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# Investigation of RC beams characteristic strengthened with different composite materials

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***Abstract***

*The current study discusses the use of externally bonded reinforcing as a method for strengthening reinforced concrete (RC) elements. While this method has shown promise, it has limitations such as rapid failure, high cost, and time-consuming installation. As an alternative, mechanical fixed aluminum plates are proposed, which offer durability and ductility while addressing some of these limitations. The experiment involved manufacturing thirteen RC beams, with one beam left un-strengthened and the others strengthened using externally bonded plates and sheets of fiber-reinforced polymer (FRP) with varying layers, arrangement, and quantity of epoxy. The results showed that all the samples with mechanical fixed plates and FRP sheets exhibited increased strength and ductility compared to the un-strengthened sample. The combination of epoxy and bolt anchors was found to be an effective technique for enhancing the durability and ductility of RC beams reinforced with aluminum plates and FRP sheets. This alternative method without bolt anchors provides a promising approach for strengthening RC elements and overcoming the limitations associated with externally bonded reinforcing.*

***Keywords: Flexural strength, Reinforced concrete, Composite materials, Laminates***

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## I. Introduction

Currently, there is a growing need to reinforce or upgrade concrete buildings due to various reasons such as natural disasters, human error, changing operational requirements, and the need for increased safety. Several conventional techniques are available for reinforcing buildings, including the use of an expanded section, externally joined steel plates, concrete blasting, and external prestressing techniques. These methods aim to enhance the structural integrity and safety of concrete structures [1]. There is a rising demand for the immediate reinforcement of concrete structures. This need for strengthening arises from various factors and requirements [2]. Over the past two decades, there has been a global focus on studying and applying fiber-reinforced polymer (FRP) as a reinforcing material for concrete structures. During this period, an expanding number of researchers have shown interest in using FRP as a reinforcement material [3,4]. There has been a growing interest in the concept of creating a hybrid composite by combining multiple strengthening bars to achieve a bilinear stress-strain relationship. By incorporating both FRP and steel reinforcements, the durability of concrete beams can be enhanced. This approach offers the potential to improve the structural performance and longevity of reinforced concrete elements [5,6]. The use of FRP in reinforced concrete structures has shown improved flexibility and durability. However, FRP-reinforced concrete can be susceptible to brittle fracture. Recent research has focused on enhancing the flexural stiffness and durability of RC elements by incorporating efficient fiber concrete and other strengthening materials in combination with FRP. This approach aims to address the brittleness of FRP-reinforced concrete and further improve the performance of RC structures [7,8,9,10,11]. Rasheed et al. (2017) used lightweight aluminum alloy plates to strengthen RC beams under flexure for the initial time. The researchers tested various beams that were reinforced with externally bonded aluminum alloy (AA) plates, some with extremity U-wraps or anchors and some without. The beams underwent four-point bending tests. The results of their study showed that the RC beams reinforced with aluminum alloy plates exhibited a 40% improvement in capacity compared to beams reinforced with FRP laminates. Additionally, the reinforced concrete beams displayed significant yielding and strain hardening before cracking, indicating enhanced ductility and toughness [12]. The emergence of high tensile construction adhesives has contributed to the increasing popularity of FRP laminates and sheeting for reinforced concrete constructions. FRP has become the preferred material for strengthening RC structures, surpassing the use of steel plates. This is due to several advantages offered by FRP, such as superior mechanical properties, corrosion resistance, reduced maintenance costs, compact size, ease of handling, high stiffness-to-weight ratio, and straightforward installation process. These factors have made FRP a highly efficient and desirable material for reinforcing concrete structures [13,14,15,16]. El-Meddawy (2014) investigated the installation of twisted anchor bolts (TAB), powder-actuated fastened (PAF), and expanding anchor bolts (EAB) in MF-FRP components. The results showed that the retrofitting samples using EAB and TAB in MF were significantly more effective in improving the bending strength of RC beams compared to those using PAF. Specifically, the EAB anchoring system exhibited notable ductility when compared to the TAB and PAF reinforced MF samples. The RC beams retrofitted with EAB experienced a combination of concrete crushing and steel yielding until an immediate bearing failure occurred on the FRP plates within the EAB. This finding suggests that the mechanical properties of the composite material were effectively utilized during all loading phases [17]. In this research, various materials made of composites, including aluminum plates, steel plates, CFRP sheets, and GFRP sheets, were used to reinforce RC beams. The beams selected for reinforcement were those that exhibited precracked regions and required restoration. The study aimed to investigate the failure mechanisms and analyze the flexural behavior of the reinforced or restored beams.

## II. Experimental Program

The testing program involved thirteen reinforced concrete beams with rectangular cross-sections. The beams had a length of 120 mm, width of 300 mm, and a clear span of 1400 mm as shown in Figure 1. One of the beams served as a control beam, while the other beams were repaired and strengthened using different composite materials. The tension reinforcement for all the specimens consisted of two steel bars with diameters of 12 mm, while the compression reinforcement used two steel bars with diameters of 10 mm. To prevent shear failure, stirrups with a diameter of 8 mm were provided at a specified spacing of 100 mm. The span effective depth ratio was 1.96. Four-point static loads were applied to the tested beams during the experiments. The concrete used for casting the specimens had a compressive strength of 25 MPa. The experimental variables of the test specimens included the type of repair, whether it was laminate only or FRP with laminate, the materials used for repair, the number of layers strengthened, the thickness of the layers, and the conditions of fixing.

The beams were divided into three groups: Group I, Group II, and Group III. Group I consisted of four beams (SB2, SB3, SB4, and SB9) repaired with a single layer. Different materials were used for repair, including steel laminate, aluminum laminate, carbon fiber-reinforced polymer (CFRP) with a U-shape, and glass fiber-reinforced polymer (GFRP) with a U-shape. Beams SB2 and SB3 were repaired using both chemical and mechanical techniques, while beams SB4 and SB9 were repaired using chemical techniques only. Group II comprised four beams (SB5, SB7, SB10, and SB12) repaired with different materials, including CFRP sheets with steel laminate, CFRP sheets with aluminum laminate, GFRP sheets with steel laminate, and GFRP sheets with aluminum laminate. These beams were repaired using both chemical and mechanical techniques. Group III consisted of four beams (SB6, SB8, SB11, and SB13) repaired with two layers of different materials. The materials used were two CFRP sheets with steel laminate, two CFRP sheets with aluminum laminate, two GFRP sheets with steel laminate, and two GFRP sheets with aluminum laminate. These beams were also repaired using both chemical and mechanical techniques. Table 1 provides further details on the methods used for repairing the RC specimens while Table 2 shows Mechanical properties of the materials used for strengthening the beams.

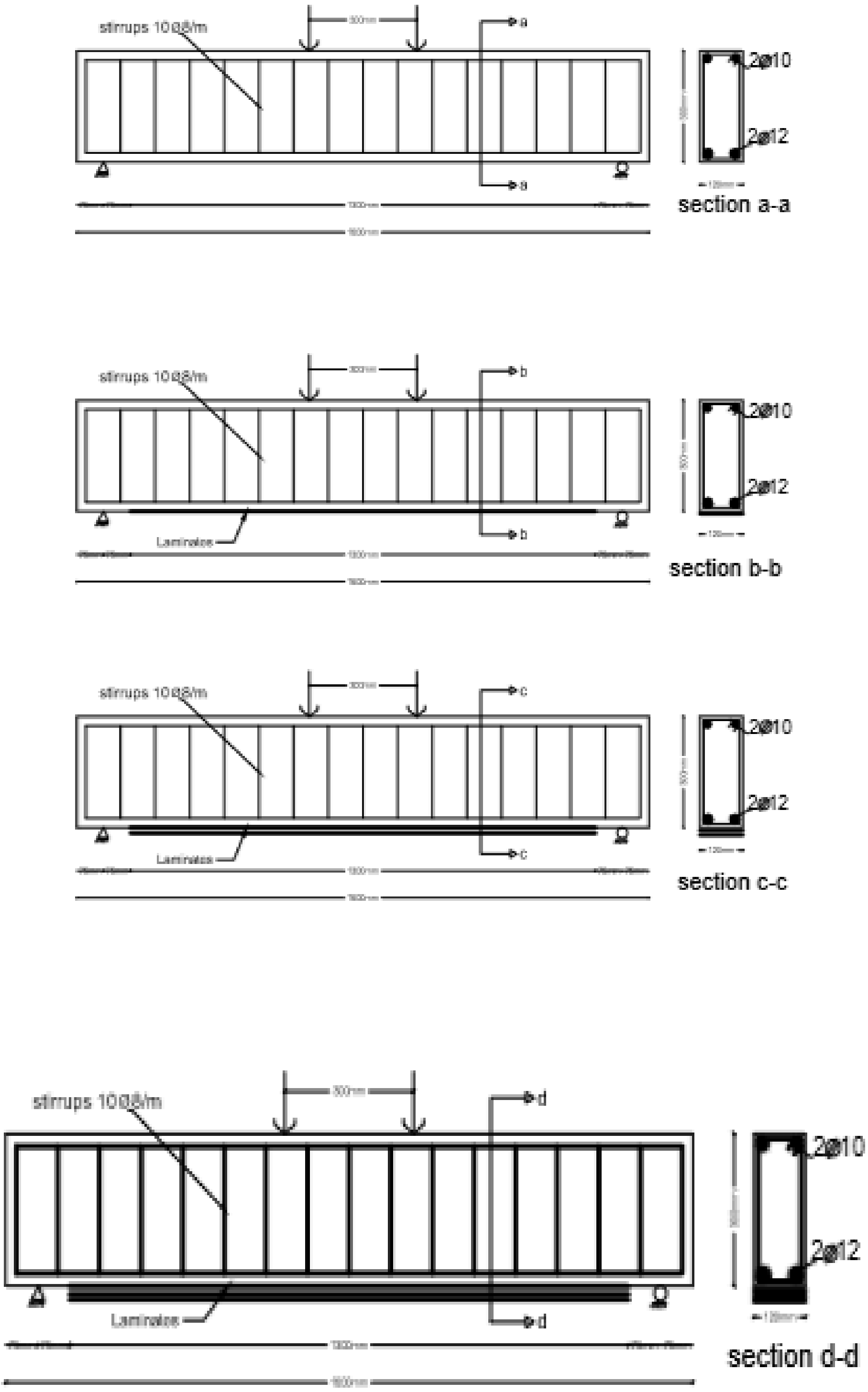


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**Figure 1:** (a) SB1, (b) group (I), (c) group (II) and (d) group (III)

| Repairing with one layer |
|---|
| Steel Laminate |
| Alumnuim Laminate |
| CFRP |
| GFRP |

| Repairing with two layers |
|---|
| CFRPST |
| GFRPST |
| CFRPAL |
| GFRPAL |

| Repairing with three layers |
|---|
| TCFRPST |
| TGFRPST |
| TCFRPAL |
| TGFRPAL |

**Table 1: Methods for strengthening the reinforced concrete beams**

| Number of groups | Specimens | Considered Parameters | Type of repaired | Number of layers | Thickness of layers (mm) | Type of fixing |
|---|---|---|---|---|---|---|
| | SB1 | | | | | |
| I | SB2 | Laminate | ST | One layer | 2 | E./A. |
| | SB3 | Laminate | AL | | 2 | E./A. |
| | SB4 | FRP | CFRP | | 0.129 | E. |
| | SB9 | FRP | GFRP | | 0.508 | E. |
| II | SB5 | FRP+Laminate | CFRPST | Two layers | 2.129 | E./A. |
| | SB7 | FRP+Laminate | CFRPAL | | 2.129 | E./A. |
| | SB10 | FRP+Laminate | GFRPST | | 2.508 | E./A. |
| | SB12 | FRP+Laminate | GFRPAL | | 2.508 | E./A. |
| III | SB6 | FRP+Laminate | TCFRPST | Three layers | 2.258 | E./A. |
| | SB8 | FRP+Laminate | TCFRPAL | | 2.258 | E./A. |
| | SB11 | FRP+Laminate | TGFRPST | | 3.016 | E./A. |
| | SB13 | FRP+Laminate | TGFRPAL | | 3.016 | E./A. |

SB = Specimen beam, SB C = Control, SB ST= Steel plate, SB AL=Aluminum laminate, SB CFRP=Carbon Fiber Reinforced Polymer, SB CFRPST = Carbon fiber with Steel plate, SB TCFRPST = two layers of carbon fiber with Steel plate, SB GFRPST= Glass fiber with Steel plate, SB CFRPAL = Carbon fiber with Aluminum laminate, SB TCFRPAL= two layers of carbon fiber with Aluminum laminate, SB GFRP= Glass fiber, SB GFRPST= Glass fiber with Steel plate, SB TGFRPST= two layers of Glass fiber with Steel plate.

(a) E. = Epoxy, (b) A. = Anchors

**Table 2: Mechanical properties of the materials used for strengthening the beams**

| properties | Aluminum | Steel | CFRP | GFRP |
|---|---|---|---|---|
| Ultimate strength (MPa) | 105 | 420 | 3500 | 537 |
| Yield strength (MPa) | 25 | 350 | | |
| Elastic modulus (GPa) | 69 | 200 | 220 | 70 |
| Thickness (mm) | 2 | 2 | 0.129 | 0.508 |
| Elongation (%) | 15 | 10 | 1.59 | 2.8 |

### 2.1 Material characteristics

#### 2.1.1 mix of concrete

All beams were constructed using concrete with an average compressive strength of 250 kg/cm2. The specific components of the concrete mix are shown in Table 3.

**Table 3: Mixture components for concrete specimens**

| Cement Kg/m$^3$ | gravel Kg/m$^3$ | Sand Kg/m$^3$ | Water L/m3 | Compressive (strength (MPa |
|---|---|---|---|---|
| 350 | 1200 | 600 | 170 | 37.33 |

**2.1.2 Cement**
The concrete mix used in this study consisted of ordinary Portland cement (CEM I (32.5 N)) from the Beni Suef manufacturer. The cement had specific characteristics, including a surface area of 3200 cm2/gm, a specific gravity of 3.15, and a compressive strength of 400 kg/cm2 after 28 days.
**Aggregates 2.1.3**
The coarse aggregate used in this study was sourced from nearby quarries and underwent examination to determine its characteristics. The aggregate had a maximum normal size of 20 mm, a specific gravity of 2.5, and a volume weight of 1.65 (t/m3). Additionally, all of the fine aggregate used in the concrete mix was obtained from nearby quarries, with a specific gravity of 2.58 and a volume weight of 1.79 (t/m3).
**The reinforcement 2.1.4**
The reinforcement used in this study included high tensile steel for tensile reinforcement and mild steel bars for stirrups. The mechanical properties of the steel bars are shown in Table 4.

**Table 4: Mechanical properties of the steel bars**

| Type | (Diameter (mm | Yield Strength ((N/mm$^2$ | (Ultimate Strength (N/mm$^2$ |
|---|---|---|---|
| | 12 | 588 | 685 |
| Bars | 10 | 469 | 554 |
| | 8 | 306 | 412 |

**2.1.5 Epoxy adhesives**
Two epoxy adhesives were used in the strengthening process. The first one was KEMAPOXY 165, which is a two-component solution with a medium viscosity. It is solvent-free and prepared using modified epoxy resin and a compatible hardening system. The second one was Sikadur-330, which is a thixotropic epoxy-based impregnating resin and adhesive. It is also a two-component product.

**2.2 Manufacturing of test specimens**
Composite materials were prepared using aluminum laminates with one layer of CFRP/GFRP and steel plates with one layer of CFRP/GFRP. The aluminum laminates and steel plates had a uniform shape, with a length of 1300 mm and a width of 120 mm for CFRP/GFRP a hon in Figures 2,3. In the case of the reinforced concrete beam (SB ST), the steel plate was attached to the bottom of the beam using five anchors and epoxy resin after the beam was cast. The same process was followed for the aluminum laminate beam (SB AL). The anchors were positioned on the tension side of the beams, and five anchors were used for each beam. The beams were strengthened using a mechanical method, and Kemapoxy 165 was applied to the bottom surface of the beam after cleaning the retrofitted faces. On the other hand, beams labeled as SB CFRP and SB GFRP were strengthened with a U-shape of CFRP/GFRP using sikadur330, as depicted in Figure --------. There were two additional types of beams, SB TCFRPST and SB TGFRPST, which were strengthened with three layers of composite materials. These three layers consisted of one layer of aluminum laminates and two layers of CFRP/GFRP.

**2.3 Industrial of test specimens**
In this study, different strengthening techniques were applied to reinforced concrete beams. In the case of beam (SB ST), a steel plate was attached to the bottom of the beam using five bolts and kimapoxy165 after the concrete beam had been cast. Beam (SB AL) underwent a similar strengthening process as beam (SB ST) but with the use of an aluminum plate. For beam (SB CFRP) and beam (SB GFRP), a U-shape configuration was employed, as depicted in Figure --------. Sikadur330 was used as the adhesive, and the length of the U-shape laminates was 500 mm, while the width was 120 mm. Beams (SB CFRPST), (SB TCFRPST), (SB CFRPAL), and (SB TCFRPAL) were prepared by layering composite material laminates without the use of adhesive sikadur330. These laminates were then strengthened on the tension face of the beams using five anchors at equal distances. The same procedure was followed for beams (SB GFRPST), (SB TGFRPST), (SB GFRPAL), and (SB TGFRPAL), but glass fibers (GFRP) were used instead of carbon fibers (CFRP) for reinforcement.

**Figure 2: laminates that used to strengthen of (SB4 CFRP) and (SB9 GFRP) beams**

**Figure 3: laminates that used to strengthen of beams**

**2.4 Testing techniques and instrumentation**

Experimental testing was conducted in the materials lab at Faculty of Engineering, Minia University. A universal testing machine, as shown in Figure 4, was utilized for the testing process. The specimens were aged for 28 days before subjecting them to a consistently increasing two-point static load. Strain measurements on the tensile steel reinforcements and steel plates were taken using electrical strain gauges, while mid-span deflection was measured using linear variable differential transformers. Pie gauges were placed at the center of each test specimen to measure the width of flexural cracks. A data logger was connected to the pie gauges, displacement transducers, and electrical resistance strain gauges. Throughout the loading process, the development and propagation of cracks were observed, noted, and recorded.

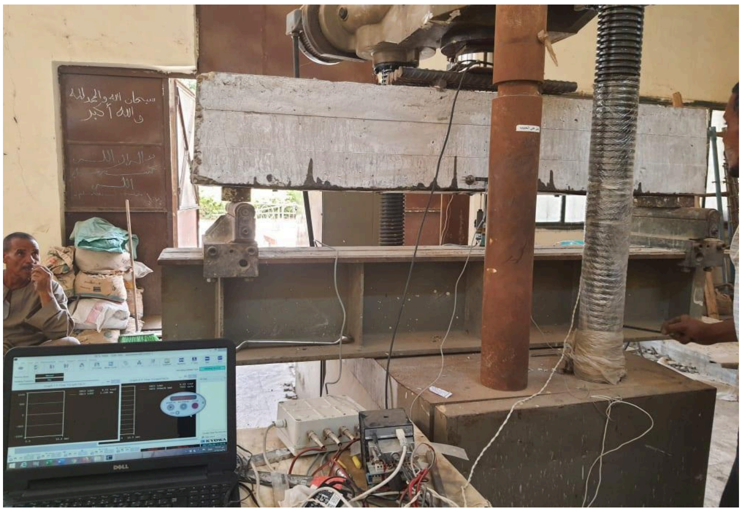

**Figure 4: Universal testing machine**

## III. Results and Discussion

The study assessed the impact of different composite materials on the bending strength of the tested beams. The deflections and cracking patterns were observed as the load increased until failure. A comparison was made between the results of the control beam and RC beams with higher strength. It was found that all the RC beams had a greater load capacity compared to the control beam. The evaluation demonstrated the positive effect of the composite materials on enhancing the overall strength of the beams

### 3.1 Failure Load

Table 5 shows the analysis of various parameters for the investigated RC beams, including the first cracked load (Pcr), the yield load of the longitudinal reinforcing bars (Py), and the ultimate load (Pu) at failure. The ultimate loads of the beams were measured and compared to assess the effectiveness of different composite materials, as shown in Figure 10.

In group I, the failure loads for RC beams SB ST, SB AL, SB CFRP, and SB GFRP were compared to the control beam SB C, resulting in increases of 22%, 14%, 11%, and 11%, respectively. In group II, the failure loads for RC beams SB CFRPST, SB CFRPAL, SB TCFRPST, and SB TCFRPAL were compared to the control beam SB C, resulting in 0%, 11%, 14%, and 10%, respectively. In group III, the failure loads for RC beams SB TCFRPST, SB TCFRPAL, SB TGFRPST, and SB TGFRPAL were compared to the control beam SB C, resulting in 0%, 11%, 14%, and 10%, respectively.

The results indicate that the inclusion of two layers with an Aluminum laminate had a positive impact on increasing the performance of the beams. Specifically, the utilization of Aluminum laminate improved the flexural strength of the RC beams.

**Table 5: Test results of RC beams**

| specimen | $P_{cr}$ (KN) | $P_y$ (KN) | $P_U$ (KN) | $\Delta_y$ (mm) | $\Delta_u$ (mm) | $\Delta_u/\Delta_y$ | Failure Modes |
|---|---|---|---|---|---|---|---|
| SB1C | 39.23 | 114.51 | 139.59 | 6.47 | 26.51 | 4.10 | cc |
| SB2 ST | 44.13 | 147.28 | 170.67 | 4.75 | 12.04 | 2.53 | cc-Debonding |
| SB3 AL | 29.42 | 142.42 | 159.65 | 4.84 | 14 | 3.11 | cc- Al. rupture |
| SB4 CFRP | 34.32 | 142.82 | 154.26 | 4.70 | 19.63 | 4.18 | cc-CFRP rupture |
| SB5 CFRPST | 29.42 | 104.19 | 140.14 | 2.95 | 9.03 | 3.06 | Debonding-ccs |
| SB6 CFRPAL | 39.23 | 143.14 | 154.86 | 4.93 | 4.53 | 4.13 | cc-Debonding-ccs |
| SB7TCFRPST | 39.23 | 126.28 | 159.64 | 4.29 | 21.69 | 5.06 | cc-Debonding-ccs |
| SB8TCFRPAL | 29.42 | 135.67 | 166.63 | 5.61 | 25.63 | 4.57 | cc-Debonding-ccs |
| SB9GFRP | 39.23 | 140.39 | 155.06 | 5.25 | 19.63 | 3.74 | cc |
| SB10GFRPST | 39.23 | 147.01 | 159.09 | 5.41 | 24.72 | 4.57 | Debonding-ccs |
| SB11GFRPAL | 39.23 | 147.84 | 153.70 | 4.11 | 10.03 | 2.44 | cc-Debonding-ccs |
| SB12TGFRPST | 39.23 | 128.80 | 155.17 | 5.47 | 10.95 | 2.00 | cc-Debonding-ccs |
| SB13TGFRPAL | 39.23 | 137.50 | 159.67 | 4.74 | 10.68 | 2.25 | cc-Debonding-ccs |

cc= concrete crushing, ccs= concrete cover separation

**3.2 Failure mode and pattern of cracks**

The cracking patterns of the tested beams were investigated until failure, and the results are shown in Figures 5. The first cracks appeared in beam SB when it was loaded at around 28% of its maximum load. In group I, the first cracks appeared at 26%, 18%, 22%, and 25% of the failure load for RC beams SB ST, SB AL, SB CFRP, and SB GFRP, respectively. In group II, the first cracks appeared at 21%, 25%, 25%, and 26% of the failure load for RC beams SB CFRPST, SB CFRPAL, SB GFRPST, and SB GFRPAL, respectively. In group III, the first cracks appeared at 25%, 18%, 25%, and 25% of the failure load for RC beams SB TCFRPST, SB TCFRPAL, SB TGFRPST, and SB TGFRPAL, respectively. The majority of cracks on the tension surface of all beams initially formed under the applied loads. The experimental results revealed that the use of glass fiber-reinforced polymer (GFPP) prevented debonding of laminates. However, when a carbon fiber-reinforced polymer (CFRP) sheet was used in RC beam SB CFRP, the opposite result was observed, indicating debonding of the laminate. Fortunately, the failure mode for RC beams SB CFRPST, SB CFRPAL, SB GFRPST, SB GFRPAL, SB TCFRPST, SB TCFRPAL, SB TGFRPST, and SB TGFRPAL was laminating debonding and separation of the concrete cover.

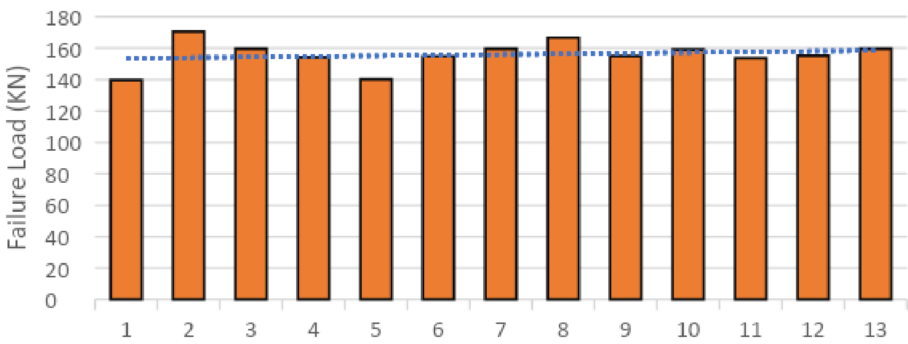


**Figure 5: Failure Load for all evaluated beams**


**Figure 6: Failure mode and pattern of cracks for SBC-control beam**

**Figure 7: Failure Mode and Pattern of cracks for strengthened beams at group (l)**

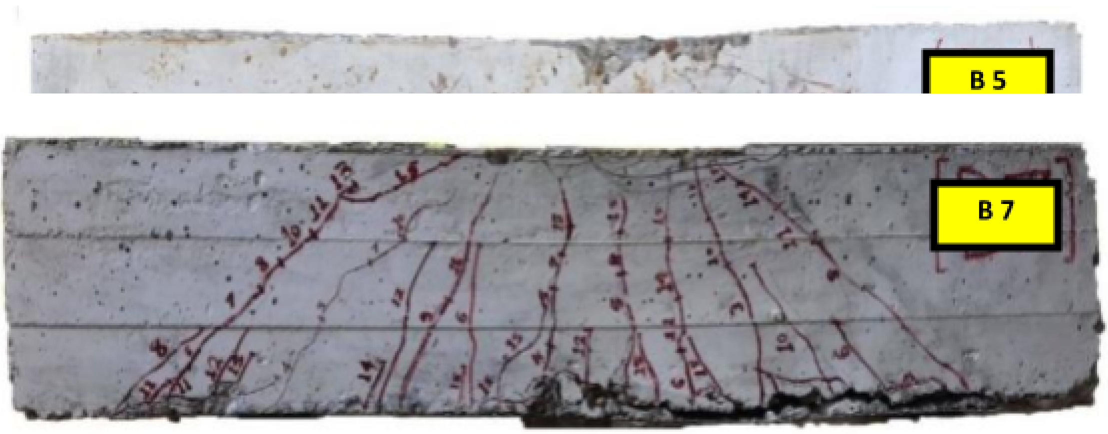


**Figure 8: Failure Mode and Pattern of cracks for strengthened beams at group (II)**

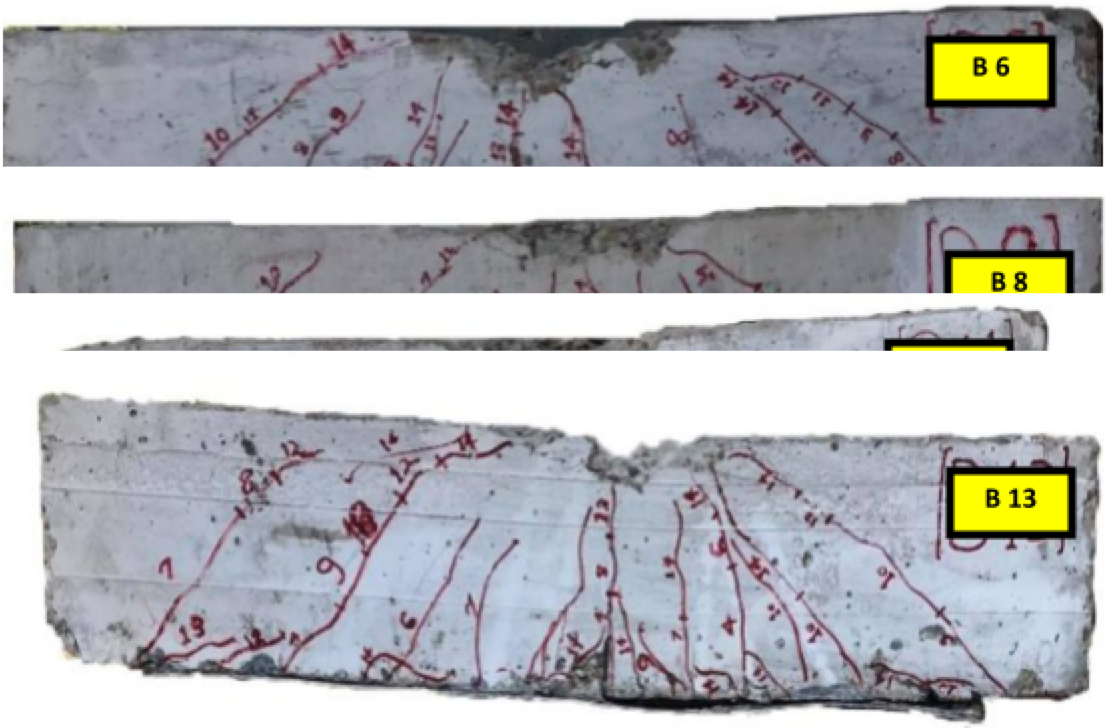


**Figure 9: Failure mode and pattern of cracks for strengthened beams at group (III)**

**3.3 Load -Deflection curves of investigated beams**

The behavior of each one of RC beams followed a linear pattern until reaching the failure load. The maximum deflection observed in the evaluation of beams SB ST, SB AL, SB CFRP, SB GFRP, SB CFRPST, SB CFRPAL, SB GFRPST, SB GFRPAL, SB TCFRPST, SB TCFRPAL, SB TGFRPST, and SB TGFRPAL was reduced by 74.05%, 34.06%, 76.73%, 93.25%, 37.83%, 81.82%, 96.68%, 52.62%, and 55.38% respectively, when compared to the control beam. The load-deflection behavior of the investigated RC beams, utilizing composite materials, is depicted in Figure 10. The graph illustrates how the addition of these materials affected the deflection under load for each beam.

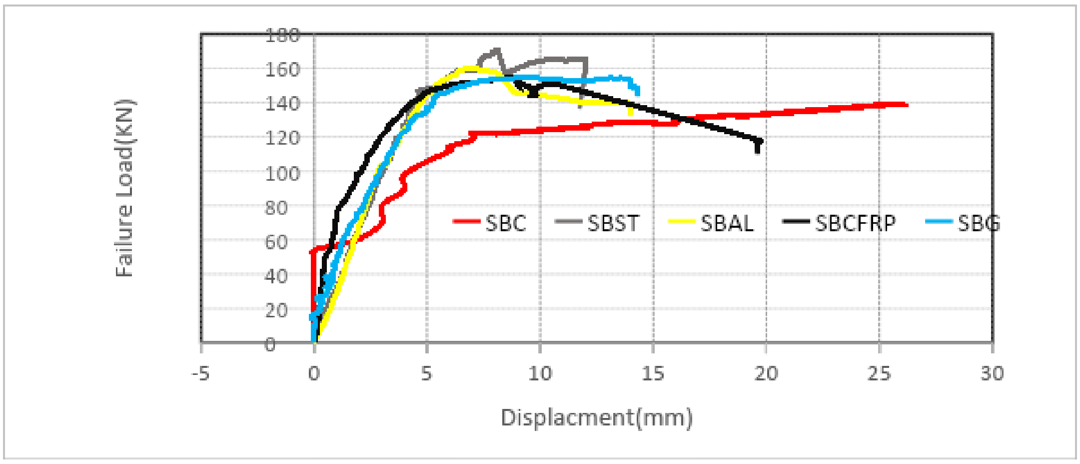


**Figure 10: Relationship between load-deflection at group (I) of evaluated beams**

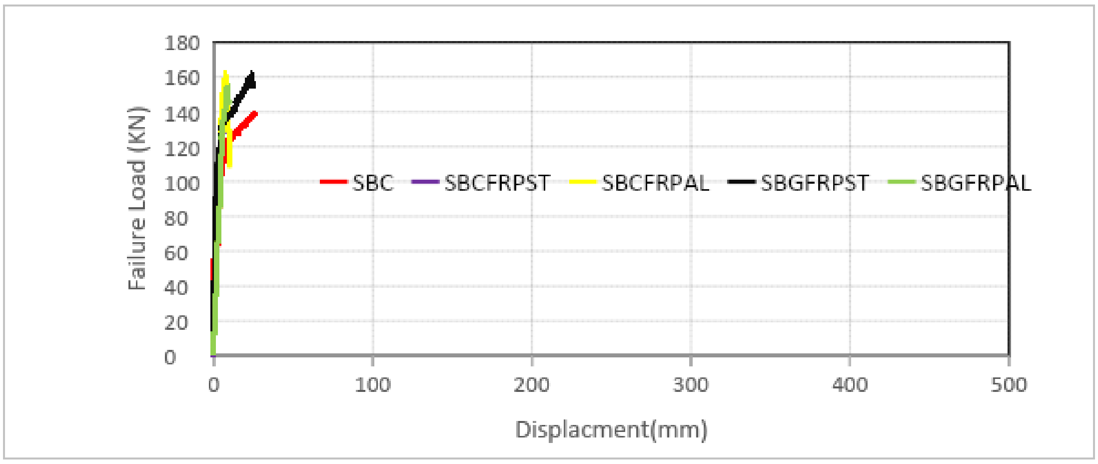


**Figure 11: Relationship between load-deflection at group (II) of evaluated beams**

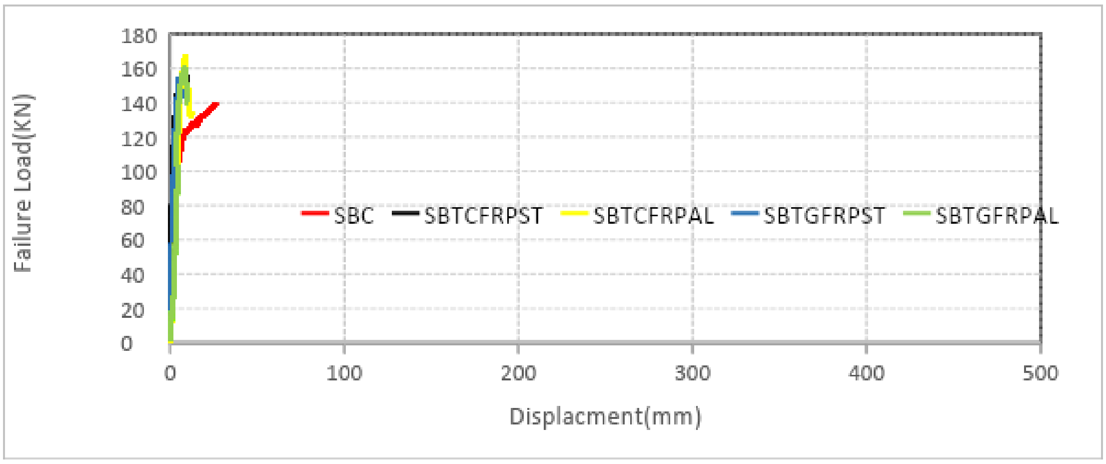


**Figure 12: Relationship between load-deflection at group (III) of evaluated beams**

## IV. Conclusions

The key findings of the current study focused on the influence of fibers on the flexural strength of concrete. The investigation yielded the following results:
1. The addition of one layer of aluminum plate with two layers of carbon fiber sheets (CFRP) improved the load-bearing capacity of the beams by 30% compared to the control beam, while also enhancing ductility.
2. The use of anchors with epoxy adhesive further improved the performance and load-bearing capacity of the strengthened beams. The selection of anchor length and diameter was crucial based on the cross-sectional measurement of the beams.
3. The interaction between the pre-drilled construction gaps and the outer layers of composite materials played a significant role in preventing sudden failures in beams strengthened solely with externally attached composite systems.
4. The inclusion of fibers in concrete increased both the tensile strength and the ultimate load-bearing capacity, as well as the flexural cracking load, with an increase in the number of fibers. Layers.
5. The number and thickness of composite material layers had an impact on the displacement, flexural strength, and load-bearing capacity of the concrete elements.
6. Increasing the proportion of fibers resulted in improved maximum displacement measurements, as concrete became more elastic and fracture-resistant.
7. Aluminum plates combined with fibers exhibited higher flexibility and tensile strength, leading to greater impacts on the flexural strength, durability, and flexibility of concrete beams compared to FRP alone.

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