Fundamental study on the bond strength between different cleaned steel surfaces and carbon fiber sheets

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1. Introduction CFRP (Carbon Fiber Reinforced Polymer) has been widely used for the structural repairing and upgrading of corroded steel structures over the last few decades. The effectiveness of the CFRP strengthening system is strongly dependent on the bond characteristics between the CFRP materials and steel plates. However, most of the research and developments focused on the strengthening method using CFRP strips or plates [1], which are limited in strengthening metallic structures with flat steel surfaces. Aiming to most of the localized corrosion damages in the steel structure, spreading in layers using carbon fiber sheets has been a more flexible composite repair method. Moreover, the effect of different cleaned steel surfaces before repairing and deterioration of CFRP on the bond strength is unclear. In this study, the main objective is to assess the mechanical performance of CFRP(dry fiber tow sheets with impregnated adhesive types)-steel composite considering different factors: i) steel surface treatments, ii) effect of the multi-layers, iii) effect of accelerating deterioration of CFRP.

2. Specimen and test method In this experiment, carbon steel plates (JIS G3106 SM490A) with dimensions of 120×60×6 mm, a unidirectional normal modulus carbon fiber materials are commonly produced as dry fiber tow sheets, and an impregnated adhesive XL800 were used to prepare the test specimens. The initial state of steel plate was milling by an NC machine (cutting diameter: 50 mm, cutting speed 215 m/min, revolutions per minute:1369 (rev./min), blade material: cermet). After milling, four surface cleaning treatments of steel plates were evaluated: 1) BS(belt sander): a unidirectional polish using belt sander machine (grit size 120 coarse, one-way grinding for at least 300s). 2) DS(disc sander): an electric rotating disk sander (grit size 120 coarse, rotated grinding evenly for at least 120s) to simulate the actual manual processing. 3) Brush: an electric rotating steel brush (wire diameter = 3 mm) operated by hand. 4) Blast: steel grit blast controlled with the pressure of 0.7 MPa for at least 20 s with a stand-off distance of 300 mm. All prepared steel substrates were then followed by compressed air cleaning. The optical microscope surface morphologies of prepared steel surfaces as shown in Fig.1.

Surface profile measurements were carried out using a non-contact laser microscope (Olympus OLS4500). Scanning area set as 10000×600μm with pitch of 1.8 μm in both directions. It has been proved the feasibility of using laser scanning confocal microscopy (LSCM) to measure the Wenzel roughness factor *r* [2], which is defined as the ratio of the actual solid surface area to the projected area of a rough surface. Besides, the three most applied line roughness parameters (Ra, Rzjis, RSm) and three surface descriptors (Sa, Sq, Sz) were calculated to characterize the surface profile. Also, the fractal dimension (Df) was calculated using the “Differential Box Counting Method” with FracLac for ImageJ software, based on the grayscale image output by LSCM. Surface morphologies calculation results of steel plates with various preparations, as shown in Table 1.

Tensile testing was performed using MSC-10/500-2, which is a desktop tension-compression testing machine. The pull-off specimens, including four groups, are shown in Table 2. Herein, aging conditions including the 10 days of wet-dry aging cycle (refer to JIS K6857, condition F) and 10 days of immersion test in 3.5 wt% NaCl aq. One-layer CFRP specimens curing finished were used for drilling and silicon coating before the aging test. After preparing the specimens, a uniform vertical compressive stress of 0.9 MPa was applied to the dolly (JIS H 4000 Aluminum alloy A2017, diameter: 20mm) and maintained for 30 min to adhere it to the target area. A two-liquid epoxy and hardener with a mixture of 1:1 were used as adhesive. Then, curing all dolly specimens for 48 hours under 35°C. All pull-off tests were repeated three times to obtain the average value of the tensile stress.

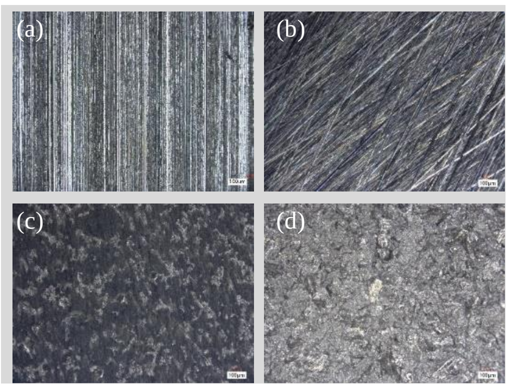

Fig.1 Surface morphology of steel plates with surface treatment (a) BS, (b) DS, (c) Brush, (d) Blast (×100)

Table 1 Surface morphologies calculation results of steel plates with various preparation.

Treatment	BS	DS	Brush	Blast
$r=A/A_0$	1.010	1.028	1.034	1.266
Ra (μm)	0.378	0.741	1.43	9.58
Rzjis(μm)	3.62	5.80	10.54	55.50
RSm(μm)	344	262	376	266
Sa(μm)	0.374	0.738	1.44	9.65
Sq(μm)	0.511	0.968	1.93	12.3
Sz(μm)	11.7	15.6	22.0	110
D_f	2.698	2.708	2.557	2.632

*Df: the same correspondence between height (1~150μm) and grayscale range (0~255).

Table 2 Dolly test list (repeat three times for each one)

Four groups	Specimen ID			
Steel substrate	BS	DS	Brush	Blast
Steel attached by multi-CFRP layers	BS-1, -2, -3	DS-1, -2, -3	Brush-1	Blast-1, -2, -3
(Aging i) Wet-dry cycles of 10 days	DS-(WD)	BS-(WD)	Brush-(WD)	Blast-(WD)
(Aging ii) Immersion of 10 days	DS-(W)	BS-(W)	Brush-(W)	Blast-(W)

*(-2，-3) represented the specimen with two or three-layers CFRP, other cases are default to one-layer CFRP.

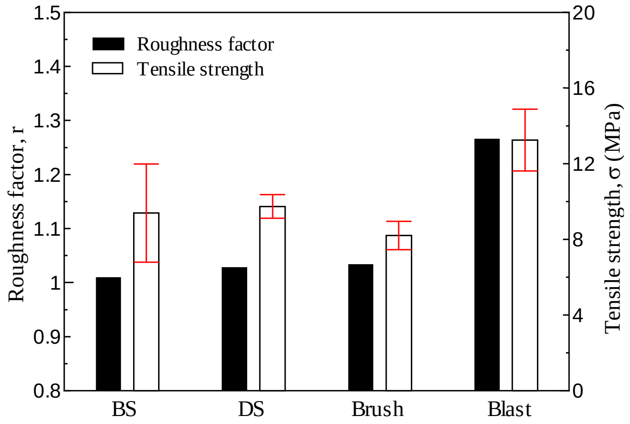

Fig.2 Roughness factor and adhesion strength of steel substrate

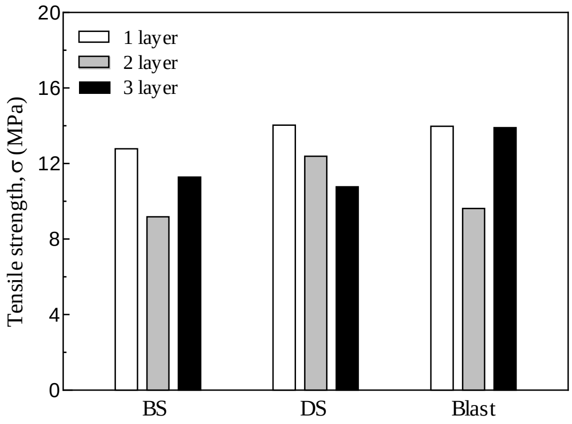

Fig.3 Adhesion strength of one, two and three-layer CFRP attached steel plate

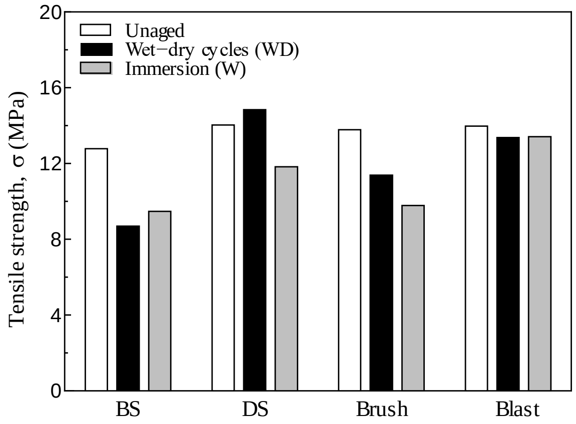

Fig.4 Comparation on the adhesive bond strength of one-layer composite from unaged to aging specimens

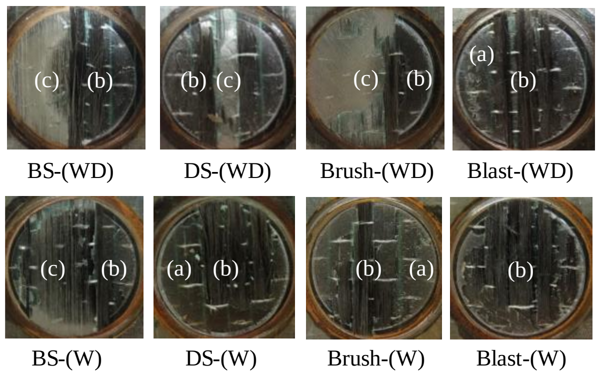

Fig.5 Comparation on the failure modes of one-layer composite from wet-dry aging to immersion aging group

3. Results and discussion The roughness parameters Ra, Rzjis, Sa, Sq, and Sz in Table 1 show a tendency of BS＜DS＜Brush＜Blast, while RSm of Brush is the maximum. As each parameter can only represent a single aspect of the surface roughness, they cannot be used to assess adhesion individually. The actual surface area was adequately expressed by a Wenzel roughness factor [2)]. An increase in surface area may well lead to a proportionate increase in adhesion. The pull-off test results of steel surface as shown in Fig.2, that the bond strength of the four types of clean steel surfaces shows Brush＜BS≈DS＜Blast, while the true surface area of Blast in the same projected area is much larger than three other cases. Through considering the surface complexity represented by Df, Brush owns a minimum Df indicates surface is relatively smooth than BS or DS, lead to its smallest surface adhesion.

The pull-off test results of the multi-layers group are illustrated in Fig.3. Herein, all test failure modes are CFRP delamination. Therefore, regardless of the steel surface, the tensile strength only depends on the bond strength of the adhesive in CFRP. However, the tensile strength of two and three layers is lower than that of one layer. It can be speculated that thicker carbon fiber sheets may be less likely to be totally impregnated by adhesive, so thicker composite materials may be more tent to be fracture failure.

Fig.4 shows the results of aging specimens after the wet-dry cycle and immersion of 10 days, respectively. Comparing with the unaged cases, the bond strength reduction of specimens exposed in immersion environment was more evident than that of wet-dry group. Different steel surface cleaning methods would also affect the deterioration of CFRP, that the Blast cases show a minimum drop ratio of bond strength in both wet-dry and immersion groups. Moreover, three kinds of failure modes, which include (a) CFRP/dolly-adhesive interfacial debonding, (b) CFRP delamination, and (c) steel/adhesive interfacial debonding, were observed. Fig.5 depicted the typical failure modes for the specimens of the unaged, wet-dry and immersion group, respectively. Failure (a) and (b) were mainly observed from the unaged group and immersion group, while failure (b) and (c) was mainly observed from the wet-dry group. It can be speculated that failure mode (b) occurs due to the CFRP delamination, and the moisture penetration facilitated this damage due to the epoxy deterioration. Failure (c) happened in wet-dry group, not only caused by the moisture penetration, but also due to the corrosion of steel base and thermal deformation difference at the interface. The wet-dry cyclic exposure would lead to steel/adhesive interfacial debonding.

4. Conclusion 1) The bond strength of the four types of steel surface treatments show Brush＜BS≈DS＜Blast. 2) Regardless of the steel surface, the tensile strength of two and three layers is lower than that of one layer. 3) After the moisture penetrated into the interface between steel and CFRP, the bond strength of specimens exposed in immersion environment was degraded faster, and the wet-dry cyclic exposure would lead to steel/adhesive interfacial debonding.

Reference 1) H. Al-Zubaidy, X. Zhao, R. Al-Mahaidi. Experimental evaluation of the dynamic bond strength between CFRP sheets and steel under direct tensile loads. International journal of adhesion and adhesives, 2013, 40: 89-102. 2) A. Li, S. Xu, H. Wang, H. Zhang, Y. Wang. Bond behaviour between CFRP plates and corroded steel plates. Composite Structures, 2019, 220: 221-235.