Investigation of the Stiffness and Ductility of Pre-Cracked RC Beams after repairing with CFRP using Different Strengthening Methods

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ABSTRACT

This study investigated the stiffness and ductility of rectangular Reinforced Concrete (RC) beams. The beams were obtained through an experimental program that included one reference and eight RC beams, divided into two separate groups strengthened with Externally Bonded Reinforcement (EBR) and Near-Surface Mounted (NSM) reinforcement in flexural using Carbon Fiber Reinforced Polymer (CFRP) laminate after they were pre-cracked or damaged at different levels. The comparison results of the reference and the strengthened beams showed that the latter had a higher degree of stiffness. The stiffness in the yielding stage increased by 6.43% to 19.81% for the EBR-strengthened group and by 31.08% to 105.8% for the NSM-strengthened group. At the 140 kN loading stage, the stiffness increased by 33 to 101.5% for the EBR-strengthened group and by 136.5% to 332.25% for the NSM-strengthened group. At the ultimate load stage, the stiffness increased by 12.72% to 46.13% for the EBR-strengthened group and by 56.85% to 122.94% for the NSM-strengthened group. On the other hand, the comparison revealed that the ductility of the reference beam was much better than that of the reinforced beams.

Keywords-stiffness; ductility; pre-cracked; CFRP; reinforced concrete; flexural strengthening

I. INTRODUCTION

A lot of Reinforced Concrete (RC) structures have been damaged. Most of them have a variety of deteriorations that are worsening, such as cracks and concrete spalling. These deteriorations may be traced back to a wide number of factors, such as the passage of time, steel corrosion, earthquakes, environmental effects, and the effects of unintended impacts on the structure. In the absence of steel reinforcements, plain concrete is more likely to crack and break apart when subjected to significant tensile pressures. Recent innovations include using Fiber-Reinforced Polymers (FRP) and steel fibers to increase the tensile strength of concrete. Once it is determined that a structure is in jeopardy, it must either be repaired or strengthened to raise its strength and either return to its prior level of strength or be able to handle an increased load. The use of Near-Surface Mounted (NSM) technology is the most effective method for reinforcing concrete structures to withstand shear and flexure loads. In addition, an Externally Bonded Carbon Fiber Reinforced Polymer (EBR-CFRP) is used to increase the existing structural element's ability to support additional loads. Structure components may be made more robust using CFRP [1-9].

Several experiments have been carried out to evaluate RC beams after being strengthened with CFRP using the EBR technique. In [10], RC beams that were pre-loaded with a steel-yielding capacity of either 40% or 60% were strengthened using hybrid and continuous carbon fiber sheets. Carbon sheets with high modulus and high strength have been used in hybrid systems. The hybrid concrete's yielding load, flexural stiffness, post-yielding ductility, and crack breadth were all improved by the addition of carbon sheets with a high modulus. The hybrid system designs ignored discrepancies in the slopes of the steel-yielding load-deflection curves. Concrete may be crushed by larger pieces of high-modulus carbon that are dispersed more widely. High-modulus carbon fibers can have these qualities if they have stiffness and low ultimate tensile strain, while debonding and fracture resistance may be improved by increasing the strength of fiber-reinforced polymer composites. In [11], continuous beams were repaired using CFRP composites, using one control beam and four CFRP-laminated beams. Shear fractures were caused by pre-loading the beams to 224 kN before CFRP wrapping. Experimental results showed that CFRP-repaired beams had 18-44% higher shear capacity, matched well with a theoretical study using an established model, and CFRP strips can improve the shear capacity of cracked continuous beams.

In [12], severely deteriorated RC beams were laminated with CFRP and end-anchored. The beams used in a medieval bridge construction were bent to increase their strength in four places. It was determined that there was a vertical displacement at the beam's midspan by using linear variable differential transformers to perform a quick discharge on specimens while applying the yield load. After CFRP strengthening, these highly compromised specimens were loaded to the point of collapse. An externally bonded CFRP layer can improve the flexural performance of an aging or badly damaged RC beam. According to this study, the yield loads of reinforced beams can reach anywhere between 5 and 36%, depending on the anchoring effect, the length of the bond, and the size of the CFRP sheet. In [13], the flexural behavior of pre-damaged RC beams reinforced with CFRP plates was studied using experimental, analytical, and FEM modeling. Before strengthening, RC beams were preloaded with yield loads of 30, 50, and 70%. Two CarboDur S512 plates and eight 3×12 RC beams were bent. CFRP plate debonding and bending zone flexural crack propagation destroyed all RC-strengthened beams, while exterior-bonded CFRP had 70-80% more moment capacity than unstrengthened beams. In [14-16], the behavior of beams after CFRP reinforcement was investigated. In [17], the length of the CFRP strip was examined on CFRP-reinforced slabs after experimental preloading. The CFRP strip length increased mid-span deflection by 59.9, 39.4, and 27.1%, improving the flexural performance of the RC slab [17]. In [18], corrosion-damaged RC beams were rehabilitated using CFRP, while in [19-20] heat-damaged RC beams and joints were repaired using CFRP [18-20].

This study focused on the stiffness and ductility of RC beams after they had been damaged and then reinforced with CFRP, based on the results of an experimental investigation.

II. EXPERIMENTAL STUDY

The experimental procedure included casting and testing nine RC beams, pre-cracked by pre-loading with various levels: 20, 40, 60, and 80% of the ultimate load of the reference beam. The beams were 2000×200×300 mm and tested for their flexural strength with a two-point static load, as shown in Figure 1, with steel reinforcement of two 12 mm bars at the bottom and two 10 mm bars at the top, as well as stirrup reinforcement of 10 mm with 125 mm spacing in the center of the beam and 80 mm in the edges. Four of the eight beams were strengthened by EBR, and the other four were strengthened with NSM.

A. Materials' Properties

Table I shows the properties of all the materials, including reinforcing steel bars, concrete, CFRP, and epoxy for the bonding between the CFRP and the beams.

B. Test Setup

Figure 2 presents the test setup details.

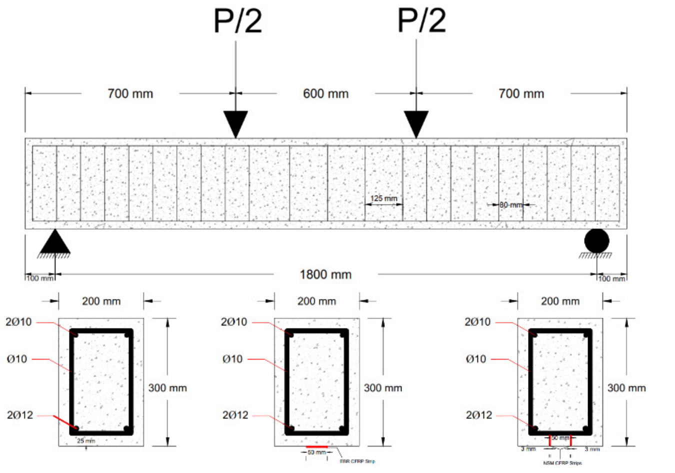

Fig. 1. The beam details and EBR and NSM groups.

TABLE I. MATERIALS PROPERTIES

Properties MPa	Steel bars		Concrete	CFRP Sika® CarboDur® S	Epoxy Sikadur-30 LP
	12mm	10mm			
Tensile yield	677	587	-	-	-
Tensile strength	772	662	-	3100	17
Modulus of elasticity	200000		26918	170000	10000
Compressive strength	-	-	32.8	-	-
Modulus of rupture	-	-	3.6	-	-

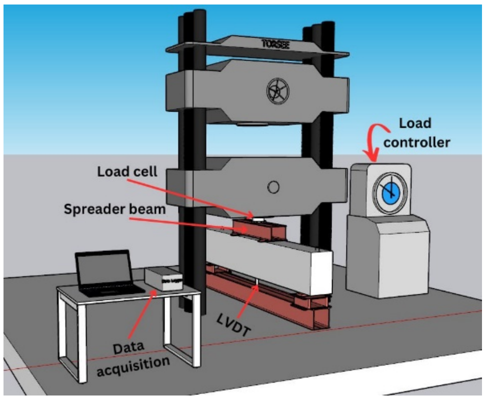

Fig. 2. Test setup.

III. RESULTS AND DISCUSSION FOR STIFFNESS AND DUCTILITY

The experimental results showed different behavior between stiffness and ductility. This difference occurred due to the effect of using CFRP as a flexural strengthening material. In terms of stiffness, the results showed that the stiffness of the beams increased after applying the CFRP compared to the reference beam for both strengthening groups. Three stages of loading were examined to investigate stiffness: the yielding load, the ultimate load of the reference beam (140.1 kN), and the final ultimate failure load. The stiffness in the yielding stage increased by 6.43-19.81% for the EBR-strengthened group and by 31.08% to 105.8% for the NSM-strengthened group. At the 140.1 kN loading stage, the stiffness increased by 33-101.5% for the EBR-strengthened group and 136.5-332.25% for the NSM-strengthened group. At the ultimate load stage, the stiffness increased by 12.72-46.13% for the EBR-strengthened group and 56.85-122.94% for the NSM-strengthened group, as shown in Table II. This results in the conclusion that CFRP significantly increased the stiffness, and is a good indicator for using the CFRP to strengthen structural members even after applying pre-loading, such as in this case. Figure 3 presents the stiffness of the beam in the three stages.

TABLE II. STIFFNESS OF THE BEAMS AT THREE STAGES OF LOADING

Specimens	Yielding Stage				140.1 kN Load Stage				Ultimate Stage			
	Δ	P	K	Increasing % in k	Δ	P	K	Increasing % in k	Δ	P	K	Increasing % in k
BC1	16.8	107.1	6.37	Ref.	35	140.1	4	Ref.	35	140.1	4.01	Ref.
B-EBR-80	18.5	117.2	6.33	-0.62	26.33	140.1	5.32	33	32.1	145.1	4.52	12.72
B-EBR-60	18.2	123.4	6.78	6.43	21.75	140.1	6.44	61	30.5	150.2	4.92	22.69
B-EBR-40	19.4	130.1	6.70	5.18	19.81	140.1	7.07	76.75	29.5	160.1	5.42	35.16
B-EBR-20	18.5	141.3	7.63	19.78	17.38	140.1	8.06	101.5	28	164.2	5.86	46.13
B-NSM-80	19	158.7	8.35	31.08	14.8	140.1	9.46	136.5	28.4	178.7	6.29	56.85
B-NSM-60	17.5	177.2	10.12	58.87	11.63	140.1	12.04	201	27.5	200.2	7.28	81.54
B-NSM-40	16.7	194.78	11.66	83.04	9.1	140.1	15.39	284.75	26.8	209.4	7.81	94.76
B-NSM-20	15.7	205.94	13.11	105.8	8.1	140.1	17.29	332.25	24.6	220	8.94	122.94

Δ: Deflection, P: load, and K: stiffness, $K = P/\Delta$.

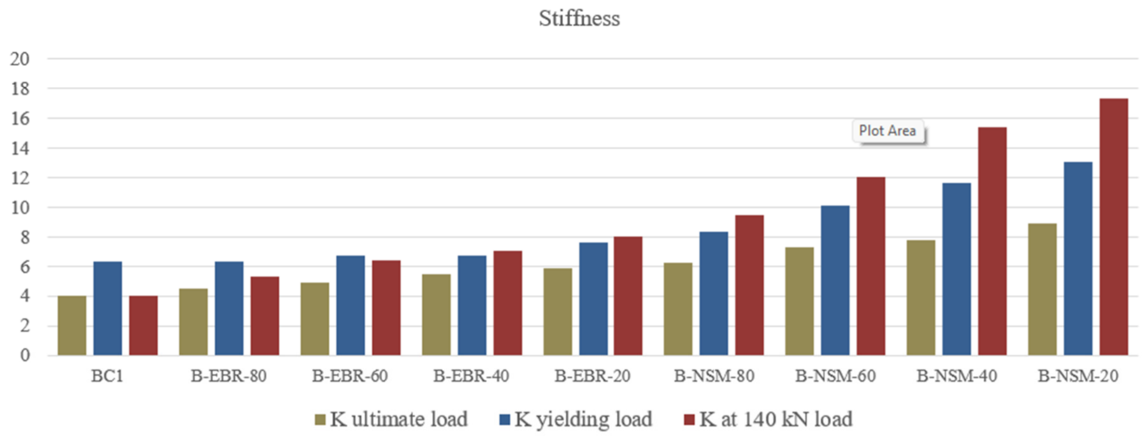

Fig. 3. Stiffness at three stages of loading.

In terms of ductility, the results showed that the CFRP as a flexural strengthening method reduced the ductility of the RC beams for both groups compared to the reference beam, from 2.08 to 1.51 and 1.56 for the beams strengthened with EBR and NSM, respectively, as shown in Table III. This was due to the CFRP being a brittle material with a low modulus of elasticity. Hence, the beam keeps having the load without a large changing deflection. Figure 4 shows the histogram of the results. The ductility was obtained by dividing the ultimate deflection by the yielding deflection [21].

TABLE III. DUCTILITY OF STRENGTHENED BEAMS

Specimens	Δ yield	Δ ultimate	Ductility
BC1	16.8	35	2.08
B-EBR-80	18.5	32.1	1.73
B-EBR-60	18.2	30.5	1.67
B-EBR-40	19.4	29.5	1.52
B-EBR-20	18.5	28	1.51
B-NSM-80	19	28.4	1.49
B-NSM-60	17.5	27.5	1.57
B-NSM-40	16.7	26.8	1.60
B-NSM-20	15.7	24.6	1.56

$Ductility = \Delta_{\text{ultimate}} / \Delta_{yield}$

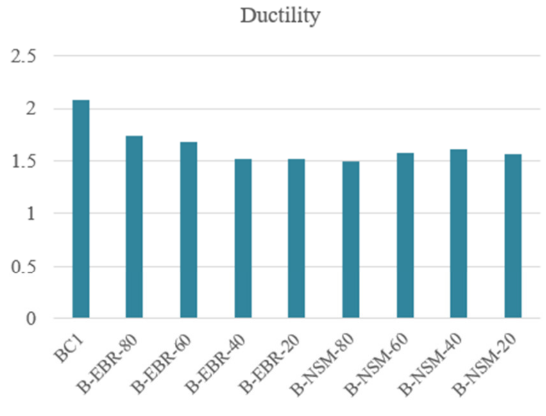

Fig. 4. Ductility of the strengthened beams.

IV. CONCLUSION

This study investigated the two essential properties, stiffness and ductility, of pre-cracked RC beams, reinforced by CFRP with EBR and NSM. These properties provide a good indicator of the behavior of the RC beams after strengthening with CFRP laminate. Based on the experimental results, the following can be concluded:

- The stiffness of the RC beams increased due to the use of CFRP laminate in all three stages for the strengthened beams in both groups compared to the reference beam. Stiffness at the yielding stage increased by 6.43-19.81% for the EBR-strengthened group and by 31.08-105.8% for the NSM-strengthened group. At the 140.1 kN loading stage, stiffness increased by 33-101.5% for the EBR-strengthened group and by 136.5-332.25% for the NSM-strengthened group. At the ultimate load stage, the stiffness increased by 12.72-46.13% for the EBR-strengthened group and by 56.85-122.94% for the NSM-strengthened group. These results show that CFRP made the RC beams stronger and increased their load before failure.
- The ductility results showed different behavior compared to stiffness. The ductility of the strengthened beams reduced compared to the reference beam from 2.08 to 1.51 and 1.56 for the EBR and NSM-strengthened beams, respectively. This is probably due to CFRP being made of brittle materials.
- The reduction in ductility observed in the strengthened beams can be attributed to the use of CFRP, which while improving other mechanical properties such as stiffness and strength, does not provide the same level of ductility as other materials.

Engineers and designers who employ CFRP materials in structural concrete applications should consider these trade-offs. Although CFRP can improve structural performance in strength and stiffness, it may not be sufficient to guarantee that the structural system has sufficient ductility to survive possible overloads or seismic events without incorporating additional mechanisms or materials.

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