Journal of Engineering Science and Technology Review 6 (2) (2013) 134-138

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Research Article

Crack-arresting and Strengthening Mechanism of Hybrid Fiber Reinforced Polymer Sheets in Strengthening of Reinforced Concrete Beams

X. B. He[1,2*], B. Yan[1], J. Y. Gu[2] and Q. Shen[3]

[1]*Dept. of Engineering Mechanics, Chongqing University, Chongqing 400030- China*
[2]*School of Civil Engineering & Architecture, Chongqing Jiaotong University, Chongqing 400074- China*
[3] *Beijing Xinqiao Technology Development LTD., Highway Research Institute of Ministry of Transport, Beijing 100001- China*

Received 15 May 2013; Accepted 25 July 2013

Abstract

The failure process of reinforced concrete (RC) beams is exactly the emergence and propagation process of cracks. According to the principles of Fracture Mechanics, if the cracks were retarded in RC beams, the structure performance would be improved. In this paper, hybrid fiber reinforced polymer (HFRP) sheets are proposed to retard crack propagation in RC beams, and the crack-arresting and strengthening mechanism of the HFRP composite in the strengthening of RC beams is revealed, which is substantiated by the finite-element-modelling (FEM) analysis and bending improvement of RC beams with externally-bonded hybrid glass/carbon FRP (Hybrid G/C FRP) sheets.

Keywords: Hybrid Fiber Reinforced Polymer, Stress Intensity Factor, Crack Closure Force, Finite Element Modelling, Structural Strengthening

1. Introduction

Due to increase of traffic volume, incident actions (e.g. earthquake and fire disaster) , ageing of materials and functional degradation of structures, structural strengthening and rehabilitating of existing reinforced concrete (RC) structures is becoming an increasingly demand in civil engineering [1], [2], [3]. Compared with traditional materials such as concrete and steel, fiber reinforced polymer (FRP) such as carbon fiber reinforced polymer (CFRP), glass fiber reinforced polymer (GFRP) and aramid fiber reinforced polymer (AFRP), has become excellent strengthening and rehabilitating materials because of its premium properties of low density, high strength to weight ratio, good ductility, good fatigue resistance and good corrosion resistance, which constitute the large-scale application in strengthening and rehabilitating of existing RC structures by the externally bonding method [4], [5], [6], [7],[8], [9], [10].

However, the linear elastic properties of high-modulus and high-strength FRP (e.g. CFRP) up to rupture have negative findings on the ductility of the strengthened or rehabilitated RC structures, while strength properties of low-modulus FRP (e.g. GFRP) have less reinforcement effect on loading capacity in the strengthening and rehabilitating of RC structures than the high-modulus and high-strength FRP [11]. Literatures indicate that hybrid fiber composite that is composed of two or more complementary fibers incorporated into a single matrix usually generates better properties not presented in any individual fiber component, which is beyond the expectation gotten from the mixing law [11]. Studies have shown that the fracture strain of hybrid glass/carbon fiber reinforced polymer (Hybrid G/C FRP) composite, with a G/C volume ratio of 0.5, increases 30% to 50% than that of CFRP; the impact toughness of hybrid glass/carbon FRP composite shaped by mixing 15% (by volume) glass fiber increases 2 to 3 times than that of CFRP. So, the concept of externally-bonded hybrid FRP (HFRP) composite for strengthening and rehabilitating of RC beams is put up [12], [13], [14], [15], [16].

But, in the strengthening and rehabilitating design of RC beams, the structural design and analysis method adopted is based on the traditional strength theory (e.g. the principle of static equilibrium at destructive state) and corresponding resolution way, which neglects the accumulated damage and crack propagations during the failure process of RC beams, and results in the fact that the typical characteristics of material failure process cannot be identified, stress concentration in the crack tip cannot be described, and structure failure cannot be precluded [17]. So, in the tradition way, it is difficult to reveal the crack-arresting and strengthening mechanism of HFRP in RC beams, and investigate the performance of beams externally-bonded HFRP composite accurately and reliably.

Whereupon, based on the principles of fracture mechanics, the crack-arresting and strengthening mechanism of HFRP sheets in the strengthening of RC structures was firstly analyzed in this paper, and the validity of the mechanism is substantiated by the finite-element-modelling (FEM) analysis, and the bending test of RC beams with the dimension of 100mm (width) ×160mm (height) ×2000mm (length) strengthened with interply hybrid G/C FRP sheets.

* E-mail address: david.hxb@gmail.com
ISSN: 1791-2377

2. Crack-arresting and Strengthening Mechanism

As is well known, for the poor tensile strength of concrete, the cracking load of RC beams is far lower than the ultimate load [17]. Therefore, under loading, the cracking of RC beams is inevitable and accepted. Once cracking in RC beams, subjected to the coupling impact of load increase, material ageing, structure fatigue, as well as impact of incident actions, the cracks will increase rapidly into macro-cracks. The emergency of macro-cracks means that the neutral axis goes up as the tension area of concrete is lost step by step, which leads to the decrease of structural rigidity dramatically, the deterioration of structure performance, and the deficiency of structure durability. While the macro-cracks continue propagating in the RC beams, structural performance worsens continuously until the structure failure occurs. Therefore, the failure process of the RC beams is actually the emergency and propagation of cracks in the RC beam.

Thus, based on the fact that the RC beams usually works with cracks during its service-life, the fracture mechanics theory can be applied to study its performance.

From the perspective of Fracture Mechanics, the cracking of RC beams inevitable leads to the stress singularities at the crack tips [17], [18]. Once the stress singularities reach to a significant extent, namely the stress intensity factors at the crack tips exceed the critical stress intensity factor of the concrete material, the cracks will begin to propagate, which will finally result in the functional obsoleteness and structural failure. Literatures have proposed some models to state the crack closure process of closure-affected cracks, which can be modified to reveal the crack-arresting and strengthening mechanism effects of HFRP composite in strengthening of RC structures [17], [18], [19], [20], [21].

Supposing that a unilateral crack under pure bending occurs in the RC beam (Figure 1). For the stress intensity factor of an edge crack is bigger than that of a central penetrated crack under the same loading sate, the crack is prone to unstable propagation [17], [19], [20], [21]. When the HFRP composite are bonded on the surface of concrete, the role of HFRP can simplified as a pair of closure forces P_{HFRP} loaded at a split-point B of the crack in the opposite direction, which make the edge crack into the internal eccentric crack as shown in Figure 1(a), and thus reduce the stress intensity factor at the crack-tip. Furthermore, as the HFRP composite usually has better fracture toughness than single-component FRP, it is difficulty for the crack-tip B to pass through into the HFRP layer, the stress intensity factor of the crack-tip A is the controlling factor in retarding crack propagation. This is to say that the propagation of cracks in HFRP-strengthened structures is fulfilled through the propagation of inner cracks of concrete structures. A series of analytic solutions state that stress intensity factors of internal eccentric cracks are far lower than those of corresponding edge cracks [17], [18]. Therefore, by externally bonding HFRP composite on the surface of concrete to reduce the stress intensity factor at the crack-tip effectively, and arrest the crack propagation of concrete beams, the anti-crack performance of the RC beam can be improved greatly. The following FEM analysis also shows, compared with the stress intensity factor at crack tip under loading, the closure forces P_{HFRP} loaded at a split-point of the crack in the opposite direction can produce reverse stress intensity factor at the crack tip to reduce the stress intensity factor at crack tips, which will retard propagation of cracks.

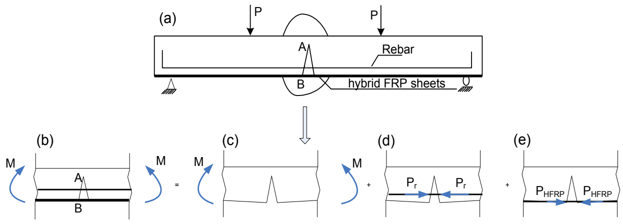

Fig. 1 Crack-arresting and strengthening mechanism

Similarly, the role of rebar in RC beams also indicates the principles of Fracture Mechanics, that is, a pair of closure forces P_r loaded at a split-point of the crack in the opposite direction reduce the stress intensity factor at the crack tip, which will retard crack propagation as shown in Figure 1(d). But, the bonding failure between the rebar and the concrete makes the crack-arresting capacity of rebar decrease continuously [21]. So, if a pair of closure forces is imposed at crack initiation before crack propagation, the negative stress intensity factor produced by the closure force would partially offset the stress intensity factor of the crack in RC beams as shown in Figure 1(e). Besides, the pair of closure forces loaded at crack initiation will produce the maximum negative stress intensity factor. Thus, according to Newton's third law, when HFRP sheets bonded on the surface of RC beams are in tensile state, the effect produced by the bonded layer is equivalent to the crack closure imposed at crack initiation by a pair of concentrated forces P_{HFRP}, which will retard the crack propagation, and improve the anti-crack performance.

According to the superposition principle of stress intensity factor, the stress intensity factor of the crack-tip A (K_I^b) in the RC beam by externally-bonded HFRP is as follows.

$$K_I^b = K_I^c + K_I^d + K_I^e$$

Where, K_I^c, K_I^d and K_I^e are the stress intensity factors at the crack tip A produced by the external load, the rebar and the HFRP sheets in the RC beam respectively.

Obviously, the stress intensity factors of K_I^d and K_I^e in the formula are in the opposite direction with the K_I^c, which reduce the stress intensity factor K_I^b at the crack tip in the RC beam, thus the structural performance, such as cracking resistance and loading capacity, can be improved.

Similarly, the arrangement of FRPs in the HFRP composite also should comply with the principle of Fracture Mechanics. Taking the hybrid G/C FRP composite for example, the CFRP with low elongation should be put in the inner layer of the HFRP, which fractures first under loading, while GFRP with high elongation in the outer layer can retard the crack propagation in the HFRP composite.

3. FEM Analysis

In order to investigate the crack-arresting and strengthening effects of HFRP composite in RC beams, pre-crack concrete beams with an edge crack at mid-span were analyzed by the FEM method, which involves the modeling of the plain concrete beam and the concrete beam strengthened with HFRP composite (the HFRP-strengthened concrete beam) subjected to the four-point load. The HFRP composite is composed of a hybrid lay-up of one layer of unidirectional

CFRP sheet (300 g/m^2) and one layer of unidirectional GFRP sheet (600 g/m^2), which are adhered to the bottom surface of concrete beams by means of an epoxy adhesive after the surface preparation (cleaning, sealing and priming) is done.

The material properties were obtained by tests (Figure 2) and listed in Table1 respectively.

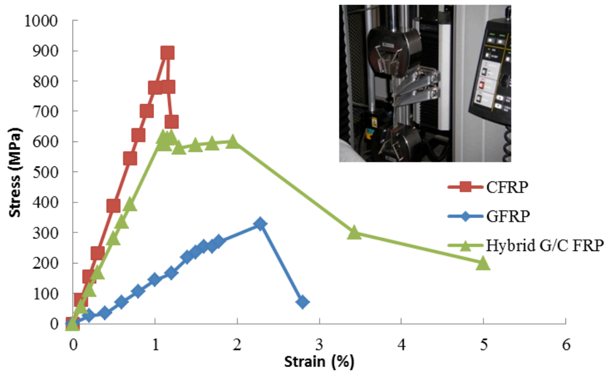

Fig. 2 Strain-stress relationship of FRP in tension

Tab. 1 Main mechanical properties of materials

	Elastic modulus / GPa	Fraction elongation / %	Strength / MPa	
			Compressive	Tensile
Concrete	35	/	40.1	/
CFRP	78	1.15%	/	894
GFRP	17	2.50%	/	328
Hybrid G/C FRP	46	1.95%	/	671

The dimensions details and loading scheme of the RC beam model are shown in Figure 3. According to the analysis method of linear elastic fracture mechanics, the isoperimetric singular element method for the two-dimensional crack was employed to analyze the crack tip; while the 8-node quadrilateral element was employed for other elements (Figure 4).

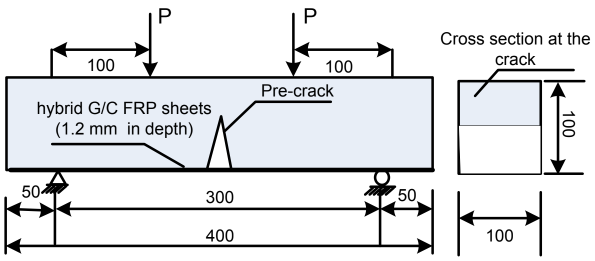

Fig. 3 Dimensions of models and loading scheme (Unit: mm)

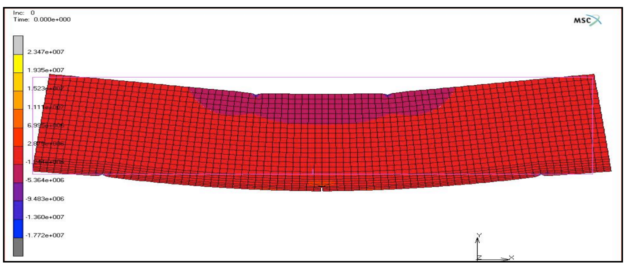

Fig. 4 FEM meshing

As shown in Figure 2, the interply hybrid G/C FRP composite is characterized with a yielding plateau, which is obviously different with GFRP and CFRP, while the tensile strength is improved by 171% compared with GFRP and the fracture elongation is improved by 70% compared with CFRP. So, the interply hybrid G/C FRP composite possesses the good stress-strain property, which can be used to improve the ductile and capacity in the strengthening of RC beams.

The results of FEM analysis are listed in Figure 5 and Figure 6.

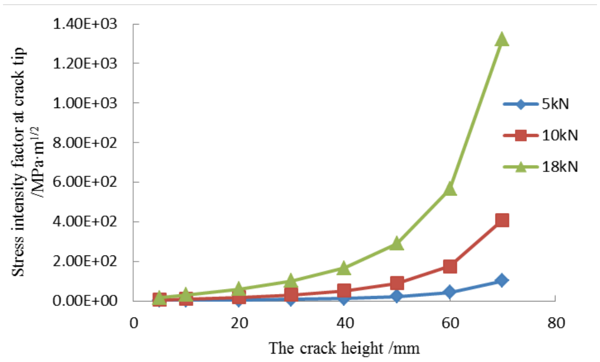

Fig.5 Plot of stress intensity factor vs. crack depth of the plain concrete beam

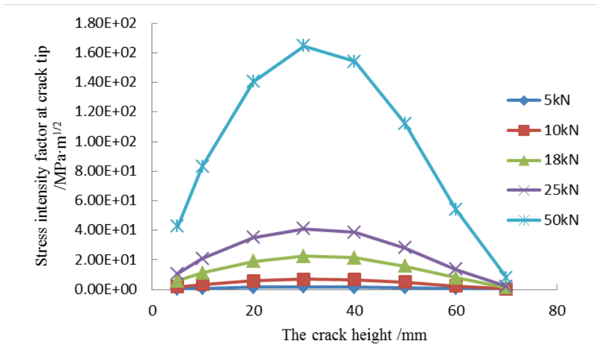

Fig.6 Plot of stress intensity factor vs. crack depth of the concrete beam strengthened with Hybrid G/C FRP

According to the FEM results, the relationship between the stress intensity factor at the crack tip and the crack height is plotted under different loading levels (5kN, 10kN, 18kN, 25kN and 50kN), which indicates that the stress intensity factor of the crack tip in the plain concrete beam increase sharply along with the rising of load and crack height (Fig. 5).

Compared with the plain beam, the hybrid G/C FRP sheets externally bonded on the surface of the plain concrete beam makes the edge crack into internal eccentric crack, and the stress intensity factor at the crack tip of the HFRP-strengthened beam increases firstly and then decreases with the increase of crack height, which is far lower than that of the plain concrete beam under the same load and crack height (Fig. 6). In the beam strengthened with hybrid G/C FRP sheets, the stress intensity factor nearly reaches the minimum at about 0.7 beam height, which means the crack will stop propagation (Fig. 6). Therefore, the crack-arresting and strengthening mechanism of the HFRP composite is substantiated, and the hybrid G/C FRP composite is good option for RC strengthening and rehabilitating.

The results also show that the ultimate load of the plain beam is 18kN, while that of the strengthened beam is 50kN, which mean that the capacity is also improved crack-arresting and strengthening effects of the HFRP composite

4 Experimental Investigation

Two types of RC beams are designed to investigate the crack-arresting and strengthening effects of HFRP composite in this study, which are all subjected to four-point bending test. One is the normal RC beam, the other is the RC beam strengthened with hybrid G/C FRP sheets (the HFRP-strengthen RC beam). The dimensions, load scheme and arrangement of strain gauges are shown in Figure 7, Figure 8 and Figure 9.

The material properties of concrete and hybrid G/C FRP sheets are listed in Tab.1. The strength and elasticity modulus of rebar used are tested to be 361Mpa and 2.1×10^5 MPa respectively.

Before occurrence of crack during the loading test, the loading rate is controlled as about 0.5kN/min; after cracking, firstly shifted to about 1kN/min up to 10kN, then about 2kN/min. After each loading, the data of cracks, LVDTs and strain gauges are recorded. From the experimental data, we can get the cracking load and ultimate load of the beams, the propagation law of cracks, rebar strains and the load-deflection curve.

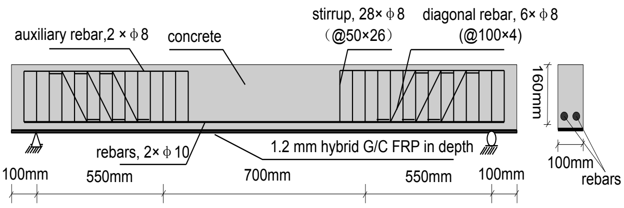

Fig.7 Details of beam specimens

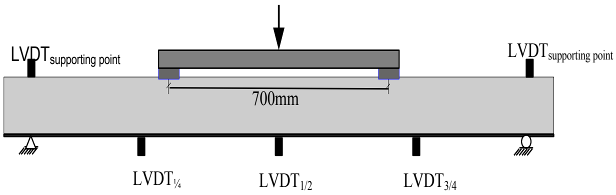

Fig.8 Loading scheme

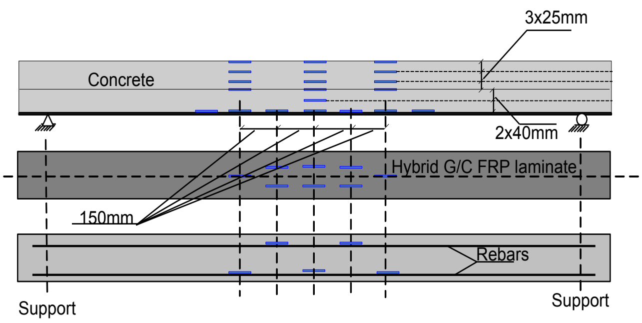

Fig.9 Arrangements of strain gauges

The relationship between load and deflection of beams at mid-span is shown in Figure 10, which indicates that, compared with normal RC beam, the cracking load and ultimate load of the HFRP-strengthened RC beam increase separately by 36% and 106%, while the structural ductility is also good.

The ductility failure of the HFRP-strengthened RC beam is also observed, which can be attributed to the good fracture toughness and stress-strain properties of hybrid G/C FRP sheets.

The maximum stain of rebar at failure in the normal RC beam is about 1780με, while the strain of the HFRP-Strengthened beam has exceeded 2450με, which means the HFRP-strengthened RC beam has better capacity than the normal RC beam.

Besides, the maximum crack width, the maximum crack height and crack spacing in the HFRP-strengthened RC beam are far less than those of the normal RC beam under the identical loading, which can be attributed to crack-arresting capability of the HFRP composite.

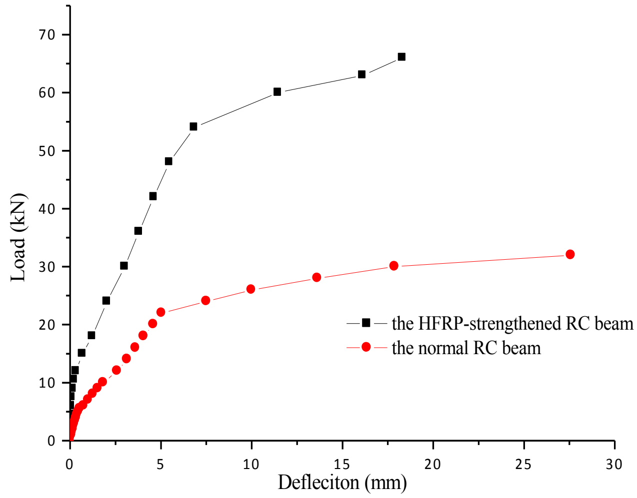

Fig .10 Curves of load vs. deflection at mid-span

5. Conclusions

From the above analysis and investigation, the following conclusions can be drawn:

1) The hybrid G/C FRP composite changes the linear elastic characteristics of the CFRP up to failure and have a yielding plateau, which has a good impact on the ductility of the strengthened RC beams; meanwhile, possesses the high strength that the GFRP usually does not have.

2) The crack-arresting and strengthening mechanism of the HFRP composite in the strengthening of RC beam is revealed based on the crack-closure model and the superposition principle of stress intensity factor, which can be used to guide the strengthening design in a different way that is not adopted in the traditional strengthening theory.

3) It is feasible to improve the bending performance of the normal RC beam by externally bonded hybrid G/C FRP sheets under the guide of principles of fracture mechanics.

4) Compared with the normal RC beam, the HFRP-strengthened RC beam has higher cracking load, higher ultimate capacity and better ductility, which is benefited from the crack-arresting and strengthening effects of the hybrid G/C FRP composite.

Acknowledgement

The research is funded by the National Basic Research Program of China (2012CB723305) and the Natural Science Foundation Project of CQ CSTC (cstc2013jcyjA30011).

References

1. Tavakkolizadeh M.; Saadatmanesh H., "Strengthening of steel-concrete composite girders using carbon fiber reinforced polymers sheets", *Journal of Structural Engineering* 129 (1), 2003, pp. 30-40.
2. Motavalli M. and Czaderski C., "FRP composites for retrofitting of existing civil structures in Europe: state-of-the-art review", *Composite & Polycon*, Tampa, FL USA, 2007, pp.1-10.
3. Brühwiler E., "Rehabilitation and strengthening of concrete structures using Ultra-High Performance Fiber Reinforced Concrete", *Beton- und Stahlbetonbau*, 108(4), 2013, pp. 216-226.
4. Khalifa A.; Nanni A, "Improving shear capacity of existing RC T-Section beams using CFRP composites", *Cement and Concrete Composites*, 22 (2), 2000, pp.165-174.
5. Bukhari I.A; Vollum R.L.; Ahmad S.; Sagaseta J., "Shear strengthening of reinforced concrete beams with CFRP", *Magazine of Concrete Research*, 62(1), 2010, pp. 65-77.
6. Dias S. J. E.; Barros J. A. O., "Performance of reinforced concrete T beams strengthened in shear with NSM CFRP laminates", *Engineering Structures*, 32(2), 2010, pp. 373-384.
7. El-Ghandour A. A., "Experimental and analytical investigation of CFRP flexural and shear strengthening efficiencies of RC beams", *Construction and Building Materials*, 25(3), 2011, pp.1419-1429.
8. Lee H. K.; Cheong S. H.; Ha S.K.; Lee C. G., "Behavior and performance of RC T-section deep beams externally strengthened in shear with CFRP sheets", *Composite Structures*, 93(2), 2011, pp. 911-922.
9. Hota GangaRao V.S.; Vijay P.V.; Abhari Reza S., "Rehabilitation of Railroad Bridges using GFRP composites" , *Proceedings of the ASME Joint Rail Conference*, Urbana, IL, United states, 2010, 1, pp. 57-64.
10. Hota GangaRao V. S.; Vijay P. V.; Abhari Reza S., "Glass fiber reinforced polymer strengthening and evaluation of railroad bridge members", *Structural Engineering International*, 20(4), 2010, pp. 423-426.
11. Summerscales J.; Short D., "Carbon fibre and glass fibre hybrid reinforced plastics", *Composite,* 9 (3), 1978, 157-166.
12. Shanmugam U.; Devadas Manoharan P.; Neelamegam M., "Experimental investigations on flexural behavior of RC beams strengthened with CFRP, GFRP and hybrid FRP wrapping under static load", *Journal of Structural Engineering (Madras)*, 38(2), 2011, pp. 174-183.
13. Honsy A.; Shaheen H.; Abdelrahman A; and Elafandy T., "Performance of reinforced concrete beams strengthened by hybrid FRP laminates", *Cement and Concrete Composites,* 28 (10), 2006, pp.906-913.
14. Deng Z. C.; Li, J. H., "Flexural performance of RC corroded beams strengthened with CFRP/AFRP/GFRP laminated hybrid fiber sheets", *Journal of Beijing University of Technology*, 35(3), 2009, pp. 338-344.
15. Chun Q.; Pan J. W., "Shear behavior of timber beams strengthened with CFRP/AFRP hybrid FRP sheet" , *Journal of PLA University of Science and Technology (Natural Science Edition)*, 12(6), 2011, pp. 654-658.
16. KimHee S.; Shin Y. S., "Flexural behavior of reinforced concrete (RC) beams retrofitted with hybrid fiber reinforced polymers (FRPs) under sustaining loads" , *Composite Structures*, 93(2), 2011, pp. 802-811.
17. Yi Z. J., Yang Q. G., Li Z. W., Zhou C. and Peng K., "A new reinforced concrete (RC) composite structure based on principles of fracture mechanics", *Structures and Materials*, 12, 2003, pp.455-461.
18. Gdoutos E. E., "Fracture Mechanics: An Introduction", Springer-Verlag New York Inc, Dordrecht, Netherland, 2005, pp.15-27.
19. He X. B.; Yang Q. G.; Yi Z. J., "Research on the fatigue performance of flexible fiber reinforced concrete", *Proceeding of 6th International Conference on Road and Airfield Pavement Technology*, Sapporo, Japan, 2008, pp.365-370.
20. He X. B.; Yang Q. G.; Yi Z. J., "Fatigue test of concrete pavement: effect of interface damage", *International Journal of Terraspace Science and Engineering* 2 (1), 2009, pp.77-80.
21. He X. B.; Huang F.; Zhang C. Y., "Mechanism and experimental verification of degradation of RC beams induced by concrete/rebar bonding failure", *Key Engineering Materials*, 452/453, 2011, pp.877-880.