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Durability of concrete beams reinforced with CFRP sheet under wet-dry cycles and loading

Li Shan Ren Huitao Huang Chengkui Cui Yunfei

(State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China)

Abstract: The test results of eight concrete beams reinforced with carbon fiber reinforced polymer (CFRP) sheets subjected to an aggressive environment under a sustained load are presented. The beams are 1 700 mm long with a rectangular cross-section of 120-mm width and 200-mm depth. The beams are precracked with a four-point flexural load, bonded CFRP sheets, and placed into wet-dry saline water(NaCl) either in an unstressed state or loaded to about 30% or 60% of the initial ultimate load. The individual and coupled effects of wet-dry saline water and sustained bending stresses on the long term behaviour of concrete beams reinforced with the CFRP are investigated. The test results show that the coupled action of wet-dry saline water and sustained bending stresses appears to significantly affect the load capacity and the failure mode of beam strengthened with CFRP, mainly due to the degradation of the bond between CFRP and concrete. However, the stiffness is not affected by the coupled action of wet-dry cycles and a sustained load.

Key words: reinforced concrete beams; reinforced; carbon fiber reinforced polymers; durability; wet-dry cycles; sustained load

Carbon fiber-reinforced polymer (CFRP) is increasingly being used worldwide for the retrofitting and repair of reinforced concrete (RC) structures. In the repair of RC structures with the CFRP method, the CFRP is bonded to the concrete surface using epoxy adhesives. The load is transferred to the CFRP material by epoxy. Both the flexural and shear strength of RC structures can be significantly increased, and adequate overall ductility can be obtained[1–2]. However, there is insufficient information on the long term durability of RC beams with CFRP exposed to aggressive environmental conditions, especially wet-dry conditions with immersion in salt solutions. Very little research has been done on the structural members wrapped with CFRP subjected to wet-dry cycles[3–7]. Moreover, the previous work mainly focuses on the individual effects of wet-dry saline water. There is a lack of experimental data on the long term behaviour of concrete beams reinforced with CFRP under wet-dry cycles and sustained bending stresses. As in service conditions, the strengthened beams can be subjected to wet-dry cycles and sustained loads simultaneously. The behavior of concrete beams under sustained loading changes with time due to creep and shrinkage of the concrete. The gradual development of creep strain in a beam causes an increase in curvature and deflection. In addition, wet-dry conditions can lead to degradation of the bond between CFRP and concrete through water absorption by the epoxy[8–10]. Thus, it is essential to investigate the overall response of the RC beams externally strengthened with CFRP sheets exposed to the conditions under sustained loads. In this paper, the responses of RC beams strengthened with CFRP sheets subjected to wet-dry conditions under sustained loads are presented.

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Biographies: Li Shan (1979—), male, graduate; Huang Chengkui (corresponding author), male, professor, huangck@dlut.edu.cn.

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1 Experimental Program

There are two aspects in this paper. They are the influence of wet-dry action on the CFRP sheet and the influence of wet-dry action on beam strength with CFRP sheets under sustained loads. The wet-dry cycle is completed by immersing the specimens in a salt solution (50 g/L water) for 12 h, followed by 12 h drying at room temperature.

1.1 Material

The average 28-day cube compressive strength of concrete is 46.7 MPa. The average yield stresses of steel bars are 360 and 305 MPa for ϕ12 and ϕ8 mm, respectively. The used carbon fabric comes in the form of unidirectional woven roving, which is from Japan (UT70-20). The resin, the JGN-T system (from Dalian Kaihua), is a two part resin, JGN-T A and JGN-T B, and it is mixed together in a ratio of 3:1.

1.2 CFRP specimens

In this section, carbon fabrics without resin (CF) and carbon fabrics with resin (CFRP) specimens are considered. The 15 mm × 350 mm CFRP specimens are made in accordance with Chinese standard CECS146. For the CF specimens, the gauge region of each specimen is not impregnated with resin. The dimensions are the same as those of CFRP specimens. The details are shown in Fig. 1.

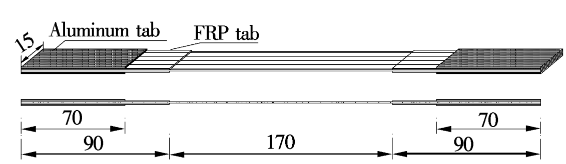

Fig. 1 Details of CFRP and CF specimens (unit: mm)

Following the cure of the resin, all of the specimens are put into a wet-dry environment. The CFRP specimens are subjected to 90 and 180 wet-dry cycles. And the CF specimens are only subjected to 180 wet-dry cycles.

1.3 Beam specimens

The beams are 1 700 mm in length, 120 mm in width, and 200 mm in depth as shown in Fig. 2. At the end of 28 d, precracks are introduced to the specimens by four point flexural loading. The calculated precracking load of the beam is 37. 28 kN, which is approximately 70% of the initial ultimate load, and the nominal load capacity is 53. 25 kN. Following precracking, the bottom surface of the concrete specimens is treated with sandpaper and cleaned, and a uniform bond surface is obtained for all the specimens. 120 mm × 1 450 mm CFRP sheets are bonded in the unloaded condition.

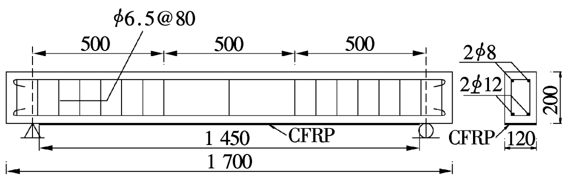

Fig. 2 Dimensions and reinforcing details for beams (unit: mm)

Following cure of the CFRP, the specimens are scheduled to be exposed to the wet-dry environment. Four beams are loaded with sustained four point flexural loads in the vertical orientation as illustrated in Fig. 3. The sustained loads provide an approximately 30% or 60% stress level of the initial ultimate load.

Fig. 3 Beams under sustained load and wet-dry saline water

After reaching 180 wet-dry cycles, the last conditioned specimens are allowed to dry out at room temperature for 7 d. Then all the beams are tested. Fig. 4 shows the schematic diagram of the test set-up. The data are recorded using the IMC digital data acquisition system powered and controlled by a PC via a USB port. The sampling rate of the data is 20 sample/s.

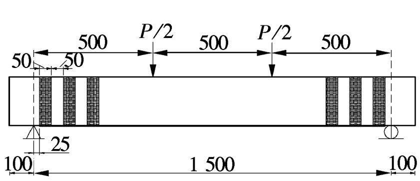

Fig. 4 Schematic diagram of the test set-up (unit: mm)

2 Environmental Effect on CFRP

The results of unconditioned CFRP and CF are listed in Tab. 1. As can be seen from Tab. 1, the CFRP exhibits higher tensile strength and strain compared with the fabric counterparts (CF), and the elastic modulus of the CFRP is close to the elastic modulus of the CF. This signifies that the resin has contribution to enhance the strength and strain of the CFRP composite, which is mainly due to the fact that the resin holds the fibers in place and transmits stresses between the fibers.

Tab. 1 Materials properties of CFRP and CF

Sample	Thickness/mm	Tensile strength/MPa	Elastic modulus/GPa	Ultimate strain/%
CF	0. 111	2 185(±6. 2%)	192. 326(±9. 5%)	1. 238(±7%)
CFRP	0. 111	4 331(±6%)	214. 438(±6%)	2. 062(±5. 4%)

Note: The value in parentheses is covariance.

The results of CFRP and CF for all of the wet-dry cycles are shown in Tab. 2. From Tab. 2, wet-dry cycles do not appear to affect the mechanical behavior of CF. However, the CFRP exhibits a declining trend in residual ultimate strength and strain. Reduction in tensile strength of the CFRP is 3. 1% and 5. 5% for the samples after 90 and 180 wet-dry cycles. The caused reduction of the CFRP is mainly due to the damage of the resin. Water absorption of resin can reduce the resin modulus, and form cracks at the fiber-resin interface, thus, decreasing the shear transfer of the fibers[11]. It is worth mentioning here that the elastic modulus of the CFRP has no significant deterioration exposed to wet-dry cycles. The reason may be that the resin has seldom contributed to enhancing the elastic modulus of the CFRP sheet, and the carbon fiber is not damaged under wet-dry cycles.

Tab. 2 The results of CFRP and CF under wet-dry cycles

Sample	Cycles	Tensile strength/MPa	Elastic modulus/GPa	Ultimate strain/%
CFRP	90	4 195(±3. 7%)	213. 804(±5. 9%)	1. 962(±5%)
	180	4 093(±2. 6%)	214. 531(±5. 1%)	1. 908(±4. 6%)
CF	180	2 193(±9%)	191. 826(±10. 3%)	1. 23(±4. 9%)

Note: The value in parentheses is covariance.

3 Environmental Effect on Beams

3. 1 Creep of conditioned beams

Fig. 5 shows the typical mid-span deflection versus time for the beam under sustained loads of about 30% and 60% of the initial ultimate load (beam BC180-30% and BC180-60%). It can be seen from Fig. 5 that the mid-span deflection is increased by 64% and 71% (the ratio of the change value during the first 14 to 180 d) during the first 14 d and then remained almost constant after 90 d for beam BC180-30% and BC180-60%, respectively.

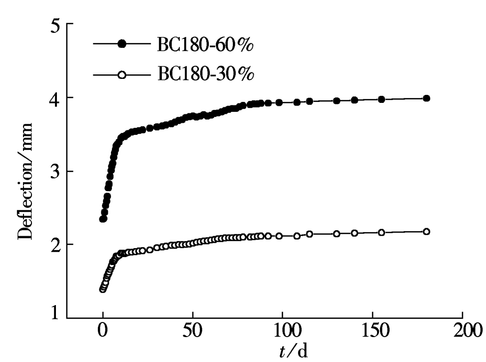

Fig. 5 Typical change in deflection under sustained load

3. 2 Failure characteristic

The failure of the reference beam is due to interfacial debonding induced by the intermediate flexural crack. The debonding initiates at an intermediate flexural crack and then propagates from such a crack towards the sheet end. Debonding occurs in the concrete substrate near the surface and the chunks of concrete are seen adherent to the CFRP sheet. A typical configuration after failure surface is shown in Fig. 6.

Fig. 6 Failure of controlled beam(BC0)

The failure of conditioned beams is also due to interfacial debonding induced by the intermediate flexural crack. However, the debonding failure modes are affected by the wet-dry cycles. Fig. 7 represents the failure surface of unstressed beams under 90 and 180 wet-dry cycles. The beam after 90 wet-dry cycles shows thin chunks of concrete adherent to the CFRP sheet, whereas it is noticed that the beam after 180 wet-dry cycles shows debonding along the interface between the adhesive and the concrete, none of the concrete is seen adherent to the CFRP sheet.

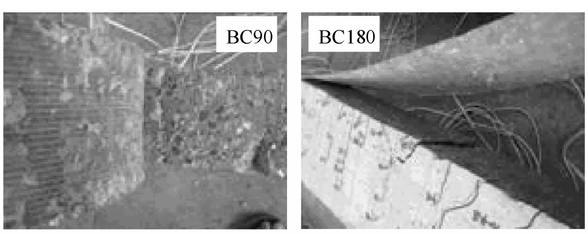

Fig. 7 Failure of beams under wet-dry cycles

Fig. 8 illustrates the observed failure surface of beams under 30% of initial load exposed to 90 and 180 wet-dry cycles. The beam after 90 wet-dry cycles shows small chunks of concrete adherent to the CFRP sheet. However, the failure of the beam after 180 wet-dry cycles is due to debonding along the interface between the adhesive and the concrete. The same debonding behavior is observed for the conditioned beams loaded at about 60% of the initial ultimate load, which is shown Fig. 9.

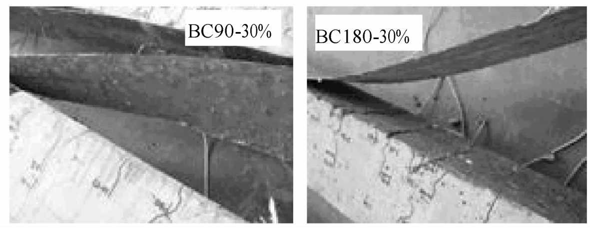

Fig. 8 Failure of beams under 30% of initial load and wet-dry cycles

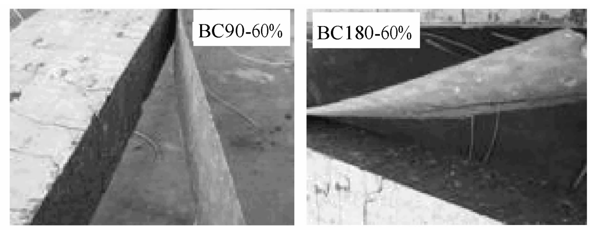

Fig. 9 Failure of beams under 60% of the initial load and wet-dry cycle

3.3 Load capacity

The test results of beam specimens for all the wet-dry cycles are shown in Tab. 3. The results include the peak load, the maximum mid-span deflection and the maximum measured CFRP sheet strain.

Tab. 3 The test results of beams

Beams	Precracking load/kN	Sustained load/%	Cycles	Ultimate load		Maximum deflection		Maximum measured CFRP strain		Failure mode
				F/kN	Change/%	δ/mm	Change/%	$\varepsilon_{frp}/10^{-6}$	Change/%	
B1				53.25		11.29				Steel yielding
BC0	38.14	0	0	65.75	0	13.39	0	7 808	0	BCF
BC90	38.20	0	90	64.73	−1.6	12.90	−3.7	7 120	−8.8	BCF
BC90-30%	38.20	30	90	63.86	−2.9	10.94	−18.3	6 913	−11.5	BCAF
BC90-60%	38.09	60	90	63.41	−3.6	12.66	−5.5	6 824	−12.6	BCAF
BC180	38.04	0	180	62.1	−5.6	12.90	−3.7	6 921	−11.4	BAF
BC180-30%	38.22	30	180	63.41	−3.6	11.89	−11.2	6 560	−16.0	BAF
BC180-60%	38.20	60	180	61.43	−6.6	11.94	−10.8	6 317	−19.1	BAF

Note: BCF refers to the failure mode of beams due to the debonding of CFRP in concrete substrate; BAF refers to the failure mode of beams due to the debonding of CFRP at the interface between adhesive and concrete; BCAF refers to the failure mode of beams due to the debonding of CFRP along the interface, associated with pulling adherent small chunks of concrete.

It is noticed that, with the number of wet-dry cycles increasing, all the conditioned beams display an obvious declining trend in the maximum measured CFRP strain, and show a more rapid decrease under the sustained load. This indicates that the combined action of wet-dry cycles and sustained loads causes severe degradation of the bond between CFRP and concrete. The degradation is also verified by the previous debonding characteristics of conditioned beams.

In order to interpret the environmental effects on the load capacity of the strengthened beams, an environmental degradation coefficient of enhanced efficiency is introduced. It is expressed as

$$C_E = \frac{(F_{ci} - F_0) - (F_{c0} - F_0)}{F_{c0} - F_0} = \frac{F_{ci} - F_0}{F_{c0} - F_0} - 1 \quad (1)$$

where F_{ci} is the ultimate load of conditioned beams strengthened with CFRP, F_0 is the ultimate load of unstrengthened beams, and F_{c0} is the ultimate load of unconditioned beams strengthened with CFRP.

Fig. 10 shows the relationships between C_E and wet-dry cycles. It shows that the strengthened efficiency of beams displays reduction with the increasing numbers of wet-dry cycles, and the presence of sustained loads accelerates this reduction. The results indicate that the combined action of wet-dry cycles and sustained loads causes severe degradation of the bond between CFRP and concrete and leads to an obvious decrease in the load capacity of strengthened beams.

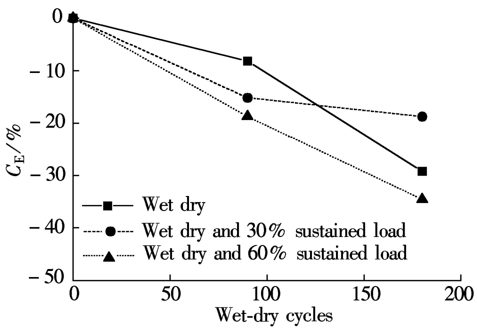

Fig. 10 Degradation coefficient C_E vs. wet-dry cycles

3.4 Load deflection behavior

Fig. 11 shows the relationships between the deflection at beam mid-span for strengthened and unstrengthened beams placed in the laboratory. The results show that there is about a 23.5% gain in the flexural strength of the beam as a result of attaching one layer of the CFRP sheet to the tension side of the beam. The gain in strengthened RC beams is not so high, which may be caused by the precrack of the RC beam. The presence of the damage in the RC beam can affect the strength of the RC beam strengthened with FRP. This was confirmed by Liu[12]. The results presented in Fig. 11 also show that a later stage of loading stiffness of the beam is enhanced due to the strengthening with the CFRP sheet.

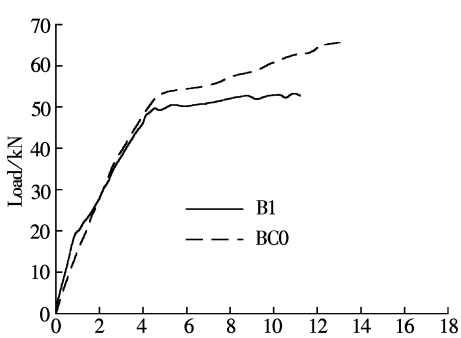

Fig. 11 Load-deflection relationships for controlled beams

Figs. 12, 13 and 14 present the load-deflection relationships for beams in unstressed states, loaded in 30% and 60% of the initial ultimate load exposed to wet-dry cycles, respectively. It is noticed that load deflection behaviors of conditioned beams are made almost the same as those of unconditioned beams. The stiffness of the strengthened beams is not affected by the individual action of wet-dry cycles or coupled action of sustained load and wet-dry cycles.

3.5 Mechanism analysis

In this experiment, the failure of all the beams strengthened with CFRP is due to intermediate flexural crack-induced interfacial debonding. When the failure of beams

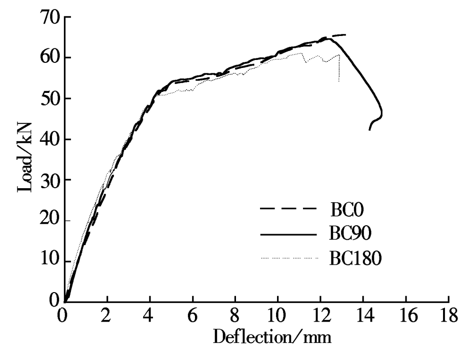

Fig. 12 Load-deflection relationships for unstressed beams

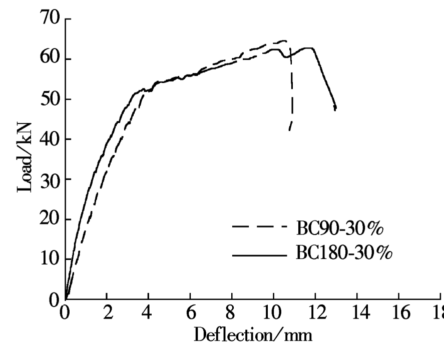

Fig. 13 Load-deflection relationships for beams loaded in 30% of the initial ultimate load

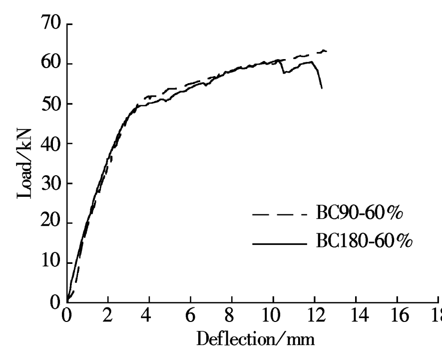

Fig. 14 Load-deflection relationships for beams loaded in 60% of the initial ultimate load

strengthened with CFRP occurred, the maximum measured CFRP strain of strengthened beams was less than 0.8%, which was smaller than the ultimate strain (1.9%) of the CFRP specimen after 180 wet-dry cycles. Moreover, wet-dry cycles had insignificant effects on the elastic modulus of CFRP specimens. Hence, it is believed that wet-dry environmental effects on CFRP do not reduce the enhanced efficiency of beams strengthened with CFRP.

When analyzing the debonding mechanism of the beams under wet-dry cycles, it is noticed that the debonding mechanism of beams is certainly different from that of the unconditioned beam. Debonding failure of unconditioned beam is mainly due to the tensile failure of the concrete, and the chunks of concrete are seen adherent to the CFRP sheet. However, in the case of wet-dry cycles, swelling and hydrolysis of the adhesive occurs due to water absorption, giving rise to stress and microcracking at the interface and it then can form microcracking at the interface between the adhesive and the concrete[11,13]. This leads to the decrease in the interface shear strength between the adhesive and the concrete. When the interface shear strength is less than the tensile strength of the concrete, debonding failure occurs at the interface between the adhesive and the concrete, and none of the concrete is adhered to CFRP sheet.

If the strengthened beam is subjected to sustained loads and wet-dry cycles, the degradation of the interface bond between the adhesive and the concrete can be more pronounced. Because loading the samples may cause some microcracking at the interface, this cracking will accelerate moisture diffusion and significantly weaken the interface's shear strength. When comparing the samples conditioned with and without sustained load, the sample which is loaded generally has a lower load capacity and a lower maximum measured CFRP strain at a given number of wet-dry cycles, and shows a rapid decrease in the maximum measured CFRP strain with an increasing number of wet cycles. It indicates that the coupled action of sustained loads and wet-dry cycles has a significant effect on interface bonds between the adhesive and the concrete.

4 Conclusions

This paper presents the results of the durability of pre-cracked concrete beams strengthened with CFRP sheets subjected to wet-dry cycles and sustained loads. Based on the test results, the following can be concluded:

1) Wet-dry environmental effect on CFRP does not reduce the enhanced efficiency of beams strengthened with CFRP for the time period (180 d) in this study.

2) The coupled action of wet-dry saline water and sustained bending stresses has a more significant effect on the bond between concrete and CFRP.

3) The coupled action of wet-dry saline water and sustained bending stresses appears to significantly affect the load capacity of strengthened beams. However, the stiffness of strengthened beams is not affected by wet-dry saline water combined with sustained bending stresses for the time period in this study.

4) The debonding failure mode for the beams is affected by wet-dry cycles combined with sustained loads.

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干湿交替与荷载作用下 CFRP 加固混凝土梁的耐久性

李 杉 任慧韬 黄承逵 崔云飞

(大连理工大学海岸和近海工程国家重点实验室,大连 116024)

摘要:对 8 根持载与恶劣环境作用后的碳纤维增强聚合物(CFRP)加固混凝土梁进行了试验研究. 梁的尺寸为 1 700 mm × 120 mm × 200 mm. 首先采用 4 点分加载方式对梁进行预裂,卸载后粘贴 CFRP 片材,然后放入腐蚀环境. 影响因素考虑了干湿交替与持载水平(持载水平分别为 30% 和 60% 混凝土梁极限荷载). 分析了干湿交替单一因素和荷载与干湿交替双重因素对 CFRP 加固梁的长期性能. 试验结果表明:荷载与干湿交替双重因素对 CFRP 加固梁的承载力和破坏形态影响较大,这主要是由于 CFRP 与混凝土界面的劣化引起;对 CFRP 加固梁的刚度几乎没有影响.

关键词:钢筋混凝土梁;加固;碳纤维增强聚合物(CFRP);耐久性;干湿交替;持载

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