Fatigue behavior of basalt fiber-reinforced polymer tendons under a marine environment

Jianzhe Shi, Xin Wang, Zhishen Wu, Zhongguo Zhu

Abstract: Due to their advantageous mechanical behaviors and anti-salt properties, basalt fiber-reinforced polymer (BFRP) tendons are a promising prestressing component under a marine environment. However, the degradation law of fatigue behavior of BFRP tendons under a marine environment is still unclear. This paper studies the fatigue behavior of BFRP tendons after aging in a salt solution by temperature-accelerated experiments. The degradation mechanism of fatigue behavior is clarified based on previous studies and analysis of the failure mode. The effect of aging temperature on fatigue strength degradation is analyzed using both experimental data and scanning electron microscopy (SEM) images. Moreover, the fatigue strength degradation of BFRP tendons at different local temperatures was predicted according to the Arrhenius equation. The results show that the fatigue strength degradation of BFRP tendons is governed by the weakened fiber-matrix interface resulting from the hydrolyzation of Si–O–Si chemical bonds in salt solution. SEM showed that specimens aged at 55 °C for 63 days demonstrate increased corrosion than those in other groups. Through the Arrhenius equation, the fatigue strengths of BFRP tendons are predicted to be 0.41, 0.43 and 0.45 f_u , respectively, at three representative northern latitudes after 100 years of aging in marine environments. The results provide guidance for fatigue design of BFRP tendons in a marine environment.

Keywords: basalt fiber-reinforced polymer (BFRP) tendons; fatigue; marine environment; mechanism; Arrhenius equation; prediction

1. Introduction

In a marine environment, a variety of durability problems in traditional infrastructure arise due to the corrosion of steel; these problems severely lower the capacity and serviceability of structures and lead to excessive maintenance expenses [1-3]. Replacing steel materials with fiber-reinforced polymers (FRPs) is an effective means to overcome these problems. FRPs have been used in externally bonded strengthening or concrete-filled FRP tubes to prevent the penetration of chloride ions through concrete cracks [4, 5]. FRPs have also been applied in concrete structures to replace steel reinforcements [6]. Among the wide applications of FRPs, prestressing tendons are considered to be the most efficient utilization due to the extremely high strength of FRPs in the longitudinal direction of the fiber as well as a relatively low elastic modulus. Prestressed FRP tendons or cables are a promising material for the use in long-span structures, such as cable-stayed bridges or girder bridges [7]. Traditional FRPs include carbon FRP (CFRP), aramid FRP (AFRP) and glass FRP (GFRP), but some defects still exist in these types of FRPs, which limits their applications in civil engineering. For example, the costs of CFRP and AFRP are excessively high for infrastructure, and GFRP has poor chemical stability and mechanical properties. In recent years, a novel basalt fiber, i.e., a type of inorganic fiber material, has been developed. This material is derived from a single raw material (molten volcanic rock) without any toxic gas emissions. Thus, it is considered to be environmentally friendly in terms of its production and disposal process [8]. The

mechanical properties (strength and modulus) and chemical stability of basalt FRP (BFRP) are significantly higher than those of GFRP [9]. In addition, the cost of BFRP is only about one-tenth to one-fifth of the costs of either AFRP or CFRP. Thus, a high cost-efficiency can be realized using BFRP. Moreover, BFRP tendons have a relatively high creep rupture stress equal to $0.52 f_u$ [10], which is comparable to CFRP ($0.7 f_u$) and AFRP ($0.55 f_u$) [11]. BFRP tendons can also survive 2 million cycles of fatigue load in the stress range of $0.55 f_u$ to $0.6 f_u$ [12]. In terms of the durability, BFRP has shown high strength retention of up to 95 % after aging in salt corrosion for 240 days (d) [13]. Owing to the above advantages, BFRP shows promise for applications such as bridge cables or external prestressing tendons under a marine environment [14, 15]. However, structures such as bridge girders strengthened by FRP tendons or cable-stayed bridges are often subjected to cyclic loads. Thus, a comprehensive understanding of the fatigue behavior degradation of BFRP tendon under seawater corrosion is necessary for its appropriate application in a marine environment.

2. Review of previous work

The fatigue behavior degradation of BFRP tendons under a marine environment is associated with two aspects. One is the fatigue behavior of BFRP in a non-corrosive environment, and the other is the degradation of the mechanical properties of BFRP under a marine environment. First, the authors have previously conducted a macroscopic study on the fatigue behavior of BFRP tendons using an effective anchorage through a winding fiber sheet [12]. S-N curves of BFRP tendons were plotted to predict the fatigue strength, and it was concluded that BFRP tendons remained undamaged within 2 million cyclic loads at the stress

range of $0.55 f_u$ to $0.6 f_u$. In terms of the fatigue failure mechanism, a microscopic study was conducted by Zhao et al. [16], and the failure modes were divided into fiber rupture, fiber-matrix interface and matrix cracking at high, middle and low stress levels, respectively. From the S-N curves and the mechanism clarification in a non-corrosive environment, the degradation of fatigue strength and the failure mechanism with exposure to a salt solution can be analyzed.

Second, many studies in the literature discuss the degradation of the mechanical properties under a marine environment. BFRP exhibits satisfactory anti-salt properties because the chloride ions lower the Fe^{2+} content in the basalt fiber, leading to a higher stability of BFRP under a marine environment [17]. BFRP bars demonstrated only a 6 % strength reduction after exposure to salt solution for 42 days at a relatively high temperature, 40 °C [18]. Furthermore, after aging in salt solution for 120 days under stress levels of 0.3 and $0.6 f_u$ (f_u = tensile strength) at normal temperature, BFRP still exhibited 93 % and 91 % strength retentions, respectively [19]. The strength reduction of BFRP is mainly caused by local hydrolyzation of Si–O–Si chemical bonds between the fibers and the matrix [20]. Moreover, chloride ions have negligible effects on the degradation of BFRP in salt solution. However, the fatigue behavior in a salt solution is different from the short-term mechanical properties since cyclic loads may enlarge the effects of fiber-matrix interface corrosion.

El Refai conducted the only study on the fatigue test with salt corrosion [21]. The fatigue strength of BFRP tendons was reduced by 25 % after aging for 70 d in a salt solution at room temperature. However, most of the specimens failed at the anchor zone; therefore, the results might not reflect the real fatigue behavior of the BFRP tendons themselves. Moreover, the

effects of different aging temperatures and durations were not taken into consideration in El Refai's research.

The current paper conducts fatigue tests on BFRP tendons after aging in a salt solution at three different temperatures for three different time durations. The degradation mechanism of fatigue behavior is clarified, and the effect of aging temperature on the fatigue strength degradation is analyzed and discussed. Finally, the fatigue strength degradation of BFRP tendons at different local temperatures is predicted with the Arrhenius equation. The results act as a guide for the application of BFRP tendons under a marine environment.

3. Experimental program

3.1 Material preparation

The BFRP tendons adopted in this study were manufactured by 1200 tex unidirectional fiber roving impregnated in epoxy resin through pultrusion. The fiber volume fraction was approximately 70 %. The diameter and total length of each specimen were 5.9 mm and 1000 mm, respectively.

Before the short-term and fatigue tests, the specimens were anchored using a special method. Bi-directional basalt fiber sheets impregnated in vinyl ester resin were first winded on the surface of the anchor zone (Figure 1(a)). Then, the anchor zone was placed into a specially designed mold (Figure 1(b)) for compression molding at a constant temperature of 120 °C for 30 minutes. The diameter and length of the anchorage were approximately 22 mm and 200 mm after molding, respectively (Figure 1(c)). A conical transition section at the loading end of the anchorage was designed to alleviate stress concentration (Figure 1(d)). This type of

anchorage performed effective in preventing premature failure of BFRP tendons at the anchor zone under cyclic loads [12].

3.2 Test setup

As shown in Figure 2, a SJY-II corrosion test chamber was adopted that contained a water bath. Environmental chambers were placed in the water bath. The water bath provided a constant aging temperature. The environmental chamber was 1200 mm long, 200 mm wide and 500 mm deep, and it was used to contain the salt solution and specimens for aging.

Short-term tensile tests and fatigue tests were conducted using a LFV-1000 servo-hydraulic dynamic fatigue tester (Figure 3). The tester has a loading capacity of ± 900 kN and a precision of 1 %. The strains of the specimens were measured by an extensometer with a gauge length of 50 mm. Load and strain data were recorded synchronously once per second by a computer in short-term tensile tests.

3.3 Aging procedure

Although the BFRP tendons were subjected to the coupling effects of fatigue and a marine environment in practical engineering, it is difficult to simulate these coupling effects in the laboratory. The fatigue test after aging in salt solution can also reflect the degradation of BFRP's fatigue behavior in salt solution, according to the research of El Refai [21]. Thus, fatigue load was applied on the specimens after aging in salt solution in this study.

Forty-five specimens were first immersed in salt solution at temperatures of 25, 40 and 55 °C for aging durations of 21, 42 and 63 d before the fatigue test. The specimens were labeled as

shown in Table 1. The letters “T” and “D” in the group names represent temperature and day, respectively. Temperatures of 25, 40 and 55 °C were adopted as the accelerated temperatures. The aging durations had an interval of 21 d because conspicuous degradation of the tensile strength was observed for BFRP at 3 weeks under an accelerated temperature in a previous study [20].

The composition of the salt solution to simulate a marine environment was 24.53 g/L NaCl, 5.20 g/L MgCl₂, 4.09 g/L Na₂SO₄, and 1.16 g/L CaCl₂, according to ASTM D1141-98 [22]. The solution was prepared using deionized water.

3.4 Loading procedure

Short-term tensile tests were conducted on five effective specimens without any failure at the anchor zone. Loading was controlled by displacement with a rate of 0.15 mm/s. The elastic modulus was calculated using the loads and the corresponding strains at approximately 50 % and 20 % of the ultimate tensile capacity, according to JSCE-E531 [23]. The measured tensile strength of BFRP tendons served as the reference for stress levels in the fatigue tests hereinafter.

The limit of the stress range of the BFRP tendons for 2 million cyclic loads is $0.05 f_u$ according to the experimental fitting in the authors’ previous study [12]. A previous finite element (FE) method also reported that the maximum stress range of the cables in cable-stayed bridges was 57.3 MPa, equal to $0.035 f_u$ [24]. Thus, the fatigue tests were conducted at a constant stress range of $0.05 f_u$ in the current study. The main variable in the fatigue tests was the fatigue maximum stress. With reference to the authors’ previous study

[12], fatigue maximum stresses were determined to range from 0.6 to 0.7 f_u , which ensured that fatigue failure took place within 2 million cyclic loads. In the fatigue tests, the load was first applied on a specimen at a rate of 0.3 kN/s up to the average cyclic load. Then, the cyclic load was applied immediately and continuously with a sinusoidal wave until the specimen failed. Fatigue tests were conducted with a frequency of 5 Hz according to JSCE-E 534 [25] to avoid a temperature effect on fatigue behavior.

4. Results and discussion

4.1 Short-term tensile properties

The five specimens in the short-term tensile test all exhibited a typical dispersed failure of fibers (Figure 4). No failure was observed at the anchor zone. The results of the short-term tensile test are shown in Table 2. The high ultimate strength (1719 MPa) and low coefficient of variation (CV) equal to 3.25 % show the feasibility of BFRP tendons for prestressing applications. The 95 % guaranteed strength is calculated to be 1628 MPa by $f_k = f_m - 1.645\sigma$, where f_k = standard value, f_m = mean value, and σ = standard deviation (SD) [26]. f_k serves as f_u hereinafter.

4.2 Fatigue failure mode and fatigue lives

In fatigue tests, the specimens exhibit a similar failure mode regardless of the fatigue load level, aging duration or temperature. The initial failure appears at the surface of the BFRP tendon specimen (Figure 5(a)) because the bundles of fibers near the surface are subjected to a larger stress than the inner fibers due to the shear lag effect. The initial failure is caused by

the debonding of the fiber-matrix interface, which is induced by the propagation of micro-cracks in the matrix. As the initial failure appears and propagates, the cross-section of the specimen decreases, which leads to a larger stress level in the specimen. Then, more failure zones at the surface appear successively, and ultimate failure occurs [12]. The ultimate failure mode, shown in Figure 5(b), is similar to that in the short-term tensile test (Figure 4). No failure is observed at the anchor zone, demonstrating the effectiveness of the special anchorage under cyclic load. The fatigue lives (total numbers of cycles at failure) of the specimens are shown in Table 3, in which $\sigma_{\max}$ and N_f represent fatigue maximum stress and fatigue life, respectively.

4.3 Fatigue Degradation mechanism

The fatigue failure of BFRP tendons at stress levels ranging from $0.6 f_u$ to $0.7 f_u$ is determined by the debonding of the fiber-matrix interface [12, 16]. Thus, the mechanism of the fatigue degradation of BFRP after immersion in salt solution is explained based on fiber-matrix interface degradation as follows. The surface of basalt fibers is treated with a coupling agent named γ -aminopropyl triethoxy (KH550). The coupling agent can establish a Si–O–Si chemical bond with basalt fibers, which is unstable in chemical solution [20]. After aging in salt solution, the hydrones infiltrate through the gap between the macromolecules or micro-cracks in the matrix and hydrolyze the Si–O–Si chemical bond between the fiber and the matrix [27], as expressed by

Hydrolyzation leads to debonding of the fiber-matrix interface [28] (Figure 6). Thus, the

weaker interface is vulnerable to cyclic loads and leads to a relatively shorter fatigue life compared to the specimens without any corrosion. However, this infiltration is so limited that only the fiber-matrix interfaces at the surface of the tendon are influenced.

4.4 S-N curves

Figure 7 shows the S-N curves of all test groups, along with the control group. A satisfactory linear relationship between the fatigue maximum stress and the logarithm of the fatigue life is observed from the data in each test group. The S-N curves of the groups aged in salt solution are slightly lower than the curve of the control group, showing the negative effect of salt solution on the fatigue behavior of BFRP tendons.

The semi-logarithmic relationship between the fatigue life and fatigue maximum stress is expressed by

$$Y_{\sigma_{\max}} = a - b \ln N_f \quad (2)$$

where $Y_{\sigma_{\max}}$ = ratio of the maximum stress to ultimate strength; N_f = fatigue life; a and b = regression constants.

The fatigue strength is calculated by substituting $N_f = 2 \times 10^6$ into Eq. (2). Values of the fatigue strength of different test groups are shown in Table 4. Compared with the control group, reductions in the fatigue strength are observed in the groups with aging in salt solution.

The group T55-D63 shows the largest reduction rate, which is equal to 13 %.

4.5 Effect of aging temperature on the degradation law

From the data in Table 4, the relationships between the fatigue strength and aging duration at

three aging temperatures are shown in Figure 8. The curves at 25 and 40 °C show similar tendencies. The fatigue strengths first decrease linearly from 0 to 42 d, and no degradation is observed from 42 to 63 d in these two curves, due to the decrease of infiltration rate with time [28]. In contrast, for the curve at 55 °C, the initial degradation rate is faster than the rates at 25 and 40 °C, and the degradation continues from 42 to 63 d. This phenomenon demonstrates that high temperature up to 55 °C has a significant accelerating effect on fatigue strength degradation. The infiltration of hydrones in salt solution is accelerated by the high temperature, which causes more rapid hydrolyzation of the Si–O–Si chemical bond between the fiber and the matrix, thereby leading to more local debonding areas on the fiber-matrix interface.

4.6 Scanning electron microscope (SEM) analysis

The microstructures of BFRP tendons after corrosion in salt solution are revealed through SEM. The cross-sections for SEM analysis were cut from the middle portion of one FRP tendon specimen to avoid the impact of concentration of corrosion at the two ends. The control specimen without aging in salt solution shows an intact cross-section (Figure 9 (a)). By contrast, the specimens aged at 55 °C for 63 d (group T55-D63) display the largest corrosion areas. By amplifying these areas, several corrosive channels are observed, which reflect the paths of salt solution corrosion from the surface to the inside (Figure 9(b)). The corrosion damage degrees of the specimens in the groups of T55-D21, T55-D42 and T40-D63 are significantly lower than that of T55-D63 (Figure 9(c)-(e)). Although debonding areas are observed at the surface, the numbers of corrosive channels are not comparable to

those of group T55-D63. For the specimens in group T25-D63, the fiber-matrix interface at the surface is intact (Figure 9(f)), indicating that the corrosion rate of BFRP tendon in salt solution is extremely slow at normal temperature (25 °C). Thus, high aging temperature and long aging duration are two essential factors for the significant corrosive effects of salt solution. The corrosion degrees of the specimens observed by SEM are consistent with the fatigue strength degradation reflected by the experimental data in Section 4.5.

4.7 Prediction of fatigue strength degradation at different temperatures

4.7.1 Arrhenius equation

Practical infrastructures are exposed to different aging temperatures. Thus, the prediction of the fatigue strength degradation of BFRP tendons at different temperatures is necessary. This prediction is based on the Arrhenius equation [29], as expressed by

$$k = A \exp(-E_a / RT) \quad (3)$$

where k = degradation rate, A = constant related to the material and degradation process, E_a = activation energy in kJ/mol, R = gas constant in kJ/mol·K, and T = absolute temperature, in K.

Generally, for calculation convenience, the above Arrhenius equation can be transformed into

$$\ln(1/k) = E_a / RT - \ln A \quad (4)$$

The prediction using the Arrhenius equation is based on the assumption that a single dominant degradation mechanism exists with different aging temperatures and durations. In this study, the temperatures were far lower than the glass transition temperature of the resin. Thus, the above requirement can be easily achieved.

265

266 4.7.2 Relationship between fatigue strength and aging duration

267 To adopt the Arrhenius equation to predict fatigue strength at different temperatures, the
268 degradation of the fatigue strength with respect to aging duration should be clarified. The
269 most commonly used degradation formula was proposed by Bank et al. [30] and has been
270 adopted by many researchers [31, 32]. The degradation formula is based on the following
271 assumption:

$$272 \quad 10^Y \propto \frac{1}{kt} \quad (5)$$

273 where Y = ratio of residual fatigue strength to the ultimate tensile strength (f_u), and t = aging
274 duration. By substituting the Arrhenius equation into Eq. (5), it is deduced that

$$275 \quad Y \propto -\ln(t) + 1/T \quad (6)$$

276 Thus, the degradation formula at a certain temperature is expressed by

$$277 \quad Y = a_1 - b_1 \ln(t) \quad (7)$$

278 Where a_1 and b_1 are regression constants, and t = service duration in days.

279 The results of the curve fitting are shown in Figure 10 and Table 5. The three fitting lines of
280 the Y - $\ln(t)$ relationship can be considered approximately parallel to each other, indicating that
281 a single dominant degradation mechanism exists during the tests.

282

283 4.7.3 Prediction of the degradation law of fatigue strength at different local temperatures

284 In Eq. (6), a linear relationship exists between Y and $1/T$ at a certain aging duration (t), as
285 expressed by

$$286 \quad Y = \alpha + 1000\beta / T \quad (8)$$

where α and β are regression constants.

The prediction is conducted by plotting a series of lines describing the relationships between the fatigue strength and $1000/T$ at different durations. Several durations were selected by considering some representative service durations of infrastructure, i.e., 1, 5, 10, 20, 50 and 100 years (Figure 11). The regression constants (α and β) and regression coefficients are shown in Table 6.

Using the prediction formula in Eq. (8), the values of fatigue strength are predicted under different local temperatures at service durations of 1, 5, 10, 20, 50 and 100 years. The local temperatures are mainly dependent on the latitude. To simplify the analysis, temperatures in the northern hemisphere were adopted in this study. The annual temperature varies little between 0° and northern latitude (NL) 20° . NL 60° is so close to the Arctic Circle that few structures are distributed in regions with a latitude higher than NL 60° . Thus, the annual temperatures at NL 20° , 40° and 60° , equal to 26°C , 16°C and 6°C , respectively [33], were selected. The fatigue strength-service duration curves at the three temperatures are shown in Figure 12. These curves decrease rapidly in the first several years and become stable after 20 years.

The prediction formula is expressed by

$$Y = A_l - B_l \ln(t) \quad (9)$$

where A_l and B_l = regression constants, and t = service duration in years.

The values of A_l , B_l and the regression coefficient for the prediction of the fatigue strength at NL 20° , 40° and 60° are shown in Table 7.

With Eq. (9), the fatigue strength of BFRP tendons can be predicted at different service

309 durations and temperatures. The values of the fatigue strength of BFRP tendons are predicted
310 to be 0.41, 0.43 and 0.45 f_u , respectively, at NL 20°, 40° and 60° after aging in marine
311 environments for 100 years. Although 0.5 f_u was considered to be the optimal stress level for
312 BFRP prestressed tendons [10, 34], the fatigue strength of 0.41 f_u is also acceptable for
313 prestressing use, which is larger than the maximum stress (approximately 0.3 f_u) in FRP
314 cable-stayed bridges during service life [24]. The results provide guidance for the fatigue
315 design of BFRP tendons applied under a marine environment.

317 5. Conclusions

318 This paper comprehensively studied the fatigue behavior of BFRP tendons under a marine
319 environment. Fatigue tests of BFRP tendons were conducted after aging in a salt solution at
320 three different temperatures (25, 40 and 55 °C) and durations (21, 42 and 63 d). The
321 degradation mechanism of fatigue behavior was clarified based on the analysis of the failure
322 mode and previous studies. The effect of aging temperature on fatigue behavior degradation
323 was analyzed from both experimental data and SEM analysis. Finally, the fatigue strength of
324 BFRP tendons at different local temperatures was predicted with the Arrhenius equation. The
325 main conclusions are listed as follows.

326 (1) Aging in salt solution allowed hydrones to infiltrate through the resin matrix on the
327 surface and hydrolyze the Si–O–Si chemical bond between the fiber and the matrix, leading
328 to local debonding of the fiber-matrix interface under cyclic loads, which was the main cause
329 of the fatigue strength degradation of BFRP tendons under a marine environment.

330 (2) SEM analysis showed that specimens aged at 55 °C for 63 d exhibited larger corrosive

331 areas than the specimens in the other groups because the infiltration of hydrones in the salt
332 solution was accelerated by the high temperature, leading to more severe hydrolyzation of the
333 Si–O–Si chemical bond between the fiber and the matrix. The results of the SEM analysis
334 were consistent with the experimental data.

335 (3) Using the Arrhenius equation, the values of the fatigue strength of BFRP tendons were
336 predicted to be 0.41, 0.43 and $0.45 f_u$ at northern latitudes of 20°, 40° and 60°, respectively,
337 after aging in marine environments for 100 years. These results can serve as a guide for the
338 fatigue design of BFRP tendons under a marine environment.

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340

341 **Figure captions**

342 Figure 1 Anchorage for the fatigue test: (a) winding fiber sheet; (b) mold; (c) anchorage after
343 molding; (d) photograph of the anchorage

344 Figure 2 Corrosion test chamber: (a) external view; (b) internal view

345 Figure 3 LFV-1000 servo-hydraulic dynamic fatigue tester

346 Figure 4 Failure mode in the short-term tensile test

347 Figure 5 Failure mode in fatigue test: (a) initial failure; (b) ultimate failure

348 Figure 6 Schematic diagram of degradation

349 Figure 7 S-N curves for the test groups and control group

350 Figure 8 Fatigue strength-aging duration relation curves

351 Figure 9 SEM of specimens in the (a) control, (b) T55-D63, (c) T55-D42, (d) T55-D21, (e)
352 T40-D63, and (f) T25-D63 groups

353 Figure 10 Curve fitting for the Y - $\ln(t)$ relationship

354 Figure 11 Curve fitting for the Y -1000/ T relationship

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Table 1

Table 1 Aging procedures for the test groups

Test group	Aging temperature (°C)	Aging duration (days)	Number of specimen
T25-D21	25	21	5
T25-D42	25	42	5
T25-D63	25	63	5
T40-D21	40	21	5
T40-D42	40	42	5
T40-D63	40	63	5
T55-D21	55	21	5
T55-D42	55	42	5
T55-D63	55	63	5

Table 2

Table 2 Short-term tensile properties

Specimen number	Tensile capacity	Tensile strength	Elastic modulus	Fracture strain
	F_t (kN)	f_t (MPa)	E (GPa)	ε_u (%)
BE-1*	48.7	1784	53.9	3.31
BE-2	45.7	1674	53.7	3.12
BE-3	45.0	1648	54.0	3.05
BE-4	46.6	1707	53.4	3.20
BE-5	48.7	1784	53.3	3.35
Mean value	46.9	1719	53.7	3.20
SD	1.5	55.8	0.3	0.11
CV	3.25 %	3.25 %	0.51 %	3.48 %
95 % guaranteed strength	44.4	1628		

*BE is the abbreviation for basalt fiber and epoxy resin.

Table 3

Table 3 Fatigue lives of the specimens

Number	$\sigma_{\max}(f_u)$	N_f	Number	$\sigma_{\max}(f_u)$	N_f	Number	$\sigma_{\max}(f_u)$	N_f
T25-D21-1	0.70	96,609	T40-D21-1	0.70	121,318	T55-D21-1	0.70	83,203
T25-D21-2	0.68	206,834	T40-D21-2	0.68	158,927	T55-D21-2	0.68	92,875
T25-D21-3	0.65	212,196	T40-D21-3	0.65	225,592	T55-D21-3	0.65	184,531
T25-D21-4	0.62	531,675	T40-D21-4	0.62	517,708	T55-D21-4	0.62	339,782
T25-D21-5	0.60	1,173,542	T40-D21-5	0.60	896,298	T55-D21-5	0.60	630,594
T25-D42-1	0.70	108,118	T40-D42-1	0.70	79,096	T55-D42-1	0.70	40,514
T25-D42-2	0.68	117,534	T40-D42-2	0.68	97,825	T55-D42-2	0.68	52,645
T25-D42-3	0.65	157,506	T40-D42-3	0.65	106,278	T55-D42-3	0.65	85,423
T25-D42-4	0.62	342,359	T40-D42-4	0.62	315,201	T55-D42-4	0.62	210,362
T25-D42-5	0.60	888,002	T40-D42-5	0.60	576,966	T55-D42-5	0.60	430,136
T25-D63-1	0.70	70,846	T40-D63-1	0.70	48,623	T55-D63-1	0.70	27,378
T25-D63-2	0.68	88,521	T40-D63-2	0.68	65,549	T55-D63-2	0.68	45,168
T25-D63-3	0.65	126,699	T40-D63-3	0.65	83,451	T55-D63-3	0.65	58,481
T25-D63-4	0.62	289,230	T40-D63-4	0.62	215,031	T55-D63-4	0.62	152,544
T25-D63-5	0.60	786,747	T40-D63-5	0.60	497,527	T55-D63-5	0.60	320,978

Table 4

Table 4 Prediction of the fatigue strength				
Test group	<i>a</i>	<i>b</i>	Regression coefficient (R^2)	Fatigue strength (f_u)
Control [12]	1.2014	0.042	0.8972	0.592
T25-D21	1.1688	0.041	0.9254	0.574
T25-D42	1.1885	0.044	0.8819	0.550
T25-D63	1.1338	0.04	0.9172	0.550
T40-D21	1.2596	0.048	0.9655	0.563
T40-D42	1.1929	0.045	0.8905	0.540
T40-D63	1.1348	0.041	0.9241	0.540
T55-D21	1.2270	0.047	0.9752	0.545
T55-D42	1.1274	0.041	0.9653	0.533
T55-D63	1.1102	0.041	0.9554	0.515

Table 5

Table 5 Values of a_1 , b_1 and regression coefficient (R^2)			
Temperature (°C)	a_1	b_1	R^2
25	0.6426	0.0232	0.87
40	0.6287	0.0223	0.87
55	0.6265	0.0262	0.93

Table 6

Table 6 Values of α , β and regression coefficient (R^2)			
Service duration (year)	α	β	R^2
1	0.1421	0.1093	0.91
5	0.0546	0.1246	0.86
10	0.0169	0.1312	0.85
20	-0.0208	0.1378	0.83
50	-0.0706	0.1465	0.81
100	-0.1083	0.1572	0.80

Table 7

Table 7 Values of A_l , B_l and regression coefficient (R^2)				
Northern latitude (°)	Annual temperature (°C)	A_l	B_l	R^2
20	26	0.5045	0.021	0.98
40	16	0.5171	0.019	0.98
60	6	0.5305	0.018	0.98

Figure 1(a)

Figure 1(b)

Figure 1(c)

Figure 1(d)

Conical transition section

Cylinder section

Figure 2(a)

Figure 2(b)

Figure 3

Figure 4

Figure 5(a)

Figure 5(b)

Figure 6

Figure 7

Figure 8

Figure 9(a)

Figure 9(b)

Figure 9(c)

Figure 9(d)

Figure 9(e)

Figure 9(f)

Figure 10

Figure 11

Figure 12