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# A new reinforced concrete (RC) composite structure based on principles of fracture mechanics

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## Abstract

Reinforced concrete structures are widely used in civil engineering. Being poor in resisting tension, an RC beam even cracks at a load level as low as 20%--30% of its ultimate carrying capacity; accompanied by the emergence and propagation of cracks, the structural performance turns worse. The study about RC structures shows that the failure process of RC structures actually means the emergence and propagation process of the cracks. From the principles of fracture mechanics, if the emergence and propagation of cracks was delayed and held back, the structural performance would be improved. Based on the principles of fracture mechanics and the study about RC structures, the authors put forward a new reinforced RC composite structure that can delay and hold back the cracks in the structure. The concept of the new structures in the article will enrich the RC theory and provide new method to realize longer span.

## 1 Introduction

The RC structures make up a main structure type in civil engineering. Even after the great development in theory and practice, the RC structures still have some inherent defects—poor anti-cracks performance and heavy self-weight [1]. How to improve the performance of RC structures has been a crucial problem for decades.

The article studies the relationship between the RC structure failure and the cracks propagation in it based on fracture mechanics, and offers a new reinforced RC composite structure mainly aimed at delaying and holding back cracks,

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which has much better anti-cracks performance as well as higher carrying capacity than traditional RC structures. The article introduces fracture mechanics concept into RC structure study to enrich the RC theory.

In the traditional RC theory the RC beams are in cracking state under serving loads and the crack widths should be checked to be under specified limits [1]. It's a passive idea to deal with the cracking problem that later had an active way out—prestressed concrete (PC) structures. The new structure proposed in the paper could also efficiently delay and hold the crack developing in the beam concrete but without prestress, it will be a good alternative to existent PC structures.

According to the new design idea, a group of new reinforced RC composite beams were fabricated and loaded in laboratory. The experiments showed that the new reinforced RC composite beams have much higher cracking load level, greater ultimate carrying capacity and better ductility compared with traditional RC beams with the same dimensions, which means longer spanning ability, better serviceability of the new structure.

## 2 The relationship between the RC beams' deterioration and the emergence and propagation of cracks

Because of the poor tensile strength of concrete, the RC beams cracks at a load level much lower compared with its ultimate load [1]. With the emergence and propagation of cracks, the cracked beam performance turns worse and worse: the section rigidity decrease; the cracked concrete under the neutral axis contribute little to the beam function but add to the self-weight; the shearing capacity of the beam has a big fall; the steel bar segments around the cracks lose adhesion to the surrounding concrete and get a drastic stress rise, in addition, expose themselves to the erosive moisture and chemicals in the air [1].

The reduction of section rigidity leads to the magnification of deflection and vibration of the beam; the corrosion of the steel bar segments around the cracks detract from the beam's durability; the cumbersome weight of the cracked concrete demote the spanning ability of the beam [1]. In a word, the emergence and propagation of cracks degrade the serviceability of RC beams.

## 3 New design concept based on the principles of fracture mechanics

With the development of civil engineering, the technology to strengthen RC structure with bonded steel plate or carbon fiber-reinforced polymer (CFRP) plate has emerged. Practices have proved that the bonding technology is effective to strengthen RC structure [2][3][4][5].

Why could those worn-out RC structures be greatly promoted in their carrying capacity and serviceability by a thin boned layer?

With resort to fracture mechanics we can find the reason why the bonding technology has so good effect is it coincides with two principles of fracture mechanics: i. Turning the edge cracks into internal cracks will dramatically

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decrease the stress intensity factor of the crack [6][7]; ii. The existence of a pair of closing forces at the crack tip will also effectively decrease the stress intensity factor [6][7]. The layer bonded to the bottom face just turns the concrete's edge cracks into internal ones (Figure 1) and simultaneously applied a pair of closing forces to the crack tip (Figure 2), so the emergence and propagation of the cracks are delayed and held back. It is natural that the bonded beam's properties would be improved.

Since the bonding technology employs fracture mechanics intuitively to improve the RC structure, it be reasonable that using fracture mechanics intendedly to delay and hold back cracks in the initial design of an RC structure could make a new structure type which has excellent anti-crack property and extraordinary carrying capacity. That is the very new concept of the authors to design structures based on fracture mechanics.

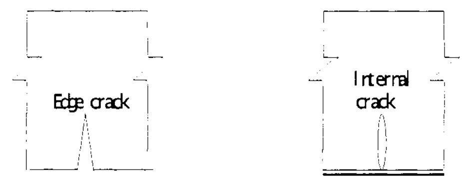

Figure 1: Turning the edge cracks into internal cracks

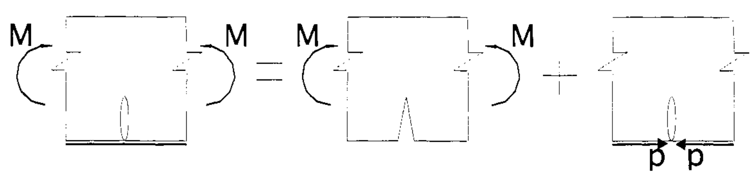

Figure 2: Applying a pair of closing forces to the crack tip

## 4 A new reinforced concrete (RC) composite structure

In the new structure, the method to delay and hold back the cracks is to bond a layer which is made of non-steel and non-CFRP material but another much more flexible material, to the structure face in disadvantageous stress state. The young's modulus of the bonded material approximately equals that of the concrete, and the bonded material strength could provide enough closing forces at the crack tips mentioned above. In the article, the surface bonded layer material is named anti-crack layer according to its effect.

The selection of such an ideal layer material does be the key problem in the new concept.

At present the bonding technologies usually adopt high-strength and high-modulus materials as the bonded layers, just like steel plate and CFRP plate [2][3][4][5]. Look back into Figure 2, it is clear that under the certain load **M**, the forces **P** needed to close the crack keep constant in spite of layer material variation. In other word, it means that much higher strength than enough to meet force **P** is unnecessary. In addition, if the bonded layer has a young's modulus far

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beyond that of concrete, the interface between the layer and the concrete often failures before the strengthened beam attained its expected carrying capacity. In fact, the young's modulus of the steel or the CFRP is about 10 times as high as that of the concrete [2][3][4][5].

According to the previous analysis, especially the closing-force principle, the authors propose adopting glass fiber-reinforced polymer (GFRP) plate as the anti-crack layer in the new RC composite structure. The warrants are: the GFRP's strength is high enough to meet the need of the closing forces; the young's modulus of the GFRP is almost equal to the concrete's so it is beneficial to the bonding and the deformation consistence between the anti-crack layer and the concrete; furthermore, the price of GFRP is much cheaper than steel or CFRP.

Since the design of the proposed structure is guided by the new concept based on fracture mechanics and the GFRP is a kind of composite material, it is called a new RC composite structure in the article.

The new structure has two main differences from the structure bonded with steel plate or CFRP plate: Firstly, the guiding theory is different. The former is based on fracture mechanics, while the latter is based on the traditional RC theory. Secondly, the application field and purpose are different. The latter usually is applied to strengthen worn-out structures passively, but the former is focused on initial structure design actively.

With the GFRP as the anti-crack layer, the new RC composite structure has some excellent properties: the interfacial bonding is improved due to the decrease of the shear stress along the interface compared with the structure bonded with steel or CFRP plate; The bar stress can reach, even surpass its yield strength in the new structure when the structure fails; the ductility of the new structure is also greatly improved.

Generally, the new RC composite structure based on fracture mechanics proposed in the article is a structure with excellent anti-crack ability, good ductility and extraordinary carrying capacity, which makes a lighter self-weight or a bigger span possible in the new design.

## 5 The experiment on the new RC composite structure

A group of new RC composite beams has been fabricated, tested and compared with the traditional RC beams. All the experiment was conducted in The Structure Engineering Laboratory in Chongqing Jiaotong University.

### 5.1 Fabrication of the RC composite beams

The beams constructed for the study were of identical spans, widths and depths (2,000mm$\times$100mm$\times$160mm) and well cured, Figure 3. The concrete average strength was 37.2MPa. The strength of the steel bars used in the beams was tested and to give an average ultimate strength of 363 MPa.

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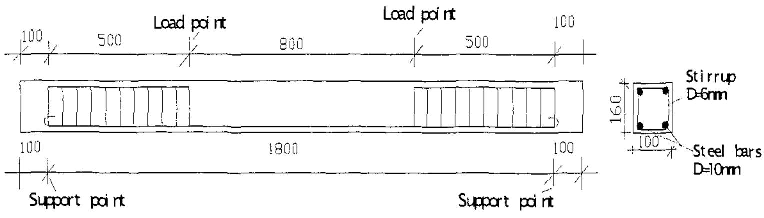


Figure 3: The dimensions and the steel bars of the tested beams

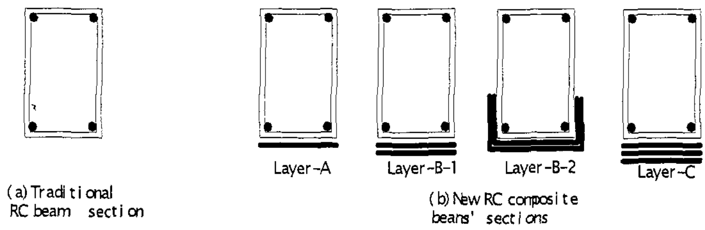


Figure 4: The sections of the beams

Figure 4 shows the traditional RC beam section and the corresponding new RC composite beam sections. The anti-crack layer thicknesses in the new RC composite beams are respectively 0.6, 1.2, 1.2, and 1.6mm. The GFRP layers were manually bonded on the bottom face of the beams 30days after the concrete was cast.

### 5.2 The experimental results

In the testing, loads were applied with a hydraulic actuator. Electrical strain gauges were used to measure the concrete strain and the steel strain, and the displacement gauges used to measure the beam deflection. Figure 5 is one of photograph of loading a beam.

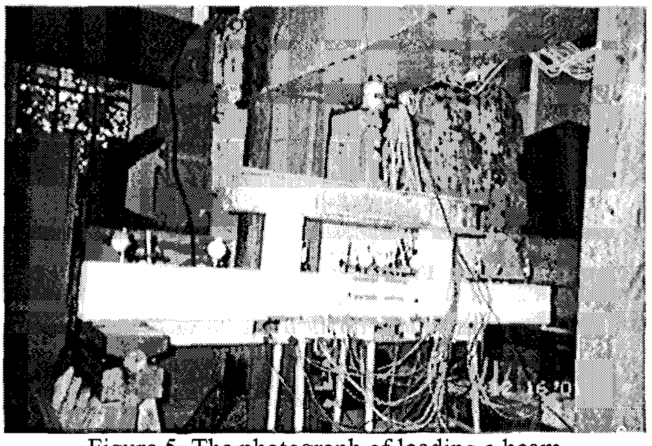

Figure 5: The photograph of loading a beam

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### 5.2.1 Load-deflection relations

The tested data clearly indicated that the cracks in the new RC composite beams emerged at much higher load levels, grew more slowly, and has shorter average spacing than the traditional RC beams.

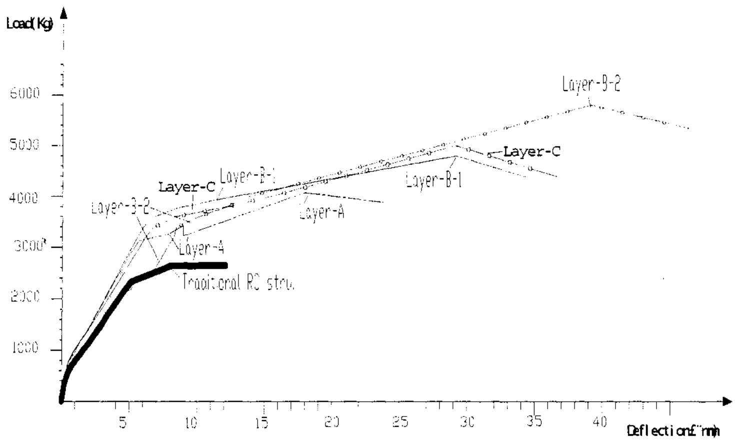


Figure 6: Load-deflection curves

From the experimental data, the load-deflection curves of the kinds of tested beams were drawn as Figure 6.

In figure 6, it is evident that the new RC composite beams have higher cracking loads, greater carrying capacities and better ductility than the traditional RC beams.

As the comparison, in other related literature [2][3][4][5], the beams bonded with steel plates or CFRP plates have only 50%--80% of the ductility of traditional RC beams with the same dimensions.

### 5.2.2 Steel bar strain

The maximum steel bar strain corresponding to the failure point of the traditional RC beams was about 1836 $\mu\varepsilon$, but that of the new RC composite beams was about 2500—4000 $\mu\varepsilon$. It means that the steel bars stress in the new RC beams surpassed the steel yield stress, and nearly reached its ultimate strength.

### 5.2.3 A surprising phenomenon

When the new RC composite beam failed, the load fell down from the peak value to a remnant level still much higher than the ultimate capacity of the traditional RC beam!

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# 6. Conclusions

From the previous analysis and the mentioned experiments, it is reasonable to draw the following conclusions:

i) It is feasible that to improve the performance of the traditional RC structure by bonding of GFRP layers under the guide of principles of fracture mechanics.
ii) Compared with the traditional RC structure, the new RC composite structure is an excellent structure that has higher ultimate carrying capacity, better ductility and serviceability.
iii) The concept of the new RC composite structure can apply to not only construction of new structures, but also strengthening old structures.
iv) For a certain carrying capacity, adopting the new RC composite structure can economize the material amount; for a certain material amount, the new RC composite structure can give a larger span.

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