Composites: Part B 60 (2014) 239–247

Contents lists available at ScienceDirect

Composites: Part B

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

Tensile behavior of FRP and hybrid FRP sheets in freeze–thaw cycling environments

Jia-Wei Shi, Hong Zhu, Gang Wu, Zhi-Shen Wu *

Key Laboratory of Concrete and Prestressed Concrete Structures, Ministry of Education, Southeast University, Nanjing 210096, China
International Institute for Urban Systems Engineering, Southeast University, Nanjing 210096, China

ARTICLE INFO

Article history:
Received 4 August 2013
Received in revised form 3 November 2013
Accepted 25 November 2013
Available online 6 December 2013

Keywords:
A. Laminates
A. Hybrid
B. Environmental degradation
B. Mechanical properties
Basalt fibers

ABSTRACT

This study presents the results of an experimental investigation of the freeze–thaw (FT) resistance, including the hybridization of fibers, of carbon, basalt and glass fiber-reinforced polymer (CFRP, BFRP and GFRP) sheets commonly used in civil engineering practice. Coupon tests were conducted to investigate the tensile properties of FRP sheets and their corresponding epoxy resins and dry fiber sheets after up to 300 FT cycles. Sustained loading was included in the testing to reflect the behavior of FRP sheets in real structures. The test results indicate that (1) BFRP and hybrid FRP sheets have better FT resistance than CFRP and GFRP sheets, and the hybridization of fibers can contribute to the stability of the tensile properties of these materials after FT exposure; (2) the tensile properties of the resin matrix deteriorate significantly with increasing FT cycles; (3) further degradation of the tensile properties of FRP sheets is caused by sustained loading during FT cycling; and (4) the tensile behavior of dry glass fiber sheets is more sensitive to FT cycling than dry carbon and basalt fiber sheets. Lastly, the degradation mechanism of FRP sheets in FT environments is discussed.

1. Introduction

Fiber-reinforced polymer (FRP) composites are attractive for use in a wide range of civil engineering applications because of their unique properties for retrofitting of structures [1]. The increasing use of FRP composites presents many challenges to researchers and engineers. One of these challenges is to understand the performance of FRP composites in long term (e.g., creep and fatigue) [2,3] and harsh environments (e.g., extreme temperatures, chemical attack and freeze–thaw cycles) [4–6]. Although many studies have been conducted on the durability of FRP composites in aerospace and naval applications, information on the durability of FRP composites in civil engineering is still very limited. The lack of data on the durability of FRP composites is a major obstacle to their acceptance on a broader scale in civil engineering. As the methods of FRP fabrication and the environments to which civil engineering structures are exposed are quite different from those for other engineering applications, there are still pressing concerns about understanding the behavior of FRP composites in harsh environments that need to be addressed [6].

Freeze–thaw (FT) cycling is one of the primary types of environmental stress that seriously threaten the service life of concrete structures in cold regions [7]. When FRP composites are used in civil engineering structures, the properties of FRP composites and the bond capacity between FRP and concrete may be degraded with increasing FT cycles [8]. Thermal incompatibility of the constituent materials and the moisture environment will damage FRP composites and consequently influence their tensile properties. Some previous research has been conducted to examine these effects [9–15]. Unidirectional tensile strengths and rupture elongations have been shown to decrease after FT cycles, whereas the elastic modulus may increase due to matrix hardening. Higher residual tensile strength in carbon FRP (CFRP) composites has been observed than in corresponding glass FRP (GFRP) composites after exposure to FT cycles. In addition, FRP composites are in a state of stress in real FRP-strengthened structures. With respect to the service loads during FT cycles, the cyclic thermal stresses on the fiber/matrix interface are likely to be magnified and more micro-cracks are likely to be formed inside the matrix. Therefore, consideration of the combined effects of harsh environments and service loads is essential to understanding the behavior of FRP composites in civil engineering applications. However, very little research has been reported on the durability of FRP composites in harsh environments under service loads.

As an emerging environmentally friendly material, basalt FRP (BFRP) composites have been shown to have synthetical advantages in structural retrofitting, seismic strengthening and serving as new structural components [16,17]. In addition, previous research has shown that the hybridization of fibers in

---

* Corresponding author. Tel.: +86 25 8379 3232.
E-mail address: zswu@seu.edu.cn (Z.-S. Wu).

1359-8368/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compositesb.2013.11.026

FRP composites not only reduces the high material costs of CFRP composites but also increases the long-term and durability resistance of FRP composites [3,18–20]. Till now, very limited information is available on the durability of BFRP and hybrid FRP composites in FT environments.

This study presents the results of an experimental evaluation of the tensile behavior of BFRP, CFRP, GFRP and hybrid FRP sheets in FT environments. The tensile properties of the corresponding epoxy resins and dry fiber sheets were considered in the test program to contribute to the further understanding of the degradation mechanism of FRP composites in FT cycling environments. The effect of sustained loading on the degradation of FRP composites was also addressed in the test program.

2. Experiments

2.1. Test coupons

To make FRP sheets, unidirectional fiber fabrics were completely impregnated with epoxy resin using a wet hand lay-up procedure. The epoxy resin used in the tests was a two-component thermosetting adhesive (a bisphenol-A epoxy as component A and a modified amine hardener as component B), which is commercially used as a bonding adhesive for fiber sheets in civil engineering applications. After the solidification of the epoxy resin, FRP coupons were cut and prepared according to the Chinese national standard GB/T-3354 [21]. Each coupon was 230 mm long and 15 mm wide, as shown in Fig. 1(a). To minimize stress concentrations near the gripping zone, aluminum tabs were bonded at both ends of the FRP coupons before tensile tests. Dry fiber sheet coupons were prepared with the same dimensions as the FRP coupons. Epoxy resin was used at the anchorage regions, and a 70-mm-long region in the center of the test coupon was protected from impregnation of epoxy resin to ensure that failure would occur in the dry fiber region, as shown in Fig. 1(b). Epoxy resin tensile and tensile shear test coupons were prepared according to the Chinese national standard GB/T-2567 [22], as shown in Fig. 1(c) and (d). All of the coupons were cured for a minimum of one week at ambient temperature prior to testing.

2.2. Sustained loading systems

A specially designed spring-reaction frame loading system, shown in Fig. 2, was used to apply and maintain sustained loading on the FRP composites during the FT tests. First, the FRP composite coupons with aluminum tabs were fixed on the clamp system. Then, the sustained load was applied by tightening the anchorage nut close to the spring and was monitored by a strain gauge placed on the FRP coupon. Considering the creep limit for FRP composites suggested in the existing guidelines (e.g., ACI 440.1R-06 [23], 440.2R-08 [24]), the sustained loads applied to the FRP composites were 30% of the ultimate load for GFRP and BFRP and 40% of the ultimate load for CFRP, as shown in Table 2. Control specimens were tested to determine their tensile properties at room temperature prior to the sustained load application. To avoid the influence of adhesive degradation of the bond between the aluminum tabs and the FRP sheets, the FRP coupons were cut at the end of the clamping plate and bonded with new aluminum tabs after exposure. To eliminate the influence of thermal expansion and contraction on the steel spring, the spring part was not put in the water during the FT cycling tests.

2.3. Test procedures

The test coupons were soaked in water in rubber boxes and subjected to accelerated FT cycle tests at 3–4 h per cycle, in accordance with the rapid FT method in the Chinese national standard GB/T-50082 [25]. A thermocouple sensor was used to monitor the temperature changes during the FT cycle tests. The temperature fluctuation during the FT cycle testing is illustrated in Fig. 3. The temperature ranged from +8 °C to −17 °C during FT tests.

After being subjected to appropriate freeze–thaw cycles, each coupon was positioned in a 30-kN tension testing machine for the tensile tests. The axial deformation was recorded using an extensometer with a gauge length of 50 mm. The tensile force was measured by a load sensor inside the testing equipment. The loading was controlled by displacement at a rate of 2 mm/min. The values of the load and the axial deformation were recorded at one-second intervals.

2.4. Test program

Two series of tests were conducted to evaluate the FT response of FRP composites. The overall experimental programs of the two series of tests are listed in Tables 1 and 2. The purpose of the first series of tests was to examine the residual tensile properties of BFRP and hybrid FRP composites after exposure to FT cycles. Layered hybridizations of basalt and carbon FRP sheets, such as 1B1C and 2B1C, were tested. The term 1B1C indicates that one layer of CFRP sheet was combined with one layer of BFRP sheet, while 2B1C indicates that one layer of CFRP sheet was sandwiched between two layers of BFRP sheets. In addition, epoxy resin coupon tests were included in the study to evaluate the degradation of epoxy resin after exposure to FT cycles. The second series of tests was conducted to study the response of FRP composites under the combined action of FT cycles and sustained loading. The effect of FT cycling and moist environments on the dry fiber sheets were also assessed in the test program. For each group of test coupons,

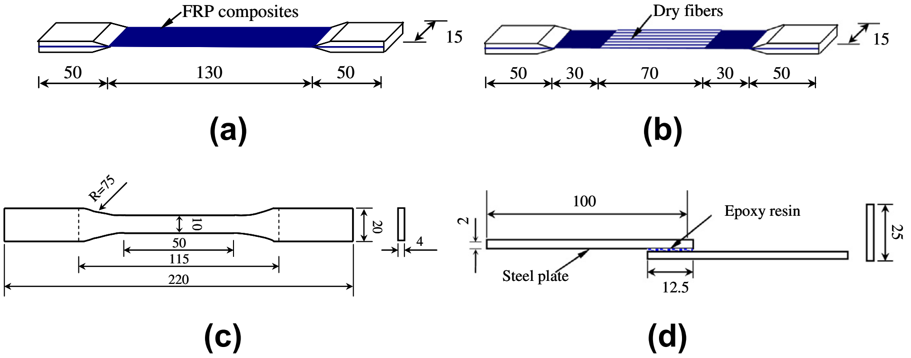


Fig. 1. Test coupons (mm): (a) FRP tensile test coupon; (b) dry fiber sheet tensile test coupon; (c) epoxy resin tensile coupon; (d) epoxy resin tensile shear coupon.

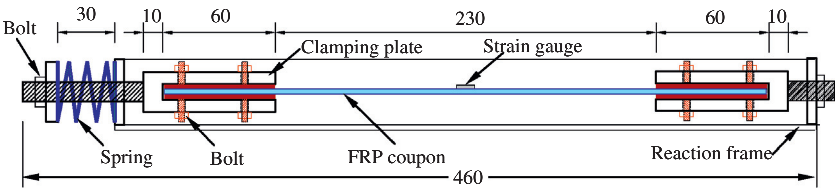


Fig. 2. Sustained loading system of FRP composites during freeze–thaw cycling (mm).

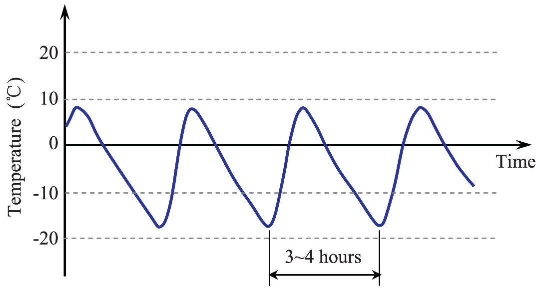


Fig. 3. Temperature fluctuations during freeze–thaw tests.

five valid test results were obtained, and the average values and variations of the tensile properties were determined.

3. Test results

The tensile strength, elastic modulus and rupture elongation of each test coupon were calculated based on the measured stress–strain relationship. The average values and standard deviations of these properties were calculated for each group of test coupons to evaluate their residual tensile properties and stability after exposure. Control specimens were tested before exposure at room temperature and served as the 0-cycled specimens in the subsequent analysis. The average results and standard deviations of the control specimens are listed in Table 3. To simplify the analysis and facilitate comparison of the results after FT exposure, the test results were expressed by normalized values with respect to the control test results. Overall, with the exception of the epoxy resin tensile shear test coupons, no obvious changes were observed in

Table 1
Details of the first series of tests.

Specimen	Material	FT cycles	Specimen	Material	FT cycles
C-50	CFRP	50	1B1C-50	HFRP (1B/1C)	50
C-100	CFRP	100	1B1C-100	HFRP (1B/1C)	100
C-150	CFRP	150	1B1C-150	HFRP (1B/1C)	150
C-200	CFRP	200	1B1C-200	HFRP (1B/1C)	200
B-50	BFRP	50	2B1C-50	HFRP (2B/1C)	50
B-100	BFRP	100	2B1C-100	HFRP (2B/1C)	100
B-150	BFRP	150	2B1C-150	HFRP (2B/1C)	150
B-200	BFRP	200	2B1C-200	HFRP (2B/1C)	200
ET-50	Epoxy (tensile)	50	ES-50	Epoxy (shear)	50
ET-100	Epoxy (tensile)	100	ES-100	Epoxy (shear)	100
ET-200	Epoxy (tensile)	200	ES-200	Epoxy (shear)	200
ET-250	Epoxy (tensile)	250	ES-250	Epoxy (shear)	250

Table 2
Details of the second series of tests.

Specimen	Material	FT cycles	Sustained load	Specimen	Material	FT cycles
C-100-0	CFRP	100	0	CF-0/W	CF sheet	0/W[***]
C-200-0	CFRP	200	0	CF-100	CF sheet	100
C-300-0	CFRP	300	0	CF-200	CF sheet	200
C-100-P[*]	CFRP	100	40% P_u[**]	CF-300	CF sheet	300
C-200-P	CFRP	200	40% P_u	BF-0/W	BF sheet	0/W
C-300-P	CFRP	300	40% P_u	BF-100	BF sheet	100
B-100-0	BFRP	100	0	BF-200	BF sheet	200
B-200-0	BFRP	200	0	BF-300	BF sheet	300
B-300-0	BFRP	300	0	GF-0/W	GF sheet	0/W
B-100-P	BFRP	100	30% P_u	GF-100	GF sheet	100
B-200-P	BFRP	200	30% P_u	GF-200	GF sheet	200
B-300-P	BFRP	300	30% P_u	GF-300	GF sheet	300
G-100-0	GFRP	100	0			
G-200-0	GFRP	200	0			
G-300-0	GFRP	300	0			
G-100-P	GFRP	100	30% P_u			
G-200-P	GFRP	200	30% P_u			
G-300-P	GFRP	300	30% P_u			

[*] P stands for the sustained load during freeze–thaw exposure.

[**] P_u is the ultimate load of the control specimen at room temperature.

[***] 0/W denotes that the fiber sheet is soaked in fresh water for the same time as that of the 300 FT cycles.

Table 3
Tensile properties of the FRP sheets, epoxy resin and dry fiber sheets at room temperature.

Specimen	Material	Nominal thickness (mm)	Tensile strength (MPa)	Elastic modulus (GPa)	Rupture elongation (%)
C-R	CFRP	0.111	4067 ± 309	239.8 ± 5.5	1.74 ± 0.09
B-R	BFRP	0.156	2077 ± 86	80.2 ± 1.5	2.68 ± 0.01
G-R	GFRP	0.198	1376 ± 121	69.8 ± 5.8	1.99 ± 0.08
1B1C-R	HFRP (1B/1C)	0.267	2482 ± 92	144.6 ± 6.5	1.74 ± 0.05
2B1C-R	HFRP (2B/1C)	0.423	2213 ± 110	124.3 ± 0.5	1.84 ± 0.05
ET-R	Epoxy (tensile)	/	47.1 ± 5.1	3.2 ± 0.2	2.39 ± 0.44
ES-R	Epoxy (shear)	/	15.1 ± 1.3	/	/
CF-R	CF sheet	0.111	2372 ± 95	233.5 ± 16.2	1.11 ± 0.10
BF-R	BF sheet	0.156	921 ± 57	76.3 ± 2.6	1.26 ± 0.16
GF-R	GF sheet	0.198	777 ± 43	59.9 ± 7.7	1.29 ± 0.15

the failure modes of the test coupons before and after FT exposure. The failure modes of the control specimens are shown in Fig. 4.

3.1. BFRP and hybrid FRP composites

Fig. 5(a)–(c) illustrate the variation in the residual tensile properties of the BFRP, CFRP and hybrid FRP sheets with respect to the number of FT cycles applied. In order to compare the durability behavior among different FRP types, test results of GFRP sheets reported in the literature [15] as having been tested with the same FT cycling procedure. The tensile strength of the CFRP and GFRP sheets decreased steadily as the number of FT cycles increased. In contrast, the tensile strength of the BFRP sheets decreased initially, then increased up to 150 cycles, and finally decreased slightly. There was almost no reduction in the residual tensile strength of the BFRP composite after 200 FT cycles. The FT cycle testing did not diminish the elastic modulus of the three types of FRP sheets. A maximum increase in the elastic modulus of approximately 10% was observed, indicating that FT cycling can make FRP composites more brittle. The rupture elongation of the three FRP sheets decreased as the number of FT cycles increased, and the BFRP sheets exhibited a higher retention rate than the CFRP and GFRP sheets after 200 FT cycles. Moreover, it is worth noting that, the tensile rupture elongation of the epoxy resin used in the test is a bit lower than that of the BFRP, as shown in Table 3. This may influence the rupture elongation of BFRP both in room temperature and FT cycling environments. Therefore, the degradation of the rupture elongation of the BFRP coupons in FT environments may be partly attributed to the degradation of the epoxy resin. Despite this, BFRP still exhibited excellent durability in FT cycling environment. If a more ductile resin was applied, lower degradation of the rupture elongation of the BFRP coupons would be expected (see Table 4).

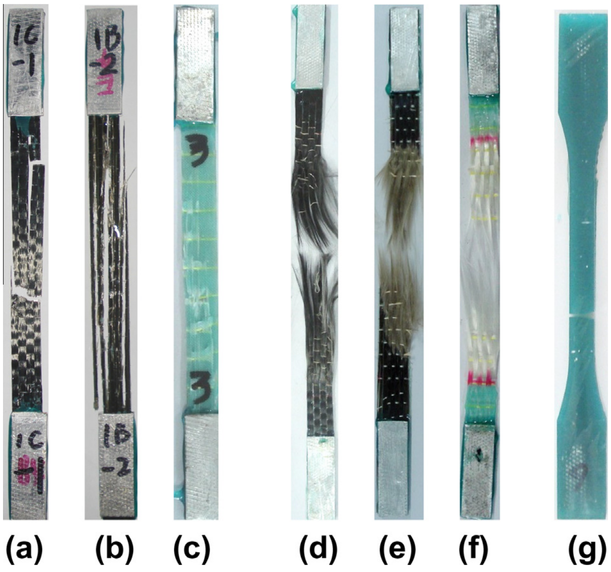


Fig. 4. Failure modes of the test coupons: (a) CFRP; (b) BFRP; (c) GFRP; (d) CF; (e) BF; (f) GF; (g) epoxy resin.

As Fig. 5 shows, the hybrid FRP sheets exhibited better resistance to FT cycles than the homogeneous FRP composites. There was almost no decrease in tensile strength or elastic modulus of the hybrid FRP composites through 200 cycles. A decrease of approximately 8% in the rupture elongation of the 2B1C hybrid FRP coupons was observed after 50 and 100 cycles, but there was almost no decrease after higher numbers of cycles. Fig. 5(d)–(f) present the scatter in the test results for the FRP sheets. Higher coefficients of variation (COV) were observed for the exposed FRP sheets than for the control sheets, which may be attributed to nonuniformity in the concentration of micro-cracking in the exposed composites. The hybrid FRP sheets had lower COV values than the corresponding homogeneous sheets after exposure, indicating that the hybridization of FRP composites may contribute to the stability of the tensile properties of FRP composites in FT environments.

3.2. Epoxy resin

The normalized results of the epoxy resin tensile and tensile shear tests are shown in Fig. 6. The tensile strength and rupture elongation exhibited almost the same trends and degradation rates with increasing FT cycles. After a maximum of 250 FT cycles, the residual tensile strength and rupture elongation were only 72% and 70%, respectively, of the control values. Damage to the resin matrix may weaken the resin's protective effect and the stress transfer capacity of fibers and result in the degradation of FRP composites. FT cycling did not diminish the elastic modulus of the epoxy resin. A slight increasing trend was observed in the average value of the elastic modulus up to 200 FT cycles, indicating that FT environments may lead to the embrittlement of epoxy resin. In addition, the exposed specimens exhibited more dispersion in the measured data than the control specimens.

Fig. 6(b) presents the failure modes of the tensile shear test coupons exposed to various numbers of FT cycles. The control specimens and low-cycled coupons exhibited partial fracture in the adhesive layer, whereas high-cycled coupons remained intact in the adhesive layer on one side of the steel plate and delaminated completely between the adhesive layer and the steel plate. This change in the failure modes indicates that FT cycling had a serious effect on the bonding between the adhesive and the steel plate. The bond between epoxy resin and fibers or the interface between FRP sheets and a structure's surface may also be significantly influenced by FT cycling environments. Fig. 6(a) shows that the tensile shear strength of the epoxy resin decreased steadily as the number of FT cycles increased. Up to 100 cycles, there was no significant

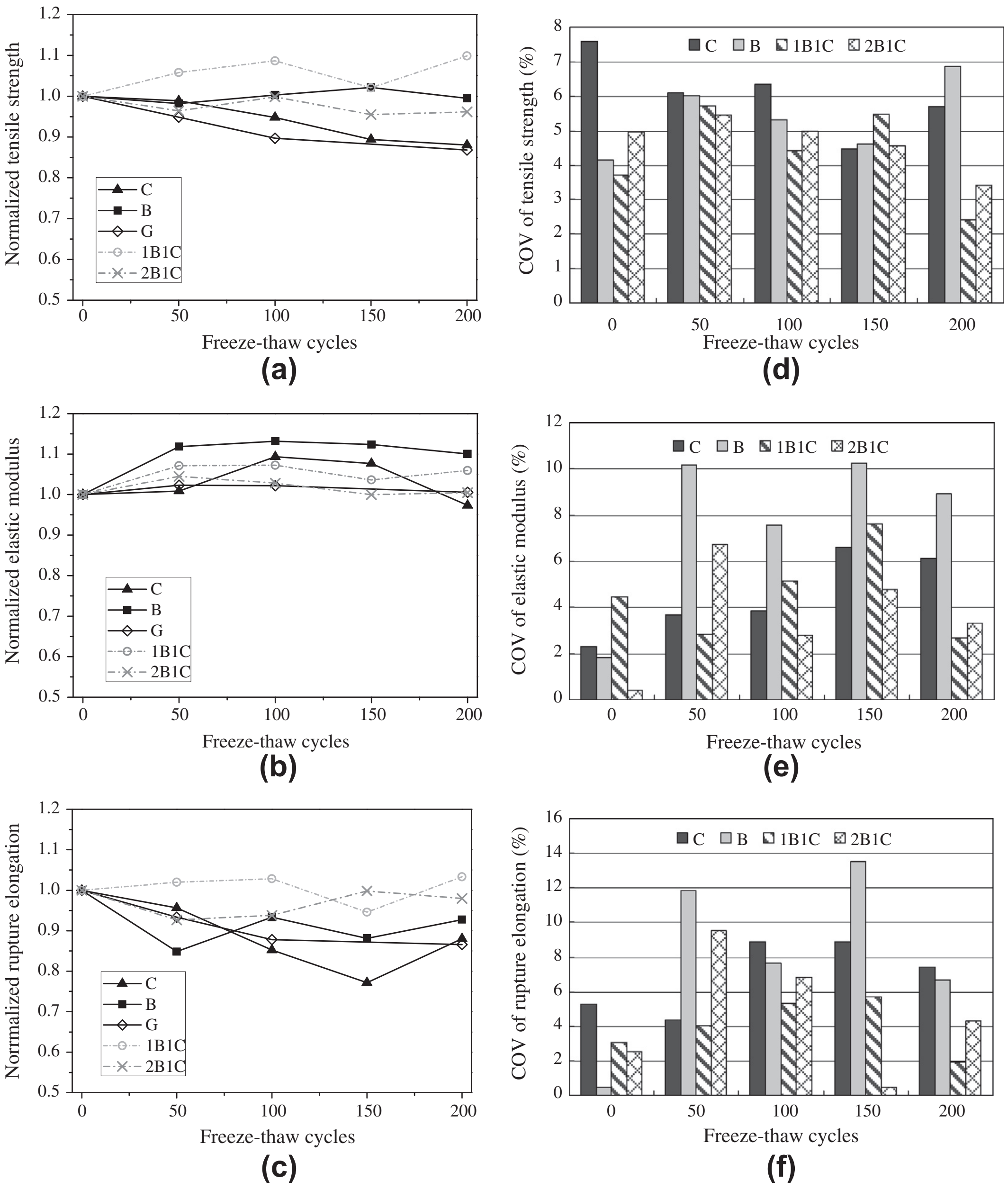


Fig. 5. Normalized tensile properties and coefficient of variation (COV) of FRP and hybrid FRP composites versus freeze–thaw cycles: (a) tensile strength; (b) elastic modulus; (c) rupture elongation; (d) COV of tensile strength; (e) COV of elastic modulus; (f) COV of rupture elongation.

Table 4
Coefficients of thermal expansion (CTE) of the materials.

Material	CTE ($\times 10^{-6}$/°C)
CFRP (longitudinal)	1.9
BFRP (longitudinal)	12.4
GFRP (longitudinal)	11.5
Steel	11–12
Epoxy resin	45–65
Carbon fiber (longitudinal)	−0.6 to −0.2
Basalt fiber (longitudinal)	6.5–8
Glass fiber (longitudinal)	5–6

difference in the degradation rate in comparison to that of the tensile strength of the epoxy resin. At a higher number of cycles, the normalized values of the tensile shear strength were much lower than the corresponding tensile strength values, due to the change in the failure mode.

3.3. Combined action of FT cycling and sustained loading

Fig. 7 presents the normalized tensile properties of the FRP sheets after the combined action of FT cycling and sustained loading. Fig. 7(a)–(c) shows that the tensile strength of each type of FRP sheet decreased steadily as the number of FT cycles increased. The specimens subjected to sustained loading exhibited lower retention ratios than the corresponding unloaded specimens, indicating that the sustained loading accelerated the degradation rate of the FRP sheets in FT environments. Of the three types of FRP composites, the BFRP composites exhibited better resistance to FT cycling. After 300 FT cycles, the tensile strength of the BFRP coupons subjected to sustained loading was reduced by only 3.5%. In comparison, nearly 10% and 20% reductions were observed for the corresponding CFRP and GFRP specimens, respectively, subjected to sustained loading during FT cycling. This trend is

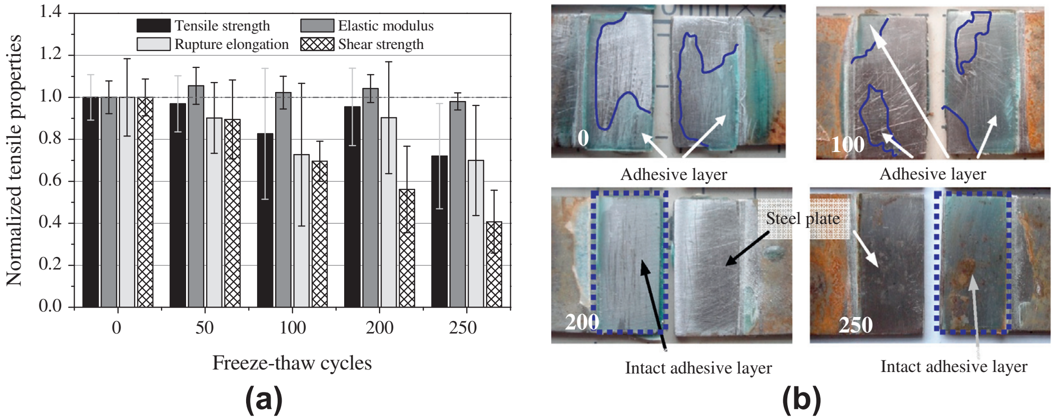


Fig. 6. Mechanical properties of epoxy resin versus freeze–thaw cycles: (a) Normalized properties; (b) Failure modes of shear strength coupons.

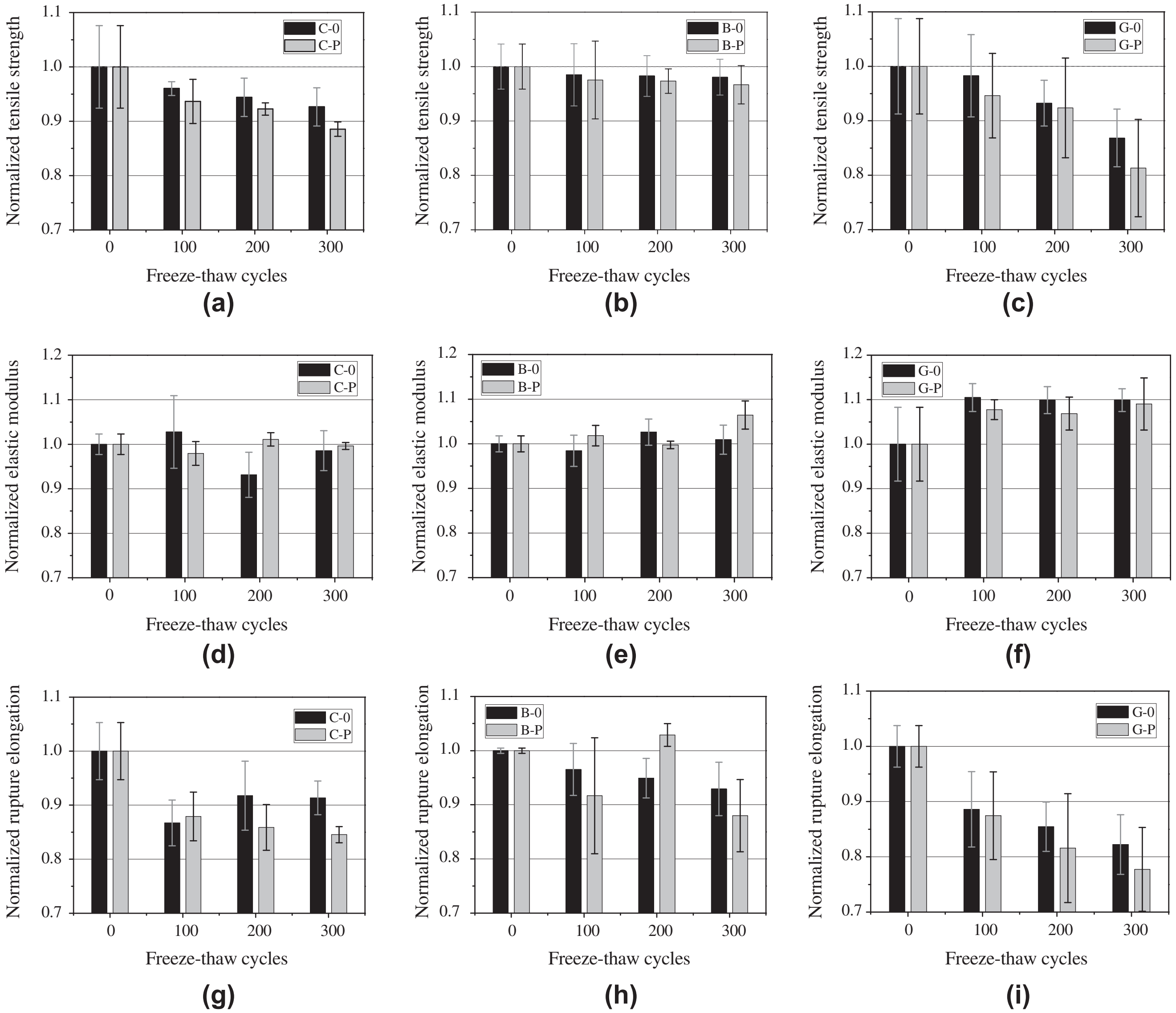
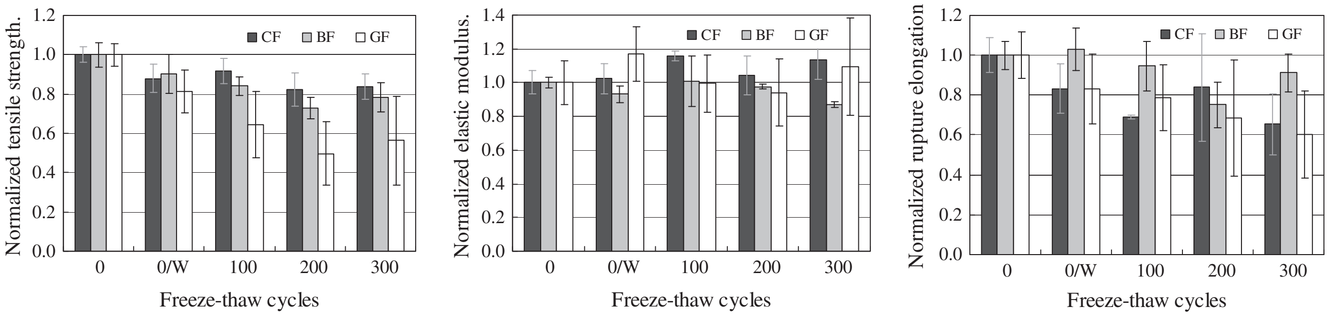


Fig. 7. Normalized tensile properties of FRP composites under the combined action of freeze–thaw cycling and sustained loading: (a) tensile strength of CFRP; (b) tensile strength of BFRP; (c) tensile strength of GFRP; (d) elastic modulus of CFRP; (e) elastic modulus of BFRP; (f) elastic modulus of GFRP; (g) rupture elongation of CFRP; (h) rupture elongation of BFRP; (i) rupture elongation of GFRP.



(a) (b) (c)

Fig. 8. Normalized tensile properties of dry fiber sheets versus freeze–thaw cycles: (a) tensile strength; (b) elastic modulus; (c) rupture elongation.

consistent with the observations of the behavior of the three types of FRP sheets in the first series of tests. The elastic modulus of the FRP composites was almost unaffected by the sustained loading during the FT cycles, and as Fig. 7(d)–(f) shows, the specimens subjected to sustained loading exhibited even higher elastic modulus values after a high number of FT cycles than the corresponding unloaded specimens. Fig. 7(g)–(i) shows that the rupture elongation degradation trend was similar to that of the tensile strength of the FRP composites. The degradation ratio of the rupture elongation was greater than that of the tensile strength, which is mainly due to the increase in the elastic modulus after FT exposure.

3.4. Dry fiber sheets

Fig. 8 compares the tensile properties of the various dry fiber sheets tested before and after FT exposure. To eliminate the influence of water during the FT cycling tests, all of the fiber sheet coupons, with the exception of the control coupons, were soaked in water for the same amount of time as those exposed to 300 FT cycles. The label "0_W cycles" indicates that the fiber sheet was soaked in fresh water but was not subjected to FT cycles. Fig. 8(a) shows that the tensile strength of the dry fiber sheets was influenced significantly by exposure to FT cycling and water immersion. After being soaked in water for approximately 60 days (equal to an exposure time of 300 FT cycles), the carbon fiber (CF) sheets and the basalt fiber (BF) sheets lost approximately 12% and 10% of their tensile strength, respectively, while glass fiber (GF) sheets lost 19% of their tensile strength, indicating that GF is more sensitive to moisture than CF and BF. Among the three types of fibers, CF and BF sheets exhibited degradation rates of 16% and 22% of their tensile strength, while the GF sheets lost nearly half of their original tensile strength after 300 freeze–thaw cycles. The presence of water during exposure and the cyclic expansion and contraction of the water are believed to be the main reasons for the degradation of fibers in freeze–thaw environments. Moisture has been shown, in the case of glass fibers, to cause degradation at the fiber level. The moisture-extracting ions in the fibers combine with water to form bases, which could etch and pit the surface of the fibers, resulting in degradation of the mechanical properties of the fibers. The elastic modulus of the dry fiber sheets was hardly influenced at all by water immersion and FT cycling, as shown in Fig. 8(b). After exposure, the rupture elongation of the BF sheets exhibited higher residual values than the CF and GF sheets, as shown in Fig. 8(c). The CF sheets had even lower residual rupture elongation than the GF sheets after FT exposure, which is consistent with the trend observed for the rupture elongation of the FT-cycled FRP sheets, as shown in Fig. 5(c).

4. Discussion

Two major effects occur when FRP composites are exposed to FT environments: thermal incompatibility and degradation of the constituent materials, including their interfaces. The first effect is related to the different thermal characteristics of the constituents of FRP composites. In general, the epoxy resins in FRP composites have coefficients of thermal expansion (CTE) that are at least an order of magnitude greater than those of the fibers [14,26], as shown in Table 3. A decrease in temperature would cause the fibers and resin to contract, resulting in the formation of residual stresses at the resin matrix–fiber interface, due to the differences in the CTE and the elastic modulus between the two materials. In FT environments, cyclic stresses are repeated at the matrix–fiber interface, potentially deteriorating their bond capacity and often resulting in debonding of the fibers from the surrounding matrix [5].

Among the three types of fibers studied in this work, basalt fibers have the closest CTE to the epoxy resin and hence better bonding between the fibers and matrix after FT cycling. In the case of CFRP, the effects are even more pronounced because the carbon fiber has a negative CTE along the fiber direction. Li et al. [14] found that CFRP sheets lost more than 10% of their tensile strength after 90 FT cycles in dry air, whereas the degradation of BFRP and GFRP composites were negligible, indicating that the thermal incompatibility is the main reason for the degradation of the tensile properties of CFRP composites in FT environment.

The other major effect is the degradation of the constituent materials and their interfaces as a result of FT exposure, especially in the presence of moisture. Exposure to cold temperatures and FT cycles generally results in an increase in the elastic modulus and embrittlement of a resin matrix but a decrease in damage tolerance, contributing to the increase in the embrittlement and the decrease in the tensile strength and rupture elongation of the FRP composites. When moisture is considered, the progression of damage to the resin matrix and the matrix–fiber interface may be the result of cyclic expansion and contraction of the entrapped water during FT cycles. In addition, a wet environment is known to cause degradation in FRP composites through changes such as plasticization and hydrolysis of the resin matrix, resin matrix–fiber interface debonding, and in the case of glass fibers, pitting, etching and cracking of the fiber itself [5]. The test results described in the previous section confirm the poor behavior of glass fiber sheets in wet and FT environments and the greater resistance of carbon and basalt fiber sheets to water and FT cycles. Previous studies have shown that the tensile properties of BFRP sheets did not decrease significantly after being soaked in fresh water for 90 days at ambient temperatures [27], whereas GFRP sheets retained only 84% of their original tensile strength after being exposed to a similar moisture environment for 30 days at ambient temperatures [28]. In addition, the bond strength of basalt fiber–matrix interface is larger than that of the glass fiber [29], indicating that glass fiber–matrix interface is easier to be affected in FT cycling environment.

As the above discussions conveys, the thermal incompatibility between carbon and epoxy resin is mainly responsible for the degradation of the tensile properties of CFRP composites in FT cycling environments. Although the glass fiber has a similar CTE compared with basalt fiber, the FT resistance of GFRP composites is inferior to BFRP composites, which is mainly due to the poor behavior of glass fibers in FT environments and relative lower bond strength between the fibers and the resin matrix. In comparison, BFRP composites have better resistance to moisture at both the fiber and FRP composites levels and higher fiber–matrix bond strength, resulting in superior durability in FT cycling environments. For carbon-basalt hybrid FRP composites, the carbon fiber initially cracks under tensile loading, and the crack propagation is restrained by the less-stiff and higher-elongation basalt fibers through the stress transfer of resin matrix. Due to the excellent durability and good fiber–matrix bond capacity of BFRP composites, the carbon-basalt hybrid FRP composites exhibited excellent durability in FT cycling environment.

Furthermore, the presence of a sustained load during FT cycling can magnify micro cracks in the matrix and at the matrix–fiber interface, increase the propagation rate of water in the matrix and affect the mechanical properties of FRP composites. Some previous studies on the durability of CFRP and GFRP composites have shown that the tensile strength and elastic modulus of FRP composites subjected to constant loading in water decreased considerably and that their weight gain increased with the load level [30,31]. The results of the tests conducted in this study are evidence of the adverse effects of sustained loads on the tensile properties of FRP composites in FT environments.

5. Conclusions

Based on the results of the experimental studies and the discussions presented in this study, the following conclusions can be drawn:

(1) FT cycling has a negligible effect on the tensile properties of both BFRP and carbon-basalt hybrid FRP sheets but does have an adverse effect on CFRP and GFRP sheets. 200 FT cycles resulted in reductions in tensile strength for CFRP and GFRP equivalent to 12% and 14%, respectively. The elastic modulus of the FRP sheets was not deteriorated by the FT cycles, while the rupture elongation showed similar degradation trends to the tensile strength. The hybridization of carbon and basalt fibers not only enhanced the durability but also contributed to the stability of the tensile properties of FRP sheets in FT environments.

(2) Significant degradation of the mechanical properties of epoxy resin was observed after FT exposure. 250 FT cycles resulted in significant reductions in tensile strength, rupture elongation and tensile shear strength equivalent to 28%, 30% and 60%, respectively. The elastic modulus of the epoxy was almost not influenced by the FT cycles. In addition, dry glass fiber sheets exhibited poorer resistance to moisture and FT cycling than corresponding carbon and basalt FRP sheets.

(3) Additional degradation on the tensile strength and rupture elongation of the FRP sheets was observed as a result of sustained loading during FT cycling, while the elastic modulus of the FRP sheets was not influenced by the sustained loading during FT cycling. Therefore, it is necessary to consider service loads during durability tests to reflect the actual conditions faced by FRP composites in harsh civil engineering environments.

(4) The degradation mechanism of FRP composites in FT environments mainly consists of two aspects: damage of the fiber–matrix interface caused by thermal incompatibility and degradation of the constituent materials, including their interfaces in freeze–thaw cycling environments. In addition, sustained load can accelerate the rate of propagation of water in the resin matrix and degrade the tensile properties of FRP composites in FT environments.

Acknowledgements

The authors are grateful for the financial support received from the National Key Basic Research Program of China (973 Program) (No. 2012CB026200), the National “Twelfth Five-Year” Plan for Science and Technology (Nos. 2011BAB03B09, 2012BAK24B03), the Natural Science Foundation of Jiangsu Province, China (No. BK2010015), and the Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

References

[1] Bakis CE, Bank LC, Brown VL, Cosenza E, Davalos JF, Lesko JJ, et al. Fiber reinforced polymer composites for construction state of the art review. J Compos Constr 2002;6(2):73–87.
[2] Wu ZS, Kim YJ, Diab H, Wang X. Recent developments in long-term performance of FRP composites and FRP-concrete interface. Adv Struct Eng 2010;13(5):891–903.
[3] Wu ZS, Wang X, Iwashita K, Sasaki T, Hamaguchi Y. Tensile fatigue behavior of FRP and hybrid FRP sheets. Compos B Eng 2010;41(5):396–402.
[4] Marouani S, Curtil L, Hamelin P. Ageing of carbon/epoxy and carbon/vinylester composites used in the reinforcement and/or the repair of civil engineering structures. Compos B Eng 2012;43:2020–30.
[5] Karbhari VM. Durability of composites for civil structural applications. Cambridge: Woodhead Publishing in Materials and CRC Press; 2007.
[6] Saadatmanesh H, Tavakkolizadeh M, Mostofinejad D. Environmental effects on mechanical properties of wet lay-up fiber reinforced polymer. ACI Mater J 2010;107(3):267–74.
[7] Sun W, Mu R, Luo X, Miao CW. Effect of chloride salt, freeze–thaw cycling and externally applied load on the performance of the concrete. Cem Concr Res 2002;32(12):1859–64.
[8] Shi JW, Zhu H, Wu ZS, Seracino R, Wu G. Bond behavior between BFRP sheet and concrete substrate under the coupled effects of freeze-thaw cycling and sustained load. J Compos Constr 2013;17(4):530–42.
[9] Rivera J, Karbhari VM. Cold-temperature and simultaneous aqueous environment related degradation of carbon/vinylester composites. Compos B Eng 2002;33(1):17–24.
[10] Wu HC, Fu G, Ronald FG, et al. Durability of FRP composite bridge deck materials under freeze-thaw and low temperature conditions. J Bridge Eng 2006;11(4):443–51.
[11] Dutta PK, Hui D. Low-temperature and freeze-thaw durability of thick composites. Compos B Eng 1996;27(3–4):371–9.
[12] Wu HC, Yan A. Time-dependent deterioration of FRP bridge deck under freeze/thaw conditions. Compos B Eng 2011;42:1226–32.
[13] Nardone F, Ludovico M, Basalo F, Prota A, Nanni A. Tensile behavior of epoxy based FRP composites under extreme service conditions. Compos B Eng 2012;43(3):1468–74.
[14] Li H, Xian GJ, Zhang H. Freeze–thaw resistance of unidirectional fiber reinforced epoxy composites. J Appl Polym Sci 2012;123(6):3781–8.
[15] Li S. Durability of concrete strengthened with FRP under environmental and loading conditions. Doctoral thesis, Dalian University of technology, Dalian, China; 2009 [in Chinese].
[16] Wu ZS, Wang X, Wu G. Advancement of structural safety and sustainability with basalt fiber reinforced polymers. In: Proceedings of 6th international conference on FRP composites in civil engineering (CICE2012), Rome, Italy; 2012.
[17] Sim J, Park C, Moon DY. Characteristics of basalt fiber as a strengthening material for concrete structures. Compos B Eng 2005;36(6–7):504–12.
[18] Wu ZS, Li WX, Sakuma N. Innovative externally bonded FRP/concrete hybrid flexural members. Compos Struct 2006;72(3):289–300.
[19] Wang X, Wu ZS. Evaluation of FRP and hybrid FRP cables for super long-span cable-stayed bridges. Compos Struct 2010;92(10):2582–90.

[20] Wang X, Wu ZS, Wu G, Zhu H, Zen FX. Enhancement of basalt FRP by hybridization for long-span cable-stayed bridge. Compos B Eng 2013;44:184–92.
[21] GB/T 3354-1999. Test method for tensile properties of oriented fiber reinforced plastics. Beijing: China standard press; 1999 [in Chinese].
[22] GB/T 2567-2008. Test methods for properties of resin casting boby. Beijing: China standard press; 2008 [in Chinese].
[23] ACI 440.1R-06. Guide for the design and construction of structural concrete reinforced with FRP bars. Farmington Hills, Michigan: American Concrete Institute; 2006.
[24] ACI 440.2R-08. Guide for the design and construction of externally FRP systems for strengthening concrete structures. Farmington Hills, Michigan: American Concrete Institute; 2008.
[25] GB/T 50082-2009. Standard for test methods of long-term performance and durability of ordinary concrete. Beijing: China Architecture and Building Press; 2009 [in Chinese].
[26] Green MF. FRP repair of concrete structures: performance in cold regions. Int J Mater Prod Technol 2007;28(1–2):160–77.
[27] Wu JY, Xian GJ, Li H. Durability study of basalt fiber and its FRP bars. Fiber Reinf Plast/Compos 2011;5:58–61 (in Chinese).
[28] Strandlund S. Freeze-thawing of polyester E-glass as an evaluation of an ASTM international test standard proposal. Master's thesis, University of Mississippi, MS, USA; 2011.
[29] Wang ZH. Research on basic properties and applications of basalt fiber reinforced polymer. Master's thesis, Southeast University, Nanjing, China; 2013.
[30] Neumann S, Marom G. Prediction of moisture diffusion parameters in composite materials under stress. J Compos Mater 1987;21(1):68–80.
[31] Meyer LJ, Henshaw JM, Houston DQ, Hagerman EM. The effects of stressed environmental exposure on the durability of automotive composite materials. Polym Polym Compos 1999;7(4):269–81.