Effect of reinforcement ratio on flexural behavior of reinforced concrete beams strengthened with CFRP plates

R Thamrin¹, Zaidir¹ and A Zakiyyah²

¹Civil Engineering Department, Engineering Faculty, Universitas Andalas, Padang, Indonesia
²Graduate Student at Institut Teknologi Bandung, Bandung, Indonesia

Corresponding author: rendythamrin@eng.unand.ac.id

Abstract. An experimental study was carried out to investigate the effect of tensile reinforcement ratio on the flexural capacity of reinforced concrete beams strengthened with Carbon Fiber Reinforced Polymer (CFRP) plates. This study aims to observe the effect of reinforcement ratio on debonding failure load of reinforced concrete beams externally strengthened with CFRP plates. Six reinforced concrete beams consisting of three control beams and three beams strengthened with CFRP plates were tested. The beams were simply supported and loaded with four-point bending. The test variable was tensile reinforcement ratio (1%, 1.5%, and 2.5%). CFRP plates were glued on the bottom of the beams with the purpose to increase the flexural strength of the beams. Analytical prediction using fiber element method was also carried out to obtain a full flexural response of the beams due to bending load. The test results show that beams with CFRP plates have higher flexural capacity for about 10% to 50% than the control beams. However, at a specified load level, two of beams with CFRP plates suddenly collapse due to delamination of CFRP plates. In addition, analytical calculation predicts well the test results in excellent accuracy.

1. Introduction

Externally glued Fiber Reinforced Polymer (FRP) plates have been researched and used to increase the flexural capacity of reinforced concrete structures for more than three decades [1-10]. Based on previous reports by other researchers, FRP plate debonding and concrete crushing are the most commonly obtained failure modes in concrete beams strengthened with FRP plates [2]. Later, another report states that the reinforcement ratio affects the failure mode of reinforced concrete beams strengthened with FRP plates significantly [6]. It was reported that beams with a small reinforcement ratio would fail due to the delamination of the FRP plate. Failure due to delamination of the FRP plates is very sudden, without any warning, and must be avoided in design. This type of failure is more common in beams strengthened with FRP plates than FRP rupture on the tensile surface [10].

From reports on previous works by other researchers, further studies on the effect of the tensile reinforcement ratio on the flexural capacity of reinforced concrete beams with FRP plates still need to be investigated. The purpose of this study was to observe the effect of tensile reinforcement ratios (1%, 1.5%, and 2.5%) on the flexural capacity of reinforced concrete beams externally strengthened with FRP plates. Moreover, the theoretical flexural response of reinforced concrete beams cross section with FRP plates was also predicted. Predictions are obtained from analysis using the fiber
element method with the help of software that has been developed by the authors in previous studies [7-9].

2. Experimental study
Six reinforced concrete beams were tested in this study. The beams tested were classified into control beams (G6C1, G6C2, and G6C3) and beams strengthened with CFRP plates (G6P1, G6P2, and G6P3). The beams were simply supported and loaded with two points load. Detail of beams dimension, loading position, and beams identification are shown in Figure 1. Beam cross-section was 125 mm width, 250 mm height, and 230 mm effective depth. The test variable used in experimental study was the longitudinal reinforcement ratio (1%, 1.5%, and 2.5%). The diameter of tensile reinforcement bars was 13 mm and the diameter of compression reinforcement was 10 mm with a yield strength of 448 MPa and 355 MPa, respectively.

All beams used stirrups to avoid premature failure due to shear forces. Stirrups installed were steel bars with a diameter of 10 mm, yield strength of 355 MPa, and a spacing of 100 mm. An additional development length of 150 mm outside the support is used to avoid bond failures due to the shifting of tensile forces on the longitudinal reinforcement in the support area [9]. CFRP plates with a wide of 50 mm and a thickness of 2 mm were glued to the tension face of the strengthened beams, as shown in Figure 1. Ultimate design strength and tensile modulus of the CFRP plate were 2.51 GPa and 139 GPa, respectively. The process of installing the CFRP plate by a certified applicator is shown in Figure 2. A ready-mix company supplied the fresh concrete, and the compressive strength of concrete at the age of 28 days was 20 MPa.

![Test setup](image)

**Figure 1.** Beam identification, dimension and loading position

Test setup, the position of load, and LVDT's on the tested beam are shown in Figure 3. The load was applied by hydraulic actuator and deflections of the beams were recorded at three positions. The load and deflection were continuously recorded using a load cell and LVDT's as shown in Figure 3. Load cell and LVDT's were connected to a data acquisition system (data logger) and the data was collected on a data storage disk.
Figure 2. The process of installing the CFRP plate by a certified applicator

Figure 3. Test setup and equipment used

3. Analytical study
Flexural analysis of reinforced concrete cross-section using the fiber element method was carried out to obtain the full flexural response of the cross-section with CFRP plates due to the applied bending moment. Figure 4 shows the analytical model using fiber element method. Strain compatibility in this method was applied using the assumption of a perfect bond between concrete and steel reinforcement as well as between concrete and CFRP plates. The linear strain is assumed for strain distribution along the beam depth. The appropriate stress state at each strain position during the calculation process must follow the constitutive material laws. Therefore, the assumed stress-strain relationship for concrete, steel, and CFRP slabs must be applied. Bilinear stress-strain model for steel bars and a linear model for the CFRP plate were used. While parabolic stress-strain model for concrete in compression was adopted from the literature [11].

Then internal forces are obtained by using corresponding strain ($\varepsilon_i$, $\varepsilon_{si}$, and $\varepsilon_p$) and stress level at each incremental curvature ($\phi$). Furthermore, the equilibrium of plated cross-section is then achieved by an iteration process. After the equilibrium in the cross-section is fulfilled, the bending moment at corresponding value of curvature can be calculated by multiplying the internal forces with the correspondence moment arms ($y_i$). Then the incremental step is continued until the maximum compressive strain of $\varepsilon_{cm} = 0.003$ is reached. A computer program for analysis using the fiber element method has been developed to speed up the computation process [7-9].

Figure 4. Analytical model using fiber element method

4. Results and discussion
The results of the experimental study are presented in the form of crack patterns and load-deflection curves. Based on the test result, all control beams (G6C1, G6C2, and G6C3) were failed in flexure indicated by concrete crushing in the top of the compression zone after yielding of tensile reinforcement. Two of beams strengthened with CFRP plate (G6P1 and G6P2) were failed in
premature failure due to delamination of CFRP plates, while beam G6P3 was failed in flexure indicated by concrete crushing in the top of compression zone. The first crack in the control beam occurred at an average load of 3.3 kN, while for the beam with CFRP plates, the first crack occurred at an average load of 9.4 kN. The higher values of the first crack in beams with CFRP plate indicate the contribution of the FRP plate to withstand the tensile force and to increase the flexural strength.

Crack patterns of the test beams are shown in Figure 5. Shear cracks propagate in the shear span zone after the growth of flexural cracks in the tension side of the beams. The levels of cracking loads were higher in beams with CFRP plate rather than control beams due to the contribution of CFRP plates. Figure 5 also shows that shear crack angles are higher with the smaller tensile reinforcement ratio. This phenomenon indicates that flexural behavior is more dominant to occur in reinforced concrete beams with a lower tensile reinforcement ratio. While on beams with a higher tensile reinforcement ratio, the flexural load force will be higher in conjunction with increasing flexural capacity so that the shear force that occurs in the beam becomes higher.

![Figure 5. Crack patterns of the beams after the test](image-url)
As shown in Figure 5, all beams show crushing of concrete in the top of compression zone. This result occurred because in this experimental study, if the debonding failure occurred (for beams G6P1 and G6P2), load continued to be applied until the beams reached the ultimate condition. Debonding failure occurred suddenly without any indication of delamination between concrete and plate, and the failure loads occurred at a load level of 48.9 kN and 63.1 kN for beams G6P1 and G6P2, respectively. Figure 6 shows the position of delamination between concrete and CFRP plate for beams G6P1 and G6P2.

The flexural capacity of the test beams is plotted in Figure 7 and 8. It can be seen from these figures that the ratio of tensile reinforcement significantly influences the flexural strength for all beams, both with and without CFRP plates. However, although an increase in the tensile strength ratio causes an increase in the flexural strength, the ductility of the beam decreases. The occurrence of CFRP plate delamination is seen in Figure 7 (b), which is shown by a sudden decrease in load-deflection curves. It is also shown in Figure 7(b) that, after the delamination of the CFRP plate, the load directly drops to the same position as the load on the control beam. This phenomenon shows that the beam returns to capacity without strengthening after the influence of the CFRP plate adhesion is no longer exist.
Figure 8 shows that the flexural capacity of the reinforced concrete beams strengthened with CFRP plate higher than the control beams for about 10% to 50% depending on the value of the tensile reinforcement ratio. A comparison between analytical (blue line) and experimental (red and black line) results are shown in Figure 8. This figure shows that the analytical results are close to the test results of all beams within a reasonable accuracy. It is also confirmed from the analytical result that the flexural strength of beams with CFRP plates is higher than that beams without plates by 8 to 55%, depending on the values of the tensile reinforcement ratio. These figures also confirm that debonding failure occurs after the yielding of tensile reinforcement (G6P1 and G6P2).

5. Conclusions
A total of six reinforced concrete beams with and without CFRP plates were tested. The comparison between flexural capacities of the beam with different tensile reinforcement ratio is discussed, and the following conclusions are drawn:
1. The flexural capacity of the reinforced concrete beams strengthened with CFRP plate higher than control beams for about 10% to 50% depending on the value of the tensile reinforcement ratio.
2. Debonding failure due to the delamination of the CFRP plate occurred in reinforced concrete beams with a small reinforcement ratio (1% and 1.5%). Flexural failure without delamination of the CFRP plate occurred in the beam with a reinforcement ratio of 2.5%. This phenomenon reveals that the stress value that occurs on the CFRP plate decreases with an increasing tensile reinforcement ratio.
3. The analytical results are close to the test results of all beams within a reasonable accuracy.

References
[1] Saadatmanesh H and Ehsani M R 1991 RC beams strengthened with GFRP plates Parts I Journal of structural engineering 117(11) pp 3417-3433
[2] Malek A M, Saadatmanesh H and Ehsani M R 1998 Prediction of failure load of R/C beams strengthened with FRP plate due to stress concentration at the plate end ACI Structural. Journal 95(1) pp 142-152
[3] Rahimi H and Hutchinson A 2001 Concrete beams strengthened with externally bonded frp plates Journal of composites for construction 5(1) pp 44-56
[4] Malek A M, Saadatmanesh H and Ehsani M R 1998 Prediction of failure load of R/C beams strengthened with FRP plate due to stress concentration at the plate end ACI Structural. Journal 95(1) pp 142-152
[5] Hassan T and Rizkalla S 2004 Bond mechanism of near-surface-mounted fiber-reinforced polymer bars for flexural strengthening of concrete structures ACI Structural Journal 101(6) pp 830-839
[6] Sayed-Ahmed E Y, Bakay R and Shrive N G 2009 Bond strength of FRP laminates to concrete: State-of-the-art review Electronic journal of structural engineering 9 pp 45-61
[7] Thamrin R and Sari R P 2017 Flexural capacity of strengthened reinforced concrete beams with web bonded steel plates Procedia engineering 171 pp 957-964
[8] Thamrin R 2017 Analytical prediction on flexural response of rc beams strengthened with steel plates MATEC Web of Conf. 103:02012
[9] Thamrin R 2018 Effect of strengthening method and anchorage length on flexural capacity of rc beams with steel plates. Journal of engineering science and technology 13(11) pp. 3781-3794
[10] Abid S R and Al-lami K 2018 Critical review of strength and durability of concrete beams externally bonded with FRP Cogent engineering 5(1) 1525015
[11] Mander J B, Priestley M J N and Park R 1988 Theoretical stress-strain model for confined concrete Journal of Structural Engineering 114(8) pp. 1804-1826

Acknowledgment
The author would like to thank PT. Fyfe Fibrewrap Indonesia for material support and installation of CFRP plates in our laboratory. The author would also like to thank the Engineering Faculty of Universitas Andalas for research fund support through Research Grant financial year 2020.