Structural behavior of MRPC beams exposure to riverine simulated circumstances using GFRP and CFRP bars

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Abstract. Reinforced polymer bars could potentially be used with fiber as a strengthening technology in MRPC. The main objective of this paper is to study the influence development of the flexural behavior of MRPC beams after 120 days of virtual corrosion-exposure in riverine simulated circumstances using GFRP and CFRP bars. Nine beams were tested via a two-point loading method up to failure, 1200 mm long, (200x100mm) cross-section. The water/binder is chosen to be 0.14 by weight. Silica fume was replaced by 8% weight of cement. The dose of superplasticizer used to the total binder weight was 0.41 percent. Three types of flexural reinforcement ratios were used individually per each cross-section; GFRP, CFRP, and traditional steel rebar, with a nominal diameter of 10 mm. The compressive strength of MRPC is 80 MPa. The experimental evidence indicates that GFRP and CFRP bars used with MRPC have higher tensile strength and anti-corroded bars. Also, the load results indicate that CFRP bars are more efficient than GFRP bars and steel rebar. Finally, the behavior of MRPC beams neither GFRP and CFRP bars submerged in Tigris river water did not chemically affect. The author recommended replacing steel rebar with GFRP and CFRP bars to improved structural behavior.

1. Introduction and problem statement
Concrete structures reinforced by steel rebar are vulnerable to both load stresses and environmental factors. The total deformation required by structural members to be able to deform a lot as much as possible before failure is called ductility. It is one of the most important parameters of the steel reinforcement benefits especially extreme events like earthquakes or tornadoes. Without any doubt, the ductile structure gives people warnings. On the other hand, the repair and maintenance program of the corroded rebars of the concrete structures is considered very expensive. Almost 43 percent of bridges in the United States of America are structurally insufficient due to corrosion [1]. Therefore, an alternative material of the FRP bar is designed as anti-corroded reinforcement to bear high traffic load, and reduce the repair cost. The general cross-section of the synthesis FRP bar contains 70% longitudinal fibers distributed along the bar. Each one fiber is approximately equal to the diameter of two human hairs that are immersing in a 30% polymer matrix to hold it together and place a final formation of FRP [2]. These fibers can be made of glass refers to GFRP or carbon refers to CFRP. FRP bar contains zero metal or ferrous material which makes it non-magnetic, non-conductive material, non-corroded material, and 100% recyclable when used in concrete. Also, the durability of the FRP is not questioned [3]. The 1st concrete bridge constructed using FRP bars was fabricated in the USA in 1996 [4].
2. Literature review

2.1. FRP bars

Three decades before, numerous studies focused on the FRP bar’s characteristics. Welsh studied the relation between the glass fiber and the polymer media [5]. Gerritse and Schurhoff studied the stress-strain behaviors of different reinforcement materials; steel rebar, GFRP, and CFRP bars. It has appeared that the strain capacity of the steel rebar is more than the FRP bar by four times [6], Figure 1.

![Tensile stress-strain curve of the FRP bars vs. steel reinforcement](image1)

Many years later, Ambrose studied the stress-strain relationship between the FRP bar and; steel rebar, concrete, and wood, the stress-strain diagram of FRP bar revealed a straight line, while the others form a curve this can have a big deal when it comes to ductility. Without any doubt, the FRP bar is less ductile material [7], Figure 2.

![stress-strain tensile behavior s of common construction materials](image2)

Uomoto studied carefully with his teammate the behavior of FRP bars subjected to chemical reactions. He illustrated relations with tensile, creep, and fatigue properties [8-10]. Other researchers have kept pace with the chemical effect study on FRP. Sasaki founds that the polymer matrix will reduce its performance when subjected to ultraviolet rays [11]. Ferrier, concerned about the alteration nature of the FRP bonds with both time and temperature. He also considered the influence of the fatigue load on his trails [12,13]. In 1999, Belarbi worked hard to validate a new invention of FRP rods focused on the pseudo-ductility. Unfortunately, the rods failed during loading [14]. In Japan, continuous fiber bars are not allowed to replace reinforcing steel and pre-stressing steel for load-bearing members. These advanced materials have not yet been accepted to replace steel, but rather enhance it. Direct substitution of GFRP rebar with steel rebar may not be possible in some cases due to differences in mechanical
characteristics and surface configurations [15]. To find suitable usability behavior, researchers from Belgium produced a new type of concrete slab using FRP [16,17]. Renée and Yunping studied the surface characteristics of the FRP bars [18]. The ultimate strengths tested for the CFRP bar is more than steel rebar and approximately 3 times more than GFRP. [19]. Borna studied the comparison between the steel rebar and FRP bar. He found that the weight of the steel rebar is three times greater than the FRP bar, but still has a less price by about 25% than the FRP bar. While the last one is approximately five times stronger than steel rebar, it seems to be engineered to have a great bond to the concrete [20].

2.2. Using CFRP and GFRP bars in MRPC
In the available literature, it is noted that not many researchers investigated the behavior of MRPC using CFRP and GFRP bars, and yet are still lacking. Adnan describes the behavior of Reactive Powder Concrete RPC columns strengthen by CFRP bars, with a concrete compressive strength f{'c} 135 MPa. CFRP bars were shown to be effective in controlling the failure of the concrete specimens [21]. Yoo founds that increasing the reinforcement ratio of GFRP if a part of GFRP rods replaced by steel rebars improved the flexural performance and stiffness of concrete which leads to less deformability [22].

3. Objectives of the study
The outcomes of this research are to study the development of MRPC characteristics and the flexural of nine specimens after 120 days of virtual corrosion-exposure in riverine simulated circumstances of Tigris river water using GFRP and CFRP bars compared to steel rebar.

4. Experimental Plan
The experimental program included cast and test via a two-point loading method up to the failure of nine beams. A prototype beams dimensions; 1200 mm long and a rectangular cross-section (200x100) mm. It also includes cast and test different concrete mix specimens of cubes, cylinders, and prisms.

4.1. Tigris water river
All the beams are submerged in a water tank filled with Tigris river water during the experimental work of 120 days before the test, this period is considered as curing time for concrete. The curing water used was taken from Tigris river Baghdad, Bab Al-Muadham location near the Iraqi ministry of health. The average results of five specimens for chemical and physical analysis of water were laboratory tested and compared with the World Health Organization WHO, Table 1.

| Characteristics                  | Tigris river specimen values | WHO Standards |
|----------------------------------|------------------------------|---------------|
| pH, (standard units)             | 7.51                         | 6.5-8.5       |
| Total dissolved Solid, (mg/L)    | 710                          | 500           |
| Calcium (Ca2+)                   | 105                          | 75            |
| Potassium (K+)                   | 5.4                          | 12            |
| Sulfate (SO42-)                  | 195                          | 250           |
| Chloride (Cl-)                   | 116                          | 250           |
| Cadmium (Cd)                     | 0.047                        | 0.005         |
| Iron (Fe)                        | 0.232                        | 0.3           |
| Copper (Cu)                      | 0.197                        | 0.1           |
| Zinc (Zn)                        | 0.682                        | 0.5           |
| Lead (Pb)                        | 0.054                        | 0.05          |

4.2. Reinforcement
The job is divided into three different test groups according to the reinforcement ratios and configurations type, Table 2. Each group has one kind of the following reinforcement; steel, CFRP, and GFRP. Correspond to the manufacturing list and the properties list in Table 3, all the reinforcements
used in this work are deformed type bars. Mean measured cross-sectional area of bar diameter 9.5mm (0.375 inch) is 67 mm² (0.104 in².) [23]. The shear reinforcement used in this experimental study is steel type deformed rebar 6 mm diameter stirrups.

Table 2. Type and number of flexural reinforcement bars

| Beams designation | Flexural reinforcement configurations type | No. of flexural Rebar Ø10 mm | Standards          |
|-------------------|-------------------------------------------|-------------------------------|--------------------|
| Group 1           |                                           |                               |                    |
| BI2               | steel                                     | 2                             | ASTM A615          |
| BI3               | steel                                     | 3                             | ACI 440.3R-12      |
| BI4               | steel                                     | 4                             |                    |
| Group 2           |                                           |                               |                    |
| BC2               | CFRP                                      | 2                             | ASTM D7205 /       |
| BC3               | CFRP                                      | 3                             | D7205M - 06(2016), |
| BC4               | CFRP                                      | 4                             | ACI 440.3R-12      |
| Group 3           |                                           |                               |                    |
| BG2               | GFRP                                      | 2                             | ASTM D7205 /       |
| BG3               | GFRP                                      | 3                             | D7205M - 06(2016), |
| BG4               | GFRP                                      | 4                             | ACI 440.3R-12,     |
|                   |                                           |                               | ASTM D7957         |

Table 3. Reinforcement properties [24]

| Tensile properties | Steel Rebar | GFRP bars | CFRP bars |
|--------------------|-------------|-----------|-----------|
| Ultimate strength, ksi | 70-100     | 75-175    | 450       |
| Ultimate strength, (MPa) | 700        | 825-860   | 3,000     |
| Elastic Modulus, ksi     | 29,000     | 6,000-8,000 | 21,000   |
| Elastic Modules (GPa)   | 200        | 40-60     | 150       |
| Specific Gravity        | 7.9        | 1.5-2.0   | 1.6       |
| Density(Kg/m³)          | 7.800      | 2,100     | 1,500-1,750 |
| Tensile strain, %       | >10        | 3.5-5.0 or 1-1.5 | -        |
| Thermal Coefficient, x10⁴°F | 6.5       | 5.5       | 0         |
| Thermal Coefficient Longitudinal, x10⁴°C | 11. | 6-10      | 0         |
| Tensile Strength MPa    | 450        | 550-800   | 1700-2500 |
| Yield Stress, ksi       | 40 – 75    | N/A       | N/A       |
| Yield Stress, (MPa)     | (276 - 517) |          |           |
| Tensile Strength, ksi   | 70 – 100   | 70 – 230  | 87 – 535  |
| Tensile Strength, (MPa) | (483 - 690)| (483 - 1600)| (600 - 3690)|

4.3. Modify reactive powder concrete mix

The term MRPC has been used to describe a super plasticized concrete, silica fume-cement mixture with a very low water/binder ratio, characterized by 0.6 mm sand, mixed with 4.75 mm crushed fine gravel. Ordinary Portland cement type I, was used, conformed to the ASTM standard [25]. Natural sand is used as a fine aggregate. The chemical and physical properties were within the limits of the ASTM [26]. A trial mix of 150 mm concrete cubes specimens has been cast, cured, and tested to find the optimum proportions of the modified reactive powder concrete materials. The average compressive strength measured is 80 MPa per BS 1881-116. Silica fume was replaced by an 8% weight of cement [27]. The super plasticizer type (Gelinume 51) was used with 0.41 percent by weight of total binder [28]. All the dry materials were blended using an electrical concrete mixer with the specified quantity of tap water and mix proportions, Table 4. The concrete casting was performed per ASTM [29], using steel molds to investigate the compressive strength and flexural strength. All the reinforced concrete beams were subjected to the same environmental conditions.
Table 4. MRPC quantities and mix proportions

| Mix notation | MRPC | Standards |
|--------------|------|-----------|
| Average nominal compressive strength $f'c$ MPa= | 80 | BS 1881-116 |
| Water/Binder= | 0.14 | ACI 318 |
| Cement kg/m$^3$ = | 800 | ASTM C150-02 |
| Fine sand 0.6 mm+ | 1000 | ASTM C33-02a |
| Fine gravel 4.75 mm, kg/m$^3$= | 0.41 | ASTM-C494-05 |
| Superplasticizer L/100 kg by total binder weight = | 8% | ASTM C1240-03 |

5. Theoretical simulation for failure style

When the load is applied to the MRPC beam, the concrete tries to bear all the stresses as much as it could. Increasing the load on the beam looks like asking the concrete to take much more bending and contradict its behavior and to prevent performing the first crack at the tension side. Therefore, Figure 3, shows the pulling procedure on the reinforced concrete to cause a crack, once that crack forms, the concrete isn’t doing anything anymore and all of the load is transferred by that rebar. Everything is all about that rebar, so the stiffer that bar is the harder concrete is, the smaller the cracks will be. and this is why that initial slope is so important. Without any doubt, the ductility is not adjective in concrete and an FRP bar as well.

![Figure 3. Concrete reinforcement tensile load](image)

The load-deflection curves of the tested beams at the mid-span at all stages of loading under flexural moment tends to bend the beams up to failure exhibits the following three distinct stages:

- At the beginning of this stage, a constant slope starts with increasing the load till the 1st cracking load point making a steep slope and higher flexural rigidity.
- The point of the 2nd stage starts from the end of the last linear steep slope point to the yield reinforcement part with a less steep slope and less rigidity than the stage before is.
- The last stage of the load-deflection curve extends to the failure. Represents the ductility of the concrete beams.

The three stages previously mentioned possibly not have the same trend for all curves shown in Figure 4. Some curves might consist of two stages only.

6. Results and Discussion

Immediately after the applied load and during the tests, the load-deflection values are recorded at the center of the bottom face of the beams. The structural behavior is normally explained using the load versus deflection diagram:
GFRP and CFRP bars are stronger, lighter, and eco-friendly products alternative to conventional steel rebar. It is the ultimate and ideal solution for concrete infrastructure projects.

Increasing the reinforcement ratio for the concrete cross-section using either GFRP, CFRP, or steel rebars; reveals a high capacity load, but minimum deformation appeared.

The highest progression value of the load applied on the tested beams starts from using CFRP bars, steel rebar, and the GFRP bar, respectively. But minimum deflection appeared.

The test results at the failure of beam BC4 using four CFRP bars, revealed the maximum load applied and the minimum deflection appeared, which are 105 kN, and 190x10-2 mm, respectively.

The test results at the failure of beam BG2 using two GFRP bars, revealed the minimum load applied and the maximum deflection appeared, which are 38.5 kN, and 510x10-2 mm, respectively.

The slope of the load-deflection diagram of the beams using GFRP bar is very different than it is for a CFRP bar, the slope at the beginning is about half of what a CFRP bar is.

The total deformation of the load-deflection diagram of the beams using the CFRP bar is half the total deformation of the GFRP bar and two-thirds the total deformation of the steel rebar.

While the initial slope of the load-deflection diagram of the beams using the GFRP bar is almost closer to steel rebar than CFRP bar, meaning the same cracking performance of steel rebar and the strength of the beams using CFRP bar is much higher than its using GFRP bar and steel rebar as well.

The deflection percentage value at the ultimate load for each beam specimen for both CFRP and GFRP to the deflection value at the ultimate load of the reference beam with steel rebar varies between (55.8 and 117.6) %; as shown in Table 5. The beam BG4 gained the maximum percentage which is considered the more ductile beam. The yield strain of GFRP is higher than steel rebar due to the unique anisotropic property of composites makes them strong in tension; this will give the engineer premature warning of the failure, beams using GFRP rebars shows more deflection before starting to fail. This can give more chances to be alerted before failure takes place, that’s agreed by [30].

### Table 5. load and deflection at 1st crack and failure

| Designation | First crack | Failure | \( \frac{\Delta_{ult}}{\Delta_{failure}} \times 100 \) |
|-------------|-------------|---------|---------------------------------|
|             | Load (kN)   | Deflection (mm x 10^-2) | Load (kN) | Deflection (mm x 10^-2) |
| BI2         | 15          | 24      | 45                     | 465          | 1                      |
| BI3         | 20          | 22      | 65                     | 420          | 1                      |
| BI4         | 30          | 32      | 87.5                   | 340          | 1                      |
| BC2         | 30          | 29      | 67.5                   | 300          | 64.5                   |
| BC3         | 35          | 28      | 84.5                   | 254          | 60.4                   |
| BC4         | 40          | 30      | 105                    | 190          | 55.8                   |
| BG2         | 12.5        | 30      | 38.5                   | 510          | 109.6                  |
| BG3         | 15          | 27      | 57.5                   | 470          | 111.9                  |
| BG4         | 25          | 35      | 80                     | 400          | 117.6                  |
Figure 4.(a) Load deflection curves for all beams

Figure 4.(b) Load-deflection curves of beams BI2-BC2-BG2

Figure 4.(c) Load-deflection curves of beams BI3-BC3-BG3

Figure 4.(d) Load-deflection curves of beams BI4-BC4-BG4

Figure 4.(e) Load-deflection curves of beams BI2-BI3-BI4
7. Crack pattern
In this study, all the beams were tested using a two-point loading method until failure. Several types of cracks occurred in concrete beams due to flexural, bearing, insufficient concrete cover, and shear cracks associated were observed either separated or combined. Details of these cracks in reinforced concrete beams are discussed in detail and summarized in Table 6.

- The crack size of the beams reinforced by both CFRP and GFRP bar is wide more than the crack size of the beams reinforced by steel rebar, this belongs to the steel stiffness which is more than GFRP and CFRP bar. The concrete cracking status would become more severe when using higher reinforcement ratios.

- Shear cracks appear near the support of the concrete beams and are inclined at 45 degrees with the horizontal. Shear cracks are increased in numbers and wide in size in direct proportion to the shear stresses. Generally, these cracks can be avoided by providing additional shear reinforcements near the supports where the shear stress is maximum. Shear stress is maximum at a distance of d/2 from the support where d is the effective depth of the beam. This type of cracks appeared in all beams tested but with varying intensity. It almost increased in beams having a low reinforcement ratio.

- All the beams tested revealed flexural bending cracks except beams BC4, BC3, and BC2 failed due to the bearing stresses at the support, Figure 5. The structural behavior of the reinforced concrete beams using different types of reinforcement is normally explained using the load versus deflection diagram, as shown in Figures (4-b, 4-c, 4-d). The load-deflection curves of the beams BC2, BC3 and BC4 almost start with the elastic stage from zero load, then continue external loading causing the normal and bending stresses. After the tensile stress in the concrete exceeds its tensile strength, the internal micro-cracks form. And the flexural and diagonal tension cracks developed immediately. In this stage the linear and constant slope part having a relatively steep slope which means that these beams are of relatively higher flexural rigidity leads to form a bearing cracks at the supports, unlike the other models that fails due to flexural cracks start at the tension face near the supports of the members and are inclined at about 25°-45° more like a mirror are identical to the both sides of the center of the longitudinal axis of the beam.

- The cracks appeared in the beams BI4, BI2, and BG2, it is taking place near the top of the side face of the compression reinforcement along the beam length. This cracks almost due to the insufficient top concrete cover, Figure 6.

- The nine beams of this study were tested until failure was shown in Figure 7 with all cracks details.
Table 6. beam designation and cracks pattern

| Beam designation | cracks pattern | BI4 | BI3 | BI2 | BC4 | BC3 | BC2 | BG4 | BG3 | BG2 |
|------------------|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Cracks types     | flexural       | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
|                  | shear          | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
|                  | insufficient concrete cover | ✓ | ✓   | ✓   | ✓   | ✓   | ✓   |
|                  | bearing        | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   | ✓   |
8. Concluding Remarks

- The type and number of reinforcement have a significant influence on the behavior of the MRPC beams.
- It was noted that steel rebar changed its color to rusty, but there are no traces of rust on the steel rebar neither tension nor compression reinforcement.
- The load capacity values of the tested beams, result that CFRP bars are more efficient compared to GFRP bars and steel rebar.
- The number of cracks and width size of the beams reinforced by both CFRP and GFRP bar is wide more than the crack size of the beams reinforced by steel rebar.
- The GFRP bars are the viable alternative reinforcement used in MRPC beams. It is considered the more ductile in comparison with both CFRP bars and steel rebar.
- Finally, the specific aims of the experimental program were to confirm the substitute the use of the GFRP and CFRP bars instead of steel rebar in concrete beams exposure in riverine simulated circumstances. For the same cross-section, the behavior of MRPC beams neither GFRP and CFRP bars submerged in Tigris river water did not chemically affect. Therefore, it is recommended for this study case to replace part of steel rebar with a reinforcement ratio of GFRP and CFRP bars to improved structural behavior of ductility, load capacity, stiffness, and money saved.
Notations
Variables and functions
MPa – Mega pascal.;
f 'c – specified compressive strength of concrete using standard cylinders of six inches diameter and twelve inches height. Usually, this is prescribed at the age of 28 days of curing.;
mg/L – milligram per litter.;
ksi – Kilo pounds per Square Inch Pressure Unit.;
GPa – gigapascal is equal to exactly one billion pascals.;
mm – Millimeter.;
kg/m³ – Kilogram per cubic meter.;
ºF – Fahrenheit is a unit of measurement used to measure temperature.;
L – Litter.;
∅ – Diameter.;
kN – kilonewtons.;
∆ult – deflection at ultimate load.;
∆failure – deflection at failure load.

Abbreviations
MRPC – Modified reactive powder concrete.
CFRP – Carbon Fiber-Reinforced Polymer.
FRP – Fiber Reinforced Polymer.
GFRP – Glass Fiber-Reinforced Polymer.
USA – United States of America.
BS – British standard.
ASTM – American Society for Testing and Materials.
ACI – American Concrete Institute.
WHO – World Health Organization.
pH – the power of hydrogen or potential for hydrogen, in chemistry, pH is a scale used to specify how acidic or basic a water-based solution is. Acidic solutions have a lower pH, while basic solutions have a higher pH.
BI2 – Concrete beam with 2 steel rebars ∅ 10 mm.
BI3 – Concrete beam with 3 steel rebars ∅ 10 mm.
BI4 – Concrete beam with 4 steel rebars ∅ 10 mm.
BC2 – Concrete beam with 2 CFRP bars ∅ 10 mm.
BC3 – Concrete beam with 3 CFRP bars ∅ 10 mm.
BC4 – Concrete beam with 4 CFRP bars ∅ 10 mm.
BG2 – Concrete beam with 2 GFRP bars ∅ 10 mm.
BG3 – Concrete beam with 3 GFRP bars ∅ 10 mm.
BG4 – Concrete beam with 4 GFRP bars ∅ 10 mm.

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