Performance of High-Strength Concrete One-Way Slabs with Embedded BFRP Bar Reinforcement

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Abstract
Since the invention of reinforced concrete, steel bars had been used as tension device to resist tensile stresses. Recently, several experimental and theoretical studies have been achieved to verify that FRP composites bars (CFRP and GFRP) may be a good competitive alternatives due to strength, durability and weight aspects. Few studies have been published about the performance of BFRP bars in reinforced concrete simply supported or continuous slabs. Thus, In the present work, a theoretical study based of the finite element approach is achieved utilizing ANSYS-15 package to investigate the performance of the reinforced concrete one-way slabs with embedded basalt (BFRP) bars under monotonic loads. Six slabs have been considered, two were simply supported and four were continuous each with two-span. Several parameter have been studied such as continuity condition, reinforcement ratio, position of reinforcement and the effect of replacement basalt bars by steel bars.

It is concluded that slabs reinforced with BFRP bars have lower performance if compared with that reinforced with steel bar reinforcement. Also, it is found that the steel is more effective in bottom face within the midspan zone and basalt bars are inactive in top compression zone. It is found with an efficient distribution of bars that for slab with reinforcement ratio of 0.7%, the load capacity is improved by 12.5% and a reduction in max. deflection 46%, while the load capacity is improved by 61% when adopting a ratio of 1% while the max. deflection is reduced by 56%.

Keywords: basalt bars, one-way slabs, over-reinforced, under-reinforced, crushing

1. Introduction
In the last few decades ago, polymer composites (FRP) as glass, carbon, and aramid were considered as an efficient alternative to the corroded reinforcing steel bars that causing deterioration of concrete elements caused by severe environment. Fiber polymer composites have some merits over steel as its high tensile strength, high stiffness/weight ratios, and being good resistant to corrosion and chemical effects, thermally controlled, good damping features, and electromagnetic inactivity (Issa et al., 2016).

Polymer composites have been used as main reinforcement in some concrete infrastructures such as bridges, substructure members, slabs, retaining walls that may be affected by corrosion. Recently, fibers made from Basalt have been utilized in introducing a new version of FRP composite, called as basalt fiber-reinforced polymer (BFRP). The most common figure of such composite is to be as bars. Such bars provided suitable substitution to the classical FRP bars (El Refai, 2015; Ge et al., 2015).

Basalt fibers are friendly environment, no-toxicity effects, corrosion resistant, Not affected by magnetism, less susceptible to heat with good insulation properties (Marlena & Bartlomiej, 2014; Meng et al., 2015). The tensile strength of continuous basalt fibers is about two times that of E glass fibers and the elastic modulus is about 15-30% higher (Ramakrtshnan and Panchalan, 2012). Based on these merits, it can be widely used in different structures such as barriers of highway, offshore structures and bridges.

In the last few years, some researches were reported on the response of concrete slabs/beams containing embedded FRP bars with simple spans. but very little studies were achieved on the behavior of continuous concrete slabs reinforced with FRP bars. Thus, this work, adopted the finite element approach to study the performance of the concrete one-way slabs with embedded basalt fiber reinforced polymer (BFRP) bars as reinforcing elements instead of the conventionally used deformed steel bars. Also, the effect of gradual substitution of BFRP bars with steel bars on the load-deflection curve is investigated.
2. Geometry of Tested Slabs

The one-way reinforced concrete slabs that have been considered in the present study were tested experimentally by Mahroug et al. The tested slabs consist of six specimens; two are simply supported slabs as shown in Figure 1 and four are continuous with different ratios of BFRP bars as shown in Figure 2. Thickness of all slabs is 150mm while the width is 500 mm with span between each two successive supports is 2000 mm with cover of reinforcement is 25mm. Designations of slabs, properties concrete are listed in Table 1, while the material Properties of FRP and Steel Reinforcing Bars are listed in Table 2. Also, Mahroug et al., analyzed the tested slabs using the ACI-440 committee method to achieve a comparison between the results recorded experimentally and those obtained theoretically.

![Figure 1. Details of the simply supported slabs (Mahroug, et al., 2014)](image1)

![Figure 2. Details of the continuous slabs (Mahroug, et al., 2014)](image2)

<table>
<thead>
<tr>
<th>Slab notation</th>
<th>reinforcing bars</th>
<th>Concrete strengths(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at mid-span(bottom face)</td>
<td>at interior support(top face)</td>
</tr>
<tr>
<td></td>
<td>No. of bars</td>
<td>Bar dia.(mm)</td>
</tr>
<tr>
<td>SU</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>SO</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>COO</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>COU</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>CUO</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>CUU</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>

S: simple span; U: under reinforced; O: over-reinforced; C: continuous beam
Table 2. Properties of BFRP and steel reinforcing bars (Mahroug et al., 2014)

<table>
<thead>
<tr>
<th>Type of bars</th>
<th>Bar dia.(mm)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Tensile strength(MPa)</th>
<th>Ultimate strain</th>
<th>Yield strength(MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFRP</td>
<td>8</td>
<td>50</td>
<td>1250</td>
<td>0.025</td>
<td>------</td>
</tr>
<tr>
<td>BFRP</td>
<td>10</td>
<td>50</td>
<td>1350</td>
<td>0.027</td>
<td>------</td>
</tr>
<tr>
<td>steel</td>
<td>10</td>
<td>200</td>
<td>645</td>
<td></td>
<td>575</td>
</tr>
</tbody>
</table>

3. Material Properties

3.1 Concrete

An elasto-plastic relationship up to the compressive strength is adopted to represent the compressive uni-axial stress-strain behavior. Then, a perfectly plastic response is adopted up to the instant of crushing. Such behavior is shown in Figure 3 and it can be represented using the following equations:

\[ f_c = \varepsilon Ec \quad \text{for} \quad 0 \leq \varepsilon \leq \varepsilon_1 \]  
\[ f_c = \varepsilon E_{c1} \left(1 + \frac{\varepsilon}{\varepsilon_0}\right)^2 \quad \text{for} \quad \varepsilon_1 \leq \varepsilon \leq \varepsilon_0 \]  
(Wolanski, 2004)
\[ f_c = f_c' \quad \text{for} \quad \varepsilon_0 \leq \varepsilon \leq \varepsilon_u \]  

and

\[ \varepsilon_1 = 0.3 * f_c'/E_c \]  
(Hooke's law)
\[ \varepsilon_0 = 2f_c'/E_c \]  
\[ E_c = 3.3 * \sqrt{f_c'} + 6.9 \]  
(Kumar et al., 2012)

Figure 4 shows the stress stiffening model adopted to represent concrete in tension. The initial modulus of elasticity is used up to the first crack. Then, the smeared crack approach was utilized to represent spreading of cracks.

3.2 BFRP and Steel Bars

In the present work, the stress-strain relations shown in Figure 5 are adopted to emulate the behavior of reinforcement of slabs. For basalt bars, the behavior is assumed elastic up to the tensile strength (ft). While, a bilinear stress-strain curve is adopted to simulate the steel behavior, full bond between concrete and reinforcement bars is assumed, but this may result in a noticeable difference from the experiments because of the small thickness allowing the slab to deform more than RC beams. To accommodate this problem, very small values for the open crack factor for concrete is assigned (\(\alpha_1=0.05\)) corresponding to a value of about (0.2) is generally assumed for RC beams.

4. Finite Element Modeling

Due to symmetry, a quarter of full slab was considered as shown in Figure 6. Shown are also, boundary condition and loading condition supports.

The elements adopted in the present study were:

Solid element, solid 65 used to simulate concrete.
Solid element, solid 185 used to simulate loading and supporting plates.
3-dim spar element, link180 used to represent steel and basalt bars.
Because that FRP bars in general are weak to resist compression comparing with steel bars. Then, link180 that represents such bars is made inactive when being in compression. In this model, a typical node has a translational degree of freedom with respect to each one of the coordinate axis.
5. Load-Deflection Results

As it has been mentioned previously that the behavior of the slabs considered in the present study have been estimated by Mahroug et. al. (2014) using the method of ACI-440 committee to compare with the experimental tests. The results for the tested slabs are shown in Figures 7 to 12. The load mid-span deflection records for the specimens SO and SU are shown in Figures 7 and 8 respectively. It can be seen that the FEM analysis for the simply supported slabs seems to be very close to that experimentally obtained prior to cracking followed by some stiffer behavior at final stages of loading. This may be due to the assumption of full bond between concrete and BFRP bars adopted in this study. This bond diminishes with the progress of loading and spreading of cracks around steel resulting from slippage of the basalt bars.

Also, it is obvious that the method reported by ACI 440 committee yields acceptable results for the over reinforced concrete simply supported slab (SO) rather than the under reinforced slab (SU). This supports the fact that the slip effect is more obvious with sections of lower ratios of longitudinal reinforcement and it seems that the ACI method didn’t treat the slip problem and the method tends to adopt high bond between reinforcing bars and concrete.

Figures 9 to 12 show the load-deflection curves for specimens SOO, SOU, SUO, SUU respectively. It can be realized generally, that a good agreement between the FEM results with experimental tests better than the ACI-440 committee results. The deflection recorded by experiments and those estimated theoretically are arranged in Table 3. It is clear that the degree of agreement for FEA (ANSYS) with experiments ranges from 99% to 109% and there some overestimation of the maximum deflection. Figure 13 illustrates the excellent agreement in load capacity and emphasizes that ANSYS can be considered as a powerful tool to estimate the behavior of such slabs reinforced with basalt bars simply supported or with continuous spans.

Taking a glace on the ratios of maximum deflection of ACI method with respect to that experimentally recorded, it is simply can be concluded that the ACI method tends to underestimate the value of maximum deflection by at least of 19% with a range of difference of (19%-49%) corresponding to (1%-9%) for FEA achieved in the present study. Comparing the results of specimens CUO , COU and COO, it can be seen that with an efficient distribution of bars (adopting CUO rather than COU ) for slab with reinforcement ratio of 0.7%, the load capacity is improved by 12.5% and a reduction in max. deflection 46%. While when the reinforcement is increased up to 1%, the load capacity is improved by 61% with a reduction in max. deflection by 56%.

It can be concluded that for reinforced concrete continuous slabs and one-way slabs reinforced BFRP bars, a slight improvement in load capacity is noticed when reinforcement ratio is lower than 0.7%. Beyond that, a considerable enhancement was seen. Therefore, when it is intended to use BFRP bars as reinforcement, it is recommended to adopt over reinforced sections.

![Figure 7. Load –deflection curves of the slab SU](image1)

![Figure 8. Load –deflection curves of the slab SO](image2)
Figure 9. Load–deflection curves of the slab COO

Figure 10. Load–deflection curves of the slab COU

Figure 11. Load–deflection curves of the slab CUO

Figure 12. Load–deflection curves of the slab CUU

Table 3. Maximum deflections recorded for the tested slabs (mm)

<table>
<thead>
<tr>
<th>Slab notation</th>
<th>Experiment (Δ_{exp})</th>
<th>Present study, (% Δ_{exp})</th>
<th>ACI 440(%Δ_{exp})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU</td>
<td>66</td>
<td>63.88(97%)</td>
<td>53.5(81%)</td>
</tr>
<tr>
<td>SO</td>
<td>65</td>
<td>66.7(102%)</td>
<td>55(85%)</td>
</tr>
<tr>
<td>COO</td>
<td>32</td>
<td>35(109%)</td>
<td>26(81%)</td>
</tr>
<tr>
<td>COU</td>
<td>26.5</td>
<td>26.6(100%)</td>
<td>16(60%)</td>
</tr>
<tr>
<td>CUO</td>
<td>48</td>
<td>48.4(101%)</td>
<td>37(77%)</td>
</tr>
<tr>
<td>CUU</td>
<td>54.3</td>
<td>54(99%)</td>
<td>28(51%)</td>
</tr>
</tbody>
</table>

6. Parametric Study

The continuous slab COO have been chosen to conduct the parametric study, the BFRP bars have been replaced gradually with steel bars and the slab is analyzed. Figure 14 shows the load–deflection curves when replacing one,
three and five BFRP bars at the bottom face by steel bars while keeping the top Basalts bars at the top face. Figure 15 shows the effect of changing the basalt bars at the top face by steel bars with keeping the bottom bars without replacement. Figure 16 shows the variation of response of the slab when replacing both the top and bottom basalt bars by steel bars simultaneously, i.e. one top/one bottom, three top/three bottom, five top/five bottom. It can be seen that replacement the bottom bars yield better results than replacing the top bars. Also, the replacement both top and bottom bars results in better response that the replacement of bottom bars only. This behavior can be realized easily if by remembering that bottom reinforcement affects on the mid-span of two spans, while top reinforcement affects the portion at interior support only.
7. Conclusions

1. The ACI code results is found to be more acceptable to predict behavior of simply supported slabs, especially for over reinforced slab sections, and less convergence with experiments for slabs with under reinforced sections with maximum divergence for the under-reinforced specimens.

2. It is found with an efficient distribution of bars (changing from CUO to COU) that for slab with reinforcement ratio of 0.7%, the load capacity is improved by 12.5% and a reduction in max. deflection 46%. while the load capacity is improved by 61% when adopting a ratio of 1% while the max. deflection is reduced by 56%.

3. For reinforced concrete continuous slabs and one-way slabs reinforced BFRP bars, a slight improvement in load capacity is noticed when reinforcement ratio is lower than 0.7% beyond that, a considerable enhancement was seen. Therefore, when it is intended to use BFRP bars as reinforcement, it is recommended to adopt over reinforced sections.

4. The nonlinear model adopted in the present investigation has a good agreement with the experiment tests for simply supported specimens. for continuous slabs, it is found that there is some divergence from experimental results in some stages beyond the first crack.

Notation

\( f_c \): stress at any strain \( \varepsilon \), (MPa)

\( \varepsilon_1 \): strain at end of elastic stage.

\( \varepsilon_o \): strain at end of elastic-plastic stage (at \( f_c \)).

\( \varepsilon_u \): strain at failure.

\( E \): concrete elastic modulus, taken in (MPa)

\( \alpha_m \): tension stiffening factor

\( f_t \): tensile strength of concrete

\( f_y \): steel yield stress

\( f_{ud} \): ultimate strength of steel or BFRP bars

Coding of Specimens

Specimen designation is either \( S_1S_2 \) (for simple spans) or \( S_1S_2S_3 \) (for continuous spans)

where;

\( S_1 \): simple span (S) or continuous (C)

\( S_2 \): ratio of reinforcement at bottom face (U or O)

\( S_3 \): ratio of reinforcement at top face (U or O)

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