Experimental Study on CFRP Strengthening of Cracked Reinforced Concrete Beams

Xuan Dat Pham and Trung Hieu Nguyen

Abstract This article presents an experimental study on the effectiveness of CFRP strengthening method on the flexural behaviour of Reinforced Concrete beams. Six identical RC beams with dimensions of 80 × 140 × 1100 mm are cast and statically loaded to complete flexural failure in this study. The specimens are divided in three categories, including: Two beams without strengthening as control specimens (Group 1), two intact beams strengthened with CFRP sheets (Group 2), and two pre-cracked beams strengthened using CFRP sheets (Group 3). The strengthening effects on the stiffness and ultimate strength, together with flexural behavior of test beams are discussed in detail based on the test results.

Keywords CFRP sheets · Strengthening · RC beam · Cracking

1 Introduction

In recent years, Fiber Reinforced Polymer (FRP) has been increasingly used for strengthening purpose on reinforced concrete (RC) structures. FRP is a composite made of high strength fibers and a matrix for binding these fibers to fabricate structural shapes (e.g. ACI 440.2R-08 [1]). Common fiber types include aramid, carbon and glass; common matrix are epoxies. FRP materials can be used to rehabilitate or restore the strength of deteriorated structural member, retrofit or strengthen a sound structural member to resist increased loads due to changes in use of the structure or address design or construction errors (ACI 440.2R-08 [1], CEB-FIB 2001 [2], TR55 [3]). The effectiveness of the FRP materials for concrete is attributed to its unique mechanical and chemical properties such as superior strength to weight ratio, high tensile strength and modulus, corrosion resistance and durability. The use of

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Fig. 1 Strengthening of cracked RC beams using CFRP sheets

FRP material also shows the convenience of construction process such as quick, simple and not require much machinery. Figure 1 shown an example of the FRP strengthening on the RC structures.

It is worth-noting that when the strengthening process is often conducted while structures are still carrying gravity loads. Most of the time reducing the applied load at this time is not available even this technique may improve the strengthening efficiency. For reinforced concrete structural elements subjected to flexural action, it is common that the strengthening process is required when flexural cracks are observed on the tension face, with the crack width ranging from 0.1 mm to 0.3 mm.

In the past, there have been a number of research works on the CFRP strengthening for RC structures under various loading conditions, such as bending, shear, and even torsion. Although the efficiency of CFRP strengthening has been well proved, most of the previous research works have focused on the behavior of RC structures when strengthening process is applied before any gravity loads. Meanwhile, strengthening practice in Vietnam has shown that CFRP application after the appearance of cracks on RC structures is in high demanding for many reasons. This motivates the current study.

This paper presents an experimental research on the effectiveness of flexural strengthening of pre-cracked RC beams using CFRP sheets. Six identical RC beams are prepared and tested under four-point loading, including two control beams without strengthening, two un-cracked and two cracked beams that are strengthened by CFRP sheets. The experimental research is carried out at Laboratory of Testing and Construction Inspection (LCTI), National University of Civil Engineering, Vietnam.

2 Experimental Research

2.1 Test Specimens and Materials

Reinforcement detail of six test beams is presented in Fig. 2. Dimensions of the beam cross-section (depth × width) are 80 × 140 mm, and the beam length is 1100 mm.

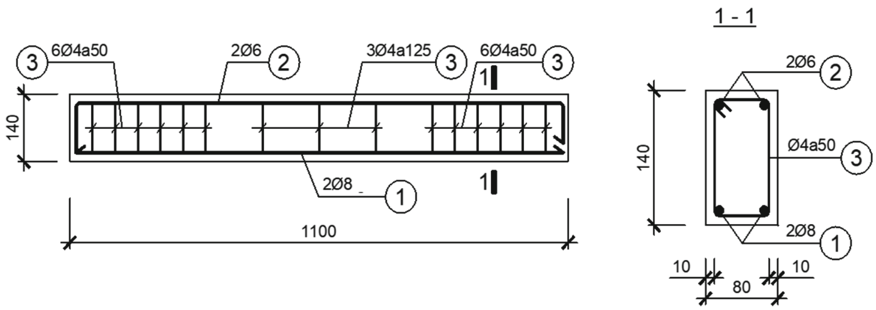

Fig. 2 Details of test RC beams

The tension and compression reinforcing bars are 2Ø8 and 2Ø6, respectively. Beam stirrups are Ø4 at a center-to-center spacing of 50 mm.

The test beams are divided in three following groups. The first group consisting of two control beams, namely, D-1 and D-2, referred as control specimens that are not strengthened. The second group with two beams (D-3 and D-4), intact but strengthened with CFRP. The last group are two beams, D-5 and D-6, are pre-loaded until the flexural crack width at the bottom face of the beam attained 0.3 mm, and then are strengthened by CFRP. It is worth noting that this cracking width value is considered as "failure" according to the crack width limit state in TCVN 5574:2018 [4].

Figure 3 presents the typical strengthening setup for three specimen groups. The strengthening CFRP sheets at the bottom face of four specimens in Groups 2 and 3 (D-3, D-4, D-5 and D-6) had dimensions 950 × 60 × 0.3 mm. The pre-cracks on D-5 và D-6 were made by four-point bending test as shown in Fig. 3c, whose maximum crack width of two beams D-5, D-6 are 0.2 mm, not greater than the limit value of 0.3 mm, according to Vietnamese design code TCVN 5574: 2018 [4].

Concrete mix ratio of the test specimens is shown in Table 1. The average cylinder strength at the age of 28 days is 23.5 MPa. Yield and fracture strengths of reinforcing bars with diameter Ø6 and Ø8 are 240 MPa and 305 MPa, respectively.

The CFRP sheets used in this study were unidirectional and manufactured by Toray Carbon Co. Ltd (Japan). Table 2 presents the mechanical properties of the CFRP sheets provided by the manufacturers.

Pre-cracking condition of the test beams has been created using a hydraulic jack through two loading-point system shown in Fig. 5. The applied load was slowly increased until the width of main cracks forming along the bottom face of the beams reach to predefined values of 0.2 (mm).

Figure 4 illustrates the strengthening procedure for specimens D-3, D-4, D-5 and D-6 that consists of four main steps, including: prepare the bottom face of the beams, apply epoxy to the prepared surface, install the CFRP laminates, and allow the epoxy to cure in 48 h. Cleanness and smoothness of the beam's bottom surface in the preparation process is the key step in this procedure that allow the CFRP sheets to develop their full strength when the beams are loaded.

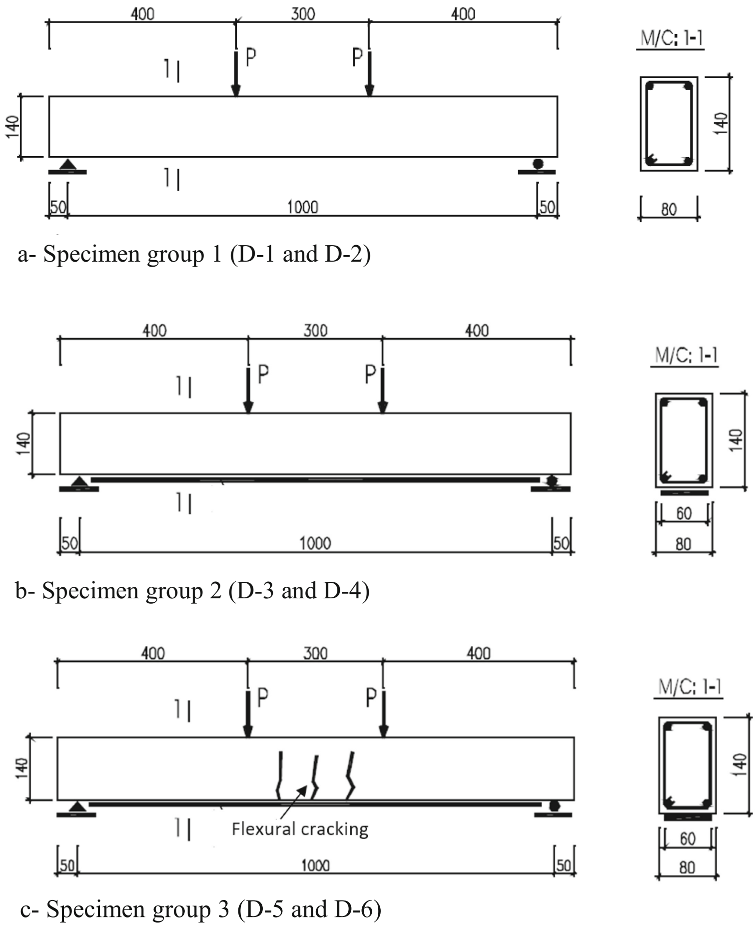

Fig. 3 Strengthening setup for three specimen groups

Table 1 Mixture proportions for $1m^3$ of concrete (kg/m^3)

Cement PCB40	Sand	Coarse aggregate	Water	Average cylinder strength R28 (MPa)
305	680	1260	175	23.5

Table 2 Mechanical properties for CFRP sheets

Thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Ultimate tensile elongation (%)
0.3	96.9	1778	1.85

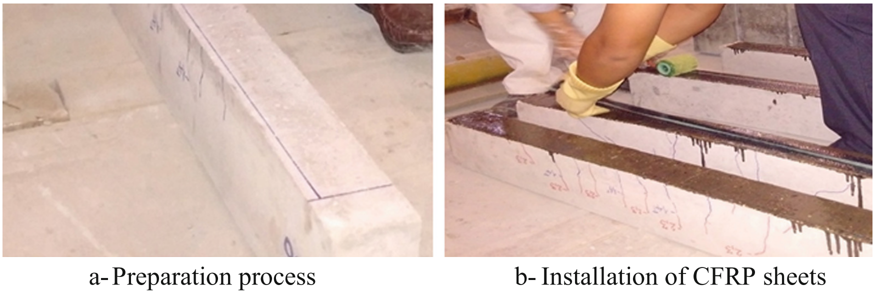

Fig. 4 The strengthending procedure for Specimen Groups 2 and 3

2.2 Test Setup and Instrumentation

Figure 5 illustrates the typical test setup for the current experimental investigation. These simply supported beams are loaded by a hydraulic jack through a two-loading-point system, creating two equal applied force P. Each loading point is 350 mm away from the beam support. Two load-cells are used to measure the applied load P. Three Linear Variable Differential Transducers LVDT-1, LVDT-2, LVDT-3 are used to measure vertical displacements at two supports and at the mid-span section of the test beams. The vertical displacement f of the beams that is used to construct the load-displacement curves can be calculated by the following formula:

$$f = f_2 - 0.5 * (f_1 + f_3) \quad (1)$$

where f_1, f_2 và f_3 are the reading values of LVDT-1, LVDT-2 and LVDT-3.

At every loading step, all test data including the applied load and vertical deformations are recorded with Data Logger TDS-530.

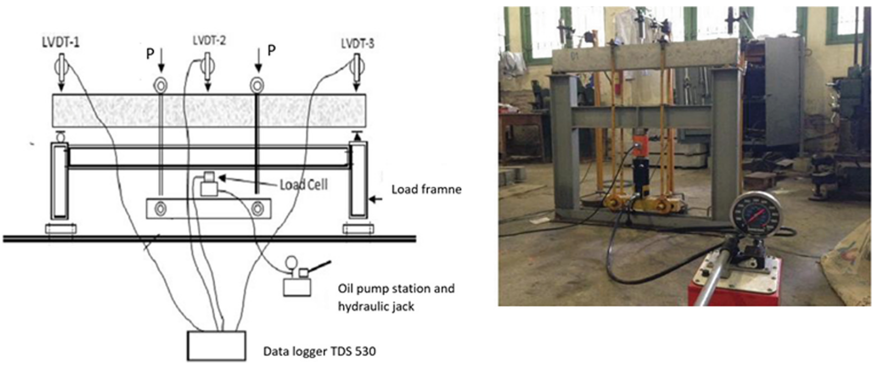

Fig. 5 Typical test setup and instrumentation

3 Test Results and Discussions

3.1 Load-Deflection Relationships

Figure 6 presents the comparison of load-displacement curves of six test specimens. As can be seen, there is no significant difference in terms of applied load and displacement when the applied load is less than 400 daN. This indicate that the strengthening sheets did not participate in the load-carrying mechanism of the beams when the applied load is small. As the load increases up to 900 daN, concrete cracking and reinforcement yielding is observed in the control specimens D-1 and D-2. Meanwhile, there was no sigh of such failure observed in four strengthened specimens in Groups 2 and 3. When the test load on these four strengthened reached about 1600 daN, only specimens (in Group 3) failed to carry the load at a displacement of 9 mm, while the other two specimens in Group 2 still remain intact. The peak test load in tests on D-3, D-4 was as high as 1800 daN, that is approximately 61.7% greater than those in the tests on the control beams in Group 1 (without CFRP installation). This comparison clearly shows the effectiveness of the CFRP strengthening method for flexural mechanism of RC beams. The test loads for all specimens are summarized in Table 3.

It is worth-noting that there is insignificant difference in terms of the initial stiffness of the test beams (both precracked and intact specimens) before tensile reinforcement yields, as shown in Fig. 6. This has shown that the effect of CFRP strengthening is not significant when the magnitude of applied load is small. Similar phenomena have already been observed and presented somewhere [5–7].

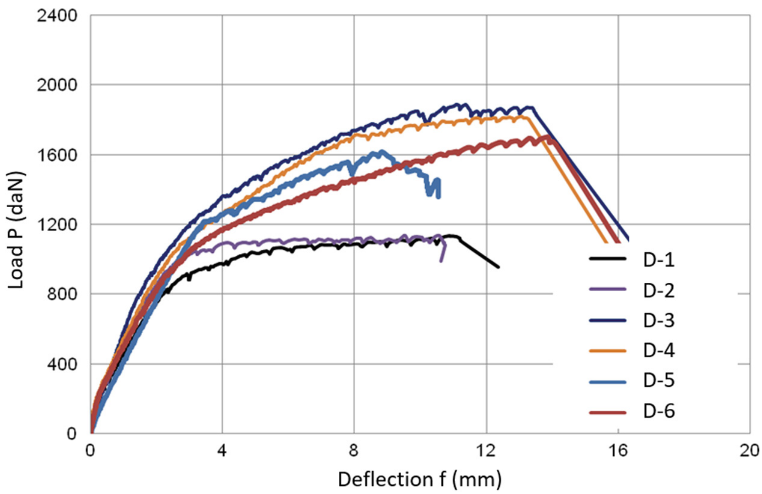

Fig. 6 Load—deflection curves of all tested specimens

Table 3 The failure loads of tested specimens

Test specimens	Failure loads (daN)	Strengthening effectiveness (%)
D-1	1130	
D-2	1140	
D-3	1870	61.7
D-4	1800	
D-5	1700	46.3
D-6	1620	

When comparing two pre-cracked specimens, D-5 and D-6, it can be seen that although the difference in terms of failure load is not significant (1620 daN to 1700 daN), that of the corresponding vertical deflection is large (9mm in D-5 test compared to 13.9 mm in D-6 test). This noticeable difference of deflection can be explained by the uneven quality of bonding surface of test beams, that lead to debonding failure modes occurring at different times as shown in Fig. 7.

3.2 *Failure Modes of Test Specimens*

Figure 7 presents the typical failure modes of the beams strengthened by CFRP. As can be seen, debonding of the CFRP sheets happened mainly due to the cracking and crushing of the concrete covers along the bottom face of all the test beams. After the debonding occurs, the test load sharply decreases indicating an obvious brittle failure of this strengthening method compared with the common ductile mode presenting by two specimens in Group 1 without CFRP application. As this can be recognized as the main weakness of the strengthening method, it is necessary to improve the

Fig. 7 Typical failure mode of the CFRP strengthened beams

bonding behaviour between the quality of the concrete cover before installing the CFRP laminates.

4 Conclusions

This paper presents an experimental study on the effectiveness of CFRP strengthening method on the flexural behaviour of Reinforced Concrete beams. Six identical RC beams in three groups (Group 1—intact beams, Group 2—intact but strengthened with CFRP, and Group 3—Pre-cracked and strengthened with CFRP) statically loaded to complete flexural failure. Based on the test results, the following conclusions can be drawn:

- The CFRP strengthening can be a suitable option for RC beams for the easiness and readiness of the strengthening procedure, and the effectiveness in both enhancing the ultimate strength and limiting crack width of such important structural components. Test results of Specimen Groups 2 and 2 have shown that the flexural behaviour of test beams applied with CFRP has been significantly improved compared with those without CFRP application, and fully satisfied the current Vietnamese design code TCVN 5574–2018.
- Debonding of the CFRP sheets is the typical failure mode of the strengthened beams that is observed in the current experimental investigation. This failure mode is more or less a very brittle mode, which is an obvious weakness of this strengthening method. Therefore, future experimental work should be conducted to address this issue.
- Future work is also needed to address the sustainability of the CFRP strengthening method in the Vietnamese climate and weather which is high in humidity and high temperature.

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