of FRP sheet with unequal debonding length on right and left

In addition, energy release rate needs to be corrected if the debonding length is not equal on right and left. Let the average debonding length between right and left debonding length as  $a$  and the difference between average debonding length and each debonding length as  $s$ , as shown in Fig. 3, the relation between deflection of the sheet,  $u$ , and load,  $P$ , can be expressed by:

$$P = \frac{1}{2} EBtx \left( 2 + \frac{\sqrt{(1+\alpha)^2 + x^2}}{\sqrt{(1-\alpha)^2 + x^2}} + \frac{\sqrt{(1-\alpha)^2 + x^2}}{\sqrt{(1+\alpha)^2 + x^2}} - 2 \left( \frac{1}{\sqrt{(1-\alpha)^2 + x^2}} + \frac{1}{\sqrt{(1+\alpha)^2 + x^2}} \right) \right) \quad (4)$$

where  $\alpha = s/a$

Integration of Eqn. (4) with respect to  $u$  under the condition that the debonding length,  $a$ , is constant, and, differentiation with respect to debonding length,  $a$ , under the condition that sheet deflection,  $u$ , is constant, gives:

$$\begin{aligned} G = & \frac{1}{4} Et \cdot \left( x^2 - 3 + \alpha^2 + 2\sqrt{(1+\alpha)^2 + x^2} + 2\sqrt{(1-\alpha)^2 + x^2} \right. \\ & - \frac{2(\alpha + \alpha^2 + x^2)}{\sqrt{(1+\alpha)^2 + x^2}} - \frac{2(-\alpha + \alpha^2 + x^2)}{\sqrt{(1-\alpha)^2 + x^2}} \\ & + \frac{2(\alpha + \alpha^2 + x^2)\sqrt{(1-\alpha)^2 + x^2}}{\sqrt{(1+\alpha)^2 + x^2}} \\ & + \frac{2(-\alpha + \alpha^2 + x^2)\sqrt{(1+\alpha)^2 + x^2}}{\sqrt{(1-\alpha)^2 + x^2}} \\ & \left. - \sqrt{(1+\alpha)^2 + x^2} \cdot \sqrt{(1-\alpha)^2 + x^2} \right) \end{aligned} \quad (5)$$

Eqn. (5) satisfies the initial condition of  $U=0$  at  $x=0$ . It is noted that the corrected energy release rate is a function of  $x=u/a$ , and  $\alpha=s/a$ . The energy release rate is calculated based on this data reduction method, if only the right and left angle between sheet and upper face of base material,  $\theta_1$ ,  $\theta_2$ , and deflection of rod,  $u$ , are measured.

## FEM ANALYSIS

### MODEL

In this study, the right half of test specimen was analyzed, since this specimen was symmetric. A finite element code, Mark, was used with quadrilateral eight node elements to model base material, adhesive and FRP sheet, as shown in the mesh division in Fig. 4. This model was analyzed under plane strain condition and large displacement condition. A crack tip was assumed to lie at interface between base material and adhesive, since a crack was observed to extend on the interface in the experiment where base material was concrete. Three types of base material were used: aluminum, mortar and concrete. In addition to, three types of initial debonding length were modeled: 100mm, 150mm and 200mm. These material properties are the same as those in the experiment.

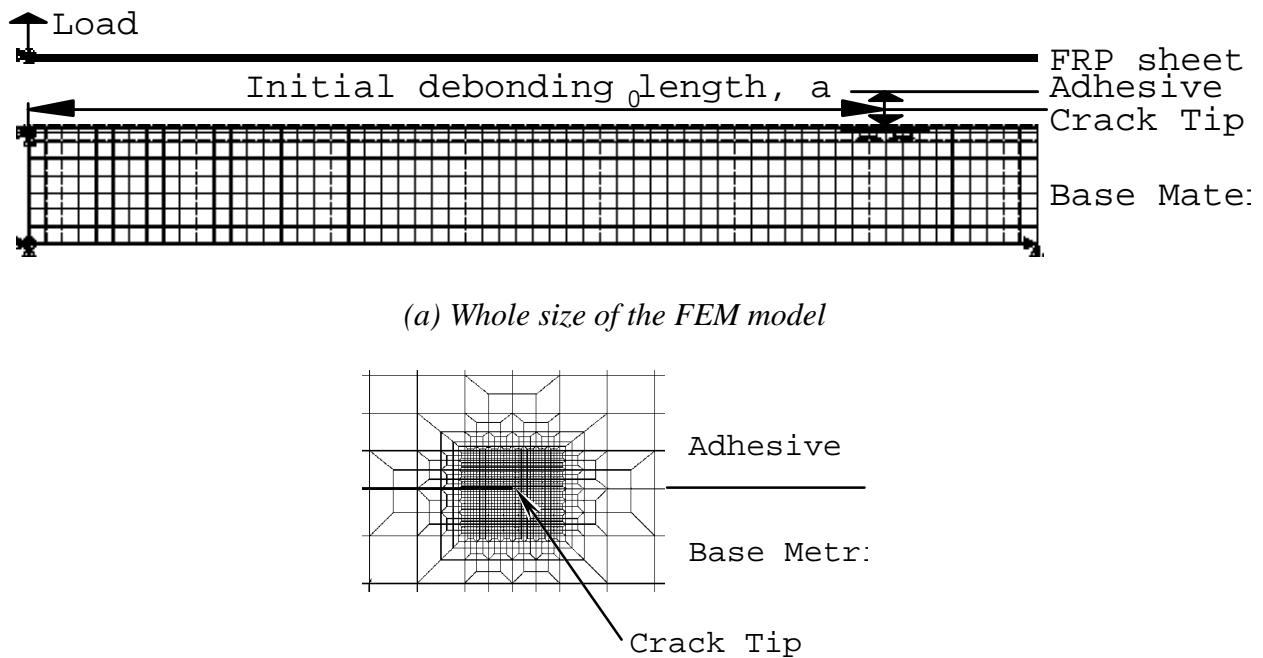


Fig. 4: Mesh division of the FEM analysis for the specimen

### RESULT

The relation between load,  $P$ , and  $x$  ( $=u/a$ ) is shown in Fig. 5 among three different types of initial debonding length and theoretical curve, where the base material in this analysis is concrete. It is shown that these curves almost coincides, which suggests that the relation between load,  $P$ , and  $x$  ( $=u/a$ ) is independent of initial debonding length. It is also shown that difference in the energy release rates among the three different base materials is quite small, as shown in Table 1.

In this model where the base material is concrete, the mode ratio of energy release rate was able to be analyzed through the ratio between crack opening stress and shear stress, since linear fracture mechanics is applied to the model. It is shown that mode II energy release rate in this test always makes up the over 80% of total energy release rate, as shown in Fig. 6.

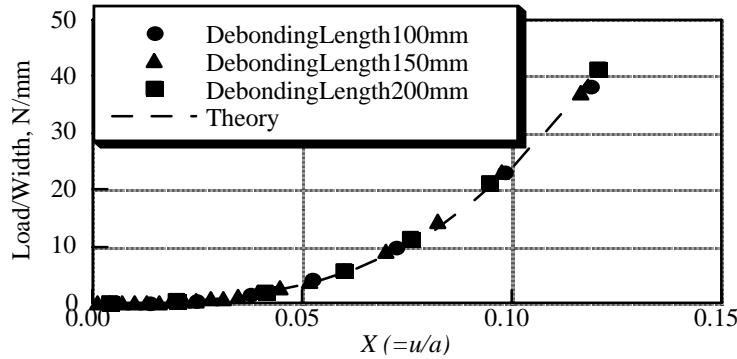


Fig. 5: The relation between load,  $P$ , and  $x$  ( $=u/a$ )

Table 1: Comparison of energy release rate among three different base materials

Base materials	$G$ , $\text{kJ/m}^2$ ( $x=0.12$ )
Aluminum	1.38
Mortar	1.37
Concrete	1.41

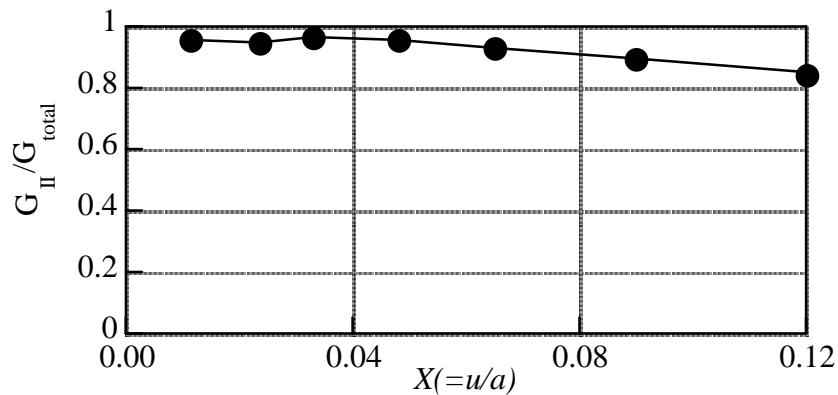


Fig. 6: The relation between the rate of mode II energy release to total that and  $X$

## EXPERIMENT

### MATERIALS

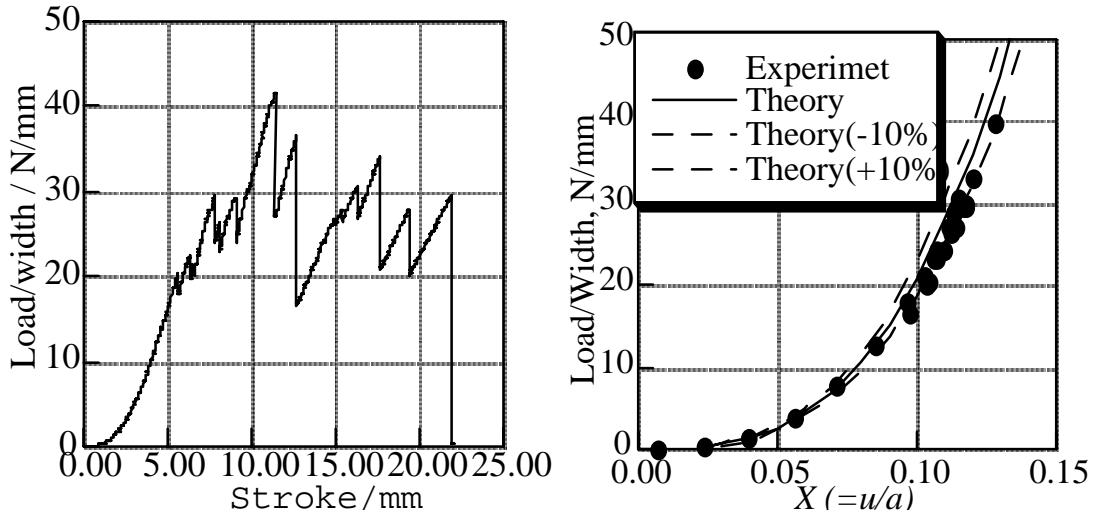
The composite used in this study was made of high tensile carbon fiber which is FTS-C1-20 of Tonen Corp., and epoxy resin which is FR-E3P of Tonen Corp. A unidirectional laminate (500mm x 500mm), consisting of a layer, is made by hand-lay-up method. After curing, the sheets were cut into strips of suitable size.

### EXPERIMENTAL VERIFICATION OF DATA REDUCTION

Aluminum was used as base material. A CF/epoxy sheet was laid on base material by using hand-lay-up method, 20mm in width, 0.75mm in thickness, and 500mm in length. The initial debonding length was  $a_0=50\text{mm}$ .

The cross-head speed was set to 0.5mm/min with continuous recording of a load-deflection curve. The angles between FRP sheet and upper surface of base material at both ends were measured with deflect meters, which are set at a certain distance away from the rod.

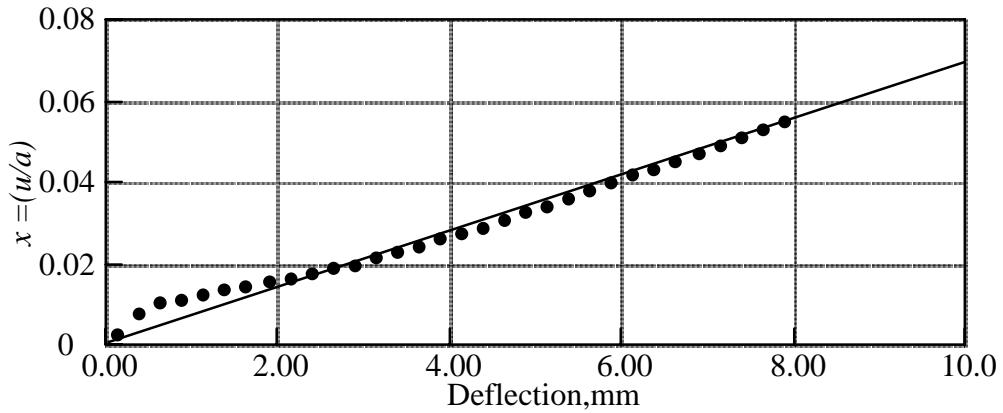
In the experiment where the difference between energy release rates were compared based on MP method and Area method, the out-of-plane load is applied to FRP sheet with loading rod and the load was unloaded after some degree of crack extension. Mortar was used as base material and initial debonding length was 100mm in this experiment.



*Fig. 7: The relations between Load per width and stroke and between it and  $x$  ( $=u/a$ )*

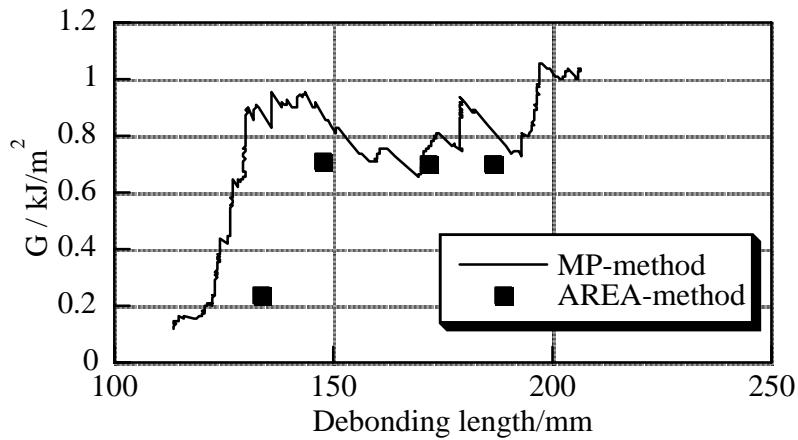
It is shown that the loading per width is a function of  $x$  ( $=u/a$ ), and that the relation between load,  $P$ , and  $x$  ( $=u/a$ ) is independent of the initial debonding length even if debonding length extended as shown in Fig. 7. These curves locate within the range of possible fluctuation of the elastic modulus of FRP sheet prepared by hand-lay-up method based on the MP theory. It is also noted that load per width is a function of  $x$  ( $=u/a$ ). It may be concluded that the "MP Method" is applicable during the extension of debonding.

The relation between  $x$  ( $=u/a$ ) and deflection,  $u$ , should be linear based on the "MP Method". Although it is not linear in the range of  $x < 0.02$ , as shown in Fig. 8, apparently a linear relation goes through the origin in the range of  $x > 0.04$ .



*Fig. 8: The relation between deflection and  $x$  ( $=u/a$ )*

The relations between debonding length,  $a$ , and energy release rates based on MP method and Area method are shown in Fig. 9. It is proved that there is little difference between energy release rate based on MP method and that based on Area method in Fig. 9.



*Fig. 9: The relations between debonding length,  $a$ , and energy release rate based on MP method and Area method*

## EFFECTS OF DIFFERENT SURFACE TREATMENTS AND DIFFERENT BASE MATERIALS

The proposed data reduction method was applied to investigate the effects of different surface treatments and primer on peeling strength of FRP sheets bonded on concrete.

Base material was concrete. CF/epoxy sheets were laid on concrete in a similar way to the actual spot process. The FRP sheet was 75mm in width, 0.75mm in thickness, and 500mm in length. The initial debonding length was  $a_0=30\text{mm}$ . In this study, three kinds of concrete surface were used: the first was no sanding, the second was treated with disk sander of GP size #20, the third with that of GP size #100. And the treated surface was given with and without the coating of primer. In total, six kinds of specimens were prepared.

The cross-head speed was set to 0.5mm/min with continuous recording of a load-deflection curve. An optical magnifier was used to observe crack growth.

These results that averaged all evaluating energy release rates of each specimen are summarized in Table 3.

It was observed that energy release rate of specimen (#0) was smaller than that of other specimens. However, there was little difference observed among specimens with and without primer.

*Table 2: Comparison among energy release rates based on different surface treatment*

Surface treatment	Energy release rate , KJ/m <sup>2</sup>	
	No-primer	Primer
No-sanding	0.590	0.525
#20	0.635	0.780
#100	0.880	0.835

This method was also applied to investigate the effects of three different base materials: aluminum, mortar and concrete. CF/epoxy sheets were made by hand-lay-up method, 500mm x 500mm in area, and 0.75mm in thickness. Each surface was treated with disk sander of GP size #20, and primer was not used. After curing, the sheets were cut into strips of suitable size and were laid on base materials.

The average energy release rates, in the range that debonding length was from 130mm to 170mm, were compared among different base materials, as shown in Table 3. It is shown that the difference of energy release rates between mortar and concrete was rather little, while energy release rate of aluminum was twice as much as the others.

*Table 3: Comparison among energy release rates based on different base materials*

Base Materials	Energy release rate, KJ/m <sup>2</sup>
Aluminum	1.49
Mortar	0.89
Concrete	0.76

This is mainly because FRP sheet peeled off due to interfacial failure between FRP sheets and adhesive and due to cohesive failure of FRP sheet, in the case of aluminum base material. In the case of mortar and concrete base materials, on the other hand the peeling occurred due to interfacial failure between base material and adhesive and to cohesive failure of base materials.

## CONCLUSIONS

A new test method was proposed to evaluate the peeling strength of FRP sheets bonded on mortar and concrete from the viewpoint of fracture mechanics. A simple data reduction method was formulated to characterize the energy release rate due to peeling based on the assumption that FRP sheets are linear elastic and thin membranes. It was shown that the proposed "MP Method" gives a reasonable data reduction for energy release rate, much simpler than "Area Method". The applicability and the limitation of the proposed data reduction were examined by the experiments and the FEM analysis. The effects of different surface treatments of concrete and different base materials on the peeling strength of FRP were successfully evaluated based on proposed data reduction.

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