Durability of carbon strand sheet to concrete bond interface under moisture condition

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ABSTRACT: In this study, pull-off bond tests and four-point bending tests are performed for carbon strand sheet (CSS) strengthened concrete beams, to evaluate the short and long-term performance of CSS/concrete interfaces. The focus is on the influences of highly moist climate during FRP implementation and the following service period. It is found that high R.H. in air during the curing of bond lines has a marginal effect on the bond performance of the CSS/concrete interfaces. However, if the concrete substrate is wet before bonding the shear failure of the CSS/concrete interface will shift into the primer/concrete interface or a very thin mortar layer, which is different from the conventional failure mode observed in a dry substrate case. Fortunately, use of a hydrophobic type of primer can prevent the interfacial bond line from the tensile strength loss caused by the wet substrate. For the CSS/concrete interfaces that have been subjected to an 8-month accelerated cyclic dry/wet exposure, microscopic observations reveal that micro-cracks are formed at the primer/concrete interface during the exposure and lead to a significant loss of the interfacial pull-off bond strength. On the other hand, flexural tests on the CSS strengthened concrete beams indicate interestingly that the shear bond force transfer capacity of the CSS/concrete interfaces does not decrease while the interfacial bond deformability increases greatly after the exposure. The critical problem is the moist-induced shear stiffness loss. These above experimental findings provide useful information for predicting the service-life performance of CSS strengthened concrete members under a cyclic moist climate.

KEYWORDS: Carbon strand sheet, concrete, moisture, dry/wet cycling, bond, epoxy

1 . INTRODUCTION

Use of fiber reinforced polymer (FRP) sheets for upgrading existing concrete structures has gained worldwide popularity over the past decade. The technology is particularly attractive for marine environment applications because FRP has immunity to corrosion, and in the meantime, as a coating layer it can prevent chloride ions from penetrating into internal concrete. Up to now, however, there have had very few practical applications of this technology for upgrading port concrete structures in Japan. One considerable reason is that the durability remains uncertain at the FRP sheet/concrete bond lines under such kind of environment. For marine environment, both highly moist condition (humid or wet concrete substrate) during the FRP installation and cyclic dry/wet actions during the service period possibly deteriorate the interface bond lines and consequently ruin the integrity of the upgraded system.

There were several research which studied the Mode I or/and Mode II fracture toughness of FRP/concrete interfaces focusing on the presence of water (Wan et al. 2006), internal moisture concentration (Au & Buyukozturk 2006), and dry/wet cycling using sodium-hydroxide solution (Davalos et al. 2005). Sen et al. (1999) applied pull-off bond test and shear torsion bond test to evaluate the bond degradation of the FRP/concrete interfaces under various exposure conditions and concluded that the dry/wet cycle is the most severe factor leading to bond degradation. Myers & Ekenel (2005) applied similar tests to evaluate the effects of construction environment on the bond strength and concluded that R.H higher than 82% and a surface moisture reading higher than 4.3% may exhibit poor bond performance. Toutanji & Gomez (1997) and Grace (2004) reported that the load-carrying capacity of FRP strengthened members exposed to wet-dry cycling and 100% humidity decreased as compared to the specimens kept under normal climate.

In summary, it has been generally recognized that the moisture absorption deteriorates the FRP/concrete interfaces. However, the issue of how to achieve a durable bond under moisture environment and how to predict its service-life performance remains unclear. The objective of this study is to investigate both short-term and long-term bond performance of a new bonding system using carbon strand sheets (CSS). Influences of the highly moist concentration during CSS implementations and the following service period will be focused on for investigations.

2 EXPERIMENTAL PROGRAM

2.1 *Test materials and specimens*

Concrete was cured for one month after being placed and had the compressive strength of 33.7MPa at testing time. Before bonding CSS, concrete surfaces were prepared with two conditions: dry and wet. The dry surface had the average surface moisture readings of 4.2%. The wet concrete surface was prepared by immersing the concrete into water for three days and then removed the surface water immediately before bonding CSS. At the time the corresponding average moisture reading was 9.0%. Two types of primers including a conventional type FP-NS and a hydrophobic type FP-WE7 were used. Also, two types of bonding adhesives, FR-E3P and CN-100, were applied for bonding the CSS to concrete. FR-E3P is a popular epoxy with a linear property and has an elastic modulus of 2.41GPa. CN-100 is a non-linear epoxy and has an elastic modulus of 0.39GPa.

Two types of tests, flexural test (see Fig.1) and pull-off bond test (see Fig.2), were applied to evaluate the interfacial shear bond and tensile bond performance, respectively. Fig.1 presents the dimensions of CSS strengthened concrete beams for the flexural tests. As seen in Fig.1 CSS is a new type of carbon fiber sheet, in which fibers are pre-cured to strands and then the strands are woven in a sheet form. The authors' previous study (Dai et al. 2007) has proved the superiority of the CSS compared to the conventional carbon fiber sheets. The current study will focus on the durability of CSS to concrete bond. As summarized in Table 1, in total 30 CSS strengthened concrete beams belonging to two groups, B-x-x and B-x-x-x, were prepared to study the influences of moist climate on the short-bond performance during FRP installation as well as on the long-term bond performance during the following service life. Test variables included preconditioned moisture in concrete substrate (dry/wet) , relative humidity (R.H) (48% and 90%) during bond curing, type of primer (FP-NS and FP-WE7), type of bonding adhesive (FR-E3P and CN-100), and period for cyclic dry/wet exposure (0 and 8 months). As indicated in Table 1, besides the flexural tests, pull-off bond tests were conducted for four testing series, which had different types of primers and different concrete substrate conditions.

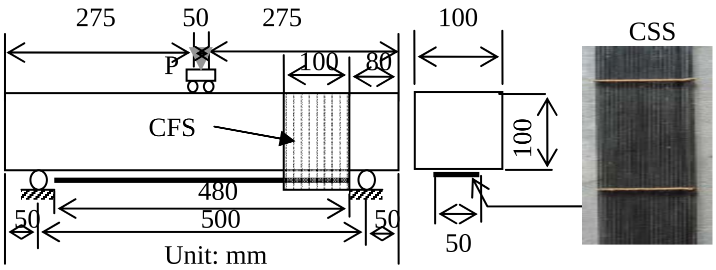


Figure 1. Flexural tests for CSS strengthened concrete beams.

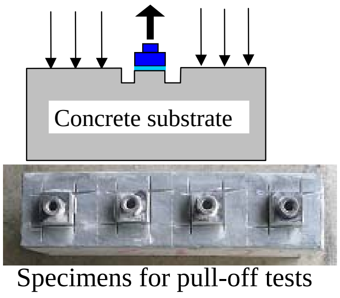


Figure 2. Pull-off bond test.

Table 1. Information of testing specimens.

Test code	Primer	Bonding adhesive	Sub-strate	Curing R.H (%)	Expo-sure period	Flexural bond test			Pull-off bond	
						P_{max} (kN)	δ_{max} (mm)	Failure mode	$\sigma_{t,inter}$ (MPa)	Failure mode
B-1-1	FP-NS	FE-Z	Dry	48%	0	18.3	2.52	A	3.73**	A
B-1-2						18.6	2.84	A		
B-1-3						19.8	2.95	A		
B-2-1	FP-WE7	FE-Z	Dry	48%	0	24.3*	4.01	*	N.A	N.A
B-2-2						17.5	3.15	C		
B-2-3						19.8	3.08	C		
B-3-1	FP-NS	FE-Z	Wet	48%	0	16.2	2.22	B	N.A	N.A
B-3-2						15.3	2.53	B		
B-3-3						14.7	2.23	B		
B-4-1	FP-WE7	FE-Z	Wet	90%	0	18.2	2.56	B	N.A	N.A
B-4-2						17.8	2.77	B		
B-4-3						17.3	2.69	B		
B-5-1	FP-NS	FE-Z	Dry	90%	0	17.5	3.39	B	N.A	N.A
B-5-2						19.3	2.83	B		
B-5-3						17.5	2.41	B		
B-6-1	FP-WE7	FE-Z	Wet	48%	0	18.3	2.95	B	4.17**	A
B-6-2						18.0	3.17	B		
B-6-3						16.5	2.16	B		
B-7-1	FP-WE7	CN-100	Wet	48%	0	26.8	4.23	C	N.A	N.A
B-7-2						27.7	4.92	C		
B-7-3						17.3*	2.65	*		
B-1-1-1	FP-NS	FE-Z	Dry	48%	8 months	17.3	9.68	B	2.31**	A/B
B-1-1-2						18.7	9.33	B		
B-1-1-3						18.7	9.33	B		
B-6-1-1	FP-WE7	FE-Z	Wet	48%	8 months	25.4	12.7	A/B/C	2.42**	A/B
B-6-1-2						22.6	12.38	A/B/C		
B-6-1-3						23.6	11.37	A/B/C		
B-7-1-1	FP-WE7	CN-100	Wet	48%	8 months	22.1	16.32	A/C	N.A	N.A
B-7-1-2						21.6	12.80	A/C		
B-7-1-3						22.4	10.05	A/C		

Note: P_{max}, δ_{max} = the flexural capacity and mid-span deflection of CSS strengthened concrete beams at the ultimate state; $\sigma_{t,inter}$ = interfacial pull-off tensile strength. *: excluded in discussion because of its big deviation from the other two tests in the same test series; **: average of four tests; A: concrete substrate failure; B: primer/concrete interface failure; C: primer/adhesive interface failure.

2.2 *Exposure climate*

Two curing conditions (48% R.H and 90% R. H) were applied for CSS bonding as indicated in Table 1. After two-week bond curing under an average room temperature of 10°C., Series B-x-x were performed bond tests while the remaining Series B-x-x-x were subjected to an accelerated cyclic dry/wet exposure for eight months and then performed bond tests. Each dry/wet cycling consisted of a 4-day submergence period in 60°C sea water and a 3-day dry period in air.

3 TEST RESULTS AND DISCUSSIONS

3.1 *Pull-off bond test results*

Figure. 3 shows the failed planes of CSS/concrete interfaces at the CSS side before (the left two pictures) and after the cyclic dry/wet exposure (the right two pictures). After the exposure, the pull-off bond failures were mainly observed at the primer/concrete interface regardless of the type of primer used. The weakness at the primer/concrete interface was also confirmed through microscopic observations on the sectional profiles of CSS/concrete interfaces (see Fig. 4) after the exposure but before bond tests. In a sound CSS/concrete interface without any experiences of exposure, these defects also existed but number was very limited. During exposure, these micro-cracks were frequently formed and propagated due to the material incompatibility at the primer/concrete interface during the reversed moist attacks.

Figure 5 presents the pull-off bond strengths of tested CSS/concrete interfaces. It is shown that test series of B-1-× and B-6-× had the similar interfacial pull-off bond strengths although their initial moist conditions (dry/wet) in concrete substrates before bonding were different. The applicability of the hydrophobic type primer FP-WE7 for the wet concrete surface had been confirmed although there were slight differences in the pull-off failure modes between the dry substrate and wet substrate cases (see the left two pictures in Fig.3), Therefore, the initial moisture concentration in the concrete substrates before bonding may not be a severe concern if only an appropriate primer material is selected. Usually, the water absorption property of a primer is important for a successful wet substrate application. If the primer is hydrophilic, the primer will absorb water before it is cured. As a consequence, the mechanical property of primer layer will be damaged. So a hydrophobic primer is needed for a wet substrate. Unfortunately, it was observed that even use of a hydrophobic primer could not prevent the pull-off bond strength loss during the cyclic dry/wet exposure. In both dry (see B-1-1-× series in Fig.5) and wet (see B-6-1-× series in Fig.5) concrete substrates cases, the interfacial tensile bond strength decreased greatly after the 8-month exposure regardless of the type of used primer. The hydrophobic primer FP-WE7 could resist the water absorption during CSS installation and prevented the short-term bond strength loss. The primer/concrete interface, however, still was the weakest link under cyclic moist attacks. There is a necessary to develop improved surface impregnating techniques to keep the long-term bond integration at the concrete/primer interface when the bonding system is exposed to cyclic moist attacks.

3.2 *Flexural test results of CSS strengthened beams before exposure*

Figures.6.a-b present the flexural capacities and the mid-span deflections of CSS strengthened beams without any exposures. Both the average of three tests characterized with the same variables and the scatter are presented. It can be seen that, except B-3-× and B-7-× series, all the other testing series exhibits the similar values. Since the flexural performance of CSS strengthened plain concrete beams reflects directly the shear bond performance of the CSS/concrete interfaces, it can be concluded that the curing R.H varying from 48% to 90% did not influence the short-term shear bond performance of the CSS/concrete interfaces (see B-1-× and B-5-×, B-4-× and B-6-× series in Figs.6.a-b). A mis-operation of the conventional primer on the wet substrate (B-3-× series), however, caused about 20% loss of the flexural strength compared to the dry substrate case (B-1 series). The hydrophobic primer FN-WE7 proved its efficiency in both dry and wet concrete substrates cases (see B-2-× and B-4-× series in Fig.6). Once the primer is


dry substrate (FP-NS) wet substrate (FP-WE7) dry substrate (FP-NS) wet substrate (FP-WE7)

Figure 3. Pull-off bond failure modes of CSS/concrete interfaces.

Figure 4. Microscopic observation on the interface bond

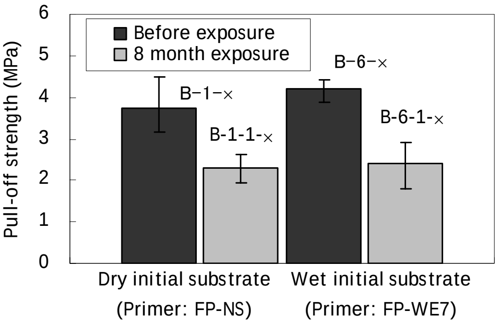
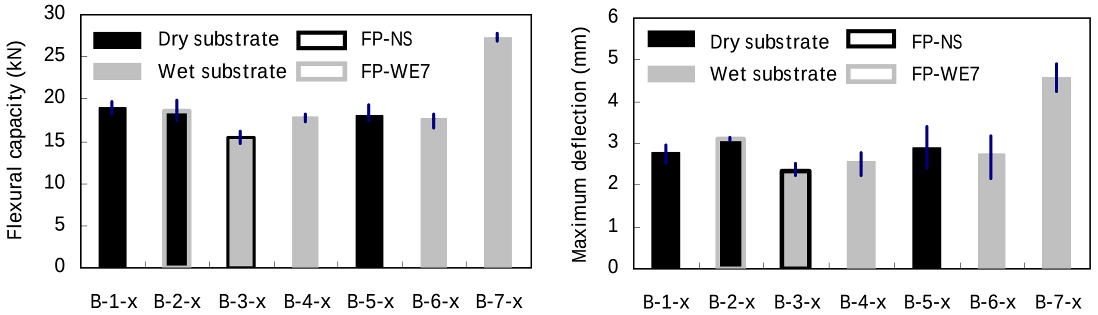


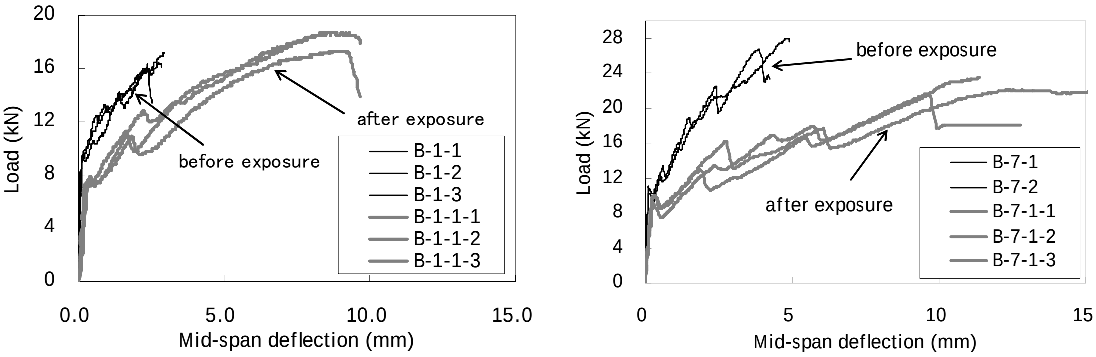
Figure 5. Pull-off bond strength

appropriately selected, it seems that the most important factor influencing the shear bond strength of CSS/concrete interfaces will be the elastic modulus of bonding adhesives. Series B-7-×, in which the low-elastic modulus adhesive CN-100 was used, achieved a flexural capacity of about 45% higher than that in the normal bonding adhesive case (B-1-× series) even though the initial concrete substrate for bonding in B-7-× series was wet. In summary, the moist conditions inside or outside the concrete substrates during the CSS installation possibly influence the short-term bond performance of the CSS/concrete interfaces as reported previously by other researchers. However, these negative effects can be successfully suppressed by selecting appropriate bonding materials.



(a) Strength performance (b) Deformation performance

Figure 6. Effects of construction moisture and bonding material on the CSS/concrete interface shear bond

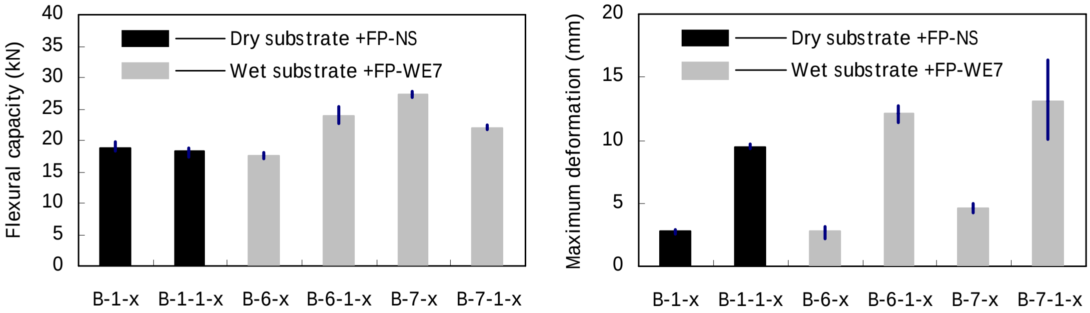


(a) Dry substrate + FP-NS (b) Wet substrate +FP-WE7

Figure 7. Load-deflection curves of CSS strengthened concrete beams.

3.3 *Flexural test results of CSS strengthened concrete beams after cyclic dry/wet exposure*

Figures. 7.a-b compare the typical flexural load versus mid-span deflection curves of CSS strengthened concrete beams before and after the 8-month cyclic dry/wet exposure. The linear ascending branches of all the cures are not influenced by the cyclic dry/wet exposure (see B-1-x and B-1-1-x in Fig.7.a, B-7-x and B-7-1-x in Fig.7.b). This is understandable because the strength and stiffness of concrete are hardly influenced by the dry/wet cycling. However, after the cracking of concrete, the flexural stiffness of CSS strengthened concrete beams that experienced dry/wet cycling decreases significantly, indicating a significant degradation of the interfacial shear bond stiffness. On the other hand, the member deformability at the ultimate debonding failure increases significantly. Figs.8.a-b present the flexural capacities and the maximum mid-span deflections in all the CSS strengthened beams, respectively. Different from the pull-off bond strength, the flexural capacity of CSS strengthened beams showed a slight increase after exposure if comparing Series B-1-× and B-1- 1-× in Fig.8.a. It is considerable that the cyclic dry/wet exposure had induced micro-cracks at the primer/concrete interface and resulted in the degradation of the interfacial bonding stiffness. However, this bonding stiffness decrease might increase the effective bond length of the CSS/concrete interface and result in an increase of the interfacial bond force transfer capacity (Dai et al. 2002). If the interfacial bonding stiffness was already low at the beginning, then the flexural capacity of strengthened beams would decrease after exposure (see B-7-× and B-7-1-× in Fig.8.a). Therefore, there may have a threshold number of dry/wet exposure cycles, until which the interfacial shear bond capacity may show slight increases due to the decrease of the interfacial bonding stiffness. A continuous exposure further to this will eventually lead to the loss of the interfacial shear bond capacity. Different from the interfacial shear bond capacity, the interfacial bonding stiffness always decreases and the interface deformability always increases with the increase of dry/wet cycles (see Fig.8.b).



(a) strength performance (b) deformation performance

Figure 8. Effects of dry/wet cycling on the CSS/concrete interface shear bond.

4 CONCLUSIONS

(1) Moisture inside or outside concrete substrate during CSS installations may influence adversely the bond performance of CSS/concrete interfaces. However, these adverse effects can be minimized through an appropriate selection of bonding materials.

(2) Microscopic observations indicate that a cyclic dry/wet exposure may cause micro-cracks at the primer/concrete interface. As a result, the interfacial tensile strength and the shear bond stiffness degrade significantly after an eight-month accelerated cyclic dry/wet exposure.

(3) Different from the interfacial tensile strength, the shear bond strength of CSS/concrete interfaces seems not always to decrease with the increase of dry/wet cycles. There may have a threshold number of the dry/wet cycles beyond which the shear bond strength will start to degrade. This threshold number may depend on the initial elastic modulus of bonding adhesives.

(4) There is a necessity to conduct dry/wet exposure tests with longer durations in order to simulate the whole service-life bond performance of CSS/concrete interfaces under cyclic moist attacks. In addition, the interfacial bonding technology needs to be improved so that the deterioration at the primer/concrete interface can be prevented under such kind of environment.

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