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Utilising Fibre Reinforced Polymer (FRP) to Enhance the Flexural Capacity of Concrete Structures After Earthquakes

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Abstract

Increasing the bending capacity of post-earthquake concrete structures is crucial for ensuring the safety and sustainability of buildings. This study evaluates the effectiveness of using Carbon Fibre Reinforced Polymer (CFRP) materials as a reinforcement solution to enhance the bending capacity of concrete structures damaged by earthquakes. CFRP was selected due to its advantageous characteristics, including high strength, corrosion resistance, and ease of application in the field. The study employs an experimental approach, utilising concrete beams with varying reductions in strength to simulate damage levels of 65%, 50%, and 30%. The tests conducted include density, compressive strength, and flexural strength assessments. The results indicate that the application of CFRP significantly increases the flexural capacity of concrete beams, reduces crack formation, and extends the service life of the structures. Specifically, the flexural strength improves 3 to 4 times for unreinforced and reinforced concrete beams. These findings confirm that CFRP is an effective and efficient solution for the rehabilitation of post-earthquake concrete structures, contributing positively to infrastructure recovery in earthquake-prone areas.

1. Introduction

Concrete construction material is renowned for its exceptional compressive strength, which allows it to withstand significant loads without failing. However, it exhibits a notable weakness in resisting tensile and bending forces. The tensile strength of concrete is approximately one-tenth of its compressive strength [1],[2], making it ill-suited for applications that require resistance to bending loads, such as beams, columns, and slabs. This inherent limitation necessitates improvements in the bending strength of concrete to ensure that structures can endure various loading conditions effectively. The bending strength is a critical parameter for assessing the performance and durability of concrete structures [1],[3], as it determines their ability to withstand external forces that may induce bending or damage [4],[5].

To enhance the bending strength of concrete, several factors must be considered, including material composition, mixing techniques, curing processes, and the incorporation of additives or reinforcement materials. Flexural strength testing plays a vital role in understanding how concrete behaves under bending loads and provides essential data for repairing and rehabilitating structures that have suffered damage from environmental stressors [3],[6]. This understanding becomes increasingly important in designing buildings resilient to dynamic loads such as earthquakes, which can significantly compromise structural integrity.

Earthquakes severely threaten building structures, particularly concrete ones [7]. Research indicates that seismic events [8],[9] can lead to substantial losses in residential buildings within urban areas due to the degradation of concrete strength and rigidity [10]. The dynamic forces generated by earthquakes can cause cracks and deformations in concrete elements, potentially resulting in structural failure if these elements lack adequate bending capacity. Therefore, reinforcing or replacing existing structures is often necessary to mitigate these risks. In many cases, reinforcing rather than demolishing is more environmentally sustainable and economically viable. Nguyen (2022) [11],[12] proposed an efficient design for reinforcing continuous RC slabs using an innovative FRP-HPC hybrid retrofit system based on ACI 440.2R. The FRP-HPC retrofit system effectively strengthens reinforced concrete slabs. The increase in retrofit effectiveness will come from the compressive strength value of HPC-coated concrete, and the tensile strength will be significant after adding FRP. The proposed method offers economic and safety advantages by optimising material strength and preventing the sudden failure of reassembled plates.

One effective method for enhancing the bending capacity of concrete structures is using Fibre Reinforced Polymer (FRP) systems. These systems provide external reinforcement that significantly improves the structure's ability to resist deformation caused by seismic activity [13]-[15]. Although there is limited experimental data on the effectiveness of FRP-reinforced concrete after an earthquake, preliminary studies suggest that Carbon Fibre Reinforced Polymer (CFRP) offers superior flexural strength compared to other types of FRP. By incorporating CFRP into concrete designs, engineers can achieve strength and durability comparable to traditional materials like steel while reducing overall material usage.

Understanding and improving the bending strength of concrete is crucial for ensuring the safety and longevity of structures exposed to seismic forces. Damage from earthquakes can lead to decreased structural stability and increased repair costs. Therefore, utilising FRP systems represents a promising solution for reinforcing and repairing concrete structures, ultimately enhancing their performance and extending their service life. Ongoing research into the effectiveness of CFRP in post-earthquake scenarios will further inform best practices in earthquake mitigation strategies for concrete construction [16]-[19].

Various studies have addressed the topic of concrete reinforcement using CFRP, but there is a need for more research that focuses explicitly on post-earthquake reinforced concrete. A comprehensive analysis is essential to evaluate the effectiveness of CFRP in increasing flexural strength under these conditions. CFRP has shown significant potential to improve the flexural strength of reinforced concrete, making it a promising material for earthquake mitigation. However, the presence of microcracks in concrete due to loading can reduce the effectiveness of this reinforcement. Therefore, further research is needed to ascertain how such cracks and related damage affect CFRP performance.

This research is crucial because structural damage caused by earthquakes can lead to a significant reduction in the flexural capacity and overall stability of concrete structures. Such damage increases safety risks, accelerates degradation, and raises costs for future repairs. Therefore, applying FRP is an essential strategy for strengthening and repairing concrete, ensuring optimal structural performance, and extending the service life of buildings. This study, which aims to evaluate the effectiveness of FRP in enhancing the flexural strength of concrete structures, is a significant step toward improving earthquake impact mitigation efforts.

2. Methodology

This research employs an experimental methodology to investigate the properties of concrete. The concrete mixture components utilised in this study comprise Portland cement, water, fine aggregate, and coarse aggregate. Specifically, the maximum grain size for the gravel is 40 mm, with a specific gravity of 2.63. At the same time, the fine aggregate falls within the category of relatively coarse sand (Zone II) according to SNI 03-2834-2000. Additionally, Type I cement is employed.

The evaluation of concrete quality is grounded in the standards outlined in ACI 440.2R-02, which stipulates that reinforcement with FRP should not be carried out on concrete with a quality of less than 17 MPa. Furthermore, the concrete mix design follows the guidelines of SNI 03-2834-2000, with a targeted slump value of 8-12 cm.

According to the Indonesian Reinforced Concrete Code (PBI 1971 N.I.-2), several classes of concrete quality are defined based on their characteristic compressive strength. Concrete quality is classified using the code 'K,' followed by the compressive strength value in kg/cm^2, with cube specimens used for testing. This study used medium-quality concrete, specifically K275, with a characteristic compressive strength of 275 kg/cm^2. Referring to SNI 03-6468-2000, ACI 318, and ACI 363R-92, medium-quality concrete has a compressive strength between 21 MPa and 40 MPa. Therefore, the K275 concrete is equivalent to 23 MPa after 28 days when using a cylindrical specimen. To ensure that the concrete used K275 quality, three cylindrical test specimens, each with a diameter of 15 cm and a height of 30 cm, were prepared. These specimens were compressed at 28 days using a compression testing machine by SNI 1974:2011. Flexural specimens use 12 beams with dimensions of 15×15×60 cm for the flexural test.

Before the flexural strength test was conducted, a concrete quality assessment was performed. This assessment was based on the standards outlined in SNI 03-3625-94 and ASTM C597-09. The Ultrasonic Pulse Velocity (UPV) test was employed to measure the velocity of ultrasonic waves propagating through the concrete. The assessment of concrete quality is predicated on the propagation speed of the waves; a higher wave speed indicates superior concrete quality in terms of density, homogeneity, and uniform distribution of the material. Conversely, a lower wave speed suggests inferior concrete quality, potentially signifying the presence of cavities or cracks within the concrete. The UPV test, illustrated in Fig. 1, was utilised to evaluate the quality of the test specimens, ensuring that the beam specimens possess uniform density and that the concrete blocks to be tested exhibit homogeneity during bending.

Fig. 1 *UPV test*

Following the UPV test, the specimens were divided into four groups, each consisting of 3 concrete blocks. The first group was the control group, which was used to determine the maximum bending load. In this study, structural damage to the remaining three groups was simulated. Damage modelling in the concrete blocks was performed by reducing the structural strength by applying bending loads at 65%, 50%, and 30% of the control specimen's maximum load. The variations in applied loads were selected based on typical damage levels observed in post-earthquake structures across various regions.

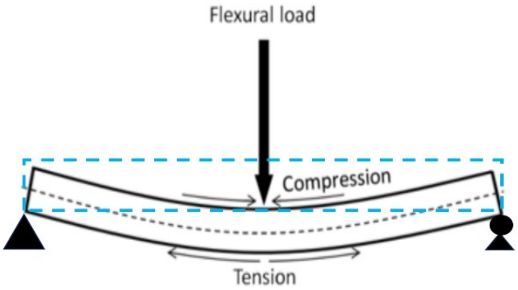

Fig. 2 *Schematic diagram of flexural stress distribution*

Fig. 3 *CFRP plating design*

Subsequently, these damaged test pieces underwent additional strengthening via CFRP coatings applied along their lower edges or areas susceptible to tensile stresses (Fig. 2). Each group received CFRP designs illustrated in Fig. 3. Installation involved attaching clean-dried surfaces with epoxy-based anchors, detailed in Fig. 4. Each group received CFRP designs, as illustrated in Fig. 3. The installation involved applying epoxy-based adhesive to clean and dry surfaces, as shown in Fig. 4. The epoxy coating for CFRP installation on concrete was applied in two layers. The first epoxy layer was applied to the concrete surface before the CFRP was attached, serving as an adhesive to ensure proper bonding between the FRP and the concrete. The second epoxy layer was applied over the FRP attached to the concrete to provide a secure bond between the FRP and the beam. This second layer also made the

FRP sheet more rigid. The design of CFRP coatings for the three groups, which were subjected to varying bending loads, is shown in Fig. 3. The coating was applied uniformly along the lower edge of the beam cross-section.

All concrete groups reinforced with CFRP were subsequently subjected to flexural testing to assess the increase in bending strength of the concrete beams following repair. The bending strength results were then compared to those of higher-quality reinforced concrete blocks exceeding K275, which included two reinforcing bars on the tensile side with a diameter of 8 mm.

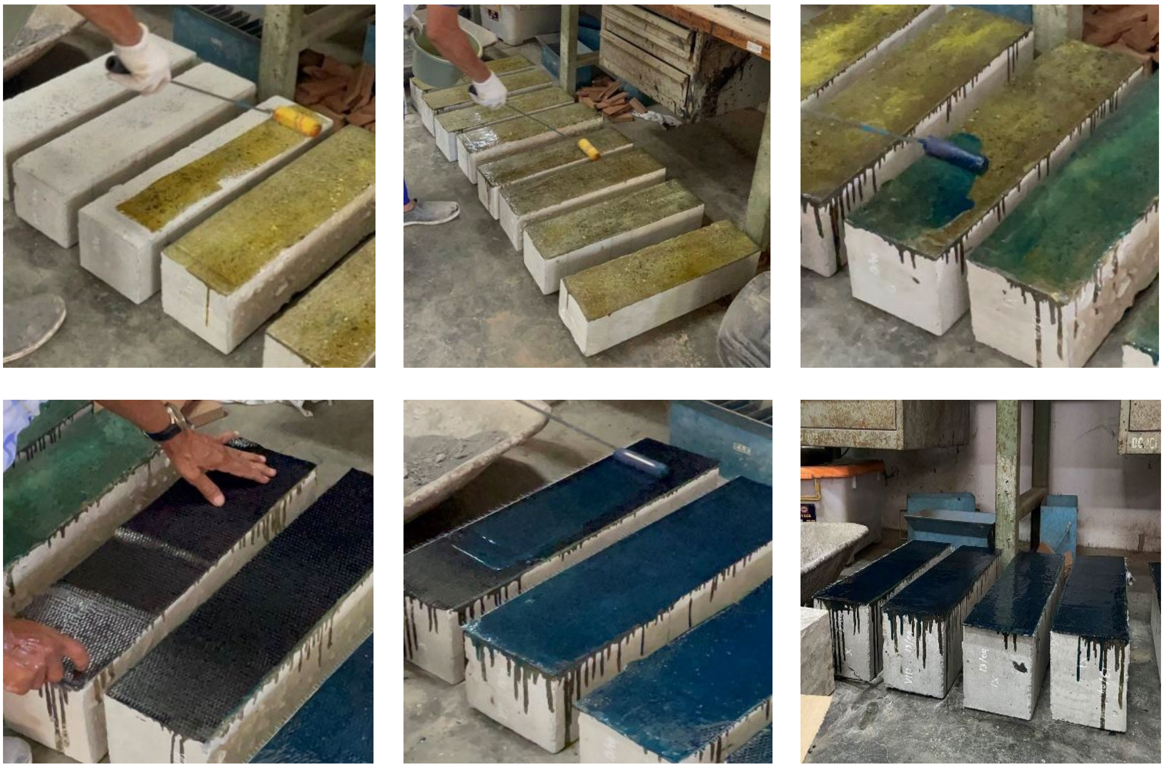

Fig. 4 *CFRP installation*

3. Results and Discussion

3.1 Compressive Strength

Table 1 presents the compressive strength values for each cylinder specimen. The compression tests revealed an average compressive strength of 23.6 MPa for the concrete samples, exceeding the initially planned value. This outcome confirms that the employed concrete mixture adheres to the specified criteria outlined in our research plan. Test Piece 1 exhibited the lowest compressive strength at 21.1 MPa, suggesting variations due to potential discrepancies in mixing, filling, or compacting processes, along with non-uniform curing conditions. By SNI 03-2834-2000, concrete must possess consistent quality and meet predetermined compressive strengths. Our findings indicate that the utilised concrete complies with these standards, boasting an average compressive strength that surpasses expectations. Additionally, this achievement signifies proper adherence to standardised mixing and implementation protocols.

Moreover, the average compression test results exceeded the minimal requirements stipulated by ACI 440.2R-02, indicating that reinforcement using CFRP would not be necessary since the concrete's quality exceeds 17 MPa. Consequently, this concrete satisfies all prerequisites and remains eligible for additional assessments, including bending and reinforcement testing involving FRP.

Table 1 *Concrete compressive strength recap*

Code	Load (kN)	f_c' (MPa)	Average (MPa)
1	372	21.10	23.60
2	406	23.00	
3	475	26.90	

3.2 Concrete Quality Inspection Using UPV

Ultrasonic Pulse Velocity (UPV) testing is a non-destructive method employed to evaluate the quality of concrete by measuring the propagation velocity of ultrasonic waves through concrete materials. The speed at which these waves travel is closely linked to the concrete's density, homogeneity, and overall quality. Fig. 5 illustrates the propagation speed of ultrasonic waves (in m/sec) at multiple test points.

Fig. 5 shows an average wave speed of approximately 4400 to 4600 m/sec. The variations in wave propagation speeds across different test points fall within an acceptable range, indicating no significant discrepancies. This speed demonstrates a linear correlation with concrete density [20]-[25]. The results of the UPV test can also be utilised to classify the quality of concrete. The quality of concrete based on the UPV test results is presented in Table 2. Based on the classification of concrete quality according to wave velocity outlined in Table 2, the concrete samples tested fall into the excellent quality category. The high wave propagation speeds reflect favourable characteristics such as good density, homogeneity, and material uniformity. These findings support the conclusion that concrete exhibits excellent homogeneity and density. According to SNI 03-3625-94 and ASTM C597-09 standards, concrete with elevated wave propagation velocities is generally associated with high quality, characterised by an absence of cavities or cracks [26].

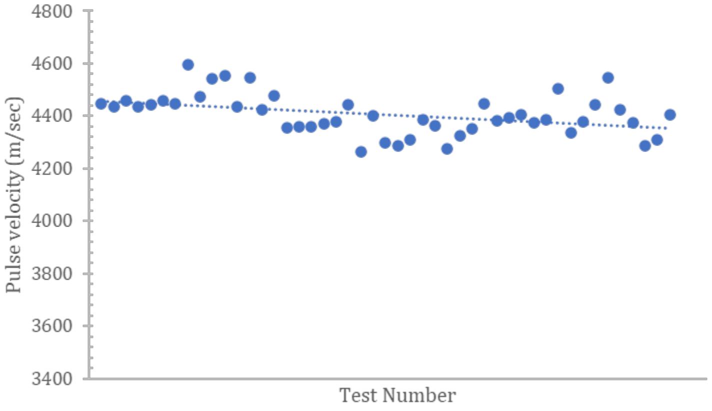

Fig. 5 *UPV test results*

Data in Table 2 shows that high-density concrete exhibits faster ultrasonic wave propagation speeds. This result suggests fewer empty spaces or pores within the concrete, resulting in a more robust material capable of bearing larger loads.

Table 2 *Classification of concrete quality based on pulse velocity [25]*

Longitudinal Wave Velocity		Concrete Quality
km/ (sec)	ft/ sec	
>4.5	> 15	Very good
3.50 – 4.50	12 – 15	Good
3.00 – 3.50	10 – 12	Fair
2.00 – 3.00	7 – 10	Poor
< 2.00	< 7	Very poor

The compressive strength values derived from the non-destructive UPV test are depicted in Fig. 6. Specifically, test specimens demonstrating lower propagation speeds yielded a compressive strength of 29.5 MPa. In comparison, those showing higher propagation velocities reached up to 33.75 MPa. These findings align with prior research indicating a linear relationship between concrete density and its corresponding compressive strength [20],[22],[24],[27]-[31].

3.3 Flexural Test

The relationships between displacement and load for the three concrete samples are illustrated in Fig. 7. All test specimens exhibit a similar curve pattern, characterised by an initial rise until reaching the peak load (maximum load), followed by a sharp or gradual decline upon reaching this maximum load. This curve pattern reflects the brittle nature of concrete. As the load increases, cracks begin to appear in the tensile section of the specimens, oriented perpendicularly to the longitudinal axis, as depicted in Fig. 8. These cracks initiate at the bottom of the beam and propagate upward with increasing load. Fig. 7 indicates that sample B3 possesses the highest strength and can withstand loads up to 28 kN with a maximum displacement of 1.6 mm. In contrast, sample B1 carries a lower maximum load than B3 but exhibits a more significant displacement. This observation suggests that B1 is more ductile, while samples B3 and B2 demonstrate brittleness due to their minimal displacement before reaching maximum load.

The crack pattern observed in concrete beams reinforced by CFRP exhibits significant differences in crack distribution and structural failure mechanisms. The crack pattern following the application of CFRP is illustrated in Fig. 9, which shows a more uniform crack distribution along the beam. This condition indicates that the stress distribution in the beams is more efficient with CFRP reinforcement than the unreinforced beam. Furthermore, while the specimens with additional CFRP reinforcement display many cracks, these cracks are smoother and tighter. This observation suggests that CFRP reinforcement enhances the ductile properties of concrete, thereby reducing structural damage and significantly increasing the concrete's capacity to withstand bending loads, instilling confidence in the performance of CFRP-reinforced concrete beams.

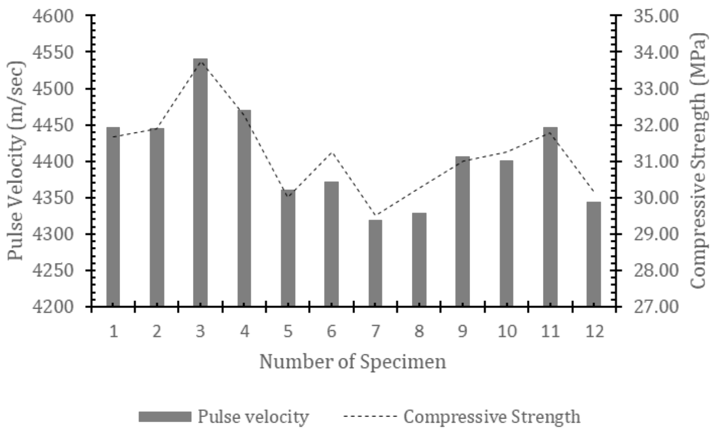

Fig. 6 *Comparison of ultrasonic wave compression and propagation speed test results*

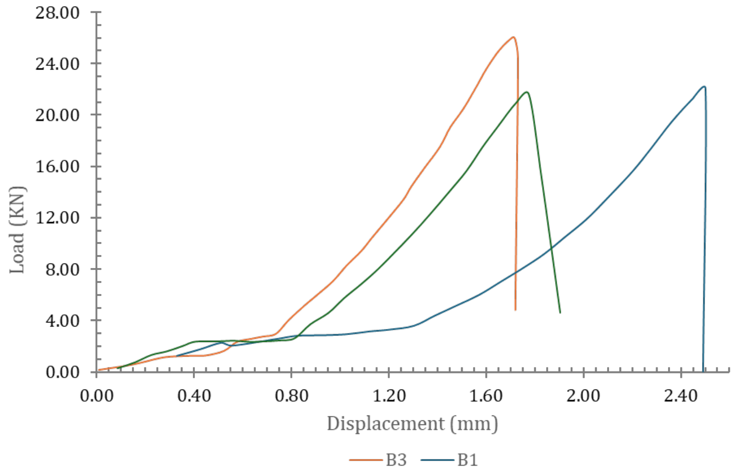

Fig. 7 *Load and deflection*

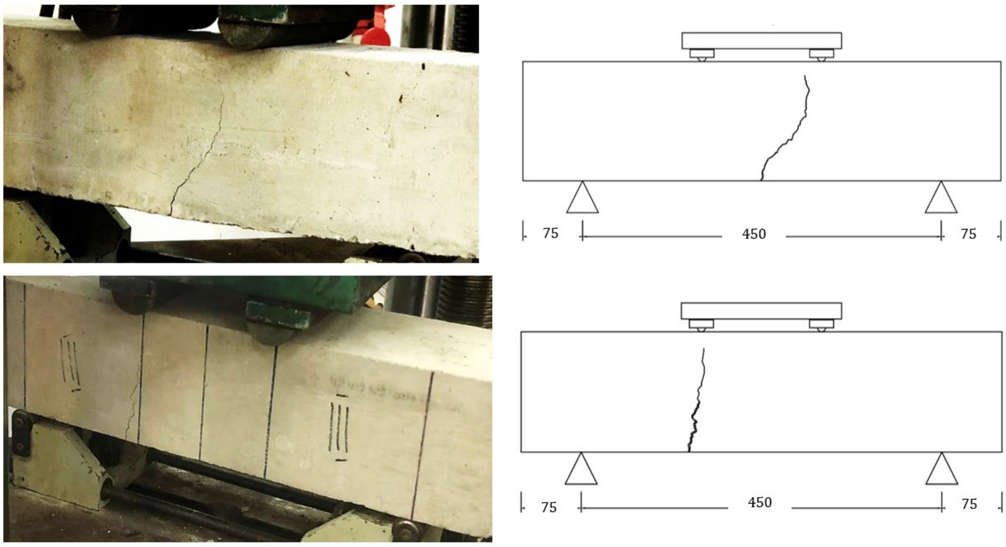

Fig. 8 *Failure mode*

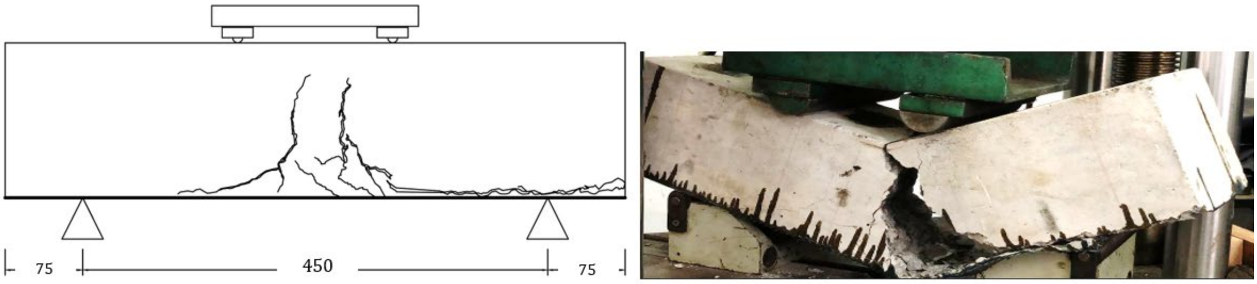

Fig. 9 *Failure mode after using CFRP*

Fig. 10 to Fig. 12 present the results of the relationship between load and displacement. The test results from all specimens indicate that concrete beams without FRP exhibit brittle behaviour. For instance, a displacement of 0.75 mm occurs under a load of approximately 3 kN, as shown in Fig. 10. In contrast, following repairs with FRP, a load of 3 kN results in a deformation ranging from 1.903 mm to 2.106 mm. Displacement tends to increase with increasing load. A similar pattern is observed in Figure 11, indicating that the concrete becomes more ductile after reinforcement with CFRP. Although CFRP itself is brittle, its combination with concrete enhances the ductile properties of the composite material. CFRP has a higher tensile capacity than concrete; thus, when tensile stress is applied to concrete, CFRP absorbs a significant portion of that stress, allowing the concrete to withstand the load for a longer duration before cracking. As concrete begins to crack, CFRP resists the tensile stress that develops, thereby preventing further crack propagation and delaying structural failure [17],[32],[33].

The trend of increasing displacement with increasing load is also evident in Fig. 11. These results demonstrate that concrete becomes more ductile following CFRP reinforcement. Although CFRP is brittle, its combination with concrete enhances ductility due to its higher tensile capacity. When subjected to tensile stress, CFRP absorbs most of this stress, allowing concrete to withstand loads for extended periods before cracking occurs. As cracks begin to form in the concrete, CFRP resists the arising tensile stress, preventing further crack propagation and delaying structural failure. Based on the load-displacement relationship graph presented in Fig. 12, it can be concluded that FRP reinforcement significantly improves both load capacity and deformation behaviour in concrete beams that have experienced a 65% reduction in strength.

Beams without CFRP reinforcement exhibit a relatively low load capacity, as indicated by a sloping curve and limited maximum displacement, which reduces rigidity and load capacity due to strength degradation. However, after FRP reinforcement (samples B4, B5, and B6), these beams significantly improve load capacity, with steeper load-displacement curves signalling enhanced stiffness. Some specimens can now support loads exceeding 80 kN, a substantial increase from the approximately 20 kN they could bear before reinforcement. Furthermore, CFRP reinforcement contributes to increased beam ductility, as evidenced by more significant displacements before failure. Despite this improvement, the failure pattern remains similar to that of beams B1-B3, marked by a sharp drop in the curve after reaching peak loads due to bond loosening between CFRP and concrete. In summary, these test results confirm that FRP reinforcement effectively restores and even augments the load capacity of concrete beams that have undergone strength degradation.

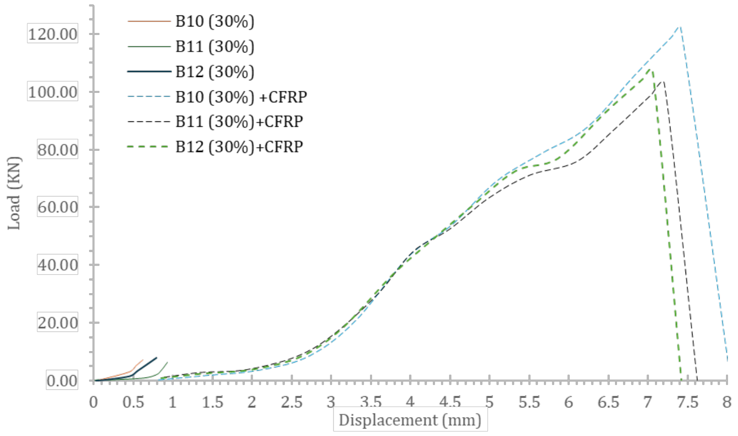

Fig. 10 *Relationship between load-displacement for 30% reduction of strength*

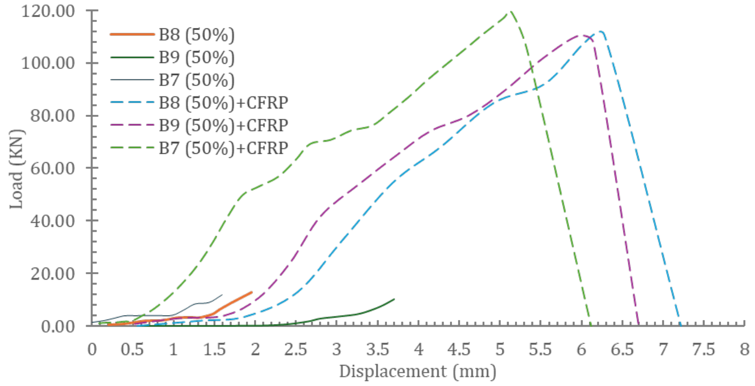

Fig. 11 *Relationship between load-displacement for 50% reduction of strength*

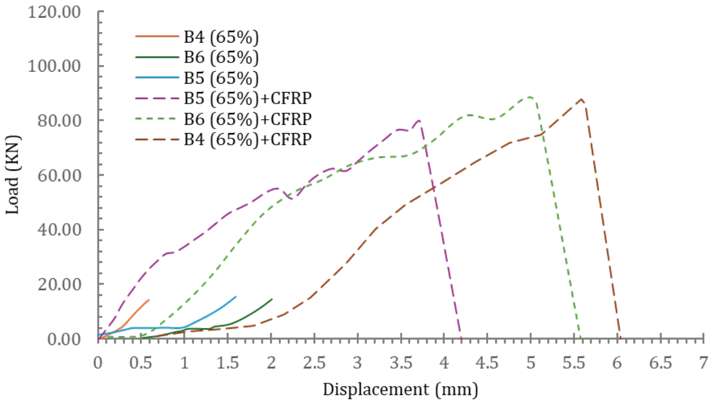

Fig. 12 *Relationship between load-displacement for 65% reduction of strength*

3.4 Flexural Strength Comparison

Fig. 13 illustrates the comparative flexural strength before and after CFRP reinforcement. The data demonstrate a substantial enhancement in flexural strength across nearly all specimens following the application of CFRP retrofits. This notable improvement underscores the efficacy of CFRP retrofitting techniques in significantly boosting the structure's bending capability.

The results of the research obtained are in line with various previous studies on the effectiveness of CFRP in increasing the bending strength of concrete [11],[34]-[37].

When comparing the flexural strength values achieved in K300 quality reinforced concrete (with a compressive strength, f_c = 25 MPa), which utilises plain rebar with a diameter of 8 mm positioned in the tensile zone of two rebars, it is evident from Fig. 14 that reinforced concrete exhibits higher flexural strength than unreinforced concrete. However, when comparing reinforced concrete to concrete whose strength has diminished but has been subsequently restored through CFRP repair, the repaired concrete demonstrates improved flexural strength. This difference is primarily attributed to the superior tensile resistance offered by FRP compared to conventional steel reinforcement. Additionally, the even stress distribution within the concrete, enhanced by FRP, contributes to improved structural integrity. Furthermore, the adhesive bond between FRP and concrete plays a crucial role in amplifying the increase in bending strength [38].

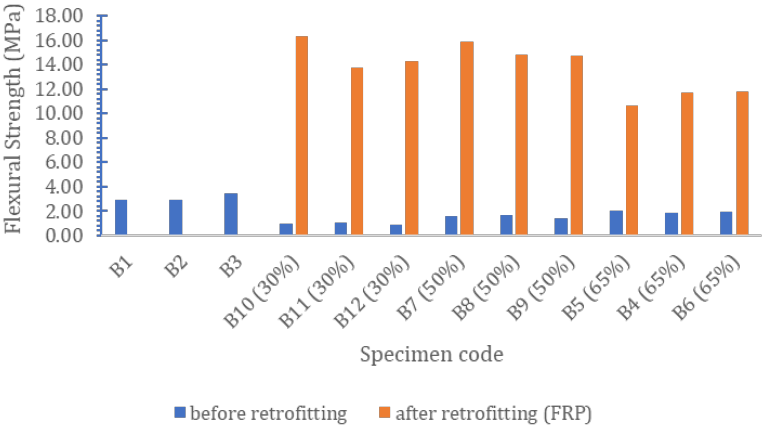

Fig. 13 *Failure strength for all specimens*

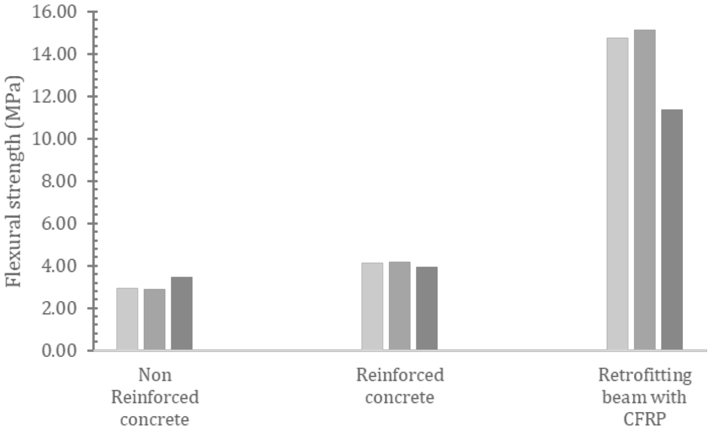

Fig. 14 *Comparison of flexural strength for all conditions*

4. Conclusion

This research significantly contributes to post-earthquake concrete reinforcement by providing practical insights into applying FRP methods. The study demonstrates the substantial effectiveness of using carbon-reinforced polymer (CFRP) in enhancing the bending strength of concrete structures. Specifically, despite reductions in strength by 65%, 50%, and 30% of the maximum bending force aimed at mitigating earthquake impacts, CFRP strengthening achieves remarkable improvements, yielding bending strengths of 11.38 MPa, 15.13 MPa, and 14.78 MPa, respectively. Utilising CFRP leads to a tripling to a quadrupling of bending capacities in unreinforced and reinforced concrete beams. Consequently, this heightened bending resilience helps minimise structural damage, fortify building integrity, and guarantee occupant safety. Beyond merely bolstering strength, CFRP implementation also elevates the durability and lifespan of the structure, rendering it an efficient and effective solution for managing earthquake risks.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Garup Lambang Goro, Stefanus Santosa & Nor Puji Lestari;* ***Data collection:*** *Jamal Mahbub, Adibtyas Samudera Putra Larosa & Aviolita Sekar Nanda Kurniawan;* ***Analysis and interpretation of results:*** *Nor Puji Lestari, Primasiwi Harprastanti & Aiun Hayatu Rabinah;* ***Draft manuscript preparation:*** *Nor Puji Lestari, Garup Lambang Goro & Aiun Hayatu Rabinah. All authors reviewed the results and approved the final version of the manuscript.*

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