International Journal of GEOMATE, July, 2025 Vol.29, Issue 131, pp.1-12
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2025.131.4829
Geotechnique, Construction Materials and Environment

EXPERIMENTAL STUDY OF DOUBLE RETROFITTED LOW AND HIGH-STRENGTH REINFORCED CONCRETE BEAMS AND SLABS USING CFRP

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*Corresponding Author, Received: 27 Nov. 2024, Revised: 17 March 2025, Accepted: 20 March 2025

ABSTRACT: During its service life, a structure may exhibit a range of deficiencies due to deterioration, construction or design errors, changes in functionality, and updates in design standards. Consequently, deficient structures need to be retrofitted to sustain their functionality. Structures that have been retrofitted once may require further strengthening during their service life. This research aims to further evaluate the behavior of retrofitted structural elements. In this study, three beams and two slabs that were retrofitted with FRP flexural reinforcement five years ago will undergo additional retrofitting. The beams will be reinforced with FRP shear reinforcement, and the slabs will receive another layer of FRP flexural reinforcement. The study evaluates two types of concrete: high-strength concrete and low-strength concrete. The main objective is to evaluate the behavior of retrofitted beams and slabs by observing their ductility, stiffness, ultimate load, mode of failure, and moment capacity. Based on the experimental results, it was found that low-strength beams still experience shear compression failure, while high-strength beams experience flexural failure with a higher ultimate load. Specifically, in high-strength beams, ductility increased significantly with the addition of FRP shear reinforcement. Both low-strength and high-strength slabs experienced shear failure due to an over-reinforced condition, exhibiting higher stiffness due to the additional layer of flexural FRP reinforcement. This study highlights the need to consider failure modes in FRP retrofitting. Shear reinforcement improves ductility in high-strength beams, while low-strength beams remain shear-critical. In slabs, excessive flexural FRP increases stiffness but risks over-reinforcement. These insights aid in optimizing structural rehabilitation.

Keywords: Beam, Slab, Low-strength concrete, High-strength concrete, FRP

1. INTRODUCTION

During its service time, reinforced concrete (RC) structures may exhibit a range of deficiencies due to the potential of structural deterioration, construction/design error, changes in functionality, standard upgrades, or subpar maintenance [1]. To address this issue, deficient structures need to be retrofitted or replaced. However, in most cases, retrofitting deficient structures is environmentally and economically preferable compared to total replacement [2]-[3].

The most common retrofitting techniques are concrete/steel jacketing, ferrocement, steel plates bonding, and fibre reinforced polymer (FRP) composites [2]. Among these methods, FRP composites are viewed as a prominent and effective strengthening material compared to other retrofitting techniques due to the corrosion resistance, high strength-to-weight ratio, lower maintenance costs, and practicality of FRP composites [4][7].

The matrix of FRP systems can be divided into three groups: glass fibres, aramid fibres, or carbon fibres [7]. Carbon Fibre Reinforced Polymer (CFRP) is more commonly used as a retrofit material compared to others. Carbon fibre offers better mechanical behavior, such as a higher strength-to-weight ratio, higher stiffness, can maintain strength up to 2000°, and higher resistance towards chemical attack [8]. The most common FRP composites strengthening techniques are externally bonded (EB) plates/sheets or embedment of FRP bars or strips [2] [4], [9][13]. Among these techniques, externally bonded (EB) Carbon Fibre Reinforced Polymer (CFRP) is more attractive due to its simple application and its effectiveness. Earlier research has shown that externally bonded CFRP can improve the flexural behavior of reinforced concrete (RC) beams, but the ductility is greatly reduced [10], [14][18]. However, most of the studies that have been done so far have focused on normal-strength concrete, and ACI 440.2R-17 emphasizes this even more when referring to potential future study topics. Therefore, this study aims to look at the matter more thoroughly and offer additional evidence.

Saribiyik et al. studied the performance of low-strength reinforced concrete (RC) beams using GFRP and CFRP laminates in terms of flexural capacity, ductility, and energy absorption capacity. Specimens were divided into eight separate groups of beams based on their type of matrix and the number of FRP layers. All the specimens were subjected to a four-point flexural experiment to evaluate the flexural behavior of FRP-strengthened beams and the influence of the number of FRP layers. Results showed that the CFRP-strengthened beam has a higher yielding load, but lower ductility compared to control beams and GFRP-strengthened beams. In addition, the CFRP and GFRP increase the stiffness. The CFRP-strengthened beams have higher load-bearing capacities, but lower energy absorption capacity as the amount of FRP wrapping layer increases. As to the crack pattern, CFRP strengthened beams showed shear fracture as the beam reached the collapsing load. However, strain analysis was not performed in this study, and this paper also does not compare the experimental moment to the predicted moment [14].

Akbarzadeh H et al. conducted an experimental and analytical investigation of continuous high strength reinforced concrete beams with FRP strengthening in terms of its flexural behavior and its compatibility with analytical studies. Specimens were divided based on the number of layers and the type of matrix. These specimens were loaded with a concentrated load at the middle of each span until failure. According to the findings, the addition of CFRP caused the failure mode to change from flexural failure to FRP tensile rupture. However, it appears that the addition of CFRP increased moment capacity, but it is also demonstrated that there is a significant ductility decrease by 70% [18].

Mahmoud et al. evaluated the flexural capacity, ductility, toughness, strain response, and energy absorption of high-strength reinforced concrete thin slabs with CFRP laminates. This study also compares the experimental moment to the predicted moment. This paper, however, emphasizes the significance of the number of layers and reinforcement ratio. Results indicate that adding CFRP reduces the slab's ductility, and it appears that all strengthened specimens failed in a brittle manner. The experimental moment in this investigation is compared to the moment predicted by ACI 440, and it appears that there is a significant error of 24.5% [19].

Despite extensive studies on FRP-strengthened beams and slabs, this research provides new insights by focusing on the effects of double FRP reinforcement and how initial failure modes influence structural behavior. By examining high-strength and low-strength concrete elements retrofitted with CFRP for both flexural and shear strengthening, this study reveals how additional reinforcement can lead to unexpected failure modes, stiffness variations, and changes in ductility. These findings contribute to a deeper understanding of FRP retrofitting strategies for long-term structural performance. Initially, a set of specimens underwent flexural strengthening only. After identifying their failure modes, another set of identical specimens was strengthened with tailored strategies to address the observed failure modes from the first set. The main objective of this study was to investigate the potential prevention of initial failure modes and their occurrence when retrofitted with CFRP reinforcement. Specifically, the research focused on cases where retrofitting aimed to prevent flexural failure without maintaining the under-reinforced section, potentially leading to undesired behavior.

2. RESEARCH SIGNIFICANCE

Strengthening is often required not only for high-strength concrete structures, such as bridges, but also for low-strength concrete structures, including historical buildings that need rehabilitation to preserve their functionality. This research enhances understanding of the performance of CFRP flexural and shear strengthening under various conditions. Additionally, it aims to determine whether initial failure modes in flexurally strengthened specimens can be prevented or will still occur with further tailored strengthening schemes, providing practical insights into optimizing strengthening schemes for improved structural performance.

3. EXPERIMENTAL METHODOLOGY

3.1 Test Specimens

A total of ten beam and slab specimens were cast and tested. These specimens were initially divided into four groups based on their compressive strength and whether they were beams or slabs, with each group including unstrengthened control specimens. Initially, the specimens were strengthened with CFRP flexural reinforcement, and their failure modes were identified to tailor the strengthening scheme for subsequent specimens. Several specimens were then further strengthened with additional flexural CFRP reinforcement, while others received shear CFRP reinforcement. Each original group was thus divided into three separate groups based on the strengthening scheme. The CFRP configurations selected for this experiment were chosen based on common practices in Indonesia. The details of the specimens are outlined in Table 1.

The cross-section and the initial reinforcement are shown in Fig.1. The requirement to preserve under-reinforced sections leads to variations in steel reinforcement ratios between specimens of high and low strength.

3.2 Material Properties

The concrete's compressive strength was determined by testing ten cylindrical specimens, each with a diameter of 100 mm and a length of 200 mm, following a standard curing period of 28 days. The average compressive strength obtained from these tests for the low-strength concrete mixture was 15.24 MPa, while high-strength concrete averaged 43.21 MPa, reflecting its mechanical performance under axial loading conditions.

Table 1: Specimen Types and Quantities for Experimental Testing

Specimen	Code	Qty
Low Strength Beam	BL	2
Low Strength Beam with CFRP (1st set)	BL-F	2
Low Strength Beam with CFRP (2nd set)	BL-F2	1
High Strength Beam	BH	2
High Strength Beam with CFRP (1st set)	BH-F	2
High Strength Beam with CFRP (2nd set)	BH-F2	1
Low Strength Slab	SL	2
Low Strength Slab with CFRP (1st set)	SL-F	2
Low Strength Slab with CFRP (2nd set)	SL-F2	1
High Strength Slab	SH	2
High Strength Slab with CFRP (1st set)	SH-F	2
High Strength Slab with CFRP (2nd set)	SH-F2	1

of 400 MPa, with each diameter of reinforcing bar used in the study exhibited an average yield stress exceeding 400 MPa.

FRP used in this study is Nitrowrap FRC 300, classified as high modulus carbon in accordance with ACI 440. Table 2 presents the mechanical properties of Nitrowrap FRC 300. The concrete, steel, FRP, and bonding agents used in these specimens were typical materials commonly used in Indonesia.

Table 2 CFRP Mechanical Properties

Property	Value
Tensile Strength, MPa	3550
Ultimate Strain, %	1.5
Modulus of Elasticity, MPa	230000
Thickness, mm	0.167
Width, mm	500

3.3 Instrumentation and Testing Setup

The specimens were tested using a four-point bending method under displacement control to accurately assess their flexural response and failure mechanisms. A controlled load rate of 5 mm/min was applied to ensure gradual loading and precise observation of structural behavior. The testing was conducted using a Dartec Limited M9500 actuator, a high-capacity hydraulic system with an 80-ton load capacity, ensuring consistent and reliable force application. The experimental setup, as illustrated in . Fig.2, was designed to capture key parameters such as load-deflection behavior, crack propagation, stiffness changes, and ultimate failure modes of the specimens.

4. RESULTS AND DISCUSSIONS

4.1 Failure Modes

The failure modes observed in low-strength beam specimens are illustrated in Fig.3. Initially, the control specimens (BL) predominantly exhibited flexural failure followed by concrete crushing at the top (Fig.3a and Fig.3b). When a single layer of flexural CFRP reinforcement was added to the bottom face of the low-strength beam specimens (BL-F), dominant shear cracks followed by shear failure were observed (Fig.3c and Fig.3d). This indicates that the addition of one layer of flexural CFRP reinforcement results in an over-reinforced section in the low-strength beams. Based on the failure modes of the initially strengthened specimens, a tailored strengthening scheme was developed to prevent premature shear failure. This was achieved by adding fully wrapped U-shaped CFRP laminates for shear strengthening (BL-F2). As shown in Fig.3e, shear failure still occurred despite the addition of shear CFRP reinforcement. This outcome is attributed to the unresolved issue of over-reinforcement. While U-shaped shear CFRP reinforcement may enhance shear capacity, the low compressive strength of the concrete results in insufficient concrete shear strength, leading to shear compression failure despite the added reinforcement. This observation is consistent with the ACI 440 guidelines, which requires the combined shear strength contribution from stirrups and CFRP laminates must be less than four times the concrete shear strength. If this requirement is not met, shear compression failure is inevitable, making additional shear reinforcement ineffective.

The failure modes of high-strength beam specimens are presented in Fig.4. The unstrengthen specimens (BH) mainly experienced flexural failure, leading to concrete crushing at the top (Fig.4a and Fig.4b). For the first set of strengthened high-strength beam specimens (BH-F), a single layer of flexural CFRP laminates was applied to the bottom face, which primarily exhibited flexural cracking, followed by CFRP laminate rupture and concrete crushing at the top (Fig.4c and Fig.4d). This implies that the CFRP has reached its tensile capacity before the ultimate failure of the beam, indicating that the laminates were fully utilized. To address the failure modes observed in the initial strengthened specimens, a tailored strengthening scheme was developed, adding fully wrapped U-shaped CFRP laminates for anchorage to prevent or delay laminate rupture (BH-F2). The results showed that this scheme only delayed CFRP laminate rupture, indicated by FRP rupture occurring at a higher load capacity. The failure modes were nearly identical to those of the first set of strengthened specimens, featuring predominant flexural cracks, CFRP laminate rupture, concrete crushing at the top, and concrete cover delamination on the side face. Although the CFRP laminate rupture was not visually observable due to the U-shaped CFRP laminate cover, it was identified based on the distinctive sound of the rupture (Fig.4e).

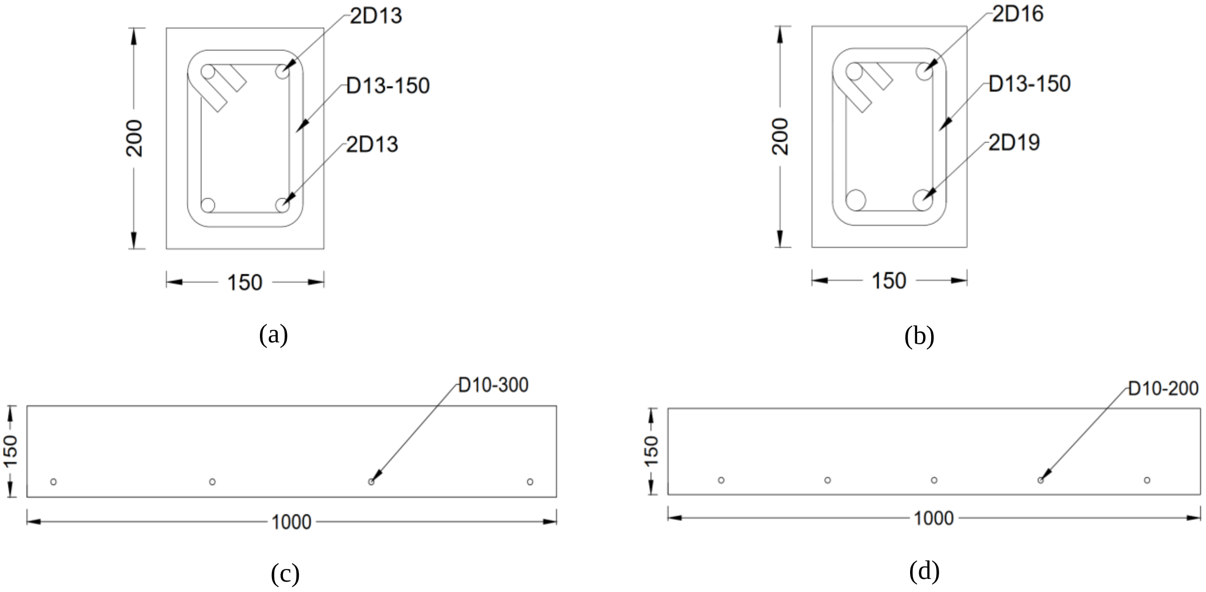


Fig.1 Cross-section detailing of specimens: (a) Beam Low Strength; (b) Beam High Strength; (c) Slab Low Strength; (d) Slab High Strength. (Note: The thickness of the cover is 20 mm on both sides.)

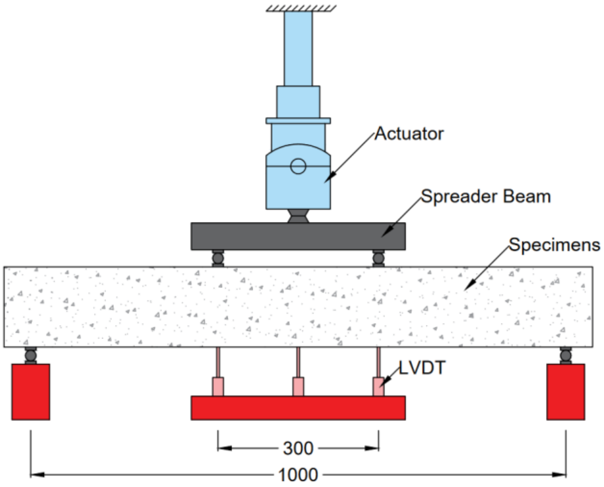


Fig.2 Four-point bending test setup

The failure modes observed in low-strength slab specimens is shown in Fig.5. The control specimens (SL) predominantly experienced flexural failure, characterized by a major vertical crack occurring not at the midspan but at the point of load application. In contrast to beam specimens, concrete crushing on the top surface did not occur in the slab specimens (Fig.5a and Fig.5b). The occurrence of a vertical crack at the point of load application could be attributed to defects in the specimens such as voids or cracks, as well as potential issues related to improper load distribution. In the first group of reinforced specimens (SL-F), a single layer of flexural CFRP reinforcement was applied across the entire square slab area. Initially, flexural cracks were observed, followed by minor shear cracks and eventual shear compression failure similar to the BL-F specimens (Fig.5c and Fig.5d). This failure indicates that the slabs became over-reinforced in flexure, shifting the failure mode from flexural to shear. In the group (SL-F2), Given the inherent integration of slabs with beams, shear strengthening of slabs is inherently impractical unlike with beams, therefore, an additional layer of flexural CFRP reinforcement was introduced to investigate its performance and failure implications. It was observed that the inclusion of an extra layer of flexural CFRP reinforcement resulted in minimal flexural cracking compared to the SL-F specimens. This indicates that additional layer of flexural CFRP reinforcement effectively minimized flexural cracking, indicating an increased flexural capacity. However, it was also observed that this addition caused significant shear cracking, leading to shear failure and CFRP debonding at the corners of the specimens which highlights the imbalance between flexural and shear capacities (Fig.5e).

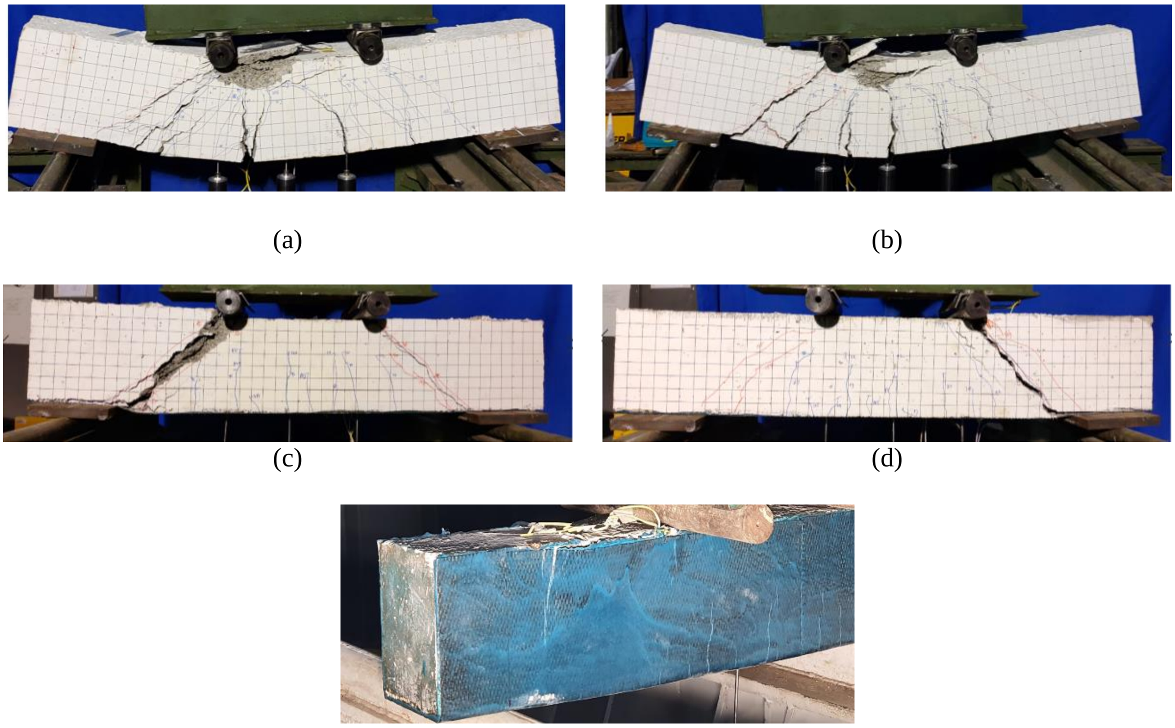
The failure modes of high-strength slab specimens are presented in Fig.6. Initially, the control specimens (SH) exhibited flexural failure, which was followed by numerous shear cracks (Fig.6a and Fig.6b). Based on these observed failure modes, a single layer of flexural CFRP strengthening was applied to the entire bottom face of the slab. It was noted that flexural cracks appeared initially, until shear cracks developed into a large crack leading to shear failure (Fig.6c and Fig.6d). Similar to the approach applied to the low-strength slab specimens, a second set of specimens was strengthened with an additional layer of flexural CFRP reinforcement to evaluate its effect on overall structural behavior and performance. In this set, flexural cracks appeared but were less prevalent than in the previous specimens. Eventually, shear cracks formed and progressed into shear failure (Fig.6e). The outcome is consistent with that observed in the low-strength slab specimens.

Based on the observed failure modes of both beam and slab specimens, it can be concluded that FRP configurations on low-strength concrete specimens require careful design. Low-strength concrete tends to have low concrete shear capacity (Vc) and a lower maximum external shear capacity to prevent shear compression failure. This makes these specimens highly sensitive to becoming over-reinforced when additional flexural reinforcement, such as CFRP, is added. This trend was observed in both low-strength concrete beams and slabs.

In contrast, high-strength concrete specimens typically exhibit higher concrete shear capacity and a greater allowable maximum external shear capacity, making their shear capacity higher while flexural capacity remains the determinant of failure. However, the results differed between high-strength beams and slabs. Slabs lack shear reinforcement, relying solely on concrete shear capacity, which proved insufficient to withstand the load after the addition of flexural reinforcement.

For low-strength concrete and slab specimens, shear failure was followed by CFRP debonding. This observation is consistent with the findings of Buyukozturk et al, who reported that debonding failure in FRP-strengthened beams often occurs prematurely, resulting in brittle failure modes and reduced ductility, particularly when cracking initiates the debonding process [20]. Similarly, Rashidi and Takhtfirouzeh demonstrated that while FRP sheets can effectively enhance the shear and flexural strength of concrete beams, inadequate anchorage or improper application may lead to premature debonding and subsequent structural failure [21].

As discussed in previous sections, shear failure resulted from the imbalance between flexural and shear capacities. This finding is consistent with the study by Wang et al., who investigated concrete beams strengthened with externally prestressed CFRP tendons and observed that, while flexural capacity significantly increased, inadequate shear capacity could lead to structural instability [22].

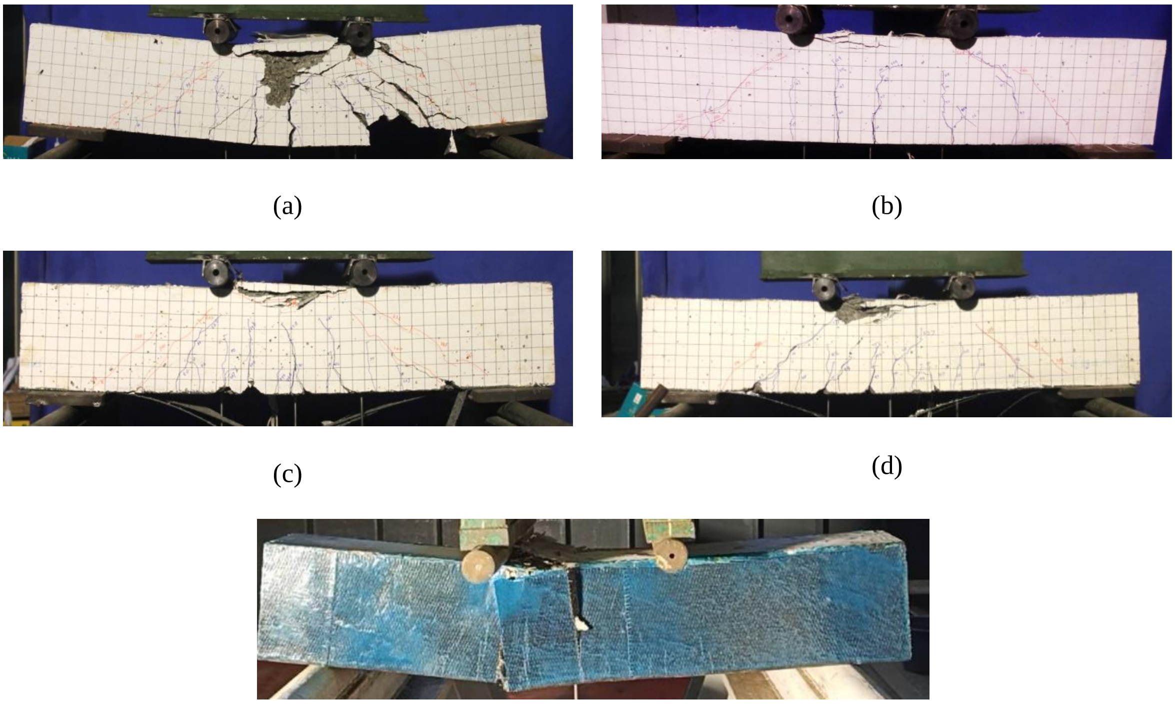


(a) (b)

(c) (d)

(e)

Fig.3 Low-strength beam group specimens' mode of failure: (a) BL-01, (b) BL-02, (c) BL-F-01, (d) BL-F-02, (e) BL-F2-0

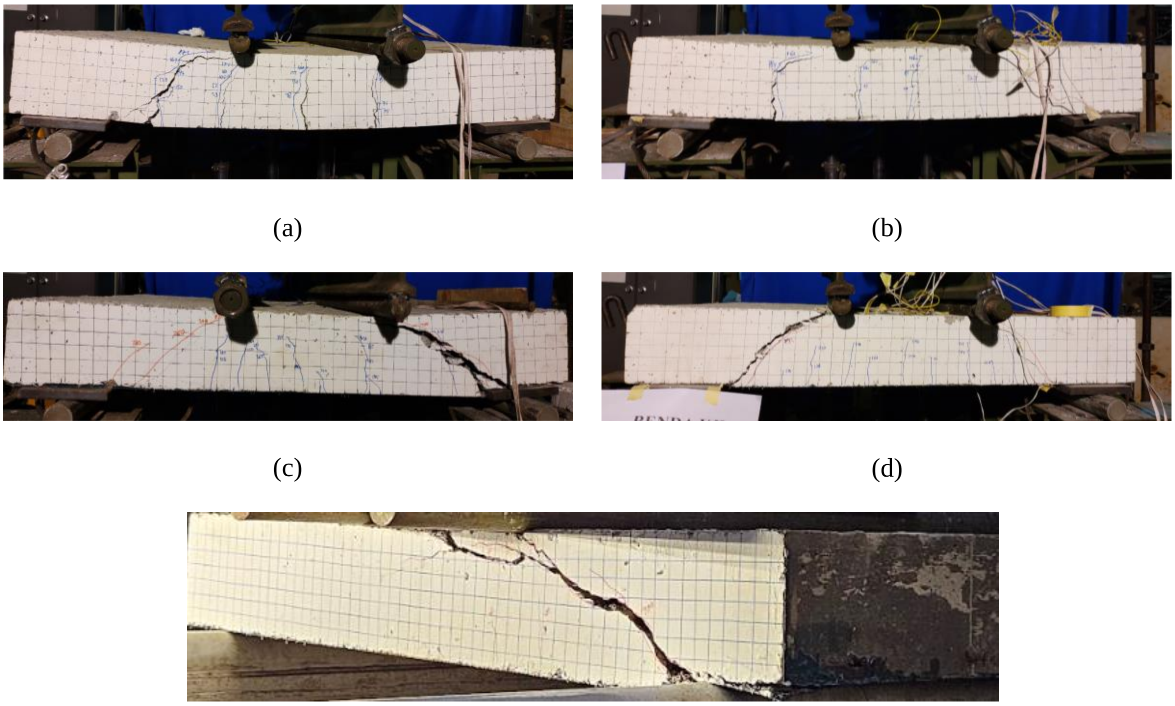


(a) (b)

(c) (d)

(e)

Fig.4 High-strength beam group specimens' mode of failure: (a) BH-01, (b) BH-02, (c) BH-F-01, (d) BH-F-02, (e) BH-F2-01

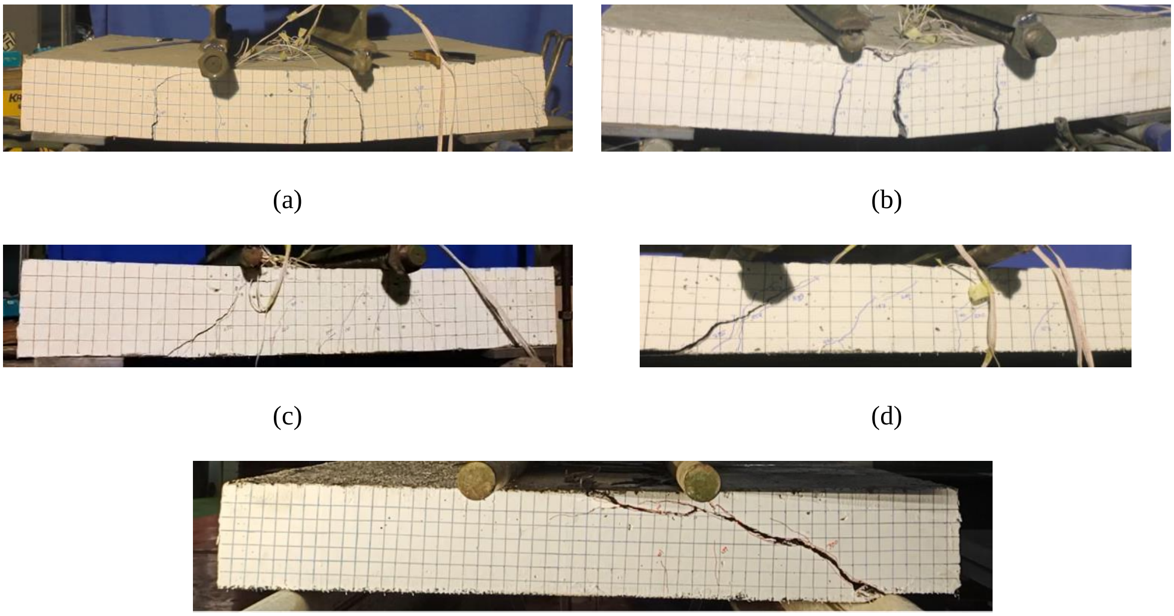


(a) (b)

(c) (d)

(e)

Fig.5 Low-strength slab group specimens' mode of failure: (a) SL-01, (b) SL-02, (c) SL-F-01, (d) SL-F-02, (e) SL-F2-01



(a) (b) (c) (d) (e)

Fig.6 High-strength slab group specimens' mode of failure: (a) SH-01, (b) SH-02, (c) SH-F-01, (d) SH-F-02, (e) SH-F2-01

Similarly, Rasheed et al. [23], examined the effect of CFRP anchorage on sectional flexural capacity and emphasized the necessity of addressing shear capacity to prevent premature shear failure in strengthened concrete beams.

4.2 Load-Displacement Behavior

The load versus midspan deflection curves for low-strength beam specimens are presented in Fig.7a. Beams BL-01 and BL-02 exhibited typical RC flexural member behavior, achieving an average ultimate load (Pu) of 116.68 kN. Their average ductility and stiffness were 11.25 and 20.545 kN/mm. In contrast, Beams BL-F-01 and BL-F-02 showed different behavior, with an average ultimate load of 129.85 kN. An increase of 15.1% in ultimate load and 63.6% in stiffness was observed, but ductility decreased by 87%. For beams BL-F2, the ultimate load was 151.86 kN, a 30.2% increase over control specimens. Ductility and stiffness were 1.87 and 22.38 kN/mm, indicating an 83.4% decrease in ductility and a 98.9% increase in stiffness. The results suggest that the addition of CFRP flexural strengthening, without maintaining an under-reinforced section, can shift the failure mode from flexural to shear failure. This shift allows for a higher ultimate load but results in a significant reduction in ductility. Simultaneously, the stiffness increases substantially due to the inherently stiff properties of CFRP materials. Adding shear strengthening does not improve ductility, as shear failure still occurs.

The load versus midspan deflection curves for high-strength beam specimens are presented in Fig.7b. Control specimens BH-01 and BH-02 achieved an average ultimate load (Pu) of 226.78 kN. Their average ductility and stiffness were 7.58 and 33.12 kN/mm, respectively. Strengthened specimens BH-F-01 and BH-F-02, with flexural CFRP strengthening, achieved an average ultimate load of 268.79 kN. This represents an 18.7% increase in ultimate load and a 9.9% increase in stiffness, with insignificant change in ductility. For beams BH-F2, the ultimate load was 295.56 kN, a 30.3% increase over control specimens. Ductility and stiffness were 7.07 and 41.04 kN/mm, indicating a 6.7% decrease in ductility and a 23.9% increase in stiffness. Table 3 summarizes the results obtained for all beam specimens, detailing ultimate load, stiffness, and ductility along with their percentage variations compared to the reference specimens. The results for high-strength beam specimens indicate that adding flexural CFRP reinforcement increases the ultimate load until CFRP rupture occurs, after which the load-deflection behavior mirrors that of the unstrengthen control specimens. The inclusion of U-wrap CFRP anchorage delays CFRP rupture, resulting in a higher loading capacity than both the control and the first set of strengthened specimens. Once the CFRP ruptures, the load-deflection curve matches that of the control specimens, indicating full utilization of the flexural CFRP, which is further enhanced by the U-wrap anchorage. Stiffness increases were not significant for BH-F-01 and BH-F-02 due to the high initial stiffness of the beams, making CFRP's contribution less apparent compared to low-strength beams. However, for BH-F2, the U-wrap configuration provided additional rigidity and confinement, limiting deformation and making the stiffness increase more noticeable. Ductility remained identical across all high-strength beam specimens due to the consistent flexural failure mode; after CFRP rupture, the behavior reverted to that of the control specimens.

The load versus midspan deflection curves for low-strength slab specimens are presented in Fig.7c. Control specimens SL-01 and SL-02 achieved an average ultimate load (Pu) of 150.3 kN. Their average ductility and stiffness were 7.925 and 36.055 kN/mm. Strengthened slabs SL-F-01 and SL-F-02, with flexural CFRP reinforcement, reached an average ultimate load of 325.015 kN (124.6% increase), with ductility and stiffness of 1.925 and 49.825 kN/mm (78% decrease in ductility, 42.2% increase in stiffness). Slab SL-F2 achieved an ultimate load of 314.58 kN (109.3% increase) and a stiffness of 49.825 kN/mm (189.3% increase), with ductility decreasing by 66%. It was observed that for slabs typically not shear reinforced, the addition of flexural CFRP reinforcement can shift the failure mode from flexural to shear failure. This shift allows for higher ultimate load and stiffness but results in significantly reduced ductility, which is not desirable for flexural RC members. Increasing the number of flexural CFRP layers does not affect ultimate load and ductility, as these are determined by shear failure. However, stiffness increases with more CFRP layers due to the material's inherent rigidity.

The load versus midspan deflection curves for high-strength beam specimens are presented in Fig.7d. The control specimens, SH-01 and SH-02 demonstrated an average ultimate load (Pu) of 219.37 kN, with ductility and stiffness values of 3.85 and 34.345 kN/mm, respectively. In contrast, the strengthened slabs SH-F-01 and SH-F-02, which had flexural CFRP reinforcement on the bottom face, achieved an average ultimate load of 390.445 kN, marking an 87% increase. These specimens showed a ductility of 1.65 and stiffness of 48.53 kN/mm, reflecting a 64.4% reduction in ductility and a 56.2% improvement in stiffness. Slab SH-F2, reinforced with two layers of flexural CFRP, exhibited an ultimate load of 452.17 kN (106.1% increase) and a stiffness of 64.51 kN/mm (91.1% increase), with ductility decreasing by 71.2%. Table 4 compiles the findings from all beam specimens, outlining ultimate load, stiffness, and ductility, including their percentage deviations from the reference specimens. The results for high-strength slab specimens aligned with those of low-strength slabs. Flexural CFRP reinforcement shifted the failure mode to shear, increasing ultimate load but decreasing ductility due to shear's sudden failure characteristics. Stiffness increased with CFRP reinforcement, though less than in low-strength slabs, like high-strength beams. High-strength concrete's inherent stiffness minimizes CFRP's impact on overall stiffness.

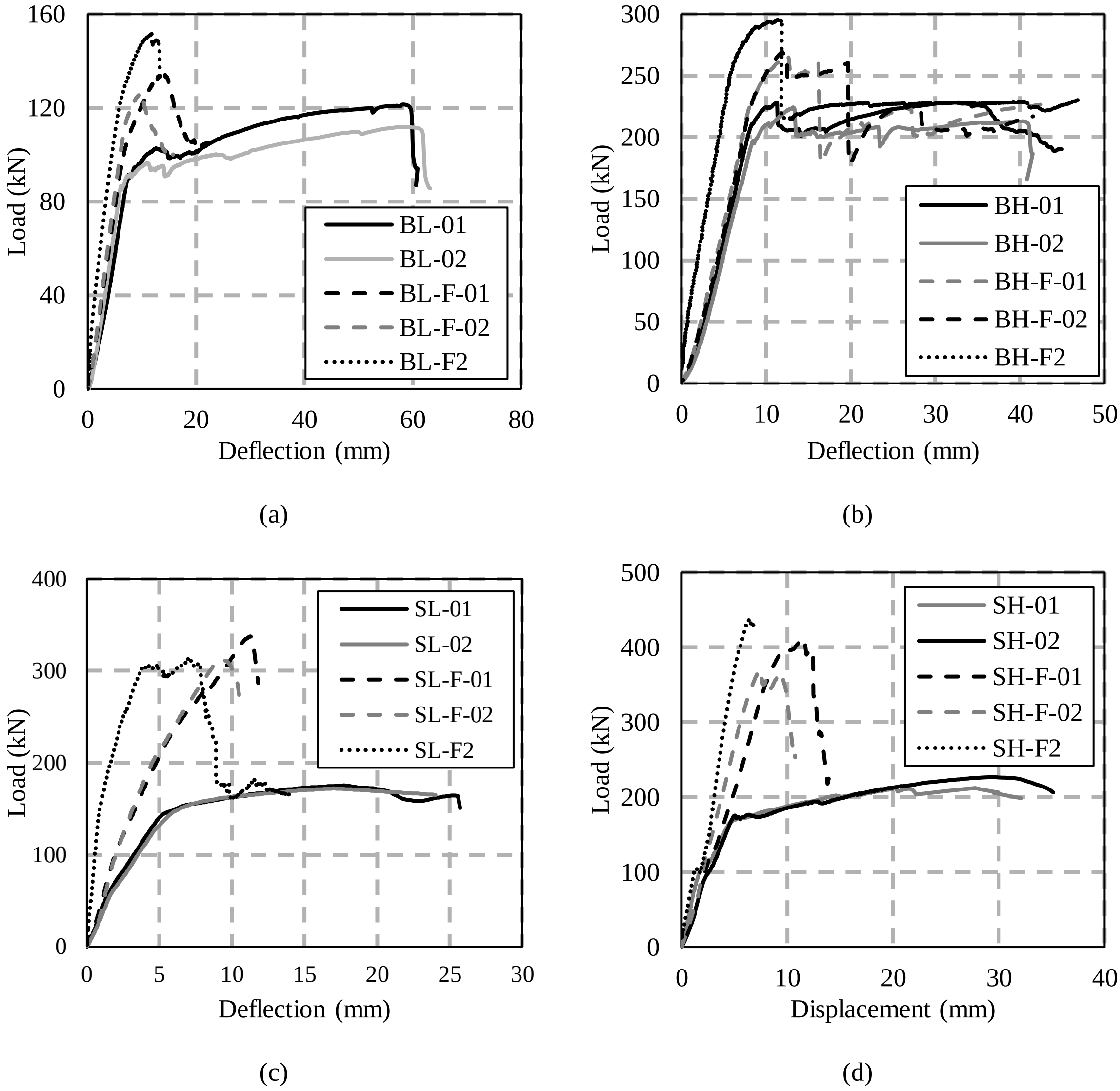
The study observed that incorporating U-Wrap CFRP shear and anchorage with CFRP flexural reinforcement on beams significantly enhances the load-bearing capacity and stiffness compared to beams with only primary reinforcement. The U-Wrap CFRP anchorage improves the bond between the CFRP and the concrete substrate, effectively preventing premature debonding of the CFRP flexural reinforcement. This strengthened bond facilitates better load transfer and maximizes the utilization of the reinforcement's tensile properties, resulting in increased stiffness and ultimate load capacity [23]. Ductility was significantly affected by the failure modes of the specimens. In specimens demonstrating flexural behavior, the addition of CFRP flexural reinforcement did not enhance ductility due to the inherently stiff and brittle nature of CFRP [24]. Low ductility in some specimens was attributed to shear failure, which was initially triggered by over-reinforcement with the CFRP flexural reinforcement.

4.3 Theoretical-Experimental Comparison

Based on the experimental findings, a comparison between the experimental moment capacity and the theoretically calculated moment capacity will be performed. The theoretical calculations will follow the prescriptive guidelines outlined in ACI 440.2R-17, specifically as described in Eq. (1). Moment capacity calculation assumes perfect bonding mechanism, thus allowing for maximum effective strain of CFRP reinforcement. Given that only the strengthened specimen BH-F and BH-F2 exhibited flexural failure, this comparison will be exclusively focused on these two specimens.

$$M_n = M_{ns} + M_{nf} = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2}\right) \qquad (1)$$

Theoretical calculations indicated that specimens BH-F and BH-F2 had a moment capacity of 46.84 kNm. Experimentally, BH-F exhibited a moment capacity of 40.32 kNm, while BH-F2 showed 44.33 kNm. Specimen BH-F2 closely matched theoretical values with a 5.4% error margin, whereas BH-F showed a higher 13.9% error. This discrepancy arises from the theoretical assumption of perfect bonding, ignoring real-world limitations. The improved accuracy of BH-F2 is attributed to its U-Wrap FRP anchorage, which enhances bonding efficiency and minimizes slip, leading to a smaller error margin. In contrast, BH-F relies solely on natural bonding with epoxy resin, which is more susceptible to premature debonding, resulting in a higher deviation from theoretical predictions.



(a)

(b)

(c)

(d)

Fig.7 Load-versus-mid span deflection curves: (a) Low-strength beam, (b) High-strength beam, (c) Low-strength slab, (d) High-strength slab

Table 3 Summary and comparison between control and strengthened beam specimens

Beam Series	Ultimate Load		Ductility		Initial Stiffness	
	P_{ult} (kN)	Δ (%)	μΔ	Δ (%)	K (kN/mm)	Δ (%)
BL-01	121.45	-	10.56	-	20.17	-
BL-02	111.91	-	11.94	-	20.92	-
BL-F-01	134.26	15.1%	1.85	-83.6%	33.61	63.6%
BL-F-02	125.45	7.5%	1.47	-86.9%	28.57	39.1%
BL-F2	151.86	30.2%	1.87	-83.4%	40.86	98.9%
BH-01	228.24	-	8.07	-	32.6	-
BH-02	225.32	-	7.09	-	33.63	-
BH-F-01	269.26	18.7%	2.31	-69.5%	36.39	9.9%
BH-F-02	268.32	18.3%	2.25	-52.1%	33.63	1.6%
BH-F2	295.56	30.3%	7.07	-6.7%	41.04	23.9%

Table 4 Summary and comparison between control and strengthened slab specimens

Slab Series	Ultimate Load		Ductility		Initial Stiffness	
	Pult (kN)	Δ (%)	μΔ	Δ (%)	K (kN/mm)	Δ (%)
SL-01	138.61	-	8.39	-	38.78	-
SL-02	161.96	-	2.94	-	33.33	-
SL-F-01	337.52	124.6%	1.74	-69.3%	51.28	42.2%
SL-F-02	312.51	107.9%	2.11	-62.8%	48.37	34.2%
SL-F2	314.58	109.3%	2.7	-52.3%	104.31	189.3%
SH-01	212	-	2.95	-	32.12	-
SH-02	226.74	-	4.75	-	36.57	-
SH-F-01	370.66	69.0%	1.93	-49.9%	52.95	56.2%
SH-F-02	410.23	87.0%	1.37	-64.4%	44.11	29.5%
SH-F2	452.17	106.1%	1.11	-71.2%	64.51	91.1%

5. LIMITATIONS & FUTURE DIRECTIONS

This study has several limitations that should be acknowledged. First, the focus was solely on CFRP (Carbon Fiber Reinforced Polymer) materials, excluding other FRP (Fiber Reinforced Polymer) options such as GFRP (Glass Fiber Reinforced Polymer) and AFRP (Aramid Fiber Reinforced Polymer), due to local availability constraints. Additionally, only externally bonded CFRP sheets were used, without exploring alternatives like NSM (Near-Surface Mounted) rods, also due to availability issues. The retrofit configuration employed is specific to practical applications in Indonesia, which enhances its applicability to local projects but may limit generalizability to other regions. Future research should consider incorporating a broader range of FRP materials and bonding techniques to evaluate their comparative effectiveness.

6. CONCLUSION

This study examined CFRP-strengthened beams and slabs through four-point bending tests under displacement control (5 mm/min) using a Dartec M9500 actuator (80-ton capacity). Ten specimens were categorized by strength and CFRP configuration. Low- and high-strength concrete averaged 15.24 MPa and 43.21 MPa, respectively, with reinforcement bars exceeding 400 MPa yield strength. Nitrowrap FRC 300 CFRP was used based on local availability. Key parameters, including load-deflection, crack propagation, stiffness, and failure modes, were assessed to evaluate the impact of additional CFRP strengthening.

Based on the present experimental investigation, the following main conclusions are drawn:

1. Low-strength concrete beams reinforced with CFRP flexural strengthening exhibit brittle behavior due to the formation of an over-reinforced section, ultimately resulting in shear failure.
2. Proper attention to shear strengthening is crucial for low-strength concrete specimens to prevent reinforcement from exceeding the limits of shear compression failure, thus avoiding redundancy.
3. Strengthened low-strength concrete beams showed an increase in ultimate load compared to control specimens, albeit with a significant decrease in ductility due to shear failure.
4. High-strength concrete beams exhibited typical flexural RC behavior, with no occurrence of shear failure in strengthened specimens due to high compression strength and resultant high concrete shear capacity.
5. Strengthened high-strength concrete beams showed an increase in ultimate load compared to control specimens due to flexural CFRP reinforcement, with no significant difference in ductility as the failure mode remained flexural.
6. Slabs typically not shear reinforced displayed brittle behavior with increased stiffness and subsequent shear compression failure when additional layers of CFRP flexural strengthening were applied.
7. The addition of an extra layer of flexural CFRP reinforcement on over-reinforced slab specimens does not improve the ultimate load and ductility, as these factors are dictated by shear failure.
8. The addition of flexural CFRP reinforcement significantly increased stiffness in low-strength concrete specimens due to the stiff nature of CFRP. However, in high-strength concrete specimens, the initial stiffness of the concrete obscured the contribution of CFRP to stiffness.

7. AKNOWLEDGEMENT

Part of this research was funded by Structural Engineering Research Group, Faculty of Civil and

Environmental Engineering, Bandung Institute of Technology, Indonesia. The author also gratefully acknowledges the support from the Structural Engineering Laboratory and Basic Science Center A Laboratory in Bandung Institute of Technology.

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