Investigating the Bending and Shearing Failure Modes in Reinforced Beams With Steel and Pre-Stressed GFRP Bars

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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 pre-stressing FRP bars to increase the bending and shearing strength of sections. Reinforcing with hybrid bar is a new method in which GFRP and steel bars are combined. In this research, first, the type of GFRP bars is determined, and then samples are pre-stressed. Samples are modeled using LSDYNA 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.

1. Introduction
In 1893, for the first time, US Department of Transportation (USDOT) invested on “Transfer of Composite Technology to Design and Construction of Bridges” project. bars and non-metal tendons outspreaded in 1980 because of their strength against corrosion. In 1983, AKZO Corporation (manufacturer of chemical materials in Netherlands) and HGB Corporation, worked together on AFRP pre-stressed tendons. Japanese also worked on a national plan of using FRP in reinforcing concrete structures. In 1980, Japanese researchers began to produce techniques for 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 pre-stressed steel tendons.

In 2005, Peter. h. bischoff studied reinforced concrete beams with FRP and steel bars and presented equations for cracking and deformation of beams. He presented equations for stress-strain and load-moment diagrams.

In 2009, Wenjun Qu conducted a Laboratory Investigation on 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 numerical laboratory on bending behavior of concrete beams reinforced with GFRP bars. They experimented nine models with different reinforcement percentages and obtained some results.

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

2.1. Data Analysis method using LSDYNA:
LS-DYNA is one of the famous Hydro-codes that has great ability in solving non-linear dynamic problems. Great ability of this code in analyzing detonation problems, shock wave diffusion, forming metals with large deformations, 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 model, initial and boundary conditions, and Proper definition of contact requires these numerical methods to be used along empirical results. The method of solving has also a significant impact on results.

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

2.2. 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 Haigun Huang cooperation. fig 1-3.

They built eight concrete beam models with 210 centimeters 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.
Figure 1. Concrete beam prepared by Wenjun Qu

Figure 2. Eight concrete beam models prepared by Wenjun Qu

Figure 3. ASTM-C78 standard test machine

Figure 4. Comparing the load-displacement diagram of B6 beam obtained from the article and LSYDNA outlet. The obtained diagrams were overlapped from the test and software in EXCEL to see the difference (Figure 4).

Figure 5. Specifications of used concrete in analysis. There were negligible differences between diagrams, so our model was accurate, and we could begin the Main modeling.

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

3.1. Determining specifications of used GFRP in analysis. We had many problems determining the GFRP bar. There were a wide range of numbers because of physical specifications like the way of twisting strings of the bar, thickness of strings, and ... In a long-term analysis on reinforced beams with GFRP bars, Yeonho Park considered the tensile strength of GFRP bars in range of 655 to 1300 MPa (Table 1).
Table 1. Specifications of GFRP bars by Yeonho Park

<table>
<thead>
<tr>
<th>FRP Bar Type</th>
<th>Bar Size (mm)</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>126.7</td>
<td>690</td>
<td>40.8</td>
<td>1.50</td>
</tr>
<tr>
<td>Type A</td>
<td>16</td>
<td>197.9</td>
<td>197.9</td>
<td>655</td>
<td>40.8</td>
<td>1.50</td>
</tr>
<tr>
<td>GH Series 4</td>
<td>13</td>
<td>126.7</td>
<td>1300</td>
<td>1300</td>
<td>60.0</td>
<td>2.42</td>
</tr>
<tr>
<td>Type B</td>
<td>16</td>
<td>197.9</td>
<td>1259</td>
<td>1259</td>
<td>64.1</td>
<td>2.24</td>
</tr>
<tr>
<td>Steel</td>
<td>12.7</td>
<td>129.0</td>
<td>620 (415 yield)</td>
<td>620</td>
<td>200</td>
<td>9.00</td>
</tr>
<tr>
<td>Grade 60</td>
<td>15.875</td>
<td>200</td>
<td>620 (415 yield)</td>
<td>200</td>
<td>9.00</td>
<td></td>
</tr>
</tbody>
</table>

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

In ACI manual, 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 material of the bars (Table 3).

Table 3. Considered coefficients for FRP bars by ACI

<table>
<thead>
<tr>
<th>Exposure condition</th>
<th>Fiber type</th>
<th>Environmental reduction factor Cₑ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete not exposed to earth and water</td>
<td>Carbon</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Aramid</td>
<td>0.9</td>
</tr>
<tr>
<td>Concrete exposed to earth and water</td>
<td>Carbon</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>Aramid</td>
<td>0.8</td>
</tr>
</tbody>
</table>

3.2. Start analysis

After determining material specifications, we began to build models and do analysis. Nine concrete models were used for this purpose. three of concrete beams were reinforced with GFRP bars, three of them with steel bars and reinforced the other three with Hybrid (GFRP and Steel) Bars. Length of beams are 4.9 meters, their height are 18 centimeters and their width are 25 centimeters.

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 1.4\( p'_{b} \), 0.6\( p'_{b} \) and \( p'_{b} \) respectively.
In addition, considering the long analyze time, can be observed in concrete beam (Figure 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 load-displacement diagram is drawn is EXCE (Figure 12-20).
3.3. Pre-stressing the samples

After getting outputs, we pre-stressed two reinforced concrete samples with hybrid bars with different reinforcement percentages of 50 and 25 (Figure 21-22).

Figure 16. Load-displacement diagram of concrete model

Figure 17. Load-displacement diagram of concrete model

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 concrete model with Hybrid bar with $p'_{b}$

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
3.4. Comparing load-displacement diagrams of modeled samples with GFRP bar

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

a. All samples had almost the same function and the same loading capacity until displacement of 90 mm. After displacement of 90 mm, gradient of load-displacement diagrams in the samples with greater percentage of reinforcement increased.

b. None of the reinforcements in samples yielded, all of the samples failed when concrete crushed.

c. Increasing ratio of reinforcing about 40% (increasing percentage of reinforcement from $0.6 \rho_b$ to $\rho_b$), caused an increase of 15% in displacement and 56% in loading capacity.

d. Re-increasing the percentage of reinforcement from $\rho_b$ to $1.4\rho_b$, caused an increase of 9% in displacement and 38% in load capacity.

e. In total, increasing percentage of reinforcement in allowable range from $0.6 \rho_b$ to $1.4 \rho_b$, caused an increase of 20% in displacement and 112% in loading capacity.

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

3.5. Comparing load-displacement diagrams of modeled samples with steel bar

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

a. Increasing percentage of reinforcement in concrete sample from $0.6 \rho_b$ to $\rho_b$, caused 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%.

b. Increasing percentage of reinforcement in concrete sample from $\rho_b$ to $1.4\rho_b$, 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%.

c. In total, increasing percentage of reinforcement from $0.6 \rho_b$ to $1.4 \rho_b$, caused:

An increase of 66% in displacement and 95% in loading capacity.

An increase of 62% in loading capacity and decrease of 45% in displacement in failing point.

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

4. Conclusion

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 be increased of sample by pre-stressing them about 65%, consequently, displacement of samples decreased. By studying bending and shearing behavior and failure modes of the beam, 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. Pre-stressing 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 author(s) declare(s) 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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