Evaluation of Adhesive Strength of Resin Liner Film*

Kenji SEO**, Masahiro KUSAKA**,
Fumio NOGATA** and Yoshiki URAKAMI***

In this study, a new method for evaluating the adhesive strength of the interface between resin liner film and cement mortar has been developed. The peel test for vinyl ester resin liner films on cement mortar surfaces was carried out. The critical energy release rate (G_c value) was obtained from the peel load and crack length measured during the peel test. G_c values were not affected by the crack length or the thickness of resin liner film. Therefore it was established that G_c values could be used to evaluate the adhesive strength of resin liner film. Furthermore, the effect of primer coats on the adhesive strength of resin liner film was revealed by obtaining the G_c values.

Key Words: Fracture Mechanics, Composite Material, Finite Element Method, Adhesive Joints, Peel Test, Adhesive Strength, Energy Release Rate, Resin Liner Film

1. Introduction

Application of vinyl ester resin liner films onto concrete surfaces is increasing in popularity as a means of protecting concrete constructions from corrosion in drainage facilities. However, the peeling of resin liner films from concrete surfaces is a problem⁽¹⁾ due to their insufficient adhesive strength. The conventional tensile test (Ken-Ken method) (JIS A 6910) has been used to evaluate the adhesive strength of resin liner films. However, since the concrete material itself is broken except in the case that the adhesive strength of resin liner films is extremely weak, the adhesive strength cannot be evaluated correctly. Furthermore, peeling of resin liner films in practical lining work is reported⁽²⁾ even in the case that the

adhesive strength is evaluated to be more than the fracture strength of concrete material using the Ken-Ken method, which indicates that the adhesive strength of resin liner films cannot be evaluated accurately.

Therefore the evaluation of adhesive strength of resin liner films has been attempted in this study by carrying out the peel test with test pieces of resin liner films on mortar in order to establish a reasonable evaluation method of the adhesive strength of resin liner films. Peel load and crack length which change with time during the peel test are measured. The critical energy release rate (G_c value) is calculated using peel load and crack length. The adhesive strength has been evaluated by these G_c values. As a result, it has been clarified that the critical energy release rate in the propagation of peeling is stable and constant, remaining unaffected by both thicknesses of resin liner films and crack length provided that the adhesive interface conditions between resin liner films and mortar remain the same. Moreover, in the case of different adhesive interface conditions between resin liner films and mortar, the adhesive strength of resin liner films cannot be evaluated by the Ken-Ken

* Received 30th March, 1995. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 60, No. 577, A (1994), pp. 1973-1978. (Received 20th December, 1993)

** Faculty of Engineering, Himeji Institute of Technology, 2167 Shosha, Himeji 671-11, Japan

*** Kakogawa Public Works Office of Hyogo Prefecture, 97-1 Tenjinboku, Teraie-cho, Kakogawa-cho, Kakogawa, Hyogo 675, Japan

method. But it has been clarified that the adhesive strength can be evaluated from the critical energy release rate.

2. Experiment

2.1 Test pieces

After sanding the surface of the mortar material of the geometry shown in Fig. 1 with sandpaper (# 60), vinyl ester resin liner films are coated. Test pieces of two different resin liner films with thicknesses (d) of 1 mm or 2 mm, with exactly the same conditions of adhesive interface between resin liner films and mortar are prepared. Furthermore, one sheet of glass fiber mat for 1 mm resin liner films and three sheets for 2 mm ones are inserted as reinforcement. As a result, the Young's moduli of resin liner films E_1 are 5.4 GPa (in the case of $d=1$ mm) and 9.2 GPa (in the case of $d=2$ mm). Moreover, before lining the mortar with resin liner films, the surface of the mortar within 5 mm from its end is covered with a sheet of masking paper to avoid drips of resin on the mortar end which may cause the inaccurate measurement of adhesive strength between resin liner films and mortar.

2.2 Experimental method

The test piece is set in the testing machine with the jig shown in Fig. 2 to maintain a distance of 20 mm from the center of the upper jig holding the resin liner film to the tip of peeling film (crack tip). The upper jig has a needle bearing installed in it to avoid generation of moment at the loading point when the resin liner film is vertically lifted and also to ensure freedom of rotation. Freedom of movement in the hori-

Fig. 1 Geometry and size of test piece

Fig. 2 Test jig

zontal direction is ensured by providing a flat bearing between the lower jig and the test piece so that only the peel load in the vertical direction can be imposed on the resin liner film. Figure 3 shows a sketch of the testing device and Fig. 4 shows a schematic diagram of the peel test. An Instron universal testing machine of maximum capacity 5 000 N is used for the test with a tensile speed of 30 mm/min. Then, both peel load P and the displacement δ at the loading point are recorded in a computer via an AD transducer. The appearance of peeling resin liner film is recorded on video tape at the same time. Then, the distance in the horizontal direction from the loading point to the peeling tip during the peel test, namely, crack length C is measured from the video screen.

2.3 Experimental results

An example of the relation between load and displacement recorded in the computer is shown in Fig. 5. During lifting of the resin liner film, the load increases nearly in proportion to the increase in displacement and finally reaches a maximum, at which the resin liner film begins to peel off and the load decreases according to the propagation of peeling. Even though the same adhesive interface conditions between mortar and resin liner film are maintained, the relation between load and displacement changes depending on resin liner film thickness d . This is because the flexural rigidity depends on resin liner film thickness. In other words, in the case of $d=2$ mm, the strong flexural rigidity increases the maximum load

Fig. 3 Sketch of testing device

Fig. 4 Schematic diagram of peel test

Fig. 5 Load-displacement curve

value and decreases the displacement to 67 mm at the time of completion of peeling ($P=0$). In contrast, in the case of $d=1$ mm, weak flexural rigidity decreases the maximum load value and increases the displacement value to 130 mm at the time of completion of peeling. From the above, it can be concluded that the peel load is not equivalent to the adhesive strength and is largely affected by the flexural rigidity of resin liner films.

3. Analysis of Energy Release Rate

The peel load during the peel test depends on the resin liner film thicknesses and cannot be used for the evaluation of adhesive strength. Therefore, the energy release rate based on fracture mechanics as a parameter to express the adhesive strength has attracted our attention. In the case that the beam theory can be applied, the following equation is given⁽³⁾ for the energy release rate in the case of peeling of the coating film on a rigid body.

$$G_{th} = 6P^2 C^2 / Ed^3 \quad (1)$$

Here,

P : Load per unit width

C : Crack length

E : Young's modulus of coating film

d : Coating film thickness

However, in the case that the crack length is comparatively short and the mortar is used as the base material, it is uncertain whether Eq. (1) can be used. Therefore, in this study, the energy release rate has been calculated using the finite element method.

3.1 Analytical method

The model shown in Fig. 6 is used for analysis and the energy release rate is calculated by the total energy method⁽⁴⁾ as the result of elastic analysis in plane stress conditions. Quadrilateral elements with four nodes are used for divisional elements and a square of 0.1 mm side length is used for the elements near the crack tip. For the analysis, after applying a

Fig. 6 Analytical model

Fig. 7 Effect of Young's modulus of base material on energy release rate

constant vertical load of $P(98 \text{ N})$ to the end of the coating film, the distance from the loading point to the crack tip (crack length) C , coating film thickness d , Young's modulus of base material E_m and Young's modulus of coating film E_1 are changed.

3.2 Results of analysis

3.2.1 Effects of Young's modulus of base material and coating film Keeping both thickness and Young's modulus of coating film at the constant values of $d=2$ mm and $E_1=8.8$ GPa, respectively, and changing Young's modulus of base material E_m by 15.0 to 2.0×10^8 GPa, the energy release rate are calculated for the cases of crack length $C=20, 50, 80$, and 100 mm. The results are shown in Fig. 7. The base material can be regarded as a rigid body since the energy release rate becomes almost constant after Young's modulus of the base material reaches more than about three times Young's modulus of the coating film. Therefore the mortar used in this study can be considered as a rigid body in comparison to the

resin liner films. Furthermore, since it is confirmed by changing Young's modulus of the coating film E_1 that the energy release rate is inversely proportional to this Young's modulus, it has been clarified that Eq. (1) can be used for the case of long crack length.

3.2.2 Effects of crack length and coating film thickness The effect of crack length on the energy release rate for the cases of coating film thickness of 1 mm or 2 mm is investigated by changing the crack length. Moreover, Young's modulus of the coating film is made $E_1=4.9$ GPa for the case of $d=1$ mm and $E_1=9.8$ GPa for the case of $d=2$ mm. The results are shown in Fig. 8. The value, G , on the vertical axis in Fig. 8 are nondimensionalized by the energy release rate G_{th} obtained using Eq. (1). The energy release rate becomes larger than the value obtained using Eq. (1) for short crack length and also for the thicker coating film. In the case that the crack length is short compared with coating film thickness, the energy release rate is affected by not only bending moment but also shearing force, and thus the energy release rate becomes larger than the value obtained using Eq. (1).

Fig. 8 Effect of crack length on energy release rate

Fig. 9 Relationship between energy release rate and crack length

3.2.3 Equation for calculation of energy release rate

The above results with the horizontal axis changed to the ratio of crack length to coating film thickness are shown in Fig. 9. The vertical axis shows $(G/G_{th}-1)$. These results indicate that the energy release rate G can be shown on a single curve regardless of coating film thicknesses. If the relation in Fig. 9 is approximated by the method of least squares (shown by a solid line in the figure), the energy release rate during the peeling of the coating film can be expressed by

$$G = \{1 + 4.56 \times (C/d)^{-1.65}\} \times G_{th}. \quad (2)$$

4. Evaluation of Adhesive Strength from Critical Energy Release Rate

The critical energy release rate G_c is calculated by substituting the peel load P and the crack length C into Eq. (2). The results are shown in Fig. 10. The values marked with $\bullet$ are the results for the resin liner film of $d=1$ mm and those marked with $\blacksquare$ are the results for $d=2$ mm.

There are large differences in the load-displacement curve depending on resin liner film thicknesses in Fig. 5. However, if the experimental results are adjusted using the critical energy release rate as shown in Fig. 10, G_c is stable and nearly constant regardless of resin liner film thickness. Furthermore, the critical energy release rate in the propagation of peeling is almost constant, though it varies slightly depending on crack length. From the above results, the critical energy release rate is not affected by resin liner film thickness or crack length, and is almost constant provided that the conditions of the adhesive interface remain the same. This indicates that the critical energy release rate is a suitable parameter for the evaluation of adhesive strength at the interface. The values of critical energy release rate G_c in Fig. 10 vary slightly. This seems to be caused by local

Fig. 10 Critical energy release rate in the propagation of peeling

differences in adhesive strength due to the local nonuniformity of adhesive interface conditions since the mortar is used as the base material in this test.

In the case of evaluating the fracture toughness of a uniform material using linear fracture mechanics, evaluation using the critical energy release rate is equivalent to evaluation using the critical stress intensity factor. However, these methods are not equivalent in the case of evaluating the adhesive strength between resin liner film and mortar as in this study. The adhesive strength in the propagation of peeling is shown by the critical stress intensity factor in Fig. 11. Since the resin liner film thickness is changed by varying the number of glass fiber mats, Young's modulus of the resin liner film varies with thickness. Therefore, the critical stress intensity factor varies depending on the resin liner film thickness as shown in Fig. 11. In otherword, even if the adhesive interface conditions between resin liner film and mortar are exactly the same, the adhesive strength using the critical stress intensity factor varies. Therefore, it is clear that the evaluation of adhesive strength using the critical energy release rate is more reasonable.

5. Evaluation of Adhesive Strength When the Adhesive Interface Conditions are Different

Whether the above method can be applied to the evaluation of adhesive strength of practical resin liner film has been investigated. Test pieces with various adhesive interface conditions between mortar and resin liner film are used.

5.1 Experimental method

Various types of primer coats are used to increase the adhesive strength between resin liner films and mortar in practical lining work. Therefore, test pieces lined with various types of primer coats as shown in Table 1 between the mortar and resin liner film as shown in Fig. 12 are prepared for the experi-

Fig. 11 Critical stress intensity factor in the propagation of peeling

ment. Three types of epoxy primer coat for different amounts of toluene are used. The lining method is exactly the same as stated above and all the resin liner film thicknesses are 2 mm. The peel test is carried out using the method described above. Moreover, the widely used conventional Ken-Ken method is employed in accordance with JIS A 6910 for comparison.

5.2 Experimental results

The maximum peel load (per unit width of resin liner film) obtained in the peel test and the adhesive strength measured by the Ken-Ken method are shown in Table 2. Fracture always occurs on the mortar side in the Ken-Ken method and all the values are about the same, corresponding to the fracture strength of mortar material. On the other hand, for the maximum peel load obtained in the peel test, the values in both cases of using vinyl ester and urethane as primer coats are approximately equal and those in the case of epoxy are the highest. Furthermore, the value in the case without primer coat is the lowest, which confirms the effectiveness of primer coats in increasing adhesive strength at the interface. Moreover, as stated

Table 1 Primer coats and their surface tension values

Sample No.	Primer	Surface tension (N/m)
α	Vinyl ester	3.02×10^{-2}
β	Urethane	2.70×10^{-2}
γ -30	Epoxy (toluene 30%)	4.31×10^{-2}
γ -60	Epoxy (toluene 60%)	3.53×10^{-2}
γ -80	Epoxy (toluene 80%)	3.21×10^{-2}
δ	No primer coat	—

Fig. 12 Structure of test piece

Table 2 Maximum peel load for each test piece

Sample No.	Primer	Bonding Strength by Ken-Ken Test (MN/m ²)	Maximum peel load (N/m)
α	Vinyl ester	1.89	1647
β	Urethane	1.93	1652
γ -30	Epoxy (toluene 30%)	2.12	1975
γ -60	Epoxy (toluene 60%)	2.00	1982
γ -80	Epoxy (toluene 80%)	2.01	1829
δ	No primer coat	2.13	1213

Fig. 13 Critical energy release rates in the propagation of peeling for epoxy primer coat and vinyl ester primer coat

before, the maximum peel load is significantly affected by both resin liner thickness and loading location, and therefore the values obtained in the test can only be compared for test pieces of the same shape. Therefore, the evaluation of adhesive strength is carried out using the critical energy release rate by the method described in this paper.

5.3 Evaluation of adhesive strength for various types of primer coats

An example of the relation between crack length and the critical energy release rate in the propagation of peeling is shown in Fig. 13. Solid lines in this figure show the results for test pieces with epoxy used as primer coats and broken lines show those for vinyl ester. Since three test pieces are prepared for each type of primer coat, each of them is identified by $\square$, $\triangle$, or $\circ$. In the case of test pieces with vinyl ester primer coat, the values of critical energy release rate, G_c , in the propagation of peeling are small. There are no significant difference in the values of G_c among test pieces, which shows that the adhesive strength at the interface is stable. On the other hand, in the case of epoxy primer coats, the values of critical energy release rates are higher than those for vinyl ester primer coat and there is a large difference in the

Fig. 14 Critical energy release rates for various types of primer coat

values of G_c among test pieces, which shows that wide scattering of adhesive strength can be seen. The values of critical energy release rate of various types of primer coats are shown in Fig. 14. The values of critical energy release rate on the vertical axis show the average of all critical energy release rates obtained in the propagation of peeling. From the above results, it can clearly be seen that the weakest test piece is that without primer coat and that the adhesive strength largely depends on the type of primer coats. Furthermore, in the evaluation with the maximum peel load as shown in Table 2, the adhesive strength is only valid for the initiation of peeling, but using the critical energy release rate, the adhesive strength can be evaluated from the information for the whole adhesive interface and the value obtained has the same dimensions as the value of fracture toughness and thus has the advantage that it can immediately be used for design.

Photographs of the peeling surface of resin liner film for various test pieces are shown in Fig. 15. In the test piece without primer coats which shows the lowest critical energy release rate, only the top surfaces of mortar with weak adhesive strength slightly adhere to the resin liner film. On the other hand, in the case that urethane or vinyl ester is used as primer coat, the mortar surface is strengthened by the primer coat and a slight trace of mortar adheres to the peeled resin liner film. Therefore, the adhesive strength seems to increase slightly compared with the case without primer coats. In contrast, in the case of epoxy primer coats, the adhesive strength appears considerably high, judging from the fact that grains of sand adhere thickly to the peeled resin liner film and cracks which seem to be caused by bending can be seen in the resin liner film. From the above observation of peeling surfaces in the peeled resin liner films,

Fig. 15 Peeling surface of resin liner film for each test piece

it can also be concluded that the differences in adhesive strength shown in Fig. 14 due to the different types of primer coats are reasonable.

Furthermore, from the above results, epoxy seems to be the best primer coat but since its adhesive strength varies considerably depending on the amount of toluene contained, with a wide scatter as shown in Fig. 13. It has some problems from the view point of its reliability such as change in adhesion with time and different service environment. We will continue to study the effects of change with time and different service environment on adhesive strength by the method described above in order to select optimal primer coats.

6. Conclusions

The peel test of resin liner films has been carried out with test pieces prepared by coating resin liner films on mortar. The method of evaluating adhesive strength of resin liner films from the critical energy release rate has been proposed based on the results of the measurement of both peel load and crack length in the propagation of peeling. It has been clarified that the adhesive strength can be reasonably well evaluated by this method. The main results obtained are the following.

(1) In the case that the base material surface is coated with resin liner film, if Young's modulus of the base material is more than about three times that of the resin liner film, the base material can be considered as a rigid body and an approximate equation can be utilized to easily calculate the energy release rate

using only the Young's modulus and thickness of resin liner film and crack length.

(2) By substituting both peel load and crack length obtained during the peel test in the approximate equation, the critical energy release rate in the propagation of peeling is calculated. As a result, provided that the adhesive interface conditions remain the same, critical energy release rate in the propagation of peeling is constant and unaffected by the resin liner film thickness. Therefore, the adhesive strength of resin liner film can be evaluated using the critical energy release rate.

(3) The adhesive strength has been evaluated using test pieces with different adhesive interface conditions prepared by employing various types of primer coats between mortar and resin liner film. As a result, the effect of primer coats on the adhesive strength can be clarified not by the conventional tensile test (Ken-Ken method) but by using the information for the whole adhesive interface according to the method described in this study.

Acknowledgements

This study was financially supported in part by a Grant-in-Aid for Scientific Research from the Japanese Ministry of Education, Science and Culture, and a Grant-in-Aid from the Kawanishi Commemoration Shin-meijiwa Educational Foundation. The test pieces were supplied by Mr. Toshitaka Nakao of Takiron Engineering Co., Ltd. and Mr. Tsuyoshi Maeda of Showa Highpolymer Ltd. We express our sincere appreciation to all the above.

References

- (1) Urakami, Y. and Yamaoka, A., A Selection of Corrosion Resistant Lining Material for Concrete, J. Jpn. Sewage Works Assoc., (in Japanese), Vol. 28, No. 323 (1991), p. 71.
- (2) Urakami, Y., Nakao, T., Takashima, S. and Ishii, K., Study on the Adhesion Strength of Resin Lined to Concrete, J. Soc. Mater. Sci. Jpn., (in Japanese), Vol. 40, No. 452 (1991), p. 625.
- (3) Malyshev, B. M. and Salganik, R.L., The Strength of Adhesive Joints Using the Theory of Cracks, Int. J. Fract. Mech., Vol. 1 (1965), p. 114.
- (4) Shiratori, M., Miyoshi, T. and Matsushita, H., Numerical Fracture Mechanics, (in Japanese), (1980), p. 62., Jikkyou Shuppan.