Effect of Steel and Prestressed GFRP Bars on Bending and Shearing Failure Modes in Reinforced Beams

Maedeh Orouji, Erfan Najaf
Department of Civil Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

Abstract
In recent years, there has been significant progress in using FRP materials as masonry in civil engineering. In this regard, researchers have investigated the behavior of reinforced beams with FRP and steel bars. One way to enhance these sections is to prestress FRP bars to increase sections’ bending and shearing strength. Reinforcing with a hybrid bar is a new method in which GFRP and steel bars are combined. In this research, the type of GFRP bars is first determined, and then samples are prestressed. Samples are modeled using LS-DYNA software. Bending and shearing failure modes of reinforced beams with FRP, GFRP, steel, and hybrid bars are analyzed, and finally, load-displacement behavior and crack width are compared. By studying the beam’s bending and shearing behavior and failure modes, we found out that using hybrid bars decreases the number of cracks wider than 0.35 mm in the same displacement and greater loading capacity. By comparing load-displacement diagrams of samples, we conclude that the sample reinforced with hybrid bars has the best function. We can benefit from the anti-corrosion property of GFRP bars by arranging the reinforcements properly. The loading capacity of the sample can be increased by about 65% by prestressing them. Consequently, the displacement of samples decreased.

Keywords
Reinforced Beams, Bending Failure, Prestressed GFRP, Shearing Failure, LSDYNA

Introduction
In 1893, for the first time, the US Department of Transportation (USDOT) invested in the "Transfer of Composite Technology to Design and Construction of Bridges" project. Bars and non-metal tendons were widespread in 1980 because of their strength against corrosion. In 1983, AKZO Corporation (maker of chemical materials in the Netherlands) and HGB Corporation worked together on aramid fiber reinforced polymer (AFRP) prestressed tendons. Japanese also worked on a national FRP plan to reinforce concrete structures. In 1980, Peter h bischoff studied FRP in reinforcing concrete structures and replacing them with steel bars. In fact, in this research, they focused on using FRP in concrete structures. In fact, in this research, they focused on using FRP in reinforcing concrete structures and replacing them with steel bars and prestressed steel tendons. In 2005, Peter h. bischoff studied reinforced concrete beams with FRP and steel bars and presented equations for stress-strain and load-moment diagrams. He presented equations for cracking and deformation of beams. He also presented equations for stress-strain and load-moment diagrams.

In 2009, Wenjun Qu conducted a Laboratory Investigation on the bending behavior of reinforced concrete beams with GFRP and steel bars. First, he built eight concrete samples with different reinforcement percentages of GFRP and steel and hybrid bars. After applying load on beams and studying the output, he obtained some results. In 2014, D.De.Domenico analyzed concrete elements reinforced with FRP bars. His analysis was based on finite element (FE-base). In 2015, Meher A.Adam conducted a numerical laboratory on the bending behavior of concrete beams reinforced with GFRP bars. They experimented with nine models with different reinforcement percentages and obtained some results.

Modeling
LS-DYNA and EXCEL were used in order to obtain results. First, a base for modeling by collecting data was prepared, and then models were built in LS-DYNA. After analyzing, results were stored in EXCEL and presented in diagrams.

Data Analysis method using LS-DYNA
LS-DYNA is one of the famous Hydro-codes with great ability to solve non-linear dynamic problems. Great ability of this code in analyzing detonation problems, shock wave diffusion, forming metals with large deformations, the collision of bodies, Infiltration of the projectile in the target, ... and also having about 200 model types and 13 equations of state and many types of contact, has turned this code into one of the strongest engineering software that can be used in solving detonation and impact problems.

It should be noted that, like many other engineering software, this software cannot provide an accurate diagnosis of Physical phenomenon alone.

Choosing proper Model type and equation of state, having information about Material specifications and required parameters of the model, initial and boundary conditions, and Proper definition of contact requires these numerical methods to be used along with empirical results. The method of solving also has a significant impact on results.

Lagrangian, Eulerian, Lagrangian-Eulerian Coupling, SMALE, MMASE, and SPH solution methods are used. Each solving method has advantages and disadvantages. The solution method has to be determined considering the type of problem.

Validation
To write this article, "Flexural Behavior of Concrete Beams Reinforced with Hybrid (GFRP and Steel) Bars' article was used, and modeled the results in software and compared them.

The mentioned article belongs to Wenjun Qu, Xiaoliang Zhang, and Haiqun Huang’s cooperation (Fig 1-3)
They built eight concrete beam models 210 centimeters in length and tested the push-over experimentation on them. They achieved the bending behavior of concrete beam reinforced with GFRP and steel bars and in the end, they presented the results on a load-displacement diagram.

There were negligible differences between diagrams, so our model was accurate, and we could begin the Main modeling.

**Evaluation and analysis**

After validation and ensuring that our model was correct, the main modeling begins. To get started, the material specifications of the model were determined. We used the same concrete Specifications used in Wenjun Qu’s article.

To determine the used steel, we had limited choices. So steel is determined according to Figure 6.
Determining specifications of used GFRP in analysis

We had many problems determining the GFRP bar. There was a wide range of numbers because of physical specifications like twisting bar strings, the thickness of strings, and so on.

In a long-term analysis on reinforced beams with GFRP bars, Yeonho Park considered the tensile strength of GFRP bars in the range of 655 to 1300 MPa (Table 1).

<table>
<thead>
<tr>
<th>FRP Bar Type</th>
<th>Bar size</th>
<th>Nominal Diameter (mm)</th>
<th>Nominal Area (mm²)</th>
<th>Guaranteed Tensile Strength (MPa)</th>
<th>Tensile Modulus of Elasticity (GPa)</th>
<th>Tensile Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA Series #4</td>
<td>13</td>
<td>126.7</td>
<td>690</td>
<td>40.8</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>16</td>
<td>197.9</td>
<td>655</td>
<td>40.8</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>GH Series #4</td>
<td>13</td>
<td>126.7</td>
<td>1300</td>
<td>60</td>
<td>2.42</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>16</td>
<td>197.9</td>
<td>1259</td>
<td>64.1</td>
<td>2.24</td>
<td></td>
</tr>
<tr>
<td>Steel (Grade 60) #4</td>
<td>12.7</td>
<td>129</td>
<td>620</td>
<td>200</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>#5</td>
<td>15.875</td>
<td>200</td>
<td>620</td>
<td>200</td>
<td>9.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Specifications of GFRP bars by Wenjun Qu

<table>
<thead>
<tr>
<th>Rebar Diameter (mm)</th>
<th>Tensile Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>778</td>
<td>37.7</td>
</tr>
<tr>
<td>12.7</td>
<td>782</td>
<td>45</td>
</tr>
<tr>
<td>15.9</td>
<td>755</td>
<td>41</td>
</tr>
</tbody>
</table>

Wenjun Qu classified GFRP bars into three groups and three different strengths based on their diameter.

In the ACI manual, the tensile strength of GFRP bars and generally FRP bars is considered 620.6 MPa regardless of their diameter or twisting type of strings. A Coefficient is multiplied only based on the material of the bars (Table 3).

The amount of used reinforcement is determined using allowable reinforcement amount equations ($p' b$) and its range is considered 0.6 to 1.4. Samples are considered $1.4p' b$, $0.6p' b$, and $p' b$ respectively.

How to get output in software

Most of the Finite element software usually evaluates load and displacement in two different diagrams with the time factor. LS-DYNA software follows the same role and presents the output as displacement-time and load-time diagrams (Fig 9).

Start of analysis

After determining material specifications, we began to build models and do analysis. Nine concrete models were used for this purpose. Three of the concrete beams were reinforced with GFRP bars, three with steel bars, and the other three with Hybrid (GFRP and Steel) Bars. The length of beams is 4.9 meters, their height is 18 centimeters, and their width is 25 centimeters.
In addition, considering the long analysis time, it can be observed in the concrete beam (Fig 11).

As you see, each row contains two numbers: force and time. In a similar way, the numbers related to displacement are obtained, and finally, the load-displacement diagram is drawn as EXCE.(Fig 12-20)

Figure 11. Different types of cracks in concrete beam diagram output of LSDYNA

Figure 12. Load-displacement diagram of concrete model with GFRP bar with 0.6 $p'_b$

Figure 13. Load-displacement diagram of concrete model with GFRP bar with 1.4 $p'_b$

Figure 14. Load-displacement diagram of concrete model with GFRP bar with $p'_b$

Figure 15. Load-displacement diagram of concrete model with steel bar with 0.6 $p'_b$

Figure 16. Load-displacement diagram of concrete model with steel bar with 1.4 $p'_b$
Figure 17. Load-displacement diagram of concrete model with steel bar with \( p'_{b} \)

Figure 18. Load-displacement diagram of concrete model with Hybrid bar with 0.6 \( p'_{b} \)

Figure 19. Load-displacement diagram of concrete model with Hybrid bar with 1.4 \( p'_{b} \)

Figure 20. Load-displacement diagram of the concrete model with Hybrid bar with \( p'_{b} \) and 25 percent of pre-stressing

Figure 21. Load-displacement diagram of concrete model with 1.4 \( p'_{b} \) and 25 percent of pre-stressing

Figure 22. Load-displacement diagram of concrete model with 1.4 \( p'_{b} \) and 50 percent of pre-stressing

Figure 23. Load-displacement diagram of concrete model with \( p'_{b} \) and 25 percent of pre-stressing

Figure 24. Load-displacement diagram of concrete model with \( p'_{b} \) and 50 percent of pre-stressing
Figure 25. Load-displacement diagram of concrete model with $p'_b$ and 75 percent of pre-stressing

Figure 26. Load-displacement diagrams of concrete samples with GFRP bars

Comparing load-displacement diagrams of modeled samples with GFRP bar

By analyzing reinforced samples with GFRP bars, these results were obtained:

1. All samples had almost the same function and the same loading capacity until displacement of 90 mm. After the displacement of 90 mm, the gradient of load-displacement diagrams in the samples with a greater percentage of reinforcement increased.
2. None of the reinforcements in samples yielded; all of the samples failed when concrete was crushed.
3. Increasing ratio of reinforcing about 40% (increasing percentage of reinforcement from $0.6p'_b$ to $p'_b$), caused an increase of 15% in displacement and 56% in loading capacity.
4. Re-increasing the percentage of reinforcement from $p'_b$ to $1.4p'_b$, caused an increase of 9% in displacement and 38% in load capacity.
5. In total, an increasing percentage of reinforcement in the allowable range from $0.6p'_b$ to $1.4p'_b$, caused an increase of 20% in displacement and 112% in loading capacity.

Load-displacement diagrams of three reinforced samples with GFRP bars are presented in Figure 25.

Comparing load-displacement diagrams of modeled samples with steel bar

By analyzing reinforced samples with steel bars, these results were obtained:

1. An increasing percentage of reinforcement in the concrete sample from $0.6p'_b$ to $p'_b$, causing an increase of 5% in displacement and 45% in loading capacity in yielding point. And finally, applying more displacement to the sample caused 37% increase in loading capacity, but displacement decreased about 26%.
2. An increasing percentage of reinforcement in a concrete sample from $p'_b$ to $1.4p'_b$, caused an increase of 66% in displacement and 98% in loading capacity in yielding point and finally, applying more displacement to the sample caused 20% increase in loading capacity, but displacement decreased about 4%.
3. In total, an increasing percentage of reinforcement from $0.6p'_b$ to $1.4p'_b$ caused:
   a. An increase of 66% in displacement and 95% in loading capacity.
   b. An increase of 62% in loading capacity and a decrease of 45% in displacement in failing point.

Load-displacement diagrams of three reinforced samples with steel bars is presented in Figure 26.

Results

- By comparing load-displacement diagrams of samples, we conclude that the sample reinforced with hybrid bars has the best function. We can benefit from the anti-corrosion property of GFRP bars by arranging the reinforcements properly.
- The loading capacity can increase the sample by prestressing them about 65%. Consequently, the displacement of samples decreased.
- By studying the beam’s bending and shearing behavior and failure modes, we found out that using hybrid bars decreases the number of cracks wider than 0.35 mm in the same displacement and greater loading capacity.
- The prestressing sample also decreases the number of bending, and shearing cracks wider than 0.35 mm in the same displacements.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
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