DURABILITY OF CFRP-CONCRETE BONDING IN A MARINE ENVIRONMENT

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Abstract

This paper presents the feasibility of CFRP installation in a tidal zone and its durability in a marine environment. Field research tests were conducted to evaluate the bond performance of FRP to concrete substrate. CFRP were applied on a concrete quay wall and bridge abutment in two different zones, dry and tidal zones, and pull-off tests were conducted to measure the bond strength eight months after the bonding. Results of bond strength in the tidal zone are compared to those in the dry zone which were not subjected to wet/dry cycles.

1. Introduction

The majority of French coastal structures aged over 50 and are subjected to many environment conditions such as chemical, mechanical or biological attacks. As a result, severe deteriorations to structural elements have taken places, and repair and strengthening need to be done to maintain the structures throughout their lifespan. Different repair techniques have been used such as shotcrete, hand placement. However, the light weight, high strength and corrosion resistance of carbon fiber-reinforced polymers (CFRP) make them ideally suited for quick and effective structural repair. CFRP have been increasingly used for the repair of concrete elements, yet the applications have mostly been done under dry conditions. The application in a marine environment has been so far minimal, and little information is known about the effect of environment during the installation on the performance of the bond between CFRP and concrete. The objective of this research is to study the feasibility of CFRP installation in a tidal condition and its durability in a marine environment. Field research was conducted to evaluate the bond performance of CFRP to concrete substrate. In a field research, CFRP were applied on concrete walls at Dunkerque Port in two different zones, dry and tidal zones, and pull-off tests were carried out to evaluate the CFRP/concrete bond eight months following exposure.

1.1 Concrete deterioration

Many structures in a marine environment such as bridges, quays, dikes and oil platforms are made of concrete. The concrete can be subjected to different types of attacks, chemical, physical or biological [1-2], (Figure 1). According to its position with respect to seawater, concrete can be in above seawater, under seawater, or in a tidal zone. Tide is the difference between the high and low water levels. It's the zone in which the concrete deterioration is the most serious because it is subjected to various mechanisms. It is subjected to wet/dry cycles giving a high level of chloride penetration, which leads to spalling of concrete. Attack caused by freezing/thawing in cold regions also occurs in this zone. In addition, it undergoes abrasion from sands or debris carried by seawater. The alternation motion of waves and tides is also one of the causes of concrete deterioration. Besides, the concrete can be deteriorated by the living organisms such as mollusks that root the structure and increase the structures load.

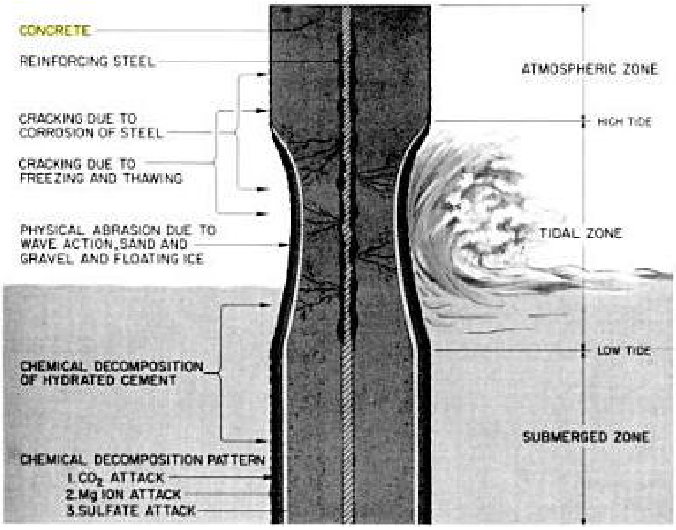

Figure 1: Deterioration mechanisms of concrete in a marine environment [2]

1.2 Repair techniques

Different techniques have been used to repair structures in a marine environment. Initially, hand placement was used to repair spalled concrete. For large repair projects, the use of shotcrete is preferred [1]. If the deteriorations occur in the submerged zone of the structure, pumping concrete or freely falling concrete are used. Another technique called "pile jacket" are often used to repair damaged pile. The disadvantages of these techniques are the problem related to durability, corrosion, cost, and the need for qualified workmanship. Recently, composite materials are widely used for repair or strengthening building structures, but their application in a marine environment or even in conditions representing that environment is very limited.

2. Recent researches

Little information is known about the environmental effect during composites application on the performance and adhesion between carbon fiber reinforced polymer (CFRP) and substrate. Myer and Ekenel [3] studied the influence of different concrete surface moisture, relative humidity, and temperature during CFRP installation on the bond strength between concrete and FRP. The tests were conducted in laboratory. It was found out that specimens strengthened with a concrete surface moisture content of 5.05 % resulted in poor bond behavior, however; those strengthened with concrete surface moisture below 4.3% exhibited satisfactory bond performance.

Seica and Packer [4] conducted a laboratory test on the feasibility of underwater confinement of tubular steel beams with composite materials. Seven tubular steel beams were tested under 4-point bending. Two principal parameters were studied: the influence of fibre/epoxy manufacturer and the curing condition of the matrix (underwater and in air). The beams wrapped and cure underwater were not able to attain the flexural capacity of those cured in air.

Sen and Mullins [5] conducted an in-situ repair of piles in tidal zone and underwater by using 2 different types of reinforcement: pre-preg (system A) and wet layup (system B). Pull-off tests were conducted on two different levels of the piles: the top part (dry region) and bottom part (tidal region) two years after the wrapping had been completed. Result showed that the bond of FRP to the concrete is poor. Most of the piles wrapped with wet layup system showed epoxy failure, and those wrapped with pre-preg showed inter-layer failure. In addition, residual bond strength isn't uniform. System B performed better in wet region, while system B performed better in dry region. Specimens tested in laboratory didn't show this difference. This difference comes from the field technique used for wrapping, the inability to maintain the same contact pressure between FRP and the concrete along the repaired piles [6].

Mullins et al. [6] developed a method for enhancing an adhesive bond for underwater repair of piles by FRP. The technique is based on maintaining a positive, constant and uniform pressure over the length of the wrapped surface. This pressure will force the resin to penetrate through the concrete pores and expel entrapped air, water or excess resin. This way, the fibers and resins have an intimate contact with the concrete.

3. Expérimental set up

Our study focuses on the feasibility of CFRP installation in a tidal condition and its durability in aggressive environments. Carbone laminates and carbon fabrics were bonded on two structures in two different experimental fields: a quay wall in a marine environment, and a bridge abutment in a river environment, both located at Dunkerque Port, at the North part of France. The marine environment has a tidal variation of about 6 m. The bridge in the river environment is locked in flood locks, and the tidal range doesn't vary so much. In both structures, the CFRP were applied in two different zones, dry and tidal zone.

3.1 Materials

Two types of CFRP systems were chosen for this study: carbon laminate and carbon fabrics. The laminates are prefabricated FRP, with a thickness of 1.2 mm and a width of 50 mm. Two types of epoxy-based adhesives associated with the two types of reinforcements were used. The characteristics of the reinforcements and the adhesives are given in tables 1 to 3.

The laminates were cut to a length of 30 cm. They were simply cleaned with a solvent to remove grease and dust. Six laminate specimens were bonded on each structure in two different zones. The fabrics were cut into a sheet of 20 cm x 30 cm. Similarly, six fabric specimens were bonded on each structure in two different zones (Figure 2). Pull-off tests are to be carried out six months after CFRP had been bonded, and every six months within three years.

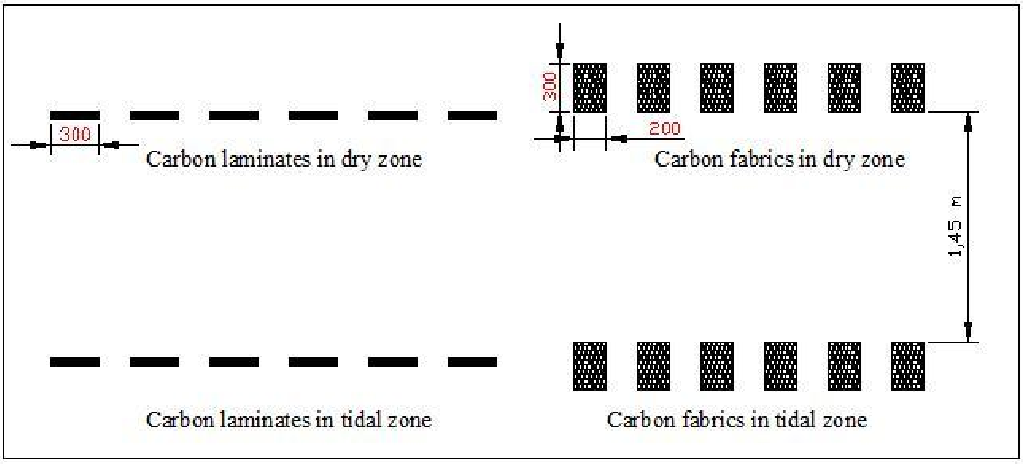

Figure 2: Details of CFRP bonding on the quay wall in the marine environment

Description	Carbon laminates	Carbon fabrics
Modulus of elasticity [GPa]	> 165	> 230
Tensile strength [MPa]	> 2800	> 3500
Elongation at break [$^{0}/_{00}$]	> 17	> 15

Table 1: Characteristics of the reinforcements

Description	Characteristics
Modulus of elasticity [MPa]	12 800
Flexural strength[MPa]	≥ 30 for 2 days at 20°C
Bond strength [MPa]	≥ 4 (break in the substrate)

Table 2: Characteristics of the adhesive for bonding carbon laminates

Description	Characteristics
Flexural modulus [MPa]	3 800 for 7 days at 23°C
Compressive strength [MPa]	≥ 55 for 2 days at 20°C
Tensile strength [MPa]	≥ 30 for 2 days at 20°C

Table 3: Characteristics of the adhesive for bonding carbon fabrics

3.2 CFRP application

3.2.1 Surface preparation

Special care must be taken for the preparation of the concrete substrate. The surface on which the CFRP are to be bonded must be cleaned; any parts not being able to adhere firmly must be eliminated. In a marine and river environment, this implies removal of all marine growth. In this study, the surfaces were pressured washed (Figure 3).

Figure 3: Surface preparation using pressured washed

Figure 4: Bonded carbon fabric specimens on a quay wall in the marine environment

3.2.2 CFRP application

The application of the carbon laminates was done by double bonding. A thin layer of adhesive was applied on the prepared concrete surface and on the laminate. The laminate is applied manually on the concrete and pressed with a pressure roller to expel air voids and to remove any excess adhesive from the edge of the laminate. The carbon fabrics were applied using a wet-layup procedure by applying an adhesive layer on the concrete substrate, and carefully impregnate the fabric with a pressure roller so as to obtain a homogenous surface (Figure 4).

3.3 Pull-off test

Pull-off test is used for bond verification between an adhesive and a substrate. The test was carried out in agreement with ASTM D 7522/D 7522M [7]. This method consists in bonding a dolly to the CFRP surface and applying a direct tensile force with a dynamometer as shown in Figure **5**. The applied force increase progressively until the dolly is detached. The pull-off strength is measured and the failure mode is noted.

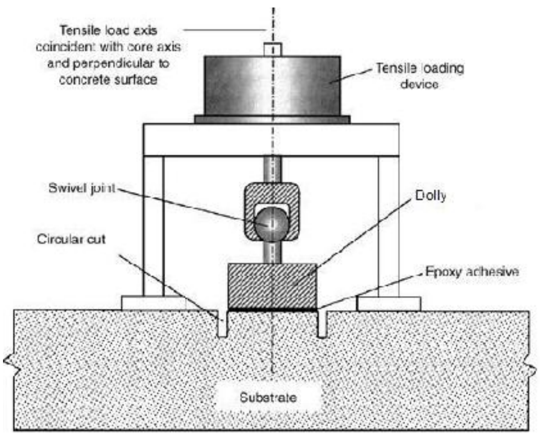

Figure 5: Pull-off experimental set-up

In this study, the dollies with dimensions of 50 mm x 50 mm were used. Before bonding the dollies with an epoxy-based adhesive, the CFRP surfaces (laminate and fabrics) were scratched to remove any marine growth and then cleaned with a solvent. The pull-off tests were carried out after the adhesive were cured. In each zone, five tests were conducted for each system, thus 20 tests per site/environment. In total, 40 tests were conducted. Figure 6 shows the carrying out of the pull-off test.

Figure 6 : Pull-off test: (a) on the quay wall, and (b) at the bridge abutment

4. Results and discussion

Pull-off tests were carried out eight months after the CFRP had been bonded. Results are given in Table 4**.** Two failure modes were observed: 1) concrete failure, and 2) failure due to debonding of the dollies.

Environment	Material	Zone	Force (kN)	Strength (MPa)	Failure mode
Marine	Laminate	Out of water	6,84	2,74	Dolly/laminate interface
Marine	Laminate	Tidal	5,73	2,29	Dolly/laminate interface
Marine	Fabric	Out of water	5,54	2,22	Concrete
Marine	Fabric	Tidal	4,64	1,86	concrete
River	Laminate	Out of water	7,24	2,90	Dolly/laminate interface
River	Laminate	Tidal	6,59	2,64	Dolly/laminate interface
River	Fabric	Out of water	6,79	2,71	Dolly/fabric interface
River	Fabric	Tidal	7,12	2,85	Dolly/fabric interface

Table 4: Results of the pull-off tests in the two environments

4.1 Quay wall in a marine environment

Figure 7 shows pull-off strengths of the CFRP bonding on a quay wall in a marine environment, their standard deviations are also indicated in the figure. The average strength of the carbon laminates and carbon fabrics in the tidal zone are 2.29 MPa and 1.86 MPa respectively. Compared with the reference values in the dry zone, we observe that the pull-off strength of the laminate and tissue decreased by 16% in the tidal zone. It is to be noted that the strengthening processes were conducted in a real in situ condition at low tide, the carbon laminates and fabrics were subjected to high tide's arrival immediately a few hours after the bonding had been completed. The decrease in the strength could possibly due to, on one hand, the disturbance of the adhesive polymerization caused by wet/dry cycles, and on the other hand, environment exposure.

In the laminate system, the failure mode occurred at the dolly/laminate due to debonding of the dolly, see Figure 8a. As for the fabric system, the failure occurred in the concrete (Figure 8b) for almost all of the tests.

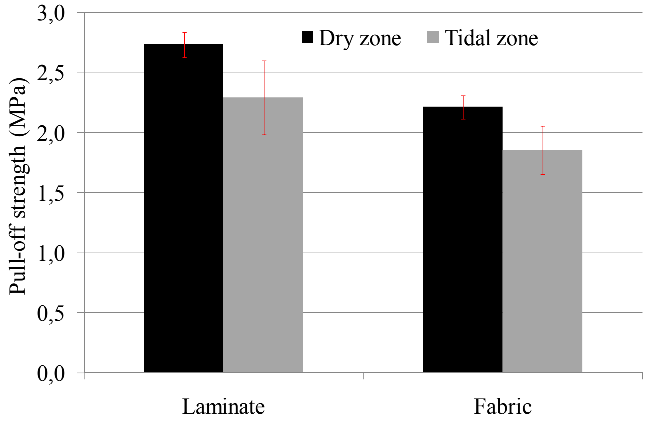

Figure 7: Pull-off strengths of FRPs after eight months exposure in a marine environment

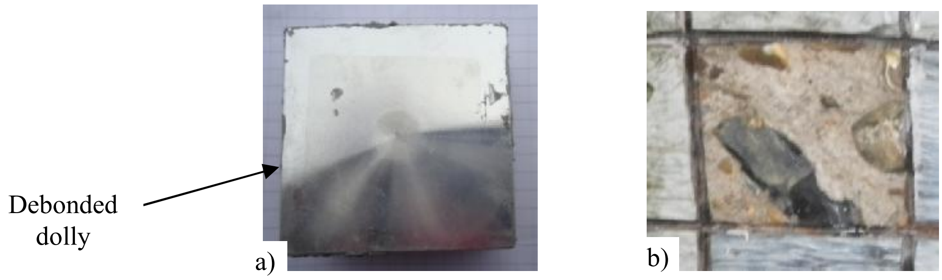

Figure 8: Different failure modes: (a) at the dolly/laminate by dolly debonding, and (b) in the concrete

4.2 Bridge abutment in a river environment

The bridge is locked in flood locks and the tidal range doesn't vary so much. The average pull-off strengths of the two CFRP systems are given in Figure 9. The pull-off strengths of the laminates in a tidal zone are 9% inferior to those in a non-submerged zone. The pull-off strengths of the fabrics in both zones are relatively close. The failures occurred at the dolly/laminate or dolly/fabric interface due to debonding of the dolly.

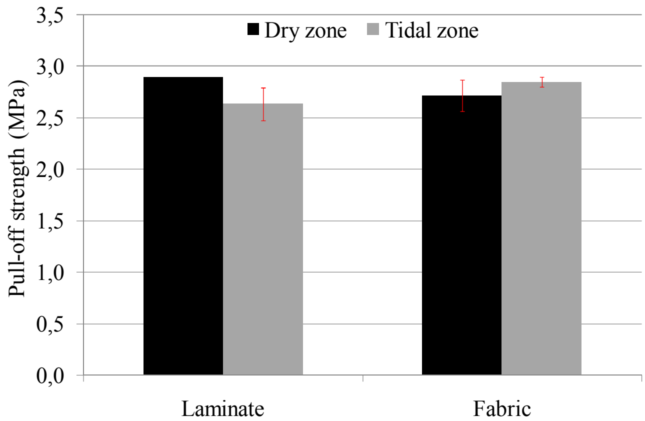

Figure 9: Pull-off strengths of FRPs after eight months exposure in a river environment

In most of the cases, the failures occurred at the dolly/laminate or dolly/fabric interfaces by debonding of the dolly. According to ASTM D 7522/D 7522M, this is due to the insufficient time for polymerization or the use of inappropriate adhesive for bonding the dollies.

Figure 10 compares the difference in performance between the two reinforced systems in the marine and river environment. It is shown that the pull-off strengths of all the CFRP bonded in the river environment are greater than those in the marine environment. Given that the compressive strengths of the concrete of the two structures are the same, one could say that exposure to the marine environment is more aggressive than in the river environment.

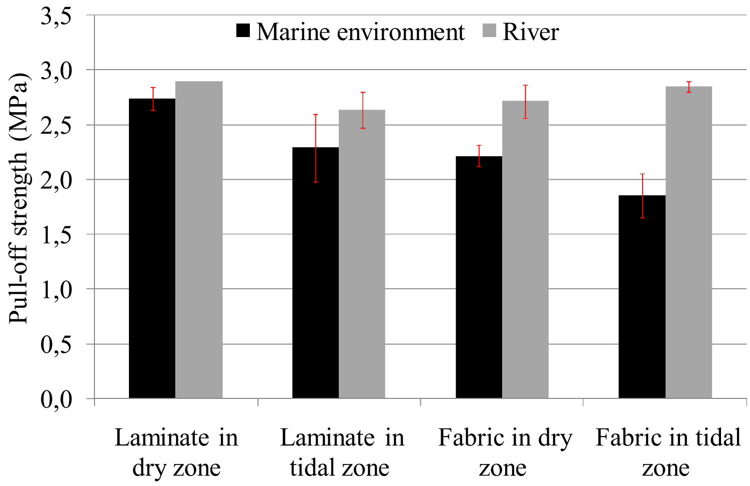

Figure 10: Comparison between marine and river environment

5. Conclusion

Application and durability of CFRPs in different environments were studied. Exposure to the marine environment is more aggressive than the river environment. The residual pull-off strengths of the carbon laminates and fabrics in the tidal zone are lower than those in the non-submerged zone; this could be due to the severity of the environment conditions during CFRPs application or during the exposure.

The results presented here were obtain eight months after the bonding had been completed, the tests will be conducted every six months within three years, and at 5 years and 10 years if the systems don't show major degradation.

6. Acknowledgment

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