コンクリート工学年次論文集，Vol.41，No.2，2019

- Technical Paper –

NUMERICAL STUDY ON FAILURE BEHAVIOR OF RC BEAM RETROFITTED BY CFC PANEL UNDER IMPACT LOAD

Jianheng ZENG[*1], Hiroki TAMAI[*2], Yoshimi SONODA[*3] and Hirotoshi OBI[*4]

ABSTRACT

To enhance the bending or impact resistance for RC beams, one of the methods is attaching carbon fiber sheets or reinforcement panels to the bottom surface. Since in this study, our interest lies on the continuous fiber composite (CFC) panel which has a multilayer structure, and its failure behavior is extremely complicated. In this study, numerical analysis for failure behavior of RC beam retrofitted by CFC panel under impact load was conducted. Several kinds of failure behaviors were classified on the basis of different combinations of bonding strength between layers.

Keywords: impact load, CFC panel, bonding effect, numerical analysis

1. INTRODUCTION

In order to improve load carrying performance and impact resistance performance of existing structural members such as RC beams and pillars, it is common to attach a sheet on the bottom surface of the member or to wrap the member with a sheet. Several studies have been done on its effectiveness [1, 2]. The authors also have been studying whether the continuous fiber composite (CFC) panel that already been proven as seismic retrofit applications [3] can be effectively applied for improving impact resistance performance by several experiments. However, the panel is a sandwich structure in which a carbon fiber sheet is sandwiched between flexible boards which are fiber reinforced cement boards. When utilizing epoxy resin to bond CFC panel on existing RC beam, the structure becomes a multilayer structure of which the failure behavior becomes very complicated under impact load.

Therefore, in this study, we firstly adopted a regular bonding method for CFC panel which has been proved to be effective in seismic reinforcement, and clarified the impact resistance of RC beam retrofitted by CFC panel by impact experiment. Furthermore, the influence of the adhesive strength between the layers on the failure behavior at impact load was investigated. By controlling the adhesive strength between layers, it was proved that the impact resistance of CFC panel can be further improved.

2. IMPACT RESISTANCE EFFECT OF CFC PANEL RETROFITTED ON RC BEAM

2.1 Experiment

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

(1) Specimen configuration

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.

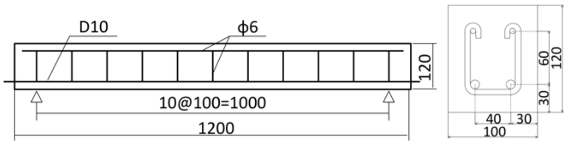


Fig.1 Reinforcement arrangement of RC beam (unit: mm)

(2) Retrofitting method by CFC panel

Several types of installation for CFC panel were proposed, attaching above or below the beam or 3-sides wrapping method. It was already known that upper retrofitting method was less effective than bottom retrofitting, while the 3-sides retrofitting method would be more sophisticated and higher uncertainty in analysis, though better reinforcement effect, only specimens retrofitted from bottom side were 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 anticipated that thickness of bonding material could be controlled around 0.5mm in average, of which the cushion effect

---

*1 Dept. of Civil Engineering, Kyushu University, JCI Student Member
*2 Assistant Prof., Dept. of Civil Engineering, Kyushu University, JCI Member
*3 Prof., Dept. of Civil Engineering, Kyushu University, JCI Member
*4 Civil Engineering Research Institute, Technology Center, Taisei Corporation, JCI Member

would not be too significant to disturb the observation on CFC panel's effect.

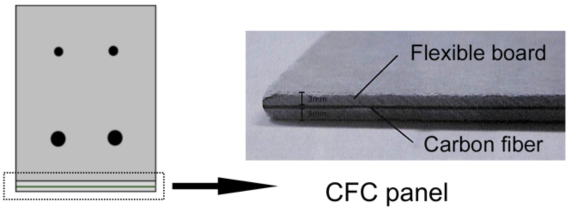


Fig.2 CFC panel Installation

(3) Loading facilities and method

The experimental facilities are shown in Fig.3. A load cell was installed on the steel hammer to determine the impact force and four load cells were designed under the support of the specimen to determine the reaction force during the impact process. 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 1m/s or 3m/s by letting hammer free fall from 5.1cm or 45.9cm above the specimen.

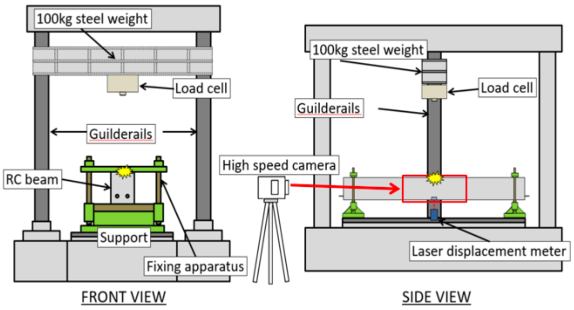


Fig.3 Falling weight impact machine

(4) Results

On the conditions above, 4 cases were listed. Under impact velocity of 1m/s or 3m/s, CFC panel retrofitted beam or un-retrofitted beam were taken into consideration. Impact force from the weight, displacement in the middle of span were the main evaluation parameters for the impact reaction.

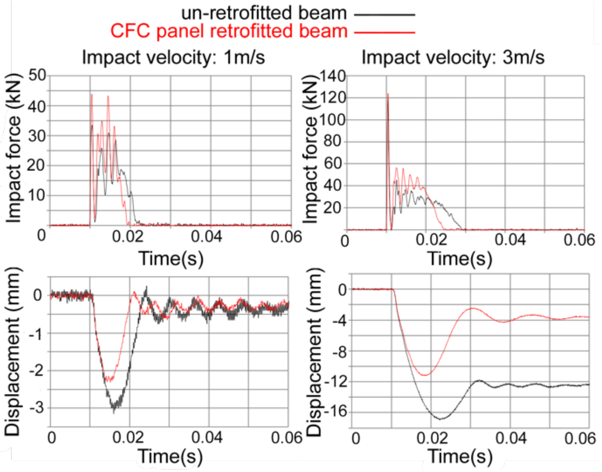


Fig.4 Impact response in experiment

In Fig.4, it shows the first round of impact loading, that one peak of wave indicates one impact load on the structure. The displacement history as well as the residual displacement of the mid-span in the retrofitted beam is smaller than un-retrofitted beam, which could be easily recognized in both 1m/s and 3m/s cases. In the case of 1m/s, the residual displacement reduction is so significant that reaches one third the un-retrofitted beam [4].

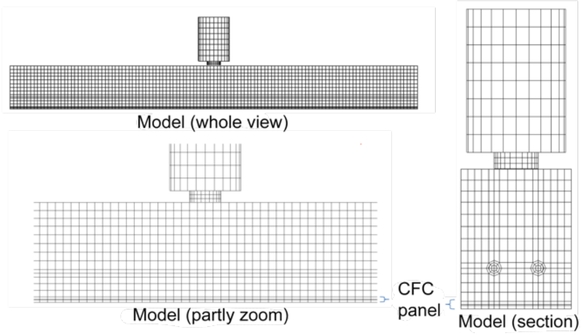


Fig.5 Mesh of model in FEM analysis

2.2 Analysis

A numerical analysis study was made based on finite element method, 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 with additional CFC panel at the bottom (shown in Fig.5). At first step, perfect bonding condition with and within CFC panel was assumed. The connection nodes of beam with CFC panel were jointed together and respectively merged into a single node, which guaranteed that no separation would occur along the contact face.

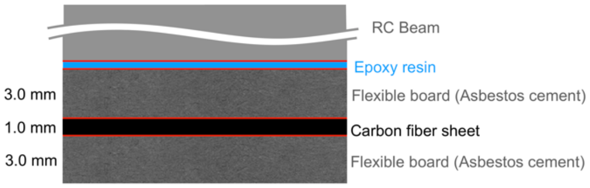


Fig.6 Figuration and component of CFC panel

(1) Geometric properties

The figuration of the beam was absolutely the same as real specimen. Tensile reinforcement bars and compressive reinforcement bars inside the concrete adopted solid element while the stirrup was set as truss element in the model. Additional interface between tensile reinforcement bars and concrete was modeled to simulate friction and slip. Restriction condition at support in the experiment could approximate as one side being fixed and the other side roller. The process of transient dynamic analysis was set within 0.05s once the loading weight attached the beam. The design structure of CFC panel was shown in Fig.6. It was a sandwich composite that carbon fiber sheet stacked in the middle and flexible board on the side. Between the laminated layers was a slight layer of bonding material of which thickness could be neglected. As bonding material between panel and beam was about 0.5mm, it is equivalently large enough that could be modeled in solid element.

(2) Material properties

The analyzing model for reinforcement bars was commonly based on von Mises yield criterion, which is part of plasticity theory that applies best to ductile materials. The average yield strength of reinforcement bars was reported as 358N/mm^2 in the experiment. Concrete, brittle material, adopted Mohr-Coulomb theory. Based on compressive strength of concrete test (JIS A 1108) and the modulus of elasticity of concrete test (JIS A 1149), it was tested that the average compressive strength of concrete is 45.5N/mm^2, average tensile strength is 2.6N/mm^2. Flexible board was mainly made of asbestos cement. It could be considered as a material possessing similar properties with cement. With the maximum compressive stress of 47.2 N/mm^2 and the tensile stress of 18.5 N/mm^2 [5]. The core retrofitting part carbon fiber sheet inside the middle of the panel is also 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, we assumed it suitable for von Mises criteria with an equivalent high value of yield stress at 3400N/mm^2. Epoxy resin is so thin that we simplify it as an elastic-plastic isotropic material under von Mises criteria with the yield stress of 85N/mm^2.

Other common properties are listed in Table 1. For all materials mentioned above, the effect of Rayleigh damping was also 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.

Table 1 Common items of material properties

	Concrete	Steel	Flexible board	Carbon fiber	epoxy resin
Mass density (10^{-3}g /mm^3)	2.499	7.855	1.6	1.818	1.11
Young's modulus (kN/mm^2)	30.3	188	13	245	10.5
Poisson's ratio	0.2	0.3	0.1	0.1	0.3

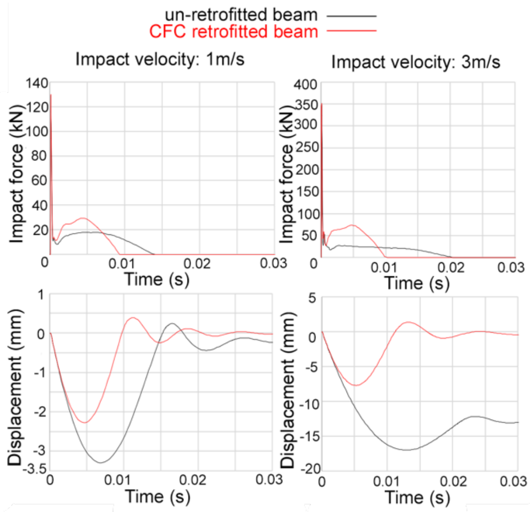
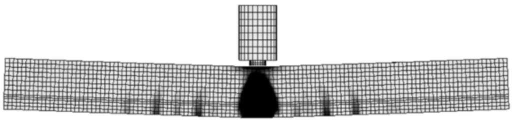


Fig.7 Impact response in FEM analysis

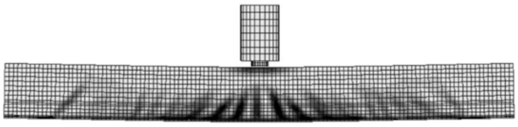
(3) Results

The responses at first impact were exported, which were the most representative during the whole process of loading. Impact force and displacement in the middle node of the whole span were shown in Fig.7. CFC panel retrofitted beam has obviously better impact resistance effect than un-retrofitted one. This phenomenon is more distinct when the impact velocity is 3m/s.

On the other hand, the crack distribution became positively uniform and small due to the installation of CFC panel at the bottom. Here only the case of impact velocity at 3m/s was figured below because its cracking pattern was easier to be distinguished than 1m/s. The maximum principal strain of elements depicted cracking pattern of the structure. As for un-retrofitted RC beam, cracks concentrated in the center of the beam that even ruptured whole section of the beam in the middle span, whereas in the case of CFC panel retrofitted beam, spacing of the cracks reduced and spread to larger areas under the beam (shown in Fig.8). In experimental results, CFC panel also showed an excellent effect on suppressing crack development. However, because CFC panel delamination occurred in the experiment but not in analysis, cracking pattern was not well evenly distributed in the experiment. It was proved that cracking propagation and distribution could be well-controlled by CFC panel.



Un-retrofitted RC beam



CFC panel retrofitted RC beam

Impact velocity: 3m/s

Fig.8 Crack distribution (Maximum principal strain)

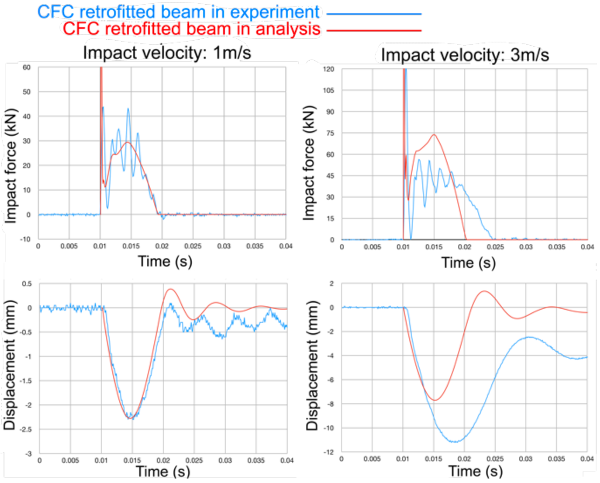


Fig.9 Impact response comparison of CFC retrofitted RC beam in experiment and analysis

2.3 Comparison between experiment and analysis

The effectiveness of CFC panel retrofitting for RC beam was validated in both experiment and analysis. However, as the CFC panel being assumed to be perfect bonded with RC beam and no delamination would occur inside the panel, analyzing result was expected to be stiffer than experimental result. As shown in Fig.9, the displacement in the analysis was smaller than that in the experiment when retrofitted with CFC panel, whereas the displacement kept the same when no CFC panel being applied, which was shown in Fig.10. Above these, it is necessary to reconsider the modeling of the CFC panel and figure out how panel's performance influences failure mode of RC beam.

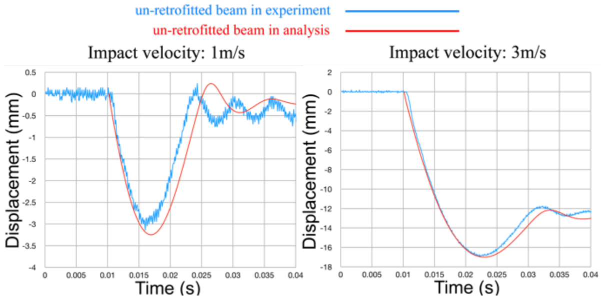


Fig.10 Impact response comparison of un-retrofitted RC beam in experiment and analysis

3. BEHAVIOR OF RC BEAM ALLOWING FOR DELAMINATION OF CFC PANEL

In the upgrading for CFC panel's model, delamination of CFC panel was taken into account. According to experimental results, cases at impact velocity of 3m/s was prone to have visible separation, while at low velocity the panel may separate but hard or laborious to detect in analysis. Hence, only impact velocity at 3m/s was studied.

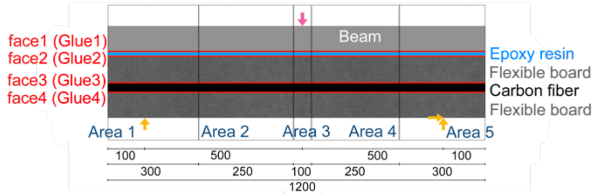


Fig.11 Contact face of inner CFC panel & Delamination regional division

3.1 Mathematic model for delamination

As already explained above, CFC panel was bonded with RC beam by epoxy resin, which was modeled as solid element. Among sandwich composite layers, epoxy resin was uniformly smeared. Even though same bonding material was adopted, different material of contact surface will cause different bonding strength. In our case, there are 4 contact faces in which 3 types of contact glue. In order to describe CFC panel delamination mode more precisely, the panel along the span was divided into 5 areas that shown in Fig.11: beam's concrete with resin, resin with flexible board, and flexible board with carbon fiber sheet. The glued connection was supposed to break up when reached a critical point.

There are many methods for modelling delamination phenomenon, for instance, adding springs between layers, creating elements such as interfaces based on fracture mechanism and etc. In this study, we tried to simulate delamination by contact analysis on the theory of BREAKING GLUE.

BREAKING GLUE model is capable of breaking up the glued connection using a stress criterion [6]. When the following criterion is fulfilled at a node, the glued contact is released:

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

where,

σ_n: Normal stress
σ_t: Tangential stress
S_n: Critical normal stress
S_t: Critical tangential stress
m, n: Dominant factor coefficient (assumed as 2)

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.

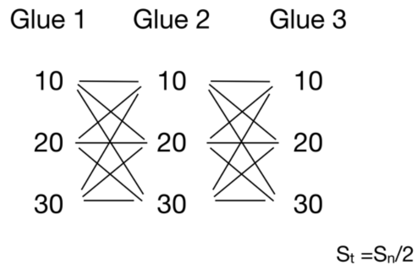


Fig.12 Combinations of critical normal stress of BREAKING GLUE (unit: MPa)

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 known that critical stress in normal direction is larger than that in tangential direction. We assumed that the ratio of critical normal stress to critical tangential stress maintains at 2 ($S_n/S_t=2$) and each glue has 3 possible critical normal stresses ranging from 10MPa to 30MPa with step of 10MPa [7]. Thus, 27 combinations were generated, which was shown is Fig.12.

3.2 Influences of CFC panel delamination on impact response

By repeating analysis with different combination of critical stresses, several common failure patterns of CFC panel arose. Final deformation at last increment and initial separated location were what we most concerned. When separation takes place at certain point, the node would be duplicated and displacement of node occurs at once. The separation could be detected by checking nodes at every increment when graphics being enlarged enough.

(1) Delamination mode

As for the final delamination of CFC panel, results could be classified into 5 types and every delamination mode was sketched in Fig.13. It should be mention above all that area 5 of face 4 in the location that exactly around the fixed support starts to separate at first in every case. However, it has trifle influences on delamination from other faces or further propagation on itself. In the elaboration of delamination mode below, these separations will not be mentioned.

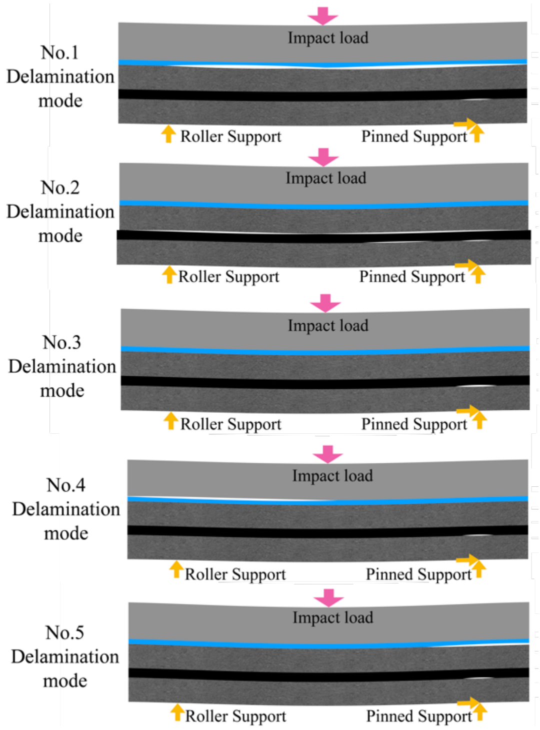


Fig.13 Delamination mode allowing for different bonding strength among CFC inner layers

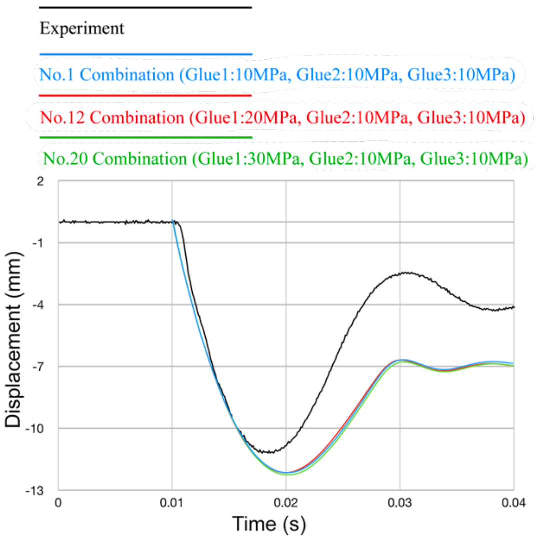


Fig.14 Examples: Impact response of RC beam in No.1 delamination mode of CFC panel

In No.1 delamination mode, which is the most representative one, area 2 and 4 of face 2 start to separate at first and propagate to adjacent areas. The void spaces are merged together in the middle, which causes almost the whole areas in layer 2 separated. In No.2 delamination mode, similarly separation starts from area 2 and 4 of face 3 and breaks through the whole layer at last. In No.3 delamination mode, no obvious large separation could be observed during the whole progress. In No.4 delamination mode, separation starts form area 2 of face 1 and extends to nearest end. No.5 delamination mode contains only 2 cases, but does not resemble with any other separation ways. It starts form area 5 of face 2 and grows to the outside end which makes area 5 of face 2 the only eye-catching separation area.

(2) Impact response of RC beam allowing for delamination mode of CFC panel

Every delamination mode contains at least two cases and every case in the same delamination mode shares a similar impact response. We randomly picked up 3 cases from No.1 delamination mode and used displacement history data of the mid-span to plot, which was shown in Fig.14. Experimental results were put in for comparison.

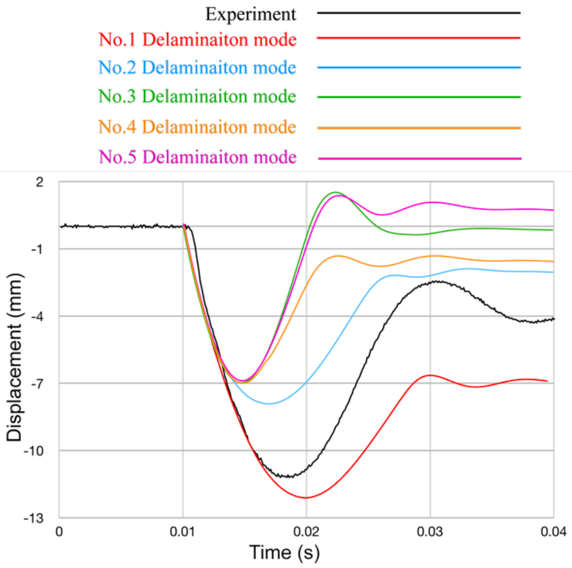


Fig.15 Impact response of RC beam in different delamination mode of CFC panel

As shown in Fig.15, it is obviously that delamination mode of CFC panel has huge influences on RC beam's impact response. The larger displacement indicates a worse reinforcement effect of CFC panel. No.1 delamination mode has the closet displacement peak value as experimental result yet larger residual displacement. While No.2 delamination mode might be the best one illustrating the real situation of impact load experiment. Bonding strength in No.3 and No.4 delamination mode was proved to be stronger than realistic situation. In No.5 delamination mode, residual displacement remains in positive value, which appears to be abnormal in this analysis.

3.3 Delamination mode with different bonding strength

Now that different delamination mode of panel causes divergences in impact response for RC beam, and the different bonding strength combinations among layers leads to different separation mode in CFC panel. 27 combinations of critical stresses were listed out and delamination mode for each combination was combed out.

(1) Regularity of delamination mode (when S_n/S_t =2)

According to Table 2, the CFC delamination mode under different combinations of bonding strength, No.1 delamination mode solely requires critical stress of glue 2 (face 2) to be small enough (10MPa). One of the basic requirements for No.2 delamination mode is that glue 3 (face 3 and 4) to be small enough (10MPa). When glue 1 is small enough (10MPa) and the other 2 glues are larger than glue 1, No.4 delamination mode will take place. No.5 delamination mode exclusively requires largest glue 1 (30MPa) and second largest glue 2 (20MPa) and glue 3 no less than 20MPa. Rest of the cases will all result in mode No.3 that no separation would occur except that area 5 of face 4 would separate on restricted level.

It should be mentioned that in the experimental results, CFC panel separated from carbon fiber upper contact face. It indicates that glue condition is closer to No.2 mode series that glue 3 is more vulnerable. However, if all the glue conditions have little differences, the contact face 2 would be the weakest.

Table 2 Combinations of bonding strength with corresponding delamination mode (unit: MPa)

S_n (Mpa)			Delamination mode	S_n (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	No.4 Delamination mode	20	30	20	
10	30	20		20	30	30	
10	30	30		30	30	20	
30	20	20	No.5 Delamination mode	30	30	30	
30	20	30					$S_t=S_n/2$

(2) Delamination mode of CFC panel when S_n/S_t =1

It was observed that almost all separations started from tangential direction which indicated that critical tangential stress might be determinant for separation. Thus, another assumption that critical normal stress is the same as critical tangential stress (S_n/S_t =1) was made to test all combinations of stresses. Another 27 combinations were generated and results were sorted out. Most results converged into No.3 delamination mode apart from cases that previously resulted in No.1 mode when S_n/S_t =2. These 9 cases have the smallest stress in glue 2 (face 2) and resulted in No.5 delamination mode.

It could be concluded that by increasing critical tangential stress of bonding, separation mode could be well-controlled and impact resistance could be improved as a result.

4. CONLUSION

The conclusions obtained in this research are as follows:

(1) It has been declared that retrofitting CFC panel on RC beam could sufficiently reduce the displacement and is capable of controlling crack distribution in experiment and analysis as well.

(2) The effect of CFC panel would be excessive evaluated in analysis. Delamination of CFC panel has influences on analyzing accuracy.

(3) In general, contact face 2 (flexible board with epoxy resin) of CFC panel is a weak but an important point in delamination. The separation of face 2 would decrease the impact resistance of the beam largely.

(4) By improving tangential resistance of bonding for CFC panel, delamination could be well-controlled and results in splendid improvement on RC beam impact resistance.

For further research, the constituent of CFC 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.

REFERENCE

[1] 船木隆史, 岸徳光, 栗橋祐介, 三上浩, “CFRP シート曲げ補強した RC 梁の耐衝撃挙,” コンクリート工学年次論文集, Vol.39, 2017. 07, pp.577-582.

[2] 佐藤元彦, 栗橋祐介, 三上浩, 岸徳光, “AFRP および PFRP シートで曲げ補強した RC 梁の重錘落下衝撃実験,” コンクリート工学年次論文集, Vol.37. 2015.07, pp.1153-1158.

[3] 岡本修一, 河村圭亮, 福浦尚之, 新藤竹文, “連続炭素繊維シート複合パネルによる柱部材の耐震補強効果確認実験,” 大成建設技術センター報, Vol.46, 2013.

[4] Hiroki Tamai and Yoshimi Sonoda, “A Study on Impact Resistant Capacity of RC Slab with Corroded Reinforcement and its retrofitting method,” Proceedings of 6th International Conference on Design and Analysis of Protective Structures, 2017.11, pp.559-564.

[5] P. D. Soden, M. J. Hinton and A. S. Kaddour, “Lamina Properties, Lay-up Configurations and Loading Conditions for A Range of Fiber-reinforced Composite Laminates,” Composites Science and Technology, Vol.58, 1998, pp.1011-1022.

[6] “MSC Marc&Mentat Manuals Volume A: Theory and User Information,”, MSC Software Corporation, 2014.2, pp.630-632.

[7] P. Hancock, R. C. Cuthbertson, “The Effect of Fiber Length and Interracial Bond in Glass Fiber-Epoxy Resin Composites,” Journal of Materials Science Vol.5, 1970, pp.762-768.