ABSTRACT

Relaxation is a key factor controlling the application of prestressing tendons. This paper focuses on the relaxation behavior of newly developed BFRP tendon for prestressing applications. A series of relaxation tests on BFRP tendons with three different initial stresses of 0.4 \( f_u \), 0.5 \( f_u \) and 0.6 \( f_u \) \((f_u = \text{tensile strength})\) were first conducted through a specially designed setup to eliminate the adverse impact of slippage at anchor zone. Theoretical value of relaxation rate based on an existing theory was calculated. An additional group of test was designed to clarify the effect of pretension on the relaxation behavior. The results show that the setup can effectively measure the relaxation loss of specimen, with monitoring the slippage at anchor zone simultaneously. Higher stress level can lead to larger relaxation loss. Theoretically calculated value of relaxation rate is consistent with the experimental results. The relaxation rates of BFRP tendon at 1000 h are 4.2 %, 5.3 % and 6.4 % under 0.4 \( f_u \), 0.5 \( f_u \) and 0.6 \( f_u \), respectively. Pretension performs effective for the controlling of relaxation loss. Specimens with pretension treatment behave only 2.6 % relaxation rate under 0.5 \( f_u \) at 1000 h, comparable to the relaxation rate of prestressing steel strand under 0.7 \( f_u \) at 1000 h (2.5 %). The load retentions at one million hours are predicted to be 93.8 %, 91.8 % and 90.0 % for BFRP tendons under 0.4 \( f_u \), 0.5 \( f_u \) and 0.6 \( f_u \), respectively. Also, a load retention of 93.3 % is predicted for BFRP tendon with pretension treatment, under 0.5 \( f_u \), at one million hours.

KEYWORDS

Basalt fiber-reinforced polymer (BFRP) tendon, relaxation, prestressing, pretension, prediction

INTRODUCTION

Fiber-reinforced polymer (FRP) composites have been treated as competitive alternatives for structural strengthening, retrofitting, and members in new construction (Triantafillou 1998; Buyukozturk and Hearing 1998) owing to their integrated advantages compared to steel such as high strength, light weight and corrosion resistance. Among the wide application fields of FRP in civil engineering, tension-only prestressing tendon is considered to be the most efficient way because of its high strength only in the longitudinal direction of the fibers. Basalt FRP (BFRP) was newly developed (Wu et al. 2012) and its potential advantages in structural
reinforcement have been gradually recognized (Wang et al. 2013; Shi et al. 2013). The most significant advantage of BFRP is its superior creep behavior, displaying a creep rupture limit of 0.52 $f_u$ ($f_u$ = ultimate strength) (Wang et al. 2014). This property allows BFRPs to be used as competitive prestressing members to carbon FRP (CFRP) and aramid FRP (AFRP), whose creep rupture limit are 0.70 $f_u$ and 0.55 $f_u$, respectively (ACI 2004). Apart from creep rupture, relaxation is also an important factor, determining the prestressing effect of tendons on prestressed structures. Systematical researches on relaxation behavior of CFRP and AFRP have been done (Saadatmanesh and Tannous 1999a and 1999b), which showed that the relaxation losses were predicted to be 5.87 % and 10.9 % for CFRP and AFRP tendons respectively, after 50 years, under 0.4 $f_u$. However, systematical and comprehensive researches on relaxation behavior of BFRP have not been found in the exist literatures. Thus, a comprehensive understanding of the relaxation behavior of BFRP is critical for the application of BFRP as prestressing members.

**EXPERIMENTAL PROGRAM**

*Specimen Preparation*

BFRP tendons with nominal diameter of 6 mm were adopted in the current study. The tendons were manufactured by using unidirectional basalt fiber roving of 2400 tex and vinyl ester resin through pultrusion. The fiber volume fraction of the BFRP tendon was approximately 65 %, and the total length of each specimen was 1260 mm. The two ends were treated by sand blasting and anchored with seamless steel tubes with outer diameter of 16 mm and thickness of 3 mm. For the relaxation test, the cross sections of the steel tubes at the loading end were processed to be flat, to guarantee their smooth contact with the steel plates in relaxation loading setup. For short-term tensile test, anchorage length was 300 mm, while for relaxation test, anchorage lengths were determined to be 200 mm for specimens with initial stress of 0.4 $f_u$ or 0.5 $f_u$, and 230 mm for specimens with initial stress of 0.6 $f_u$. Epoxy resin was used to fill the gap between the steel tube and the BFRP tendon, and the resin was allowed to cure for seven days to ensure achieving sufficient strength.

*Loading Setup*

The short-term tensile test was conducted on electronic creep tension testers RD-200 with a load capacity of 200 kN (Figure 1(a)). The deformation of each specimen was measured simultaneously by an extensometer with a gauge length of 120 mm (Figure 1 (c)).
Figure 1 RD-200 tester and extensometers

For the long-term relaxation test, a set of reaction equipment was designed, as shown in Figure 2. The load was applied on the tendon, through a special loading screw. A load cell, with minimum resolution of 10 N, was set to monitor the load in tendon during both loading procedure and relaxation stage. Two aluminum sheets with thickness of 3 mm were fixed on the surface of tendon with epoxy glue near the anchorage to monitor the relative slippage between tendon and anchorage during the relaxation test. Two LVDTs were installed, in contact with the aluminum sheets, to measure the displacement caused by anchor slippage. The minimum resolution of LVDTs was 0.001 mm.

**Loading Procedure**

According to JSCE (1995a), for the short-term tensile test, the load was applied at a constant rate of 500 MPa/min until failure. The original data for load and deformation were recorded via a computer once every second. Five effective specimens without any failure at the anchorage zone were used to determine the tensile strength of BFRP tendons, which was used as reference for different levels of initial loads applied in the relaxation tests.

For the relaxation test, the load was applied on the tendon artificially by two wrenches, one was kept still on the loading screw and the other was used to twist the nut during loading procedure (Figure 3). The loading procedure lasted approximately 3 min. Initial stresses of 0.4 $f_u$, 0.5 $f_u$ and 0.6 $f_u$ were designed to investigate the relaxation behavior of BFRP tendon under different stress levels, according to JSCE (1995b). To clarify the effect of pretension, another series of test were conducted on the specimens with initial stress of 0.5 $f_u$, after pretension of
0.6$f_u$ level and 3 h duration, which was validated to be the optimum pretension treatment for BFRP tendon (Shi et al. 2015). Three specimens were prepared for each test group according to JSCE (1995b).

According to JSCE (1995b), the data of load and displacement were recorded at the following times: 1, 3, 6, 9, 15, 30, and 45 min; and 1, 1.5, 2, 4, 10, 24, 48, 72, 96, and 120 h. Subsequent measurements were conducted once every 120 h. Duration for each relaxation test was determined to be 1000 h.

RESULTS AND DISCUSSIONS

Short-term Tensile Property

The failure mode of the BFRP tendon is shown in Figure 4, displaying a typical dispersed failure of fibers in the FRP tendon. The results of the ultimate tensile properties are shown in Table 1. In reference to the results, the ultimate tensile strength of the BFRP tendons was determined to be 1500 MPa with a 95 % strength guarantee through Eq. 1 according to GB 50608-2010.

\[
f_s = \mu_f (1-1.645\delta_f)
\]

where $f_s$, $\mu_f$ and $\delta_f$ represent the standard value, mean value and coefficient of variation (CV) of ultimate strength, respectively. $f_s$ serves as $f_u$ in the following results and discussions.
Table 1 Test results of tensile properties

<table>
<thead>
<tr>
<th></th>
<th>Mean value</th>
<th>Coefficient of variation (CV)</th>
<th>95 % guaranteed strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Strength ($f_u$)</td>
<td>1571 MPa</td>
<td>2.74 %</td>
<td>1500 MPa</td>
</tr>
<tr>
<td>Elastic modulus ($E$)</td>
<td>55 GPa</td>
<td>1.36 %</td>
<td></td>
</tr>
<tr>
<td>Fracture strain ($\varepsilon_u$)</td>
<td>2.87 %</td>
<td>3.14 %</td>
<td></td>
</tr>
</tbody>
</table>

**Relaxation Curves**

Considering the slippage of specimens at two anchorages, the axial load in specimen was modified through Eq. 2.

\[
F = F_0 + E(A_{d_1} + d_2)/l
\]

where $F$ = modified load; $F_0$ = measured load; $E$ = elastic modulus; $A$ = cross-sectional area; $d_1$ and $d_2$ = displacements measured by the two LVDTs; $l$ = distance between the two monitoring points.

The relation curves of load retention (ratio of the modified load to initial load, in percentage) against time, i.e. the relaxation curves, are shown in Figure 5. The curves under different initial stresses perform similar tendency, which can be divided into two stages. During the first stage, an initial rapid decrease of stress in the specimen can be observed. Then, the rate of relaxation loss gradually decreases with respect to time. That tendency of relaxation loss is caused by straightening of the originally uneven fibers. The specimen performs a stable and slow rate of relaxation loss during the second stage. At this stage, fibers are straightened and relaxation loss can be controlled. Some slight fluctuations can be seen in the relaxation curves, which are caused by the difference of thermal expansion rate between steel frame and BFRP tendon. The thermal deformations of specimen and steel frame are not synchronous when ambient temperature varies.

![Relaxation Curves](image-url)
Effects of Initial Stress

The relaxation rates of BFRP tendon specimens with different initial stress levels are shown in Figure 6. The relaxation rate increases in direct proportion to the stress level. At 1000 h, the relaxation rates are 4.2 %, 5.3 % and 6.4 %, for the stress level of 0.4 $f_u$, 0.5 $f_u$ and 0.6 $f_u$. Higher stress level leads to larger viscoelastic strain in BFRP tendon, resulting in larger stress loss, as speculated from Eq. 3.

$$\sigma = E \cdot \varepsilon_{\text{total}} = E \cdot \varepsilon_v(\sigma, t)$$  \hspace{1cm} (3)

where $\sigma$ = stress in tendon; $\varepsilon_{\text{total}}$ = total strain, equal to the sum of elastic and viscoelastic strain; $\varepsilon_v$ = viscoelastic strain, associated with stress ($\sigma$) and time ($t$).

Theoretical Relaxation Rate

Theoretically, the relaxation rate can be calculated from Eq. 3, with known viscoelastic strain of specimen during 1000 h, which has been obtained by the previous research on creep behavior of BFRP tendon (Wang et al. 2014). The reduction of stress during relaxation should be taken into consideration. The viscoelastic strain is also considered to be in direct proportion to the square of stress (Wang et al. 2014). Iterative calculations were conducted at 1, 5, 10, 20, 40, 60, 80, 100, 500, 1000 h. The theoretical relaxation rate in the current study is calculated to be 5.0 % at 1000 h under 0.5 $f_u$, with only 5.7 % relative error compared to the experimental value.

Effects of Pretension

Pretension has been validated to be effective for creep strain controlling (Shi et al. 2015, Wang et al. 2015). Similarly, as shown in Figure 7, relaxation rate can also be effectively controlled through pretension. Pretension facilitates the straightening of uneven fibers, creating an opportunity for fibers to realize better cooperation. Furthermore, as can be seen from Figure 7, there is a slight increment of load at the beginning of relaxation after pretension treatment (0.6 $f_u$ and 3 h). This phenomenon is caused by elastic aftereffect, defined as the gradual restoration of deformation after unloading, which can also be observed in concrete material. The above results further validate the effectiveness of pretension on relaxation controlling. The whole relaxation curves of 1000 h of specimens with pretension are shown in Figure 8, in which, P-0.5 denotes the test group with initial stress of 0.5 $f_u$ after pretension. The relaxation rates of the three specimens are 2.5 %, 2.7 % and 2.7 % at 1000 h,
comparable to the low relaxation of prestressed steel strand, equal to 2.5 % under 0.7 \( f_u \) (JGJ/T 279-2012).

\[ R_r = a - b \ln t \]  
(4)

where \( R_r \) = load retention rate, %; \( a, b \) = empirical constants; and \( t \) = test time, h.

Through fitting the relaxation curves, the predicted value of load retention at one million hour (114 years) can be figured out, as shown in Table 2. It is noteworthy that since the slight increase of relaxation curve at beginning, the curve fitting of specimens with pretension was conducted using the data after 10 h, otherwise, the regression coefficient will be excessively low. Under a stress level of 0.4 \( f_u \), the load retention is predicted to be 93.8 % at one million hours. The load retention at one million hours for CFRP tendon (Leadline) under 0.4 \( f_u \) is predicted to be 89.5 % using the formula proposed by Saadatmanesh and Tannous (1999 b). The lower load retention of CFRP tendon may be caused by the inevitable long-term anchor slippage in Saadatmanesh and Tannous’s test, demonstrating the effectiveness of the setup for relaxation test in this study. BFRP tendon with pretension treatment behaves 93.3 % load retention, close to that under 0.4 \( f_u \).
Table 2 Predicted mean values of load retention at one million hours

<table>
<thead>
<tr>
<th>Initial stress</th>
<th>0.4 $f_u$</th>
<th>0.5 $f_u$</th>
<th>0.6 $f_u$</th>
<th>0.5 $f_u$ (with pretension)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean value</td>
<td>93.8 %</td>
<td>91.8 %</td>
<td>90.0 %</td>
<td>93.3 %</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

This paper investigated the relaxation behavior of BFRP tendon. Relaxation tests were conducted under 0.4 $f_u$, 0.5 $f_u$ and 0.6 $f_u$. Theoretical relaxation rate was calculated. The method for relaxation controlling was proposed and validated. Values of load retention at one million hours were predicted. The main conclusions can be drawn as follows.

1. The proposed specially designed setup for relaxation test has the capability of reflecting the real relaxation loss in FRP tendon by eliminating the influence of slippage at anchor zone.

2. The relaxation rate increases in direct proportion to the stress level. At 1000 h, the relaxation rates are 4.2 %, 5.3 % and 6.4 %, under the stress level of 0.4 $f_u$, 0.5 $f_u$ and 0.6 $f_u$.

3. Relaxation rate can be theoretically calculated through viscoelastic strain of the material under certain stress level, obtained by creep test. The theoretical and experimental values of relaxation rate at 1000 h show a satisfactory consistence.

4. Pretension treatment performs effectiveness of controlling relaxation loss. The relaxation rate can be lowered to approximately 2.6 % at 1000 h under 0.5 $f_u$, comparable to the low relaxation of prestressed steel strand under 0.7 $f_u$ (2.5 %), further showing a great potential of BFRP tendon as prestressing component.

5. The values of load retention at one million hours are predicted to be 93.8 %, 91.8 % and 90.0 % under 0.4 $f_u$, 0.5 $f_u$ and 0.6 $f_u$, respectively. A load retention of 93.3 % is predicted for BFRP tendon with pretension treatment, at one million hours under 0.5 $f_u$.

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