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Flexural Performance of Concrete Structures Reinforced with Fiber Reinforced Polymer (FRP)

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ABSTRACT

One of the most recent uses of FRP is to replace the use of steel in reinforced concrete structures. There are multiple reasons for deciding to choose FRP instead of steel such as their lightweight which can be quite beneficial to the design of buildings, high strength, and high flexibility. However, the initial use of this material was anticipated in the retrofitting of heritage buildings or any other damaged structures. There are several studies that concentrated on the use of FRP to enhance shear and flexural strength of concrete structures. However, limited studies concentrated on the effect of FRP on flexural behavior of concrete beams. Therefore, the aim of this research is to investigate the flexural performance of concrete beams that are reinforced using fiber reinforced polymers. The experimental program that was conducted in this study was divided into 4 different beams, 2 of them were reinforced using ordinary steel, while the other 2 were reinforced using carbon fiber reinforced polymer (CFRP). The highest potential deflection occurred in steel beam was 4.2 mm after applying a maximum of 42 MPa. The second beam was reinforced with FRP and accomplished 38.06 MPa, and the resulted deflection was around 12mm. The third beam was reinforced with steel and highest flexural strength measured was 75.56 MPa, while the deflection resulted from this load is 5.52 mm. Finally, the last beam was reinforced using FRP rebar and resulted deflection was 11.11 from 60.84 MPa. This study has showed the potential of using FRP in concrete structures especially in terms of flexural performance. Further studies are needed to investigate the influence of water and chemical substances on the performance of concrete beams reinforced with FRP.

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1. Introduction

Fiber Reinforced Polymer (FRP) has been described as a suitable practical substitution of different structural materials in the construction industry. It can be mainly used to enhance the shear and flexural performance of structural elements that are made of reinforced concrete, such as shear walls, beams, and slabs (Chen, Chen, & Teng, 2012). It can also be used to enhance the internal capabilities of reinforced bars by replacing steel components. The major advantages of using FRP are strength to weight ratio, lightweight, corrosion resistance, and non-conductivity (Ebead & Saeed, 2017). Many developed countries started to rely on FRP in multiple structures such as Switzerland, Germany, United Kingdom and Canada, and it was also commonly used in bridge decks and other potential projects that might be subjected to water and corrosive environment. In all of these projects FRP has shown a great potential to replace the use of conventional steel rebars in reinforced concrete structures.

One of the major challenges in current buildings is the deterioration and aging of its structural component and the numerous amounts of investments that are required for retrofitting and ensuring the safety of structures. Moreover, steel reinforcement corrosion has been a concern for reinforced concrete structures (Gkoumas et al., 2019). Therefore, the use of FRP has been promoted by several studies either to replace the use of steel reinforcement or can also be used for strengthening concrete structural elements (Yang, Haghani, Blanksvärd, & Lundgren, 2021).

There are many noteworthy properties of FRP including high corrosion resistance, superior strength, and lightweight. Bonded FRP can be easily used on construction sites and aid in improving the capacity of concrete buildings and their serviceability (Hollaway, 2010). Even though there has been a lot of studies regarding the use of FRP for the strengthening of concrete buildings during the past few years, there is yet a huge gap regarding the experimental investigation of FRP and its impact on the flexural performance of concrete. Therefore, this paper aims to explore the flexural performance of concrete that is reinforced with FRP as a replacement of conventional steel.

2. Literature Review

During the past few years, multiple studies investigated the performance of one-way slab and simply supported beams that are reinforced using bars made of FRP. These studies examined the crack width, spacing of cracks, flexural capacity, and expected failure mode and their generation (Grace, Abdel-Sayed, & Saleh, 1998). Furthermore, other studies were done to estimate the deflection criteria in concrete beams that are reinforced using FRP, the reason for having such goal is that a significant design limitation is the lack of serviceability in the design of beams and further examination was needed. Nowadays, most studies concentrated on simply supported beams that are reinforced using FRP bars, but there should be more focus on the behavior continuous beams. The results of previously investigated matters by authors indicated that there is a moment distribution in the analyzed continuous beams.

Grace et al. (1998) demonstrated the results of an experiment on 7 different continuously supported beams. The reinforcement of these beams was various combinations of shear reinforcement and longitudinal reinforcement using carbon FRP, glass FRP, and steel bars. The conclusion of this study stated that beams that had various arrangement in FRP reinforcement offered better load capacity than beams reinforced with steel, but the ductility and failure modes were quite different as well.

Habeeb and Ashour (2008) introduced experimental results of three continuous Glass FRP-reinforced concrete beams with different combinations of reinforcement ratios at mid-span. Signs of moment redistribution were observed in some of the tested beams such as higher end reactions than the expected elastic reactions. In addition, another study investigated the behavior of continuous beams that are reinforced using ordinary steel, carbon fiber reinforced polymer, and glass fiber reinforced polymer. The basic aim of this study was to investigate the performance of continuous beams in terms of accomplishing moment distribution especially continuous beams that are reinforced using carbon or glass FRP, and the study also investigated the use of multiple reinforcement configurations in order to estimate the most suitable design. Furthermore, the results of this experiment were compared to any theoretical models, and other code equations to estimate the possible capacity of maximum load and load deflection responses.

Hamdy and Arafa (2021) experimentally investigated the use of basalt FRP as a replacement of steel in the design of concrete beams. The reason for using basalt FRP is basically due to the excellent durability, high tensile strength, and affordable cost. The experiment was based on comparing the flexural performance of beams reinforced with steel and another reinforced with basalt FRP. The experimental program included six beams reinforced with steel, BFRP, and dispersed steel fibers. A four bending test was adopted to determine the total deflection, failure mechanisms, and total failure mode. It was concluded that the total failure load that can be resisted by basalt FRP is greater than steel, but the deflection was also higher in FRP if compared to steel under the same loading conditions. After reviewing the literature about the adoption of FRP in the design of concrete structures, it was clear that there is a lack of sufficient number of studies about the flexural performance of carbon FRP and whether it can provide the same capabilities of steel. Hence, this research demonstrates an experimental test that offers a greater understanding of the difference between carbon FRP and steel if used as a reinforcement in concrete structures.

Yang et al. (2021) presented an experimental study about the use of FRP to strengthened beams that are reinforced with corroded steel. Ten beams were examined using a 4-point bending test, two of them were not deteriorated and not strengthened, and the other 8 beams had corroded steel and were subjected to flexural loads. A 3-D scanning was also used to evaluate the level of local corrosion in the beam. The results have shown that corroded steel reduces the load carrying capacity of the beam despite that the level of corrosion was at around 20%. If the level of corrosion was increased, the potential generated cracks on the surface of the beam would have a total width of around 1.9 mm. Hence, it can be concluded that the use of FRP helped in reducing the flexural stiffness and load carrying capacity of tested beams. Nevertheless, further research is required to enhance the level of understanding of deformation capacity of beams strengthened using FRP.

3. Materials and Methods

In order to explore the flexural performance of FRP as a reinforcement in concrete beams, an experimental program was developed. The experimental procedure included the following steps:

- The dimensions of the beam were 10*15*100 cm. The basic design procedure included 4 different beams, two of them were reinforced using steel, while the other two were reinforced using FRP. In the first two beams, one was reinforced using 1 steel reinforcement bar with a 12 mm diameter, while the other was reinforced using a GFRP bar having a 12 mm diameter. In the other two beams, one was reinforced using two steel rebars of diameter 12 mm, and the other was reinforced using 2 GFRP rebars also having a diameter of 12 mm.
- Each beam included steel stirrups, which was 8*8 in each meter.
- The experiment also included additional concrete cubes to determine the compressive strength of concrete and Fcu of designed mixture, and the cubes had a dimension of 100x100x100mm.
- The mixture was then prepared by mixing sand, concrete, coarse aggregate, and water. The weight of cement used in the mixture was 24 kilograms, fine aggregate used was measured to be 30 kilograms, and finally only 10.5 kilograms of water was used.
- Each mold was properly cleaned using oil to prevent the sticking of the sample inside the mold.
- The mixture was then placed in each mold in addition to placing the required reinforcement in the needed position. Then, compaction was done through applying 25 different cycles in each layer to form 3 different layers with a total of 75 hitting cycles. Figure 1 shows the placing of concrete into steel molds and wood beams.

Figure 1: Placement of concrete beams into wood framed mold and steel cubes

- Each mold was then removed from the sample in order to be left for curing. Figure 2 shows the concrete beams after being removed from wood mold and left for drying.

Figure 2: Concrete beams after being removed from wood molds

- Each specimen was tested after 28 days from curing in order to ensure that concrete reached its compressive strength.
- After leaving the concrete beams for curing, they were left to dry for one day.
- Each beam was prepared for a four-point loading beam test to determine the load-deflection.
- The experimental test also involved assigning some electrical gauges in order to detect and measure the stresses at which the beam fails as shown in Figure 3.

Figure 3: Electrical gauges used to measure stresses applied on the beam at location of failure

- Figure 4 demonstrates the machine that was used to measure flexural failure of beams through assigning certain loading criteria that keeps on increasing until the failure of the specimen.

Figure 4: Testing machine used in the experiment to indicate flexural failure

- The load was applied in increments to determine the load, displacement, and strain at each increment using a data acquisition unit.

4. Calculations

The design procedure that was followed in this research was 'specific surface area'.

4.1 Concrete Mix Design

The concrete mix design is well detailed in the following table.

Table 1:
Well detailed concrete mix design

F_{min}	$250 \frac{kg}{cm^2}$
Aggregate type	Crushed dolomite
Specific weight of cement	3.1
Specific weight of coarse aggregate	2.6
Specific weight of fine aggregate	2.55
Fine modulus	2.4
Specific surface area of coarse aggregate	$3 \frac{cm^2}{gm}$
Specific surface area of fine aggregate	$55 \frac{cm^2}{gm}$
Slump	30 to 60 mm (low)

The following conditions were well considered in the experimental program:

- The compressive strength depends on the specific surface area of total aggregate.
- The range of specific surface area at which the maximum compressive strength takes place is 22 to 26 cm^2/gm
- The higher the cement content, the lower the specific surface area.
- For a constant specific surface area, the optimum water content is directly proportioned to the cement content.
- It is advised to be used for small jobs with good or fair degree of quality control.

  - For $Fc < 200kg/cm^2$ => $S = 80 \frac{kg}{cm^2}$
  - For $Fc > 200kg/cm^2$ => $S = 120 \frac{kg}{cm^2}$
  - $Fm > 250 + 120 = 370 \frac{kg}{cm^2}$

Using Absolute Volume Theory:

Weight of total Aggregate

$$\frac{W}{1000} + \frac{C}{3.1 * 1000} + \frac{A}{1000 * gt} = 1$$

$$\frac{175}{1000} + \frac{400}{3.1 * 1000} + \frac{A}{1000 * gt} = 1$$

- Gt = $(0.72 * 2.6) + (0.28 * 2.55) = 2.586 => A = 1800\text{kg}$
- Wf = $1800 * 0.28 = 504\text{kg}$
- Wc = 1800*0.72 = 1296 kg

4.2 Proportion of Mixture

Cement: Fine Agg: Coarse Aggregate: Water
400 : 504 : 1296 : 175
Total weight = $2375 \frac{kg}{m3}$

5. Experimental Results

After applying the experimental steps, all results were processed after studying the behavior of the concrete, steel, and FRP under the 4-point beam loading test. Therefore, the results of compressive strength will be presented in this section in addition to demonstrating the stress strain curve that indicate the development of stress and strain in each tested beam.

5.1 Concrete Beam Reinforced with Steel

The first type of beams that was examined in this research was a concrete beam reinforced with steel. Two different beams were tested in this stage and the results are shown below.

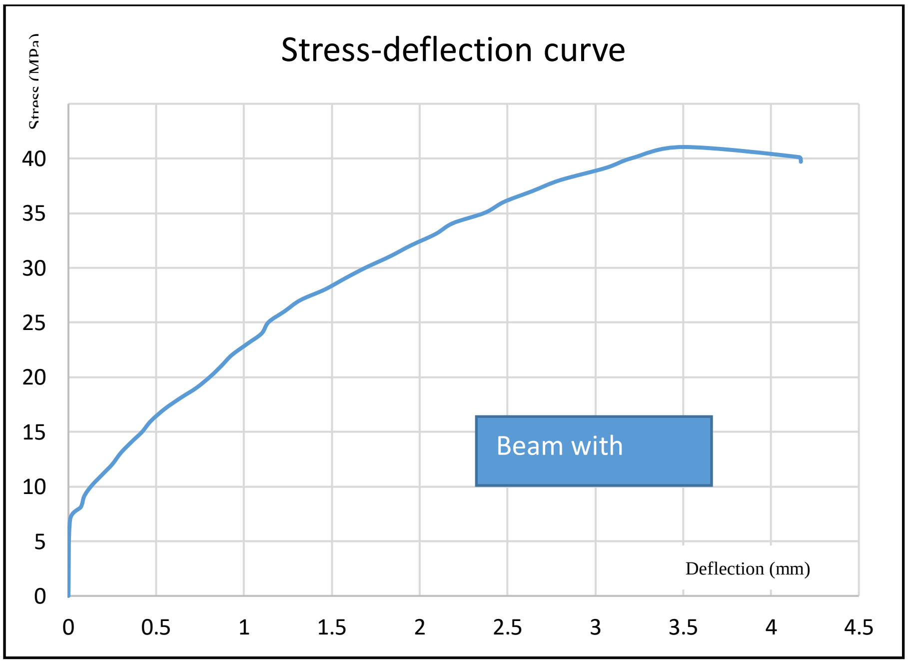

Figure 5: Stress deflection curve for concrete beam reinforced with steel (1)

The highest stress reached by this beam that is reinforced with steel was around 42 MPa, while the occurred deflection was just higher than 4mm. Figure 6 indicates the failure mode of the beam and some flexural cracks that were observed.

Figure 6: flexural cracks that occurred on Steel beam (1)

Figure 7 shows the stress-deflection curve for the second tested beam that was reinforced with steel.

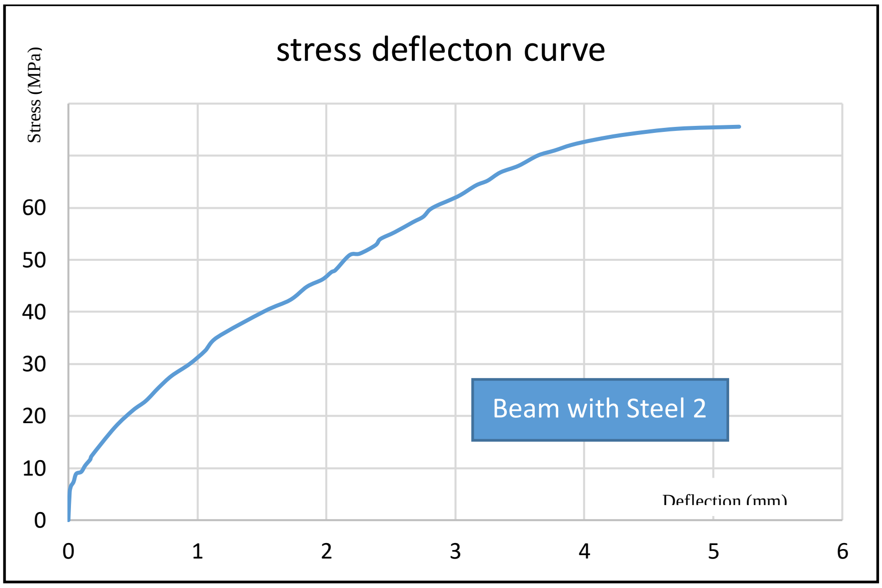

Figure 7: Stress deflection curve for concrete beam reinforced with steel (2)

5.2 Concrete Beam Reinforced with FRP

The second type of beams that was examined in this research is concrete beams reinforced with FRP. Two different beams were tested in this stage.

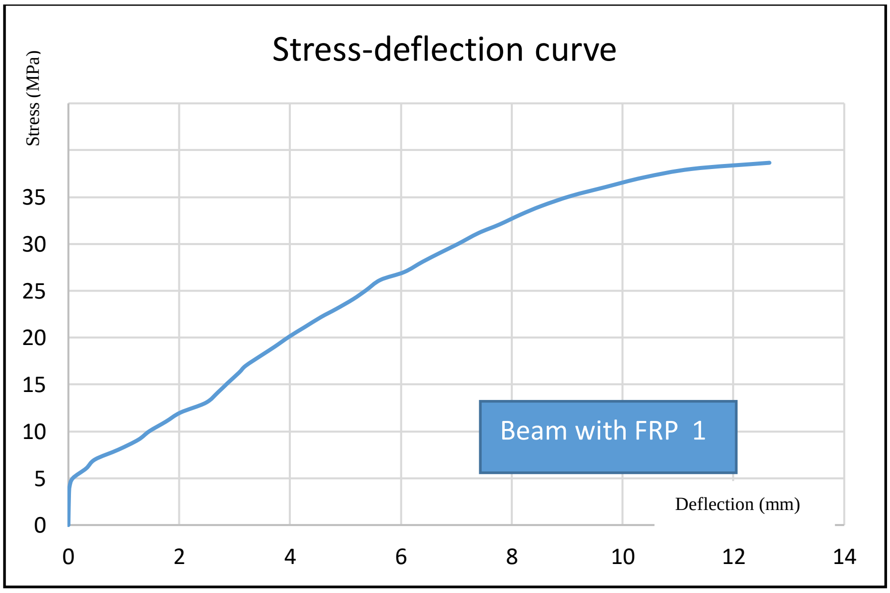

Figure 8: Stress deflection curve for concrete beam reinforced with FRP (1)

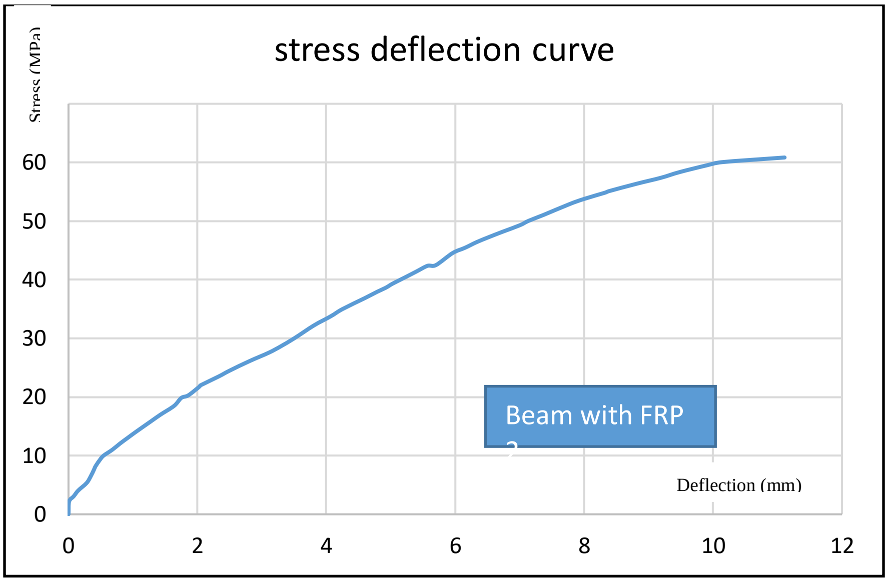

Figure 9: Stress deflection curve for concrete beam reinforced with FRP (2)

Figures 9 and 10 show the stress deflection curve and flexural cracks of beam specimen reinforced with FRP respectively.

Figure 10: Flexural cracks that occurred on FRP beam 2

6. Conclusion

The wide acceptance of FRP materials in the construction sector is mainly related to the composite action of FRP reinforced concrete rather than concentrating on the bond between concrete and FRP. Proper composite action occurs when the loads are correctly transmitted from the reinforcement to the concrete. The behavior of the bond is quite different between FRP and steel as both of them are affected by different parameters in the process of accomplishing a better bond performance. One of the major concerns regarding the capability of FRP to redistribute moments and loads in any continuous beam is the linear elastic performance of FRP bars until it reaches the final failure.

Thus, because of limited amount of research regarding this aspect, design guidelines and codes do not provide the ability to design for moment distribution for continuous beams that are reinforced using FRP. There is also a lack of research about the flexural performance of concrete that is reinforced with FRP. Hence, this paper presented an experimental investigation of the flexural performance of concrete beams that are reinforced with carbon FRP instead of steel. Four beams were examined, two of them were reinforced with steel, and the other two were reinforced with FRP. The results have shown that FRP can withstand lower stresses than steel under the same loading conditions but with more deflection rate. Figure 11 shows a brief comparison between steel and FRP. It could be concluded that the resulted deflection in FRP is quite high if compared to the applied stresses and the use of steel rebars might result in having a lower deflection with significantly higher stresses.

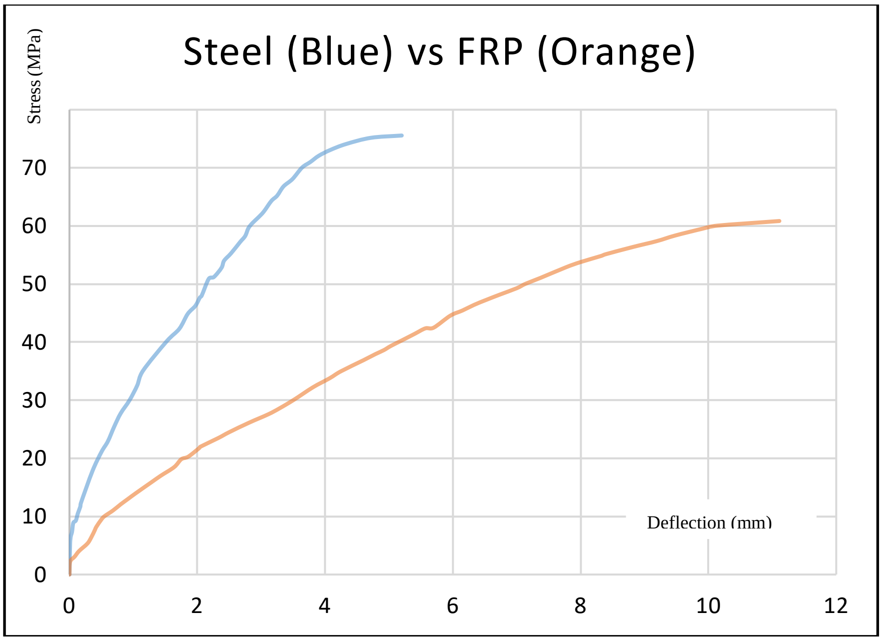

Figure 11: Comparison of deflection and stress between steel 2 and FRP 2 (Orange: FRP, Blue: Steel)

This study has shown the potential of using carbon FRP in the design of concrete structures. FRP can be considered a proper replacement of steel in case the building might be subjected to corrosive materials and environment. Nevertheless, further studies are needed to understand the long-term capabilities of FRP if used instead of steel as it may provide better performance.

Authors Contribution

Wahbi Albasyouni: study design and concept, analysis, drafting, critical revision, incorporation of intellectual content.
Mohamed Radwan: literature search, data collection, drafting

Conflict of Interests/Disclosures

The authors declared no potential conflicts of interest w.r.t the research, authorship and/or publication of this article.

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