

## CF パネル補強した RC 梁の耐衝撃性能に関する数値研究

Numerical study on impact resistance of CF panel retrofitted RC beam

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## 1. Introduction

To improve load carrying performance and impact resistance performance of existing structural members such as RC beams and pillars, it is common to install supporting sheets under the bottom of the members. Many researchers have been working on how to improve structural impact resistance by utilizing carbon fiber reinforced materials such as CFRP and AFRP<sup>1)</sup>. The authors have also been studying the retrofitting effect of continuous fiber composite panel (CF panel) on RC beam under free fall impact load. However, CF panel is a sandwich structure in which carbon fiber sheet is sandwiched between two flexible boards made of fiber reinforced cement. When using epoxy resin to bond CF panel on existing RC beam, the structure becomes multilayered and its failure behavior becomes extremely complicated under impact load.

Therefore, in this study, the authors firstly conducted a validation experiment for CF panel retrofitting method, and clarified the impact resistance of RC beam under free fall load. Furthermore, the influence of adhesive condition between layers of CF panel under impact load was investigated. CF panel peeling model was created and its retrofitting effect was validated by numerical analysis. Through controlling adhesive strength between layers, it was proved that the impact resistance of CF panel can be further improved.

## 2. Validation for CF panel retrofitting effect

## 2.1 Experimental program

## (1) Specimen

To clarify the impact resistance effect of CF panel for RC beam, the falling weight impact experiment was conducted. The test specimens RC beams with or without CF panel were set up.

RC beam and the reinforcing bars arrangement were shown in Fig-1. The size of RC beam specimen was 100×120×1200mm (width× height× length) with a span of 1000mm. The reinforcing bars inside the beam contained 2 tensile reinforcing bars of D10 (SD295A), 2 compressive reinforcing bars of D6 (SR295), and 11 stirrups of D6

(SR235). The stirrup spacing for RC beams was designed to be 100mm.

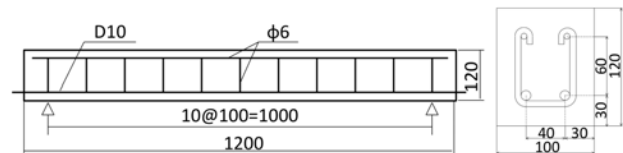


Fig-1 Reinforcement arrangement of RC beam (unit: mm)

## (2) Retrofitting method of CF panel

The specimen retrofitted from bottom side was taken into study in this paper, which was shown in Fig-2. The bonding material between panel and the surface of the beam is low-viscosity epoxy resin. It was measured that thickness of bonding material could be controlled around 0.5mm in average.

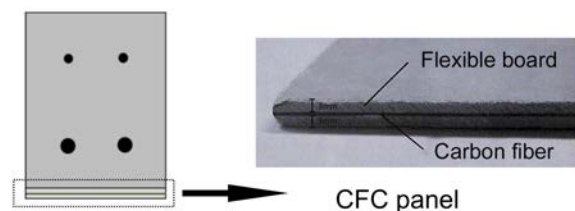


Fig-2 CF panel Installation

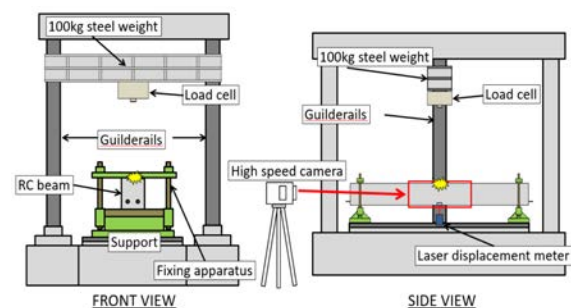


Fig-3 Falling weight impact machine

## (3) Loading and measurement method

The experimental facilities are shown in Fig-3. Two steel yokes were used as fixing apparatus to restrain the vertical movements of RC beams. The original weight of one steel

hammer was 100kg. The impact velocity was set to be 3m/s by letting hammer free fall from 45.9cm above the specimen. A load cell was installed on the steel hammer to determine impact force and laser reflection plate was set on the side of the beam to measure its mid-span displacement.

## 2.2 Numerical validation

A numerical analysis study was made based on finite element method in analysis software MSC Marc (2014.1). To be similar with the experimental study, 2 kinds of model were created: one was the regular beam contained 3 types of reinforcement bar, the other was with additional CF panel at the bottom (shown in Fig-4).

In this chapter, perfect bonding condition with and within CF panel was assumed. The connection nodes of RC beam with CF panel were jointed together and respectively merged into a single node, which guaranteed that no separation would occur along the contact face.

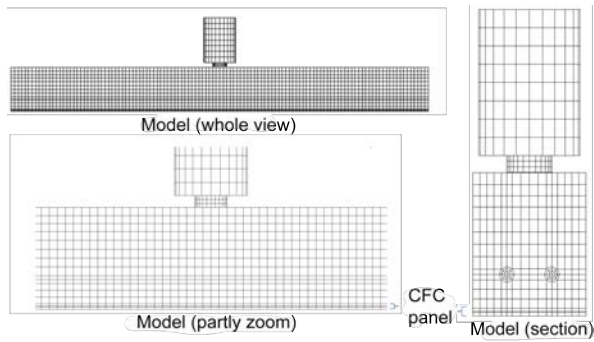


Fig-4 Numerical model in FEM analysis

### (1) Geometric properties

The whole structure was cut into several elements. In RC beam, the stirrup was set as 3-dimensional linear straight truss element with constant cross section. Other materials including loading hammer were all modeled as 3-dimensional 8-node hexahedral arbitrarily distorted brick solid element.

### (2) Material properties

#### I. Steel

The reinforcement bars and stirrup that made of steel were commonly taken as encountered isotropic ductile material that based on von Mises yield criterion.

#### II. Concrete

The generalized Mohr-Coulomb model developed by Drucker and Prager was applied into concrete material. According to Drucker-Prager yield criterion expressions (1a), the value A and B could be acquired, which could derivate the value of other two parameters  $\bar{\sigma}$  and  $\alpha$  that expressed as linear function of the hydrostatic stress (1b) in Mohr-Coulomb theory. The  $\bar{\sigma}$  was calculated as 4.9189 and  $\alpha$  was 0.5114.

$$\sqrt{J_2} = A + BI_1 \quad (1a)$$

$$\text{where, } A = \frac{2}{\sqrt{3}} \left( \frac{\sigma_t \sigma_c}{\sigma_t + \sigma_c} \right); B = \frac{1}{\sqrt{3}} \left( \frac{\sigma_t - \sigma_c}{\sigma_t + \sigma_c} \right)$$

$$f = \alpha J_1 + J_2^{1/2} - \frac{\bar{\sigma}}{\sqrt{3}} = 0 \quad (1b)$$

## III. Flexible board

Flexible board was mainly made of asbestos cement. In this study, allowing for the thickness and the actual main stress direction, it was simplified as a material possessing similar properties with cement. With the maximum compressive stress of 47.2 N/mm<sup>2</sup> and the tensile stress of 18.5 N/mm<sup>2</sup>,  $\bar{\sigma}$  at 26.4814 and  $\alpha$  at 0.2522 were acquired on applying Linear Mohr-Coulomb theory.

## IV. Carbon fiber

The core retrofitting part carbon fiber sheet inside the middle of the panel is a kind of anisotropic material. Carbon fiber sheet remained almost perfect undamaged during the experiment due to its high strength and stiffness. On the foundation of that, it was assumed to be suitable for von Mises criteria yield criterion<sup>2)</sup>.

## V. Epoxy resin

Epoxy resin is a kind of polymer which should adopt Tsai-Hill yield criterion, but in our specimen the thickness is so thin that we simplify it as an elastic-plastic isotropic material under von Mises yield criteria.

Table-1 Common items of material properties

Member	RC beam		CF panel		
	Concrete	Steel	Flexible board	Carbon fiber	Epoxy resin
Mass density (10 <sup>-3</sup> g /mm <sup>3</sup> )	2.499	7.855	1.6	1.818	1.11
Young's modulus (kN/mm <sup>2</sup> )	30.3	188	13	245	10.5
Poisson's ratio	0.2	0.3	0.1	0.1	0.3
Yield stress (N/mm <sup>2</sup> )	45.5	385	47.2	3400	85

Other common items of material properties were listed in Table-1. The effect of Rayleigh damping for steel and concrete was taken into consideration. Classical Rayleigh damping uses a system damping matrix that defined as  $C = \mu M + \lambda K$ . The mass matrix multiplier was calculated as 270 and stiffness matrix multiplier as 0.0002.

## 2.3 Comparison of experimental and analytical results

Under impact velocity of 3m/s, impact force (shown in Fig-5) and mid-span displacement (shown in Fig-6) were taken as evaluated parameters for impact resistance effect.

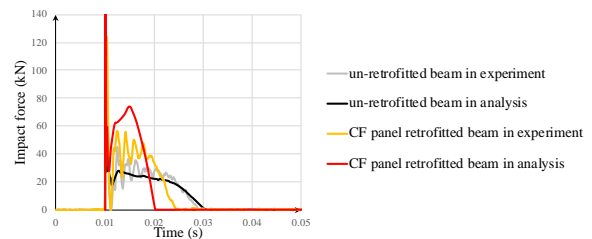


Fig-5 Impact force under impact of 3m/s

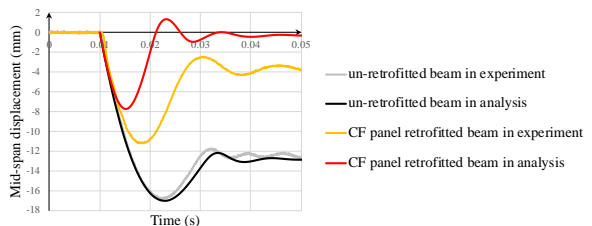


Fig-6 Mid-span displacement under impact of 3m/s

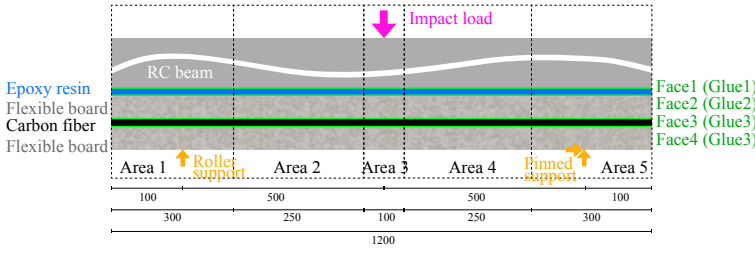


Fig-7 Contact faces of CF panel layers & Delamination regional division

In both experiment and analysis, the CF panel retrofitted beam has smaller peak displacement and residual displacement than un-retrofitted beam. It also displayed more hysteretic impact response and larger impact force than un-retrofitted beam. The effectiveness of CF panel retrofitting for RC beam was confirmed.

However, impact force and displacement of un-retrofitted beam in analysis was well consistent with that in the experiment, while CF panel retrofitted beam in analysis displayed larger impact force and smaller displacement than that in experiment. It was considered that when the CF panel was assumed to be perfect bonded with RC beam, the structure behaved larger stiffness.

Above these, it is necessary to reconsider the model of the CF panel and clarify how CF panel failure progress influences RC beam impact resistance effect.

### 3. CF panel delamination influences

#### 3.1 Structure of CF panel

Among CF panel sandwich composite layers, epoxy resin was uniformly smeared. As different material of contact surface lead to different bonding strength, there were 4 contact faces in which 3 types of contact glue in our case: beam's concrete with resin, resin with flexible board, and flexible board with carbon fiber sheet. To describe CF panel delamination mode more precisely, the panel along the span was divided into 5 areas (shown in Fig-7). The glued connection was supposed to break up when it reached a critical point.

#### 3.2 Numerical model for delamination

There are several methods to simulate CF panel delamination phenomenon. For instance, adding breakable spring links between layers, creating interface elements that allowing bond-slip, etc. In this study, contact model based on the theory of Breaking Glue was attempted to simulate CF panel delamination.

BREAKING GLUE model can break up the glued connection node using a stress criterion<sup>3)</sup>. When the following criterion is fulfilled at a node, the glued contact is released:

$$\left(\frac{\sigma_n}{S_n}\right)^m + \left(\frac{\sigma_t}{S_t}\right)^n > 1 \quad (2a)$$

where,

$\sigma_n$ : Normal stress

$\sigma_t$ : Tangential stress

$S_n$ : Critical normal stress

$S_t$ : Critical tangential stress

$m, n$ : Dominant factor coefficient (assumed as 2)

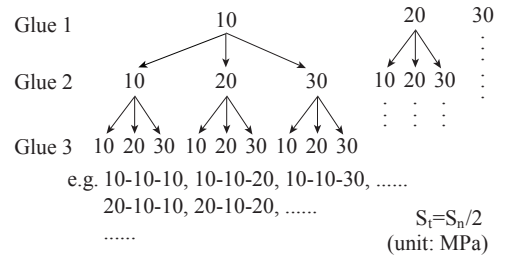


Fig-8 Combinations of  $S_n$  (critical normal stress) in bonding strength

When a node is released, its status is changed from being glued to standard contact, permitting separation and friction. The contact stresses are calculated using extrapolated stresses for solid elements.

To clarify the relationship of bonding strength with separation mode and impact response, a series of combination for bonding strength of different contact face were listed. It was assumed that the ratio of critical normal stress to critical tangential stress keeps a constant value 2 ( $S_n/S_t=2$ ) and each glue has 3 possible critical normal stress values ranging from 10MPa to 30MPa with step of 10MPa. Thus, 27 combinations were generated (shown in Fig-8).

#### 3.3 CF panel delamination failure types

By repeating analysis with different combinations of critical stress, several common failure patterns of CF panel arose. Final deformation at last increment and initial separated location were what we most concerned. When separation took place at a certain point, the node was duplicated and displacement of node occurred at once. The separation could be detected by checking node condition and contact condition at every increment.

Based on the delamination progress and final failure condition of CF panel, 5 types of delamination mode were classified, which was sketched in Fig-9. Bonding strength numerical characteristics of each delamination mode were concluded in Table-2. It should be mentioned that area 5 of face 4 where fixed support was started to separate at first in every case. However, this phenomenon had little influences on other faces delamination nor furtherly propagated itself. In the elaboration of delamination mode below, these separations were not mentioned.

##### (1) No.1 delamination mode

It was the most representative one that solely required critical stress of glue 2 (face 2) to be small enough (10MPa). Area 2 and area 4 of face 2 started to separate at first and propagated to adjacent areas. The void spaces are merged together in the middle, which causes almost the whole areas in face 2 separated. Only area 1 of face 2 kept partly unseparated.

##### (2) No.2 delamination mode

When glue 3 (face 3 and 4) was small enough (10MPa), No.1 delamination mode occurred. The separation started from area 2 and 4 of face 3 and propagated to adjacent areas as well. It broke through the whole face 3 at last.

##### (3) No.3 delamination mode

No.3 mode was considered as the regular expected delamination mode without specific characteristics. No obvious dominated separation could be observed during the whole progress.

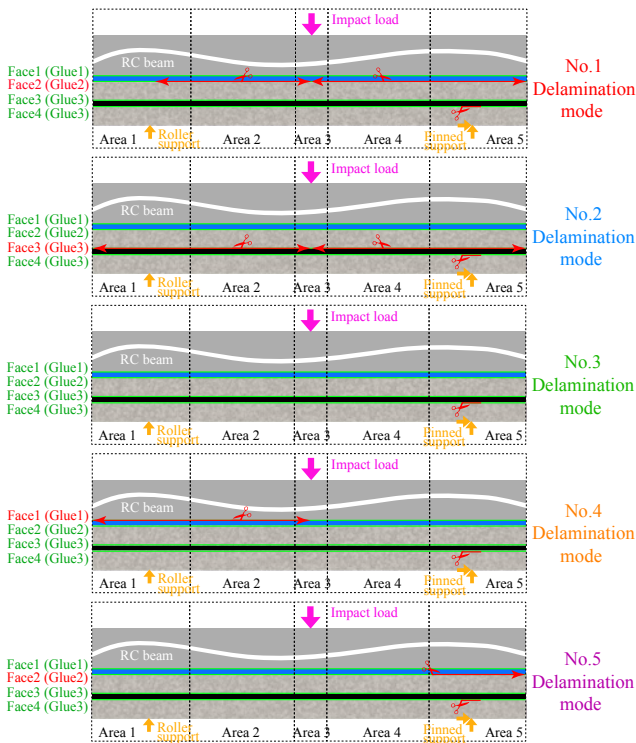


Fig-9 Delamination failure types of CF panel under different bonding strength combination

#### (4) No.4 delamination mode

When glue 1 was small enough (10MPa) and the other 2 glues were larger than glue 1, No.4 delamination mode took place. The separation started from area 2 of face 1. It extended through area 1 of face 1 to the nearest end.

#### (5) No.5 delamination mode

This mode exclusively required largest glue 1 (30MPa) and second largest glue 2 (20MPa) and glue 3 no less than 20MPa. It contains only 2 cases, but did not resemble with any other separation progress. Separation started from area 5 of face 2 and grew to the outside end which made area 5 of face 2 the only eye-catching separation area.

#### 3.4 Impact response under different delamination mode

Every delamination mode contains at least two cases and every case in the same delamination mode shares a similar impact response. As shown in Fig-10, it is obviously that delamination mode of CF panel has huge influences on RC beam's impact response. A larger displacement indicates a worse reinforcement effect of CF panel. No.1 delamination mode has the closest displacement peak value as experimental result yet larger residual displacement. No.2 delamination mode might be the best one illustrating the real situation in the impact load experiment, according to delamination progress and final condition of CF panel. Bonding strength combinations in No.3 and No.4 delamination mode was proved to be better than realistic situation. Residual displacement in No.5 delamination mode remains in a positive value, which appears to be abnormal in this analysis.

It should be mentioned that in the experimental results, CF panel separated from carbon fiber upper contact face. It indicates that real glue condition is closer to No.2 mode series that glue 3 is more vulnerable. However, if all the

Table-2 Bonding strength combinations for each delamination mode

$S_u$ (MPa)			Delamination mode	$S_u$ (MPa)			Delamination mode	
Glue 1 (Face 1)	Glue 2 (Face 2)	Glue3 (Face 3,4)		Glue 1 (Face 1)	Glue 2 (Face 2)	Glue3 (Face 3,4)		
10	10	10	No.1 Delamination mode	10	20	10	No.2 Delamination mode	
10	10	20		10	30	10		
10	10	30		20	20	10		
20	10	10		20	30	10		
20	10	20		30	20	10		
20	10	30		30	30	10		
30	10	10		10	20	20		No.3 Delamination mode
30	10	20		20	20	20		
30	10	30		20	20	30		
10	20	30		20	30	20		
10	30	20	20	30	30			
10	30	30	30	30	20			
30	20	20	30	30	30			
30	20	30	$S_u = S_u/2$					

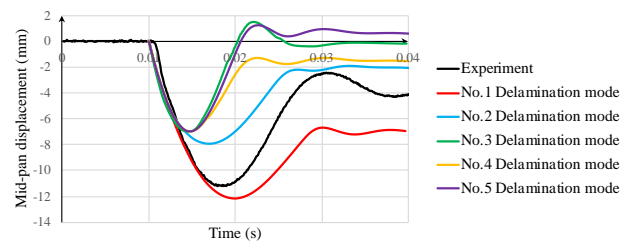


Fig-10 Structural displacement of each delamination mode

glue conditions have little differences, the contact face 2 is most likely to break.

#### 4. Conclusion

The conclusions obtained in this research are:

a. It has been confirmed that retrofitting CF panel on RC beam could sufficiently reduce the displacement and improve structural impact resistance effect.

b. The effect of CF panel tends to be excessive evaluated in analysis. Delamination of CF panel has influences on analyzing accuracy.

c. In general, the bonding face of flexible board with epoxy resin in CF panel is a crucial face in controlling structural impact response. The separation of it would decrease the impact resistance of the beam largely.

For further research, the constituent of CF panel should be reconsidered, including material properties and bonding strength. More combinations of critical stresses are expected to be tested in the purpose of optimization on the bonding condition.

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