Available online at www.sciencedirect.com

SCIENCE DIRECT®

Composites Science and Technology 64 (2004) 2557–2564

COMPOSITES SCIENCE AND TECHNOLOGY

www.elsevier.com/locate/compscitech

Experimental study on RC beams with FRP strips bonded with rubber modified resins

Bo Gao [a], Jang-Kyo Kim [a,*], Christopher K.Y. Leung [b]

[a] *Department of Mechanical Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong*
[b] *Department of Civil Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong*

Received 10 February 2003; received in revised form 17 May 2004; accepted 30 May 2004
Available online 31 July 2004

Abstract

This paper presents the effects of adhesive properties on structural performance of reinforced concrete (RC) beams strengthened with carbon fiber reinforced plastic (CFRP) strips. The epoxy adhesives modified with liquid rubber of different content were used to bond the CFRP strips, and four point bending experiments were carried out on RC beams. The experimental results show that different CFRP strip thickness of 0.22 and 0.44 mm resulted in a transition of failure mechanism from interfacial debonding along the CFRP-concrete interface to concrete cover separation starting from the end of CFRP strips in the concrete. Moreover, it is suggested that no matter interfacial debonding or concrete cover separation, the rubber modifier enhanced the structural performance by increasing the maximum load-carrying capacity and the corresponding ductility, compared with the beams bonded with a neat epoxy resin. The improvement of structural performance due to modified adhesive was associated with the modification of stress profiles along the CFRP-concrete interface especially the stress concentration at the end of FRP, and the enhanced interlaminar fracture toughness. Rubber modified epoxy therefore is worth further studying in practical repair applications.

Keywords: A. Fibres; A. Adhesive joints; C. Failure criterion; C. Stress concentrations

1. Introduction

The number of civil engineering structures in the world continues to increase, as does their average age. The need for increased maintenance is inevitable. Complete replacement is likely to become an increasing financial burden and is certainly a waste of natural resources if upgrading is a viable alternative. Therefore, strengthening and rehabilitation of these structures are considered to be the most practical method. As a result, the infrastructure repair and rehabilitation represent a significant challenge facing the concrete industry. Upgrading structural load capacity is a substantial part of the rehabilitation market, and seismic retrofit of concrete components in earthquake regions is now becoming a mainstream. As a combined result of structural rehabilitation needs, strengthening and rehabilitation of concrete construction have become the industry's major growth area. Amongst various methods developed for strengthening and rehabilitation of reinforced concrete (RC) beam structures, external bonding of fiber reinforced plastic (FRP) strips to the beam has been widely accepted as an effective and convenient method. This method is economical due to easy and reliable surface preparation as well as reduced maintenance of strengthening system and mechanical fixing [1–4].

Typical failure modes of FRP strengthened RC beams can be grouped into seven categories. They are (a) flexural failure by FRP rupture, (b) flexural failure

* Corresponding author. Tel.: +852-2358-7207; fax: +852-2358-1543.
E-mail address: mejkkim@ust.hk (J.K. Kim).

0266-3538/$ - see front matter
doi:10.1016/j.compscitech.2004.05.016

by crushing of compressive concrete, (c) shear failure, (d) concrete cover separation, (e) plate end interfacial debonding, (f) interfacial debonding induced by intermediate flexural crack and (g) interfacial debonding induced by intermediate flexural shear cracks [5]. Concrete cover separation and various types of interfacial debonding are premature failure modes, which prevent the full utilization of the tensile strength of the FRP plate. It is widely accepted that these premature failure modes are caused by the stress concentrations at the FRP strip ends or the bottom of flexural/flexural shear cracks in the concrete beam [6–10]. Therefore, in order to understand these failures and develop accurate strength model, extensive analytical studies have been performed on the prediction of the stress distribution along the interface and the stress concentration at the edge of laminate or flexural crack tip. Smith and Teng [11–13] have given some comprehensive reviews on existing solutions for predicting interfacial stresses. Based on different approaches such as a staged analysis or direct consideration of deformation compatibility, various models have been formulated [14–22]. Moreover, Shen et al. [23] presented a better theoretical interfacial stress analysis including the consideration of the non-uniform stress distributions in and satisfaction of the stress boundary conditions at the end of adhesive layer. A new approach using the fracture mechanics concepts was carried out in the model by Rabinovitch and Frostig [24]. Also, the interfacial stress distributions along the interface have also been studied by numerical methods, such as finite element analysis [18,25–29]. A finite element model was presented [9] with particular emphasis on stress singularities and appropriate finite element meshes to determine accurate interfacial stresses. Parametric studies [9] were also made of the effect of adhesive and FRP material as well as the effect of a spew fillet that may be formed from squeezed-out adhesive on interfacial stresses. Of special interest is that crack propagation in strengthened RC beam could be simulated based on a discrete crack model [30].

The efficiency of RC beam strengthening with FRP strips depends on proper bonding between the concrete and the strips with an epoxy or vinylester adhesive. The adhesive plays an important role for connecting FRP and concrete. Particularly for interfacial debonding and concrete cover separation, the mechanisms relate to the adhesive mechanical properties and interlaminar fracture toughness. Therefore, there is a need to improve ductility and toughness of adhesive. In our previous study [31], high interlaminar fracture toughness and high crack growth stability were successfully achieved between the carbon fibre reinforced plastic (CFRP) strip and concrete beam by adding a reactive liquid rubber consisting of functional polybutadiene/acrylonitrile rubber into the epoxy and vinylester resins. Experimental results based on the asymmetric double cantilever beam test showed the critical energy release rate of the specimens with 10% and 20% rubber contents in adhesive increased by 6.2% and 12.8%, respectively, compared to those without rubber.

This paper is the continuation of our previous study [31] on modified epoxy adhesives, and employed RC beams with bonded CFRP plates that are prepared with epoxy adhesives containing different contents of rubber modifier. The effects of modified epoxy adhesive on load-carrying capacity, ductility, stiffness and failure mode of the RC members loaded in four point bending test were specifically evaluated. Also, the influences of modified epoxy adhesive on interlaminar stress distributions were simply presented by finite element analysis.

2. Experiments

2.1. Materials

The RC beams were fabricated using concrete, steel rebars, CFRP composite prepregs and epoxy adhesive, whose properties are summarized in Table 1. The concrete was a mixture of water, cement, sand and aggregate in the ratio 0.68:1:2:3 by mass. The concrete was cured for 28 days before removal from the curing room. Testing of the beams took place about 50 days after casting. The compressive strength of concrete was measured using a series of cylindrical specimens of 100 mm in diameter and 200 mm in height. The stirrups and the compressive longitudinal steel rebars were made of mild steel 8 mm in diameter. The tensile longitudinal rebars were made of hot rolled, high yield steel 10 mm in diameter. The CFRP strips were prepared using unidirectional, 0.11 mm thick prepregs (MRL-T7-200 supplied by Reno Carbon Fibre). An epoxy adhesive was used to bond the CFRP strip, which consisted of MRL-B2 curing agent, MRL-A2 primer and MRL-A3 resin. A mixture of

Table 1
Properties of materials

Materials	Young's modulus (GPa)	Yield strength (MPa)	Compressive strength (MPa)	Poisson's ratio
Concrete	25	–	35.7	0.2
Steel	200	531	–	0.3
CFRP plate	235	4200	–	0.35
Epoxy resin	1.0	30	–	0.35

Table 2
Tensile and interlaminar properties of epoxy adhesive with and without rubber modifier

Epoxy	Tensile strength (MPa)	Tensile modulus (MPa)	Interlaminar fracture toughness (kJ/m^2)
Control	29.8	992	0.211
10% rubber	25.8	713	0.224
20% rubber	21.7	443	0.238

MRL-A2 and MRL-B2 in the ratio of 100:35 by mass was applied to concrete surface as the primer to enhance the bonding of CFRP strip. The cured resin was a mixture of MRL-A3 and MRL-B2 in the ratio of 100:35 by mass.

The epoxy resin was modified using a low-viscous (500,000 cp) reactive liquid rubber (Goodrich carboxyl terminated butadiene acrylonitrile copolymer (CTBN) 1300×13) that contained 26% of acrylonitrile and 32% of carboxyl. Different modifier contents of 0%, 10% and 20% were added into the epoxy adhesive. The tensile properties of the control and modified adhesive were measured using dog-bone shaped specimens, and are presented in Table 2. Also, the interlaminar fracture properties of CFRP-concrete interfaces determined in our previous study are included in Table 2 [31].

2.2. Four point bending test of RC beams

Eight beams were fabricated for the four point bending test, and the details of CFRP strip reinforcements and rubber modifier content are summarized in Table 3. All concrete beams had the same overall cross-sectional dimensions, internal longitudinal reinforcement and stirrup arrangement. The specimen geometry and dimensions are presented in Fig. 1. They were 200 mm × 150 mm in cross-section, 2000 mm in length and 25 mm in concrete cover depth. The beams were reinforced with steel rebars (10 mm in diameter) on the tension side and steel rebars (8 mm in diameter) on the compression side. Eight millimetre stirrups were included at the 75 mm centre-to-centre space. The steel reinforcement ratio was about 0.86%. All the beams were overdesigned in shear to avoid conventional shear failure.

Table 3
Specimen designation

Beam designation	Thickness of CFRP (mm)	Thickness of adhesive (mm)	Rubber content (% in resin)
CON1	0	–	–
CON2	0	–	–
A0	0.22	2	0
A10	0.22	2	10
A20	0.22	2	20
B0	0.44	2	0
B10	0.44	2	10
B20	0.44	2	20

Before bonding the FRP strips, the soffit surface of the beams was roughened using a jet chisel to remove all laitance and to expose the aggregates. The rough surface was then cleaned with water and compressed air. A primer, consisting of primer (A2), hardener (B2) and liquid rubber modifier, was used to cover the roughened surface. The CFRP sheets were bonded to the surface with the adhesive consisting of a mixture of epoxy (A3), hardener (B2) and liquid rubber. The CFRP strips were 75 mm wide and 1200 mm long with two different thicknesses, producing the CFRP reinforcement ratio of 0.055% and 0.11%.

All RC beams were tested in four point flexure under displacement control on an MTS810 universal testing machine with a maximum load capacity of 500 kN. The load–displacement data were automatically recorded through a data logger. The specimen supports consisted of a pin support and a roller support at the two ends. The outer loading span was 1500 mm and the inner loading span was 500 mm. A total of four

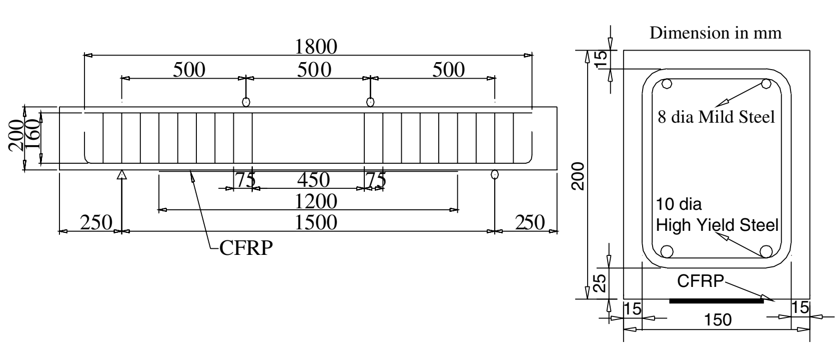

Fig. 1. Geometry and dimensions of RC beam specimen.

linear variable displacement transducers (LVDTs) were used to measure the deflection of the beam.

3. Results and discussion

The load–deflection responses for the individual specimens are plotted in Fig. 2, while the summary of ultimate failure loads are presented in Table 4. To provide some insights into the accuracy of the test results, comparisons were made of ultimate failure loads predicted based on previous analytical models [5,32], as shown in Table 4. These theoretical models considered interfacial debonding and concrete cover separation as the major failure modes, respectively, allowing the prediction of ultimate load capacities of the strengthened RC beams.

The two control beams (CON1 and CON2) showed a typically ductile flexural response. The first visible crack appeared at about 20 kN, and propagated extensively with an associated reduction in stiffness. After yielding of tensile steel reinforcement at a load of approximately 47 kN, the stiffness showed a significant drop and more flexural cracks were developed until concrete crushing occurred in the inner loading span at the top of concrete beam due to the high compressive stress. At failure, one could observe many vertical cracks at the bottom of the concrete beam.

It is obvious that with the CFRP strip reinforcements, the RC beams gave rise to systematic improvements in stiffness and strength, but lower ductility compared to the control beam. The thicker the CFRP strips, the higher the load-carrying capacity and the lower the ductility. When the CFRP strip thickness was 0.22 mm (two CFRP prepreg layers), interfacial debonding occurred rather catastrophically in an unstable manner, with a thin layer of concrete residue attached to the delaminated CFRP sheet as shown in Fig. 3 along with a schematic drawing of failure mode. In contrast, when the CFRP strip thickness was 0.44

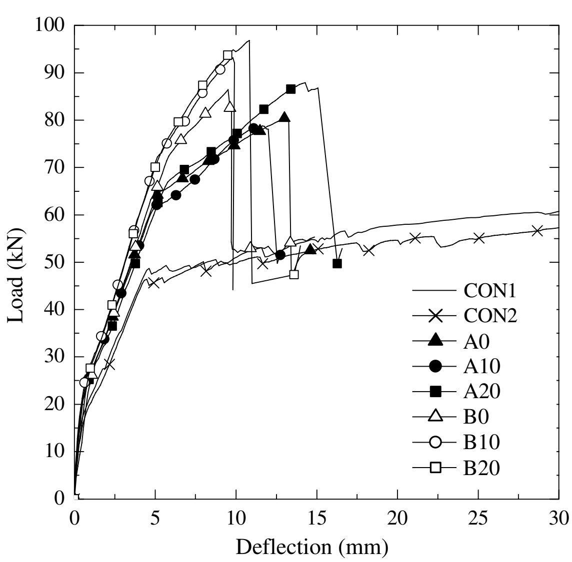

Fig. 2. Load vs. deflection response of four point bending tests.

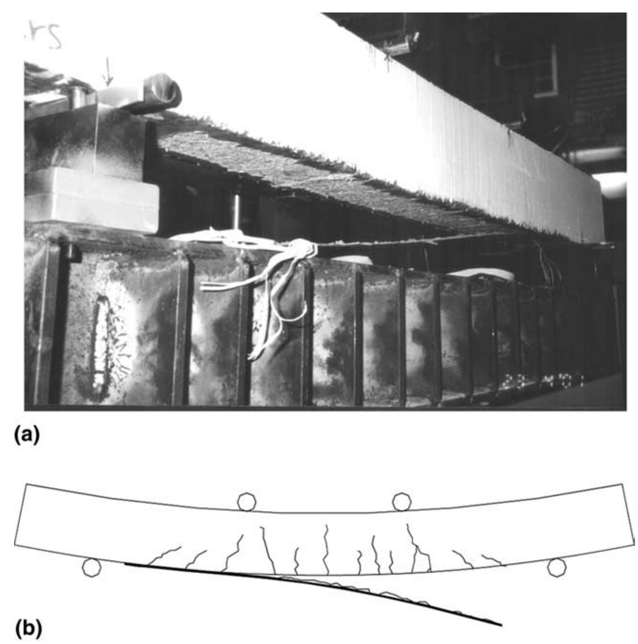

Fig. 3. (a) Interfacial debonding failure and (b) schematic drawing.

Table 4
Summary of four point bending test results

Designation	Ultimate load (kN)	Predictions of load capacity (kN)	Deflection at failure (mm)	Failure mode
CON 1	61.8	56	34.8	Flexural failure by crushing of concrete
CON 2	59.1	56	39.3	Flexural failure by crushing of concrete
A0	80.7	80.8[a]	13.1	Interfacial debonding
A10	78.7	80.8[a]	11.6	Interfacial debonding
A20	87.9	80.8[a]	14.3	Interfacial debonding
B0	86.4	101[b]	9.5	Concrete cover separation
B10	93.2	109[b]	9.8	Concrete cover separation
B20	96.8	118[b]	10.8	Concrete cover separation

[a] Based on Teng et al. [5].
[b] Based on El-Mihilmy and Tedesco [32].

mm (four layers), the concrete cover separation occurred. After the initiation of the crack at the end of CFRP strip in concrete, debonding of the CFRP strip occurred gradually with lumps of concrete detached from the longitudinal steel rebar (see Fig. 4). Since the beams tested were the medium scale and FRP strips were not terminated very close to the supports, the interfacial debonding obtained happened rather instantaneously and the concrete cover separation showed a relatively stable manner. The change of failure mode with CFRP thickness has also been reported previously, and the similar results are observed [4,6].

3.1. Effect of rubber modifier

To study the effect of rubber modifier, 0%, 10% and 20% CTBN 1300×13 were added into the epoxy adhesive. It is found that the rubber modifier increased both the load-carrying capacity and ductility for all CFRP thicknesses studied, but had little influence on the failure mode. To highlight the effect of the rubber modified adhesive, the beams with four layer FRP sheets are discussed firstly. It is clearly seen in Fig. 2 that the rubber modifier had a beneficial effect on ultimate failure load: the higher the liquid rubber content in the adhesive, the higher the ultimate load. The highest value (96.8 kN) was obtained for the specimen with a 0.44 mm thick CFRP strip and 20% rubber modifier in the adhesive (beam B20), which was 12% higher than that for the specimen B0 without liquid rubber (86.4 kN) and 61% higher than that for the control beams without CFRP strengthening (60.5 kN). When 10% rubber modifier was added in the adhesive, the beam B10 showed an ultimate load of 93.2 kN, which was 7.9% higher than that for the specimen B0 without liquid rubber and 54% higher than that for the control beams.

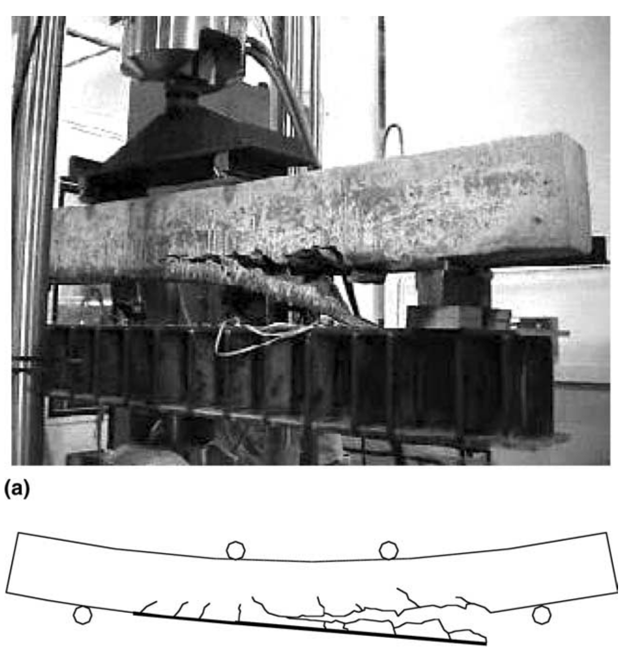

Fig. 4. (a) Concrete cover separation failure and (b) schematic drawing.

The effect of rubber modifier on the beam deflection at failure was also significant. The higher the liquid rubber content in the adhesive, the higher the deflection at failure of concrete beam, although the difference was marginal compared to the control beams. The specimen with 20% rubber modifier in adhesive (beam B20) showed a deflection at failure of 10.8 mm, which was 10.3% and 13.8% greater than those having 10% rubber content and without rubber modifier (9.8 mm for beams B10 and 9.5 mm for beam B0), respectively. Also, the beam B10 with 10% rubber modifier showed an increase of 3.2% than the beam B0.

When the beams were strengthened with two layers of FRP sheet, the beam A20 with 20% rubber modifier in the adhesive gave an improvement of 8.9% and 9.2%, respectively in load capacity and deflection at failure over the beam A0 without rubber. The beam A10 containing 10% rubber modifier in the adhesive showed rather unexpected results with the maximum load and the corresponding displacement slightly lower than the control beam A0. All RC beams, with the exception of A10, displayed basically the same trend in that the higher the rubber content in the adhesive, the larger the increase in load capacity and deflection at failure. The ameliorating effect of rubber modifier was particularly pronounced in the beams strengthened with thicker FRP strips.

The beams with and without rubber modifier in adhesive in general displayed a similar load–deflection response before steel reinforcement yielding. Thereafter, increasing rubber content gave rise to the improvement of ultimate load and corresponding deflection as well as a slight improvement of stiffness in the region immediately prior to failure. The possible reason is that the compliant adhesive with its small elastic modulus due to the added rubber modifier reduced the stress concentration at the CFRP strip ends as well as that under the flexural or shear/flexural cracks, thus leading to a higher ultimate load and corresponding deflection. This is partly confirmed by the FE analysis in the following section. In addition, the rubber modifier improved both the CFRP-concrete interlaminar fracture toughness and the interlaminar crack growth stability [31]. This is another reason for the improvement of strengthening performance due to rubber modifier, especially for interfacial debonding failure occurred in the beams with two layer FRP sheets. Since the addition of rubber modifier resulted in only 12% increase in load-carrying capacity and slight improvement in ductility, one may feel that the effect is of little significance. It should be pointed out, however, that the incorporation of rubber modifier into epoxy is a very simple procedure that can be easily handled by normal workers. Hence, without causing additional material and labour costs, the improvement in the performance of the retrofitted member can be achieved. Therefore, rubber modified epoxy in practical repair applications involving the bonding of FRP to RC beams is worth further investigating.

3.2. Influence of rubber modifier on interlaminar stress distribution

In order to investigate the interlaminar stress profiles and stress concentrations along the CFRP strip-concrete interface, the finite element method was used. The model consisted of a FRP strip bonded with an adhesive layer to the RC beam subjected to four point bending to simulate the actual test conditions. Fig. 5 presents the model and the mesh near the CFRP strip end created based on a code ANSYS 5.7. The steel rebar was modeled as one-dimensional link elements, while eight-node plane stress elements were used for all the other components. The symmetric loading geometry of the test allowed a two-dimensional analysis of a half-beam. At the symmetric axis of beam, the nodes were tied to the boundary and only vertical displacement was allowed. To ensure sufficient accuracy of the results the elements in the vicinity of CFRP strip ends were refined, where stresses are highly concentrated. All components used in the model were assumed isotropic and linear elastic, and the FRP-concrete interface was perfectly bonded. The mechanical properties of components are given in Tables 1 and 2. The applied load of 20 kN was considered, which corresponds to the end of linear elastic deformation.

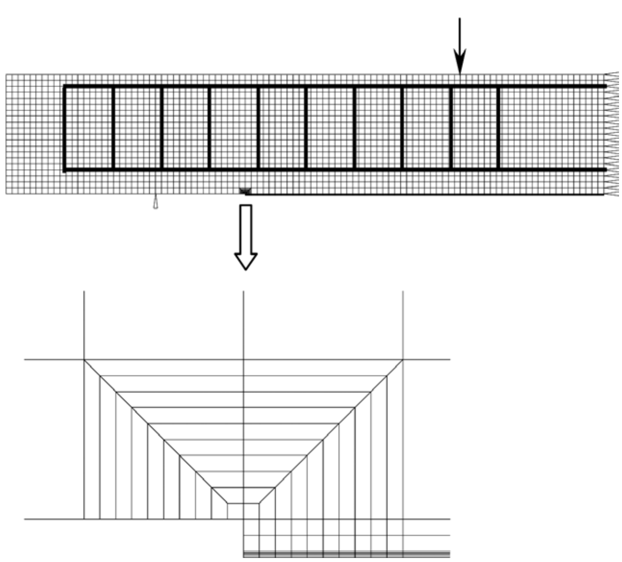

Fig. 5. 2D FE model with a mesh refined at CFRP strip end.

Comparisons of typical stress profiles including shear, normal, principal stresses are presented in Fig. 6 as a function of distance from the CFRP plate end for different rubber contents in the epoxy adhesive in different CFRP thicknesses. It is shown that the significant stress concentrations appeared in the vicinity of CFRP plate ends for all kinds of stresses considered. Note that the magnitudes of all stress concentrations decreased gradually with increasing rubber modifier content, consisting of shear, normal and principal stresses. The same conclusion can also be obtained by other studies, taking into consideration of the reduced elastic modulus due to adding rubber modifier in epoxy. The numerical parametric study by Teng et al. [9] showed that as the elastic modulus of the adhesive is decreased, the interfacial normal and shear stresses also decreases. And this trend can be confirmed by some theoretical analysis, such as the model by Malek et al. [18]. The accurate prediction by

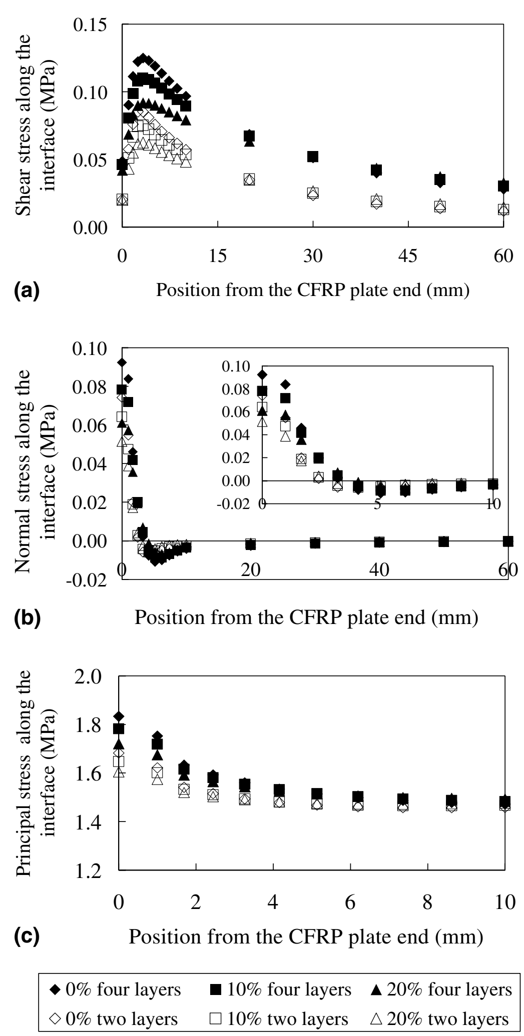

Fig. 6. Influence of rubber modifier content on interfacial stresses profiles: (a) shear stress, (b) normal stress, and (c) principal stress.

the present FE model is limited due to the inability of elastic analysis to take into account the actual non-linear behavior of concrete, as well as the existence of many cracks in practice [29]. The stress distributions predicted by most elastic numerical and/or analytical models based on linear elasticity differ significantly from those measured in real experiments. Nevertheless, using the elastic numerical model is acceptable if a focus is made on the effect of a particular component, such as adhesive, on general mechanical response of the RC beam, as in the present study.

As noted above, the rubber modifier in epoxy adhesive resulted in lower stress concentrations of shear, normal and principal stresses components at the CFRP strip ends. For the beams with four layers of CFRP strips, the concrete cover separation occurred, which initiated from the end of FRP strips. The lower stress concentration implied a higher load-carrying capacity before failure or damage, which was consistent with the experimental results based on four point bending of RC beams. For beams with two layers of CFRP strip, interfacial debonding occurred, which is believed to initiate by the opening of internal flexural or shear/flexural crack at the bottom of the beam. The effect of various parameters on the crack-induced stress concentration has been analysed by Leung [8]. The effect of reduced adhesive modulus due to the addition of rubber modifier is equivalent to the use of a thicker adhesive layer, and would result in a reduction in the concentrated shear stress that causes delamination. The consequence is that the load-carrying capacity increased with rubber content.

4. Conclusion

The structural performance of RC beams strengthened with CFRP strips is evaluated. The flexural tests carried out in this study demonstrated that the external bonding of FRP strip offered an effective means for strengthening. The adhesive was modified by adding rubber modifier in epoxy. The experimental results showed that the rubber modified adhesive could improve the structural performance of RC beam by increasing both the load-carrying capacity and the corresponding ductility compared with the beams bonded with a neat epoxy resin, whether interfacial debonding or concrete cover separation occurred as the dominant failure mechanism. The improvement of structural performance due to modified adhesive arose from the modification of stress profiles along the CFRP-concrete interface, in particular the reduction in stress concentration at the CFRP ends, as well as the enhanced interlaminar fracture toughness. Rubber modified epoxy therefore is worth further investigation for practical repair applications.

Acknowledgements

This work has been supported by the Research Grants Council of the Hong Kong Administrative Region, China (Project No. HKUST 6050/99E). The technical supports by the Construction Materials Laboratory, Advanced Engineering Material Facilities (AEMF) and Design and Manufacturing Services Facility (DMSF) at HKUST are also acknowledged.

References

[1] Saadatmanesh H, Ehsani MR. RC beams strengthened with GFRP plates. I: experimental study. J Struct Engrg 1991;117(11):3417–33.
[2] Triantafillou TC. Shear strengthening of reinforced concrete beams using epoxy-bonded FRP composites. ACI Struct J 1998;95(2):107–15.
[3] Hollaway LC, Leeming MB. Strengthening of reinforced concrete structures. Boca Raton, Boston, New York, Washington (DC): CRC Press; 2000.
[4] Rahimi H, Hutchinson A. Concrete beams strengthened with externally bonded FRP plates. J Compos Constr 2001;5(1):44–56.
[5] Teng JG, Chen JF, Smith ST, Lam L. FRP-strengthened RC structures. Chichester: John Wiley & Sons; 2002.
[6] Maalej M, Bian Y. Interfacial shear stress concentration in FRP-strengthened beams. Compos Struct 2001;54:417–26.
[7] Mukhopadhyaya P, Swamy N. Interface shear stress: a new design criterion for plate debonding. J Compos Constr 2001;5(1):35–43.
[8] Leung CKY. Delamination failure in concrete beams retrofitted with a bonded plate. J Mater Civ Engrg 2001;13(2):106–13.
[9] Teng JG, Zhang JW, Smith ST. Interfacial stresses in reinforced concrete beams bonded with a soffit plate: a finite element study. Constr Build Mater 2002;16(1):1–14.
[10] Buyukozturk O, Gunes O, Karaca E. Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. Constr Build Mater 2004;18:9–19.
[11] Smith ST, Teng JG. Interfacial stresses in plated beams. Engrg Struc 2001;23:857–71.
[12] Smith ST, Teng JG. FRP-strengthened RC beams. I: review of debonding strength models. Engrg Struc 2002;24:385–95.
[13] Smith ST, Teng JG. FRP-strengthened RC beams. II: assessment of debonding strength models. Engrg Struc 2002;24:397–417.
[14] Roberts TM. Approximate analysis of shear and normal stress concentrations in the adhesive layer of plated RC beams. The Struct Eng 1989;67(12):229–33.
[15] Triantafillou TC, Pleveris N. Strengthening of RC beams with epoxy bonded fibre composite materials. Mater Struct 1992;25(148):201–11.
[16] Taljsten B. Strengthening of beams by plate bonding. J Mater Civ Engrg 1997;9(4):206–12.
[17] Varastehpour H, Hamelin P. Strengthening of concrete beams using fiber-reinforced plastics. Mater Struct 1997;30:160–6.
[18] Malek AM, Saadatmanesh H, Ehsani MR. Prediction of failure load of R/C beams strengthened with FRP plate due to stress concentration at the plate end. ACI Struct J 1998;95(1):142–52.
[19] Saadatmanesh H, Malek AM. Design guidelines for strengthening of RC beam with FRP plates. J Compos Constr 1998;2(4):158–64.
[20] Maalej M, Goh WH, Paramasivam P. Analysis and design of FRP externally-reinforced concrete beams against debonding-type failures. Mater Struct 2001;34:418–25.

[21] Sebastian W. Significance of midspan debonding failure in FRP-plated concrete beams. J Struct Engrg 2001;127(7):792–8.
[22] Yang J, Ye J. Interfacial stresses in plated beams with cracks. Compos Struct 2002;57:125–34.
[23] Shen HS, Teng JG, Yang J. Interfacial stresses in beams and slabs bonded with thin plate. J Engrg Mech 2001;127(4):399–406.
[24] Rabinovitch O, Frostig Y. Delamination failure of RC beams strengthened with FRP strips-a closed form high order and fracture mechanics approach. J Engrg Mech 2001;127(8):852–61.
[25] Arduini M, Di Tommaso A, Nanni A. Brittle failure in FRP plate and sheet bonded beams. ACI Struct J 1997;94(4):363–70.
[26] Chen JF, Yang ZJ, Holt GD. FRP or steel plate to concrete bonded joints: effects of test methods on experimental bond strength. Steel Compos Struct – an International Journal 2001;1(2):231–44.
[27] Lau KT, Dutta PK, Zhou LM, Hui D. Mechanics of bonds in an FRP bonded concrete beam. Composites Part B 2001;32:491–502.
[28] Leung CKY, Tung WK. A three-parameter model for debonding of FRP from concrete substrate. In: Proceedings of the International Conference on FRP Composites in Civil Engineering, Hong Kong, China, 2001. p. 373–9.
[29] Pesic N, Pilakoutas K. Concrete beams with externally bonded flexural FRP-reinforcement: analytical investigation of debonding failure. Composites Part B 2003;34:327–38.
[30] Yang ZJ, Chen JF, Proverbs D. Finite element modeling of concrete cover separation failure in FRP plated RC beams. Constr Build Mater 2003;17:3–13.
[31] Gao B, Kim JK, Leung CKY. Effect of rubber modifier on interlaminar fracture toughness of CFRP-concrete interface. Compos Sci Technol 2003;63:883–92.
[32] El-Mihilmy MT, Tedesco JW. Prediction of anchorage failure for reinforced concrete beams strengthened with fiber-reinforced polymer plates. ACI Struct J 2001;98(3):301–14.