

Flexural Strengthening Reinforced Concrete Beams Subjected to Flexural Damage with CFRP

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ABSTRACT

In 2020, about 12% of bridges in Indonesia were assessed to be damaged. CFRP is a material that is widely used for repair reinforced concrete bridges. The behavior of reinforced concrete beams strengthened with externally bonded CFRP sheets was investigated experimentally. The research was to investigate the influence of CFRP sheet numbers on the mechanical behavior of concrete beams under flexural loading. Furthermore, the stiffness of the new reinforced concrete beams with those after being repaired with CFRP will be compared. Three CFRP reinforced concrete beams with the same dimension but the different number of layers of CFRP sheets have been tested. Besides, a normal reinforced concrete beam without reinforced with externally bonded CFRP sheets also has been tested as a comparison specimen. Before the reinforced concrete beams are reinforced with externally bonded CFRP sheets, the beams have tested to yield steel; then the beams were repaired by patching the cracks. The results of this research indicated that the loading capacity of the reinforced concrete beams strengthened with externally bonded CFRP sheet increased, but the deflection decreased. The ratio of the maximum load of normal concrete with 1 layer, 2 layers, and 3 layers of FRP has increased by 29.05%, 34.63%, and 16.58%, sequentially. The stiffness value after being reinforced with FRP experienced a decrease in the stiffness value by 27.43% - 56.70%, but the ductility index increased by 39.72% - 66.21%.

Keywords: CFRP, Stiffness, Maximum Load, Ductility.

1. INTRODUCTION

In 2020, about 12% of bridges in Indonesia were assessed to be damaged, mainly due to the age factor. The condition of the existing bridge is also damaged due to the development of the volume of vehicles in Indonesia which is increasing every year so that it can cause the elements of the bridge structure to support overload, and the load capacity of the bridge structure to be deficient. This has led to the importance of developing effective, reliable, and cost-effective methods of repair and retrofitting for existing bridge structural elements.

This FRP layer is a better solution than steel plate, in repairing and strengthening existing concrete structural elements; because, apart from being easy to implement, it is also corrosion-resistant, lightweight, and has high strength. Many experimental studies show that reinforced concrete beams reinforced with FRP layers have increased load capacity up to three times, depending on the reinforcement ratio, the ratio of concrete and FRP strength, the mechanical properties of FRP, the nature of

the adhesive material, and the condition of the level of damage to the existing concrete structural elements.

Experimental research in the laboratory to determine the behavior of reinforced concrete beam structural elements with repair and reinforcement with FRP layers is generally carried out on reinforced concrete beam structural elements in intact condition, the structural elements have not been loaded. Meanwhile, the main purpose of installing the FRP layer on the lower surface of the reinforced concrete beam structure is to repair and increase the capacity of the beam structural elements that have been damaged. Thus, it is necessary to conduct an experimental study to find out how the actual behavior of the existing beam structural elements that have been damaged, and the decrease in load capacity of the flexural load is needed.

2. BACKGROUND

The use of FRP coating material for repairing reinforced concrete structural elements provides several

advantages, namely resistance to rusting, high tensile stress, lightweight, and easy workability [8].

The concrete reinforcement study on the testing of fourteen reinforced concrete beams reinforced using steel plates and FRP, showed an increase in beam stiffness by 18% to 116%. In addition, the flexural capacity of the ultimate beam increased from 47% to 97%. However, failure does not occur in the maximum moment area but occurs at the ends due to delamination between FRP and concrete [6].

Structural failures in beams with FRP reinforcement have been identified in previous studies. FRP failure/damage in general applied to beams consists of, intermediate crack debonding where that when flexural cracks or shear flexural cracks begin to form in the concrete, the concrete accommodates the concentration of strain in the cracks resulting in local debonding of the FRP and stopping the spread cracked. Furthermore, the tensile stress is released with the formation of cracks in the concrete which is transferred by FRP and reinforcing iron so that the stress at the interface between the concrete and FRP is formed around the crack. Debonding at the ends of the FRP is this failure begins with the occurrence of shear at the interface between the FRP and the concrete and the normal stress around the ends of the FRP which exceeds the strength of the concrete elements. Debonding occurs starting from the end of the FRP and spreading to the center of the concrete beam. This can happen if the width of the FRP is much smaller than the width of the beam. Debonding at the end of the FRP can also result in the separation of the concrete blanket, namely the release of the bond between the reinforcing steel and the concrete. Critical diagonal crack (CDC) debonding is a type of debonding failure that occurs in beams reinforced with FRP in the flexural region while the FRP ends are in zones with high shear forces but with low moments (e.g., FRP ends are close to the beam support) and a minimal amount of shear reinforcement. The form of damage is a major diagonal shear crack (CDC) and cuts through the FRP, and usually occurs near the ends of the FRP. When the crack widens, high interfacial stresses between the FRP and the concrete are induced, thereby causing debonding failure between the concrete beam and the FRP, the cracks around the debonding area propagate from the crack gap to the area around the FRP tip [7].

The effect of yielding reinforcement and the presence of cracks during reinforcement with GFRP sheets affects the decrease in the ultimate load of the beam compared to the estimated ultimate load using the theory of reinforced concrete beams. So, it is necessary to conduct further studies related to the effect of yielding reinforcement and the presence of cracks on the flexural capacity of reinforced concrete beams reinforced with GFRP sheets. To determine the effect of yielding

reinforcement and the presence of cracks on the concrete surface, a study was carried out by repairing the cracks that occurred by grouting, then installing FRP to see the increase in flexural capacity [3].

The use of FRP after yield reinforcement has increased the moment capacity by 19.13% and the maximum load that can be carried by the beam increases by 17.65%. With these results, it is proven that the FRP sheets on reinforced concrete beams that have been loaded to yielding reinforcement have a higher flexural capacity than the original beam. The effect of melting reinforcement and the presence of cracks during reinforcement with FRP sheets affects the decrease in the ultimate load of the beam compared to the estimated ultimate load using the theory of reinforced concrete beams. So, it is necessary to conduct further studies related to the effect of yielding reinforcement and the presence of cracks on the flexural capacity of reinforced concrete beams reinforced with FRP sheets. To determine the effect of yielding reinforcement and the presence of cracks on the concrete surface, a study was carried out by repairing the cracks that occurred by grouting, then installing FRP to see the increase in flexural capacity.[5]

3. RESEARCH METHOD

Dimension of the beams and reinforcement were analyzed using the ultimate strength design method and beam testing was carried out using standard beam testing tools [1][2].

3.1 Test Object

Four specimens of the reinforced concrete beams are made with beam cross-sectional dimensions of 200 mm x 300 mm x 3300 mm, and details of longitudinal and transverse reinforcement as shown in **Figure 1**. The three specimens are reinforced with a layer of FRP on the lower surface of the beam with the number of 1, 2, and 3 layers of FRP, whereas one beam as a control test object, is not reinforced by the FRP layer.

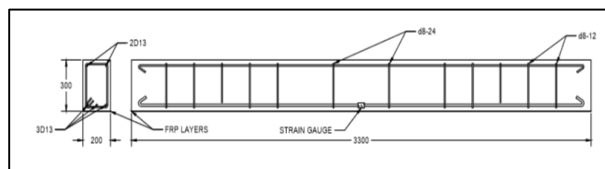


Figure 1 Detail of Test Object.

The longitudinal and transverse reinforcement is assembled according to the plan. After that, a strain gauge is installed on the tensile longitudinal reinforcement, in the middle of the span, to observe the magnitude of the tensile strain that occurs in the tensile reinforcement, as shown in **Figure 2**.

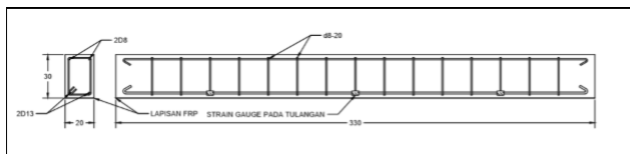


Figure 2 Set-up strain gauge on reinforcement.

3.2 Experimental Procedure

3.2.1 Test Set-up

Reinforced concrete beams that have reached the design compressive strength, are placed on the loading frame, with simple supports. The strain gauge was attached to the top fiber concrete surface, in the middle of the span. This is done to determine the compressive strain of concrete that occurs during the test. The beam spreader was placed just below the actuator in the middle of the beam specimen span. To determine the magnitude of the vertical deflection during the test, the LVDTs were installed in the middle of the span and just below the two ends of the spreader beam. The magnitude of the load, deflection, and strain that occurs were read through a data logger that was connected to a computer monitor.

3.2.2 Initial Test without FRP Reinforcement

The loading tests on reinforced concrete beams with FRP were carried out until failure; but before the beams were reinforced with FRP, the beams had carried out initial testing. The tests were carried out with load control, monotonic loading, and third points with a loading frame capacity of 500kN. The loading was done incrementally until the tensile reinforcement yielded. This can be seen from the strain gauge attached to the tensile reinforcement. During the test, changes in the magnitude of the load, the deformation that occurs in the concrete and reinforcement, as well as the pattern and distribution of cracks on the surface of the concrete beams were observed. After the yield strength of the tensile reinforcement was reached, loading and testing were stopped. Furthermore, repairs were made to the test objects that have been damaged, namely on the lower surface of the concrete due to the cracks that occur. Grouting was done to cover and filled the cracks that occur. Then, reinforcement was carried out by attaching a layer of FRP along and as wide as the bottom surface of the beam, according to the planned number of layers of FRP. The FRP layers were pasted with epoxy adhesive on the bottom surface, along the concrete beam. Beam 02 was installed with one layer of FRP, and Beam 03 was installed with 2 layers of FRP, and Beam 04 was installed with 3 layers of FRP.

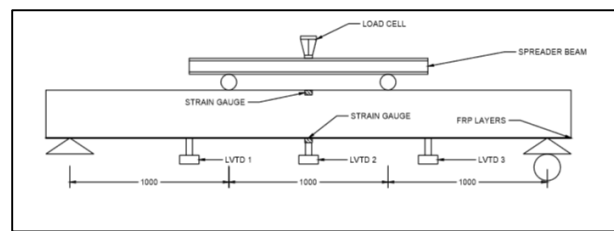


Figure 3 Illustration of Testing.

After the FRP layer was installed, to determine the strain that occurs in the FRP, a strain gauge was attached to the bottom surface of the FRP layer, in the middle of the beam span. Likewise, a strain gauge was installed on the surface of the top fiber of the concrete beam in the middle of the span, to determine the amount of strain that occurs in the maximum compressive fiber of the concrete, as shown in **Figure 3**.

3.2.3 Testing with FRP Reinforcement

Testing continues with the same system as the initial test. During the test, the magnitude of the load, mid-span deflection, strain on the surface of the compression fiber concrete, tensile reinforcement, and FRP, as well as the pattern of cracks that occurred were observed. Likewise, the bond between the FRP surface and the concrete was observed, to determine the pattern of failure, to determine the aspect that initiated the failure, for example, the presence of delamination. Testing, the loading of the beam test object was continued until it collapses.

4. RESULT DAN DISCUSSION

4.1 Beam 01 Test Results

Beam 01 was a control beam, the beam without FRP reinforcement. **Figure 4** shows a graph of the load-deflection relationship from the test results of beam 01 subject to the flexural load. The maximum load was 58kN with a deflection that occurred in the middle of the span of 46 mm. While the maximum deflection at mid-span that occurred just before the beam collapsed was 85.71 mm when the beam was loaded at 54.54 kN.

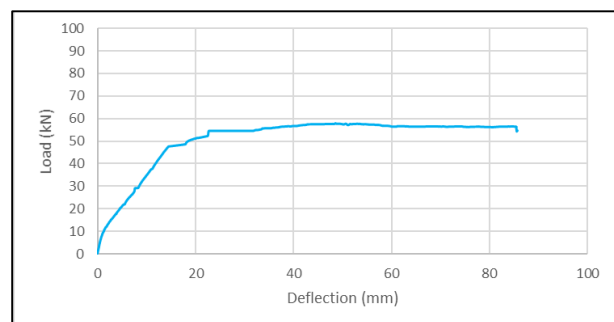


Figure 4 Beam 01 Load-Deflection Relationship.

Figure 5 shows the crack pattern of beam 01. The first crack occurred when it reaches a load of 7.27 kN. The crack began to occur in the middle of the span, in the large moment region. The cracks developed relatively perpendicular to the neutral line of the beam, approaching the neutral axis. These cracks were classified as flexural cracks. Cracks developed followed by oblique/diagonal cracks from the face of the load point to the support. These oblique cracks were a continuation of flexural cracks and were known as flexural shear cracks. The stiffness and ductility of the reinforced concrete beam were 9.35 kN/mm, and 2.00, respectively.



Figure 5 Crack pattern of Beam 01

4.2 Beam 02 Test Result

Beam 02 was the concrete beam with 1 layer of FRP reinforcement. **Figure 6** shows a graph of the load versus the deflection relationship of the test results of beam 02 to the flexural load. The graph shows that the first crack of the beam, at initial testing, occurred when it reached a load of 11.03 kN with a deflection that occurred in the middle of the span of 1.75 mm. The test was stopped when steel tensile yielded, reached a strain of 0.01862. It reached a load of 49.70 kN and the deflection at the mid-span reached 16.98 mm. The stiffness of the beam was 6.30 kN/mm.

Furthermore, the cracks that occurred in the beam were patched with an epoxy-based until it reached the setting time. Then, the beam was reinforced with a CFRP layer. Figure 6 shows a graph of the load vs. deflection relationship of the test results of beam 02 which has been reinforced by CFRP against bending loads. The graph shows that the first crack of the beam occurred when it reached a load of 9.7 kN with a deflection that occurred in the middle of the span of 1.51 mm. The maximum load that occurred reached 74.53 kN at a deflection of 57.69 mm. The maximum deflection at mid-span that occurred just before the beam collapsed was 57.69 mm when the beam was loaded at 71.16 kN.

Figure 6 also shows a comparison of the graph without and with CFRP reinforcement, which shows the difference in stiffness values. The stiffness and ductility

of the reinforced concrete beam were 6.42 kN/mm, and 3.33, respectively.

The first crack in the beam that had not been reinforced with CFRP occurred when it reached a load of 11.03 kN. These cracks began to occur in the middle of the span in the large moment region. The cracks developed relatively perpendicular to the neutral line of the beam, approaching the neutral axis. These cracks were classified as flexural cracks. Cracks developed followed by oblique/diagonal cracks from the face of the load point to the support. These oblique cracks were a continuation of flexural cracks and are known as flexural shear cracks.

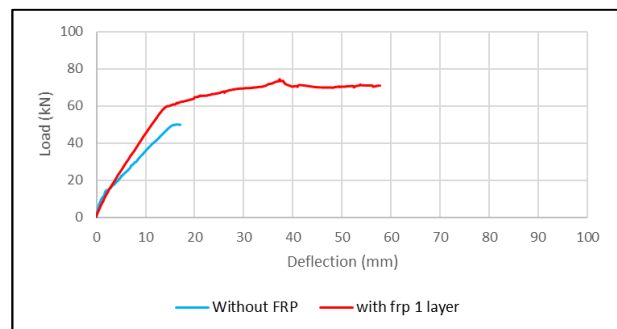


Figure 6 Beam 02 Load-Deflection Curve Relationship

After the beam was reinforced with the CFRP sheet, there were no new cracks occurred in the beam. The test was stopped when debonding occurs between the concrete interface and the CFRP layer, when the load reached 58 kN at a distance of one-third of the span, as shown in Figure 7. The bond failure between the concrete surface and the CFRP layer occurred when the concrete had not collapsed as indicated by the concrete strain value 0.000563.29, which means that the concrete had not collapsed ($\epsilon_c=0.003$); while the strain of the tensile reinforcement had yielded. However, testing continued, so that at this stage only concrete worked to withstand the load on the test object. The beam collapsed at a load of 71.16 kN. **Figure 7** shows that the crack pattern that caused the failure was the dominant flexure. Therefore, the cause of the failure that occurred was a flexural failure.



Figure 7 Crack pattern of beam 02

4.3 Beam 03 Test Result

Beam 03 was the concrete beam with 2 layers of FRP reinforcement. Figure 8. shows a graph of the load vs. deflection relationship of the test results of beam 03 to the bending load. The graph shows that the first crack of the beam occurred when it reached a load of 7.65 kN with a deflection that occurred in the middle of the span of 0.85 mm. The test was stopped when the reinforcement has yielded when the reinforcement reached a strain of 0.019 when it is loaded with 49.05 kN and the deflection at the center of the span reached 16.32 mm. The stiffness of the beam was 9.00 kN/mm.

Furthermore, the cracks that occurred in the beam were patched with an epoxy-based until it reached the setting time. Then, the beam was reinforced with a CFRP layer. **Figure 8** shows a graph of the load vs. deflection relationship of the test results of beam 03 which has been reinforced by CFRP against bending loads. The graph shows that the first crack of the beam occurred when it reached a load of 6.04 kN with a deflection that occurred in the middle of the span of 1.55 mm. The maximum load that occurred reached 77.773 kN at a deflection of 37.87 mm. The maximum deflection at mid-span that occurred just before the beam collapsed was 37.87 mm when the beam was loaded at 77.54 kN.

Figure 8 also shows a comparison of the graph without and with CFRP reinforcement, which shows the difference in stiffness values. The stiffness and ductility of the reinforced concrete beam were 6.42 kN/mm, and 3.33, respectively.

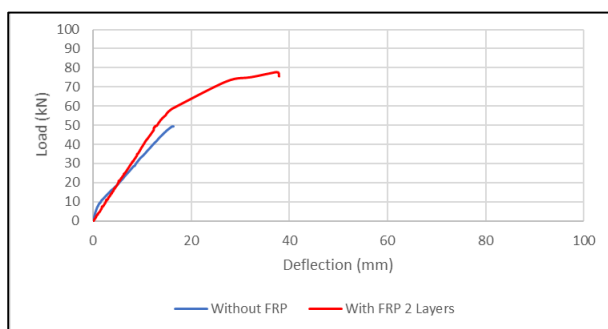


Figure 8 Beam 03 Load-Deflection Relationship

The first crack in the beam that had not been reinforced with CFRP occurred when it reached a load of 7.65 kN. These cracks began to occur in the middle of the span in the large moment region. The cracks developed relatively perpendicular to the neutral line of the beam, approaching the neutral axis. These cracks were classified as flexural cracks. Cracks developed followed by oblique/diagonal cracks from the face of the load point to the support. These oblique cracks were a continuation of flexural cracks and are known as flexural shear cracks.

After the beam was reinforced with the CFRP sheet, there were no new cracks occurred in the beam. The test was stopped when debonding occurs between the concrete interface and the CFRP layer, when the load reached 71.6 kN at a distance of one-third of the span, as shown in Figure 9. The bond failure between the concrete surface and the CFRP layer occurred when the concrete had not collapsed as indicated by the concrete strain value 0.000421, which means that the concrete had not collapsed ($\epsilon_c=0.003$); while the strain of the tensile reinforcement had yielded. However, testing continued, so that at this stage only concrete worked to withstand the load on the test object. The beam collapsed at a load of 71.6 kN. Figure 9 shows that the crack pattern that caused the failure was the dominant flexure. Therefore, the cause of the failure that occurred was a flexural failure.



Figure 9 Crack pattern of beam 03 CFRP

4.4 Beam 04 Test Result

Beam 04 was the concrete beam with 3 layers of FRP reinforcement. **Figure 10** shows a graph of the load vs. deflection relationship of the test results of beam 04 to the bending load. The graph shows that the first crack of the beam occurred when it reached a load of 7.85 kN with a deflection that occurred in the middle of the span of 0.75 mm. The test was stopped when the reinforcement has yielded when the reinforcement reached a strain of 0.0198 when it is loaded with 46.00 kN and the deflection at mid-span reached 14.52 mm. The stiffness of the beam was 10.46 kN/mm.

Furthermore, the cracks that occurred in the beam were patched with an epoxy-based until it reached the setting time. Then, the beam was reinforced with a CFRP layer. Figure 10 shows a graph of the load vs. deflection relationship of the test results of beam 04 which has been reinforced by CFRP against bending loads. The graph shows that the first crack of the beam occurred when it reached a load of 4.33 kN with a deflection that occurred in the middle of the span of 0.57 mm. The maximum load that occurred reached 67.33 kN at a deflection of 45.38 mm. The maximum deflection at mid-span that occurred just before the beam collapsed was 45.38 mm when the beam was loaded at 58.54 kN.

Figure 10 shows also a comparison of the graph without and with CFRP reinforcement, which shows the difference in stiffness values. The stiffness and ductility of the reinforced concrete beam were 7.59 kN/mm, and 1.86, respectively.

The first crack in the beam that had not been reinforced with CFRP occurred when it reached a load of 7.85 kN. These cracks began to occur in the middle of the span in the large moment region. The cracks developed relatively perpendicular to the neutral line of the beam, approaching the neutral axis. These cracks were classified as flexural cracks. Cracks developed followed by oblique/diagonal cracks from the face of the load point to the support. These oblique cracks were a continuation of flexural cracks and are known as flexural shear cracks.

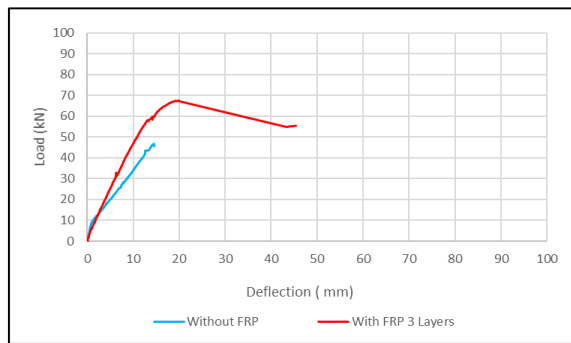


Figure 10 Beam 04 Load-Deflection Relationship

After the beam was reinforced with the CFRP sheet, there were no new cracks occurred in the beam. The test was stopped when debonding occurs between the concrete interface and the CFRP layer, when the load reached 66.65 kN at a distance of one-third of the span, as shown in Figure 11. The bond failure between the concrete surface and the CFRP layer occurred when the concrete had not collapsed as indicated by the concrete strain value 0.000302, which means that the concrete had not collapsed ($\epsilon_c=0.003$); while the strain of the tensile reinforcement had yielded. However, testing continued, so that at this stage only concrete worked to withstand the load on the test object. The beam collapsed at a load of 58.54 kN. Figure 11 shows that the crack pattern that caused the failure was the dominant flexure. Therefore, the cause of the failure that occurred was a flexural failure.



Figure 11 Condition of Beam 04 Collapsed

4.5 Effect of FRP on Load-Deflection

The effect of CFRP on reinforced concrete beams can be seen in Figure 12. From the graph, beam 03 with 2 layers of CFRP reinforcement has the highest increase in strength, which is 34.63% compared to beam 01, which was without CFRP. Beam 04 with 3 layers of CFRP reinforcement has the smallest increase compared to the others, which is 16.58%. This may be because the maximum number of layers of CFRP has been passed so that it has decreased the strength. Meanwhile, from layer 1 to layer 2 there is an increase, it was 29.05%.

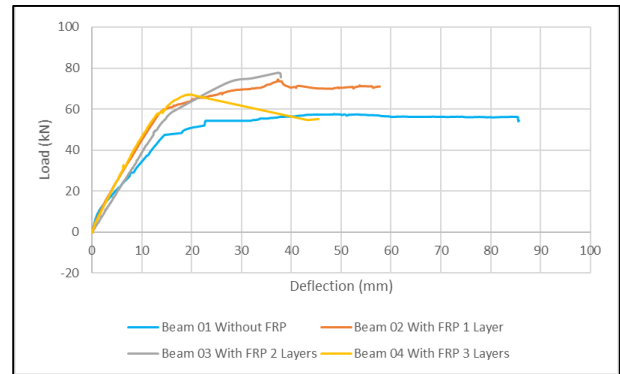


Figure 12 Comparison of Load-Deflection

4.6 Effect of CFRP reinforcement on Stiffness of The Beams

The stiffness of reinforced concrete beams depends on the ratio of the load and displacement. From the experimental results of the test beams, as can be seen in **Table 1**. CFRP reinforcement could decrease in stiffness value at Beam 03 and Beam 04 which were 27.43% and 56.70% compared to the control beam, respectively.

Table 1 Beam Stiffness.

Specimen	without CFRP reinforcement	With CFRP reinforcement	Difference
Beam 01	9.36	-	-
Beam 02	6.30	6.42	1.92%
Beam 03	9.00	3.90	-56.70%
Beam 04	10.47	7.60	-27.42%

4.7 Effect of CFRP reinforcement on Ductility

The ductility of reinforced concrete beams depends on the ratio of the ultimate to yield strain. Table 2 shows the ductility values obtained from the beam test results, for the number of FRP layers of 1 layer, 2 layers, and 3 layers.

Table 2 shows that CFRP reinforcement could increase in ductility at Beam 02 and Beam 03 which were 39.72% and 66.21% compared to the control beam, respectively.

Table 2 Index Ductility.

Specimen	Yield		Failure		μ
	ϵ_y (mm/mm)	P_y (kN)	ϵ_u (mm/mm)	P_u (kN)	
Beam 01	0.00197	54.07	0.00395	54.53	2.00
Beam 02	0.00189	49.7	0.00628	71.46	3.33
Beam 03	0.00190	49.06	0.00532	75.63	2.80
Beam 04	0.00205	46.59	0.00382	66.74	1.86

5. CONCLUSION

The behavior of reinforced concrete beams and reinforced concrete beams reinforced with externally bonded CFRP sheets was experimentally investigated. The results show that reinforced concrete beams reinforced with externally bonded CFRP sheets increase the loading capacity but reduce the deflection. Beams reinforced with 2 layers of CFRP achieve maximum loading capacity but in minimum deflection. In addition, interfacial debonding easily propagates along with the interfacial concrete layer at loads that are below the maximum expected strength of the CFRP-reinforced structure.

The behavior of reinforced concrete beams after being reinforced with FRP does not differ much in each layer. The ratio of the maximum load of normal concrete with 1 layer of FRP increased by 29.05%, for 2 layers of FRP it has increased by 34.63%, and 3 layers of FRP has increased by 16.58%.

The stiffness value after being reinforced with FRP experienced a decrease in the stiffness value by 27.43% - 56.70%, and the ductility index increased by 39.72% - 66.21%.

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