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Characterization of debonding energy release rate of FRP sheets bonded on mortar and concrete

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Abstract—A new peeling test of FRP sheets bonded on mortar and concrete was proposed to characterize the peeling strength and examine the effects of different surface treatment and primer. A simple data reduction method was proposed for the energy release rate due to peeling from the viewpoint of fracture mechanics and theory of thin membrane. The effect of surface treatment and primer was compared by energy release rate, initiation load, and maximum load. Observing energy release rate and initiation load, it was shown that there were some differences between non-primer and primer, and observing maximum load, it was shown that there were some differences among different surface treatments.

Keywords: FRP sheets; peeling; concrete; energy release rate; surface treatment.

1. INTRODUCTION

Much attention has recently been paid to rehabilitation such as repair and preservation of infrastructure with the use of fiber reinforced plastic (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], show-

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ing 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 as shown in Fig. 1. The bonding strength is generally evaluated based on the average strength by the test methods as shown in Fig. 1a, b, and c [5–7]. These methods 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 as shown in Fig. 1d and e [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 and examine the effects of different surface treatment and primer. In this test method, it was shown that load is a function of deflection-to-debonding-length ratio from the geometrical consideration and equilibrium condition of thin elastic membrane, so that the energy release rate due to peeling is also expressed as a function of deflection-to-debonding-length ratio by a simple formula. This formula gives the basis for a simple data reduction method for the critical energy release rate. The bonding of carbon fiber (CF) sheets to concrete was performed in a similar way as the actual spot process, where an epoxy resin is applied as matrix and also as primer for good

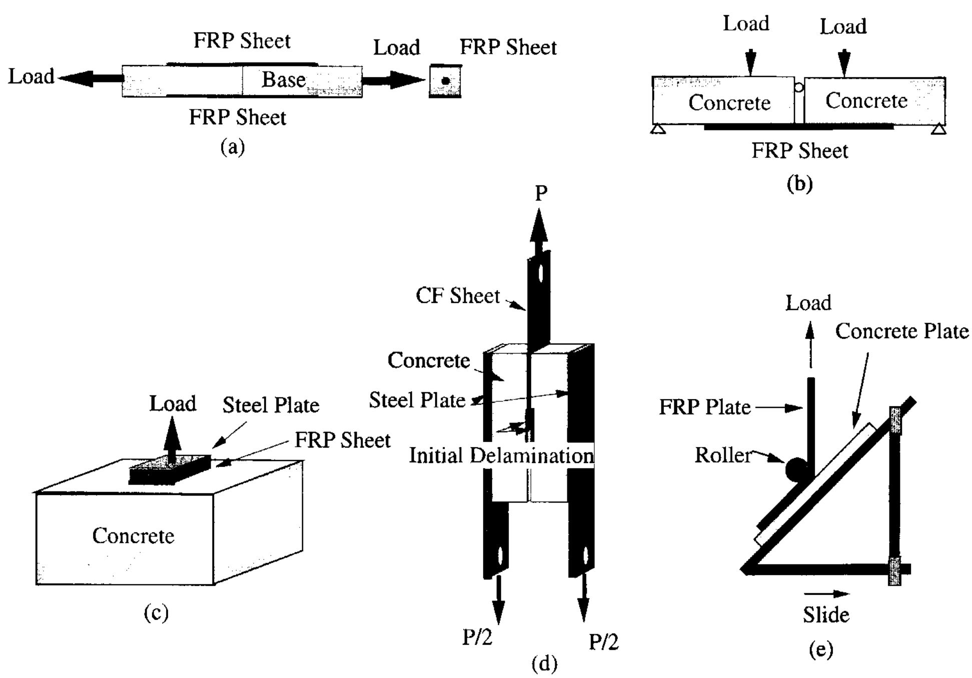

Figure 1. Existing test methods to evaluate bonding strength.

bonding characteristics before the lay-up of CF sheets. The concrete surface was treated with two different disk sanders in comparison with no treatment. The treated surface was given with and without the coating of primer. The effect of surface treatment and primer was compared by the energy release rate.

2. PROPOSAL OF MEMBRANE PEELING TEST

Consider a test specimen and a testing method as shown in Fig. 2, 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. 2. The resulting nonlinear load–deflection curves due to the extension of debonding are schematically shown in Fig. 3. 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 an useful simple data reduction as discribed later. Hence this method is hereafter referred to as the 'Membrane Peeling (MP) Test'.

3. DATA REDUCTIONS

Because a load–deflection curve in this test method is not linear, the conventional 'Compliance Method' is not appropriate for evaluation of the energy release rate. Two methods of data reduction are proposed for evaluating the energy release rate. The first is referred to as the 'Area Method' and the second is referred to as the 'Membrane Peeling (MP) Method'.

3.1. Area method

The energy release rate can be evaluated based on the area encircled by the load–deflection curve, dissipated energy, ΔA, divided by the area of crack exten-

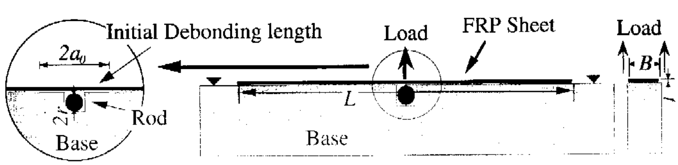

Figure 2. Specimen and testing method 'Membrane Peeling Test'.

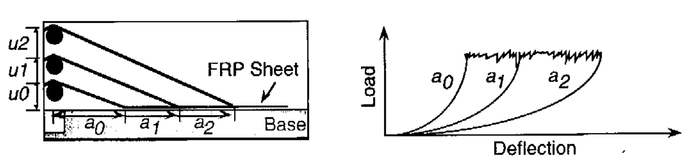

Figure 3. Schematical load–deflection curves due to extension of debonding.

sion, $B\Delta a$:

$$G = \frac{\Delta A}{2B \cdot \Delta a}. \tag{1}$$

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

3.2. 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. 4.

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

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

where $x = u/a$.

Integration of equation (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. Differentiation of the strain energy with respect to a, under the condition that sheet deflection, u, is constant, gives:

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

From equation (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 a critical energy release rate to be calculated from extentional rigidity and deflection-to-debonding-length-ratio. When bonding strength is evaluated based on energy release rate in this data reduction, mesurement 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 extention can be obtained.

In addition, energy release rate needs to be corrected if the debonding length is not equal on right and left. If the average debonding length between right and left

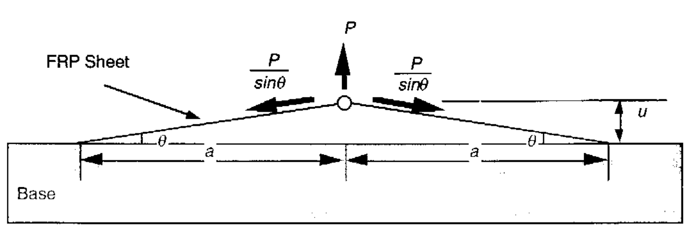

Figure 4. Equilibrium of forces between sheet and rod under a given deflection, u.

debonding length is a and the difference between average debonding length and each debonding length is s, as shown in Fig. 5, the relation between deflection of the sheet, u, and load, P, can be expressed by:

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

where $\alpha = s/a$.

Integration of equation (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:

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

Equation (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, θ_1, θ_2, and deflection of rod, u, are measured.

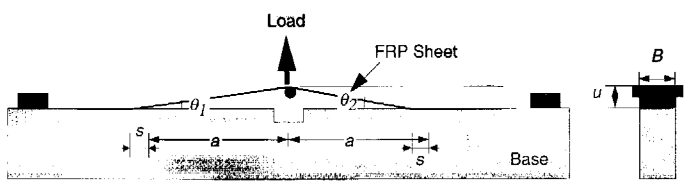

Figure 5. Debonding of FRP sheet with unequal debonding length on right and left.

4. EXPERIMENTAL

4.1. Materials

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

4.2. Experimental verification of data reduction

Aluminum was used as base material. A CF/epoxy sheet was laid on the base material by using the hand-lay-up method, 20 mm in width, 0.75 mm in thickness, and 600 mm in length. The initial debonding length was $a_0 = 100$ mm.

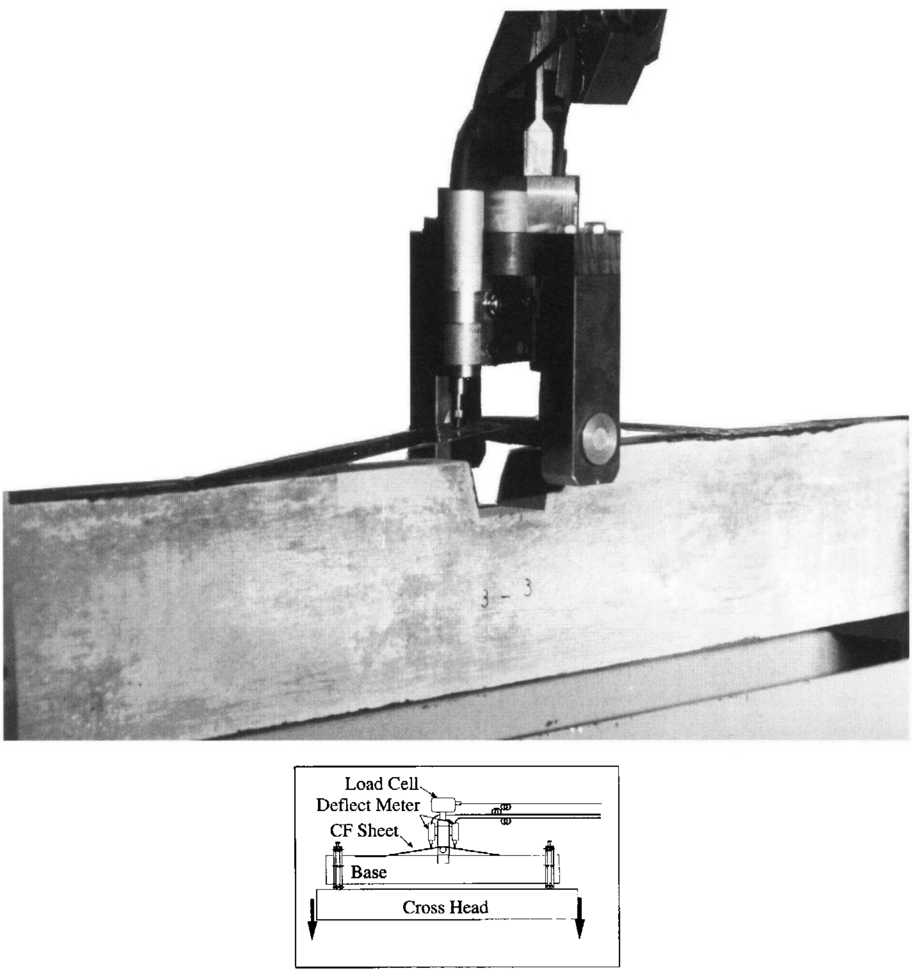

Figure 6. Experimental set-up for 'Membrane Peeling Test'.

The test method is shown in Fig. 6. The cross-head speed was set to 0.5 mm/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 were set at a certain distance away from the rod.

The relation between load, P, and x $(= u/a)$ before the initial debonding length extended is shown in Fig. 7. Three cases of measured P–x-curves are apparently independent of the initial debonding length. 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 $(= u/a)$.

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 $x > 0.04$.

It is shown that the loading per width is a function of x $(= u/a)$, and the relation between load, P, and x $(= u/a)$ is independent of the initial debonding length even if it extended as shown in Figs 9 and 10. It may be concluded that the 'MP Method' is applicable during the extension of debonding.

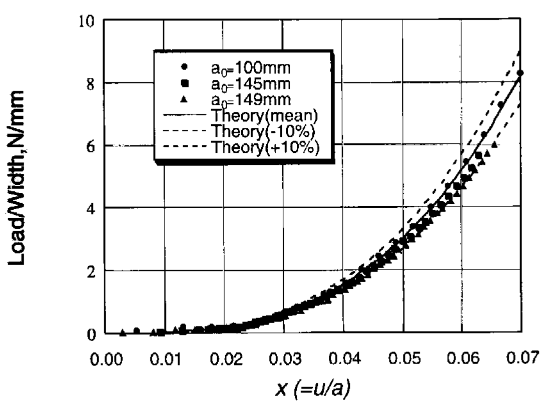

Figure 7. Relation between x $(= u/a)$ and load per width for three kinds of initial debonding length.

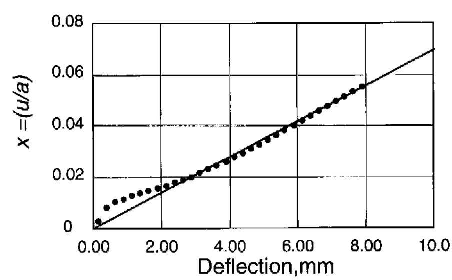

Figure 8. Relation between x $(= u/a)$ and deflection.

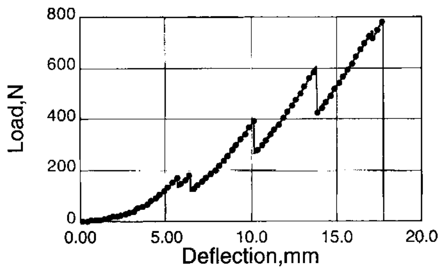

Figure 9. Load–deflection curve when debonding length extended.

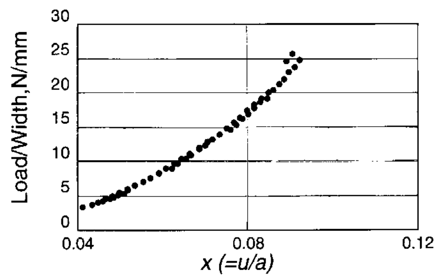

Figure 10. Relation between x $(= u/a)$ and load per width when debonding length extended.

5. EFFECTS OF DIFFERENT SURFACE TREATMENTS

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. The energy release rates were comparatively evaluated based on the 'Area Method' and the 'MP Method'.

The base material was concrete. CF/epoxy sheets were laid on concrete in a similar way to the actual spot process. The FRP sheet was 75 mm in width, 0.75 mm in thickness, and 500 mm in length. The initial debonding length was $a_0 = 30$ mm. In this study, three kinds of concrete surface were used: the first was with no treatment (indicated by #0), the second was treated with the 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 0.5 mm/min with continuous recording of a load–deflection curve. An optical magnifier was used to observe crack growth. The load was applied through a rod, until the debonding extended to a certain amount. Then the load was removed and applied again, repeating the process several times.

A typical load–deflection curve (#100-Non-Primer) is shown in Fig. 11, where the energy release rate was calculated based on the 'Area Method'. The points shown by open circles in Fig. 11 correspond to the energy release rate based on the 'MP Method'. The results that averaged all evaluating energy release rates of each specimen are summarized in Table 1.

It is shown that G^{AREA} is nearly as large as G^{MP} respectively in all types of specimens. It was observed that G^{MP} of specimen #0 was smaller than that of other

Table 1.
Comparisons between energy release rates based on the 'Area Method' and on the 'MP Method'

Specimen	G^{MP} (kJ/m^2)	G^{AREA} (kJ/m^2)	Specimen	G^{MP} (kJ/m^2)	G^{AREA} (kJ/m^2)
#0-Non-primer	0.590	0.651	#0-Primer	0.525	0.619
#20-Non-primer	0.635	0.749	#20-Primer	0.780	0.893
#100-Non-primer	0.880	0.918	#100-Primer	0.835	0.716

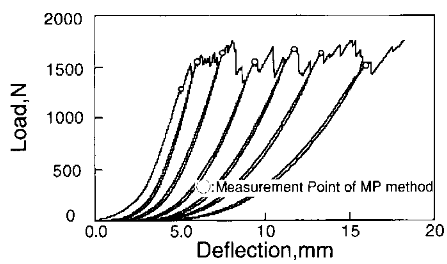

Figure 11. Load–deflection curves due to repeated loading and unloading.

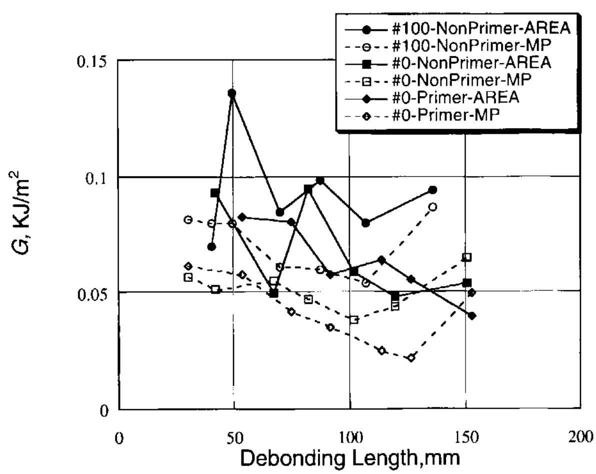

Figure 12. Comparison between energy release rates based on the 'Area Method' and on the 'MP Method'.

specimens. However, there was little difference observed among specimens with and without primer.

Relations between debonding length and critical energy release rate are compared between the 'Area Method' and the 'MP Method', as shown in Fig. 12. The three kinds of solid marks are based on the 'Area Method' and the other three kinds of open marks are those for the 'MP Method'. It is shown that the data scatter appears to be larger in the critical energy release rate based on the 'Area Method' than that based on the 'MP Method' which might be expected since evaluating enery release rate based on the 'Area Method' corresponds to an average of energy release rate during crack extension, while that based on the 'MP Method' corresponds to energy release rate at the start of crack extension.

6. 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 the 'Area Method'. The applicability and the limitation of the proposed data reduction were examined by the experiments. The different effects of surface treatments of concrete on the peeling strength of FRP sheets were successfully evaluated based on proposed data reduction.

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