Effect of Sustained Load and Environment on Long-Term Tensile Properties of Glass Fiber-Reinforced Polymer Reinforcing Bars

by Gilbert Nkurunziza, Brahim Benmokrane, Ahmed S. Debaiky, and Radhouane Masmoudi

This paper describes a research effort to evaluate the creep behavior of glass fiber-reinforced polymer (GFRP) bars in different environments under sustained load. Twenty GFRP bars (E-glass in vinyl ester matrix) 9.5 mm in diameter for four series have been tested for over 417 days (10,000 h) under combinations of different sustained load levels and surrounding mediums in ambient temperature. The bars were subjected to two levels of sustained tensile stress at 25 and 38% of guaranteed tensile strength while being surrounded by either alkaline solution (pH 12.8) or de-ionized water (pH 7.0). The initial strain applied to the bars varied between 4000 and 6000 microstrain, which are 2.9 and 4.3 times the maximum allowable sustained strain given by ACI 440.1R-03 (20% εu).

ACI 440.1R-03 allowable sustained strain is limited by both environmental and creep rupture considerations. Axial strain in the central conditioned part of the bars was monitored with time to evaluate the creep behavior. Following the extended creep test, the GFRP bars were tested in axial tension until failure for residual tensile strength, elastic modulus, and axial strain. The experimental results obtained showed that the tested GFRP bar performed very well under these extreme loading and environmental conditions. The average residual tensile strength was found to be 139 and 144% of the design tensile strength for bars conditioned in de-ionized water at 25 and 38% stress level, respectively. In alkaline solution, this range was 126 and 97%. More importantly, no significant change in the elastic modulus was observed under the stress levels and environmental conditions used. The entire group of bars had a residual modulus ranging from 38.5 to 42.9 GPa, which is almost in the range of the original elastic modulus.

Keywords: load; polymer; strain.

INTRODUCTION

Corrosion of steel in concrete has been identified as a prime factor of deterioration and structural deficiency in North America. Various remedies, including replacing deteriorated concrete and using epoxy-coated or galvanized steel, have been proven to be costly and inadequate over the long run. Fiber-reinforced polymer (FRP) bars are a promising solution to this problem. Other attractive properties of FRP materials include light weight, corrosion resistance, and high strength. Glass FRP (GFRP) bars are gaining popularity as reinforcement for concrete bridge decks and other concrete structures due to their low initial cost compared with carbon FRP bars.1-6 Upon establishing the structural integrity of the FRP composite bars for initial service life, the industry is still in need of long-term durability data for wider acceptance of FRP in infrastructure applications.7-8 Several design guidelines9-12 specify strength reduction factors to account for sustained stress, fatigue, and environmental conditions. These factors, however, were offered without a significant experimental foundation and are criticized for being based on low-performing materials.13

Research focusing on the durability of FRP materials is considered to be in an early stage due to the wide spectrum of durability issues and effects to be investigated.8 The long-term creep behavior of FRP bars has not been addressed by any design equation14 while only long-term deflection equations for FRP-reinforced concrete members have been proposed. Literature indicates a need to conduct tension tests and moisture absorption tests on GFRP bars for extended periods to predict with confidence the long-term behavior of the bars.15-17 The level of stresses has been identified as a major factor in the response of the FRP product to the harsh environments because it causes microcracks in the resin, resulting in exposure of the fibers to the environment.18 The authors therefore concluded that any durability study must be performed under sustained loading to resemble field conditions. The authors and others have undertaken an extensive research program on the behavior of GFRP bars in concrete, taking into account the different environments that affect reinforced concrete structures and applying higher stress levels to the FRP bars than is currently recommended.15-19

FRP materials in general, and GFRP bars in particular, have low modulus of elasticity. This directly affects the design of concrete element using FRP as reinforcement due to serviceability criteria (deflection and crack width), which usually control the design.9 Having established this fact, stronger emphasis on the creep behavior of the GFRP bars in alkaline or moist environments must be made to better understand the long-term serviceability behavior of the structure.

The mechanism by which sustained stress might affect the properties of the FRP bars is a function of the constituents of the bars themselves (fibers, and resin matrix) and manufacturing process (rate and thoroughness of curing, and fillers). The resin matrix has a larger ultimate tensile strain than the fiber. When fibers are impregnated with resin during the manufacturing process, however, pores in the resin matrix cannot be avoided. These pores give rise to stress concentrations in the resin matrix which, when the bars are subject to tensile stress, initiates microcracks.20 These microcracks may result in invasion of the matrix by the surrounding mediums (alkaline and water) which in turn may reach and attack the fibers. The presence of voids.
in the matrix is therefore believed to be a factor in the time-
to-failure as a function of the stress level applied (Fig. 1). At 
lower stress levels, the bars fail after extended periods of
time because the low stresses applied do not expand the
matrix voids enough to create cracks. No direct attack of the
fibers takes place and the surrounding medium penetrates the
bar only by diffusion. At moderate stress levels, the matrix
suffers microcracking that gives greater access to the
environment to attack the fiber, shortening the bar’s service
life. At high stress levels, the fibers fail by rupture in relatively
shorter periods.

This paper reports the findings of tests on the creep
behavior of exposed GFRP bars subject to stress. Results
from 9.5 mm-diameter bars after 10,000 h (417 days) of
exposure under ambient temperature are reported. The bars
were subjected to either alkaline or de-ionized water
environments while under constant tensile stress. The stress
levels applied on the bars slightly exceeded the allowable
limit set by the current codes and guides. The decision to use
9.5 mm-diameter bars, which is the smallest practical GFRP
bar size for bridge applications, was made to obtain the most
severe environmental effects on bar properties. Bars with
larger diameters would experience less degradation in the
mechanical properties because the diffusion of water into
FRP bars is proportional to time and distance so that, for a
given time frame, an outer layer of fixed thickness, independent
of bar diameter, is affected. Therefore, its effect on the entire
bar section is maximum in small-diameter bars.

**RESEARCH SIGNIFICANCE**

The effect of sustained loading and environmental parameters
on the modulus of elasticity is of particular importance
because the design of concrete structures reinforced with
GFRP bars is predominantly controlled by serviceability
criteria, rather than strength. Because the current GFRP
products have high strength beyond the strength design
requirements, the modulus of elasticity becomes the greater
concern. Any decrease in the modulus of elasticity will affect
crack width, deflections, and other serviceability parameters.
This research provides much needed data on the creep strain
in GFRP bars in ambient temperature, the change in the
modulus of elasticity with time under load, and the residual
tensile strength of the bars. The main objective of this
research is to evaluate the creep behavior of GFRP reinforcing
bars under alkaline and water environments and to measure
the change in the tensile properties, including strength,
modulus, and ultimate elongation. Sustained tensile loading
combined with these environments were applied to the bars
during the entire duration of the test to investigate whether
creep rupture would occur and to obtain creep strain versus
time up to 10,000 h.

**EXPERIMENTAL PROGRAM**

The GFRP bar used in this study was made from high-
strength E-glass fibers (75% fibers by volume) with a vinylester
resin. The bar has a circular section of 9.5 mm in diameter
and is manufactured by combining the pultrusion process
and an in-line coating process for the outside coarse sand
surface, as shown in Fig. 2(a) and (b). Table 1 gives the main
properties of the bars in terms of average ultimate tensile
strength, modulus of elasticity, and average ultimate tensile
strain. The guaranteed and design tensile strengths are also
given based on ACI 440.1R-03. Two different aqueous
solutions were used in this study: de-ionized water simulating
100% relative humidity and a simulated-concrete alkaline
solution with a pH of 12.8, as recommended by ACI
440.3R-04. A comprehensive study on the durability of
GFRP bars involving three different bar sizes was recently
completed.

The GFRP bars were cut to 1100 mm length specimens;
each end was placed in 410 mm-long steel tubes that were
then grouted with a resin-mortar matrix, creating grip ends.
for axial tension. Two strain gages were attached on opposite sides at the middle portion of the specimen using M-bond AE adhesive and aligned in the longitudinal direction to monitor the strain in the bar, as illustrated in Fig. 3(a). The gages (with a 350-ohm resistance and a gage factor of 2.09) were connected with the 350 ohm precision resistors to form a half-bridge. This setup was designed to cancel any strain due to bending of the bar. The middle part of the specimen was also instrumented with a thermocouple wire for temperature measurement. The specimens were wired to a computer with a data acquisition system. To subject the specimen to the solution needed, the middle part was inserted inside a 63 mm-diameter and 250 mm-long plastic tube that worked as a reservoir for the solution. Figure 3(b) shows a view of typical instrumented specimen.

Two parameters were used in this research:

1. Surrounding media—Two different media were used to simulate the most common state of the bars in the field: de-ionized water (pH of 7.0) and alkaline solution (pH of 12.8). The composition of the simulated-concrete alkaline solution consisted of 118.5 g of Ca(OH)$_2$, 0.9 g of NaOH, and 4.2 g of KOH in 1 L of de-ionized water, as suggested by ACI 440.3R-04. The alkaline solution simulates the cement paste surrounding the bars; the pH level of the solution was checked periodically and was kept at a level of 12.8. It should be noted that using an aqueous solution on the bars causes much faster degradation than actual concrete because it propagates into the bar material directly and faster.

2. Sustained tensile stress—Axial tension was applied on all bars during the entire duration of the test to mimic field conditions. The bars were subjected to two levels of sustained tensile stress at 25 and 38% of guaranteed tensile strength while being surrounded by either alkaline solution or de-ionized water. The initial strain applied to the bars varied between 4000 to 6000 microstrain, which is 2.9 to 4.3 times the maximum allowable strain for sustained loads (creep) given by ACI 440.1R-03 (allowable strain for creep = 1400 microstrain, as shown in Table 1). These levels of stress are higher than the values recommended by current codes and guides (CAN/CSA-S6-00, CAN/CSA-S806-02, ACI 440.1R-03, ISIS-M03-01). This was done to explore the potential of the material and evaluate how conservative the current codes and guides are. Figure 4 shows the load-magnifying steel creep frames used to apply the sustained load on the bars.

### Table 1—Tensile properties of GFRP bars used in this study as provided by manufacturer

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate tensile strength, $f_{u,ave}$</td>
<td>658 ± 10 MPa</td>
</tr>
<tr>
<td>Guaranteed tensile strength, $f_u^*$</td>
<td>628 MPa</td>
</tr>
<tr>
<td>Design tensile strength (ACI 440.1R-03)</td>
<td>$f_u = C_E \times f_u^*$, $C_E = 0.7$</td>
</tr>
<tr>
<td>Modulus of elasticity, $E_{f,ave}$</td>
<td>40 ± 2 GPa</td>
</tr>
<tr>
<td>Ultimate strain, $e_{u,ave}$</td>
<td>1.6 ± 0.2%</td>
</tr>
<tr>
<td>Guaranteed strain, $e_u^*$</td>
<td>1.0%</td>
</tr>
<tr>
<td>Design strain (ACI 440.1R-03)</td>
<td>$e_u = C_E \times e_u^*$</td>
</tr>
<tr>
<td>Allowable strain for sustained load (ACI 440.1R-03)</td>
<td>20% $e_u$</td>
</tr>
</tbody>
</table>

*Fig. 3—(a) Details and dimensions of glass fiber-reinforced polymer test specimen; and (b) specimen ready for installation.*

*Fig. 4—Schematic of load-magnifying frame (above) and frames with loaded bars (below).*
DISCUSSION OF RESULTS

The following discussion focuses on the creep strain and residual mechanical properties of the bars. Before analyzing any results, the reader is reminded of the nature of the test apparatus used, where only the central portion of each bar was exposed to the environments. Since the remainder of the bar was outside the plastic reservoir containing the medium, it was free of any exposure. This configuration made the two sections of the bars at the ends of the reservoir of a distinct nature. These boundary sections were at the transition between environmentally exposed and unexposed parts of the bars (wet and dry parts), and therefore were prone to premature failure during the tensile test of the conditioned bars. This conclusion is based on extrapolation of the corrosion behavior of steel-reinforced concrete in splash zones. This situation is unlikely in a real structure where the entire GFRP bar is surrounded by the concrete; therefore, the obtained residual tensile properties are expected to be lower than those of bars encased in concrete. It was observed during the tension tests on conditioned bars that failure initiated, in most cases, at these critical sections, as shown in Fig. 5. Therefore, the authors believe that the results obtained for the residual strength represent a lower bound for embedded bars under uniform environment.

Creep tensile strain

The change in the axial strain with time under the constant applied stress defines the creep characteristics of the GFRP under consideration. Figure 6 represents this change for bars in alkaline solution and de-ionized water. It can be observed that there is almost no effect from the level of initial stress on the strain increase. The maximum increase in strain was approximately 300 microstrain (at 38% level), which is only 5% of the initial strain. The increase was 130 microstrain (at 25% level), approximately 3% of the initial strain. Lower levels of strain change were observed in the bars submerged in alkaline solution with less than a 100 microstrain increase after 10,000 h.

When trying to extrapolate the results obtained herein to forecast the creep strain over the service life of concrete structures (75 years), it should be realized that creep strain decays greatly with time. The 10,000-h term has been well established as the acceptable range where most of the creep strain will take place. This was proven by a another group of tests performed by the authors on 12.7 mm GFRP bars under the same level of sustained stress and solutions for 114 days at 60 °C.24 This elevated temperature is believed to accelerate the absorption, and hence the degradation of the bars, over the exposure period, simulating 75 years of natural aging.25 Under these conditions, the GFRP bars experienced only an 8% increase in axial strain at the 38% stress level.

Residual tensile strength

After 10,000 h of exposure, the average residual strength of the bars was 138.6 and 143.9% of the design tensile strength, respectively. These values dropped to 126.2 and 97.2% of the guaranteed tensile strength for bars in alkaline solution. Table 2 summarizes the results found from the tension test and a comparison of the residual strength and strains to the limits of ACI 440.1R-03. The combined effect of high sustained stress at 38% of the guaranteed ultimate tensile strength in alkaline solution caused the highest drop in strength. The 38% stress level is, however, considered very high for practical application, and it corresponds to 4.3 times the maximum allowable strain for sustained load. In de-ionized water, the stress levels used did not have a significant effect on the residual strength. The residual tensile strength was still in range of the guaranteed ultimate tensile, and is higher than the specified design strength as recommended by ACI 440 design guidelines. The distribution of the residual strength is illustrated in Fig. 7—with the mean values, the mean value of each group is represented by a bar and the individual bar strengths are represented by plotted points. The third group (at 29% stress in alkaline solution) has a lower average due to a single bar with low residual strength; this single value could be excluded from the stress/strain analysis.
be due to a problem in the end grips. If this value is omitted, the average of this group would be as high as the other two subjected to de-ionized water.

The effect of the surrounding environment on the residual strength should be viewed instead of the applied stress on the bars. At low stress levels, no difference should be observed when comparing the alkaline and water mediums. This is because the strain of the matrix is much less than the resin’s ultimate strain and, therefore, no microcracking will occur so direct access to the fibers by the alkaline and water mediums is blocked. The failure of the bar in this case will be dominated by the diffusion of the mediums through the resin. When microcracks start to form in the matrix, in those cases, water ions travel through the cracks faster and easier than alkaline ions, as they have smaller molecular size. Therefore, the damage from the water attack will be higher than that from the alkaline medium at this level of stress. However, when the microcracks become large enough to allow alkaline molecules to pass, the damage by the alkaline solution will exceed that of water. This can occur at higher stress levels. The failure in this case will be dominated by the propagation of microcracking. The hypothesis has been verified by performing microstructural analysis on stressed conditioned bars. The presence of microcracks in bars subjected to higher stresses supports this theory.25

Residual ultimate elongation
The ultimate elongation (strain) obtained from tension test at the end of the 10,000-h exposure phase indicates that conditioning by de-ionized water had no effect on the residual ultimate strain of bars subjected to the two stress levels. An average of 1.49 and 1.58% strain was obtained from this group. On the other hand, alkaline solution had a more profound effect, resulting in a residual strain of 1.35 and 1.06% for stress levels of 29 and 38% f<sub>u</sub>*, respectively. While the lowest value obtained (1.06% after exposure to alkaline solution and 38% stress level) is approximately 0.66 of the original value, it is still 1.5 times the design value recommended by the ACI 440.1R-03.

Residual modulus of elasticity
The residual modulus of elasticity was very close to the original value, with averages between 40.2 to 41.3 GPa as given in the last column of Table 2. The lower bound value is still within the range of variation of the original modulus (40 ± 2 GPa). This fact indicates that the sustained load and the different environments used caused the point of failure of the bars to move downward by a slight factor on the same.

<p>| Table 2—Distribution of test specimens, applied strains, and results from tension test at end of exposure |</p>
<table>
<thead>
<tr>
<th>Series</th>
<th>Specimen ID.</th>
<th>Applied stress, % f&lt;sub&gt;u&lt;/sub&gt;</th>
<th>Specimen (tension test)</th>
<th>Strain (tension test)</th>
<th>Residual modulus, GPa</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Residual, MPa</td>
<td>f&lt;sub&gt;u&lt;/sub&gt;/f&lt;sub&gt;u,ave&lt;/sub&gt;, %</td>
<td>f&lt;sub&gt;u&lt;/sub&gt;/f&lt;sub*u&lt;/sub&gt;, %</td>
<td>f&lt;sub&gt;u&lt;/sub&gt;/f&lt;sub&gt;u&lt;/sub&gt;, %</td>
</tr>
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<td>De-ionized water</td>
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<tr>
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<td>92.0</td>
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<td>68.2</td>
<td>97.4</td>
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</table>

Fig. 7—Distribution of residual tensile strength in conditioned bars.
elastic line (Fig. 8) or, in other words, the changes in the ultimate strength and strain had the same ratios.

From these results, it is very clear that this range of sustained tensile load (25 to 38% of the guaranteed ultimate tensile strength) combined with alkaline or de-ionized water environment. The following conclusions can be drawn from the results and the tension tests at the end of the exposure phase:

1. Creep strain in the GFRP bars are less than 5% of the initial value after 10,000 h of sustained tensile loading. This value was obtained under high stress of 38% of the guaranteed tensile strength;

2. Alkaline solution tends to have more harmful effects on the bars than de-ionized water at higher stress levels. This is because the level of stress in the bars controls the formation of microcracks in the resin matrix. At lower levels of stress, only natural pH water can readily migrate through the micro-cracks due to its smaller molecular size compared to the molecules of an alkaline solution;

3. The residual tensile strength of the bars after extended exposure to de-ionized water is almost unchanged. The alkaline solution, on the other hand, causes the residual strength to drop to 88 and 68% of the guaranteed strength under 29 and 38% stress levels, respectively. Compared with the design stress, the residual strength values are 126 and 97%, respectively. The higher value is approximately 4.3 times the currently recommended value by ACI 440.1R-03 for creep. Compared to the ACI design limit, the residual strength of the all bars exceeded this limit comfortably, except for those in alkaline solution under 38% stress level;

4. The modulus of elasticity of the bars is very stable and almost unaffected by the conditions and sustained stress levels used. This finding is critical in the design of concrete elements reinforced with FRP bars because the modulus is directly related to the crack width, deflection, and other serviceability concerns; and

5. No single case of creep rupture was observed in this study over 417 days of sustained loading at the high level of stress used. The reported results on residual tensile strength and residual tensile elongation should be considered as lower boundary values due to the presence of critically weak sections in the tested specimens. These sections were at the boundary zone between the wet and dry parts of the conditioned bars, and therefore were prone to premature failure during the tensile tests. This situation is considered rare in service because the entire length of an embedded bar is considered subject to the same environment.

CONCLUSIONS

Long-term testing for 417 days (10,000 h) has been completed on E-glass/vinylester FRP bars 9.5 mm in diameter under constant sustained load at up to 38% of the guaranteed ultimate tensile strength combined with alkaline or de-ionized water environment. The following conclusions can be drawn from the results and the tension tests at the end of the exposure phase:

1. Creep strain in the GFRP bars are less than 5% of the initial value after 10,000 h of sustained tensile loading. This value was obtained under high stress of 38% of the guaranteed tensile strength;

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