Engineering Structures 175 (2018) 76–85

Contents lists available at ScienceDirect

Engineering Structures

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

# Bond behavior of CFRP-steel double-lap joints exposed to marine atmosphere and fatigue loading

Qian-Qian Yu[a,b,*], Rui-Xin Gao[b], Xiang-Lin Gu[a,b], Xiao-Ling Zhao[c], Tao Chen[a,b]

[a] Key Laboratory of Performance Evolution and Control for Engineering Structures (Tongji University), Ministry of Education, Shanghai 200092, China
[b] Department of Structural Engineering, Tongji University, No. 1239 Siping Road, Shanghai 200092, China
[c] Department of Civil Engineering, Monash University, Wellington Road, Clayton, VIC 3800, Australia

ARTICLE INFO

*Keywords:*
Bond
CFRP
Fatigue loading
Marine atmosphere
Steel

ABSTRACT

External bonding with carbon fiber-reinforced polymer (CFRP) has been considered great potential in fatigue strengthening of defected steel components. Generally, it takes one to two weeks for a structural adhesive to achieve full strength in such a repair scheme. The potential risk of an environmental attack at the curing stage of adhesive has not been well understood. This paper presents an experimental study on the interfacial behavior of CFRP-steel double-lap joints subjected to salt fog spray or high relative humidity (RH) at the curing stage. Afterwards, the specimens were statically loaded to failure or applied by a pre-set number of fatigue cycles followed by a static test. CFRP laminate-patched specimens had the ability to resist six million high-stress range cycles while CFRP sheet-patched specimens only survived two million low-stress range cycles. After environmental exposure and fatigue loading, the bond strength loss ranged from 1% to 11%. Proper silane treatment was promising to maintain both the strength and stiffness of the bonded joints. Exposure to the harsh environment at the curing stage was detrimental to the mechanical properties of the structural adhesive Araldite 420. The unfavorable effects on the elastic modulus and ultimate strain were comparable to that of long-term exposure for well cured structural adhesive.

## 1. Introduction

Fatigue is one of the most important causes involved in damage and failure of a wide range of structures and infrastructure. It is suggested that 50 to 90 percent of mechanical failures are resulted from fatigue [1]. Due to the attack of service loads and environmental conditions, cracks may emanate from stress concentration zones.

Traditional retrofitting techniques like hole drilling or new plate attachment/replacement are vulnerable to new fatigue damage due to welding or fastening. These approaches are also complex to fix and time-consuming [2]. Carbon fiber-reinforced polymer (CFRP) composite materials having high strength-to-weight ratio, good resistance to fatigue and corrosion and ease of installation, are now considered as an alternative method for retrofitting aged infrastructure [3–7].

Extensive studies have been carried out to investigate the fatigue behavior of cracked steel plates strengthened by CFRP overlays [8–14]. Crack propagation was significantly retarded and the fatigue life was considerably prolonged. Thus, external bonding with CFRP has become an innovative method to improve the fatigue behavior of steel elements. Research on strengthening steel beams and welded joints with CFRP materials has also been performed [15–22].

It is believed that the main contributions of CFRP in such a fatigue strengthening system include: (a) sharing the far-field load, (b) constraining the crack mouth opening, and (c) reducing the stress ratio when the prestress technique is applied [23], which mainly rely on the load transfer between CFRP and substrate. Therefore, the interfacial bond behavior between CFRP and steel has been a major concern, especially the fatigue durability subjected to service loads and environmental attacks [24,25]. Table 1 summarizes some of the studies on the performance of CFRP-steel bonded joints subjected to environmental exposure and fatigue loading [26–37].

In experiments conducted by Dawood and Rizkalla [26], 30 CFRP-steel double-lap shear joints were exposed to wet/dry cycles in a 5% by weight NaCl solution at a temperature of 38 °C for up to six months. A silane coupling agent, a glass fiber layer and a combination of both were adopted to explore their protection effects. Test results implied that the silane treatment was preferred to improve the bond durability and the glass fiber layer increased the initial bond strength. The effect

* Corresponding author at: Key Laboratory of Performance Evolution and Control for Engineering Structures (Tongji University), Ministry of Education, Shanghai 200092, China; Department of Structural Engineering, Tongji University, No. 1239 Siping Road, Shanghai 200092, China.
*E-mail address:* qianqian.yu@tongji.edu.cn (Q.-Q. Yu).

https://doi.org/10.1016/j.engstruct.2018.08.012

**Table 1**
Studies on CFRP-steel bonded joints subjected to environmental exposure and fatigue loading.

| Reference | Specimen | Environmental exposure | Fatigue loading |
|---|---|---|---|
| Dawood and Rizkalla [26] | CFRP-steel double-lap shear joint | Wet/dry cycles in a 5% NaCl solution at a temperature of 38 °C for up to six months | No |
| Nguyen et al. [27] | CFRP-steel double-lap shear joint | (1) simulated sea-water at 20 C and 50 C up to 1 year in a temperature-controlled sea-water tank, (2) constant and (3) cyclic temperatures with a high level of relative humidity (RH) up to 1000 h | No |
| Borrie et al. [28] | CFRP-steel double-lap shear joint | 5% by weight NaCl solution for up to 6 months at three different temperatures (20, 40, and 50 °C) | Load ratio (maximum load in the fatigue spectrum to the static ultimate strength at the room temperature) is 0.2 or 0.5<br>Fatigue cycles are 1 or 6 millions |
| Heshmati et al. [29] | CFRP/GFRP-steel double-lap shear joint | (1) immersion in distilled water at 20 °C and 45 °C, (2) immersion in de-icing salt solution at 20 °C and 45 °C and (3) exposure to 95% relative humidity at 45 °C up to three years. | No |
| Agarwal et al. [30] | CFRP-steel single-lap joint | Wet thermal cycling (10 °C and 50 °C) | No |
| Heshmati et al. [31] | CFRP-steel double-lap joint | Distilled water at 45 °C | No |
| Agarwal et al. [32] | CFRP-steel single-lap joint | (1) wet thermal cycling (10–50 °C) and (2) wet thermal cycling between 10 °C and 40 °C | No |
| Nguyen et al. [33] | CFRP-steel double-lap joint | Cyclic temperature between 20 °C and 50 °C | No |
| Nguyen et al. [34] | CFRP-steel double-lap joint | UV exposure with a irradiation setting of 1.26 W/m$^2$/nm @ 340 nm | No |
| Agarwal et al. [35] | CFRP-steel single-lap joint | Freeze-thaw cycle: immersion bath (100% relative humidity chamber) at 38 °C for 8 h (thawing) followed by freezer at -18 °C for 16 h (freezing) | No |
| Liu et al. [36] | CFRP-steel double-lap joint | No | Load ratio (maximum load in the fatigue spectrum to the static ultimate strength) between 0.18 and 0.49<br>Fatigue cycles between 0.27 and 10 millions |
| Wu et al. [37] | CFRP-steel double-lap joint | No | Load ratio (maximum load in the fatigue spectrum to the static ultimate strength) between 0.21 and 0.62<br>Fatigue cycles between 0.05 and 10 millions |

of more complicated environmental conditions on the performance of CFRP-steel bonded joints was investigated by Nguyen et al. [27], i.e., simulated sea-water at 20 °C and 50 °C for up to one year as well as constant and cyclic temperatures with a high level of relative humidity (RH) for up to 1000 h. It was found that one year of simulated sea-water exposure was more detrimental to both the strength and stiffness of the joints compared to 1000 h of exposure to combinations of temperature and high RH. Finally, a prediction model on the degradation of the bond strength and stiffness was proposed. A study on the fatigue resistance of bonded joints in addition to the effect of environmental conditions was conducted by Borrie et al. [28]. They first prepared CFRP laminate- and sheeting- patched double-lap shear joints subjected to a 5% by weight NaCl solution at 20 °C, 40 °C and 50 °C as well as a certain static tensile load for one and six months. Afterwards, fatigue loading was applied to these specimens up to six million cycles. The residual static strength of the joints underwent a maximum decrease of 28%. Besides the concern of environmental attack on the bond behavior, the fatigue or static strengthening efficiency when subjected to harsh conditions was also investigated. Valsangkar [38] and Mahmoud et al. [39] developed a new experimental set-up for the underwater fatigue test of CFRP strengthened large-scale steel panels, aiming to investigate the feasibility of CFRP bonding repair for steel hydraulic structures. Borrie et al. [40] immersed tri-layered high modulus CFRP repaired steel plates into a 5% by weight NaCl solution for up to six months at 20 °C and 50 °C with a static tensile load applied. The tested fatigue life of the precracked steel plates after exposure demonstrated a great potential of the retrofitting approach. Wang et al. [41] exposed center cracked steel plates strengthened with CFRP laminates into wet/dry cycles with 3.5% by weight NaCl solution. After 180 cycles, the specimens witnessed a strength loss of 20%.

To the best knowledge of the authors, in most previous studies of laboratory accelerated tests, the marine environment was simulated by salt water. Whereas there have been limited attempts to assess the effect of salt fog exposure which is frequently occurred to cross-sea bridges. Also, the effect of fatigue cycles combined with environmental exposure was less reported.

Generally, specimens in these aforementioned studies were first cured in room condition for two weeks and then exposed to aggressive conditions [26–29,31,32,34,35]. The effect of environmental exposure at the curing stage of structural adhesive has not been well understood. Taking Araldite 420 as an example, based on the manufacturers' datasheet, the mixed portions A and B gel in three to four hours at 25 °C and become sufficiently cured to allow handling after five hours. 90% of the full strength could be achieved in four to five days and the full-strength development takes one to two weeks at room temperature.

This paper presents a series of experimental studies on the performance of CFRP-steel double-lap shear joints. This research focused on the effect of harsh environmental conditions at the curing stage of structural adhesive on the performance of the CFRP-steel bonded joints and the adhesive's mechanical properties. Specimens were exposed to 5% by weight NaCl fog or 80% RH at 35 °C for two weeks. Afterwards, they were either subjected to static tensile loads or applied by a certain number of fatigue cycles followed by a static test. Variables including the type of CFRP, silane treatment protocol, environmental condition and fatigue load spectrum, were considered. This study extends the understanding of the bond behavior between CFRP and steel and provides some useful suggestions for strengthening.

## 2. Experimental program

### 2.1. Configuration of test specimens

The test program was conducted in the Key Laboratory of Performance Evolution and Control for Engineering Structures at Tongji University, China. A total of 40 specimens were designed and tested, as summarized in Tables 2 and 3.

Single/double-lap shear joints are the most commonly used test set-up for the investigation of the interfacial behavior between CFRP and steel. The double-lap shear joint as shown in Fig. 1 was adopted in the present experimental program. The specimen was composed of two