EXPERIMENTAL TIME-DEPENDENT DEFLECTIONS OF CONCRETE BEAMS REINFORCED WITH GFRP BARS

Cristina MIÀS
MSc
Universitat de Girona
Escola Politècnica Superior. Av. Montilivi s/n. Girona. SPAIN
cristina.mias@udg.edu*

Lluís TORRES
PhD
Universitat de Girona
Escola Politècnica Superior. Av. Montilivi s/n. Girona. SPAIN
lluis.torres@udg.edu

Albert TURON
PhD
Universitat de Girona
Escola Politècnica Superior. Av. Montilivi s/n. Girona. SPAIN
albert.turon@udg.edu

Cristina BARRIS
PhD
Universitat de Girona
Escola Politècnica Superior. Av. Montilivi s/n. Girona. SPAIN
cristina.barris@udg.edu

Abstract
Control of deflections can usually be expected to be a limiting factor in the design of fibre reinforced polymer reinforced concrete (FRP RC) structures. Deflections due to creep and shrinkage can be several times larger than the instantaneous values. Reported experimental data on time-dependent deflections of FRP RC structures are still limited compared to conventional steel RC structures. Results available in the literature indicate that the principles underlying the formulation used for predicting the long-term deflections of steel RC structures can also be used for FRP RC structures. The results of an experimental study of beams reinforced with glass fibre reinforced (GFRP) bars subjected to sustained load during 360 days are presented. Two levels of sustained load and two different reinforcement ratios were tested. The experimental long-term deflections are compared to the predictions made using CEB-FIP, ACI 440.1R-06 and CSA-S806-02 procedures. Deflections obtained with CEB-FIP procedure are in a good agreement with the experimental values. However, some differences are found when ACI 440.1R-06 or CSA-S806-02 procedures are applied.

Keywords: deflection, fibre reinforced polymers, long-term, sustained load

1. Introduction
Fibre reinforced polymer (FRP) bars offer an alternative to steel reinforcement in concrete structures where the corrosion in steel can be present. Due to the lower stiffness of FRP compared to steel, deflection control can usually be expected to be a limiting factor in the design of FRP reinforced concrete (RC) structures. Although instantaneous deflections have been widely studied, further experimental work seems to be necessary for the case of long-term deflections. Published data on short and time-dependent deflections of FRP RC members
indicate that the principles underlying the formulation used for predicting the long-term deflections of steel RC structures can also be used for FRP RC structures [1]. Based on experimental results [2,3], ACI 440.1R-06 [4] suggests a similar approach for FRP RC structures as for steel introducing a reduction factor of 0.6 in the ACI 318-08 approach [5,6] equation. On the other hand, experimental results of GFRP RC beams [7,8] show that general CEB-FIP procedure [9,10] together with creep and shrinkage curvature coefficients found in Ghali and Favre [11] can predict accurately the deflections of FRP RC members. The procedure accounts for the influence of the geometry, material and environmental conditions. In this paper, results of experimental long-term deflections of GFRP RC beams, subjected to a sustained load for a period of 360 days, are presented and analysed. The experimental data are compared with the CEB-FIP [9-11] procedure, together with other methodologies specific for FRP RC structures such as ACI 440.1R-06 [4] and CSA-S806-02 [12].

2. Experimental test program

2.1 Beams specifications

A total of 8 concrete beams of 140x190x2450 mm (Figure 1) with a clear cover equal to 20mm were cast with two different amounts of GFRP (2Ø12 or 2 Ø 16) bars placed at the tension side (bottom). For comparison purposes 2 additional beams were reinforced with 2Ø10 steel bars, having similar stiffness to those reinforced with Ø 16 GFRP. No compression reinforcement was used. The shear-span was reinforced with steel stirrups (Ø8mm/80mm) to avoid shear failure, however, no stirrups were provided in the central pure bending zone.

The beams are designed as H_Lx-Gyyz (Table 1), where x denotes the level of sustained load; yy, the diameter of the GFRP bar; and z the existence of a notch at mid-span (z=a notch, z=b no notch). This notch was introduced to ensure the propagation of a crack at the central section, which was instrumented by means of strain gauges placed on concrete and rebar.

![Figure 1. Geometric details of the tested beams](image_url)

<table>
<thead>
<tr>
<th>Table 1. Geometric properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø bar (mm)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>H_L1_G12a</td>
</tr>
<tr>
<td>H_L1_G12b</td>
</tr>
<tr>
<td>H_L2_G12a</td>
</tr>
<tr>
<td>H_L2_G12b</td>
</tr>
<tr>
<td>H_L1_G16a</td>
</tr>
<tr>
<td>H_L1_G16b</td>
</tr>
<tr>
<td>H_L2_G16a</td>
</tr>
<tr>
<td>H_L2_G16b</td>
</tr>
<tr>
<td>H_L1_S10</td>
</tr>
<tr>
<td>H_L2_S10</td>
</tr>
</tbody>
</table>
2.2 **Material properties**

The experimental compressive strength, \( f_c \), was 56MPa and the modulus of elasticity, \( E_c \), was 29GPa. Both were determined from cylinder tests. GFRP bars (ComBAR) with nominal diameters of 12mm and 16mm, and modulus of elasticity of 60MPa, were used.

2.3 **Test set-up**

The experimental program consisted of testing simply supported beams spanning 2200mm, and subjected to two concentrated loads for a period of time 360days (Figure 1). Before the application of the sustained loads, \( P_{sus} \), the beams were subjected to service load and then cycled twice between the maximum load and a minimum of 2kN. The service load was designed to obtain a maximum bar strain equal to 2000 \( \mu \varepsilon \). Immediately after this “instantaneous” test, the beams were moved to the corresponding sustained load frames (Figure 2a). The sustained loads were designed to obtain instantaneous concrete compressive stresses of 0.3\( f_c \) and 0.45\( f_c \) at the mid-span section. The magnitudes of the sustained loads are given in Table 2.

**Table 2. Sustained loads**

<table>
<thead>
<tr>
<th>Beam series</th>
<th>H_L1_G12</th>
<th>H_L2_G12</th>
<th>H_L1_G16</th>
<th>H_L2_G16</th>
<th>H_L1_S10</th>
<th>H_L2_S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load, ( P_{sus} )(kN)</td>
<td>13.5</td>
<td>19</td>
<td>17</td>
<td>22</td>
<td>17</td>
<td>22</td>
</tr>
</tbody>
</table>

**Figure 2. Set-up of (a) long-term flexural tests (b) creep tests**

In order to determine the creep coefficient according to ASTM C512-02, concrete cylinders (150Ø, \( L=450\)mm) with embedded strain gauges were loaded with a constant pressure equal to 150bars (Figure 2b). Additional specimens were left unloaded and were also monitored to determine free shrinkage strain. All the specimens were placed on the same room and conditions as the beams.
3. Experimental results

3.1 Time-dependent concrete properties

Obtained results from tests of creep and shrinkage of concrete are shown in Figure 3. Figure 3a shows the evolution of creep coefficient obtained from the strain measurements of the cylinders placed on the loading frame shown in Figure 2b. At 360 days, the experimental creep coefficient was equal to 1.86, and the free shrinkage strain was equal to $378 \, \varepsilon$ (Figure 3b).

![Figure 3. Experimental free shrinkage strain](image)

3.2 Time-dependent deflections

Experimental total deflections versus time of tested beams are presented in Figures 4-6. The total deflection includes immediate and long-term deflections due to creep and shrinkage. As it can be observed, the experimental values of beams reinforced with GFRP and steel bars present the same trend. The ratios between the total deflections and the instantaneous deflections at 360 days are presented in Table 3, being equal to 1.4 for beams reinforced with 2Ø12 GFRP bars, and 1.5 for beams reinforced with 2Ø16 GFRP and steel bars, which were designed to have a similar stiffness.

![Figure 4. Total deflections for beams reinforced with 12mm diameter bars](image)
Figure 5. Total deflections for beams reinforced with 16mm diameter bars

Figure 6. Total deflections for beams reinforced with 10mm diameter steel bars

Table 3. Ratio between the total deflection and the corresponding deflection at time of loading, $\delta / \delta_0$

<table>
<thead>
<tr>
<th>Time(days)</th>
<th>H_L1_G12</th>
<th>H_L2_G12</th>
<th>H_L1_G16</th>
<th>H_L2_G16</th>
<th>H_L1_S10</th>
<th>H_L2_S10</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>1.40</td>
<td>1.41</td>
<td>1.49</td>
<td>1.48</td>
<td>1.54</td>
<td>1.53</td>
</tr>
</tbody>
</table>

According to ACI 440.1R-06 [4], for beams containing no compression reinforcement, the total deflection including the effect of creep and shrinkage, $\delta_{T(ACI440)}$, of FRP RC members can be obtained from the initial deflection due to sustained load, $\delta_{(sus)}$:

$$\delta_{T(ACI440)} = (1 + 0.6\xi)\delta_{(sus)}$$  \hspace{1cm} (1)

where $\xi$ is a time-dependent factor for sustained loads which is equal to 1, 1.2, 1.4 and 2.0 for three, six, twelve and sixty months, respectively.

The Canadian Standard CSA-S806-02 [12] provides a similar approach but more conservative:

$$\delta_{T(CSA)} = (1 + \xi)\delta_{(sus)}$$  \hspace{1cm} (2)

On the other side, based on the procedure presented in the CEB Manual on Cracking and Deformations [10], described and illustrated in Ghali et Favre [11], total deflections, $\delta_{T(CEB)}$.
The predicted total deflections for each state (1 and 2) can be obtained as the sum of the initial deflection, \( \delta(t_0) \), and the long-term deflection due to creep and shrinkage, \( \Delta \delta(t_0) \):

\[
\delta_{T,i} = \delta(t_0) + \Delta \delta(t_0)
\]

where the subscript \( i \) takes the value of 1 for the uncracked state and 2 for the fully-cracked state. The long-term deflection due to creep and shrinkage are obtained from the following expression:

\[
\Delta \delta(t) = \delta(t_0) \varphi(t) + \varepsilon_{sh} \frac{d}{8d} \kappa_{sh}
\]

where \( \varphi \) and \( \kappa_{sh} \) are the curvature coefficients related to creep and shrinkage, respectively. A detailed explanation of the procedure for obtaining \( \varphi \) and \( \kappa_{sh} \) can be found in Appendix F of [11]. Since calculation of \( \varphi \) and \( \kappa_{sh} \) is not immediate, design charts have been developed for practical applications [10,11].

The experimental total deflections versus time since loading are compared with the analytical predictions based on CEB procedure [9,10], ACI 440.1R-06 [4], CSA-S806-02 [12]. Since the sustained loads were applied after quasi-static loading cycles, and ACI and CSA procedures do not specifically account for this condition, the short-term deflection has been calculated using Bischoff’s equation, eq. (6), with a \( \beta \) coefficient of 0.5 [13,14]:

\[
I_c = \frac{I_{cr}}{1 - \beta \left( \frac{M_{cr}}{M_c} \right)^2 \left( 1 - \frac{I_{cr}}{I_c} \right)}
\]

In Figure 7-8 total deflections of GFRP RC beams are shown and compared with theoretical values. As it can be observed, predictions using the CEB-FIP procedure fit accurately with the experimental results, however, ACI 440.1R-06 and CSA-S806-02 overestimate the total deflections in all the cases.

Figure 7. Total deflections versus time since loading for beams reinforced with 2Ø12 GFRP bars
Figure 8. Total deflections versus time since loading for beams reinforced with 2Ø16 GFRP bars

The ratio between the experimental and predicted deflections after 360 days of sustained load is given in Table 4. On average, the ratios between the theoretical values and the experimental deflections, using ACI 440.1R-06 and CSA-S806-02 recommendations for FRP RC beams, are 1.24 and 1.62, respectively. On the other hand, this ratio is equal to 0.94 using the CEB-FIP procedure. This last method accounts for the influence of geometry, materials and environmental conditions, included in the creep coefficient and free shrinkage strain as well as the influence of the different sectional stiffness on the long-term behaviour.

Table 4. Ratio between theoretical and experimental total deflection at 360 days.

<table>
<thead>
<tr>
<th>Beams</th>
<th>( \frac{\delta_{\text{CEB-FIP}}}{\delta_{\text{exp}}} )</th>
<th>( \frac{\delta_{\text{ACI}}}{\delta_{\text{exp}}} )</th>
<th>( \frac{\delta_{\text{CSA-S806}}}{\delta_{\text{exp}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H_L1_G12</td>
<td>0.93</td>
<td>1.26</td>
<td>1.66</td>
</tr>
<tr>
<td>H_L2_G12</td>
<td>0.92</td>
<td>1.26</td>
<td>1.64</td>
</tr>
<tr>
<td>H_L1_G16</td>
<td>0.95</td>
<td>1.18</td>
<td>1.55</td>
</tr>
<tr>
<td>H_L2_G16</td>
<td>0.96</td>
<td>1.24</td>
<td>1.64</td>
</tr>
<tr>
<td>Mean</td>
<td>0.94</td>
<td>1.24</td>
<td>1.62</td>
</tr>
</tbody>
</table>

4. Conclusions

In this article, results from an experimental program of 8 GFRP and 2 steel RC beams subjected to a sustained load for a period of 360 days are presented. From the obtained experimental results it can be concluded that:

- The experimental values of beams reinforced with GFRP and steel bars present the same trend, in their evolution with time.
- The ratio of total deflection increase to initial deflection was 1.4 for beams reinforced with 2Ø12 GFRP bars, and 1.5 for beams reinforced with 2Ø12 GFRP and 2Ø10 steel bars.

Additionally, experimental deflections are analyzed and compared with prediction models. CEB-FIP procedures give accurate predictions for all the tested specimens, while ACI 440.1R-06 and CSA S806-02 do not predict the long term deflections with the same level of accuracy for all cases.

Although CEB-FIP procedure requires a greater degree of calculation, it allows taking into account the influence of geometry, material properties, and environmental conditions, included in the creep coefficient, and the free shrinkage strain, as well as the influence of the different sectional stiffnesses, on the long-term behaviour.
5. Acknowledgements

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6. References


