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Creep Rupture Testing of GFRP Bars under Sustained Loading

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Abstract

One of the major limitations to the exploitation of GFRP bars is represented by their relatively low creep rupture strength against sustained loads that is limited to 20% of the instantaneous Guaranteed Tensile Strength (GTS) by ACI 440.1R-15.
This study presents the results of creep rupture tests performed on a GFRP bar. The results are analyzed to extrapolate a guaranteed value for the creep rupture strength of the material system considered. The proposed approach provides a safe value that can be used for design purposes. This procedure yields a creep rupture strength equal to 46% of the GTS corresponding to more than two times the limitation imposed by ACI 440.1R-15.
The results of this experimental campaign support the relaxation of creep rupture limitations currently imposed by ACI guidelines following the example of other authoritative standards in the US and Canada. The implications on the engineering practice are relevant allowing for a more efficient design with GFRP bars and potentially allowing to deploy GFRP bars and strands in pre-tensioning applications where reinforcement is bonded to the concrete without the use of mechanical anchors.

Keywords: GFRP bar, creep rupture, sustained load, design guidelines.

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Introduction

Existing guidelines and specifications provide practitioners with the tools they need for the design and construction of Fiber Reinforced Polymer Reinforced Concrete (FRP-RC) structures [1, 2]. Guidelines are periodically updated to reflect advancements in the state-of-the-art and allow for more efficient design. The creep rupture strength of GFRP bars under sustained load was identified as a limiting factor in some applications [3]. Recent studies into the creep rupture strength of GFRP bars [4] capture the improved performance of material systems manufactured according to current material specifications [5] and benefit from the adoption of a standardized test method [6]. However, the procedures and safety factors adopted remain unchanged since the first edition of ACI 440.1R [7] and do not provide a clear indication of the associated safety level. Therefore, investigation into the creep rupture behavior of GFRP bars remains a priority.

Experimental Investigation

In this study, one type of GFRP bar made with ECR fibers and vinylester resin with helically-wrapped surface enhancement was tested to evaluate its creep rupture strength. The first part of the study dealt with characterizing the geometry and mechanical properties of the bar. Specimens were tested in tension according to ASTM D7205 [8]. Area measures were performed according to ASTM D7205 subsection 11.2.5.1 [8]. The tested bar has a nominal diameter (d_n) of 12.7 mm, a nominal area (a_n) of 129 mm^2, and an average effective area (a_f) of 149 mm^2. It has an average Ultimate Tensile Strength (UTS) ($F_{fu,m}$) of 165 kN with a coefficient of variation equal to 4.9%, a Guaranteed Tensile Strength (GTS) (F_{fu}*) of 140 kN, and an average elastic modulus (E_f) of 57 GPa computed on the effective area. The second part of the study dealt with conducting creep rupture tests according to ASTM D7337 [6] using the test setup shown in Figure 1. Creep rupture points were collected over six different load levels ranging from 89% UTS to 75% UTS. All the specimens were tested until failure.

Discussion of Results

The creep rupture strength of GFRP bars decreases logarithmically at increasing endurance time. Creep rupture points can be plotted in a logarithmic diagram where the x-axis reports the logarithmic time-to-failure and the y-axis reports the level of sustained load as shown in Figure 2. A mean creep rupture curve can be defined as reported in Eq. 1.

$$\frac{F_{fc,m}}{F_{fu,m}} = 1 - B_m \log_{10}\left(\frac{t}{t_0}\right) \tag{1}$$

Where: $F_{fc,m}$ is the mean creep rupture strength at endurance time t, $F_{fu,m}$ is the average UTS at time zero (t_0) equal to 0.0001 hours, and B_m is an adimensional regression parameter equal to 0.031. For consistency with tensile test results, when t equals t_0, the mean creep rupture strength must equal the average UTS of the material system as shown in Figure 2. A quasi-static tensile test has a total duration of approximately 10 minutes [8]; however, the maximum load is maintained on the specimen only for one instant, corresponding to the final step in the load ramp. Therefore, a quasi-static tensile test is a case-limit creep rupture test with a load duration t_0 equal to a fraction of a second.

Both tensile test results and creep rupture test results are statistically variable. In tensile tests, the load duration is set, and results are scattered along the load axis. Conversely, in creep rupture tests the sustained load is set, and rupture points are scattered along the time axis. Modelling the variability in tensile test results using a normal distribution, and the variability in times-to-failure using Weibull distribution, a characteristic creep rupture curve can be defined. The characteristic curve is translated downwards and rotated leftwards with respect to the mean curve to account for variabilities along both axis and is represented by a dashed line in Figure 2. The characteristic creep rupture curve represents a lower-bound propriety of the material but does not define a safe threshold for design purposes yet. To that aim, further conservatism can be introduced following the design-assisted-by-testing procedure detailed by EN 1990 [9]. The resulting guaranteed curve is translated downwards with respect to the characteristic curve to account for the additional conservatism required on the load axis and is represented by a continuous line in Figure 2.

Discussion of Results

The tested GFRP bar has a mean creep rupture strength equal to 65% UTS, and a guaranteed creep rupture strength equal to 39% UTS (46% GTS). The ratio of the guaranteed creep rupture strength to the guaranteed tensile strength defines the unconditioned creep rupture knock-down factor that can be taken equal to 0.46 when designing using the GFRP bars tested in this study. The value is more than two times the 0.20 coefficient currently recommended by ACI 440.1R [1] and approximately 50% higher than the 0.30 coefficient currently recommended by AASHTO [2].

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Figure 1 – Creep rupture test setup.

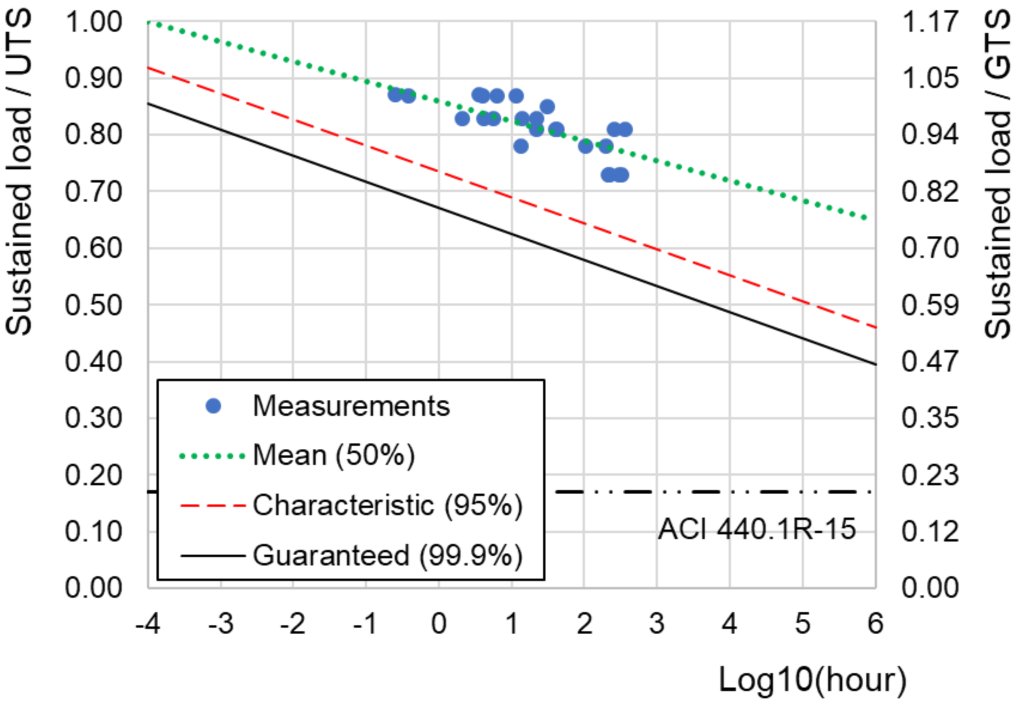

Figure 2 – Creep rupture test results in a logarithmic diagram.