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# Effect of Multi- steel bolt anchorages on Composite Beams

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## ABSTRACT

*Using fiber-reinforced polymer (FRP) to retrofit or strengthen the concrete structures is an attractive option in construction areas nowadays. However, premature debonding failures limit the efficacy of fiber utilization. It is presently accepted that anchorage system is an attractive option to solve this problem. Much effort has been made through experimental testing and numerical modeling to investigate the anchorage systems, meanwhile various systems were created and developed. However, research on the mechanism of the anchorage systems is still too rare to build a countable and union design guideline with respect to different premature debonding failure modes. The present paper focused on two commonly documented anchorage methods: steel bolt anchorage and CFRP end wrapping anchorage and conducted a specially design experiment to further analyze the mechanism of effect of both systems on premature debonding failures (concrete cover separation and IC debonding). Results show that CFRP wrapping and Steel bolts can both effectively stop or suppress the propagation of IC debonding. Further, the ultimate load is effected by the final failure mode, which changed with different height of steel bolt.*

**Keywords:** CFRP, Steel bolt anchorage, Concrete cover separation (*CCS*), IC debonding (*ICD*), RC beam

## 1.0 INTRODUCTION

Externally bonding fiber-reinforced polymer (FRP) to the tension face of reinforced concrete (RC) beams was widely recognized as a popular method for flexural strengthening or retrofitting. The suitability of this material is largely due to its light weight, superior tensile strength, and its resistance to corrosion when compared to steel material (Kalfat *et al.* 2013). However, challenges still exist and the biggest one maybe the commonly faced premature debonding failure. This type of failure often occurs with the strain of FRP material much lower than the full level of utilization, which narrows the application of the externally bonding FRP method. Two main failure modes were observed: intermediate crack debonding (IC debonding) and concrete cover separation (CCS).

IC debonding initiates from a major flexural crack in the high moment region and propagate along the interface between the FRP plate and the concrete towards the FRP plate end (Teng *et al.* 2003; Lu *et al.* 2007). This type of failure has been studied for more than one decades, and extensive test results and strength models on the IC debonding has been reported ( Chen *et al.* 2006; Wu and Niu 2007; Bilotta *et al.* 2013; Elsanadedy *et al.* 2014). Compared to IC debonding, CCS was more widespread, which initiates at the critical plate end and then propagate horizontally along the tension reinforcement towards the mid-span (Yao and Teng 2007; Zhang *et al.* 2012(a); Zhang *et al.* 2012(b) ).

Both kinds of premature debonding failure bring low utilization rate of the FRP material, which has been an important limitation of the FRP flexural strengthening technique. It is understood that the premature debonding failures could be suppressed or prevented when sufficient anchorage is provided (Galal and Mofidi 2010). Three main types of anchorage systems have been developed to date (Kalfat *et al.* 2011): (1). Mechanically fastened metallic anchors (Garden and Hollaway 1998; Duthinh and Starnes 2001; Wu and Huang 2008); (2) U-jacket anchors (Smith and Teng 2003; Al-Amery and Al-Mahaidi 2006; Yalim *et al.* 2008); (3) FRP anchors (Lam and Teng 2001; Eshwar *et al.* 2005; Micelli *et al.* 2010; Zhang and Smith 2012). As more and more anchorage systems developed, efforts taken on the mechanism of anchorage systems are still far away from practice. The strength model of strengthened beams with anchorage systems should be investigated and newly developed.

Against the above background, this paper presents an experimental study with specially designed specimens that adopted steel bolt anchorages at one side and CFRP end wrapping at the other of the same CFRP strengthened beam. Five specimens were tested with two serials of three-point bending to: 1) further analyze the mechanism of effect of steel bolt anchorage system on IC debonding and concrete cover separation; 2) explore the influence of CFRP end wrapping anchorage on IC debonding; 3) help build a systematic analytical model to predict debonding load with respect to various premature failures.

## 2.0 EXPERIMENT PROGRAM

### 2.1 Testing Specimens

The experiment consisted of five CFRP strengthened beams with anchorages. The same geometry and reinforcement arrangement was adopted as detailed in Fig. 1. All specimens were 200 mm in width, 150 mm deep and employed two deformed bars of diameter 10 mm as internal steel reinforcement in compression and tension, respectively. For all beams 10 mm diameter plain bar stirrups were placed along the entire length of the beam with a spacing of 100 mm except the two supports with a spacing of 50 mm. Values of inferior, superior and sideward concrete cover were 20 mm, 15 mm and 25 mm, respectively. One layer of CFRP wrapping with a width of 100 mm was bonded to the CFRP laminate end for anchorage, and one layer of CFRP wrapping with a width of 70 mm was bonded to the mid-span of the beams to avoid IC debonding propagate from one side to the other. For control specimen, only mid-span was wrapped by a layer of CFRP laminate.

Two serials of three-point bending test were conducted. The second serial was a modified three point bending test with a shear span of 322.5 mm for specimens whose steel bolts and concrete cover were still in good condition after the first three point bending test as shown in Fig. 2. Three linear variable differential transformers (LVDTs) were used to measure deflections at different locations: two at the two supports, and one at the mid-span of the beam, respectively (Fig. 1 and Fig. 2).

The parameters of specimens in two serial tests are listed in Table 1, where la, bf, nf represents the length of steel bolt, the total width of CFRP laminate at bottom surface and number of layers of CFRP laminate, respectively. Specimens were named L1500-x-y, x was the height of the steel bolts

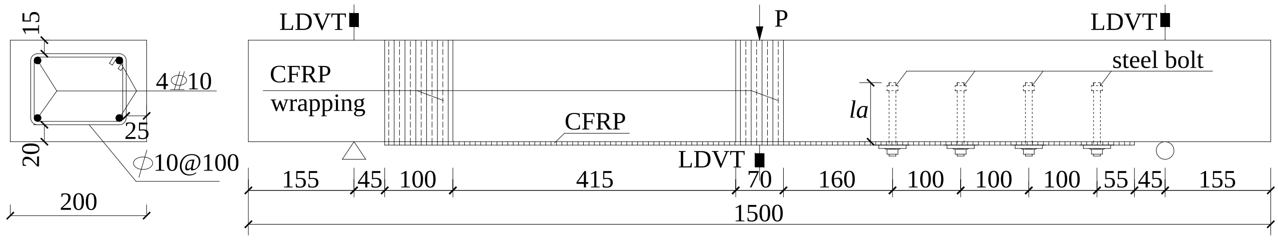



**Fig.1.** Geometry and reinforcement arrangement (unit: mm)

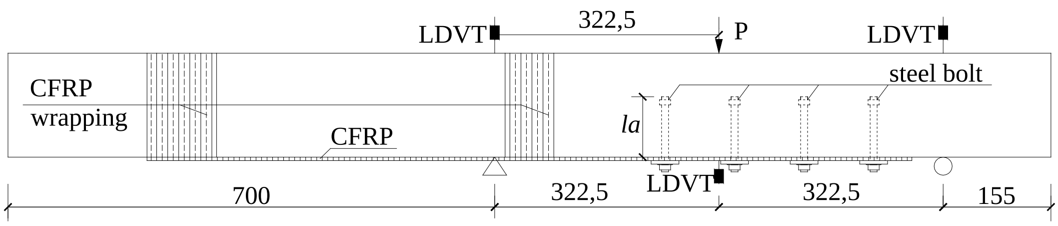



**Fig.2.** The second serial three point bending test (unit: mm)

**Table 1.** Parameters of specimens

| Case | Label | Shear span (mm) | $l_a$ (mm) | $b_f$ (mm) | $n_f$ | Ultimate load $P_u$ (kN) | Failure mode |
|---|---|---|---|---|---|---|---|
| I | L1500-0-1 | 595 | 0 | 160 | 4 | 55.77 | ICD |
| | L1500-50-1 | 595 | 50 | 160 | 4 | 71.49 | CCS |
| | L1500-70-1 | 595 | 70 | 160 | 4 | 62.14 | ICD |
| | L1500-120-1 | 595 | 120 | 160 | 4 | 65.00 | ICD |
| | L1500-150-1 | 595 | 150 | 160 | 4 | 66.25 | ICD |
| II | L1500-0-2 | 322.5 | 0 | 160 | 4 | 71.79 | CCS |
| | L1500-70-2 | 322.5 | 70 | 160 | 4 | 82.86 | CCS |
| | L1500-120-2 | 322.5 | 120 | 160 | 4 | 83.81 | CF |
| | L1500-150-2 | 322.5 | 150 | 160 | 4 | 104.17 | CF |

Note: CCS=concrete cover separation; ICD=IC deboning; CF=combined failure, local metallic fastens failure and failed to suppress CCS or ICD.

anchorages and y was the number of test serial. L1500-0-1 was control specimen without steel bolts tested in serial I.

## 2.2 Materials

A same batch of ready-mixed concrete was used in casting the beams. The measured cubic compressive strength (*fcu*) of three 150 mm concrete cubes was 31.27 MPa after 28 days of curing. The elasticity (E), yield strength (*fy*) and ultimate strength (*fu*) of the stirrups were 204.85 GPa, 342.5 MPa and 499.5 MPa, respectively. For longitudinal reinforcement, the values were 204.40 MPa, 463.0 MPa and 575.5 MPa, respectively. The performance of the steel bolt, CFRP laminate and the adhesive were provided by manufacturer as shown in Table 2.

**Table 2.** Parameters of specimens

| Material | diam-eter /mm | thick-ness /mm | *E* / GPa | *fy* / MPa | *fu* / MPa |
|---|---|---|---|---|---|
| Steel bolt | 10 | / | 152.8 | / | 824.0 |
| CFRP laminate | / | 0.111 | 241 | / | 3696 |
| adhesive | / | / | 2.83 | / | 52 |

## 2.3 Specimen Preparation

Wooden molds were prepared for beams casting. Four holes were preset for steel bolts at designed locations as shown in Fig. 3 using PVC tube with a diameter of 20 mm. All specimens and concrete cubes were extracted from the molds 24 hours after casting and then cured in the ambient environment for 28 days. During the first 7 days of curing, the beams were poured with clean water once a day and then covered with plastic film. Three cubes used to determine the concrete strength were dealt with same procedure. Before the installation of the CFRP laminates and steel bolts, the concrete surface was properly prepared by the order of sandblasting, brushing and cleaning, which were done to guarantee an ideal bond between the CFRP laminate and the concrete.

Wet-layup procedure was adopted for CFRP laminate bonding. As shown in Fig. 3, two strips of CFRP laminates were attached to the bottom surface of the specimens. Each strip of CFRP laminate consisted of four layers of unidirectional textile. Each layer had a width of 80 mm, length of 1100 mm. Steel bolts of different lengths were inserted into the preset holes, followed by injecting in epoxy resin to form a bond between the concrete and steel bolts. A 5 mm thick, 40 mm wide steel plate was settled on the CFRP laminate with steel nuts. The specimens were then placed in a room-temperature environment for at least seven days. Eight strain gauges were glued to CFRP laminate (Fig. 3) before test. For control group L1500-0, each side was glued eight strain gauges symmetrical about the centre line.

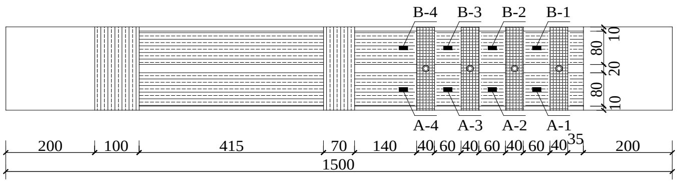
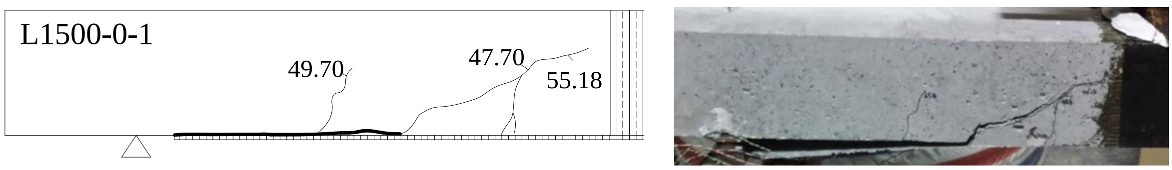
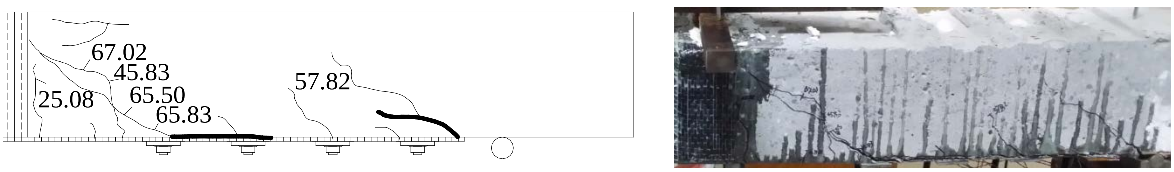


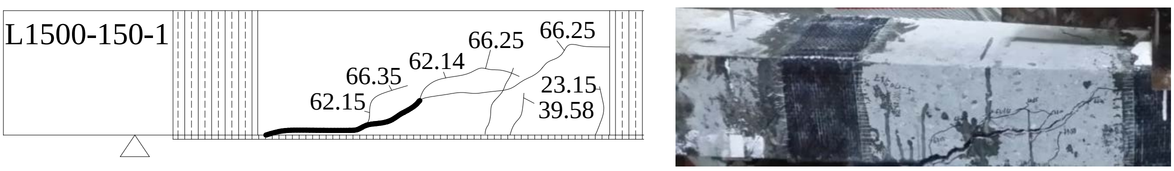

**Fig.3.** Bottom surface of the specimens (unit: mm)




(a) Failure of L1500-0-1




(b) Failure of L1500-50-1




(c) Failure of L1500-150-1

**Fig.4.** Typical crack distribution of test serial I (unit: kN).

## 3.0 RESULTS AND DISCUSSIONS

### 3.1 Failure Mode

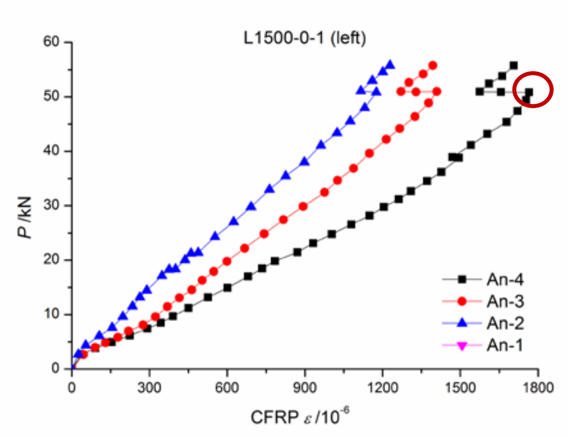
Three kinds of failure modes were observed as listed in Table 1: CCS, IC debonding and CF. Typical crack distribution of test serial I are shown in Fig. 4,, all specimens except L1500-50-1 failed by CFRP end wrapping rupture caused by IC debonding, which is why the ultimate loads of L1500-70-1, L1500-120-1 and L1500-150-1 were almost same. For L1500-50-1, the IC deboning occurred at the side with steel bolts and was suppressed by steel bolts. As the load increased, the specimen finally failed by CCS. However, the ultimate load of L1500-50-1 was even higher than L1500-150-1, which may be caused by the scatter of specimens. In the test serial II, CCS was prevented with the increase of the height of steel bolt anchorages, and the failure mode changed to CF with too large deformation of steel plates (Fig. 5).

The typical load-strain relationships of some specimens are plotted in Fig. 6. 'An' in the figures represents the average strain of point A and B (Fig. 3).

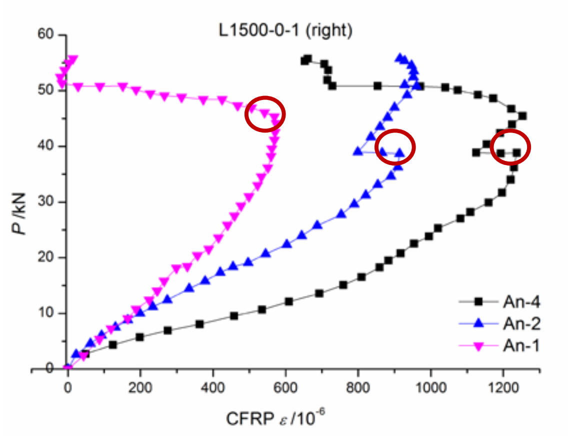
**Fig.5.** Combined failure of L1500-150-2.

### 3.2 Load-strain response (CFRP)

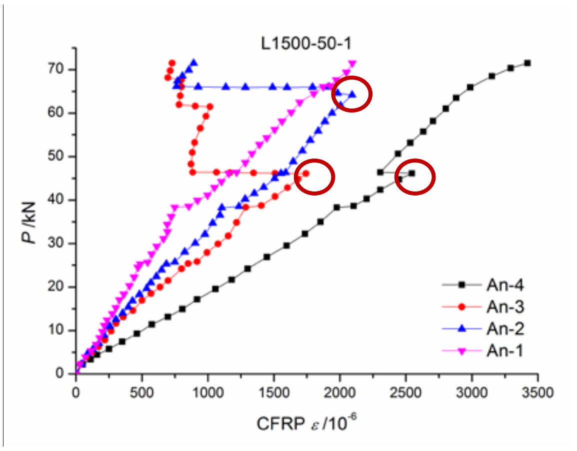
On the strain curves, a sudden drop could be found when the load was about 40 kN, which corresponded to the initiation of IC debonding. For L1500-0-1, the drop point of the curves occurred almost at the same load, which showed that the IC debonding propagated to the CFRP laminate end soon after the initiation. Instead, an increase of drop point can be found for the other specimens by the location order from 4 to 1, indicating the propagation was effectively suppressed or even stopped by steel bolts.



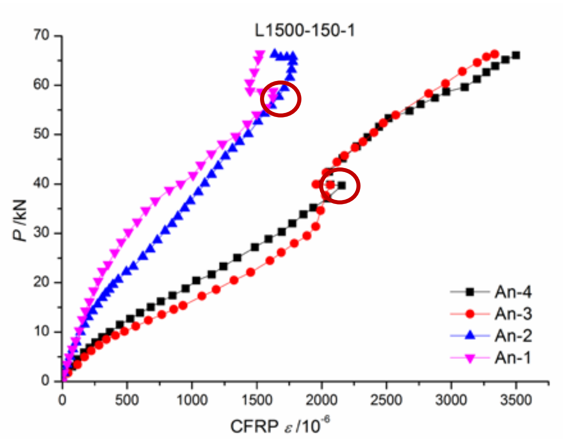

(a) L1500-0-1(left)




(b) L1500-0-1(right)




(c) L1500-50-1




(d) L1500-150-1

**Fig. 6.** Load-strain correlation curves

## 4.0 CONCLUSIONS

Effects of steel bolt anchorage and CFRP end wrapping anchorage on premature debonding failures were investigated in the present paper. The experiment contained two serials of three-point bending tests. Three conclusions and observations could be made as follows:

1. Both CFRP wrapping and Steel bolts can effectively stop or suppress the propagation of IC debonding. However, the initiation of IC debonding was nearly not influenced by anchorages.

2. Concrete cover separation could be prevented with enough high steel bolts. The ultimate load is affected by the finally failure mode, which could be changed with different height of steel bolt.

3. The performance of steel plates of the steel bolt anchorage should be paid more attention. The excessive deformation of the steel plate is more critical than the pull out of steel bolt, and the effect of anchorage would be affected.

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