Stress-Rupture Performance of Glass-Fiber Reinforced Composites

Mark E. Greenwood

Research Associate
Owens Corning Science and Technology Center
2790 Columbus Road
Granville, Ohio 43023

740.321.7259
740.321.7433 - fax
mark.greenwood@owenscorning.com

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ABSTRACT

A new family of materials is available to address the issue of premature failure of reinforced concrete structures as a result of rusting of steel reinforcements. Composite reinforcing bars have been recognized by ACI as an acceptable alternative to steel and epoxy-coated steel rebars for the use in reinforced concrete structures. This report summarizes an initial study conducted to quantify stress limits for one class of composite rebars to assess their capability to provide 50 years of service. Stress-rupture testing was conducted to assess the combined effects of constant stress and a concrete environment on the life of pultruded composite rods. The results provide proof of concept that glass-fiber reinforced composite bars can provide long-term performance as a reinforcement system for concrete structures.

BACKGROUND

Steel reinforcing bars rust and become a major cost for the repair and replacement of bridges, parking garages and many other structures (1). Epoxy coating has been used extensively in the U.S. to minimize the effects of rebar rusting, but the benefit has mixed reviews (2). Composite reinforcing bars offer a new opportunity for the construction of reinforced concrete with the potential to preclude the adverse effects of the rusting of steel rebars.

Fiber-reinforced polymer (FRP) reinforcing bars are made from millions of continuous filaments and a thermoset or thermoplastic polymer. The fiber reinforcements are made of glass (GFRP), carbon (CFRP) or aramid (AFRP) with each type of fiber having its unique value. The polymer is typically a thermoset material that is made with polyester, vinylester or epoxy resins that are thermally reacted to form a solid polymer. The general family of FRP materials has been successfully used in industry for more than 55 years in combating the ill effects of corrosion.

The American Concrete Institute (ACI) has recently published 440.1 R-01 (3), a guide to the design and construction of reinforced concrete structures using non-metallic (i.e., composite materials) reinforcements. Section 3.3 states that there is a lack of standard creep rupture test methods, standard reporting methods and "little data are currently available for endurance times past 100 hours." Section 8.4 offers "values for safe sustained stress levels" in Table 8.3 based on previous work and a 1.67 factor of safety.

Debates about the issue of establishing stress limits for glass-fiber reinforced composite materials result from the following evidence:

- bare glass fibers are subject to alkali-silica attack, and
- glass-fiber reinforced composites have demonstrated good performance for many years in a concrete environment without adverse effects from the high pH environment.

Other than the ASTM methods, most general test methods currently proposed and used
offer a means of defining relative performance (4, 5) or confirm the performance of predefined operating stress limits (6). However, a test method is need for defining the stress limits for a specific material in a concrete environment and under load (7, 8). Appendix B of ACI 440.1R-01 (3) indicates that creep rupture behavior and endurance times of FRP bars are needed to better define the stress limits used for design. The study undertaken in this report is in response to this need.

**PROPOSED TEST PROTOCOL**

To assess the long-term performance of composite materials, an array of proposals has been made and evaluated. The majority of these methods addresses the relative performance of one type of product versus another or assesses the long-term performance relative to a specified stress limit recommended for the product. The need has been identified for a method that will quantify the upper limit for operating stress for a product that is under load and operating in an environment.

ASTM test methods offer such protocols for specific applications such as pressure pipe with ASTM D2992 and sewer pipe with ASTM D3861. These test methods require the combined conditions of stress and environment to assess their superimposed effects on the product performance. These methods also allow the long-term performance limits to be assessed by extrapolation well beyond the time of testing. Excellent performance history with these products offers anecdotal evidence that these methods provide reasonable information on which product design can be based. Therefore, a conclusion is made that the use of superimposed stress and environment with a least-squares extrapolation method provides reasonable quantification of the stress limits of composite products that are useful in design of the products.

As a means of providing a functional test method that is appropriate for composite rebars, Devalapura, Gauchel, Greenwood, Hankin and Humphrey proposed a test method to determine the durability of composite materials (9, 10). The proposed test method provides a means of quantifying the long-term performance of a composite material under sustained stress in the presence of an environment. The form of the test coupon used for this study was a pultruded rod with a 6.4-mm (0.25-inch) diameter. This form of coupon was used to provide initial data to represent a composite reinforcing bar. The pultruded rod was selected as the test coupon configuration to reflect an array of structural components to assess the influence of the glass reinforcement and resin system on the composite material behavior. The mode of testing is simple tension that is relatively easy to apply for a long period of time. The environment is provided by total immersion in the gage length of the coupon. The analysis method follows the same method recommended in the existing ASTM test methods of using a linear regression fit of the log stress to log time-to-failure data. The primary benefit of this type of test method is the results can be used to define allowable stress levels for use in structural design.

Cantilevered loading frames as shown in Figure 1 were used to apply a constant load until failure. The environmental exposure is accomplished by placing a glass tube over the test coupon in the gage length with the environment sealed into the container with rubber stoppers. The environment container was further equipped with a heating element and insulation jacket to facilitate testing at temperatures above 23° C. The room was maintained at a temperature of 23°
C $\pm$ 2$^\circ$. Load was transferred to the test coupon through the end grip system with a standard cable chuck used in prestressed concrete manufacturing. The ends of the pultruded composite rod were reinforced with epoxy-bonded steel sleeves. A steel receptacle that threaded onto the loading frame and accepted the loading chuck was the load transfer device.

After the proper load has been applied to the frame and the environment has been added to the chamber, load is slowly applied to the test coupon and the timer is started. Figure 2 shows a test coupon in test. When the coupon fails, the timer is automatically stopped, recording the time-to-failure.

A range of loads was applied to a series of test coupons to allow data to be recorded for failure times ranging from less than one hour to over three years. Experience has indicated that data collected in 6 to 9 months is sufficient for accurately predicting long-term performance. This observation was further evaluated and previously reported (11).

Section 3.3.1 of ACI 440.1R-01 (3) specifies a creep rupture test protocol to establish the upper stress limits used in design. The stress-rupture test protocol that is discussed herein and creep rupture as discussed in the ACI 440.1R-01 are the same.

TEST SAMPLES

FRP reinforcing bars can be offered in a variety of products from glass-fiber reinforced polymer (GFRP) to carbon-fiber reinforced polymer (CFRP). The GFRP materials are more reasonably priced and have been used for more than 20 years as concrete reinforcing bars. CFRP materials have a higher modulus of elasticity and have excellent resistance to the combination of stress and high pH. Both systems are considered as viable materials for use as concrete reinforcements. The study summarized in this paper is a study of the GFRP materials.

Test coupons were taken from 6.4-mm (0.25-inch) diameter pultruded rods made with a highly cross-linked isophthalic polyester (AOC F701) with 45% styrene content reinforced with two types of glass-fiber reinforcements: traditional E-glass and a new boron-free E-type glass, Advantex®. The target glass fiber reinforcement content was 75% by weight. Densities for the constituent materials are 1.17 g/cc for the cured resin, 2.59 for the traditional E-glass fibers and 2.62 for the Advantex glass fibers. The composite material density is approximately 2.0 g/cc. The pultruded rod samples were commercially cured to within 10$^\circ$ C of the ultimate TG for the resin system, which is 110$^\circ$ C. Initial properties and other data are summarized in Table 1. The initial properties were used to establish a baseline for strengths and stiffnesses for the samples used in the testing program. The listed tensile strengths were used as 100% of ultimate load capacity base for all tests conducted with the given sample type. When normalized to 57.4% by volume (approximately 75% by weight) of glass-fiber reinforcement (and adjusting for density differences between glass compositions), the strengths and stiffnesses were statistically identical for all samples, indicating that the samples were properly made and property variation is attributable to only the variation in reinforcement content. The pooled (weighted average) standard deviation of strength and modulus values provides a coefficient of variation of less than 5%, indicating high quality samples.

The isophthalic polyester resin was selected for this series of tests because this general family of resins is used for many structural pultrusion applications and has become the
workhorse of the industry. Premium resins may offer superior performance in a Portland cement environment, and therefore a reasonable lower bound for stress limits should be established by using the isophthalic polyester resin system.

ENVIRONMENT

The focus of this study was to assess the stress-rupture behavior of composites exposed to a type 1 Portland cement concrete. To simulate a concrete environment, a cement extract solution was used for testing purposes. The cement extract was formulated by mixing 1 part of type 1 Portland cement with 2 parts of tap water, set for 24 hours and the extract was decanted to simulate pore water in concrete. The pH of the cement extract was stable with time with a pH meter measurement of 12.6.

Tests were conducted at both 23°C and 60°C to further accelerate the rate of degradation by elevating the temperature with environmental exposure. Stress-time-temperature superposition (11) was used for data analysis.

Testing was conducted with “air” to provide a baseline for comparison and assess the “partial factors of safety” that are discussed in product design methods (12, 13).

TEST RESULTS

Testing has been conducted to establish a means of quantifying stress limits for FRP materials that must carry load in an adverse environment. This study provides a starting point with more work needed to establish safe working stresses for the FRP reinforcements. Work completed to date is intended to form a foundation on which later work can be based and a platform for further ACI 440 specifications development.

The primary objective for conducting stress-rupture (creep rupture) testing was to identify a reasonable stress level that could be used for the design of concrete structures reinforced with glass-fiber reinforced composite reinforcing bars. The results of the testing are summarized in Figures 3 through 6. These figures are a log time to failure versus log load as a percentage of ultimate. The plots reflect the traditional format of plotting durability data with the time shown on the x-axis, even though the time to failure was the dependent variable in these tests. The regression analysis reflects time to failure as the dependent variable. Two to four samples were tested at each load increment for each test series.

Figure 3 provides the stress-rupture performance with an air environment for materials reinforced with both traditional E-glass reinforcements and Advantex glass reinforcements. The stresses at which 50-year performance can be expected are statistically the same for the two laminate types. Stress levels should be maintained at less than 45% of the ultimate strength to achieve 50 years of performance for the glass-fiber reinforced isophthalic polyester composite system tested.

Figure 4 provides similar data with the cement extract environment. The environment has a significant influence on behavior. The laminate with traditional E-glass reinforcements will provide 50 years of performance when the stress level is maintained at less than 15% of the ultimate tensile strength. The Advantex glass reinforced laminate offers superior performance
with a 50-year stress limit of 25% of the initial ultimate stress.

Figures 5 and 6 demonstrate the ability to use elevated temperature to further reduce the
time to generate meaningful test data for long-term extrapolation. Figure 5 shows the individual
data at 23° C and 60° C. The regression analysis of the data results in parallel lines, indicating
the same mode of degradation. The shift to account for the temperature acceleration is 1.31 log
cycles of time to failure. Figure 6 shows the superimposed data for 23° C after the time shift of
the elevated temperature data.

Another issue that interests civil engineers is creep. Creep testing was conducted to
assess the potential long-term effects of a constant load on the composite pultruded rod material.
Figure 7 shows strain with log time data collected from tests conducted at 35% of ultimate load
capacity to assess the creep behavior of glass-fiber reinforced composite rods. The additional
strain as a result of creep for a 50-year service is 4.7% of the initial strain.

DISCUSSION OF RESULTS

When considering the superimposed effects of constant loading and a cement extract
environment on the long-term performance of glass-fiber reinforced polymer composite
reinforcing bars used for concrete construction, insight has been gained through this study. Table
2 is offered as a summary of the stress-rupture performance of composite rods made with
isophthalic polyester resin and glass-fiber reinforcements of either traditional E-glass or
Advantex glass. With a 75% glass-fiber content by weight, the pultruded composite rods had an
initial tensile strength of 1103 MPa (160,000 psi). The results clearly demonstrate the following:

1. The stress-rupture performance in air of the two glass-fiber reinforced composite
materials is about the same.
2. The cement extract environment has an effect on the long-term stress-rupture
performance of glass-fiber reinforced composite materials.
3. The Advantex glass reinforced composite is less affected by the cement extract
solution than the traditional E-glass reinforced composite.
4. Elevated temperature is a reasonable means of further accelerating the aggressive
effect of environment and stress on the performance of GFRP materials.
5. The creep behavior of the glass-fiber composite rods indicates the 50-year strain will
be increased by approximately 4.7% of the initial strain or 415 micro strain with loading of
35% of the initial tensile strength. To provide a long-term calculation of deflection or crack
width as a result of creep of the GFRP reinforcing bars, the tensile modulus could be reduced
by 5%.

The data was fit to a simple power law equation that well represents the data with a linear
regression fit of log (stress) to log (time to failure) as follows:

\[
\text{Time to failure} = b \left( \frac{\% \text{ load/ultimate load}}{} \right)^m \quad \text{or}
\]

\[
\log(\text{time to failure}) = b + m \log(\% \text{ load/ultimate load})
\]

Previously reported creep rupture testing (14) indicates an endurance limit of 55% of the
ultimate strength at 50 years. The stress-rupture results generated in this report, with an air environment, are in reasonable agreement with a stress limit of 45% for a 50-year endurance. The definition of initial strength may explain the total difference between the two studies. Along with the definition of the creep rupture (or stress-rupture) test protocol, a method for describing the initial ultimate tensile strength is needed. Testing at two strain rates may make a significant difference in the initial ultimate tensile strength or using a mean value versus a 95% LCL may offer another variation.

With improved processes for making FRP reinforcing bars, improved reinforcements such as the Advantex glass evaluated herein and improved resin systems; the stress limits have an opportunity to be increased. An increase in stress limits would result in more economical designs or better long-term performance of FRP reinforced concrete structures. This study has demonstrated the significant difference in stress-rupture performance offered by an alternative glass formulation. For materials made with resin systems other than an isophthalic polyester resin, the results of the stress-rupture testing may be significantly improved.

CONCLUSIONS

1. Stress-rupture (creep rupture) testing offers a reasonable means of providing data that can be used to predict the long-term performance of composite materials when exposed to the combined effects of stress and environment.
2. Glass-fiber reinforced polymer composite reinforcing bars can be used in concrete environments and expected to perform for over 50 years.
3. The maximum stress limits for glass-fiber reinforced isophthalic polyester composite pultruded rod in air is approximately 45% of the ultimate tensile strength when using either traditional E-glass or Advantex glass as fiber reinforcements.
4. The maximum stress limits for glass-fiber reinforced isophthalic polyester composite reinforcing bars used in concrete is approximately 25% of the ultimate tensile strength when using Advantex glass and 15% when using traditional E-glass as reinforcements.
5. When loading a GFRP rod at 35% of its ultimate capacity, the 50-year creep strain is 4.7% of the initial strain or an additional 415 micro strain.

REFERENCES


### TABLE 1 Properties of Pultruded Rod Test Samples

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Number of tests</th>
<th>Tensile Strength MPa (ksi)</th>
<th>Std. Dev. MPa (ksi)</th>
<th>Tensile Modulus GPa (msi)</th>
<th>Std. Dev. GPa (msi)</th>
<th>Glass Content (weight%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional E-glass</td>
<td>10</td>
<td>1124 (163)</td>
<td>13.1 (1.9)</td>
<td>47.6 (6.9)</td>
<td>1.4 (0.2)</td>
<td>77.2</td>
</tr>
<tr>
<td>Advantex Glass</td>
<td>10</td>
<td>1069 (155)</td>
<td>27.6 (4.0)</td>
<td>45.4 (6.6)</td>
<td>0.7 (0.1)</td>
<td>73.2</td>
</tr>
</tbody>
</table>

### TABLE 2 50-Year Maximum Mean Stress of Isophthalic Polyester Composite Pultruded Rods at 23°C
<table>
<thead>
<tr>
<th>Environment</th>
<th>Traditional E-glass</th>
<th>Advantex Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%Ultimate</td>
<td>MPa (ksi)</td>
</tr>
<tr>
<td>Air</td>
<td>44.6</td>
<td>490 (71)</td>
</tr>
<tr>
<td>Cement Extract</td>
<td>14.8</td>
<td>165 (24)</td>
</tr>
</tbody>
</table>

FIGURE 1 Stress-rupture test fixtures.
FIGURE 2  Sample under load in stress-rupture test frame.

Figure 3  Stress-rupture performance of GFRP composite rods in tension in air.

Advantex Glass - blue, $r^2=0.93$, log(TTF) = 56.9 - 30.87 log(% ult)
Trad. E-Glass - red, $r^2=0.86$, log(TTF) = 57.6 - 31.51 log(% ult)
Continuing tests - yellow

50 years
45.8%
44.6%
Figure 4 Stress-rupture performance of GFRP composite rods in tension in cement at 23°C.

Figure 5 Stress-rupture performance of Advantex glass composite rods in cement at two temperatures.

Figure 6 Stress-rupture performance of Advantex glass composite rods in cement at 23°C.
Figure 7 Creep behavior of GFRP composite rod with stress at 35% of ultimate.

Change in 50 Years
initial = 8825
50 years = 9240
change = 415 microstrain
change = 4.7%