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Behavior of Polymer Concrete Beams Reinforced with Polymer-Based Fiber Bars

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الملخص: كثيرا ما تكون الكمرات الخرسانية المسلحة بأسياخ من الألياف الزجاجية ذات رابطة تماسك ضعيفة. مقارنة بتماسك الخرسانة مع حديد التسليح . ونتيجة لذلك ، لا يمكن الاستفادة من الاجهاد الفعلي لأسياخ الالياف الزجاجية فمن المعروف أن هذه الاسياخ تملك قوة شد اكبر بكثير من حديد التسليح . وخاصة عند عمل وصلات لحديد التسليح فإن تماسك الخرسانة مع وصلة حديد التسليح تكون اضعف ما يمكن. ولا تزال البحوث في عمل نتوءات او ترميل سطح أسياخ الفايبر لزيادة التماسك الاستفادة بأكبر قدر ممكن من قوة شد أسياخ الفايبر، ويمكن التفكير في إستخدام خرسانة بوليمرية مع أسياخ الالياف الزجاجية. وأجريت تجارب على مجموعة من كمرات الخرسانة التقليدية المسلحة بحديد التسليح ومجموعة من كمرات الخرسانة البوليمرية المسلحة بأسياخ الألياف الزجاجية ومجموعة من كمرات الخرسانة البوليمرية المسلحة بحديد التسليح، حيث تحتوى كل مجموعة على أربع عينات من الكمرات ذات أطوال وصلات مختلفة فى الشد .وتشير النتائج إلى أن كمرات الخرسانة البوليمرية ذات قوة تماسك أعلى من الخرسانة التقليدية مما يزيد من قوة تحمل الكمرات للإجهادات . وعند مقارنة العينات ذات أطوال الوصلات المختلفة ،أظهرت عينات الخرسانة البوليمرية اجهادات شد أكبر من نظيرتها من الخرسانة التقليدية.

ABSTRACT: The primary objective of this study was to evaluate the effect of fiber reinforcement bars with different development length on the behavior of polymer concrete beams. This research focused on comparing the failure modes of beams with different development lengths, types of reinforcement, and investigating the effect of adding polymers to concrete. GFRP bars were made by using a simple pultrusion process, ensuring that the fiber density was not less than 65% of the size of one bar to provide higher tensile stress. The behavior of specimens was studied under flexural failure. The first phase involved studying the behavior of GFRP bars reinforcement with conventional concrete beams with different development lengths (full bars, 200mm, 100mm, zero), the second phase involved steel bars reinforcement with polymer concrete beams, and the third phase involved GFRP bars reinforcement with polymer concrete beams with the same development lengths. Test results show that the use of GFRP bars reinforcement with polymer concrete increased the capacity of beams. Moreover, it led to benefiting from the maximum tensile strength of the GFRP bars, unlike its counterpart with conventional concrete. Additionally, in the use of polymer concrete beams reinforced with different development lengths of bars, a notable increase in the capacity of beams was observed, surpassing the theoretical failure load calculated from ACI & ECP due to the effect of the polymer on the bond.

Keywords: Reinforced polymer concrete, GFRP bars, Beams reinforced with fiber bars, Development length of reinforcement, Bond between GFRP bars and concrete beam.

1. Introduction

Concrete and steel reinforcement are among the most widely used materials in the construction industry. The most common type of concrete comprises three main ingredients: water, aggregate, and cement, which act as a binder. These components are combined in different ratios depending on the desired characteristics. Tensile strength of normal concrete is known to be weak, as well as brittle and easily erodible by chemicals and high-velocity water flow. The same applies to steel reinforcement, which is affected by rust and corrosion. This has become an ever-growing problem in today's society, with the need for minimal maintenance and longer-lasting structures. Fortunately, there is a solution to this problem: polymer concrete with fiber bars reinforcement [1,2, 3].

Reinforced concrete elements are designed to satisfy safety, serviceability, and economy. Reinforcing concrete beams with glass fiber reinforced polymer (GFRP) bars [4,5,6] is crucial nowadays for increasing strength and reducing reinforcement needs, especially in mega projects around the world that face high stress levels. However, fully utilizing the strength of fiber reinforcement proves challenging due to various failure modes between the fiber bars and conventional concrete [7]. The modes of failure in reinforced concrete beams with GFRP bars can be summarized as follows:

1- Rupture of the FRP bars in tension zone followed by concrete crushing (Brittle Failure) [8].

2- Slippage of the FRP bars from the concrete in tension zone followed by concrete crushing (Brittle Failure) [9].
3- Crushing of the concrete in compression zone before rupture or slippage of the FRP bars (Brittle Failure) [10].

2. Materials and Experimental Program

2.1 Material Properties

The test specimens used in this program were made from local materials except polymer material. Coarse and fine aggregates were composed of ordinary siliceous sand, gravel of good quality and free from injurious materials. Cement used in all specimens was ordinary Portland cement. Super- plasticizer (Sikament -163M) is used as a highly effective water reducing agent and super-plasticizer for the production of high-quality concrete in hot climates. With strong early and final strengths, Sikament-163M's dual action accelerates hardening. The dosage was 0.6 - 2.5% by weight of cement and is manufactured by Sika Company. Sika fume is a concrete additive of a new generation in powder form. It is used with a dosage of 2 – 10 % by the weight of the cement and is also manufactured by Sika Company. The polymer material used was according to the manufacturing company's data sheets.
Two different types of reinforcement were used in this program. The first type was steel reinforcement bars: normal mild steel with a yield strength of 240 MPa and a diameter of 8mm, which were used for stirrups; and high tensile steel reinforcement bars with a yield strength of 510 MPa and diameters of 10mm, which were used for the main reinforcement of all the beams in group 2 and the control beam. The second type was GFRP reinforcement bars, which were made in laboratory and used for the main reinforcement of all the beams in groups 1 and 3.

2.2 Mix Properties

Two concrete mixes were used in this research. The targeted characteristic strength of concrete was 60 MPa for both conventional and polymer concrete. For the first mix the water/cement ratio used was 0.34, water quantity was 1.75 kN/m3, cement quantity was 5 kN/m3, volume of coarse aggregates was 0.7 m3 and volume of fine aggregates was 0.35 m3. Sikament-163M quantity was 0.125 kN/m3, and Sika Fume quantity was 0.50 kN/m3. For the second mix the polyester/cement ratio used was 0.5, polyester quantity was 2 kN/m3, cement quantity was 4 kN/m3, volume of coarse aggregates was 0.7 m3 and volume of fine aggregates was 0.35 m3 as shown in **Table (2.1)** & **(2.2).**

Table 2.1 Proportions of Concrete (First Mix)

Material	Amount (kN/m^3)	% to cement
Water	1.70	34
Cement	5	100
Coarse aggregates	10.50	210
Fine aggregates	6.90	138
Sikament -163M	0.125	2.50
Silica Fume	0.50	10

Table 2.2 Proportions of Concrete (Second Mix)

Material	Amount (kn/m^3)	% to cement
Polyester	2	50
Cement	4	100
Coarse aggregates	10.50	262.50
Fine aggregates	7.26	181.50
Peroxide (hardener)	0.04	1

2.3 Mixing, Casting and Curing

The reinforcement is placed in its positions in the forms.Casting took place immediately after mixing. In order to achieve complete compaction, the concrete was placed around the reinforcement using a mechanical vibrator and a hand tamping. The beams were left in the forms for 48 hours, after which the sides of the forms were stripped away. For conventional concrete, the specimens were submerged in water for the next week. Then, they were left in the ordinary atmosphere with an average temperature of 24°C for at least 28 days. For polymer concrete, the specimens were covered with tarpaulin for the next week. Then, they were left in the ordinary atmosphere with an average temperature of 24°C for at least 28 days.

2.4 Experimental Program and Testing

2.4.1 Mechanical Properties of GFRP Bars

The mechanical properties (i.e., tensile load, modulus of elasticity and stress-strain relationship) were evaluated in the first phase. GFRP bars were made by making a simple pultrusion process as shown in figure (2.1) and (2.2). These bars were used for the main reinforcement of all the beams in groups 1 and 3. Tests were made for 3 samples of GFRB bars manufactured, with 1.0-meter-long and 10mm diameter to know their properties. The manufacturing process involves several steps:

1. Prepare the quantity of fiber yarns needed to make a bar with a 10 mm diameter, ensuring that the density of the fiber is not less than 65% of the size of one bar.
2. Immerse the fiber yarns in a bath of polyester resin with a suitable amount of hardener.
3. Insert the fiber yarns into the die with a diameter equal to the required final diameter (10 mm) while keeping the bar pulled during this process.
4. Create fiber protrusions on the bar's surface to achieve the final shape, using the same material as the bars. Ensure that the fiberglass yarns are well submerged in polyester resin.
5. Leave the bars in the air for enough time to reach the final hardening point.

2.4.2 Flexural Behavior of Beams

In the second phase of the current experimental program, one control beam and three groups consisting of twelve beams. All beams had a cross section 120 mm x 250 mm. The beams were simply supported with a clear span of 1800 mm with the existence of some variables. Control beam B0 with conventional concrete reinforced with steel bars. Group 1 consisted of four beams: B11, B12, B13 and B14 with conventional concrete reinforced with GFRP bars. Group 2 consisted of four beams: B21, B22, B23 and B24 with polymer concrete reinforced with steel bars.Group 3 consisted of four beams: B31, B32, B33 and B34 with polymer concrete reinforced with GFRP bars. The specific parameter of each specimen is described in Table (2.1). A significant feature of the RC beams was that their shear capacity exceeded their flexural capacity. The flexural failure mode of beams was ensured by this design. Furthermore, a testing machine with one hydraulic jack was used with capacity 250 kN (Figure 2.3). Through the actuator, loads were monotonically applied.

Figure 2.1: Pultrusion Process

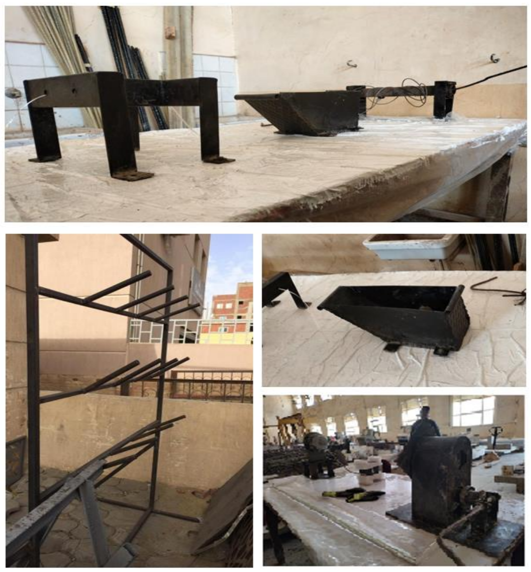

Figure 2.2: Pultrusion Process Components

Figure 2.3: Testing Frame

The test beams were mounted on the frame and adjusted on the supports. Two concentrated loads were applied. The spacing between the two loads was 600mm, and each load was at a distance of 300mm from the midpoint of the span. The displacement of the beams was carried out at three points; one at the midspan zone and the other two at a distance of 300mm from the midpoint of the span. It was monitored by three LVDTs, and load cell. Strain data were recorded using a data logger. An additional strain gauge, fastened to the reinforcing surface, was used to track the longitudinal tension bars. Using a small grinder, the rebar was flattened and sanded to ensure that the strain gauges adhered properly to the steel.

Table 2.1: Specific parameter of each beam

Beam	Concrete type	Reinforcement	Concrete compressive strength N/mm^2	Development length mm
B0	Conventional concrete	Steel bars	60	Full bars
B11	Conventional concrete	GFRP bars	60	Full bars
B12	Conventional concrete	GFRP bars	60	200
B13	Conventional concrete	GFRP bars	60	100
B14	Conventional concrete	GFRP bars	60	Zero
B21	Polymer concrete	Steel bars	60	Full bars
B22	Polymer concrete	Steel bars	60	200
B23	Polymer concrete	Steel bars	60	100
B24	Polymer concrete	Steel bars	60	Zero
B31	Polymer concrete	GFRP bars	60	Full bars
B32	Polymer concrete	GFRP bars	60	200
B33	Polymer concrete	GFRP bars	60	100
B34	Polymer concrete	GFRP bars	60	Zero

3. Result And Discussion

3.1 Mechanical Properties of GFRP Bars

After testing the samples, the failure points of the samples were in the middle, as shown in **Figure (3.1).** The failure loads for the three samples were 83.74 kN, 75.7 kN and 78.123 kN, respectively. The stress-strain relationship of the GFRP bars was linearly elastic up to failure. The ultimate stress of the GFRP bars were 1066 MPa, 964 MPa and 995 MPa respectively. The GFRP bars modulus of elasticity were 54553 MPa, 54506 MPa and 54302 MPa respectively, according to the samples test results as shown in **Figure (3.2).** Average of the ultimate stress and modulus of elasticity for the GFRP bars were 1000 MPa and 54450 MPa respectively, according to the samples test results. The dimeters of the GFRP bars were 10 mm, as shown in **Table (3.1)** and **Figure (3.3).**

Figure 3.1: Failure of The Samples

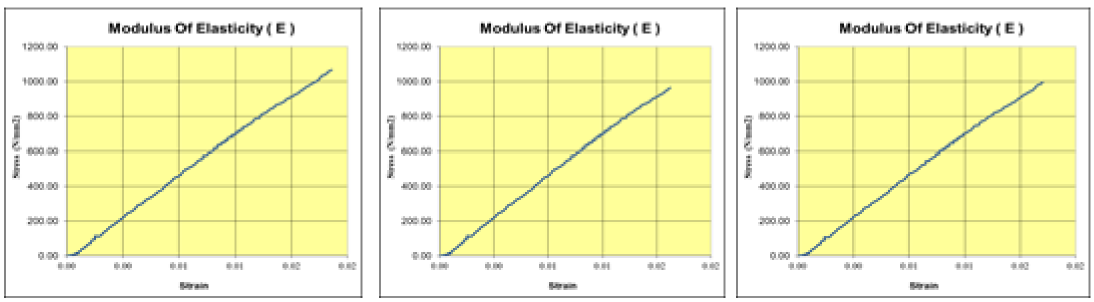

Figure 3.2: Stress-Strain Curve For 3 Samples

Table (3.1): Failure load, Stress, Strain and Modulus of Elasticity for test results of GFRP bars.

Sample No.	Failure Load (kN)	Stress (N/mm2)	Strain	Modulus of Elasticity (N/mm2)
1	83.740	1066	0.0188877	54553
2	75.700	964	0.0169846	54302
3	78.123	995	0.0176068	54506
Average	79.188	1000	0.0178263	54450

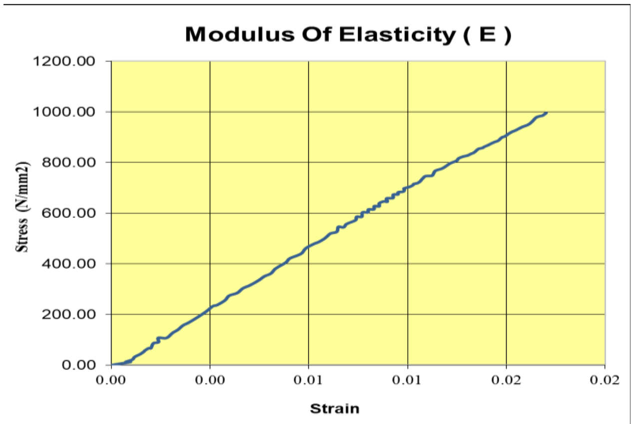

Figure 3.3: Average of Stress-Strain Curve

3.2 Behavior of Beams

3.2.1 Flexural Behavior of Beams

Thirteen standard cubes, 150x150x150 mm and 100x100x100 mm, were taken from the concrete at regular intervals during casting of the girders as shown in Figure (3.4). These control specimens were cast, compacted, and cured simultaneously with each tested specimen, and they were tested at the same time as the beams. The results of the cube testing are presented in **Table (3.2)** and **Figure (3.5).** Failure load of the tested beams was conducted. The failure loads were compared with the type of reinforcement and development length for all beams. For the control beam, the following results were observed: cracks appeared at midspan of the beam at 10 kN. The cracks increased progressively with the increase of loads, and failure occurred at 101 kN due to yielding of the steel. **Figures (3.6)** show the failure mode and crack pattern of the control beam.

Table 3.2: Results of the compression test on standard cubes

Group	Control beam			
Cube	C1			
F_{cu} (MPa)	59.2			
Group	1			
Cube	C1	C2	C3	C4
F_{cu} (MPa)	61.1	60.5	59.6	62.4
Group	2			
Cube	C1	C2	C3	C4
F_{cu} (MPa)	60.4	58.9	61.9	61.5
Group	3			
Cube	C1	C2	C3	C4
F_{cu} (MPa)	61	61.5	61.2	58.5

Figure 3.4: standard cubes of The Samples

Figure 3.5: Failure of The Samples

Figure 3.6: Failure Mode and Crack Pattern of Control Beam

For Group 1

In this group, the effect of reinforced conventional concrete beams by GFRP bars with different development lengths was investigated. For B11, GFRP full bars; the cracks appeared at 10 kN. The failure occurred at 123 kN due to rupture of GFRP bars.

For B12, GFRP bars with development length = 200 mm; the cracks appeared at 10 kN. The cracks increased normally with the increase of loads. The failure occurred at 59 kN due to slipping of GFRP bars from concrete.

For B13, GFRP bars with development length=100 mm; the cracks appeared at 10 kN. The cracks increased normally. The failure occurred at 34 kN due to slipping of GFRP bars from concrete.

For B14, GFRP bars with development length=zero; The cracks appeared at 10 kN. The cracks did not increase because the failure load was nearby, but the width of the cracks increased. The failure occurred at 16 kN due to failure of concrete at midpoint between of bars. **Figure (3.7)** shows the failure mode and crack pattern of group1.

For Group 1 the following remarks could generally be concluded:

- The reinforcement of GFRP bars in the conventional concrete caused increase in the capacity of beams.
- GFRP bars have a negligible bond with conventional concrete.
- In beam B14, it is evident that the capacity is small due to the weak bond between the concrete and the reinforcement to transfer the force between the bars at the point of contact, putting into consideration that the development length is zero.

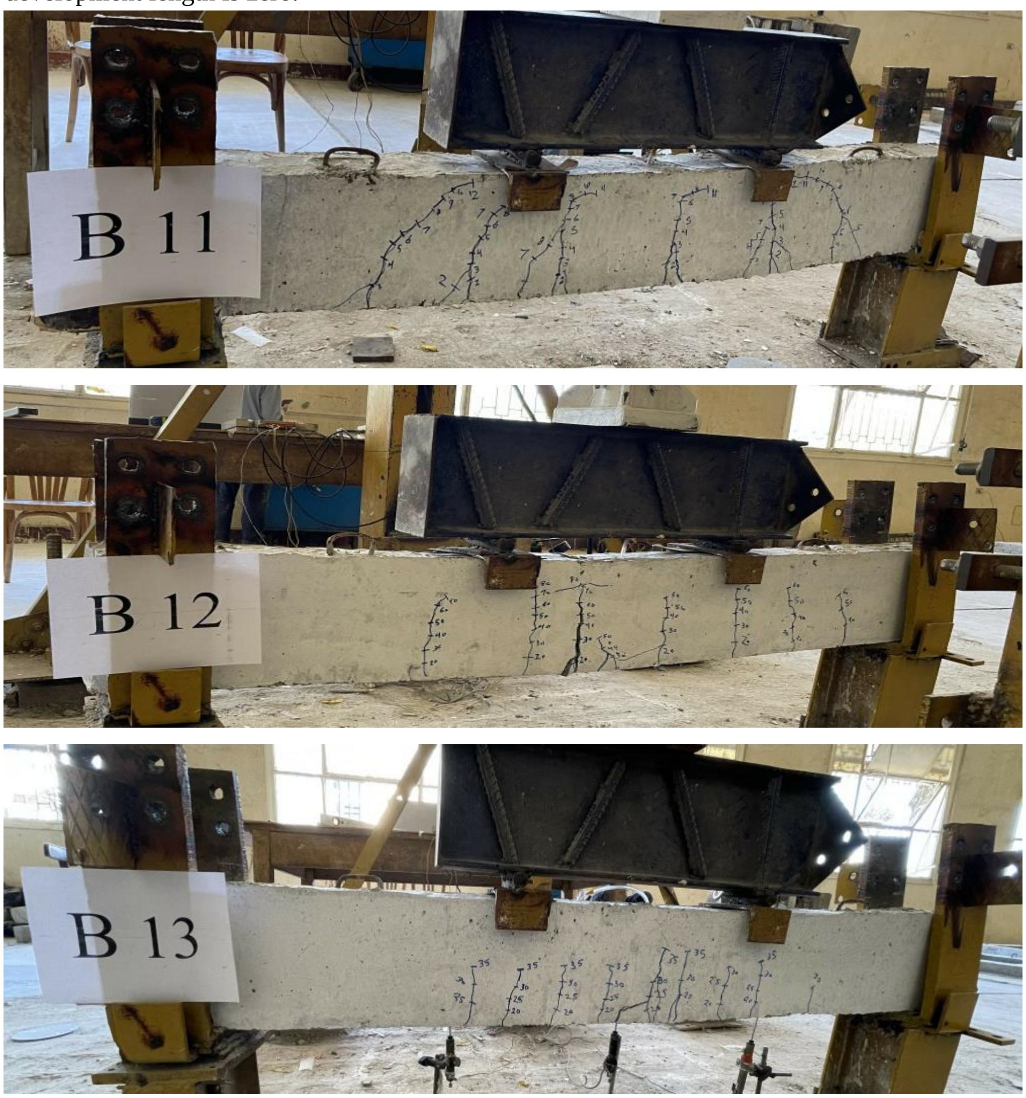

Figure 3.7: Failure mode and crack Pattern of Group 1-Conventional concrete beam reinforced with GFRP bars with different development lengths

For Group 2

In this group the effect of reinforced polymer concrete beams by steel with different development lengths was investigated. For B21, steel full bars; the cracks appeared at 15 kN. The cracks increased normally with the increase of loads. The failure occurred at 123 kN due to yielding of steel.

For B22, steel bars with development length = 200 mm; the cracks appeared at 15 kN. The failure occurred at 93 kN due to slipping of steel bars from concrete.

For B23, steel bars with development length = 100 mm; the cracks appeared at 15 kN. The failure occurred at 51 kN due to slipping of steel bars from concrete.

For B24, steel bars with development length = zero; the cracks appeared at 15 kN. The cracks did not increased because the failure load was nearby, but the width of cracks increased. The failure occurred at 24 kN due to failure of concrete at midpoint between of bars. Figure (3.8) shows the failure mode and crack pattern of group2.

For Group 2 the following remarks could generally be concluded:

- The polymer concrete caused increase in the capacity of beams.
- Steel bars have a good bond with the polymer concrete.
- In beam B24, it is evident that the capacity is small due to the weak bond between the polymer concrete and the reinforcement to transfer the force between the bars at the point of contact. putting into consideration the development length is zero.

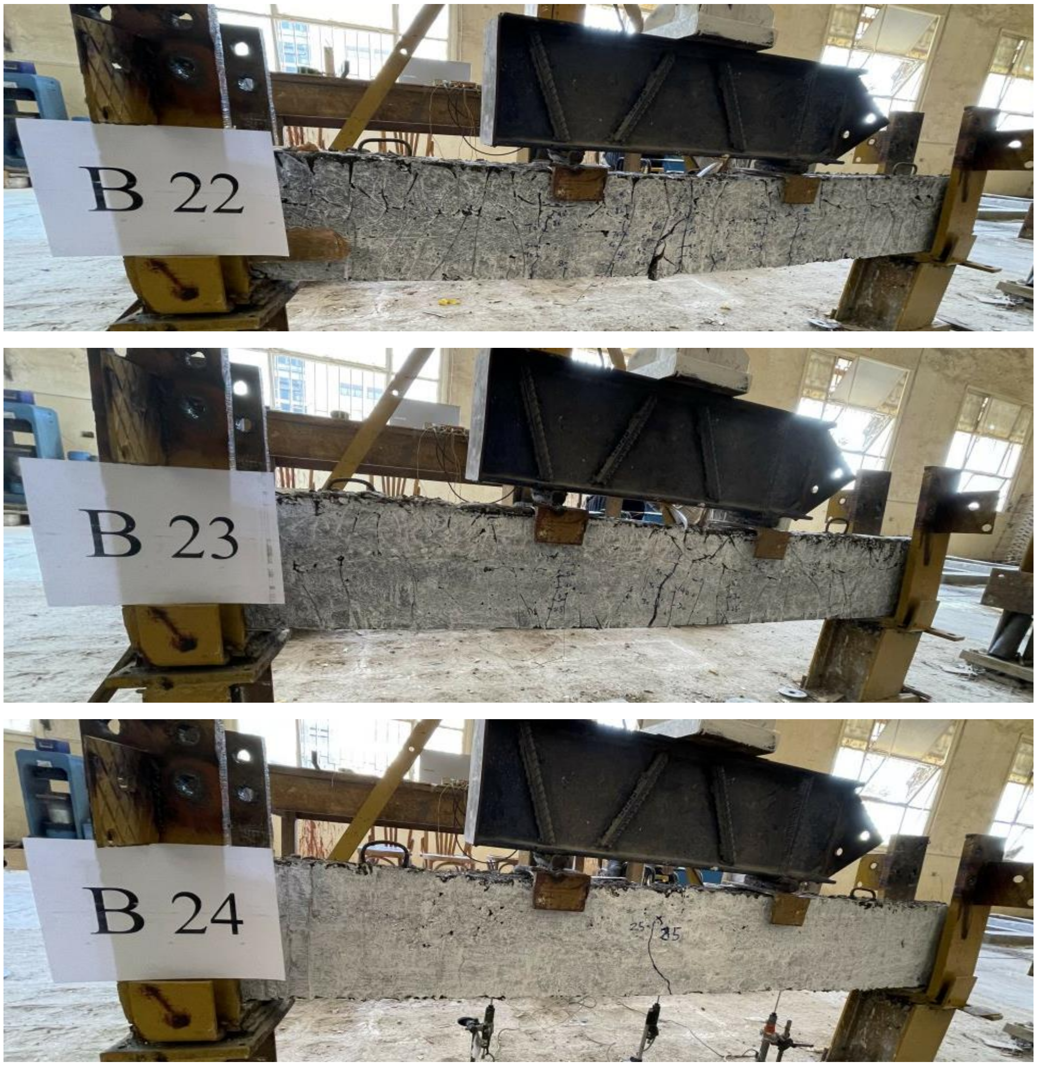

Figure 3.8: Failure mode and crack Pattern of Group 2- Polymer concrete beams reinforced by steel with different development lengths

For Group 3

In this group the effect of reinforced polymer concrete beams by GFRP bars with different development lengths was investigated. For B31, GFRP full bars; the cracks appeared at 15 kN. The cracks increased normally with the increase of loads. The failure occurred at 197 kN due to rupture of GFRP bars.

For B32, GFRP bars with development length = 200 mm; the cracks appeared at 15 kN. The failure occurred at 130 kN due to slipping of GFRP bars from polymer concrete.

For B33, GFRP bars with development length = 100 mm; the cracks appeared at 15 kN. The failure occurred at 79 kN due to slipping of GFRP bars from polymer concrete.

For B34, GFRP bars with development length zero; the cracks appeared at 15 kN. The cracks did not increase because the failure load was nearby, but the width of cracks increased. The failure occurred at 40 kN due to failure of concrete at midpoint between the bars. Figure (3.9) shows the failure mode and crack pattern of group 3.

For Group 3 the following remarks could generally be concluded:

- The polymer concrete reinforced with GFRP bars caused increase in the capacity of beams.
- GFRP bars have a good bond with the polymer concrete.

- In beam B34, it is evident that the capacity is not small due to the good bond between the polymer concrete and the reinforcement to transfer the force between the bars at the point of contact, putting into consideration that the development length is zero.

The cracking load, failure load and mode of failure for all beams are shown in **Table (3.3). Figures (3.10,3.11**,**3.12)** show the failure load Comparison of beams according to groups and development lengths.

Table (3.3): Failure load, Cracking load and mode of failure for experimental results

Beam	Cracking Load (kN)	Failure Load (kN)	Mode of Failure
B0	10	101	Tension failure due to yielding of steel bars
B11	10	123	Tension failure due to rupture of GFRP bars
B12	10	59	Tension failure due to slipping of GFRP bars
B13	10	34	Tension failure due to slipping of GFRP bars
B14	10	16	Tension failure due to slipping of GFRP bars
B21	15	123	Tension failure due to yielding of steel bars
B22	15	93	Tension failure due to slipping of steel bars
B23	15	51	Tension failure due to slipping of steel bars
B24	15	24	Tension failure due to slipping of steel bars
B31	15	197	Tension failure due to rupture of GFRP bars
B32	15	130	Tension failure due to slipping of GFRP bars
B33	15	79	Tension failure due to slipping of GFRP bars
B34	15	40	Tension failure due to slipping of GFRP bars

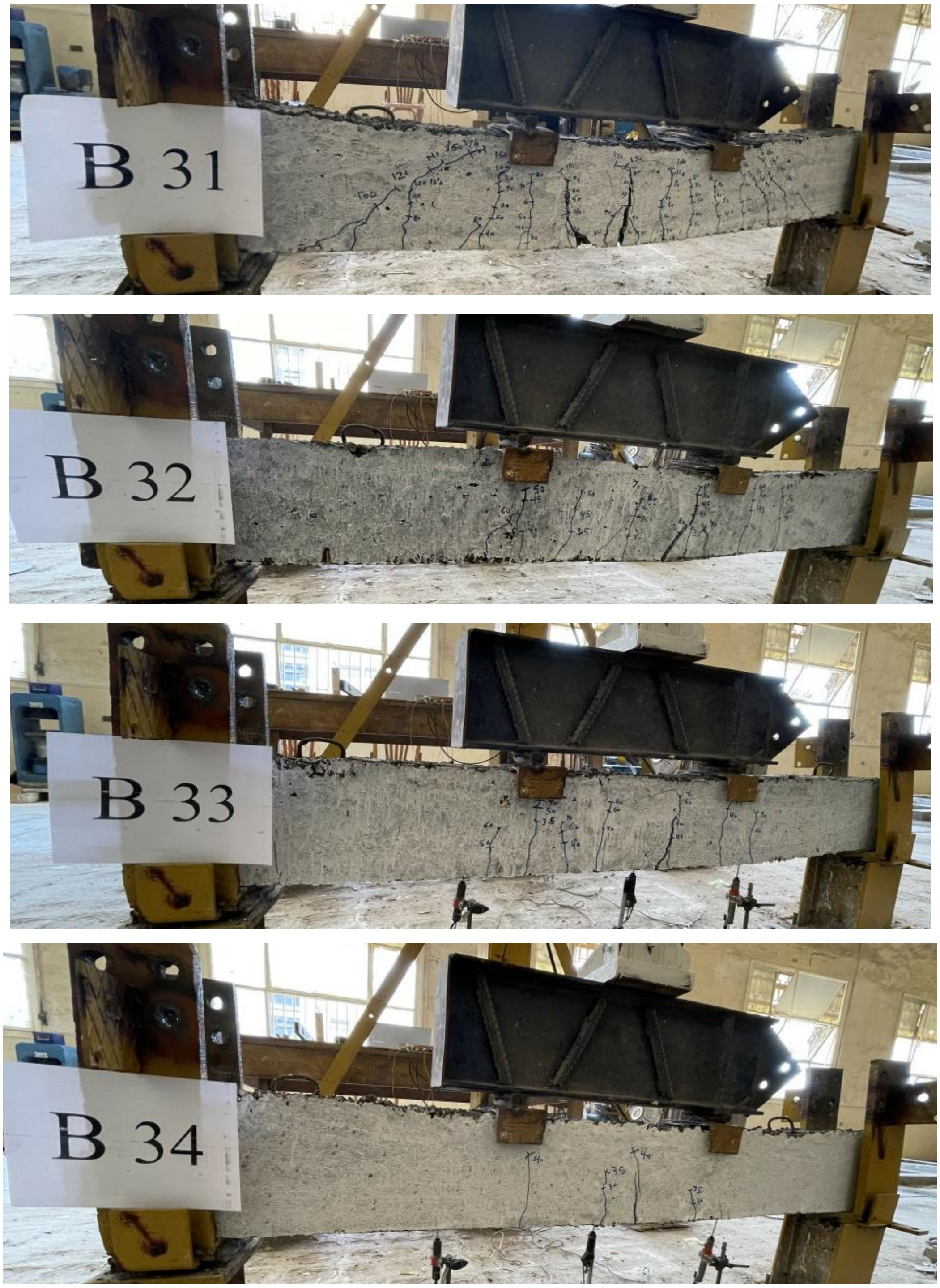

Figure 3.9: Failure mode and crack Pattern of Group 3- Polymer concrete beams reinforced with GFRP bars with different development lengths

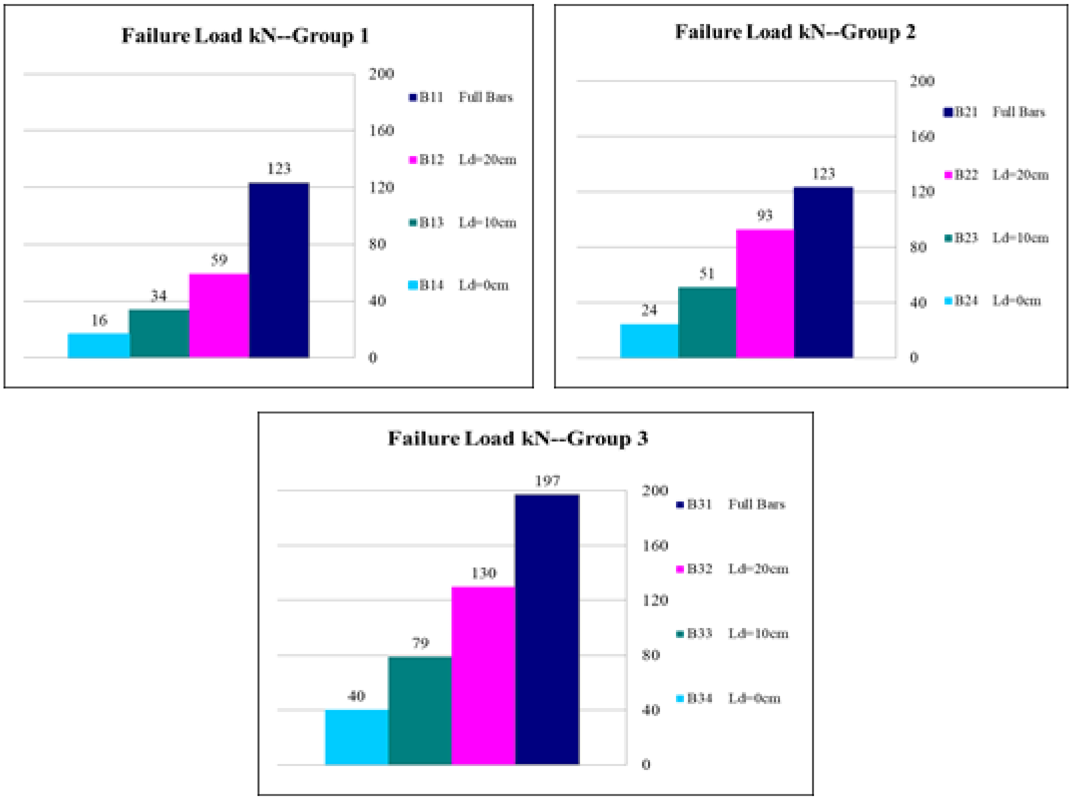

Figure 3.10: Failure loads of groups

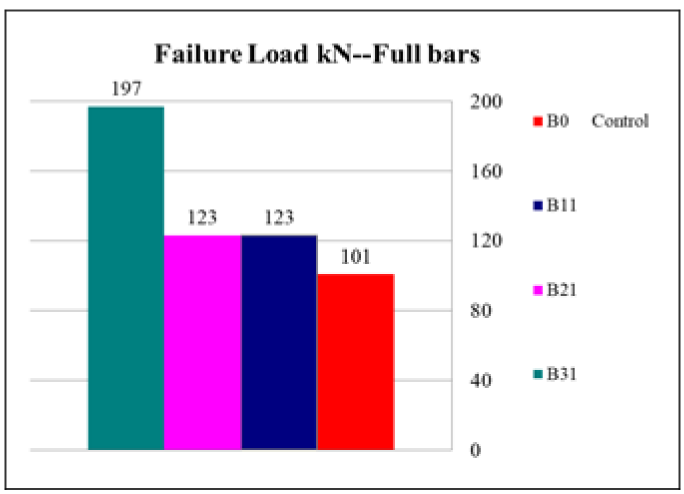

Figure 3.11: Failure loads comparison with Full bars

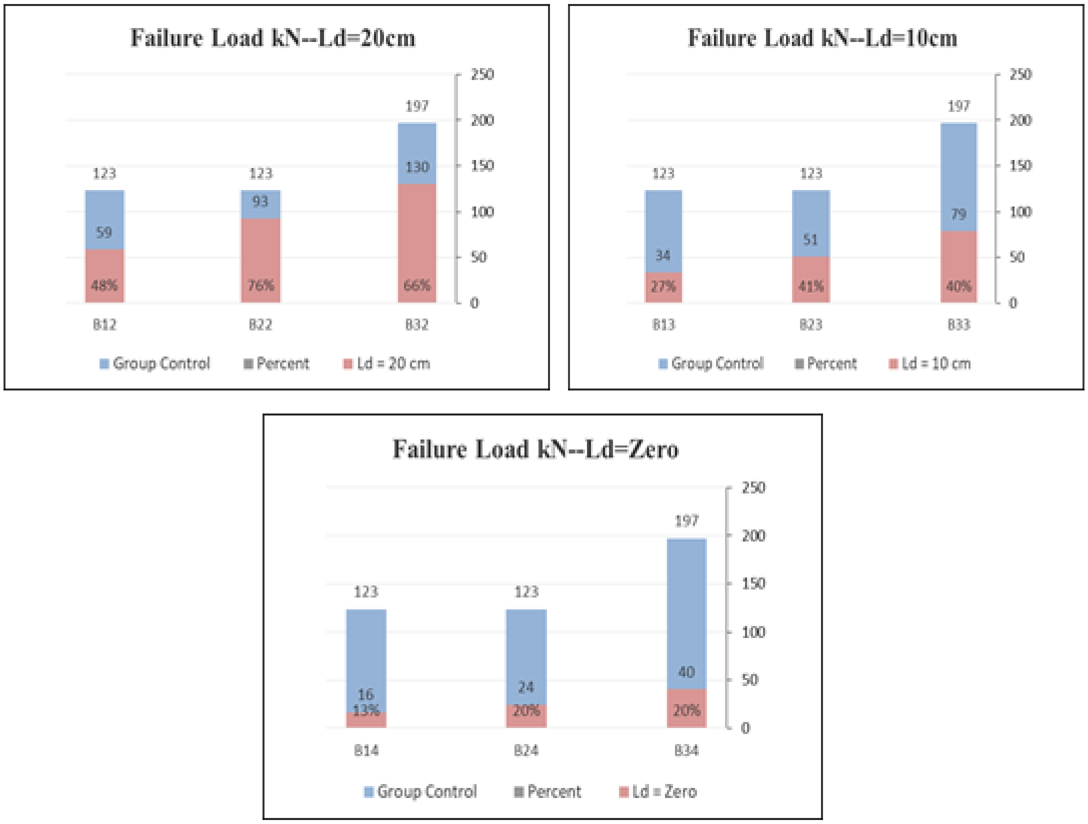

Figure 3.12: Failure loads comparison with bars different development lengths

3.2.2 Load-Deflection and Moment-Curvature Curves

The experimental load deflection curves at midpoint are shown in **Figures: (3.13)** and **(3.14)**.

For control beam: The deflection increased with the increase of load and the failure occurred at deflection 16.5 mm.

For Group 1: The deflection increased with the increase of load and the failure occurred at deflection 24 mm for B11. The deflection decreased with the decrease of development length until it was almost non-existent for beams B12, B13, and B14. The failure occurred at deflections 10.5, 7 and 2.6 mm respectively.

For Group 2 : The deflection increased with the increase of load and the failure occurred at deflection 44.2 mm for B21. The deflection decreased with the decrease of development length until it was almost non-existent for beams B22, B23, and B24. The failure occurred at deflections 19.4, 4.5 and 2.6 mm respectively.

For Group 3: The deflection increased with the increase of load and the failure occurred at deflection 36 mm for B31. The deflection decreased with the decrease of development length for beams B32, B33, and B34. The failure occurred at deflections 25.5, 17 and 7.5 mm respectively**.** Comparison considering development length with different types of reinforcement and concrete types is shown in **Figure (3.14).**

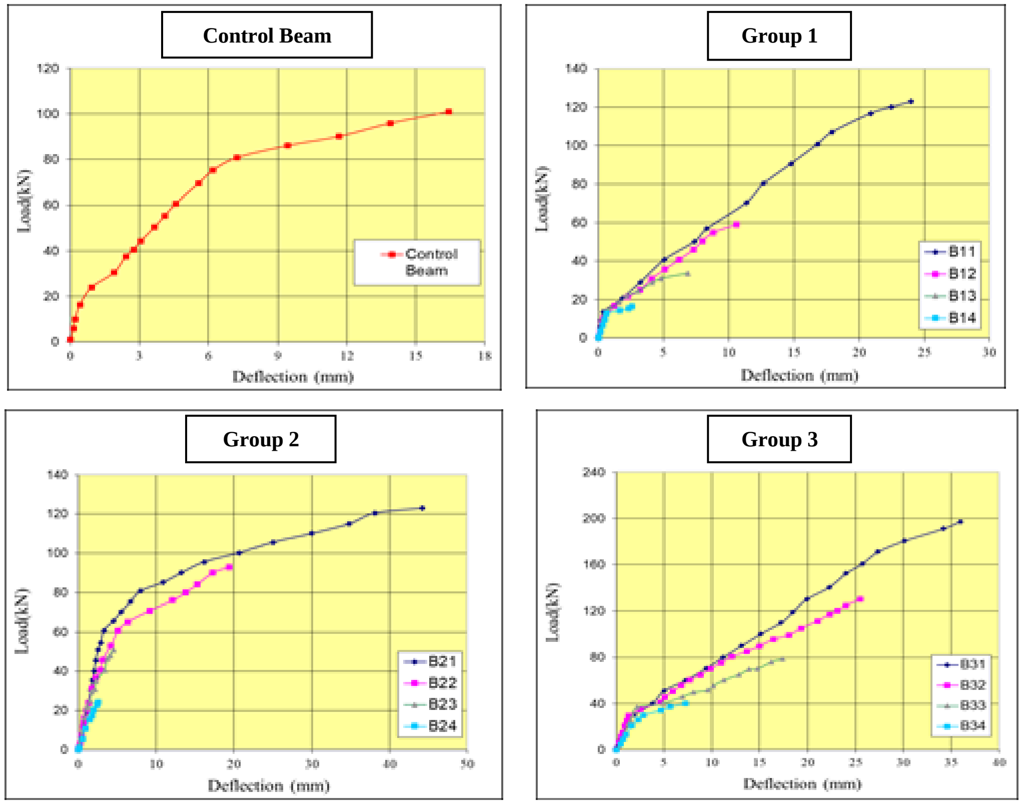

Figure 3.13: Load deflection relationship for groups

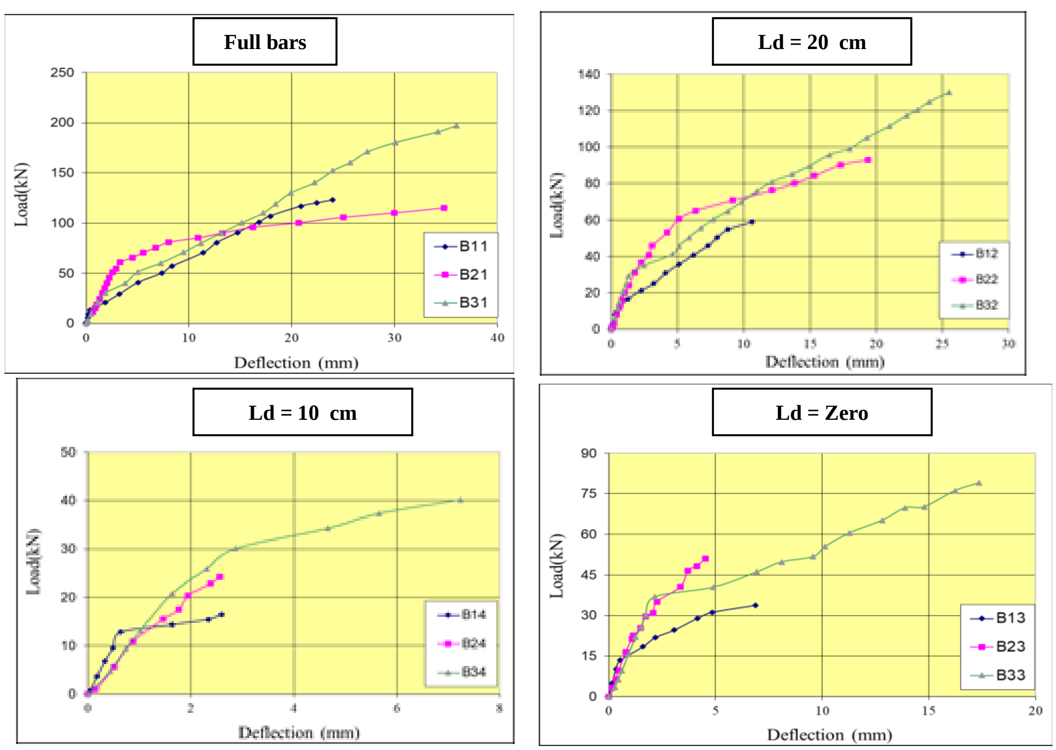

Figure 3.14: Load deflection relationship for different development lengths of reinforcement

4. Conclusion

The main objective of the present study was to study the flexural behavior of polymer concrete beams reinforced with polymer-based glass fiber (GFRP) bars. The variables studied were: types of concrete used (conventional concrete - polymer concrete), types of reinforcement used (steel bars - GFRP bars) and development length of reinforcement. Previous experimental studies led to the following conclusions and recommendations:

1) The increase in the density of Fiber yarns in the size of one bar caused the higher of tensile strength and improved the quality of bars.
2) The use of polymer concrete with reinforcement of steel resulted in good bonding, as the development lengths in the reinforcement of steel can be reduced, unlike its counterpart with conventional concrete.
3) Using of GFRP bars reinforcement with conventional concrete showed no notable effect of the increasing the capacity of beams with different development lengths, due to a decrease in the bond between them.
4) The use of GFRP bars reinforcement with polymer concrete increased the capacity of beams with ratio exceeding about 65%.
5) There was a notable increase in the bond between the polymer concrete and the GFRP bars reinforcement, which led to benefiting from the maximum tensile strength of the GFRP bars, unlike its counterpart with conventional concrete.
6) In the use of polymer concrete, beams reinforced with development length = zero of steel bars increased the capacity of beams with ratio about 50%, unlike its counterpart with conventional concrete.
7) Finally, the use of polymer concrete beams reinforced with development length=zero of GFRP bars increased the capacity of beams with ratio about 150%, unlike its counterpart with conventional concrete.

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