Materials and Design 64 (2014) 721–728

Contents lists available at ScienceDirect

Materials and Design

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

Evaluation of prestressed basalt fiber and hybrid fiber reinforced polymer tendons under marine environment

Xin Wang [a,b,c], Gang Wu [a,b,c,*], Zhishen Wu [a,b,c], Zhiqiang Dong [c], Qiong Xie [c]

[a] National and Local Unified Engineering Research Center for Basalt Fiber Production and Application Technology, Southeast University, Nanjing 210096, China
[b] Key Laboratory of C & PC Structures Ministry of Education, Southeast University, Nanjing 210096, China
[c] International Institute for Urban Systems Engineering, Southeast University, Nanjing 210096, China

ARTICLE INFO

Article history:
Received 27 May 2014
Accepted 29 July 2014
Available online 8 August 2014

Keywords:
Basalt fiber
Hybrid fiber
Fiber reinforced polymer
Marine environment
Prestressing

ABSTRACT

This paper studies the degradation of the tensile properties of prestressed basalt fiber-reinforced polymer (BFRP) and hybrid FRP tendons in a marine environment. Two levels of prestressing toward typical prestressing applications were applied in the experiment. The variations of tensile strength, elastic modulus and the relevant coefficient of variation (CV) were first investigated. The effect of prestressing on tensile property degradation was discussed. The characteristics of prestressed hybrid FRP tendons in a marine environment simulated by a salt solution were clarified. Moreover, a prediction model of BFRP tendons with different levels of prestressing in a marine environment was proposed. The results show that the BFRP tendons' superior resistance to salt corrosion and the degradation rate of their tensile strength is nonlinearly proportional to the prestressing ratios, whereas the elastic modulus remains constant regardless the prestressing ratio and aging duration. Although prestressing on BFRP tendons accelerates degradation, it can still lower the variation of the strength of the BFRP tendon. Hybridization can lower the degradation rate of basalt and carbon FRP (B/CFRP) without prestressing, whereas basalt and steel-wire FRP (B/SFRP) exhibit much faster degradation due to the internal corrosive steel wires. The model regression by the Napierian logarithm equation well represents the degradation trend of BFRP tendons under different levels of prestressing.

1. Introduction

Basalt fibers are environmentally friendly and nonhazardous materials because they are produced from volcanic rocks using single-component raw materials and by drawing fibers from the molten rocks [1,2]. Basalt fiber-reinforced polymer (BFRP) has been newly developed for applications in civil infrastructure and show obvious advantages in their mechanical and chemical behavior as well as their high ratio of performance to cost in comparison to other FRP composites and conventional steel materials. For instance, BFRP has an approximately 25% higher strength and modulus, a similar cost, and is more chemically stable compared to E-glass FRP (GFRP) and a wider range of working temperatures and much lower cost than carbon FRP (CFRP). Further, they have over five times the strength and approximately one-fourth the density of commonly used low-carbon steel bars. One of the most important properties of BFRP is the high creep rupture stress of approximately 60% of its static tensile strength (fu) at one million hours, as predicted by previous experiments [3], which is approaching the level of CFRP and is much higher than that of GFRP [4]. Due to the above advantages, BFRP has become an attractive alternative for conventional construction materials, especially in prestressing applications. From the perspective of structures, it is recognized that the most useful application of FRP is as a prestressed, tension-only member in structures, rather than as normal reinforcement in reinforced concrete (RC) structures due to their anisotropic property, relatively low modulus and high strength compared to steel [5]. Several previous studies have revealed that FRPs as stay cables in cable-stayed bridges and as external prestressed tendons in bridge girders exhibit prominent advantages compared with steel cables [6–10]. Among the above studies, BFRP cables were shown to exhibit additional advantages of performance to cost in comparison with CFRP and AFRP, especially in relatively moderate span bridges [6]. Furthermore, adopting the method of a hybrid design of composite materials, the performance of cable-stayed bridges with BFRP cables can be further enhanced by hybridizing basalt and carbon FRP (B/CFRP) and by hybridizing basalt fibers and steel-wire FRP (B/SFRP) [7].

* Corresponding author at: National and Local Unified Engineering Research Center for Basalt Fiber Production and Application Technology, Southeast University, Nanjing 210096, China. Tel.: +86 2583793232

E-mail address: g.wu@seu.edu.cn (G. Wu).

http://dx.doi.org/10.1016/j.matdes.2014.07.064
0261-3069/

The above studies indicate potential advantages of BFRPs and the related hybrid FRPs for prestressing structures in comparison with conventional materials. However, to guarantee long-term performance, the durability of the promising BFRPs and the related hybrid FRPs should be first assessed before they can be adopted in practical applications. Because prestressing structures such as cable-stayed bridges are usually located near the sea, the marine environment becomes the controlling factor affecting the service life of materials. Thus, a chloride ion solution is adopted to simulate this environment and the behavior of the BFRP and the related hybrid FRP tendons are evaluated to identify their degradation in a marine environment. Meanwhile, considering the load condition of the structural elements of those prestressing structures, the different prestressing ratios are considered in the current study for the simulation of the actual load condition.

Numerous studies on the durability of carbon and glass fiber composites, mainly emphasizing the behavior under alkali, acid and salt environments [11,12], have been reported in the literature. Because the initial application of FRPs in civil infrastructure is the replacement of steel reinforcement in concrete structures, the durability of FRPs under an alkali environment is of significant interest. In general, CFRP exhibits superior performance in resisting different corrosive effects, whereas the GFRP exhibits relatively weak resistance to alkali and acid. For the newly developed BFRP, fewer durability studies have been performed compared to other FRP composites. Within the limited literatures of the durability of BFRP, most of them emphasized alkali resistance and moisture absorption [13,14]. Few studies investigated the degradation of BFRP sheets under seawater and analyzed the corrosion mechanism [15,16]. No particular study on the salt resistance behavior of BFRP tendons/bars can be found in the existing literature. Although it was revealed in the authors' previous studies [16] that BFRP sheets exhibited high resistance to salt corrosion among other corrosive environments, the degradation of BFRP tendons should still be further investigated. Because the differences between FRP sheets and tendons not only lies in the production technology (hand layer-up to pultrusion) but also in the matrix types (epoxy to vinyl ester), relevant forming temperatures (room temperatures to 150°) and fiber volume fraction, those differences can definitely affect the degradation behavior of BFRP under corrosive environments. Thus, considering the lack of existing studies of BFRP composites in marine environments, the current study will emphasize the behavior of BFRP tendons for prestressing applications in marine environments. It is noted that the accelerated degradation by prestressing is of significant interest, whereas the conventional acceleration method by elevated temperatures is not adopted.

2. Experimental program

2.1. Materials and specimens

Four types of FRP tendons are adopted in this study: BFRP, CFRP, hybrid basalt and carbon FRP (B/CFRP), and hybrid basalt and steel-wire FRP (B/SFRP), as shown in Fig. 1. All of the FRP tendons were manufactured using unidirectional fibers or steel wires and vinyl ester resin via pultrusion technology. For hybrid FRP tendons, the volumetric proportion of basalt and carbon fibers is 3:1, and for basalt fibers and steel wires, a proportion of 4:1 is adopted, in which nine steel wires with a diameter of 0.7 mm are distributed. The entire volumetric proportion of the fibers/steel wire in the FRP tendon is approximately 60%. All of the specimens have a constant diameter of 6 mm and a length of 1000 mm. The cross-sectional configuration of different FRP tendons is shown in Fig. 1. The minor composition of steel wires and carbon fibers in hybrid FRP tendons is uniformly distributed along the cross-section. The commercial basalt roving of 4800tex and carbon fiber roving of T300 and 12 k are provided by the GBF and Toray companies, respectively [17,18]. Steel wires with a diameter of 0.7 mm are purchased in the local market. The tested average strength of the steel wire is 2178 MPa, and the CV is 0.2%.

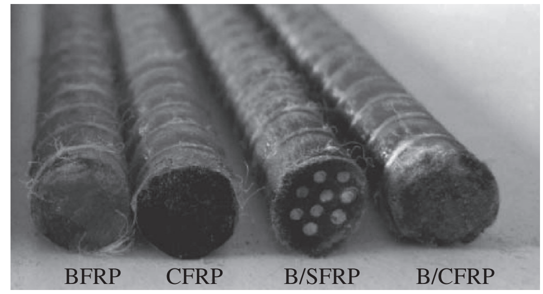

Fig. 1. Surface and cross-section of FRP tendons.

The specimens for testing the tensile properties are made according to ACI 440 [19] as shown in Fig. 2. The two ends are treated by sand blasting over a length of 300 mm and anchored with seamless steel tubes with an outer diameter of 14 mm and a thickness of 2 mm. Epoxy resin was used to fill the gap between the steel tube and the BFRP tendon, and the specimen was allowed to be cured for 7 days to ensure that a sufficient strength is achieved. For each type of FRP tendon, five specimens were tested to determine the original tensile property.

2.2. Test setup and procedure

To apply prestressing loads on the specimens, a set of reaction equipment was designed and manufactured and a polyvinyl chloride (PVC) tee-shaped tube with an internal diameter of 16 mm was installed at the central part of the specimen, as shown in Fig. 3. After prestressing to the required stress, the two ends of the PVC tube were sealed by epoxy resin, and the upper end for adding the salt solution was also covered by a PVC cover after perfusion. During the experiment, the salt solution in the tube was checked by every one week, including the sealed condition at two ends and the solution level inside the tube. If it was found the solution level was lowered or solution was leaked at the ends, additional salt solution with the same concentration will be added in the tube. On the other hand, since the inner diameter of the tube is 16 mm, the volume of solution in the tube is more than 6 times than that of the tendon. Thus, the overall concentration of salt solution cannot be significantly affected during the aging.

The prestressing load is applied through a hydraulic jack and maintained for one hour to relieve the influence of the initial relaxation and is subsequently anchored by a tightened bolt. The prestressing loss induced by the bolt is neglected due to the minimal prestressing loss induced by this type of anchorage. The

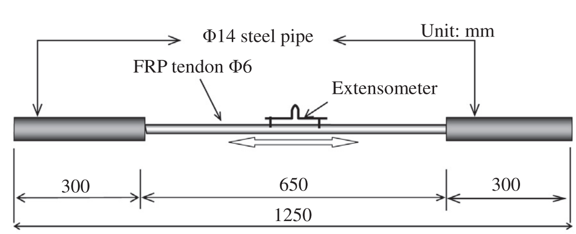

Fig. 2. Dimension of the specimens for tensile test of different FRP tendons.