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# Analysis and evaluation of debonding of reinforced concrete beams

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**Abstract**

One of the causes of prosperity and success in the construction industry and one of the most common debonding is the debonding of the concrete cover and the separation of the concrete surface and the reinforcement plate. This paper evaluated the beams in the experiments due to an external force applied perpendicular to the longitudinal axis. The five reinforced concrete beams test specimen dimensions were $200 \times 140 \times 1300$ mm, with rebar 10 for the bottom and 6 for the top, rebar 8 for the girders, and the concrete grade was considered 350. The final strength of 28 days with GFRP fibers in two layers, three classic layers, two layers, and three U-shaped layers are subjected to a four-point bending test. A control specimen was used for evaluation. The experimental results showed that the three U-shaped GFRP layers performed better than the other specimens and performed better in the biaxial bending test. The three U-shaped GFRP layers sheet had the most significant effect on flexural reinforcement and prevention of debonding compared to the classic U-shaped two-layer, three-layer, and two-layer GFRP sheets. In addition, Two U-shaped layers have more resistance to external load pressure than a U-shaped layer and have a more significant impact.

Keywords: Debonding, Bending reinforcement, Reinforced concrete beams
2020 MSC: 74K10

## 1 Introduction

engineering applications often require a combination of material properties. For example, the aerospace industry needs high strength, lightweight with suitable abrasion-resistant materials. Therefore, composite materials were invented, for it is impossible to find a material with all the desired properties. Composites are multi-component materials whose properties are generally better than each component. The civil engineering composite materials are Fiber Reinforced Polymer materials. FRP materials in the building industry on a global scale do not have a long history. Technology development in the building industry dates back about three decades ago. It has been a decade since FRP materials have been used in the construction industry of Iran. The main advantage of FRP materials is their high resistance to weight ratio and high corrosion resistance. The high strength, while lightweight, makes them easier to move and transport, in less cost and labor. Also, their resistance to corrosion makes them durable and stable. The FRP thicknesses have at least twice the strength of steel at the same thickness, which can be up to 10 times the strength of steel thickness, while their weight is only 20% of the steel. In thick polymer reinforced beams with FRP,

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under bending, there is always the possibility of debonding due to the separation of the sheet from the joint, which can lead to catastrophic accidents.

Carbon Fiber Reinforced Polymer (CFRP) sheets is of particular economic importance since the goal is to determine the optimal design model. Therefore, excessive reinforcement in the direction of stress causes excessive bending stiffness in concrete beam sections, which can cause severe damage to the structure. GFRP is suitable glass fiber with very high tensile strength, chemical resistance, and insulation. The bonding of FRP by epoxy adhesive has emerged as an advanced reinforcement technology in response to the growing need to repair and reinforce concrete structures. Although the bonding of the FRP plate by the adhesive layer has many advantages, in most cases, brittle and with little (or no sign) debonding of reinforced beams occur. The most common causes of these debonding have been reported as cracking the concrete cover and separation of the concrete surface and the reinforcement plate. FRP can be used in concrete beams and slabs to replace all or part of the required tensile rebar. It can also be used in concrete joints and increase the ductility of the joint. Numerous studies on the structural behavior of FRP thick reinforced beams show that although the application of composite materials in the execution during the reinforcement operation is successful, in most cases, there is a brittle debonding before the structures reach the final capacity obtained through the theoretical calculations. This can limit the advantages of this method by causing catastrophic outcomes. The most common debond is split concrete cover and separation of the concrete surface and the reinforcement plate [1].

## 2 An Introduction to FRP

FRP is a composite material consisting of two parts of fiber or reinforcing fibers surrounded by a polymer resin base or matrix. The most basic form of composite material is a form in which two components are combined to produce a material with properties that differ from the properties of its components. Reinforced polymers are made up of fragile fibers enclosed by a base material. The fibers are of different materials and are produced in the form of short pieces, long strands, and woven fabrics. The base material in FRPs protects the fibers and transfers stress between them, and the fibers play a bearing role. FRP parts are made in various industrial, semi-industrial or handmade methods. FRP materials consist of two primary components; reinforcers or fibers and resin (base material). Fibers, which are elastic, brittle, and very durable, are the main bearing components in FRP materials. The fibers may be glass, carbon, aramid, vinyl, and basalt. The composite products are GFRP, CFRP, AFRP, VFRP, and BFRP.

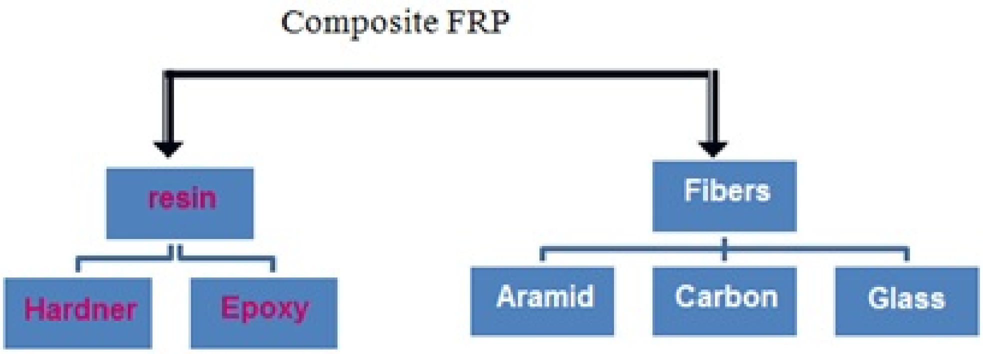

Figure 1: Types of FRP fibers

## 3 Application of FRP in shear and flexural reinforcement of beams

Reinforced concrete beams reinforcement techniques include fibers, flexural reinforcement, or shear reinforcement. A positive or a negative bending capacity is obtained by attaching FRP plates to the lower and the upper side of the beam [2]. It is also possible to provide suitable shear capacity by connecting FRP plates to the two sides of the beam. Figure 2 shows how to reinforce the beams with FRP fibers.

## 4 Materials and methods

In this paper, five laboratory specimens of reinforced concrete beams with dimensions of 200 × 140 × 1300 mm, each with two longitudinal rebars of grade 10 ribbed type AIII at the bottom, 16 pieces of stirrup of grade 8 ribbed

Figure 2: FRP flexural and shear reinforcement

type AIII, and the other two longitudinal rebars are modeled from grade 6 without tread type AIII at the top of the section, for the distances between the braces and the assembly of the beams. Each of these five specimens is named B5, B4, B3, B2, and B1.

### 4.1 Specifications of FRP reinforced beams

The following figures show how each specimen approximation. Specimen B1 is the control loaded and tested without reinforcement (Figure (3-a). Specimen B2 is reinforced by two layers classically by GFRP (Figure (3-b). Specimen B3 is reinforced by three layers, classically by GFRP (Figure (4-a). Specimen B4 is reinforced by two classic layers continuing up to 5 centimeters above the cover in a U-shape on the sides (Figure (4-b). Specimen B5 is reinforced by three classic layers continuing up to 5 centimeters above the cover in a U-shape on the sides (Figure 5).

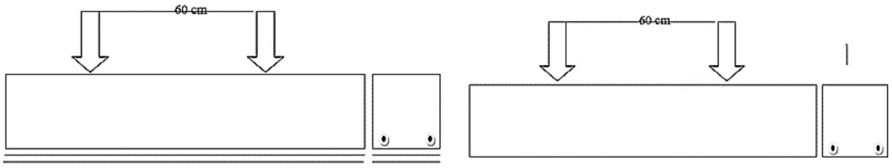

Figure 3: a) Specimen B1, b) Specimen B2

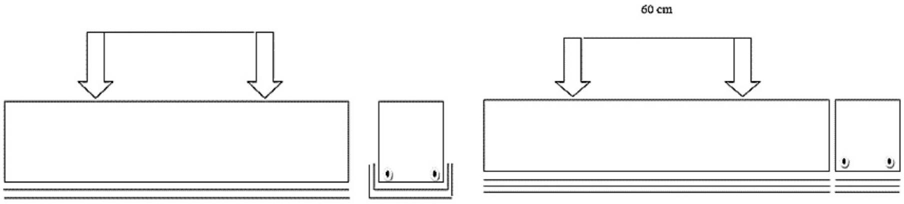

Figure 4: a) Specimen B1, b) Specimen B2

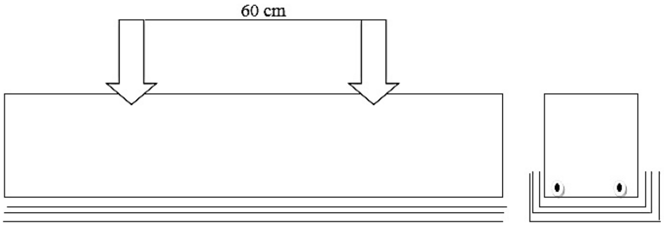

Figure 5: Specimen B5

Figure 6: View of metal molds

### 4.2 Granulation characteristics of specimens

To make the specimens, first, the materials were tested to determine the quality according to ASTM C33. The granulation characteristics for 3000 g of sand shown in Table 1 were used to obtain the numerical modulus of softness.

Table 1: Granulation characteristics of specimens

| Sieve No. | Sieve hole diameter | Weight left on each sieve | Remaining weight percentage | Cumulative percentage | Pass percentage |
|---|---|---|---|---|---|
| 3.8# | 10 | 7.1 | 0.23 | 0.23 | 99.77 |
| 4# | 4.75 | 810.5 | 27 | 27.23 | 72.77 |
| 8# | 2.36 | 456.4 | 15.2 | 42.43 | 57.57 |
| 16# | 1.18 | 390.3 | 13 | 55.43 | 44.57 |
| 50# | 0.30 | 868.1 | 28.9 | 84.33 | 15.67 |
| 100# | 0.15 | 378.6 | 12.6 | 96.93 | 3.07 |
| 200# | 0.075 | 89.1 | 3 | 99.93 | 0.07 |

The mixing scheme mentioned in the ACI211 regulation per cubic meter has been used to make the concrete used in the specimens and achieve a minimum strength of 30 MPa. This ratio for construction is presented in Table 2.

Table 2: Specifications of consumable concrete

| Material | Water | Cement | Gravel | Sand |
|---|---|---|---|---|
| Amount ($kg/m^2$) | 230 | 510 | 750 | 750 |

Based on this ratio, a material mixing plan has been prepared and used to make specimens based on the table below for each number of beams.

Table 3: Specifications of consumable concrete

| Material | Water | Cement | Gravel | Almond gravel | Pea gravel |
|---|---|---|---|---|---|
| Amount ($kg/m^2$) | 9 | 17.5 | 56.25 | 20.75 | 12.25 |

### 4.3 Specifications of fibers

This paper has used the GFRP fibers. Tables 4 and 5 present all FRP mechanical and resin specifications. The mixing ratio of resin to hardener in this study is the Mixing ratio= 0.58: 1.

Table 4: Mechanical properties of the fibers

| Thickness(mm) | Modulus OF Elasticity (Gpa) | High strength(Mpa) | Fiber |
|---|---|---|---|
| 0.16 | 118 | 2060 | Glass Fiber |

Table 6 presents the complete specifications of the used rebars after the tensile test:

Figure 7: Specimen of fibers used in the specimens

Table 5: Specifications of the resin used

| **Tensile Strength** $N/mm^2$ | **Flextural Modulus** $N/mm^2$ | **Tensil Modulus** $N/mm^2$ |
|---|---|---|
| 30 | 2800 | 3500 |

Table 6: Specifications of the rebar used

| **Material** | **Water** | **Cement** | **Gravel** | **Almond gravel** | **Pea gravel** | **Pea gravel** |
|---|---|---|---|---|---|---|
| – | 25 | 360 | – | 240 | 6 | AI |
| 207 | 16 | 600 | 0.0021 | 400 | 8 | AIII |
| 207 | 16 | 600 | 0.0021 | 400 | 10 | AIII |

### 4.4 Preparing specimens for installing FRP fibers

The process of preparing the tensile surface for the installation of FRP fibers begins After 28 days of processing the specimens. A layer of the desired surface is removed using a milling machine and a stone for abrasion of concrete. There is no trace of concrete syrup, and its aggregates are visible. Then, any dust and pollution are removed from the concrete surface using a compressed air compressor. After completing the above steps, the specimens are prepared for reinforcement by the surface installation method. In the surface installation method, a thin and uniform adhesive layer is rubbed on the concrete surface; then, the FRP sheet is placed on it. The adhesive is removed using a spatula to ensure the FRP sheet's complete and uniform connection to the concrete surface. Then a uniform layer of adhesive is rubbed on the FRP sheet to protect the fibers and complete the proper bonding of the fibers to each other. The specimens are stored for seven days after the FRP sheet is glued and ready to be loaded.

## 5 Testing the specimens

All specimens were subjected to two articulated ends and four-point flexural loading to test. Loading is applied to control specimen displacement in the middle of the opening at a speed of 10 kg per second, with a 250-ton jack device recording the load-displacement diagram.

## 6 Discussion

The test results of beams are as follows. The Beam B1 has been considered a control specimen tested without external reinforcement and only for comparison with other beams. The final strength of this beam is 5553 kg with a displacement of 16.32 mm for the middle of the beam. The beam is debonded by bending cracks in the middle under a four-point bending load. The Beam B2 with two layers of GFRP is classically reinforced in tensile aspect and subjected to a four-point bending load. Before reaching the full bending capacity with reinforcement, the beam underwent debonding and was destroyed from the support to the application site at a load of 5866 kg and with a maximum displacement in the middle of the beam of 15.37 mm, due tobending and shear cracks tensile area. The

Beam B3 with three layers of GFRP is classically reinforced in tensile aspect and subjected to a four-point bending load. Before reaching the full flexural capacity with reinforcement, the beam underwent debonding and was destroyed from the support to the application site at a load of 7572 kg and with a maximum displacement in the middle of the beam of 15.58 mm, due to flexural and shear cracks in the tensile area. The Beam B4 is classically reinforced with two layers of GFRP, and then it continued in a U-shaped cover on the sides to 5 cm in a tensile manner and was subjected to a four-point bending load. The beam underwent debonding and was destroyed from the support to the application site at a load of 8149 kg and with a maximum displacement in the middle of the beam of 16.29 mm due to bending and shear cracks in the tensile area. The Beam B5 with three layers of GFRP is classically reinforced in tensile aspect and subjected to a four-point bending load. Before reaching the full flexural capacity with reinforcement, the beam underwent debonding and was destroyed from the support to the application site at a load of 9014 kg and with a maximum displacement in the middle of the beam of 16.45 mm due to flexural and shear cracks in the tensile area. Figure 8 shows the load-displacement diagrams for the specimens.

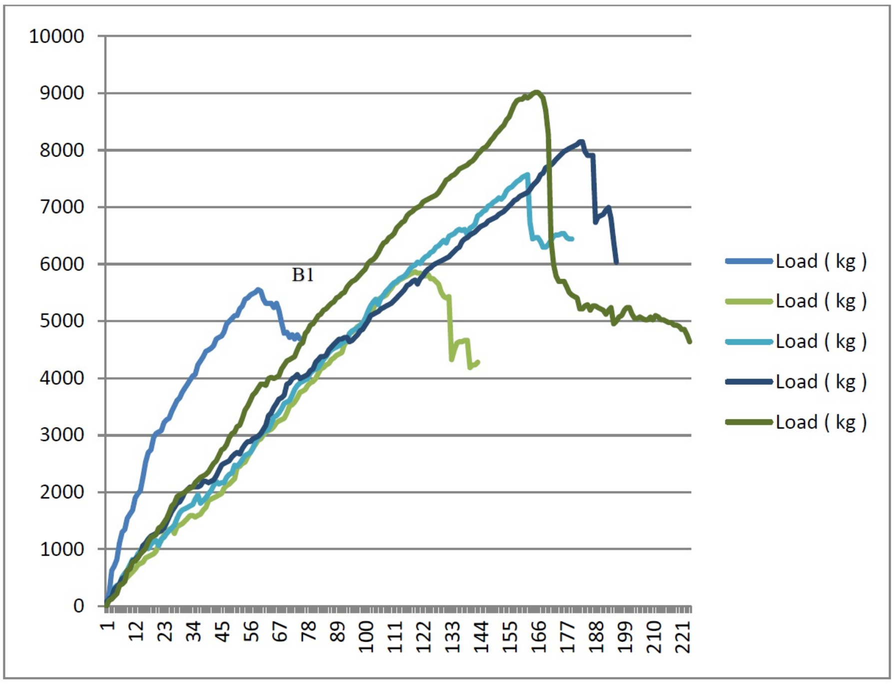

Figure 8: Load diagram - displacement of the specimen beams

Table 7 also summarizes the values of resistances and displacement for comparison.

Table 7: Comparison of test results on specimens

| **Specimen No.** | **Relocation of the middle of the opening in the final resistance (mm)** | **Final resistance (kg)** | **Percentage increase of final resistance compared to unreinforced state** |
|---|---|---|---|
| B1 | 16.32 | 5553 | – |
| B2 | 15.37 | 5866 | 10.56 |
| B3 | 15.58 | 7572 | 36.35 |
| B4 | 16.29 | 8149 | 46.74 |
| B5 | 16.45 | 9014 | 62.32 |

As can be seen, FRP sheets are beneficial for reinforcement. However, due to the debonding, the cross-sectional capacity is greater than the value obtained from the experiments. The theoretical study of cross-sectional capacity using ACI 3-818 was performed to investigate the case and compare the results of the above experiments and the theoretical results. Table 8 presents the results of theoretical calculations and experiments for comparison.

According to the tables and graphs, the cross-sectional capacity is higher in the U-shaped reinforced beam specimen (without increasing the FRP percentage) than in the classical model. In beam B2, the bending capacity in the experimental method is very close to the theoretical method. It was also observed that the amount of displacement in

Table 8: Bending capacity of sections according to calculations and tests

| **Specimen No.** | **Cross-sectional bending capacity according to calculations after reinforcement (kg)** | **Cross-sectional bending capacity according to post-reinforcement tests (kg)** | **Percentage difference with theoretical value** | **Percentage increase in capacity compared to unreinforced** | **Failure type** |
|---|---|---|---|---|---|
| B1 | 5800 | 5553 | 4.44% | – | Compressive |
| B2 | 6000 | 5866 | 2.28% | 10.56% | Debonding |
| B3 | 8400 | 7572 | 10.89% | 36.35% | Debonding |
| B4 | 9200 | 8149 | 12.89% | 46.74% | Debonding |
| B5 | 9800 | 9014 | 8.71% | 62.32% | Debonding |

Table 9: Displacement of sections according to experiments

| **Specimen number after reinforcement tests** | **Section displacement (mm)** |
|---|---|
| B1 | 16.32 |
| B2 | 15.37 |
| B3 | 15.58 |
| B4 | 16.29 |
| B5 | 16.45 |

this specimen is minimal. It can be said that this reinforcement method has caused a delay in beam failure and brought the flexural capacity closer to the computational results. Therefore, it can be said that this type of reinforcement is a new method to increase the bending capacity of the beams.

## 7 Conclusion

Numerous studies on the structural behavior of FRP thick reinforced beams show that although the application of composite materials in the execution during the reinforcement operation is successful, in most cases, there is a brittle debonding before the structures reach the final capacity obtained through the theoretical calculations. This can limit the advantages of this method by causing catastrophic outcomes. The most common debonding is split concrete cover and detachment of concrete joint surface and reinforcement plate. The reinforced beam shows a higher ultimate bearing capacity than the unreinforced state in all of these evaluations. However, no similar increase in beam yield has been reported. The experimental results showed that the three U-shaped layers of GFRP acted more and better than the other specimens and had a better performance in the biaxial bending test. The three-layer U-shaped GFRP sheet had the most significant effect on flexural reinforcement and debonding prevention compared to the classic U-shaped, two-layer, three-layer U-shaped, and two-layer GFRP sheets. The U-shaped two-layer has more resistance to external load pressure and is more significant than the U-shaped one-layer.

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