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Experimental study on tensile property of FRP cable on sea-crossing cable-stayed bridge under multi-factors coupling aging action

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Aging tests of FRP cable have been carried out taking into account multifactorial influences including preloads, UV radiation, damp heat and salt spray aging. The tensile properties and microstructure of fiberglass cables have been tested for the analysis of the fracture mechanics of the cables. Based on the test results, the influence of multifactor effects on the long-term characteristics of fiberglass cables is analyzed. This study could improve the use of fiberglass cables on cable-stayed bridges across the sea, which will have important theoretical and applied value in engineering.
Keywords: FRP cables, sea-crossing cable-stayed bridges, multi-factors coupling, aging test, microstructures.

Експериментальне дослідження міцності на розтягнення кабелю зі склопластику на морському вантовому мосту в умовах багатофакторного старіння зв'язку. *Wentao Shang, Yaqiang Yang, Meng Wang, Dongyue Wu, Daochuan Zhou, Zhihong Pan, Sujun Guan, Chenchen Zhang*

Проведено випробування на старіння кабелю зі склопластику з урахуванням багатофакторних впливів, включаючи попередні навантаження, ультрафіолетове випромінювання, вологе тепло і старіння у соляному тумані. Протестовано властивості при розтягуванні і мікроструктура кабелів зі склопластику для аналізу механіки руйнування кабелів. На підставі результатів випробувань проаналізовано вплив дії багатофакторних впливів на довготривалі характеристики кабелів зі склопластику. Це дослідження може поліпшити застосування кабелів зі склопластику на вантових мостах через море, що матиме важливе теоретичне значення і прикладну цінність в інженерії.

Проведены испытания на старение кабеля из стеклопластика с учетом многофакторных влияний, включая предварительные нагрузки, ультрафиолетовое излучение, влажное тепло и старение в соляном тумане. Протестированы свойства при растяжении и микроструктура кабелей из стеклопластика для анализа механики разрушения кабелей. На основании результатов испытаний проанализировано влияние действия многофакторных воздействий на долговременные характеристики кабелей из стеклопластика. Это исследование может улучшить применение кабелей из стеклопластика на вантовых мостах через море, что будет иметь важное теоретическое значение и прикладную ценность в инженерии.

1. Introduction

Due to its long span and light, beautiful structures, the cable-stayed bridge has become the best choice for sea crossings. As the span of the bridge increases, the severe sagging effect and low durability of traditional steel cables limit the development of longer spans and the improvement in the overall performance of cable-stayed bridges across the sea [1]. To achieve longer span and improve the long-term performance of the sea-crossing cable-stayed bridge, it is necessary to develop the high-performance cables with high strength, light weight and superior durability. Fiber Reinforced Polymer (FRP) cable can overcome the bottleneck problem of traditional steel cables with its superior mechanical and chemical properties [2], such as high strength-to-weight ratio, good fatigue resistance and superior anti-corrosion properties. FRP includes the carbon fiber reinforced polymer (CFRP), basalt fiber reinforced polymer (BFRP) and hybrid carbon fiber and basalt fiber reinforced polymer (B/CFRP). Research on the use of FRP cables on long-span cable-stayed bridges began in 1980s when Meier [3] proposed the 8400m span cable-stayed bridge with CFRP cable across the Strait of Gibraltar. After that, the key problems of the anchorage performance [4, 5], vibration characteristics [6] and damping properties [7] of the FRP cables have been studied. The previous studies on the long-term performance were focused on the influence of a single factor such as the prestressing, ultraviolet irradiation, humid heat or salt fog aging [8, 9]. However, in actual use, fiberglass cables of a cable-stayed bridge over the sea are subjected to the combined effects of prestressing, ultraviolet radiation, aging under conditions of humid heat and salt fog. It leads to a large error between the test results and the practical situation. To effectively evaluate the long-term performance of the FRP cable on sea-crossing cable-stayed bridge, the aging tests of FRP cable were designed and carried out taking into consideration multi-factors. Moreover, the degradation mechanism of the FRP cables under multi-factor aging was studied by the tensile mechanical tests; the failure mechanism was revealed based on the microstructural analyses.

2. Multi-factor aging test

In the actual service environment, the FRP cables of sea-crossing cable-stayed bridge are subjected to the combined effects of aging under conditions of prestressing, ultraviolet radiation, humid heat and salt fog. To improve the correlation between the test results and actual situation, a new multi-factor aging test was designed based on the International Electro technical Commission (IEC) standards testing. This test took one day as a cycle period, which was divided into 12 stages as shown in Fig. 1. In the whole test process, the prestressing acts all the time, which was indicated by the black squares. As an acceleration factor, temperature also effects during the entire process (indicated by red squares). In practice, there is an alternation of ultraviolet radiation, moist heat and salt fog, which is indicated by a purple square, a blue square and a yellow square, respectively. In Fig. 1, a white square means that the factor is irrelevant. According to Fig. 1, one cyclic process can be described as follows: the ultraviolet irradiation affects aging when the sun appears; then the rainfall begins to act and ultraviolet irradiation stops work because the ultraviolet irradiation cannot penetrate through the clouds while raining; afterwards the salt fog comes into play with rain-stopping; the next alternating actions are ultraviolet irradiation, rainfall and salt fog. During the cyclic process, the prestress and temperature are constantly ctive.

Using this new method of coupled multi-factor aging testing, the FRP cables on sea-crossing cable-stayed bridge were tested. According to a study of the marine environment in typical coastal area of China, inten-

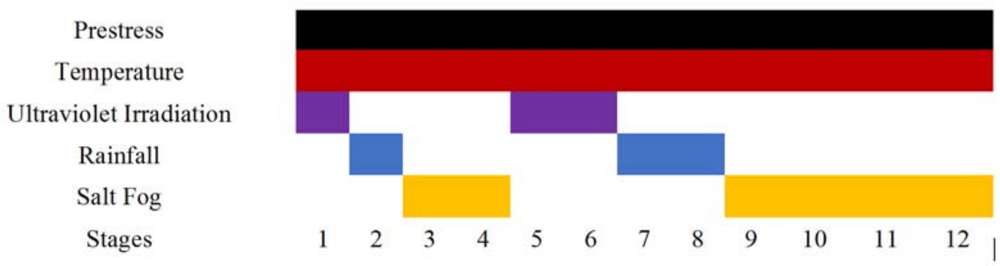


Fig. 1. Multi-factor aging test method.

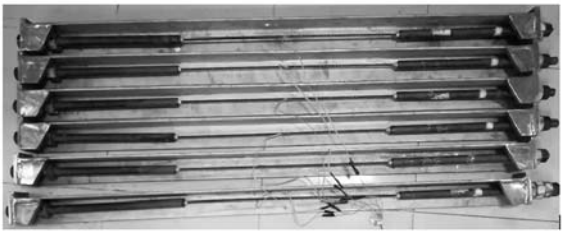


Fig. 2, Device for axial-load application.

sity of ultraviolet irradiation and salinity of salt fog were set as 19.41 W/m^2 and 32.33 % respectively to more closely simulate actual condition. Five parameters were investigated in this study:

1. Sustained load: In existing cable-stayed bridges, the stress level of the stayed cable was maintained with a tensile strength of less than 54 %. In this study, two stress levels: 30 % and 50 % tensile strength were made using by a device for axial-load application as shown in Fig. 2.

2. Temperature: Two temperatures were selected: 35°C and 50°; the temperature-controller of the multi-function aging machine was employed.

3. Matrix type: To manufacture the FRP cable, two matrix types were selected: epoxy and vinyl.

4. Fiber type: To evaluate the aging resistance, two different fibers were selected: carbon fiber and basalt fiber.

5. Aging times: To study the degradation of tensile property of the FRP cables, three aging times were adopted: 120 hours, 240 hours and 480 hours. The tensile properties of unaged FRP cables were tested as a control group.

As shown in Fig. 3, the coupled multi-factor aging tests were carried out using a multi-functional aging test machine, which can simulate the aging action of ultraviolet irradiation, moist-heat and salt fog aging. After that, the tensile properties were tested on the ACI440.3R-04 B2 device; the overall length of each specimen was 1000 mm. Each end was sandblasted and

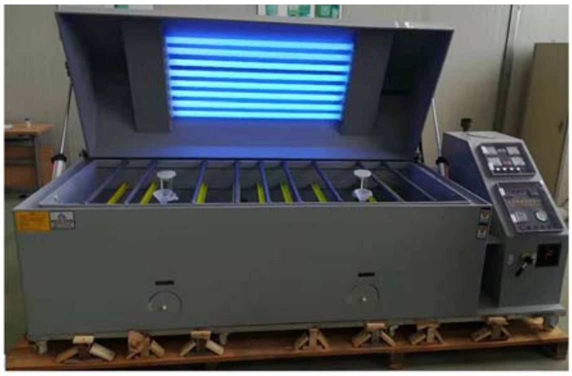


Fig. 3. Multi-function aging test machine

placed in a 300 mm long threaded steel tube grouted with an epoxy matrix to create grip ends for axial tension. As shown in Fig. 4, the length of the test section was 400 mm, which is 40 times the nominal diameter of the FRP cable. The elastic modulus was obtained from an attached extensometer. Three specimens were tested for each condition.

3. Test results and discussion

After the specified aging times were reached, the load was removed. The FRP cable surface was washed with deionized water and dried in air before testing. The tensile property test was carried out using a universal tension-compression test machine with a capacity of 2000 kN. The loading rate was set at 2 mm/min until failure. The results are shown in Table, where B-V denotes BFRP cable with vinyl resin, B-E means BFRP cable with epoxy resin, C-V represents CFRP cable with vinyl resin, C-B indicates CFRP cable with epoxy resin.

The test results showed that the variation of the elastic modulus and elongation at break were small and displayed no obvious regularity. The elastic modulus and elongation at break could thus be treated as unaffected and are not discussed further.

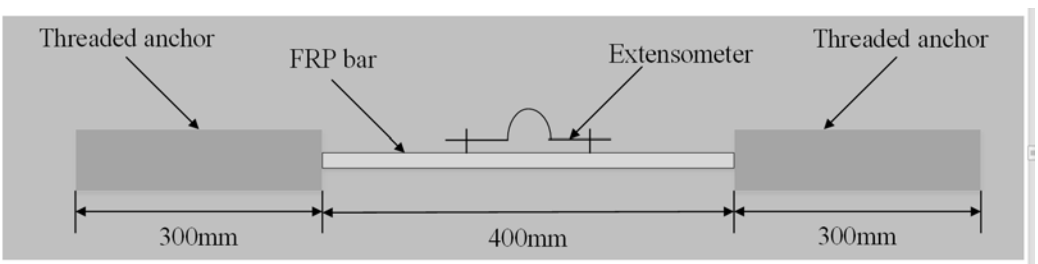


Fig. 4. Specimens for tensile tests.

Table. Test results

FRP cable	Stress level, %	Temperature, °C	Aging time, h	Ultimate load, kN	Tensile strength, MPa	Strength Retention, %	Elastic Modulus, GPa	Elastic Modulus Retention, %	Elongation at break, %
B-V	0	Ordinary temperature	0	18.47	1469.79	100.00	58.23	100.00	100.00
	0	35	120	17.44	1387.63	94.41	58.22	99.98	4.12
	0	35	240	16.10	1281.19	87.17	56.57	97.15	3.66
	0	35	480	15.41	1226.82	83.47	56.32	96.72	3.71
	0	50	120	16.71	1329.43	90.45	57.87	99.38	3.62
	0	50	240	15.49	1232.66	83.87	57.56	98.85	3.58
	0	50	480	14.65	1165.54	79.29	56.84	97.61	3.45
	30	35	120	16.88	1343.42	91.40	56.01	96.19	3.71
	30	35	240	15.71	1250.43	85.08	57.57	98.87	3.68
	30	35	480	15.04	1196.85	81.43	57.77	99.21	3.44
	30	50	120	15.01	1194.46	81.27	56.01	96.19	3.34
	30	50	240	13.76	1094.99	74.79	57.25	98.32	2.96
	30	50	480	12.52	996.29	67.78	56.46	96.96	3.03
	50	35	120	15.33	1220.18	83.02	55.24	94.87	3.46
	50	35	240	14.41	1146.71	78.02	56.43	96.91	3.51
	50	35	480	13.61	1083.05	73.69	55.79	95.81	3.35
	50	50	120	12.46	991.54	67.46	56.21	96.53	3.26
	50	50	240	11.91	947.77	64.48	55.95	96.08	2.58
	50	50	480	11.33	901.35	62.33	55.93	96.05	2.52
B-E	0	Ordinary temperature	0	21.93	1745.13	100.00	58.86	100.00	100.00
	30	50	480	19.03	1514.36	86.33	56.71	96.35	3.96
	30	50	960	14.63	1164.22	66.71	57.64	97.93	2.86
C-V	0	Ordinary temperature	0	26.89	2139.84	100.00	184.36	100.00	100.00
	30	50	480	22.55	1794.47	83.86	179.89	97.57	2.37
	30	50	960	22.39	1781.74	83.27	180.71	98.02	2.13
C-E	0	Ordinary temperature	0	38.68	3078.06	100.00	186.08	100.00	100.00
	30	50	480	36.45	2900.59	94.23	182.69	98.17	2.56
	30	50	960	35.36	2813.86	91.42	184.84	99.33	2.45

Effect of temperature

The strength retentions of BFRP cables at different temperature are shown in Fig. 5a. For the stress-free BFRP cable, the strength retentions were 83 % and 79 % at 35°C and 50°C, respectively, after 480 aging hours. The coupled stress level has a great influence on the tensile strength, the strength retentions of BFRP cable with the stress level of 30 % dropped to 81 % and 67 %, respectively, at 35°C and 50°C after 480 aging hours, which is lower than that of stress-free BFRP cable. At the same time, the strength retentions of BFRP cable with the stress level of 50 % dropped further to 73 % and 62 % at 35°C and 50°C after 480 aging hours. It can be seen that the higher the temperature, the faster the degradation. That is because the diffusion rates of the corrosive media are accelerated with an increase in temperature, which leads to a larger affected cross-sectional area of the FRP bars.

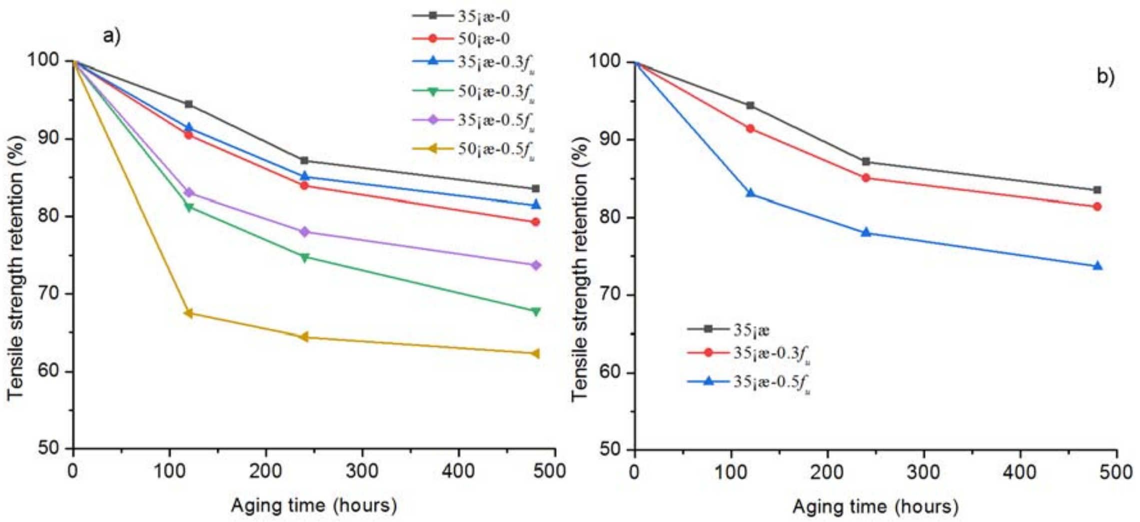


Fig. 5. Effect of temperature and pre-stress on tensile strength retention of BFRP cables. (a) Temperature on tensile strength retention, (b) Pre-stress on tensile strength retention.

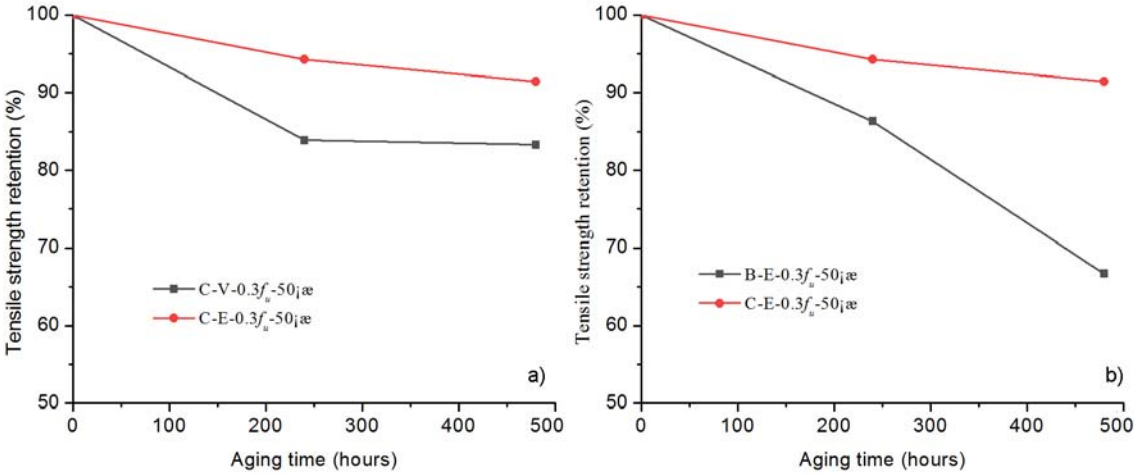


Fig. 6. Effect of matrix type and fiber type on tensile strength retention of FRP cables. (a) Effect of matrix type, (b) Effect of fiber type.

Effect of prestressing

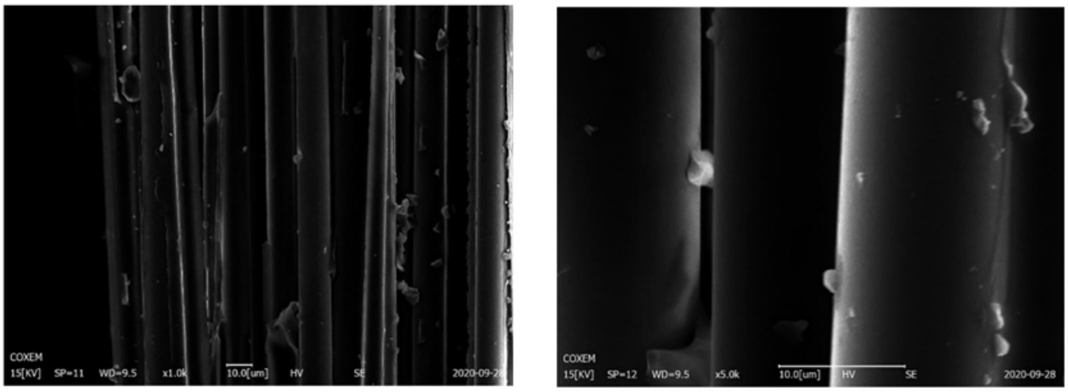
Fig. 5b compares tensile-strength retention of BFRP cables under different stress levels. It can be observed that the strength retention decreases with an increase in the stress level, which indicates that the coupled stresses will increase the damage of the BFRP cable. According to the curves in Fig. 5b, there are important differences in the acceleration effects of different stress levels. The curves of the cables with stress levels of 0 and 35 % were very close to each other. However, when the stress level reached 50 %, the degradation of BFRP cables was obviously accelerated. It can be concluded that a low coupled-stress level has a minor effect on the degradation of the BFRP bars.

Effect of matrix type

As shown in Fig. 6a, the degradation rate of CFRP cable with vinyl resin was obviously faster than that of CFRP cable with epoxy resin. However, the coefficients of variation of the CFRP cable with vinyl resin were lower than that of the CFRP cable with epoxy resin. Although the tensile mechanism of the FRP cable with epoxy resin is better than that of the FRP cable with vinyl resin, the tensile property of the FRP cable with vinyl resin is more stable.

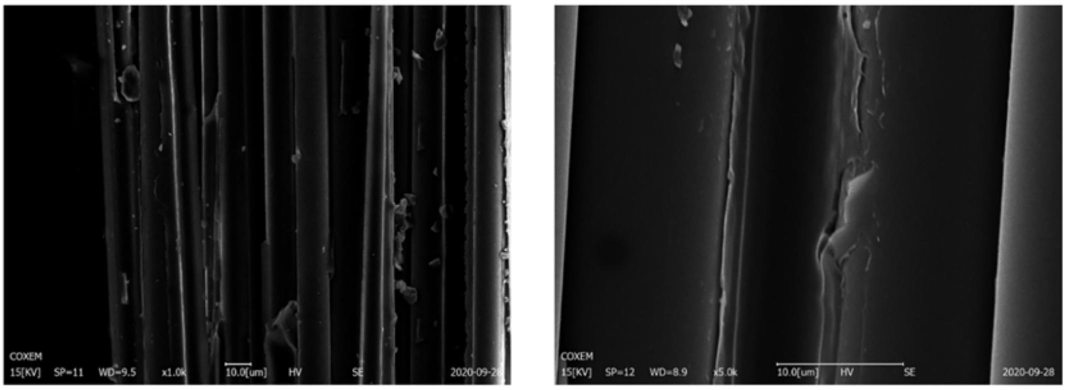
Effect of fiber type

It can be seen from Fig. 6b, that the tensile strength of BFRP cable drops 15 % and 33 % after 480 hours and 960 hours of aging. However, the strength retention remains more than 90 % after 480 hours and 960 hours under the same aging conditions.



(a) 1000×cross-section (b)5000×cross-section

Fig. 7, Micrographs of the transversal section of reference sample at 50°C after 240 hours of aging: (a) 1000×cross-section, b) 5000×cross-section.



(a) 1000×cross-section (b)5000×cross-section

Fig. 8. Micrographs of the transversal section of reference sample at 50°C after 960 aging hours. (a) 1000×cross-section, (b) 5000×cross-section.

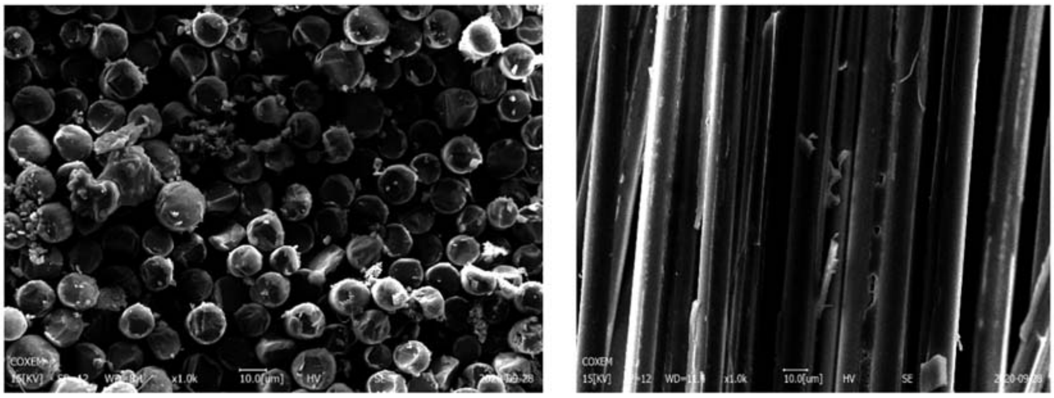
According to the test data, the tensile performance of the CFRP cable is significantly better than that of the BFRP cable. Taken the cost of different fibers into consideration, the BFRP cable has a higher cost-efficiency than CFRP cable.

4. Microstructure analysis and degradation mechanism

To study the mechanical failure of the FRP cables during multi-factor aging, scanning electron microscopy observations and image analysis were performed on FRP cable specimens. The specimens were first embedded in epoxy resin, cut with a low-speed saw, and then polished with sandpaper and fluffy cloth. Microstructural observations were thereafter carried out on a COXEM Ultra Plus Field Emission SEM. The microstructure images of a longitudinal section of the stress-free FRP cable at 50°C after aging for 240 hours are shown in Fig. 7. It can be seen that the fiber is integral without significant damage. However, there is a slight interfacial debonding at the interface between the fiber and resin.

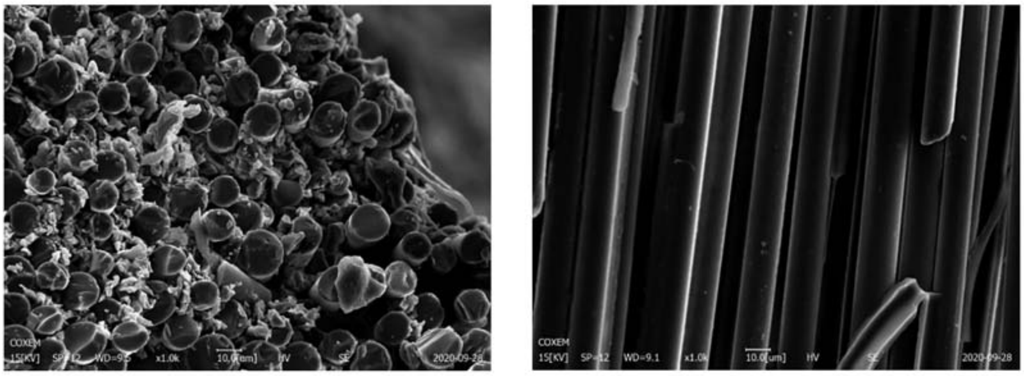
Compared to stress-free fiberglass cable at 50°C, after 960 hours of aging, the damage to the fiber/resin interface increases with aging time, as shown in Fig. 8. Due to the hydration and corrosion with chlorine ions (salt fog), the fiber/resin interface is subject to further erosion and damage.

For the FRP cable specimen with stress-level of 30 % at 50°C after 480 aging hours, the outer fibers become loose, while inner fibers are still compact as shown in Fig. 9. It indicates that surface layer of the FRP cable is eroded by the environment firstly and seriously. Moreover, the debonding of the fiber/resin interface can be observed in this condition. Due to the important role in the load transfer from matrix to fiber of the fiber/resin interface, the



(a) transversal section (b) longitudinal section

Fig. 9. Micrographs of reference sample with stress-level of 30 % at 50°C after 480 aging hours. (a) transversal section, (b) longitudinal section.



(a) transversal section (b) longitudinal section

Fig. 10. Micrographs of the reference sample with stress-level of 30 % at 50°C after 960 aging hours. (a) transversal section, (b) longitudinal section.

tensile strength of the FRP cable will be reduced when the interface destroys.

As shown in Fig. 10, the erosion of FRP cable increases with the aging time. The fiber/resin interface gets more damaged; even the fracture of the fiber appears. It is manifested by the obvious decline of the tensile strength of the FRP cable with stress-level of 30 % at 50°C after 960 aging hours.

According to the microstructure analyses and test results of tensile tests, prestressing has more important effect on the tensile strength of the FRP bars compared to other coupled factors, which can change the failure mechanism. It seems that debonding of the fiber/matrix interface and cracks don't take place at low stress levels (perhaps less than 30 %). The main failure of the FRP cable is caused by diffusion of the corrosive ions. However, at high stress levels, the FRP cables will break even without contact with corrosive solution after a period of time. That is because the creep-fracture characteristics of the FRP cable become critical for crack propagation. At this stage, crack propagation becomes the dominant fracture mechanism. Furthermore, the test results indicate that the action of multi-factor coupled aging can accelerate the failure process.

5. Conclusions

To study the tensile properties of FRP cables on a sea-crossing cable-stayed bridge under the action of coupled multi-factors aging, the tests of FRP cables were carried out on the basis of a new developed method. The results of tensile tests and microstructure analysis of original and aged FRP cables indicate that the elastic modulus of the FRP cables was relatively stable and almost independent of a combination of several factors. The degradation rate was obviously accelerated due to the rise in temperature and stress levels. The FRP cables with carbon fiber and epoxy resin have better tensile properties. The microstructural analyses revealed that the fiber/resin interface played important role in keeping the tensile properties of FRP cables after coupled multi-factor aging. With an increase in the stress level, the mechanism of damage to fiberglass cables changed from predominant diffusion to a mode with predominance of crack propagation.

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