The Behavior of Low Strength Concrete Beams Reinforced with Carbon Fibre Reinforced Polymer Under Cyclic Loading

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ABSTRACT
Concrete is a material that is currently widely used in various constructions. However, the development of material and construction technology does not make it perfect. The problem often encountered is that the compressive strength of the concrete used in construction does not meet the initial specifications, even below the minimum requirements. One of the most widely used structural strengthening methods is Carbon Fibre Reinforced Polymer (CFRP). However, CFRP is also widely applied to concrete with lower compressive strength than standard without knowing the risks. This study used an experimental method with various low-strength concrete beams tested under cyclic loading. The specimens are concrete beams with 300 x 200 x 3000 mm with various compressive strengths of 11.44 MPa, 12.88 MPa, and 15.76 MPa. Each variant had normal specimens (without CFRP reinforcement) and specimens reinforced with 1 and 1 layers of CFRP. Based on the test results, it was found that the use of CFRP on low-strength concrete beams resulted in an increase in the flexural strength of the beam by 28-34% compared to normal specimens on 1-layer reinforcement and 26-44% on 2-layers CFRP reinforcement. However, it should be noted that the ductility in the specimens with CFRP reinforcement is significantly reduced. In the failure mode, it can be observed that the failure pattern is ductile in normal specimens, while the failure of specimens with CFRP reinforcement was brittle.

Keywords: *CFRP, Cyclic Loading, Low-strength Concrete, Reinforcement.*

1. INTRODUCTION

The structural part is a vital part; therefore, it must be planned in such a way as to support the load that will later exist. In addition, the implementation of construction must be carried out and possible to minimize unwanted things. The use of concrete materials in building construction is very often used in addition to steel materials. However, with the development of construction technology today, there are still many errors, including the planned compressive strength of the concrete that is not following the initial specifications. Structural elements that should have high strength become prone to collapse. Structural failure factors can be caused by carelessness during construction, planning errors, loss of strength due to age and the environment, and switching the function of the building without taking into account the effects that may occur. Structural failure can lead to complete collapse and irreparable defects of the building [1].

This problem makes the contractor have to carry out demolition and rebuilding because the structure is not suitable. In addition to the loss of energy and costs, the time required increases while the user must operate the building immediately. This problem encourages the need for alternative solutions to low-strength concrete. One alternative is to repair and retrofit. One of the most widely used structural reinforcement methods is Carbon Fibre Reinforced Polymer (CFRP).

In Indonesia, CFRP reinforcement has been applied to various building constructions that must be reinforced, including low-strength concrete below the minimum compressive strength. However, the reinforcement is still used without knowing the characteristics after the reinforcement is carried out. In addition, there are essential factors in planning the building structure, namely its strength and ductility [2]. Therefore, further research is needed to study this problem.

In this study, experimental results will be presented of concrete beams with low compressive strength reinforced using CFRP and tested by cyclic loading. In addition, this study aims to determine the resulting performance on the impact of CFRP reinforcement on low compressive strength concrete beams.

2. LITERATURE REVIEW

SNI 2847:2019 states that the minimum compressive strength for structural concrete is at least fc' 17 MPa. Low-strength concrete is not intentionally created, primarily due to construction errors and negligence in its control. Carbon Fibre Reinforced Polymer (FRP) is a global trend in transportation, industry, infrastructure, and settlements. CFRP consists of a polymer resin matrix reinforced with fibres. The advantages of CFRP are high tensile strength, corrosion resistance, and lightweight, making it easier to work without the need for various complicated equipment. CFRP material has a tensile strength that is much greater than the tensile strength of steel which is almost ten times. CFRP consists of 2 types, namely in the form of fibre or fibre with a thickness of less than 0.14 mm and a plate or laminate type with a thickness of 1.66 mm. The number of layers of CFRP reinforcement used in concrete beams is the most effective in the number of layers 1-3 [3]. Meanwhile, other reinforcements such as jacketing require complex equipment and are difficult to carry without heavy equipment [4].

Several previous studies had researched low-strength concrete reinforced using Carbon Fibre Reinforced Polymer [5-7]. The use of CFRP material makes the reinforced concrete beam structure withstand initial cracks and withstand more excellent tensile and flexural strength than beams without CFRP reinforcement [8].

Based on those research, CFRP reinforcement in low-strength concrete results in increased strength in cylindrical specimens. Furthermore, reinforcement of CFRP on beams with various variations of reinforcement has been carried out. The results show that strengthening the flexural and shear sections of CFRP U-Wrap reinforcement is the most effective method of strengthening [7, 9].

Cyclic loading uses an alternating load direction and will stop at a particular load or deflection according to a predetermined target. Based on ASCE 41-17, there are several loading patterns: fully-reversed cyclic loading, monotonic loading, one-sided cyclic loading, and near-fault loading. In this study, the type of loading pattern used is a cyclic loading pattern with a one-sided cyclic adjustment to the existing test equipment. In addition, the maximum flexural strength value was obtained from the peak load on the envelope load-deflection curve while to obtained the ultimate flexural strength based on ACI 374.1-05, it should not be less than a 25% decrease from the peak load that had been obtained.

Previous research using cyclic loading has been carried out on beam specimens [10-11]. Based on the study results, it can be seen that the beam specimen with a compressive strength of 30 MPa with FRP reinforcement tested with cyclic loading increases its strength, but the ductility that occurs in the beam will decrease and cause a brittle failure.

3. METHODOLOGY

The method in this study is an experimental test to see the characteristics and behaviour of concrete beams with low compressive strength reinforced using CFRP. In general, the stages of implementing this research consist of preparation, manufacture of test objects, testing, data analysis, and stages of research conclusions.

3.1 Specimen and material

Concrete beams specimens have various variations in compressive strength quality, which are divided into three groups. Each group has three specimens with one normal specimen without reinforcement, specimens with one layer of CFRP reinforcement, and specimens with two layers of CFRP reinforcement which are declared successively with the markings N, 1, 2 on the back of the name. Data from these groups can be seen in Table 1.

Table 1. Specimen Detail

No	Specimen	Concrete Strength (MPa)	CFRP Reinforcement (layer)
Group A			
1	AN	11.44	0
2	A1	11.44	1
3	A2	11.44	2
Group B			
1	BN	12.88	0
2	B1	12.88	1
3	B2	12.88	2
Group C			
1	CN	15.76	0
2	C1	15.76	1
3	C2	15.76	2

The results of that compressive strength are the average of cylindrical specimens at the age of 28 days. The CFRP material used is EstoWrap 300 with the modulus of elasticity, tensile strength, and maximum stretch of the sheet based on the manufacturer's catalog are 230000 MPa, 4900 MPa, and 0.166 mm/mm [12]. The sizes of the reinforcing steel used are 13 and 8 mm in diameter. The test results for reinforcing steel materials can be seen in Table 2.

Table 2. Tensile Strength Test of Reinforcing Steel

Specimen Code	KS13	KS8
Diameter (mm)	13	8
Yield Stress (N/mm^2)	502.79	410.80
Fracture (N/mm^2)	620.93	595.36

The specimen is a concrete beam with dimensions of 200 x 300 x 3200 mm. The specifications for steel reinforcement are two pieces of compression reinforcement with a diameter of ∅8 and four pieces of tensile reinforcement with a diameter of D13. The installation of CFRP for flexural reinforcement is with an area of 200 mm and shear reinforcement (U-Wrap) is with a width of 75 mm and a distance of 75 mm. Specimen details can be seen as in Figure 1.

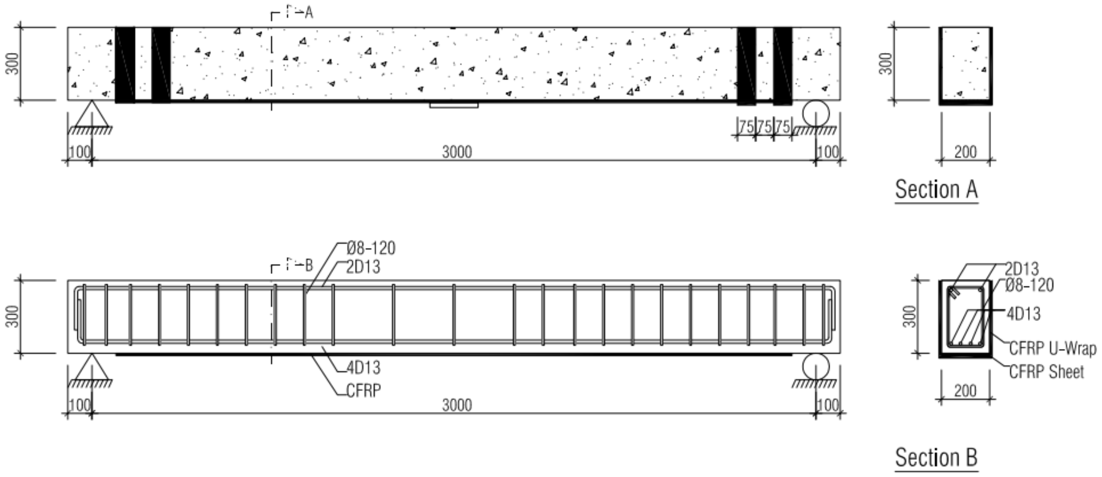


Figure 1 Section details of the specimen

3.2 Test Setup and loading method

The specimen was placed on a loading frame with roller-joint support at the end. The load was given at 1/3 of the beam span length, i.e., a distance of 1000 mm from the support. Loading measurement used hydraulic jack and load cell. In addition, LVDT (Linear Variable Displacement Transducer) was installed to determine the deflection when the test object is given a load. It was installed at the bottom of the test specimen as many as three pieces: in the middle and 1/3 of the span from both support ends. The test setup can be seen in Figure 2.

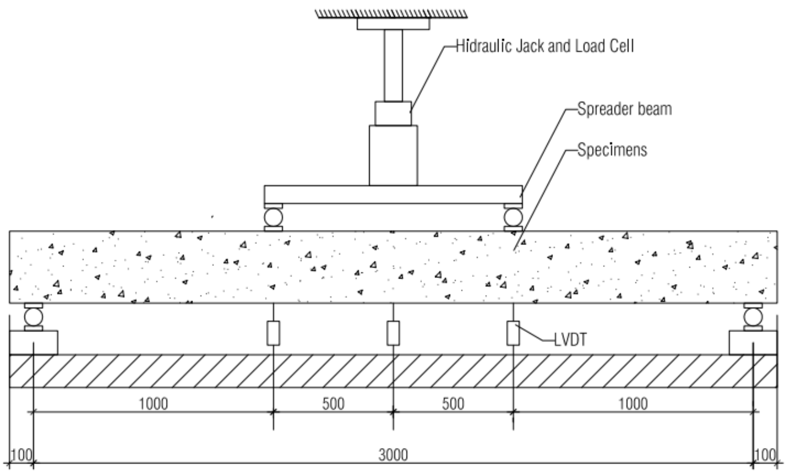


Figure 2 Test Setup

Cyclic loading was carried out using a Universal Testing Machine (UTM) with a loading capacity of 500 tons. The beam test was carried out using the Third-Point Load method on the beam and was given a cyclic loading with a compression loading pattern; the ramp actuator speed used is constant at 0.05 mm/s until the beam collapses or decreased by 25% from its peak load.

The loading setup was carried out based on ACI 374-1-05 with some modifications to suit the available equipment. In this study, the target drift was a multiple of not less than 1.25 and not more than 1.5 from the previous drift. In each drift, there are four cycles carried out. The first drift was taken as 0.1% of the total length of the test object (3000 mm) so that the first drift target was 3 mm. Then, the determination of another target drift is determined based on the multiple limitations. The loading pattern can be seen in Figure 3.

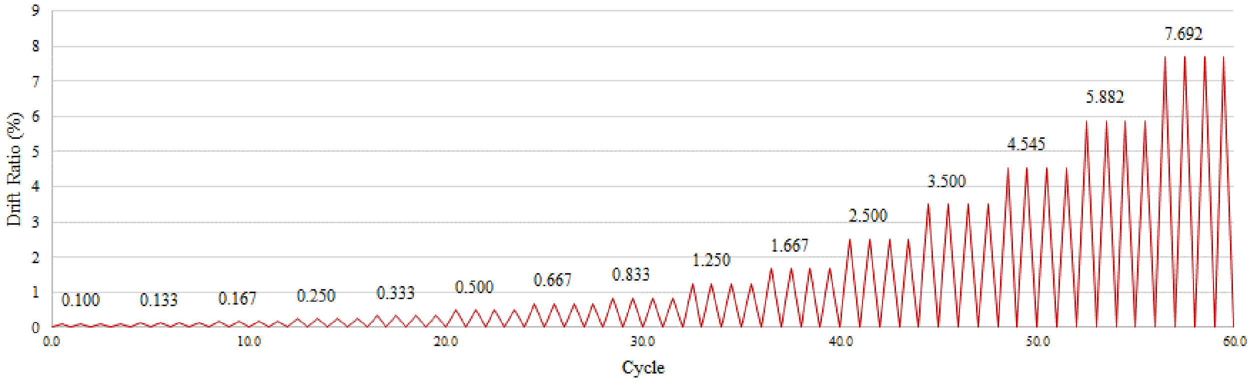


Figure 3 Cyclic loading pattern

4. RESULT AND DISCUSSION

In this study, experimental tests were carried out on nine beam specimens with several variations of low compressive strength. The specimens were normal specimens and specimens with 1 and 2 layers of CFRP reinforcement. The loading is carried out with a cyclic loading pattern referring to ACI 374-1 05.

4.1. Hysteresis Curve

The results of the hysteretic curve from the cyclic test on one of the test objects can be seen in Figure 4. Based on this curve, the envelope curve of the load-deflection of each test object will be obtained. The combined results of the load-deflection envelope curves for each group can be seen in Figure 5.

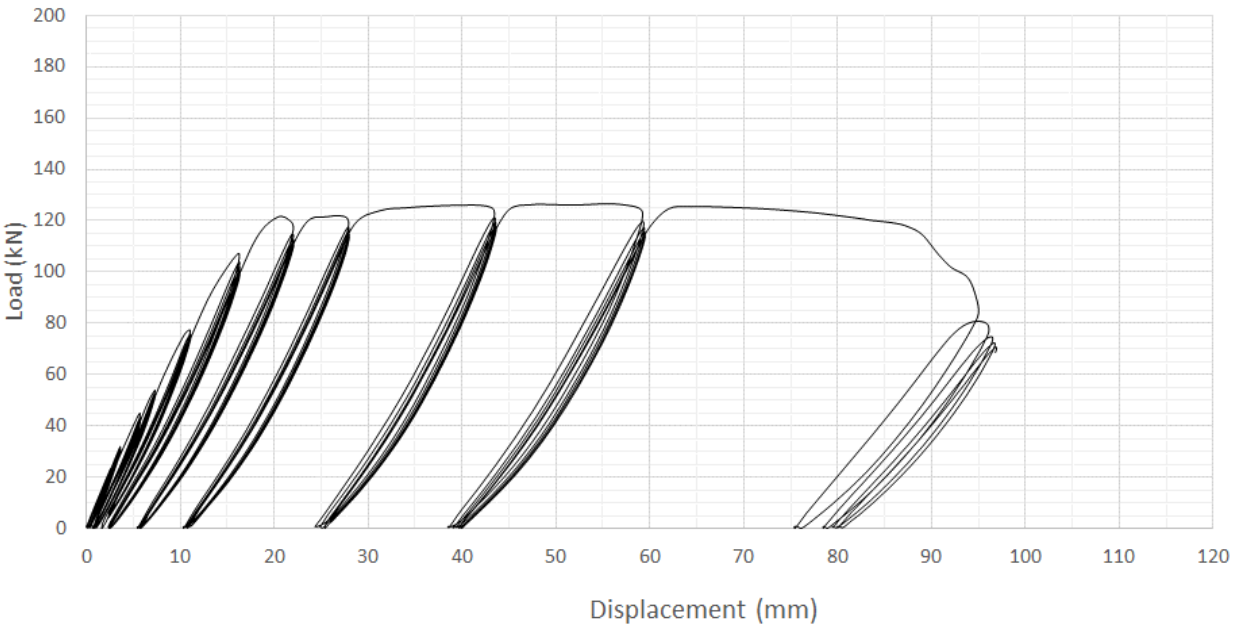
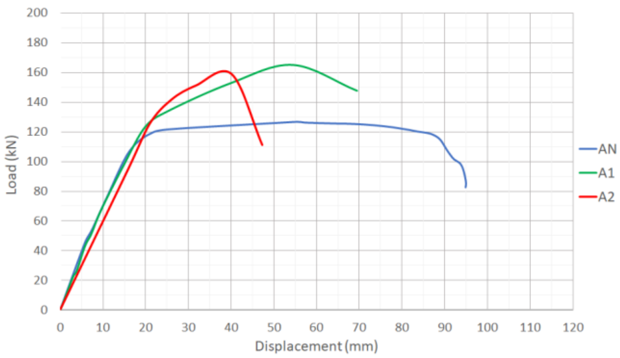
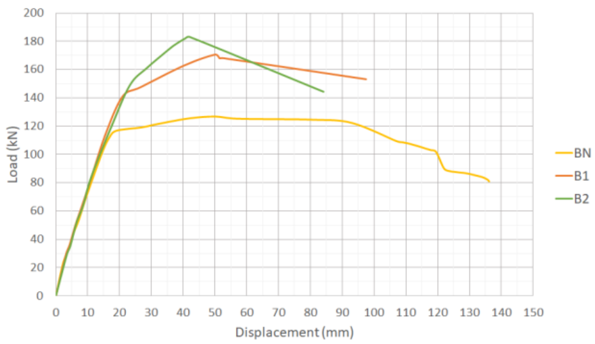


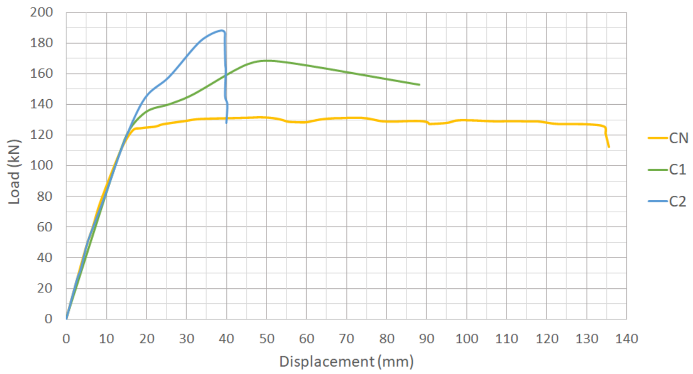
Figure 4 Hysteresis Curve of specimen AN



(a) Load-displacement for Group A



(b) Load-displacement for Group B



(c) Load-displacement for Group C

Figure 5 Load-displacement Curve for each group

4.2. Strength

Based on the load-deflection curve in the middle of the span above, it can be seen that the deflection load curve is similar at the initial stage of loading in each group. Thus, the specimens with CFRP reinforcement have a higher load-bearing capacity than normal specimens. However, the deflection by the CFRP-reinforced specimen is minimal compared to normal specimens. This matter is because the specimen collapsed before reaching a decrease of 25% from its peak load. The measurement of the maximum load on each test object can be seen in Table 3.

Table 3. Maximum Load

No	Specimen	Pmax (kN)	Percentage
Group A			
1	AN	126.562	0%
2	A1	164.937	30%
3	A2	159.032	26%
Group B			
1	BN	126.706	0%
2	B1	170.403	34%
3	B2	183.058	44%
Group C			
1	CN	131.464	0%
2	C1	168.014	28%
3	C2	188.167	43%

Concrete beam specimens with one layer CFRP reinforcement (A1. B1, and C1) increase maximum load-bearing (Pmax) by 28%-30% compared to normal specimens in their group. Meanwhile, specimens with two layers of reinforcement (A2, B2, C2) had a more significant increase with a percentage of 26%-43%. The most significant increase occurred in Group C (concrete with compressive strength of 15,76 MPa), so it can be concluded that increasing concrete compressive strength and the number of layers of CFRP reinforcement increases the load-bearing strength.

4.3. Ductility

Based on the load-deflection, the value was derived from the ratio of the ultimate deflection value to the yield deflection (δu/δy). The calculation of the yield point used the energy balance method that had been carried out in several previous studies [12]. The value of the ductility calculation can be seen in Table 4.

Table 4. Ductility

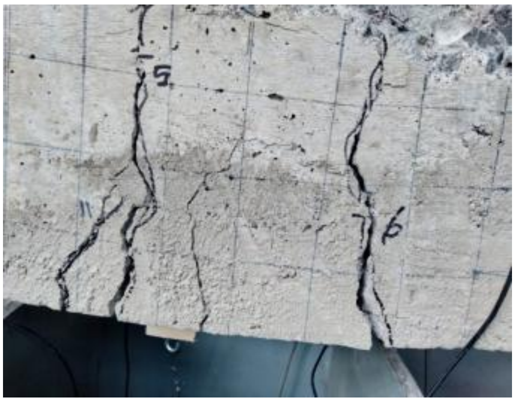
No	Specimen	δu	δy	Ductility	Percentage
Group A					
1	AN	94.2	20.3	4.627	0%
2	A1	54.4	31.0	1.751	-62%
3	A2	40.1	28.1	1.424	-69%
Group B					
1	BN	120.9	19.8	6.092	0%
2	B1	49.9	27.4	1.820	-70%
3	B2	41.9	28.4	1.477	-76%
Group C					
1	CN	129.2	16.8	7.655	0%
2	C1	53.5	27.4	1.949	-75%
3	C2	38.4	26,6	1.442	-81%

Although the strength increased, the specimen with CFRP reinforcement had a higher brittleness than the normal specimen. This matter is caused by the addition of CFRP, which causes the beam specimen to be over-reinforced. The ductility calculation shows that the normal specimens in each group have a more excellent value than the specimens with CFRP reinforcement. The decrease in ductility in specimens with one layer of CFRP reinforcement is between 62%-75%, while in specimens with two layers of reinforcement, it is 69%-81%. So, it can be said that with increasing layers of CFRP reinforcement, the ductility decreases.

4.4. Failure Mechanism

The failure mechanism in unreinforced specimens (AN, BN, and CN) had a typical pattern. Based on the observations of crack patterns in the tested beams, in the initial drift, there were no cracks because the load applied was relatively small. With increasing load applied to the beam, cracks are formed and more visible in hair cracks, primarily seen in the flexural area. These cracks formed in the mid-span area up to a third span from the load source, which begins with cracks in concrete cover in the vertical direction. The addition of the load causes the deflection to increase, and the initial crack spreads (propagation) with increasing length and width. New cracks are created as the load increases, where these cracks are created in the bending and shear areas. When the specimen reaches the maximum load, the specimen experiences cracks widening and elongating. The test finally stopped when loading had reached a reduction of 25% of its peak load or when the deflection had reached the tool limit. Crushing also occurs in the beam compression section, which occurs in every concrete beam without CFRP reinforcement. The failure that occurs is ductile with large deflections. The failure mechanism at one of the unreinforced specimens (AN) can be seen in Figure 6.

(a) Ductile failure in Specimen AN



(b) The crack pattern in Specimen AN

Figure 6 Failure in specimen AN

Specimens with one or two layers of CFRP reinforcement (A1, A2, B1, B2, C1, and C2) have a typical failure mechanism pattern. Cracks are not visible at the initial load, but cracks begin to appear and get more prominent with increasing load. The failure is brittle and occurs suddenly, accompanied by a small explosion by the broken shear CFRP reinforcement (CFRP U-Wrap), and causes the grip of the flexural CFRP reinforcement in the area near the support to fail. This failure indicated that the reinforcement of CFRP U-Wrap in the shear area strengthens the structure against shear loads and strengthens the bond of flexural CFRP reinforcement near the end. After the shear CFRP reinforcement collapse, a sudden collapse occurred in the flexible CFRP reinforcement accompanied by debonding and partial release of the concrete cover until the steel reinforcement was visible. The failure that occurs is brittle with a slight deflection. The failure mechanism at one of the CFRP reinforcement specimens with one layer (A1) can be seen in Figure 7.

(a) Brittle failure in Specimen A1

(b) Broken of CFRP U-Wrap

(c) Concrete Cover Separation

Figure 7 Failure in specimen A1

5. CONCLUSION

Based on the analysis and experimental test results on low-strength concrete beams with or without CFRP reinforcement, the following conclusions can be drawn:

1. Reinforcement of low-strength beams using CFRP made the beam withstand greater flexural strength when compared to unreinforced specimens when tested by cyclic loading. This result happens to specimens of one layer of CFRP reinforcement with an increase of 28%-34% and two layers of CFRP reinforcement with an increase of 26%-44% percentage.
2. The unreinforced specimen had higher ductility than the CFRP reinforced specimen. This case is because the addition of CFRP causes the beam to be over-reinforced and collapse suddenly. The percentage decrease in ductility in the specimens observed was 62%-73% for the specimens with one layer CFRP reinforcement. The percentage decrease was 69%-80% for the specimens with two layers of CFRP reinforcement.
3. The failure pattern in the unreinforced CFRP specimens (normal) in each group is a ductile failure with a significant deflection. In contrast, the failure is brittle for the specimens with CFRP reinforcement with one or two layers. In addition, the specimen with CFRP reinforcement experienced a collapse simultaneously as the CFRP, which was deboned from the concrete cover. This also causes the ultimate load value to be the same as the peak load because the beam collapses at the same time as the peak load is reached.
4. The failure of the specimen without CFRP reinforcement is in the form of crushing damage. In contrast, the specimen with one layer and two layers of CFRP reinforcement has a typical failure: debonding between CFRP and the concrete cover and a little bit of crushing damage in the concrete.

The use of CFRP reinforcement in concrete with low compressive strength (at 11.44 MPa, 12.88 MPa, and 15.76 MPa) will increase its flexural strength. However, it is necessary to consider other impacts that significantly reduce ductility and failure patterns as brittle damage.

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