FLEXURAL ANALYSIS OF ONE-WAY CONCRETE SLABS REINFORCED WITH GFRP REBARS

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Abstract
In the paper an investigation on the flexural behaviour of FRP reinforced concrete one-way slabs, is presented. Cracking and deflection of FRP reinforced concrete structures are analysed both theoretically and experimentally. A general non-linear procedure, founded on slip and bond stresses, is adopted for prediction of cracking and deflections, while the experimental investigation refers to one-way slabs concrete structures reinforced with GFRP deformed rebars (C-BAR™). Four one-way slabs, three reinforced with GFRP rebars and one reinforced with traditional steel rebars, have been tested up to failure varying the reinforcement ratio, the rebar diameter and the rebar spacing. The comparison between deflections, crack configurations and crack width of GFRP reinforced slabs and those of steel reinforced concrete slabs is carried out and the different behaviour is analysed and discussed. Finally a comparison is made between experimental results and theoretical predictions.

Introduction
Fiber Reinforced Polymer (FRP) materials are currently used as reinforcement for concrete structures in which corrosion protection is a primary concern. FRP materials are corrosion resistant and exhibit several properties that make them suitable as structural reinforcements. However, the use of FRP materials in substitution of steel reinforcements requires a better understanding of the behavior of FRP reinforced concrete members. Current design codes provide no guidance on how to modify the existing requirements when reinforcing with materials other than steel [1].

Physical and mechanical properties of FRPs are, in fact, very different from those of steel. Such differencies arise both from materials properties and interaction mechanism between the FRP reinforcement and the concrete [2]. As a consequence, procedures and methodologies adopted for the design of steel reinforced concrete members, cannot be used for the analysis of FRP reinforced concrete members. Such structures, as well-known, in comparison with steel reinforced concrete structures have lower stiffness and, hence, larger deflection and crack widths are expected [3, 4].

An analysis of flexural behavior of FRP reinforced concrete structures is, then, essential both to evidence the influence of parameters governing the static problem and to obtain useful information for design purpose.

The analysis described in the paper, refers to FRP reinforced concrete one-way slabs; structures in which the main state of stress is of flexural type. The behavior of FRP reinforced concrete slabs is not well understood since the stiffness of a member degrades rapidly after cracking and serviceability may become the design driver.

The flexural behavior of slabs reinforced with Glass FRP is investigated both theoretically and experimentally. A non-linear procedure is adopted to evaluate the deformability of a cracked element; the procedure, found based on slip and bond stresses, allow to determine crack widths, crack spacing and deflections. Flexural tests were made on slabs up to failure in static loading condition. Parameters considered in the analysis include type of reinforcement (steel and FRP), amount and size of FRP rebars and thickness of concrete cover.

The objective of the analysis were: i) investigate the ultimate strength of GFRP reinforced concrete slabs and the modes of failure, ii) examine the flexural behavior regarding deflection, crack width and ductility in comparison with steel reinforced concrete slabs, iii) address the factors that influence the flexural behavior; iv) propose a design approach for computing the flexural capacity, crack width and deflection.

A comparisons between experimental results and theoretical predictions is made and obtained results are presented and discussed.

**Experimental investigation**

In the following are described the first results of an on going experimental research program. Four full-scale, reinforced concrete one-way slabs have been tested up to failure. The slabs were divided into two series designated as A and B. Series A, focused on the flexural behavior of simply supported slabs reinforced with deformed GFRP rebars while series B addressed the flexural behavior of slabs reinforced with conventional steel rebars and provide a base line for comparison purposes. The variables investigated included the amount of reinforcement, the reinforcement size and spacing, the concrete cover thickness. All slabs were designed to fail in flexure.

The slabs had a total span of 2743.2 mm and a rectangular cross-section of 457.2 mm wide and 101.6 mm deep. The details and dimensions of the tested slabs are given in Table 1.

**Materials properties** All the slabs were made from the same batch of a ready-mix normal weight concrete and were used conventional fabrication and curing techniques. Twelve 150 x 300 mm concrete cylinders were cast along with each group and cured under the same conditions as the specimens. The cylinders were tested just after the completion of the specimen test; the average compressive concrete strength was determined to be 26.21 MPa. The composite bar used were C-BAR, Glass FRP reinforcing bars manufactured Marshall Industries Composites, Inc. Mechanical properties of these bars are given in Table 1.

<table>
<thead>
<tr>
<th>SLABS</th>
<th>d (mm)</th>
<th>Rebars**</th>
<th>$A_r$(mm$^2$)</th>
<th>$F_r$ (MPa)</th>
<th>$E_r$ (GPa)</th>
<th>$\varepsilon_{ru}$</th>
</tr>
</thead>
</table>

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<table>
<thead>
<tr>
<th>Slab</th>
<th>d (mm)</th>
<th>N</th>
<th>Area (mm²)</th>
<th>Ultimate Tensile Strength (MPa)</th>
<th>Young's Modulus (GPa)</th>
<th>Strain at Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB3</td>
<td>76.20</td>
<td>2</td>
<td>2 # 4</td>
<td>253.35</td>
<td>815.48</td>
<td>42.9</td>
</tr>
<tr>
<td>SB4</td>
<td>76.20</td>
<td>3</td>
<td>3 # 4</td>
<td>380.03</td>
<td>815.48</td>
<td>42.9</td>
</tr>
<tr>
<td>SB5</td>
<td>76.20</td>
<td>4</td>
<td>4 # 4</td>
<td>506.70</td>
<td>815.48</td>
<td>42.9</td>
</tr>
<tr>
<td>SSB2*</td>
<td>76.20</td>
<td>2</td>
<td>2 # 5</td>
<td>372.13</td>
<td>393.68</td>
<td>206</td>
</tr>
</tbody>
</table>

* Steel reinforced concrete slabs;  
** Rebar diameter: #4 (d_b=12.7 mm), # 5 (d_b=15.9 mm)

In the Table 1, SB is the tested slab identification, d is the effective depth of the sections, A_r is the area of the GFRP rebars, F_r and E_r are the ultimate tensile strength and the elastic modulus of reinforcement materials (GFRP and steel), respectively, while \( \varepsilon_{ru} \) is the strain at ultimate of GFRP reinforcements.

**Test setup and instrumentation.** All specimens were tested as simply supported beams subjected to a four-point load. A hydraulic jack was used to apply a concentrated load on a steel distribution beam to produce two-point loading condition. Five linear variable differential transformers (LVDTs) were used for each specimen to monitor the vertical displacements; one LVDT was located at mid-span, two LVDTs were located at quarter-span and two LVDTs were located at the specimen supports to measure support settlement, if any. For each specimen, eight strain gages were attached to GFRP reinforcement to monitor the strain during loading; strain gages were attached at mid-span and quarter-points as well as at intermediate points. Three additional strain gages were attached directly to the concrete surface at mid-span and a quarter-points to measure the maximum compressive strains in concrete.

A load cell was used to monitor applied load and a data acquisition system was used to record the experimental measures.

**Test procedure.** The specimens were subjected to quasi-static loading cycles. In the first cycle, each slab was loaded up to cracking, then it was unloaded. This way followed by more loading-unloading cycles until the specimen failed. Results obtained, illustrated in the next paragraph as applied loads versus deflection at the midspan (maximum deflection), represent the envelopes of these load cycles.

**Experimental results**

For specimens of series A (GFRP reinforced concrete slabs), the first crack was initiated at mid-span and was accompanied by a sudden increase in deflection due to stiffness reduction of the specimen. The magnitude of mid-span deflection after cracking and the width of the first crack increased as the amount on the reinforcement ratio reduced. As the load increased, additional cracks started to form throughout the length of the specimen, widening and propagating upward until failure occurred by the crushing of compression concrete at a maximum load directly proportional to the amount of FRP reinforcement.

For the specimen of the series B, the conventional mode of failure of steel yielding followed by the crushing of concrete was attained. The first crack was initiated
at mid-span. In comparison with the first series, very small deflection and crack widths was measured after cracking; this is due to the higher stiffness of steel reinforcement compared to that of GFRP. This behavior was observed up to yielding of steel reinforcement where the stiffness of steel degraded significantly and the deflection and crack width started to increase under almost constant load. As the load was maintained, additional cracks started to form throughout the length of the specimen, widening and propagating upward until failure occurred by the crushing of compression concrete.

The main experimental results for tested slabs were reported in Table 2. Ultimate capacity of GFRP reinforced concrete slabs was determined using the design approach proposed by ACI Committee 440H [1]. In the Fig. 1 was show the experimental load-deflection curves for the \textit{SB4} and \textit{SSB2} slabs that are reinforced with almost the same amount of rebar area. It is possible to evidence the relevant difference between curves corresponding to the GFRP concrete reinforced slab and those corresponding to the steel reinforced slab. As expected, the deflections of the GFRP reinforced slab is higher than that of steel reinforced slab; at the ultimate the ratio between deflections values ($\delta_{\text{GFRP}}/\delta_{\text{steel}}$) is equal to 2.59.

Table 2. Test results of series A and B

<table>
<thead>
<tr>
<th>SLABS</th>
<th>Experimental ultimate load (N)</th>
<th>Failure mode</th>
<th>Maximum deflection (mm)</th>
<th>Theoretical ultimate load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB3</td>
<td>16.79</td>
<td>Concrete crushing</td>
<td>132.33</td>
<td>17.19</td>
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<tr>
<td>SB4</td>
<td>21.90</td>
<td>Concrete crushing</td>
<td>128.27</td>
<td>20.18</td>
</tr>
<tr>
<td>SB5</td>
<td>29.98</td>
<td>Concrete crushing</td>
<td>124.97</td>
<td>22.50</td>
</tr>
<tr>
<td>SSB2</td>
<td>22.16</td>
<td>Yielding steel-Concrete crushing</td>
<td>49.53</td>
<td>20.18</td>
</tr>
</tbody>
</table>
 Experimental moment versus deflection at the midspan curves for the slabs $SB3$, $SB4$ and $SB5$ are shown in the Fig. 2. These slabs, as reported in the Table 1, are reinforced with GFRP rebars having the same diameter ($d_b=12.7\ mm$) while the reinforcement amount is variable. Results evidence as the stiffness of slabs increase with the reinforcement ratio.

**Theoretical investigation**
The theoretical analysis of the flexural behavior of reinforced concrete elements was carried out by means of a numerical procedure founded on a slip and bond stress analysis. The theoretical model and the numerical procedure adopted to solve the static problem are described in [5]. Results of a numerical investigation are presented and discussed; for a commercial Glass FRP rebar type the estimation of parameters defining the bond-slip law is carried out by means of bond tests results available in the open literature. The analysis refers to a concrete element between two contiguous cracks; the tension-stiffening effect and the interaction between the FRP rebars and the concrete, are expressed through the bond-slip law.

Comparison between theoretical and experimental results

By using the above mentioned procedure a comparison between theoretical and experimental results is made. In the following are shown comparison between measured and predicted maximum crack width for two tested slabs. In the Figures 3 and 4 are shown curves $m-w_{\text{max}}$ being $m=6M/bdf_{c_t}$ the non-dimensional bending moment, $f_{c_t}$ the concrete tensile strength and $w_{\text{max}}$ the maximum crack width. Theoretical prediction were evaluated assuming the following estimated values for the bond-slip law [5]:

$\tau_k = 8.49 \text{ N/mm}^2; \quad u_k = 0.718 \text{ mm}; \quad \alpha_k = 0.245$

![Graph showing theoretical and experimental comparison](image-url)
The analysis of results evidence a good agreement between theoretical predictions and experimental values mainly in the service conditions corresponding to a load level less than 50% of the ultimate load. It should be noted that theoretical predictions are strongly dependant on the bond slip law; for the examined cases, the estimated values of bond - slip parameters for the used GFRP rebars seem to be adequate for a reliable structural analysis.

**Conclusions**

An experimental investigation on flexural behaviour of GFRP reinforced one-way slabs is described in the paper. Obtained results allow to draw the following concluding remarks:

- the stiffness of the GFRP reinforced concrete slabs is significantly lower than the steel reinforced members after cracking, resulting is larger crack widths and deflection;
- the ultimate capacity of slabs increases with the amount of GFRP rebars. This is true, obviously, for case in which the failure mode is compression-controlled (crushing of the concrete);
- ultimate capacity, crack width and deflections can be predicted with acceptable accuracy using analytical models. In particular the model adopted in the paper furnishes a good predictions of crack widths; however, it needs of an accurate definiton of the bond-slip law and, often, their use can be onerous from a computational point of view.

**References**