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Environmental durability of a CFRP system for strengthening steel structures

Mina Dawood [a,*], Sami Rizkalla [b]

[a] University of Houston, Department of Civil and Environmental Engineering, N107 Engineering Building 1, 4800 Calhoun St., Houston, TX 77204-4003, USA
[b] North Carolina State University, Constructed Facilities Laboratory, Campus Box 7533, 2414 Campus Shore Dr., Raleigh, NC 27695-7533, USA

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ABSTRACT

Recently a high modulus CFRP system was developed to enhance the load carrying capacity and serviceability of steel bridges and structures. However, the environmental durability of the system has not yet been demonstrated. This paper presents the findings of a research program that was conducted to evaluate the environmental durability of the bond of the proposed CFRP strengthening system to steel surfaces. The program consisted of testing 44 steel-CFRP double-lap shear specimens. The specimens were exposed to severe environmental conditions for different durations, up to 6 months. Different methods to enhance the bond durability were studied including pre-treating the steel surface with a silane coupling agent, inserting a glass fiber layer within the adhesive and a combination of both methods of protection. The research findings indicate that the use of a silane coupling agent significantly enhanced the bond durability. While the presence of the glass fibers helped to enhance the initial bond strength of the system, it did not improve the durability of the bond. The use of both techniques enhanced both the overall bond strength and the environmental durability of the strengthening system.

1. Introduction

Research on the use of CFRP materials for strengthening steel structures has been ongoing for more than 10 years. A number of studies have been conducted to evaluate the flexural behavior of beams strengthened with CFRP, buckling behavior of slender and tubular members subjected to compression loading, use of CFRP materials for repair of cracked steel members and bond behavior of CFRP materials to steel surfaces [1]. However, comparably little is known about the environmental durability of the bond between CFRP materials and steel surfaces. While it is well known that exposure to environmental conditions can reduce the strength of bonded joints, other researchers have demonstrated that environmental exposure can also reduce the ductility of bonded joints between CFRP materials and steel surfaces [2].

In most bonding applications, the ingress of water can cause severe deterioration of the bonded joint. Water can penetrate a bonded joint by diffusion through the adhesive, wicking along the interfaces between the adhesive and the adherends, capillary action through cracks and voids in the adhesive or absorption through porous adherends [3]. Once moisture has penetrated into the joint, degradation can occur due to one of two primary mechanisms: degradation of the adhesive/adherend interface or degradation of the properties of the adhesive itself [3]. At the interface, degradation can occur due to displacement of intermolecular adhesive forces or due to instability of the oxide layers on the surface of metallic adherends. Further, the presence of moisture can affect adhesive properties in a reversible manner, such as by plasticization, or in an irreversible manner, such as by chemical or physical breakdown of the adhesive. In addition, when joining dissimilar materials the possibility of galvanic corrosion should also be considered.

Adhesion is typically attributed to secondary van der Waals forces which are relatively weak intermolecular forces [4]. These intermolecular forces can be easily displaced in the presence of moisture which can lead to spontaneous debonding between the two materials. It is commonly accepted that proper surface treatment is essential to ensure the long-term environmental durability of a bonded interface [5]. Proper surface treatment of metals should produce a rough surface free from contamination with a fresh, stable oxide that has a favorable chemical composition. This can be achieved by using three basic steps: (i) remove contaminants from the surface by degreasing, (ii) expose a fresh, chemically active surface and (iii) modify the surface by a chemical process to produce an interface resistant to hydration [6]. Grit blasting is the preferred method of surface abrasion for preparation of metallic surfaces [7,8]. However, grit blasting alone does not typically produce an environmentally stable interface and other methods of surface preparation are often necessary. For civil engineering applications the use of a silane coupling agent has been shown to be a promising method to enhance the bond durability at the steel–adhesive interface [9].

* Corresponding author. Tel.: +1 713 743 2023; fax: +1 713 743 4260.
E-mail addresses: mmdawood@uh.edu (M. Dawood), sami_rizkalla@ncsu.edu (S. Rizkalla).

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1.1. Galvanic corrosion

Galvanic corrosion can occur when two metals are coupled together and submerged in an electrolyte. Four conditions are necessary for galvanic corrosion to occur [10]: (i) the two metals in contact must exhibit a sufficient difference of electrical potential (ii) an electrical connection must exist between the two metals, (iii) the two metals must be bridged by an electrolyte and (iv) a sustained cathodic reaction must proceed on the more electropositive metal which typically involves the consumption of dissolved oxygen. If these four conditions are satisfied, a galvanic current will form between the two metals. The current will increase the corrosion rate of the anode and may decrease or halt the corrosion of the cathode. To help minimize the occurrence of galvanic corrosion between steel and CFRP materials, an electrical insulator can be placed between the two materials to break the electrical contact and prevent the formation of a galvanic current. Tavakkolizadeh and Saadatmnesh studied the effect of using an epoxy adhesive as an insulator between steel and carbon fibers [11]. They found that coating the carbon fibers with a 0.25 mm thick layer of adhesive reduced the galvanic corrosion rate of steel in seawater by 21 times compared to uncoated fibers. Another study suggested that embedding a layer of glass fibers in the adhesive between the steel and the CFRP helped to prevent electrical contact between the two materials, particularly in locations where there may be a void in the adhesive [9].

2. Material properties of the strengthening system

The proposed CFRP strengthening system consists of pultruded high modulus CFRP plates which are bonded to the tension surface of the steel member by an epoxy adhesive. The average measured tensile modulus and ultimate strength of the CFRP used in the proposed strengthening system were 418,000 MPa and 1490 MPa respectively [12]. The CFRP strips were bonded to the steel surface using a two-part epoxy adhesive which was cured under ambient room temperature conditions. The details of the adhesive selection process for the proposed strengthening system are presented by Schnerch [13]. The average measured tensile modulus and ultimate strength of the cured adhesive were 2980 MPa and 38 MPa respectively [14]. Both the CFRP and adhesive materials exhibited essentially linear-elastic behavior to failure. The glass transition temperature of the adhesive was determined using Differential Scanning Calorimetry according to ASTM E 1356-03 [15,16]. The midpoint glass transition temperature of the cured adhesive, T_m, was found to be 62 °C. The steel materials used in the experimental program had an average elastic modulus and 0.2% offset yield strength of 215,000 MPa and 334 MPa respectively [17].

3. Experimental program

The experimental program consisted of 44 steel-CFRP double-lap shear specimens that were tested to evaluate the environmental durability of the proposed CFRP strengthening system. Typical test specimens consisted of two 9.5 mm thick × 32 mm wide steel plates bonded together using two 4 mm thick × 19 mm wide CFRP strips as shown in Fig. 1. The width of the CFRP strips was selected to be less than the width of the steel plates to represent a typical field strengthening application in which the entire width of the tension flange may not be covered with CFRP, therefore leaving a portion of the flange exposed to environmental action. The experimental program is summarized in this paper and presented in detail elsewhere [18].

The four different bond configurations considered in the experimental program are shown in Fig. 2. The first configuration, Detail A, consisted of bonding the CFRP strips to the steel surface using only a relatively thin layer of adhesive. This configuration represents the most economical use of the materials; however, it could increase the possibility of direct electrical contact between the steel and the CFRP leading to possible galvanic corrosion. For the second configuration, Detail AS, the steel surface was pretreated with a silane coupling agent to enhance the durability of the interfacial zone between the steel and the adhesive. For Detail AG a unidirectional glass fiber layer was embedded in the adhesive between the steel and the CFRP to act as an electrical insulator between the two materials which is believed by others to help reduce the possibility of galvanic corrosion [9]. Detail AGS included the use of a silane adhesion promoter and the use of a glass fiber layer.

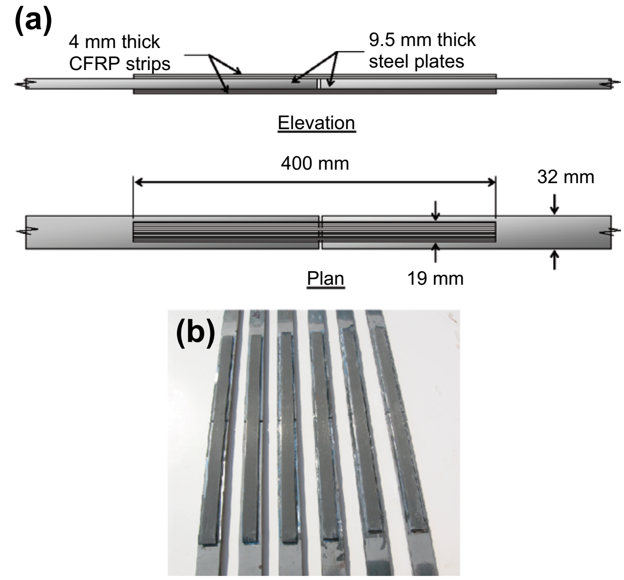

Fig. 1. Typical double-lap shear test specimens (a) schematic representation and (b) actual test specimens.

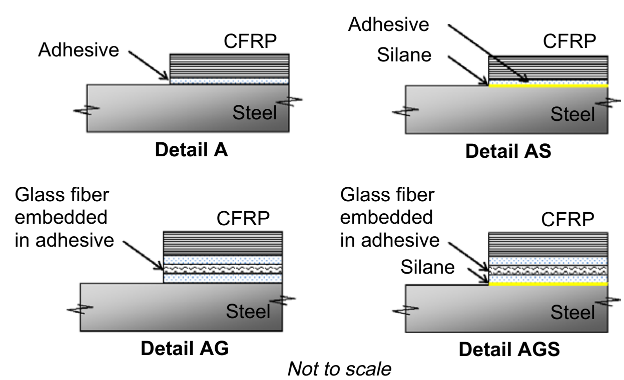

Fig. 2. Schematic representation of different bond configurations.

To maintain consistency of the test specimens, a standard fabrication process was adopted and 10 specimens were fabricated simultaneously. The steel surface was cleaned with acetone, sandblasted to a white metal finish and re-cleaned with acetone. The steel plates were aligned in a specially designed fixture and clamped in place. For the Detail AS and AGS specimens the steel surface was then treated with a γ-glycidoxypropyltrimethoxysilane (silane). Due to the complex nature of the chemical reactions which occur at the steel–adhesive interface, the selection of the silane and the method of application should be conducted in conjunction with the silane manufacturer while taking into account