Experimental Study on Flexural Behavior of Reinforced Concrete Beams Strengthened with CFRP Sheets Under Sustaining Load

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Abstract
Flexural strengthening of RC beams using carbon fiber composite (CFRP) sheets is a solution that shows many advantages in comparing to traditional strengthening solutions. The main goal of this study is to examine the effects of initial load on the effectiveness of strengthening by externally bonded CFRP laminates. Two identical beams were tested. One beam was used as control specimen while one other beam was strengthened in flexure under sustaining load. The value of the intial load was determined on the basic of cracking of concrete in tension zone, with crack width value is 0.3 mm. The obtained results have shown that for RC beams that are already cracked and deformed under sustaining loads, the effectiveness of CFRP strengthening can be demonstrated by the significant increase in the flexural stiffness and the load-carrying capacity of the strengthened RC beams.

Keywords: CFRP laminate, Strengthening, Cracking.

1 Introduction

The reduction of load-bearing capacity, the demand of changing usage purpose and the load acceleration have posed a problem for building structure strengthening. Beside traditional strengthening methods such as widening cross-section, post-tensioned reinforcement, steel section, etc…, the method of using fiber reinforced polymer (FRP) in enhancing building structure has been popularly applied in developing countries around the world. The strengthened building structures include RC column, beam, slab structures and mansory structures… One of the composite materials used for strengthening the RC structures is Carbon fiber reinforced polymer (CFRP). The strengthened method by externally bonded CFRP laminates promoded the superiority of this material such as high compressive strength and elastic modulus, light weight, not to be corroded, etc… In addition to the advantage of mechanical characteristics, structures strengthened by CFRP conveniently performs during construction process such as fast and straightforward strengthening process, not to use many types of equipment, a short period of construction time.

One of the problems given to structure strengthening is that the structure is being affected by load while the strengthening process is operating. Reducing the load affecting structure at strengthening point of time is opposed to be one of the solutions ensuring the efficiency of strengthening work. In fact, reducing the load, which mainly is the reduction of live load, usually encounters difficulties. For flexural RC structures, at the strengthening time, cracks have been appeared in the compressive strength area (beam or slab). According to the result of authors in buildings'practical situations, the cracks have been found from 0.1mm to 0.3 mm.

Fig. 1 illustrates the strengthening work of RC beam, which is cracked and deformed because its height is not guaranteed, by CFRP. At strengthening point of time, the building construction has been conducted and beams of the building are being affected by its self-weight.

Fig 1. Cracked and deflected RC beam strengthened by CFRP

Experiential research of RC structure behavior strengthened by CFRP and the efficiency of strengthening work were researched inside and outside of Vietnam in which some typical researches were illustrated in references [7-10]. The results indicated that the solution of using CFRP was suitable for some circumstances such as strengthening flexural and shear resistance, resistant-increased compression and torsion… Meanwhile, the behavior of the structure was complicated with many types of failure and the efficient strengthening depended on factors in which mechanical characteristic of CFRP and strengthening work were the most important. Besides, it is possible to recognize that almost all of researches were conducted on initially- strengthened specimens when the structure did not affect the load. This led to differences in assessing the efficient strengthening compared to the practice of this work when strengthening work was carried out in load-affected structure.

This article demonstrates the behavior of the strengthened RC beams and the efficient of strengthening work by CFRP in the circumstance that the strengthening work is conducted when the structure is affected the load and the investigative parameter is the value of the affected load at strengthening point of time. The experiental research has been carried out in Laboratory of Construction Testing and Inspection, National University of Civil Engineering (NUCE).

2 Experimental research

2.1 Test specimens and Materials

In this research, 02 RC beams which have identical rectangular cross-section, reinforcement and the strength of concrete were manufactured. All beams tested have 2000 mm long and the same size b × h = 150 × 200 mm. According to general calculation to avoid shear failure, two 12 mm-diameter round bar in tensile area and two 10 mm-diameter round bar in compressive area was used. Shear reinforcement consisted of 6mm-diameter round steel spaced at 10 0mm center-center near the bearing support. Among tested beams, 01 beam, denoted by D-0, was not strengthened to use as control specimen and the other beam denoted by D-1. D-1 specimen was subjected to an initial sustaining load which made the maximum crack with of concrete in tensile zone of 0.3 mm. This crack width value is considered as "failure" according to the crack width limit state in TCVN 5574:2018 [6]. The D-1 specimen was strengthened by externally bonded CFRP sheets at the bottom face of specimen and the strengthening CFRP sheets had dimensions of 1950 × 120 × 0.111 mm. The reinforcement details of two beam specimens were illustrated as Fig. 2. Fig. 3 demonstrates strengthening solution for D-1 specimen.

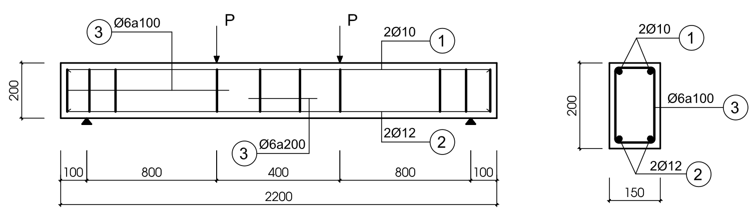

Fig 2. Detail of tested RC beams

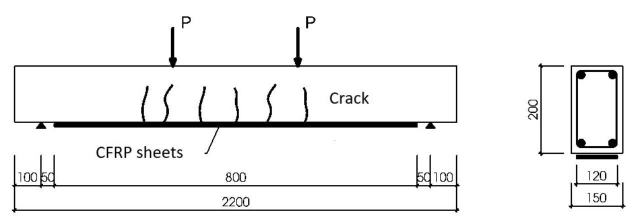

Fig 3. Strengthening setup

Concrete mix ratio of the test specimens is shown in Table 1. The average cylinder strength at the age of 28 days is 34.7 MPa. Yield strengths of reinforcing bars with diameter ∅10 and ∅12 are 380 MPa and 410 MPa, respectively.

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

Cement PCB30	Sand	Coarse aggregate	Water	Average cylinder strength R28 (MPa)
380	670	1260	185	34.7

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 manufacturer.

Table 2. Mechanical properties for CFRP sheets

Thickness (mm)	Modulus of elasticity (GPa)	Ultimate tensile strength (MPa)	Ultimate tensile elongation (%)
0.111	245.0	3400	1.6

2.2 Generating and maintaining initial load acting on strengthened beam and CFRP strengthening process.

To generate initial load acting on D-1 beam and constantly maintain this load during strengthening process, hydraulic jack, load frame and anchor bolts were used in this experiment. Firstly, 02 concentrated loads had the same value acting on tested beam, spanned a distance of 400 mm and spaced at 800 mm from the support of each side are generated by hydraulic jack, load frame and load-distributing beam. After creating the required load, 2 anchor bolts were set up to maintain these loads. The crack width of pure bending area of concrete is fundamental value for detemining the value of these load, which had the value of 0.3 mm. To control the behavior of anchor bolts in maintaining load acting on D-1 specimen, Data-logger P3 (manufatured by Vishay - America) boxs were used to follow the modification of tensile strain of two ∅12 longitudinal bars at the middle of the RC beam through 02 strain gauges put on these longitudinal bars before pouring concrete. The results obtained from strain measuring data of the 02 logitudinal bars indicated that the load-maintaining system with anchor bolts has responsed to the requirement.

Fig 4. Pre- loading on D-1 beam

Fig. 5 illustrates the strengthening procedure for D-1 specimen 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 hours. 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 5. The strengthending procedure for D-1 specimen

2.3 Test Setup and Instrumentation

Fig. 6 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 800 mm away from the beam support. One load-cell is 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. At every loading step, all test data including the applied load and vertical deformations are recorded with Data Logger TDS-530.

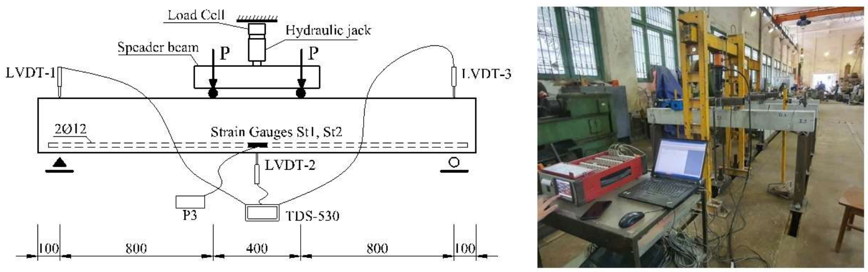

Fig 6. Test setup

3 Test Results and Discussions

3.1 Load-Deflection Relationships

Fig. 7 illustrates load-deflection curves of D-0 and D-1 beam specimens and Table 3 presents the ultimate capacities and deflection characteristics of two tested beams. For the load-deflection curve of D-0 beam, it can be seen that there are three different behavioral zones. The first zone OA represents the initial stiffness of the uncracked beam D-0. The first visible crack load was determined based on a first change in slope of the load- deflection curve. As can be seen, there is no significant difference in terms of applied load and displacement when the applied load is less than 12 kN. This indicate that the strengthening sheets did not participate in the load-carrying mechanism of the beams when the applied load is small.

The second zone (AB) represents the stiffeness of cracked section. For D-1 beam, the slope of the load-deflection curve was higher than that of the corresponding control beam D-0. As a result, for any give value of load, the deflections of strengthened beam were lower. This result show that the contribution of CFRP layer to the structural stiffness was found to be significant. When the test load on D-0 and D-1 specimens reached about 55 kN, the tensile steel reinforcements were yielded (generally seen as a second change in slope of the load-deflection curve). It can be seen that, for pre-cracked D-1 beam, the external CFRP layer reduced the stress in the tensile steel reiforcement and hence guaranteed the yield load of the strengthened beam.

The third zone corresponds to a damaged tested beams with wide crack, yieiding reinforcement and rupturing the CFRP sheet. As shown in Fig. 7 and Table 3, the ultimate load carrying capacity of strengthened beam D-1 was higher than that of the control beam D-0. This result again shows the effectiveness of the CFRP sheets for strengthening of RC structures.

Table 3. The ultimate loads of tested specimens

Test specimens	Ultimate loads (kN)	Strengthening effectiveness (%)
D-0	60.5	-
D-1	66.7	9.1 %

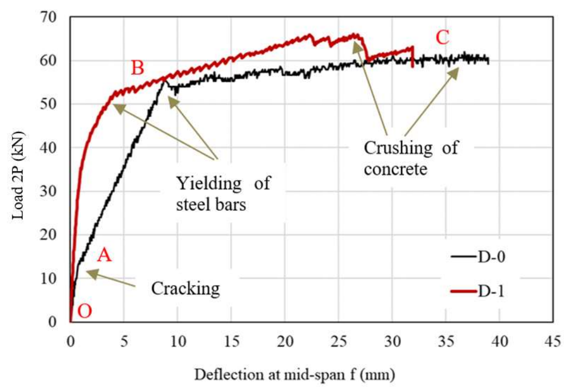

Fig 7. Load – deflection curves of D-0 and D-1 specimens

3.2 Failure modes of test specimens

Fig. 8 presents the failure mode of the strengthened beam D-1. The control beam failed by yielding of steel reinforcement followed by crushing of concrete in compressive zone at the middle span. The strengthened beam D-1 failed prematurely without warning by rupture of the CFRP sheets after yielding of steel reinforcement.

Fig 8. Failure mode of D-1 specimen

4 Conclusions

The results of the above-mentioned experimental program have improved the understanding of the behavior of cracked RC beam strenthened with CFRP sheets. Based on the test results of this study, the following conclusions are drawn:

- For RC beams that are already cracked and deformed under sustaining loads, the effectiveness of CFRP strengthening can be demonstrated by the significant increase in the flexural stiffness and the load-carrying capacity of the strengthened RC beams.
- Rupture of the CFRP sheets is the failure mode of the strengthened beam that is observed in the current experimental investigation. This failure mode is a very brittle mode, which is an obvious weakness of this strengthening method.
- Future work is also needed to address the sustainability of the CFRP strengthening method in the Vietnamese climate and weather.

Acknowledgements

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