

RETROFITTING REINFORCED CONCRETE BEAMS USING CARBON FIBER REINFORCED POLYMER SHEETS AFTER EXPERIENCING FLEXURAL CRACKING DAMAGE

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ABSTRACT

This study investigates the retrofitting of reinforced concrete beams that have experienced flexural damage due to overloading using Carbon Fiber Reinforced Polymer (CFRP) sheets. The tested beam had previously developed flexural cracks and tensile steel yielding but had not reached complete collapse, indicating the presence of residual structural capacity and ductility. Prior to strengthening, the existing cracks were repaired using Sikadur-31 CF epoxy to restore continuity in the damaged region. Subsequently, CFRP sheets were externally bonded along the tension face to enhance flexural performance. Experimental testing was conducted using a two-point loading system to evaluate load–deflection behavior, crack propagation, stiffness, and failure mode before and after repair and strengthening. The results showed that the retrofitted beam achieved a significant improvement in structural performance. The maximum load capacity increased by approximately 20.47%, accompanied by enhanced stiffness, while the ultimate deflection remained nearly unchanged. This indicates that the beam became stronger without a significant loss of deformation capacity within the tested range. Crack patterns after strengthening remained dominated by the tension zone, confirming a flexural behavior. Failure was initiated at the CFRP segment joints rather than in the compression zone, highlighting the importance of bond and joint detailing in CFRP applications. Overall, the study demonstrates that beams with prior flexural damage and steel yielding can be effectively rehabilitated and strengthened using CFRP, provided that sufficient residual ductility remains and proper design considerations are applied to avoid brittle failure.

Keywords: repair, crack, damage, cfrp, concrete, flexural

INTRODUCTION

Strengthening of reinforced concrete structures has become an important issue in structural engineering, particularly for existing buildings that experience deterioration, overloading, functional changes, or damage caused by extreme actions such as earthquakes (Parghi & Alam, 2018). In reinforced concrete buildings, beams are among the most critical flexural members because their damage directly affects structural safety, serviceability, and overall performance. Flexural damage in beams commonly begins with crack formation in the tension zone and may progress into a plastic condition under increasing load (Hernowo & Lisantono, 2016). Once the tensile steel reinforcement yields, the beam no longer performs as initially designed, and reductions in strength, stiffness, and ductility become inevitable. In practical situations, such damage is not merely a theoretical concern but a real problem in the assessment and rehabilitation of existing structures, especially when engineers must decide whether a damaged beam can still be restored and strengthened effectively rather than replaced (Huo et al., 2018).

To address this problem, many strengthening techniques have been developed and studied over time (Zhao et al., 2020). Conventional methods such as section enlargement, external steel plate bonding, and concrete jacketing have been used to improve the load-carrying capacity of damaged members (Alshamrani et al., 2024). However, these methods generally increase member size and self-weight, interfere with architectural space, and require relatively intensive construction work (Purba & Lisantono, 2023). For these reasons, fiber-reinforced polymer (FRP) systems, especially Carbon Fiber Reinforced Polymer (CFRP), have become increasingly attractive in structural retrofitting (Zai & Purba, 2025). CFRP offers several advantages, including high tensile strength, light weight, corrosion resistance, and ease of installation (Zai & Purba, 2025). Numerous studies have shown that externally bonded CFRP sheets can significantly improve the flexural strength and stiffness of reinforced concrete beams by providing additional tensile resistance in the tension zone (Purba & Perangin-angin, 2025). This method has therefore been recognized as an efficient alternative to conventional strengthening systems for both deficient and deteriorated structural members (Purba et al., 2023).

Despite these advances, the existing literature is still largely focused on beams that are either intact, pre-cracked at a relatively low level, or damaged within a limited service range (Purba et al., 2022). Many studies evaluate CFRP as a strengthening material for beams before severe flexural failure develops, so the internal steel

reinforcement still retains much of its original tensile function (Obaidat et al., 2019). Some studies have reported the effectiveness of epoxy-based crack repair in restoring continuity of cracked concrete, while others have examined the contribution of externally bonded CFRP sheets in increasing flexural capacity (Hu et al., 2025). However, these two stages are often investigated separately, and limited attention has been given to the actual condition frequently encountered in practice: a beam that has already experienced severe flexural cracking, entered a plastic state, and reached a condition in which the tensile reinforcement has yielded (Lv et al., 2024). Under such circumstances, the original tensile resistance of the beam is no longer fully available, and the structural problem becomes more complex than ordinary strengthening of an undamaged or lightly cracked beam (Al-Nsour et al., 2023).

This condition reveals an important gap in previous research. The question is not only whether CFRP can strengthen a reinforced concrete beam, but whether a beam that has truly suffered plastic flexural damage and partial loss of tensile steel function can be structurally recovered through a combined repair-and-strengthening sequence. More specifically, there is still insufficient understanding of how a severely damaged beam behaves after its flexural cracks are first repaired using epoxy and then strengthened using externally bonded CFRP sheets. The issue that has not been adequately explored is whether such a beam can regain its original structural performance, or even achieve a higher load-carrying capacity than before damage, despite the fact that the internal tensile reinforcement has already yielded. This unresolved issue is highly relevant for structural rehabilitation because, in real engineering practice, many damaged beams are not strengthened in pristine condition but after substantial inelastic damage has already occurred.

Based on this need, the present study focuses on reinforced concrete beams that are intentionally brought to a plastic flexural cracking condition, representing a severely damaged state in which the tensile steel has yielded. The flexural cracks are then repaired using Sikadur CF31 Normal epoxy to restore continuity in the cracked concrete substrate, after which the beam is strengthened by externally bonding CFRP sheets to the tension face. In this configuration, the CFRP sheet is expected not merely to supplement the existing reinforcement, but to take over a significant portion of the tensile force that can no longer be resisted effectively by the yielded steel

reinforcement. The scientific value of this approach lies in the integration of crack repair and external CFRP strengthening into a single rehabilitation sequence for beams that have already undergone substantial flexural damage.

Accordingly, this study aims to experimentally evaluate the structural performance of reinforced concrete beams after experiencing plastic flexural cracking, followed by crack repair using Sikadur CF31 Normal epoxy and strengthening with externally bonded CFRP sheets. The investigation is directed toward understanding the extent to which this combined method can restore or enhance the beam's flexural strength, stiffness, and ductility. Through this approach, the study seeks to provide a more realistic and practically relevant contribution to the rehabilitation of damaged reinforced concrete members, particularly for cases in which the beam has already reached a severe damage state before repair and strengthening are applied.

METHODS

Overview of the Experimental Program

This study employed an experimental method on a reinforced concrete beam specimen that had previously experienced structural damage in the form of cracking during an earlier investigation. The damage was caused by excessive loading applied in the constant moment region of the beam. As a result, the beam developed a diagonal flexural crack pattern. The damaged beam was then selected as the object of repair and strengthening in the present study.

The main purpose of this research was to evaluate the repair and strengthening performance of a damaged reinforced concrete beam using Carbon Fiber Reinforced Polymer (CFRP) sheets and to determine the effectiveness of the CFRP strengthening system in improving the structural response of the beam. The study was conducted through a combination of literature review and laboratory testing.

The concrete used in the beam specimen was classified as normal-strength concrete with a compressive strength of 14.62 MPa. This value was obtained from a standard cylinder compression test conducted in the previous study on companion concrete specimens. The condition of the beam specimen before repair and strengthening is shown in Figure 1, while the crack pattern observed on the specimen is presented in Figure 2.



Figure 1. Longitudinal view of the beam specimen before repair and strengthening

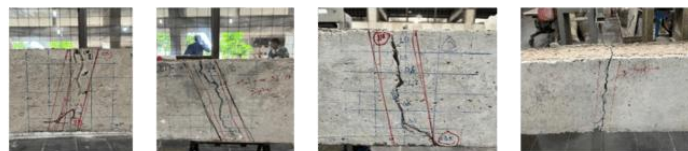


Figure 2. Detailed crack pattern of the beam specimen

Experimental Procedure

To achieve the objectives of this study, the experimental work was carried out systematically through the following stages:

1. Understanding the structural damage experienced by the reinforced concrete beam, including its causes, repair method, CFRP strengthening technique, and relevant technical testing data.
2. Conducting a literature review to broaden the theoretical basis related to reinforced concrete behavior, damage mechanisms, epoxy repair materials, and CFRP strengthening systems.
3. Preparing the damaged beam specimen and compiling all related technical data.
4. Performing laboratory flexural testing on the repaired and strengthened reinforced concrete beam.
5. Analyzing the test results based on the measured structural response and relevant supporting literature.
6. Drawing conclusions regarding the effectiveness of the proposed repair and strengthening method.

Existing Beam Specimen

The specimen used in this study was an existing reinforced concrete beam that had already developed flexural cracks due to a previous two-point loading test. The beam was therefore not in an intact condition at the start of this study, but in a damaged state representative of a structural member that had experienced excessive flexural action. The visual condition of the beam is presented in Figure 1, and the

detailed crack pattern before repaired is shown in Figure 2.

The reinforced concrete beam used in this research had a measured concrete compressive strength of 14.62 MPa. This value was obtained from cylinder compression tests conducted in the previous study. The compressive strength data served as an important mechanical property in evaluating the structural behavior of the repaired and strengthened beam.

The study used a reinforced concrete beam specimen that had already experienced cracking damage. The beam had a cross-sectional dimension of 120 mm $\times$ 240 mm and a total length of 3000 mm. The longitudinal reinforcement consisted of four plain steel bars of 10 mm diameter (4 ϕ 10) used as the main reinforcement. The transverse reinforcement consisted of ϕ 6 stirrups spaced at 100 mm in the support regions and ϕ 6 stirrups spaced at 150 mm in the span region. The concrete cover thickness was 25 mm. The geometry and reinforcement layout of the beam specimen are illustrated in Figure 3.

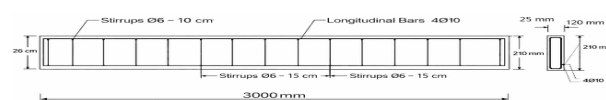


Figure 3. Reinforced concrete beam reinforcement details

Repair and Strengthening Materials

After the repair process, the beam specimen was strengthened using CFRP sheets bonded to the tension face with epoxy resin. The epoxy material used in this study was Sikadur-31 CF Normal, which functioned both as a crack-filling repair material and as a bonding medium between the concrete surface and the CFRP sheet.

The CFRP used in this study was a carbon fiber plate/sheet with dimensions of 80 mm $\times$ 500 mm and a thickness of 0.5 mm. The CFRP sheet was installed along the tensile zone of the beam in the damaged region in order to enhance its flexural performance. The CFRP sheet is shown in Figure 4, while the installation details are presented in Figure 5 and Figure 6.

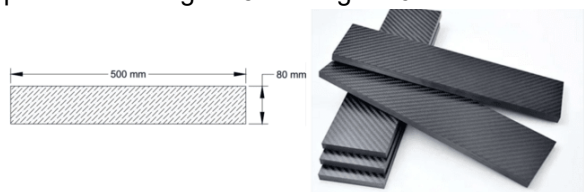


Figure 4. CFRP sheet used for strengthening



Figure 5. The view of CFRP installation on the beam specimen (mm)



Figure 6. Three-dimensional view of CFRP installation on the beam specimen (mm)

Laboratory Test after Repair and Strengthening

The laboratory test was carried out after the beam had been repaired and strengthened with CFRP. The loading method employed in this study consisted of two concentrated loads applied in the span region, corresponding to the damaged zone where flexural cracks had previously developed. The load was applied gradually in order to determine the maximum flexural capacity of the repaired and strengthened beam specimen. This loading arrangement allowed the researchers to observe the beam response, crack progression, deflection behavior, and final failure mode after the application of epoxy repair and CFRP strengthening. The loading and the condition of the repaired and strengthened sketch specimen are shown in Figure 7 and Figure 8, respectively.

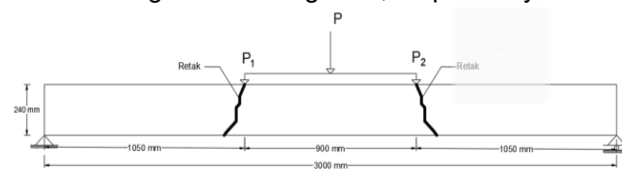


Figure 7. Flexural failure with cracked detail

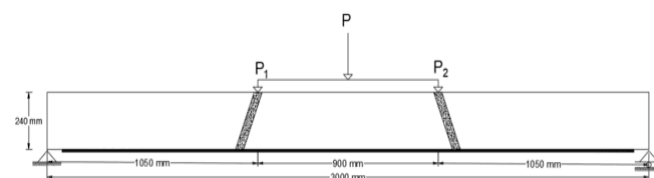


Figure 8. Condition of the beam after repair and CFRP strengthening

Repair and Strengthening Procedure

The reinforced concrete beam that had developed cracks in the previous test was first repaired before strengthening was applied. The repair process began by chiseling the cracked regions located along the side surfaces and the tension face of the beam. This process was carried out carefully and in detail to avoid creating additional cracks or unnecessary surface damage.

The chiseling process served two main purposes. First, it created a rough and clean surface, which is necessary to improve the bonding quality of the repair and strengthening materials. Second, it opened the concrete pores and crack paths, allowing the epoxy material to penetrate and fill the damaged zones more effectively. In this study, chiseling was performed around both major cracks in the tension zone of the

beam as shown in Figure 9. The chiseled groove had an approximate width of 2.5 cm and a depth of 2 cm. This preparation facilitated epoxy application and helped ensure that the crack region was filled as completely as possible.



Figure 9. Chiseling around the cracked area of the beam specimen



Figure 10. Application of Sikadur-31 CF epoxy to the cracked zone

Before applying the epoxy, the cracked area was cleaned thoroughly to maximize the effectiveness of the repair process and to ensure proper adhesion. The repair material used was Sikadur-31 CF, prepared by mixing component A and component B in a 2:1 ratio until a uniform mixture was obtained. From Figure 10, It can be seen that the epoxy was then applied into the crack grooves using a scraper, which functioned both as a filling tool and as a means to level the material evenly over the repaired zone. The application process was adjusted to the width and depth of the chiseled area so that the epoxy could fill the crack cavity thoroughly. The repair stage had to be performed carefully to ensure that the crack voids were fully filled and that no leakage or unfilled portion remained in the damaged zone. The installation of the CFRP sheet was conducted after the beam crack repair using Sikadur-31 CF had been completed. In this experimental program, the CFRP was installed one day after the repair process.

The strengthening procedure consisted of the following steps:

1. The tension surface of the reinforced concrete beam was cleaned thoroughly to ensure good adhesion between the concrete substrate and the CFRP sheet.
2. Sikadur-31 CF epoxy was applied over the entire tension surface of the beam to act as the bonding medium between the beam and the CFRP sheet.
3. The epoxy thickness was maintained at approximately 2–3 mm to achieve adequate bonding and load transfer.
4. The CFRP sheets were then attached to the beam surface, with an overlap length of approximately 2.5 cm at the joint between adjacent CFRP segments to improve continuity and structural performance.
5. Additional epoxy resin was applied in the overlapping region to reduce the risk of premature failure or debonding at the CFRP joint.
6. After installation, the beam was left to cure for approximately 24 hours, depending on the type of epoxy used and the ambient temperature.

This strengthening method was intended to enable the CFRP sheet to act effectively in the tension zone of the beam, particularly after the internal tensile steel had already yielded due to prior overloading.

Testing of the Repaired and Strengthened Beam

Before the flexural test was conducted, several preparation steps were undertaken to ensure the accuracy and reliability of the experimental results. Proper test setup was crucial because any misalignment or measurement error could affect the observed structural response of the beam. The beam specimen was placed carefully on the loading frame. During installation, special attention was given to positioning the beam correctly on the support system in order to avoid eccentricity and data irregularities.



Figure 11. Installation process of CFRP sheets on the beam specimen

The beam was supported on a pin-roller support system, with each support located 10 cm from the beam end. Above the beam, a steel IWF loading beam measuring 150 cm × 14 cm with two loading

legs of 3 cm diameter was placed. The spacing between the two loading points was 90 cm, and the total weight of the steel loading beam was 76.85 kg. The purpose of this steel loading beam was to convert the single-point load from the loading frame into a two-point loading configuration acting on the test specimen. To measure beam deflection, Linear Variable Differential Transformer (LVDT) sensors were installed. The LVDT is a device used to measure the linear displacement of a structure with high precision by converting linear movement into a proportional electrical signal. The overall test setup and the installation of the sensors are presented in Figure 12 and Figure 13.



Figure 12. The beam specimen after repaired and strengthened

After the test setup had been completed, the repaired and strengthened reinforced concrete beam was subjected to flexural testing. Four personnel participated in the testing process, each responsible for specific tasks, including monitoring the beam deflection, marking crack development, documenting the test process, and operating the hydraulic jack. The load was applied through a hydraulic pump, which transmitted force to the steel IWF beam and subsequently distributed it as two concentrated loads onto the beam specimen. The load was increased gradually using an incremental loading procedure until the beam reached its maximum capacity or until failure occurred in the CFRP strengthening system.

In this study, loading was terminated when the CFRP sheet experienced failure or when debonding occurred between the CFRP sheet and the concrete beam surface. This termination criterion was selected because the objective of the test was to evaluate the effectiveness and failure behavior of the repair-and-strengthening system rather than the beam alone. The flexural test setup using the hydraulic jack, LVDT, Load-Cell, Loading Frame are shown in Figure 14.

This study examines two fundamental questions. First, can a beam that has already experienced flexural cracking, tensile steel yielding, and plastic deformation still be rehabilitated so that its structural behavior returns to a stable level comparable to its pre-damaged condition? Second, can externally bonded CFRP, acting as supplemental tensile reinforcement in accordance with ACI 440 principles, increase the ultimate flexural resistance of that rehabilitated beam beyond its previous capacity? These questions are particularly important because CFRP strengthening of previously yielded beams must be approached with caution. Since CFRP exhibits very high tensile strength and linear-elastic behavior up to failure, excessive strengthening may shift the failure mechanism from a desirable tension-controlled ductile response toward an undesirable compression-controlled brittle response. Therefore, successful strengthening is not defined solely by a higher peak load, but also by preservation of an acceptable failure mechanism and residual deformability.



Figure 13. Experimental test setup

RESULTS AND DISCUSSION

The present results show that both structural objectives were achieved within the scope of this experiment. The repaired beam recovered stable load-carrying behavior, indicating that the epoxy repair restored sufficient continuity in the previously cracked region to re-establish structural function. At the same time, the CFRP-strengthened beam developed a higher ultimate load and a higher bending moment than the beam before repair and strengthening, demonstrating that the externally bonded CFRP was successfully mobilized as a strengthening system rather than acting merely as a surface repair layer. At the same time, the beam remained governed by tensile-region deterioration within the observed test range, which is a favorable indication that the intervention did not immediately force the member into brittle compression failure. Thus, the general structural response observed in this study supports the interpretation that the intervention achieved both rehabilitation and strengthening, while also highlighting the importance of residual ductility as a

prerequisite for retrofitting previously yielded reinforced concrete beams.

Load–Deflection Response

Load-Deflection was continuously recorded during testing using an LVDT and Load Cell sensors, and the resulting load–deflection curves are presented in Figure 14. The comparison between the responses before and after repair and CFRP strengthening provides direct evidence of the structural effect of the intervention, not only in terms of peak load, but also in terms of stiffness retention, cracking progression, nonlinear response, and deformation capacity. Overall, the repaired and CFRP-strengthened beam exhibited a higher load-carrying capacity and a more stable response in the post-cracking range than the beam before repair and strengthening.

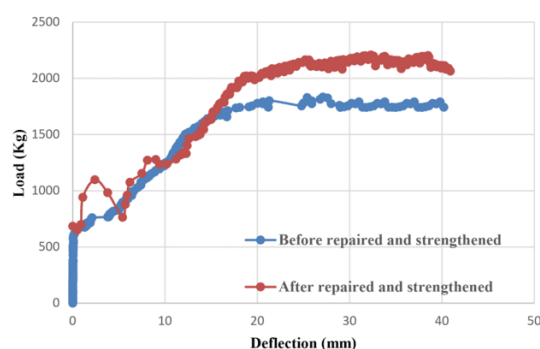


Figure 14. Load–deflection curves before and after repair and CFRP strengthening

The response of the beam before repair and strengthening reflects the behavior of a reinforced concrete beam that had already undergone significant flexural damage. In the initial stage of loading, the curve rises relatively steeply, indicating that the member still retained its basic flexural resistance despite prior damage. However, this early response cannot be interpreted as the behavior of an intact beam, because the specimen had already experienced previous cracking and yielding of the tensile reinforcement. Therefore, the initial slope more properly reflects the residual stiffness of a damaged beam rather than the true elastic stiffness of a virgin section. As loading progressed, the curve continued to rise but with a gradually reduced slope, indicating progressive stiffness degradation associated with reopening of the damaged tension zone and further development of flexural cracks. After this stage, the beam entered a more pronounced nonlinear response region, in which substantial increases in deflection were accompanied by only limited gains in load. This behavior is characteristic of a beam whose tensile zone has already lost part of its original effectiveness due to prior yielding and cracking. The maximum load recorded for the beam before strengthening was approximately 1832.9 kg, reached at a deflection of about 41 mm. Beyond the mid-range of deformation, the curve becomes relatively flat,

indicating that the beam had approached its residual flexural capacity and was no longer capable of developing significant additional resistance.

This pre-strengthening behavior is important because it establishes the actual baseline condition of the specimen. The beam was not simply cracked; it had already entered a post-yield damage state. As a result, its response was governed by a combination of reopened cracking, degraded tensile-zone stiffness, and residual load transfer through previously yielded steel reinforcement. In structural terms, the beam before intervention had not yet collapsed, but it had already consumed part of its ductility and stiffness reserve. This makes the subsequent recovery in response after repair and strengthening far more meaningful than if the beam had only been lightly pre-cracked.

The response of the beam after repair and CFRP strengthening shows a distinctly improved structural behavior. At very small deflections, the strengthened beam exhibits some local irregularity in the early loading stage, which is reasonable in tests involving repaired cracks, adhesive interfaces, and manual hydraulic loading. These initial fluctuations may be associated with seating effects, local adjustment of the repaired crack surfaces, and early engagement of the CFRP–epoxy–concrete composite action. However, once this initial stage passes, the strengthened curve develops a clearer upward trend and carries substantially higher load than the pre-strengthened beam over almost the entire deformation range.

In the lower-to-middle deflection range, the strengthened beam demonstrates a steeper ascending branch than the beam before strengthening. This indicates that the combined repair and strengthening system was effective in restoring stress continuity and improving tensile resistance in the critical flexural zone. The epoxy repair allowed the previously cracked concrete substrate to transfer stress again across the damaged region, while the externally bonded CFRP sheet provided additional tensile resistance at the soffit. This dual action explains why the strengthened beam not only recovered load-carrying ability, but did so with improved stiffness retention once the section re-entered the cracked flexural range.

As the load increased further, the strengthened beam continued to sustain a higher level of resistance and reached a maximum load of approximately 2208.1 kg at a deflection of about 40.9 mm. Compared with the

beam before strengthening, this represents a clear increase in flexural capacity while maintaining nearly the same ultimate deformation. This is a very important result. It shows that the intervention did not merely restore the damaged beam to serviceable behavior, but upgraded its resistance beyond the pre-strengthened condition. At the same time, the beam still reached a terminal deformation level comparable to that of the original damaged beam, which indicates that the strengthening process did not cause an immediate loss of global deformability within the observed test range.

A closer reading of the two curves reveals an important behavioral difference. The beam before strengthening shows earlier flattening of the curve, meaning that stiffness degradation became dominant sooner and the beam exhausted its effective resistance at a lower load level. By contrast, the strengthened beam maintains an ascending response over a wider deformation range before reaching its peak. This indicates that the strengthened beam was able to delay structural softening and sustain flexural action more efficiently after cracking. In practical terms, the repaired-and-strengthened beam showed a better ability to carry additional load after re-entering nonlinear behavior, which is precisely the expected structural consequence of effective CFRP strengthening.

This observed behavior supports two related interpretations. First, from a rehabilitation perspective, the epoxy repair restored sufficient continuity in the previously cracked section to allow the damaged beam to function again as a flexural member. The member no longer behaved merely as a severely compromised cracked beam, but as a rehabilitated section capable of re-establishing stable load transfer. This is consistent with the basic logic of rehabilitation in existing concrete structures, where the purpose of repair is to restore structural functionality after damage.

Second, from a strengthening perspective, the CFRP sheet clearly acted as supplemental tensile reinforcement in the flexural tension zone. This is especially significant in the present study because the internal tensile steel had already yielded in the previous loading stage. Therefore, the CFRP did not simply assist undamaged internal reinforcement; it compensated for part of the tensile deficiency that remained after prior yielding. This explains why the strengthened beam showed both a higher sustained load and a higher peak load than the beam before strengthening. In other words, the CFRP sheet was not merely protective or superficial, but structurally active and effective in mobilizing additional flexural resistance.

The fluctuations observed in the strengthened curve above approximately 2000 kg are most reasonably interpreted as the combined result of manual hydraulic pump operation and nonlinear response near the upper load range. Such fluctuations do not invalidate the results, because the global envelope of the curve remains clearly above that of the beam before strengthening. The important point is that the strengthened beam consistently maintained superior load-carrying performance in the medium-to-large deflection range, despite local oscillations in recorded load. Specimen flexural test result can be seen in Figure 15. Another key observation is that the strengthened beam reached a significantly higher load while maintaining nearly the same ultimate deflection as the original damaged beam. This means that the intervention produced a meaningful gain in strength without driving the beam into premature brittle response within the test range. For a previously yielded beam, this is a favorable outcome. It suggests that the intervention enhanced flexural resistance while preserving a structurally meaningful level of deformation capacity. Such behavior is especially important in the context of damaged reinforced concrete beams, where retrofitting should not only increase strength, but also avoid an undesirable shift toward brittle failure.

Therefore, the load–deflection response shown in Figure 1 provides strong experimental evidence that the combined use of epoxy crack repair and externally bonded CFRP sheets was structurally effective. The beam before intervention exhibited the response of a damaged post-yield member with reduced stiffness and limited residual flexural capacity, whereas the beam after repair and strengthening displayed restored structural continuity, improved post-cracking behavior, higher peak resistance, and better stiffness retention throughout the nonlinear loading range. These findings confirm that the intervention achieved both recovery of structural function and enhancement of flexural performance.

Cracking Behavior and Failure Progression

The observed cracks during the second test were primarily flexural cracks originating from the tension face of the beam as shown in Figure 16. Initial visible cracking after repair and strengthening appeared at approximately 941.1 kg, and progressive propagation became more apparent around 1097.4 kg. Most cracks followed or re-opened along the same lines as the previous damage that had been filled with epoxy.

This is a structurally meaningful result. The old crack lines remained the weakest zones in the member, even after repair. The epoxy restored continuity, but it did not erase the fact that the specimen had already undergone significant prior damage and internal yielding. In other words, the repair changed the beam from a failed/damaged condition into a functional load-carrying condition, but the damaged region still acted as the preferred crack path under renewed loading. That behavior is realistic and should not be interpreted as a weakness of the method; rather, it reflects the actual mechanics of rehabilitation of previously damaged reinforced concrete members.

At the onset of reloading, crack development was gradual. The repaired beam did not show sudden unstable cracking at low load levels, which indicates that the epoxy repair was effective in re-establishing local crack bridging and in preventing immediate reopening under small increments of load. As the load increased, crack widths enlarged and diagonal tendencies appeared, particularly near the

loading region. This suggests interaction between flexural tension demand and local shear-flexure stress redistribution in the previously damaged span zone.

The fact that the cracks propagated from the tension zone upward is consistent with ordinary reinforced concrete beam behavior under two-point loading. However, their repeated alignment with prior crack locations also indicates that the structural memory of damage remained embedded in the specimen. This should be emphasized in the discussion because it strengthens the practical value of the study: real rehabilitation cases rarely involve pristine members, and repaired members often continue to localize damage in pre-existing weak planes.

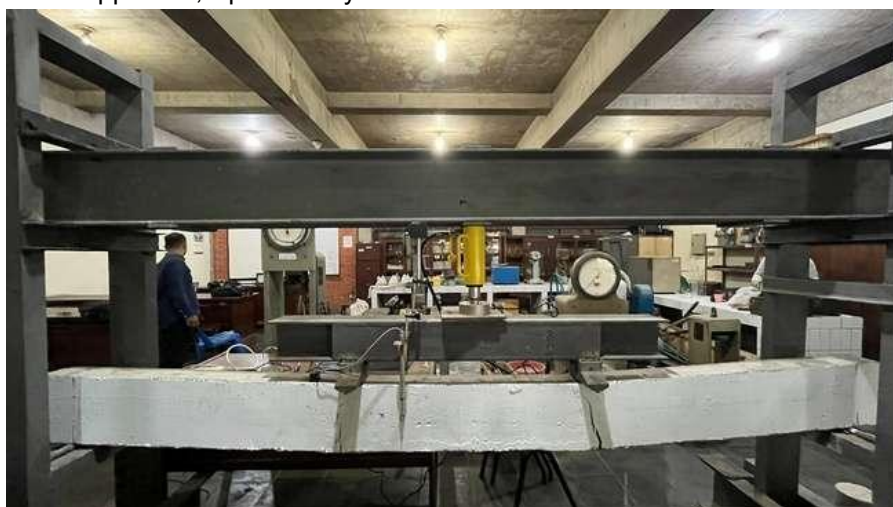


Figure 15. Flexural specimen test failure after repaired and strengthened

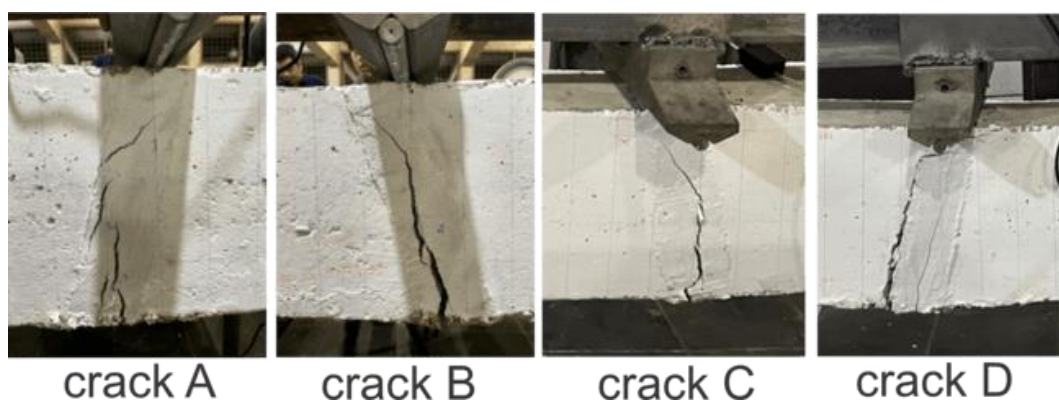


Figure 16. Crack in concrete repaired (Crack A, B, C, D)

In Figure 15 it can be seen that the concrete repaired cracked in area A-D. The dominant response remained flexural, with diagonal inclination developing as crack height increased. The diagonal geometry, especially in the

vicinity of the loading points, indicates that principal tensile stresses were not purely vertical. Instead, as load increased, the stress field rotated and the cracks grew along the direction of maximum tensile demand.

The wider crack openings near the bottom face confirm that the soffit remained the critical tension region throughout the test.

From a strengthening perspective, this is important because the CFRP sheet was installed exactly in that region. The observed crack morphology therefore supports the strengthening concept: the external sheet was correctly placed in the zone where additional tensile reinforcement was most needed. This is fully consistent with ACI 440 design philosophy for externally bonded FRP flexural strengthening, where the FRP is positioned on the tension face to supplement flexural tensile capacity.

Failure mode

When the beam reached a deflection of approximately 40.9 mm, failure of the CFRP strengthening system occurred by progressive debonding and eventual local rupture/damage as shown in Figure 17. The failure began with loss of bond at the adhesive interface and developed gradually rather than instantaneously. This failure mode is highly significant analytically. Externally bonded FRP systems often depend not only on the tensile capacity of the FRP itself, but also on the integrity of the bond between the FRP, adhesive, and concrete substrate. ACI 440 specifically recognizes the importance of material properties, installation quality, and bond behavior in determining the effectiveness of externally bonded FRP systems. In the present beam, the debonding-type failure suggests that the strengthening system had mobilized substantial tensile force before failure, which is why the beam could achieve a higher ultimate load than the original specimen.

Equally important, the beam did not fail in a sudden brittle collapse immediately after debonding started. Residual force transfer remained available for a short period, and the beam retained its overall shape. This implies that the CFRP system had already delivered meaningful strengthening before bond failure, and that the final failure process was progressive enough to be structurally observable rather than catastrophic.



Figure 17. Debonding failure of CFRP

Flexural Capacity Based on Moment Calculation

To quantify the improvement in structural performance, the support reactions and bending moments were calculated from the measured maximum test loads using static equilibrium for the two-point loading arrangement. Before strengthening, the beam carried a maximum applied load of 1832.9 kg (≈ 17.975 kN). Including the self-weight contribution of the IWF loading beam (76.85 kg ≈ 0.753 kN), the total load became 18.728 kN over a span of 3.0 m.

The maximum bending moment at the constant-moment region was: $M_u = 9.832$ kNm. This value represents the flexural capacity of the beam before repair and CFRP strengthening. After repair and strengthening, the beam carried a maximum applied load of 2208.1 kg (≈ 21.639 kN). Including the same IWF beam contribution, the total load became 22.392 kN.

The support reactions increased to the maximum bending moment in the constant-moment region became: $M_u = 11.756$ kNm. Thus, the strengthened beam developed a higher flexural moment capacity than the original beam.

The increase from 9.832 kN·m to 11.756 kN·m corresponds to an improvement of approximately 20.47%. This is the most direct evidence that the intervention did more than simply “repair” the beam. If the intervention had only restored the beam to its previous condition, the post-repair ultimate moment would have been expected to return to roughly the original value. Instead, the measured moment exceeded the original capacity by a significant margin.

That result is the clearest basis for distinguishing rehabilitation from strengthening in this study. The epoxy repair component can be interpreted as the rehabilitation mechanism, because it restored the damaged section sufficiently for the beam to behave again as a functioning flexural member. The CFRP sheet, by contrast, provided the strengthening mechanism, because it raised the ultimate flexural resistance above the original beam capacity. This interpretation is consistent with ACI 562’s treatment of repair/rehabilitation of existing concrete structures and ACI 440’s treatment of FRP as supplemental reinforcement for strengthening concrete members.

Table 1 presents a comparison of the key load–deflection parameters of the reinforced concrete beam

before and after repair with Sikadur-31 CF and strengthening with CFRP sheets. The parameters compared include cracking load (P_{crack}), yield load (P_{yield}), and maximum load (P_{max}), as well as deflections at crack, yield, and ultimate stages (U_{crack} , U_{yield} , U_u).

- Before strengthening: The beam before repair and strengthening showed the typical behavior of a reinforced concrete beam that had already experienced cracking and stiffness degradation. As loading increased, cracking developed in the tension zone, and the beam entered a lower-stiffness regime, as reflected in the decreasing slope of the load-deflection curve.

- After repair and CFRP strengthening: After crack repair with Sikadur-31 CF and CFRP strengthening, the beam exhibited a significantly improved structural response. The maximum load capacity (P_{max}) increased by 20.47%, indicating that the combined repair and strengthening system not only restored the beam's load-carrying capacity but also enhanced its flexural resistance.

Table 1. Comparison of Load–Deflection Parameters Before and After Repair and CFRP Strengthening

Specimen	P_{crack}	P_{yield}	P_{max}	U_{crack} (mm)	U_{yield} (mm)	U_{max} (mm)	K_{crack} (kg/mm)	K_{yield} (kg/mm)	K_u (kg/mm)
Before strengthening	649	1538.8	1832.9	1	10	41	649	153.88	44.71
After repair and CFRP strengthening	940	2000	2208.1	2.4	18	40.9	391.67	111.11	53.99

Table 2. Percentage Comparison of Structural Performance Before and After Repair and CFRP Strengthening

Parameter	Before strengthening	After repair and CFRP strengthening	Increase / Decrease (%)	Structural meaning
P_{crack}	649.0 kN	940.0 kN	44.84	Crack initiation was delayed after repair and strengthening
P_{yield}	1538.8 kN	2000.0 kN	29.97	The strengthened beam sustained higher load before entering the inelastic stage
P_{max}	1832.9 kN	2208.1 kN	20.47	Flexural strength increased significantly
U_{max}	41.0 mm	40.9 mm	-0.24	Ultimate deformation remained nearly unchanged
K_{sec}	44.71 kg/r	53.99 kg/r	20.75	Overall flexural stiffness increase
K_{crack}	649.00 kg/mm	391.67 kg/mm	-39.64	The early-stage apparent stiffness affected by repair zone response and crack reactivation mechanism
K_{yield}	153.88 kg/mm	111.11 kg/mm	-27.75	The strengthened beam entered yielding at a higher load but over a longer deformation interval

- Stiffness: The table also shows the stiffness of the beam at different stages, including the cracking stiffness (K_{crack}), yield stiffness (K_{yield}), and ultimate stiffness (K_u). The addition of CFRP resulted in a noticeable increase in stiffness, with K_u increasing by 20.75%, indicating that the strengthened beam had improved resistance to deflection under load.

Table 2 provides a percentage comparison of the structural performance improvements before and after repair and CFRP strengthening. Each key parameter—cracking load (P_{crack}), yield load (P_{yield}), and maximum load (P_{max})—was analyzed to assess whether the repair and strengthening achieved the desired structural goals.

Additionally, stiffness and ultimate deflection were compared.

- **Strength improvement:** The P_{crack} value increased by 44.84%, which indicates that the repair and CFRP strengthening significantly enhanced the beam's ability to resist load before cracking occurred.
- **Flexural capacity improvement:** The P_{max} value increased by 20.47%, demonstrating that the beam's flexural resistance after repair and strengthening surpassed its original capacity.
- **Stiffness:** The comparison of stiffness before and after strengthening revealed a significant increase, with K_u rising by 20.75%, indicating that the repaired and strengthened beam was able to resist deflection more effectively and provided a stiffer response under loading.

CONCLUSION

This study successfully evaluated the effectiveness of repair and strengthening of reinforced concrete beams that had previously sustained flexural damage due to overloading. The repair was carried out by filling the cracks with Sikadur-31 CF epoxy, and strengthening was performed using CFRP sheets along the tension face of the beam. Experimental results showed that both the repair and strengthening successfully restored the beam's capacity to its original state and even improved its flexural capacity.

Overall, the beam that was repaired and strengthened with CFRP showed an increase in maximum load capacity by 20.47%, along with a significant increase in stiffness. This capacity improvement indicates that CFRP can function effectively as external reinforcement to compensate for the lost capacity due to initial damage. Furthermore, the testing revealed that while failure occurred at the CFRP segment joints, the beam continued to exhibit plastic behavior, primarily controlled by the yielded tensile reinforcement, which still retained strain hardening and residual ductility.

However, the study also found that the joints between the separated CFRP segments became a weak point in the strengthening system. Failure at the CFRP segment joints was observed, highlighting the need for further attention to this issue in CFRP applications in the field. Additionally, while the beam's capacity increased, design considerations should be made to ensure that the beam still experiences tensile failure, rather than brittle compression failure due to the high tensile strength of the CFRP.

In conclusion, this research provides important contributions to the development of repair and strengthening methods for damaged concrete structures, particularly for reinforced concrete beams that have suffered damage from overloading. The results of this study can serve as a reference for field applications in repair and strengthening of damaged concrete beams, as well as a foundation for further research on optimizing CFRP strengthening systems and its influence on beam behavior after repair and strengthening.

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