Construction and Building Materials 94 (2015) 750–757

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Creep behavior enhancement of a basalt fiber-reinforced polymer tendon

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HIGHLIGHTS

- Creep strain rate of BFRP tendon can be significantly lowered by pretension.
- BFRP tendons can sustain a stress level of 0.7 f_u without fracture within 1000 h.
- One million-hour creep rupture stress is enhanced from 0.59 f_u to 0.63 f_u.

ARTICLE INFO

Article history:
Received 4 April 2015
Received in revised form 20 June 2015
Accepted 14 July 2015
Available online 18 July 2015

Keywords:
Basalt fiber reinforced polymer (BFRP)
Creep behavior enhancement
Creep rupture stress
Pretension
Creep strain rate

ABSTRACT

Creep behavior is a key factor controlling the long-term behavior of basalt fiber-reinforced polymer (BFRP) tendons when employed as prestressing members. This paper studies the creep behavior of pretension-treated BFRP tendons and evaluates its potentials in prestressing applications. Based on an effective enhancement by pretension, the evaluation of the creep behavior of pretension-treated BFRP tendons was conducted. The parameters comprise the creep strain–time relationship, creep strain rates, residual strength and elastic modulus after creep and the prediction of the creep rupture stress based on a reliability analysis. In addition, the creep behavior of pretension-treated BFRP was also compared with the results of original untreated BFRP tendons. The results show that pretension-treated BFRP tendons can sustain a stress level of 0.7 f_u without fracture within 1000 h, 17% higher than the untreated BFRP tendons (0.6 f_u). The creep strain rates of BFRP tendons after pretension exhibit a substantially low level in comparison to those without the pretension process, demonstrating the effectiveness of the pretension on creep strain rate control. The one million-hour creep rupture stress of BFRP tendons is effectively enhanced from the original 0.59 f_u to 0.63 f_u based on experimental fitting and from 0.52 f_u to 0.54 f_u according to a reliability analysis.

1. Introduction

Fiber-reinforced polymer (FRP) composites have emerged as competitive alternatives for structural strengthening, retrofitting, and acting as members in new construction [1–3] owing to their integrated advantages compared to steel such as a high strength, light weight and corrosion resistance. Aside from conventional carbon, aramid and glass fibers, basalt fiber is a newly developed inorganic fiber characterized by its environmental friendly properties in both the production process and disposal because it is produced using a single component raw material by drawing fibers from molten volcanic rock [4]. In recent years, with an increasing number of studies and a deeper understanding of the basalt FRP (BFRP), its potential advantages in structural reinforcement have been gradually recognized [5–7]. Aside from the superior mechanical properties and corrosion resistance of BFRPs when compared to a glass FRP (GFRP), the most significant advantage of a BFRP is its superb creep behavior, displaying a creep rupture limit of 0.52 f_u [8]. This superior property allows BFRPs to be used as competitive prestressing members to a carbon FRP (CFRP) and an aramid FRP (AFRP) (with creep rupture limits of 0.70 f_u and 0.55 f_u, respectively). By contrast, a GFRP is not recommended as prestressing members because of its excessively low creep rupture stress

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http://dx.doi.org/10.1016/j.conbuildmat.2015.07.118
0950-0618/

(0.29 f_u) [9]. For prestressing applications, the high strength and light weight advantages of a BFRP can be fully displayed. However, the creep strain rates of a BFRP under a high level of sustained load are relatively large compared to steel prestressing tendons and CFRP tendons [8], inducing a prestressing loss in the strengthened structures. Therefore, to sufficiently utilize the advantages of a BFRP, its creep behavior should be further enhanced. The creep behavior of enhanced BFRPs must be comprehensively evaluated in prestressing applications.

2. Review of previous work

There are sufficient studies on the creep behavior for CFRP, AFRP and GFRP. The research by Yamaguchi et al. revealed a linear relationship between creep rupture stress and the logarithm of time for each type of FRP bar [10]. They reported that the ratios of stress level at creep rupture to the initial strength of the GFRP, AFRP, and CFRP bars after one million hours were linearly extrapolated to be 0.27, 0.45, and 0.92, respectively. In addition, the creep study of specially braided AFRP and twist CFRP bars with different diameters showed that the diameter of bars did not affect their creep behavior [11]. As a new type FRP material, few studies on the creep behavior of a BFRP are available in the literature. Banibayat and Patnaik [12] investigated the creep rupture stress of BFRP bars after being corroded in an alkaline environment under high temperatures. They concluded that the one million-hour creep rupture stress levels for the actual exposure and converted time were 0.11 f_u and 0.15 f_u, respectively. However, the high temperature acceleration can generate matrix degradation, which cannot reflect the real degradation of FRP in construction. Thus, these conclusions cannot serve as a reference for BFRP applied in real environments. As revealed in a previous study conducted by the authors [8], the creep rupture stress of a BFRP tendon was 0.52 f_u with 95% reliability, and the creep strain rate of BFRP was 3.68% after 1000 h under a sustained stress of 0.5 f_u, relatively larger than that of steel (2.5% under 0.7 f_u). To further enhance the creep behavior of the BFRP, methods for controlling creep behavior were investigated. Aside from creep control by the hybridization of different fibers and modification of matrix [13,14], a method of pretension on BFRP tendons was proposed because of two findings in previous experiments. First, the scatter of residual strength of BFRP tendons after the creep test becomes significantly smaller compared to the scatter of the ultimate tensile strength before creep test [8]. Second, no creep can be observed for the fibers themselves, and a significant creep occurred in the resin [15]. The mechanism of creep control by pretension is that the uneven fibers in an FRP can be straightened and redistributed during the pretension process because of the viscoelastic deformation of resin clarified in authors' previous study [16] as shown in Fig. 1. Through a pretension process, premature failure in fibers subjected to higher stress because of fiber unevenness can be avoided and less creep deformation can be realized. It is worth noting that the mechanisms between pretension and matrix modification on creep behavior enhancement are different. The main purpose of matrix modification is to control the creep deformation in matrix by toughening with particles such as carbon nanotube. The pretension method facilitates the redistribution of uneven fibers, benefitting the collaboration of fibers and enhancing creep behavior. Therefore, pretension has little effect on the creep behavior of resin.

The effectiveness of pretension on controlling creep strain rates under short-term duration was demonstrated in a previous study [16]. To comprehensively validate the enhancement effects on creep behavior of a BFRP tendon using pretension, the parameters associated with creep behavior (including the creep strain to time relationship, creep strain rates, residual strength and elastic modulus) and a prediction of long-term creep rupture stress should be further studied under a long-term sustained load.

3. Experimental program

3.1. Materials and specimen preparation

BFRP tendons with a nominal diameter of 6 mm were adopted in the current study. These tendons were manufactured by using unidirectional basalt fiber roving of 2400 tex and a vinyl ester resin through pultrusion. The fiber volume fraction of the BFRP tendon was measured to be approximately 65%, and the total length of each specimen was 1250 mm [17]. The two ends were treated by sand blasting over a length of 300 mm and anchored with seamless steel tubes with an outer diameter of 14 mm and thickness of 2 mm. Epoxy resin was used to fill the gap between the steel tube and the BFRP tendon, and the specimens were allowed to be cured for seven days to ensure achieving a sufficient strength (Fig. 2).

3.2. Test setup

The short-term mechanical test and long-term creep test in the current study were both conducted on electronic creep tension testers RD-200 with a load capacity of 200 kN (Fig. 3(a)). The deformation of each specimen was measured simultaneously by an extensometer with a gauge length of 120 mm (Fig. 3(c)).

3.3. Pretension treatment of specimens

According to the previous study [16], a pretension level of 0.6 f_u with duration of 3 h is the most appropriate pretension process for BFRP tendons. If the pretension duration is too short (e.g., 1 h or 2 h) or the level is too low (e.g., 0.5 f_u), then the

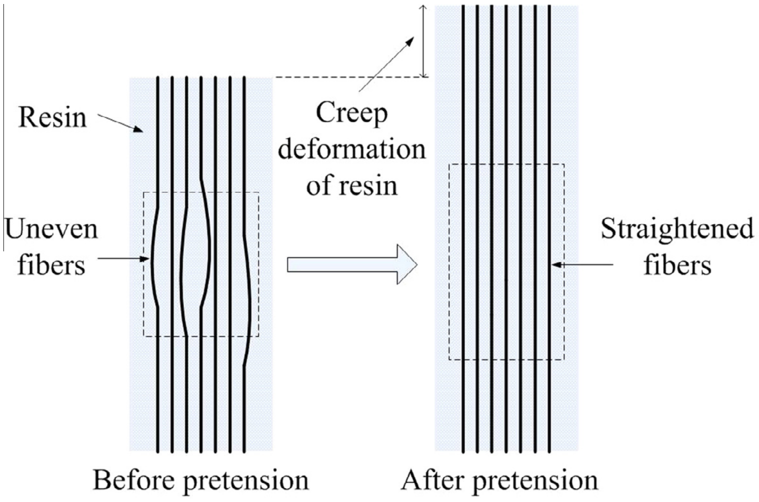

Fig. 1. Conceptual graph for the straightening of fibers.