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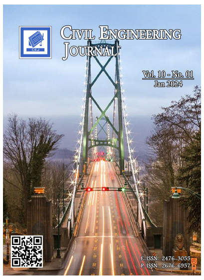

# Study of Post-Spalling Reinforced Concrete Beam Repair Using Grouting and GFRP Reinforcement

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**Abstract**

Reinforced concrete beams must meet strength and durability standards, but aggressive environmental factors are the main cause of corrosion, which can affect the strength and durability of building structures. Maintenance, retrofitting, and reinforcement of structures are important to ensure safety. It is necessary to take appropriate measures to address corrosion problems in building structures early on. One way to achieve this is by repairing damaged structures using more modern and effective technologies and materials. This study aims to determine the flexural behavior of reinforced concrete (RC) beams repaired with Sikagrout-215 material and reinforced with GFRP sheets with different layer configurations. The study used three RC beams as the control group, three RC beams coated with Sikagrout-215 mortar, and six RC beams reinforced with GFRP. All beams were subjected to 4-point bending tests to determine their load capacity, crack response, ductility, and energy absorption capacity. The results showed that repair with grouting decreased the load capacity, while reinforcement with a combination of mortar grouting and GFRP increased the maximum load. Reinforcement of the support region could restore the function of the beam by 9.3%. Among the three types of reinforcement, BGRST significantly improved the first crack response, yield response, and ultimate performance of the RC beams. Beam fracture occurred more frequently with Sikagrout-215 mortar reinforcement, while reinforcement with GFRP composites partially protected the load capacity after fracture.

*Keywords:* Reinforced Concrete; Spalling; Grouting; GFRP.

## 1. Introduction

Reinforced concrete beams are one of the important parts of building structures that must meet strength and durability standards to ensure the wearer's safety. However, environmental factors such as corrosion and damage from heavy loads can affect the strength and durability of reinforced concrete beams [1]. Durability, maintenance, and retrofitting of structures are some of the issues that are of growing concern to the international construction scene. Nowadays, it is not uncommon to find buildings operating at the limits of stability and safety (such as some bridges or residential buildings, for example). The fragile condition of civil structures will further endanger the public by ignoring simple procedures such as periodic inspections and preventive maintenance, eventually leading to solutions for retrofitting and sometimes total demolition of the structure [2].

Extensive research over the past few decades led to the development and use of cement as a cost-effective solution for repair [3, 4]. Several new types of advanced repair materials and techniques have been successfully developed to restore the chipped cover of RC structures. One such method is patch repair with grouting [4]. Patching is usually done

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by applying mortar or concrete by hand, recasting with mortar or concrete, spraying concrete, or ferrocement with mortar or concrete. Gergess et al. [4] and Chalioris et al. [5] focused on the repair of RC beams damaged to the point of yielding longitudinal reinforcing steel bars simulating RC structural elements in existing structures subjected to increased service loads. Alwash et al. [6] rehabilitated reinforced concrete column-beam (RC) specimens that corroded when subjected to bending moments and axial forces. Corrosion reinforcement damage can be addressed by patching repair techniques and replacing the corroded steel reinforcement. Machmud et al. (2019) [7] conducted an innovative reinforcement system by combining cement mortar with the same benefits (lightweight, easy to install, and non-rusting) as the FRP system, increasing the bond between concrete and reinforcement and thus increasing the ultimate capacity of RC beams.

Strengthening and repairing damaged structural elements is considered necessary to restore structural performance and avoid the demolition and reconstruction of new structural elements [8]. Efficiency will be even better if these materials are combined with the use of fiber-reinforced polymer (FRP) because it can increase the stiffness of structural elements, residual flexural strength, and load capacity of reinforced concrete [9]. They are currently using cementitious materials for repairs, and FRP as structural reinforcement has proven to have great benefits in restoring the service life of old building structures. FRP is also used for new structures, where it is used as reinforcement and as prestressing for concrete structures. Since FRP composites are also easy to apply in structural reinforcement, they have become quite effective as an alternative reinforcement element. Compared to steel reinforcement, FRP has several advantages, such as higher tensile strength, a lower modulus of elasticity, bonding characteristics, and being lightweight and non-corrosive [10].

Structural rehabilitation is mandatory for RC conditions that are porous due to corrosion and have experienced separation between concrete blankets and reinforcement. Gergess et al. (2020) [4] found that the repair of severely damaged RC beams with high-strength cement grout can increase 1.4 to 1.5 times the flexural load-bearing capacity of RC beams from the level of damage. Using high-grade cement in combination with CFRP reinforcement is very effective for increasing the flexural capacity of RC. An experimental study by Ortega et al. [11] on damaged reinforced concrete columns treated with mortar patches and then subjected to axial loads until failure can provide better results even though they are made with low-grade concrete. Pineda et al. (2017) [12] CFRP grid treatment in a mortar (CGM) and Carbon Fabric Reinforced Cementitious Mortar (CFRCM) showed better results for increased shear capacity compared to epoxy-based systems (CFRP sheets). Ferrari et al. (2013) [3] RC reinforcement method using a combination of High-Performance Fiber Reinforcement Cement-Based Composite (HPFRCC) and Carbon Fiber Reinforced Polymers (CFRP) obtained RC with pseudo-strain-hardening behavior, high strength, and fracture toughness.

The use of FRP in decades related to handling brittle RC concrete proved to increase the strength and stiffness of concrete structures so that they could withstand greater loads and reduce deformation [13, 14]. Glass Fiber Reinforced Polymer (GFRP) has high strength and modulus, good compatibility with concrete, dimensional stability, and corrosion resistance [8, 15]. GFRP is becoming more economical and suitable for various projects [9, 16]. Almusallam (2006) conducted a study of concrete with a compressive strength of 36.4 MPa reinforced with GFRP and showed that general GFRP sheets significantly improved the flexural strength and ductility of beams.

In this study, RC beam specimens were produced in a critical condition and therefore needed to be treated to increase their service life and flexural capacity. Compared to the real condition of RC treatment, if replaced with a new condition, it will require a high cost and a long time, so experimental research is carried out to restore the structure's service life. Treating critical beams starts with restoring the beam dimensions to make them perfect again using Sikagrout-215, then reinforcing the RC with GFRP installation. The impact of the strengthening of the beams has been investigated on flexural strength, ductility, and energy absorption capacity. This study aims to investigate the effectiveness of rehabilitation using the grouting method and reinforcement of RC with GFRP sheets.

## 2. Material and Methods

### 2.1. Concrete and Steel

The concrete used in all RC beams was sourced from a ready-mix company. Slump tests were taken for cylindrical specimens and concrete cubes at the time of production and arrival at the laboratory area. The average compressive strength for 28 days was found to be 21 MPa, the strain capacity was found to be 0.0026, and the elasticity module was found to be 28360 MPa. As a result of the standard tests conducted, the yield strength of steel reinforcement with Ø 8 has been calculated as 375 and the tensile strength as 496 MPa; the yield strength of steel reinforcement with Ø 13 has been calculated as 420 and the tensile strength as 520 MPa. The modulus of elasticity (Es) of the reinforcement is 200 GPa.

### 2.2. Cement mortar (Sikagrout-215)

Sikagrout-215 is a ready-to-use grouting cement with non-shrink characteristics, used to fill gaps or spaces between concrete structural elements, such as columns, beams, and retaining walls, and other structural elements, such as steel, iron, or prestressed concrete. Sikagrout-215 has non-shrink properties that enable its use in conditions that require resistance to deformation, as well as special formulations that can extend service life and reduce the risk of cracking due to shrinkage. In addition, Sikagrout-215 can also be applied easily and quickly, with mixes requiring only the addition of water. The mechanical properties of the mortar are shown in Table 1.

**Table 1. Mechanical properties of cement mortar**

| Sample test (days) | Compressive strength (MPa) | Flexural strength (MPa) |
|---|---|---|
| 7 | 28 | 4 |
| 28 | 34 | 10.6 |

## 2.3. Glass Fiber Reinforced Polymer (GFRP)

As an externally bonded reinforcing material to the structure, the unidirectionally knitted glass fiber composite GFRP is both all-weather and saltwater-resistant [17, 16]. To apply GFRP webbing as a reinforcing element in RC specimens, the bonded surface must be cleaned of all kinds of impurities, such as dust or the like. The adhesion strength of GFRP and the RC beam surface is greatly influenced by the way the epoxy glue is applied; the glass fiber matting attached to the RC surface is attached using a special roller and then pressed as much as possible so as not to form air bubbles outside [15, 18]. Table 2 illustrates the specifications of the GFRP sheets manufactured by Fyfe Co., LLC. The adhesive used in this study was sourced similarly to GFRP production, consisting of two epoxies. Both are combined and mixed quickly to ensure their uniformity before use. The mechanical characteristics of the adhesives used are shown in Table 3.

**Table 2. State of GFRP composites**

| Material Properties | Test Score |
|---|---|
| Ultimate Tensile Stress | 575 MPa |
| Tensile Modulus | 26.1 GPa |
| Strain | 2,20% |
| Thickness of Composite | 1.3 mm |

**Table 3. Material characteristics of epoxy resin**

| Material Properties | ASTM Method | Test Score |
|---|---|---|
| Tensile Strength | ASTM D-638 | 72.4 MPa |
| Tensile Modulus | - | 3.18 GPa |
| Percent Strain | ASTM D-638 | 5% |
| Flexural Strength | ASTM D-790 | 123.4 MPa |
| Flexural Modulus | ASTM D-790 | 3.12 GPa |

## 2.4. Detail of Specimens

Twelve reinforced concrete (RC) beams have been fabricated with cross-sectional dimensions of 150×250 mm and an overall length of 3300 mm, with an effective span of 3000 mm. Two variations of RC beams were produced: control beams and RC beams that underwent repair and reinforcement (Table 4). For the RC beam serving as the control beam, 3D13 and 2F8 steel reinforcements were used for the tensile and compressive sides, respectively (Figure 1). This was done to ensure the strength and durability of the beams in withstanding the loads acting on the tensile and compressive sides. To prevent failure due to shear during testing, the tested beams were provided with transverse reinforcements (stirrups) f8 spaced at 80 mm intervals in each shear zone (from the support to the centered load). The transverse reinforcement in the flexural zone (between the two centered loads) was spaced at 200 mm. The purpose of using transverse reinforcement was to enhance the strength and reliability of the beams against shear forces that occur during testing. Nine variation beams used 3f8 and 2f8 steel reinforcement for the tensile and compressive sides (Figure 2). The change in the use of reinforcement in the variation of RC beams is assumed to be a change in the extremity of the RC beams that requires immediate and appropriate treatment. This indicates that the beam extremities significantly influence the need for repair and reinforcement. Meticulous and precise steps are crucial throughout the manufacturing and testing of these RC beams to ensure strength, reliability, and good structural performance. By using control beams and RC beams that underwent repair and reinforcement, this study aims to identify the effectiveness of the applied repair measures and provide appropriate recommendations for further treatment of RC beams experiencing similar conditions.

**Table 4. Details of test specimens**

| Type | Beam code | Item | Action | Materials | Treatment of RC Beams |
|---|---|---|---|---|---|
| 1. | BK | 3 | Control | - | No |
| 2. | BGR | 3 | Grouting | Sikagrout-215. | 5 cm patch |
| 3. | BGRS | 3 | Grouting and reinforcement GFRP Sheet | Sikagrout-215, GFRP | 5 cm patch, GFRP sheet layer on the bottom side |
| 4. | BGRST | 3 | Grouting, reinforcement GFRP Sheet and U-Wrap | Sikagrout-215, GFRP | 5 cm patch, GFRP sheet layer on the bottom side and U-Wrap on the support area |

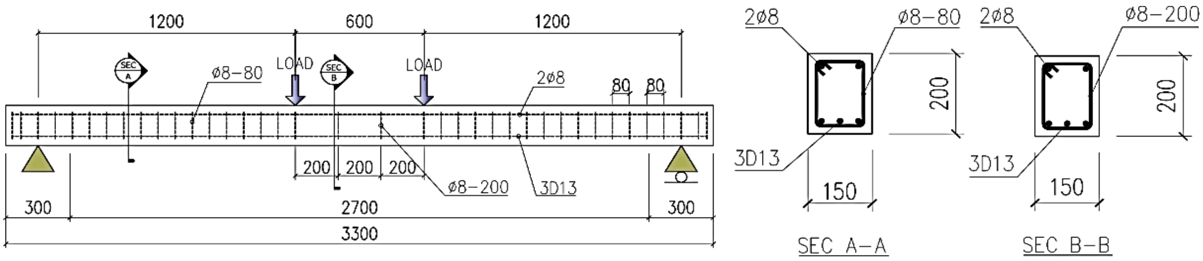
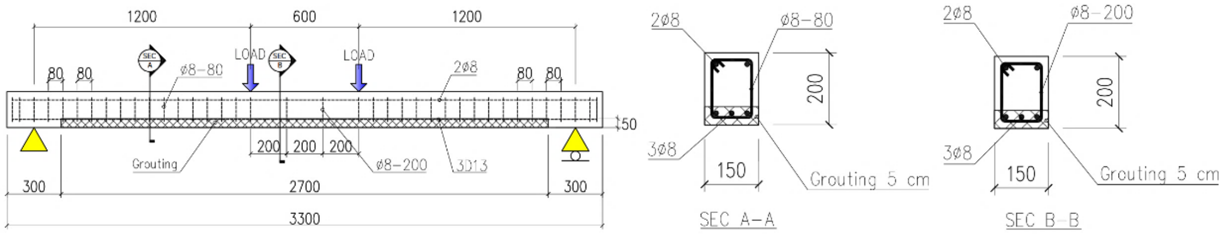
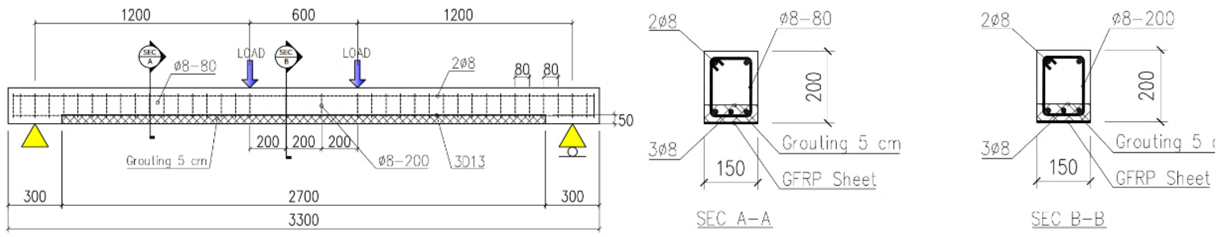


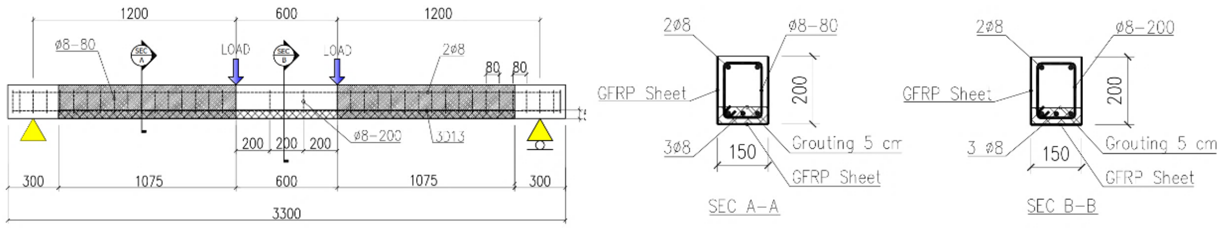

**Figure 1. Details and dimensions of control beams**




**BGR variation type**




**BGRS variation type**




**BGRST variation type**

**Figure 2. Details and dimensions of variation beams**

## 2.5. Fabrication and Set Up Specimen

In RC beam specimens made in the laboratory are assumed to experience spalling at the bottom of the RC beam so that the reinforcement is also reduced. The RC beam test specimen variation is the result of reinforcement reduction from the control RC beam by 38.5%, namely the change in the use of iron reinforcement diameter 13 to reinforcement diameter 8. The procedure for making test specimens generally consists of three parts: making RC beam test specimens, grouting RC beams and utilizing GFRP in RC beams as reinforcement material. As an initial step for the manufacture of RC beams, of course, it begins with preparation, assembly of steel reinforcement, casting and then the use of Sikagrout-215 mortar, preparation of epoxy and installation of GFRP sheets. When casting, the concrete surface is not fully cast but leaves a limit of 5 cm with a length of 3000 mm as an assumption that the RC beam has experienced peeling of the concrete blanket up to the steel reinforcement area. Figure 3 illustrates the flowchart of the research methodology employed to accomplish the objectives of this study.

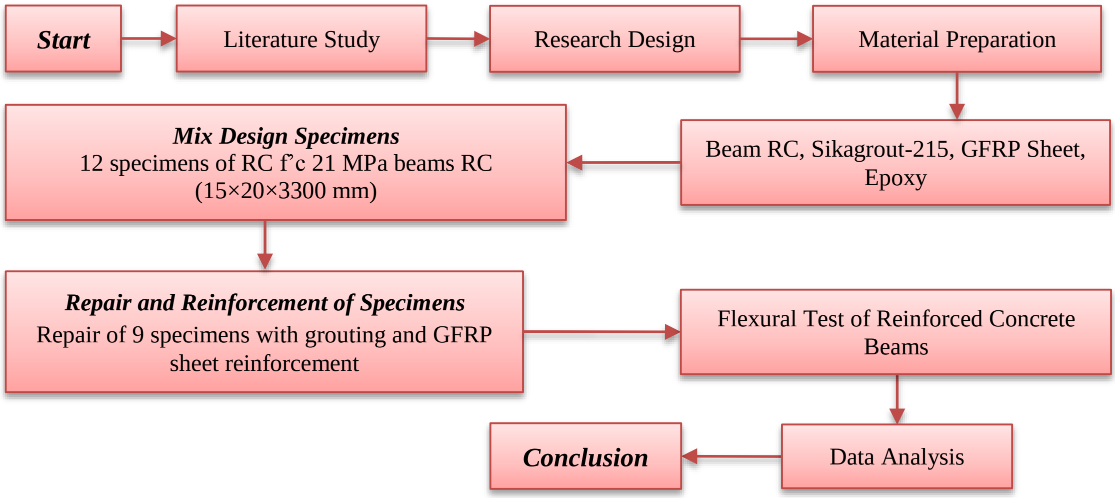



**Figure 3. Research procedure flowchart**

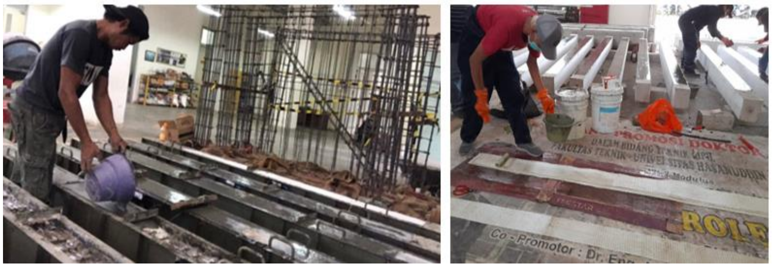
To facilitate casting work and achieve the research concept, the position of the RC beam variation at the bottom is assumed to have experienced spalling, so the RC beam is changed to an upward position to facilitate casting and make it easier to continue further work. The second procedure is grouting work using Sikagrout-215 mortar mixed in the old concrete, with a maintenance period of 14 days. It is necessary to ensure that the condition of the old concrete is clean from dirt or dust, and then use Sika adhesive as a bonding agent to help make it homogeneous between the old and new concrete joints. Utilization of Sikagrout-215 as a new joint to restore the dimensions of RC concrete and corrective measures for RC concrete, which was in a critical condition due to the peeling of concrete skin 5 cm deep. BGR is the code name for RC beam specimens repaired using Sikagrout-215, with three RC beams ready to be tested for flexural strength.

The last procedure for making test objects is reinforcing RC beams using GFRP composites. a) leveling the surface of the beam to be reinforced with GFRP and U-wrap layers and cleaning it from any dirt that might reduce concrete adhesion; b) preparing a mixture of epoxy resin adhesive components A and component B with a weight ratio of 2:1. The stirring process should not be excessive to produce foam and bubbles that can be trapped as air voids in the adhesive; c) Attach the reinforcement material that has been cut and treated with adhesive in the longitudinal direction of the beam and gently press against the adhesive that is still wet. Air voids trapped between the reinforcement layer and the concrete surface will be released by roller pressure in the direction of the reinforcement fibers so that the adhesive blends with the fibers and the concrete surface. Roller pressure perpendicular to the fiber direction is not allowed, as it may change the fiber direction or damage the fiber. Apply the second-stage adhesive over the fully adhered Tyfo SEH-51 GFRP surface to ensure fiber adhesion to the concrete surface. There are two variations of GFRP composite sheet installation on RC beams: reinforcement at the bottom position of RC beams that have been patched (BGRS) and installation of GFRP U-Wrap on both support areas of RC beams (BGRST). The main materials used in this research are shown in Figure 4, and some photos of the procedure for making RC beam specimens are shown in Figure 5.

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

**Figure 4. (a) D 13 iron reinforcement and ϕ 8 (b) Sikagrout-215 mortar and Sika bonding adhesive (c) GFRP Woven sheet (d) epoxy resin FRP components A and B**

(a) (b) (c)



(d) (e)

(f) (g)

**Figure 5. (a) Casting of specimens assuming spalling (b) specimens aged 14 days ready for grouting (c) Production of Sikagrout-215 mortar (d) Repair of RC beams with grouting mortar after coating with bonding agent (e) Application of epoxy resin on GFRP sheet (f) Test specimens that have been grouted and cleaned of all kinds of dirt (g) RC beam specimens that have been coated with GFRP sheet (BGR) and U-Wrap at the support area (BGRST).**

Three test specimens of each BGRS and BGRST RC beam were tested for their ability to bear structural loads under the conditions of repair grouting and reinforcement with GFRP composites. Load cell readings for beam tests were taken at every 1 kN loading. To record the deflection that occurs in the beam, three LVDTs (Linear Variable Displacement Transducers) are placed at the bottom of the beam. As shown in Figure 6, testing of reinforced concrete beams was carried out to determine the ability of the beams to carry loads. Load cell readings for beam testing were taken every 1 kN loading. The load was applied by a 1000 kN capacity hydraulic jack attached to a computer-controlled electric pump. The bending test was carried out using a bending load frame with a capacity of 100 tons with a four-point bending test, as presented in Figure 6.

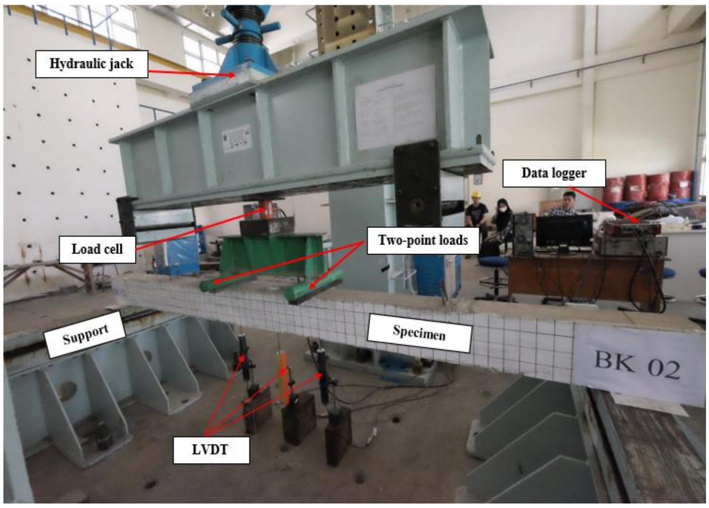



**Figure 6. Setup of test specimens on the UTM device**

Three LVDTs with a capacity of 100 mm with an accuracy of 0.01 mm were installed on the test beam to determine the deflection that occurred. One was placed at the center of the span, and two under each load connected to a data logger to record the amount of load and deflection on the beam. The tests were carried out on a frame made of steel profiles designed with simple joints to test the flexural strength of a beam with a span length of 3300 mm and a rectangular cross-section with dimensions of 150 mm × 200 mm. The beam is supported with a clear span of 3000 mm with a distance of 1200 mm between two loading points, and a shear span of 600 mm. According to Figure 1, the beam is separated into three zones: zones 1 and 3 have low bending moments and high shear loads at a distance of 1200 mm from the right and left supports; zone 2 is a zone that only has efficient bending moments. Load distribution beams are placed on top of the experimental beams, and loads are then placed on the load distribution beams. This way, the load is evenly distributed on the experimental beam, making the deflection measurement results more accurate.

# 3. Results and Discussion

## 3.1. Load and Deflection Relationship

Table 5 presents the average values of the RC concrete bale test results. The average value of the load on the three control beams at the initial crack reached 2.61 kN; a deflection of 1.29 mm occurred at the center of the beam; and the first flexural crack occurred at the 2nd zone of the bottom of the beam. When the applied load reached the yield of 25.87 kN, a deflection of 17.67 mm occurred, and as the loading continued, the load increase remained limited, but the deflection continued to increase. When the applied load peaked at 29.74 kN, the experimental beam experienced a deflection of 53.59 mm (Figure 7). Three RC beams in critical condition, coded BGR, were repaired by mortar grouting of the bottom surface. When the average load reached 2.38 kN in beam BGR, a deflection of 2.18 mm occurred at the center of the beam. The reinforcement began to yield an average load of 12.17 kN, and the deflection corresponding to this load was measured to be 19.06 mm. When it reached the peak load, the beam lost bearing capacity and collapsed at a load of 14.39 kN, deflected by 28.17, lost its bearing capacity, and collapsed (Figure 8 and Table 5). There was a significant loss in the load-bearing capacity of the BGR beam of up to 51.58% when compared to the control beam.

**Table 5. Average value of RC beam test results**

| Beams | Concrete Cracking | | Steel Yielding | | Ultimate Stage | |
|---|---|---|---|---|---|---|
| | Load (kN) | Deflection (mm) | Load (kN) | Deflection (mm) | Load (kN) | Deflection (mm) |
| Control beam | 2.61 | 1.29 | 25.87 | 17.67 | 29.74 | 53.59 |
| BGR | 2.38 | 2.18 | 12.17 | 19.06 | 14.39 | 28.17 |
| BGRS | 7.22 | 4.85 | 20.35 | 24.97 | 27.81 | 50.24 |
| BGRST | 17.46 | 17.49 | 28.07 | 46.11 | 32.50 | 46.15 |

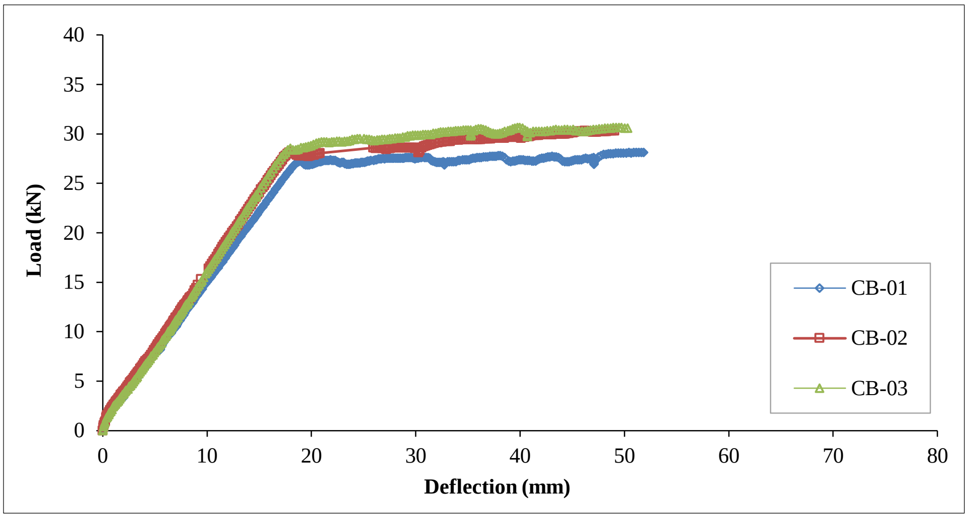



**Figure 7. Load-deflection relationship for control beams**

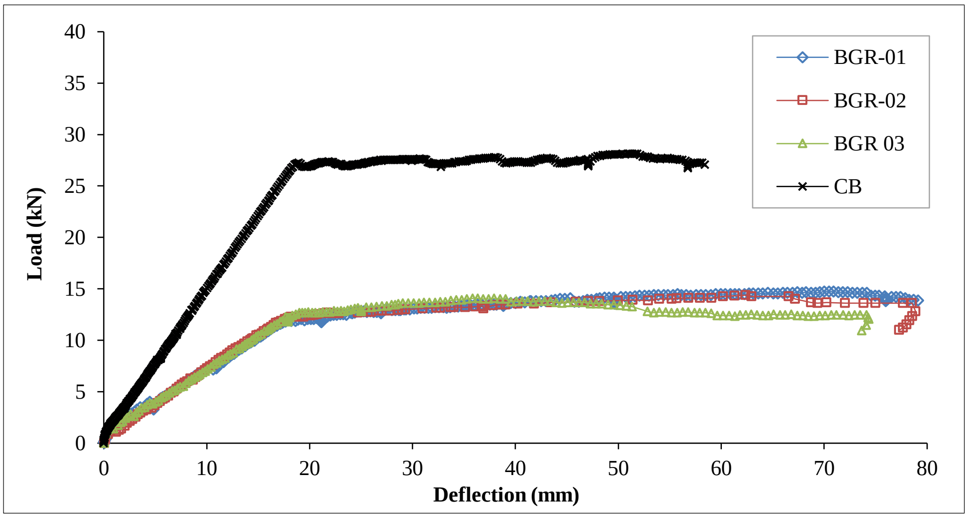



**Figure 8. Load-deflection relationship for BGR beams**

In contrast to the work done by Ortega et al. [11], the quality of the mortar was able to increase the load capacity up to 65% of the control beam as well. According to Ferrari et al. (2013) [3] and Gergess et al. (2020) [4], the grouting mortar used successfully increased the load-carrying capacity by 72% and 120%, respectively.

Therefore, it is necessary to make more thorough repairs to the BGR-type beams, for example, by using additional materials such as GFRP sheets to provide stronger mechanical support. With proper repairs, the beams are expected to regain adequate bearing capacity to withstand loads safely and meet the desired design requirements. The advantage of repairing with Sikagrout-215 mortar is that it can help fill the gaps in the concrete and make it denser, thus restoring the beam to its original dimensions and reducing the risk of damage to the beam in the future. However, this repair is only suitable if the damage to the beam is mild and the load-carrying capacity is still high enough. If the load-carrying capacity of the beam is already very low, then repair with mortar grouting will not be effective enough, and a more thorough repair method should be considered. Cracks in mortar grouting in RC concrete indicate that the homogeneity between old and new concrete affects the quality of the concrete; the joint area can become a weak point in the concrete structure, which can cause cracks or damage to the area [12]. If the joint area is continuously subjected to loads, such as repeated or heavy static loads, the area can become susceptible to cracks or damage.

Three RC beams coded BGRS were rehabilitated using Sikagrout-215 mortar and then reinforced by coating the bottom surface of the beams with GFRP composite sheets. When the average load was 7.22 kN at the initial crack in the BGRS beam, a deflection of 4.85 mm occurred at the center of the beam, and the first flexural crack occurred at the 2nd zone of the beam bottom. When the applied load reached 20.35 kN, the reinforcement started to yield, and the deflection corresponding to this load was measured to be about 18.50 mm. When the applied load reached 27.81 kN, the beam experienced a deflection of 50.24, lost its bearing capacity, and collapsed (Figure 9-Table 5). After grouting, reinforcement was performed on the three RC beams (BGRS). Then the GFRP sheet reinforcement of the composite BGRS specimens experienced a difference in ultimate bearing capacity of 6.47% from the control beam. Previous research [8, 15, 16] reinforced the beam at the bottom surface of the beam, successfully maintaining the quality of the beam structure from repetitive loads and extreme conditions.

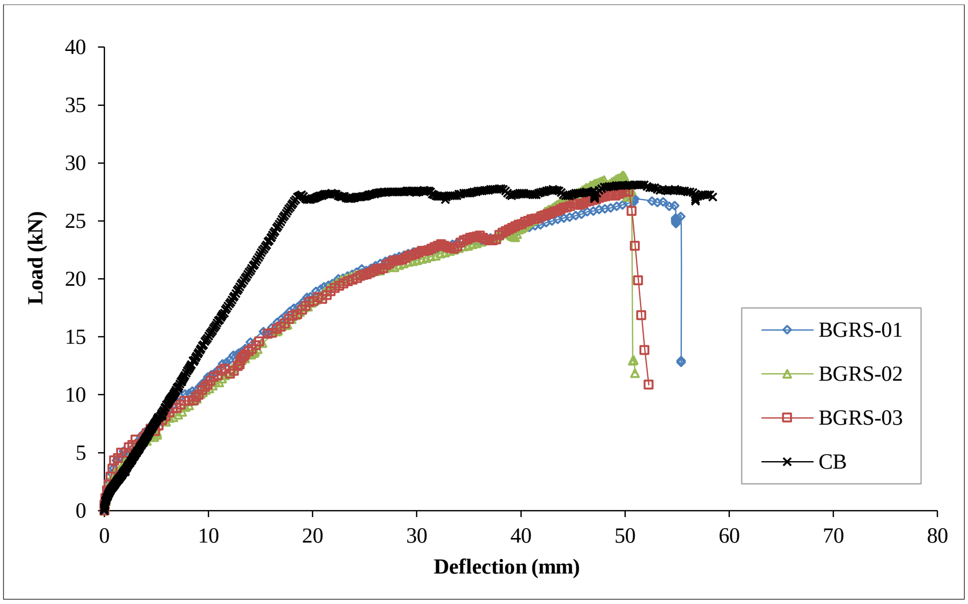



**Figure 9. Load-deflection relationship for BGRS beams**

The use of composite GFRP sheets on the underside of the concrete has yet to fully restore the beam's functionality, as in the case of the control beam. However, it can withstand loads during its service life compared to the need for new concrete. The indication of the lower ultimate bearing capacity of the repaired reinforced concrete beam is influenced by the material strength of the reinforced concrete and the quality of the reinforcement used in the test specimens, which is lower than that used in the control beam [18]. The reinforcement process may have needed to have been more optimal, thereby failing to provide a maximum increase in bearing capacity. The achieved load strength value of the repaired reinforced concrete beam may sometimes differ from that of the control beam [19]. The objective of repairing the BGRS beams is to strengthen damaged or weak structures to meet the necessary safety requirements. Therefore, as long as the attained load strength values comply with the safety and reliability requirements of the structure, the repair can be considered successful.

Three RC beams coded BGRST were reinforced by grouting and then reinforced with one transverse glass fiber wrap on the bottom and side surfaces at the support area, or zones 1 and 3, to investigate the effect of the amount of glass fiber wrap on the load-bearing capacity and were tested. When the load reached an average of 10.06 kN on the BGRST beam, a deflection of 6.94 mm occurred at the center of the beam, and the first flexural crack occurred at the 2nd bottom zone of the beam. When the applied load reached 20.37 kN, the reinforcement started to yield, and the deflection corresponding to this load was measured to be about 36.11 mm. When the applied load reached 32.50 kN, the beam experienced a deflection of 46.15 mm, lost its bearing capacity, and collapsed (Figure 10 and Table 5). There was an effect on the BGRST beams with the use of GFRP in zones 1 and 3; the capacity of the beams in critical condition under reinforcement proved to be able to exceed the load capacity of the control beam by 6.25%. Attari et al. (2012) and Saribiyik et al. (2016) performed different strengthening configurations using FRP, while GFRP was made similar to the BGRS model, and the results showed an increase in strength of 118% and 90% compared to the control beam specimen.

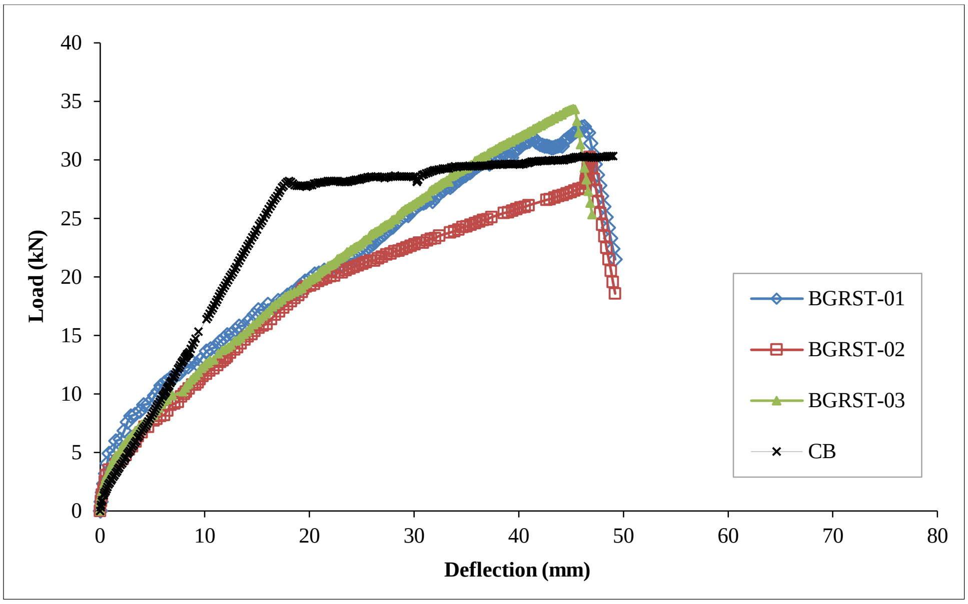



**Figure 10. Load-deflection relationship for BGRST beams**

Beams reinforced with 1200 mm wide and 200 mm high strips in zones 1 and 3 with GFRP fibers at 90° to the longitudinal axis of the beam; when the fiber direction is perpendicular to the crack line, the reinforcement effect increases the bearing capacity of the beam. The high deflection values of the BGRS beams were influenced by loads exceeding the bearing capacity, and the critical condition of the beams had been grouted so that the old and new concrete bonds were easily detached. Beams that were repaired with GFRP fibers at the support region had greater stiffness than those repaired only at the bottom surface, indicating that the BGRST repair approach resulted in a more ductile failure. The BGRST repair approach showed better durability when compared to the BGRS repair approach.

## 3.2. Performance of Beams Ductility

Ductility in reinforced concrete beams can be defined as the ability of a structure to exhibit plastic behavior before experiencing failure [20]. In the context of reinforced concrete beams, ductility refers to the beam's capacity to demonstrate good flexural behavior and absorb energy before fracture or ultimate failure [5]. The higher the ductility value of reinforced concrete beams, the better the performance and reliability of the structure in resisting external loads [21]. This is crucial to ensuring the safety and reliability of buildings or structures that utilize reinforced concrete beams as structural elements. The use of GFRP layers has a positive impact on RC beams in terms of increased strength and stiffness and contributes to enhancing ductility [22]. In this study, ductility is described using an index in the form of deflection. It is quantitatively defined as the ratio between the deflection at peak load ($\delta_{max}$) and the deflection at yield load ($\delta_y$). Figure 11 illustrates that the ductility of the BGR beam decreased by 37% compared to the CB, indicating that the BGR has not been able to restore its serviceability when deteriorated concrete is rehabilitated with Sikagrout-215 mortar; it only restores the original cross-section. BGRS still exhibits a marginal 7% decrease in ductility relative to the control beam.

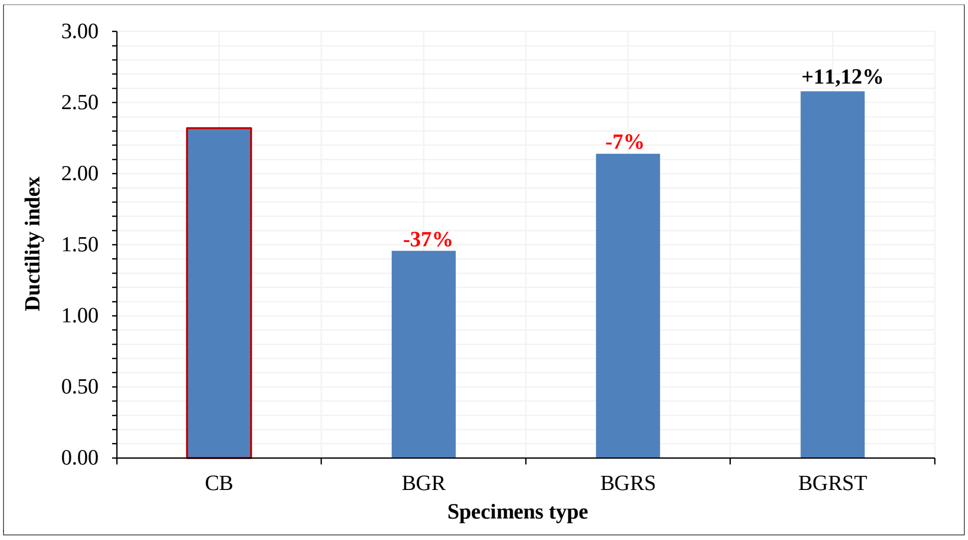



**Figure 11. Comparison of ductility performance of test specimens**

Figure 11 shows that the BGR and BGRS beams are insufficient to significantly decrease the neutral axis, which leads to immediate compressive concrete failure after the tensile reinforcement of the beam is fractured. The deflection response of BGRST compared to the control beam indicates that its ductility index has a higher value, as shown in Figure 11. The rehabilitation of the beam with 50 mm thick Sikagrout-215 mortar reinforced with GFRP sheets (BGRST) results in an 11.12% increase in ductility compared to BGR, BGRS, and the control specimen. Compared to BGR, the reinforcement enhancement with GFRP on the bottom of the beam (BGRS) tends to raise the effective stress, ultimately shifting the neutral axis closer to the extreme concrete compression zone. It is suspected that the BGRST beam, influenced by the use of GFRP in Zone 2, can enhance the strength and ductility of the reinforced concrete structure. GFRP contributes positively to the increased ductility of reinforced concrete beams due to its ability to form a strong bond with concrete and steel reinforcement. With a strong bond, the steel reinforcement can develop full plastic deformation before the concrete in the compression zone experiences ruptures. This allows the reinforced concrete beam to exhibit better plastic behavior and absorb more energy before failure occurs [23].

Overall, beams rehabilitated using these three approaches show promising results, not only in terms of significant ultimate capacity improvement but also without compromising structural ductility significantly. The results obtained in this study appear to be consistent with the findings of Alwash et al. [6] on RC beams reinforced with mortar, which provided less ductile performance, and the use of GFRP [24] as reinforcement material in critical beams, which had a greater impact on ductility compared to mortar.

## 3.3. Crack Pattern Analysis

Table 6 and Figures 12 to 15 show the characteristics and crack patterns at the failure of the control, repaired, and strengthened beams. In Figure 12, a normal cracking pattern is observed starting at the flexural span between the test supports, with cracks mainly vertical and concentrated at the mid-span, indicating that the beam was subjected to pure buckling. The beam also experienced combined flexural-shear failure, especially in the middle third of the beam, characterized by vertical to diagonal cracking, as shown in Figure 12. The control beam experienced the classic concrete crushing failure in the compressive zone. The cracks in the control beam started at the mid-span flexure between the two test pedestals. They developed into additional flexural cracks propagating away from mid-span with increasing slope as they approached the two test pedestals. Combined flexural-shear cracking also occurred, mainly in the middle third of the beam. At the failure of the control beam, most of the cracks extended across the entire beam surface, with crack lengths of 60–162 mm. There were 26 and 6 main cracks in the buckling region at mid-span. The crack pattern of the control beam indicated pure mid-span buckling, as the cracks were concentrated at the center. Shear cracks appear due to shear stress, so the cracks become increasingly skewed and move toward the two concentrated load points [25].

**Table 6. Details of cracks in test specimens**

| Test Item Code | Crack length (mm) | | Max crack width (mm) | Total cracks in the beam | Crack type |
|---|---|---|---|---|---|
| | Min | Max | | | |
| BK | 60 | 162 | 2,35 | 26 | Flexural |
| BGR | 73 | 182 | 85,8 | 38 | Flexural- the concrete was peeled off |
| BGRS | 75 | 173 | 35,7 | 32 | Bending-debonding |
| BGRST | 55 | 153 | 8,9 | 19 | Bending-debonding |

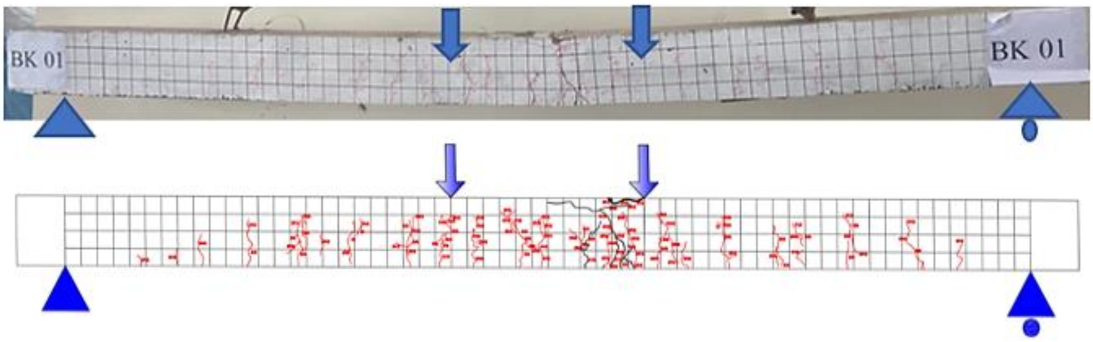



**Figure 12. The crack pattern of the control beam (CB)**

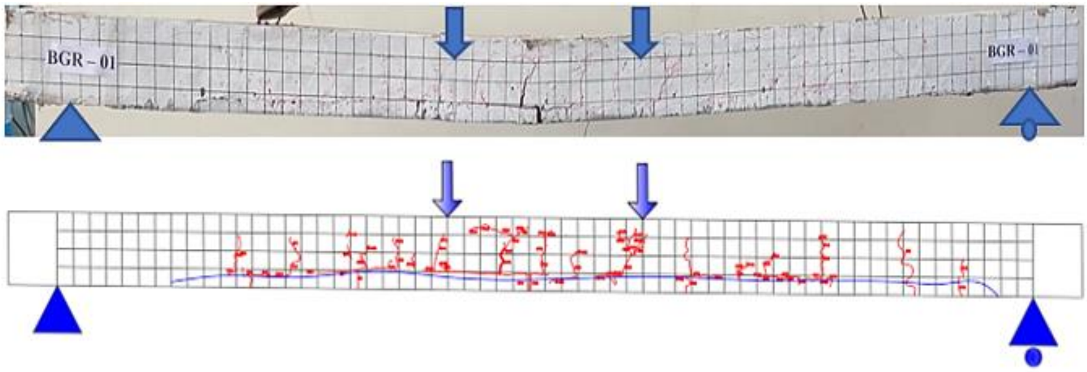



**Figure 13. The crack pattern of the BGR beam**

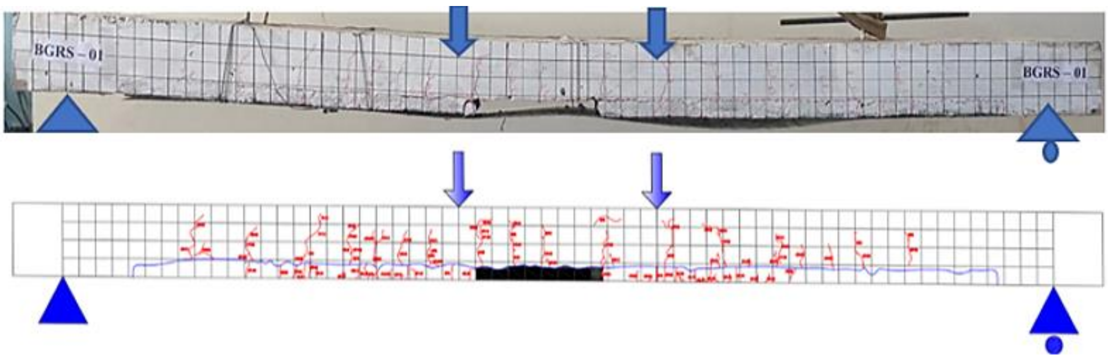



**Figure 14. The crack pattern of the BGRS beam**

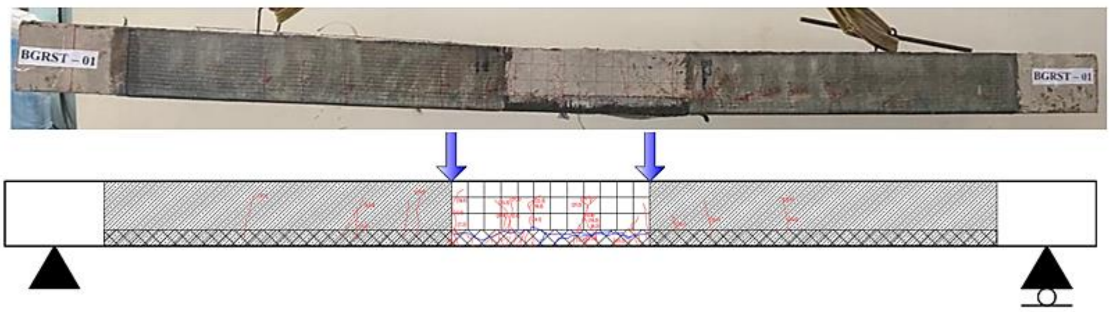



**Figure 15. The crack pattern of the BGRST beam**

Likewise, the failure modes of all the repaired BGR beams (shown in Figure 13) were mostly cracking and cold jointing at the joint bond between the old concrete and Sikagrout-215 mortar. Based on the visual observation of the specimens and the progressive load-deflection curves displayed on the monitor during the actual tests, in general, the failure of all the mortar-repaired (BGR) beams was caused by vertical cracking at the joint region at mid-span, after the yielding of the bottom steel reinforcement and before the crushing of the concrete during compression. The initial failure cracks appeared at the joint area, beginning with hairline cracks that propagated slowly vertically until they broke apart. The minimum and maximum crack lengths of 73–182 mm with a vertical direction tendency caused a crack width of

85.8 mm already at the crushing stage, so the test was stopped with the number of cracks occurring up to 38 points. Flexural fracture occurs in BGR when the load applied to the beam or structure exceeds the strength limit that the structural material can withstand. BGR beams are damaged or broken in the bending section or around the point of the applied load. BGR beams that have experienced flexural fractures can no longer be trusted to withstand the loads applied to the structure.

Based on observations during the test, Figure 14 shows that in the failure mode in the BGRS beam, a vertical crack extends from the tensile side and leads upwards to the neutral axis area at the initial loading. The reinforcement melts, which causes the crack to increase in length and width. The detachment of the attachment between the GFRP and the concrete surface (debonding) starts in the middle of the span and is then followed by cracks in the grouting connection. When the GFRP sheet debonding occurred, the load decreased drastically; shortly after, the concrete collapsed on the compressive side. During loading capacity testing, a loud sound was heard on the BGRS beam like a punch, indicating the release of the GFRP sheet bond and cracks in the concrete joints—material fatigue caused by the continuous load applied to the beam. With a crack length of 75–173 mm in the test beam and a maximum width of 35.7 mm, it is enough to endanger the structure that continues to be loaded until it is destroyed. If the beam is continuously loaded and there is no strong bond between concrete and GFRP, the GFRP material and concrete can fatigue and weaken so that debonding can occur [15].

In the case of BGRST, the crack properties resembled RC control and BGRS beams with vertical hairline cracks (shown in Figure 15) but splice cracks at midspan. BGRST showed 19 visible cracks until failure, a value generally lower than the two repaired RC beams. Regarding the crack length of the BGRST beams, Table 6 shows that the corresponding values range between 55 and 153 mm and are in the middle of the values of the control specimens. The effectiveness of using GFRP sheets to protect the damaged beams from possible re-damage can be seen from the reduced number of cracks in the concrete layer, as shown in Table 6. It can be seen that the number of concrete cracks occurring in the other variation beams is higher than that of the BGRST beams, with a 40% reduction in the number of cracks with beam reinforcement at the support area, indicating the effectiveness of GFRP sheets in suppressing crack development at critical beam conditions. The crack direction also appears to propagate smoothly in the GFRP layer from the bottom to the top concrete section, as shown in Figure 15. In general, all specimens' repair and reinforcement configurations showed weaknesses in the bond between the Sikagrout-215 mortar reinforcement layer and the old concrete surface, which all developed cracks. Still, the GFRP reinforcement minimized the number of cracks and crack widths [26, 27].

## 4. Conclusions

This study investigated the flexural behavior of RC beams repaired using Sikagrout-215 and reinforced with GFRP sheets using different coating configurations. All beams subjected to flexural failure, consisting of three RC beams coated with Sikagrout-215 mortar, six RC beams reinforced with GFRP, and three control beams, underwent four-point flexural tests to determine loading performance, crack response, ductility, and energy absorption capacity. The following are the conclusions obtained from the experimental and analytical results.

The 38.5% reduction in reinforcement due to corrosion significantly reduces the beam's capacity to carry loads. Repair grouting (BGR) decreased by 48.5% against the control beam; reinforcement with mortar grouting and GFRP sheet (BGRS) as repair and reinforcement material was able to increase the maximum load of reinforced concrete beams by 6.5%; and reinforcement at the support area (BGRST) was able to restore the maximum service function of the beam by 9.3% even though the beam was in critical condition. Although 50-mm-thick grouting of the RC beam was performed, it did not show ductility and toughness comparable to the control beam. Still, treatment with BGRST caused the ductility to increase by 0.8% and increased the energy absorption value of the initial RC beam by 31%.

The three reinforcement systems used, the BGRST type is more significant in improving the first crack, yield, and ultimate response performance of the initial RC beam. In addition, the BGRST type is also more effective in reducing the number of cracks by 27% than the number of cracks in the control beam. Fracture of beams was more common in reinforcements made with Sikagrout-215 mortar mix. Most of the beams did not bear any load after the fracture. However, the fracture was softer in the reinforcement made with GFRP composites, and it was seen that the beams had partially protected the load capacity after the fracture.

## 5. Declarations

### 5.1. Author Contributions

Conceptualization, A.Z.N. and R.D.; methodology, H.P. and R.I.; software, A.Z.N.; validation, R.D. H.P., and R.I.; formal analysis, A.Z.N.; investigation, A.Z.N.; resources, A.Z.N.; data curation, A.Z.N.; writing—original draft preparation, A.Z.N.; writing—review and editing, A.Z.N.; visualization, A.Z.N.; supervision, R.D. H.P., and R.I.; project administration, A.Z.N.; funding acquisition, A.Z.N. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data presented in this study are available in article.

### 5.3. Funding and Acknowledgements

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### 5.4. Conflicts of Interest

The authors declare no conflict of interest.

## 6. References


[1] Yang, J., Haghani, R., Blanksvärd, T., & Lundgren, K. (2021). Experimental study of FRP-strengthened concrete beams with corroded reinforcement. Construction and Building Materials, 301. doi:10.1016/j.conbuildmat.2021.124076.

[2] Ganesh, P., & Murthy, A. R. (2019). Repair, retrofitting and rehabilitation techniques for strengthening of reinforced concrete beams - A review. Advances in Concrete Construction, 8(2), 101–117. doi:10.12989/ACC.2019.8.2.101.

[3] Ferrari, V. J., De Hanai, J. B., & De Souza, R. A. (2013). Flexural strengthening of reinforcement concrete beams using high performance fiber reinforcement cement-based composite (HPFRCC) and carbon fiber reinforced polymers (CFRP). Construction and Building Materials, 48, 485–498. doi:10.1016/j.conbuildmat.2013.07.026.

[4] Gergess, A. N., Shaikh Al Shabab, M., & Massouh, R. (2020). Repair of Severely Damaged Reinforced Concrete Beams with High-Strength Cementitious Grout. Transportation Research Record, 2674(6), 372–384. doi:10.1177/0361198120919116.

[5] Chalioris, C. E., Kytinou, V. K., Voutetaki, M. E., & Papadopoulos, N. A. (2019). Repair of heavily damaged RC beams failing in shear using U-shaped mortar jackets. Buildings, 9(6), 146. doi:10.3390/BUILDINGS9060146.

[6] Alwash, N. A., Kadhum, M. M., & Mahdi, A. M. (2019). Rehabilitation of corrosion-defected RC beam-column members using patch repair technique. Buildings, 9(5), 120. doi:10.3390/buildings9050120.

[7] Machmud, H., Tjaronge, M. W., Djamaluddin, R., & Irmawaty, D. R. (2019). The Capacity of Reinforced Concrete Beams Post Rebars Yielded with FRP Sheet Strengthening. International Journal of Civil Engineering and Technology, 10(9), 232-241.

[8] Djamaluddin, R., Irmawaty, R., & Tata, A. (2016). Flexural capacity of reinforced concrete beams strengthened using GFRP sheet after fatigue loading for sustainable construction. Key Engineering Materials, Trans Tech Publications Ltd., 692, 66–73. doi:10.4028/www.scientific.net/KEM.692.66.

[9] Saribiyik, A., & Caglar, N. (2016). Flexural strengthening of RC beams with low-strength concrete using GFRP and CFRP. Structural Engineering and Mechanics, 58(5), 825–845. doi:10.12989/sem.2016.58.5.825.

[10] Goyal, A., Pouya, H. S., Ganjian, E., & Claisse, P. (2018). A Review of Corrosion and Protection of Steel in Concrete. Arabian Journal for Science and Engineering, 43(10), 5035–5055. doi:10.1007/s13369-018-3303-2.

[11] Ortega, I., Pellicer, T. M., Calderón, P. A., & Adam, J. M. (2018). Cement-based mortar patch repair of RC columns. Comparison with all-four-sides and one-side repair. Construction and Building Materials, 186, 338–350. doi:10.1016/j.conbuildmat.2018.07.148.

[12] Pineda, P., García-Martínez, A., & Castizo-Morales, D. (2017). Environmental and structural analysis of cement-based vs. natural material-based grouting mortars. Results from the assessment of strengthening works. Construction and Building Materials, 138, 528–547. doi:10.1016/j.conbuildmat.2017.02.013.

[13] Masoud, S., & Soudki, K. (2006). Evaluation of corrosion activity in FRP repaired RC beams. Cement and Concrete Composites, 28(10), 969–977. doi:10.1016/j.cemconcomp.2006.07.013.

[14] Yousefi Moghadam, S., Ranjbar, M. M., Madandoust, R., & Kazemi, M. (2017). Analytical study on the behavior of corrosion-damaged reinforced concrete beams strengthen with FRP. Revista Romana de Materiale, 47(4), 514-521.

[15] Djamaluddin, R., & Irmawaty, R. (2017). Relationship Model of the Moment Capacity of GFRP Sheet Strengthened RC Beams to the Duration of Sea Water Exposure. Procedia Engineering, 180, 1195–1202. doi:10.1016/j.proeng.2017.04.280.

[16] Sultan, M. A., & Djamaluddin, R. (2017). Effect of Sea Water Soaking on the Adhesion Capacity of GFRP-Sheet in Reinforced Concrete Beams. Jurnal Teknik Sipil, 24(1), 35–42. doi:10.5614/jts.2017.24.1.5.

[17] Almusallam, T. H. (2006). Load-deflection behavior of RC beams strengthened with GFRP sheets subjected to different environmental conditions. Cement and Concrete Composites, 28(10), 879–889. doi:10.1016/j.cemconcomp.2006.07.017.

[18] Idris, M., Parung, H., & Djamaluddin, R. (2019). Flexural Behavior of Shear-Cracked Reinforced Concrete Beam Strengthened with GFRP Sheet. International Journal of Civil Engineering and Technology, 10(10), 64-72.

[19] Attari, N., Amziane, S., & Chemrouk, M. (2012). Flexural strengthening of concrete beams using CFRP, GFRP and hybrid FRP sheets. Construction and Building Materials, 37, 746–757. doi:10.1016/j.conbuildmat.2012.07.052.

[20] Guades, E. J., Stang, H., Schmidt, J. W., & Fischer, G. (2021). Flexural behavior of hybrid fiber-reinforced geopolymer composites (FRGC)-jacketed RC beams. Engineering Structures, 235. doi:10.1016/j.engstruct.2021.112053.

[21] Solahuddin, B. A., & Yahaya, F. M. (2023). A state-of-the-art review on experimental investigation and finite element analysis on structural behavior of fiber reinforced polymer reinforced concrete beams. Heliyon, 9(3), 14225. doi:10.1016/j.heliyon.2023.e14225.

[22] Faroz, S. A., Ghosh, S., & Pushkaran, T. (2023). Optimum calibration of a corrosion rate instrument using information gain criterion within a Bayesian framework. Structural Safety, 104. doi:10.1016/j.strusafe.2023.102354.

[23] Özakça, M., Hind, M. K., & Ekmekyapar, T. (2016). A Review on Nonlinear Finite Element Analysis of Reinforced Concrete Beams Retrofitted with Fiber Reinforced Polymers. Journal of Advanced Research in Applied Mechanics, 22(1), 13-48.

[24] Makhlouf, M. H., & Mansour, M. H. (2023). Efficiency of innovative strengthening techniques and anchorage systems using different materials on flexure performance of R.C beams. Case Studies in Construction Materials, 18. doi:10.1016/j.cscm.2022.e01733.

[25] Zhang, X., Zhang, Y., Liu, B., Liu, B., Wu, W., & Yang, C. (2021). Corrosion-induced spalling of concrete cover and its effects on shear strength of RC beams. Engineering Failure Analysis, 127, 105538. doi:10.1016/j.engfailanal.2021.105538.

[26] Naser, M. Z., Hawileh, R. A., & Abdalla, J. A. (2019). Fiber-reinforced polymer composites in strengthening reinforced concrete structures: A critical review. Engineering Structures, 198, 109542. doi:10.1016/j.engstruct.2019.109542.

[27] Napoli, A., Bank, L. C., Brown, V. L., Martinelli, E., Matta, F., & Realfonzo, R. (2013). Analysis and design of RC structures strengthened with mechanically fastened FRP laminates: A review. Composites Part B: Engineering, 55, 386–399. doi:10.1016/j.compositesb.2013.06.038.