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Evaluation of bond properties of degraded CFRP-strengthened double strap joints

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ABSTRACT

The application of CFRP has become a popular strengthening technique for retrofitting of metallic structures. However, knowledge is very limited on the durability of CFRP composites under different environmental conditions. This paper presents the outcomes of a research program on the bond characteristics and environmental durability of degraded CFRP-strengthened steel plate double strap joints. Investigations were carried out on failure mode, ultimate load, joint strength, effective bond length and the effect of embedded GFRP layers for double strap joints. Shear stress-slip curves were developed for degraded CFRP-steel composite using the experimentally measured strain data. Results show that the failure modes and joint capacities are highly dependent on the number of CFRP layers utilised in the composite systems under environmental conditioning. The use of embedded GFRP layers can improve the long-term durability of the composite system. However, optimum structural properties could not be achieved using embedded GFRP as the innermost layer. The bond-slip responses for degraded CFRP double strap joints were shown to have an approximately bilinear relationship.

1. Introduction

Existing civil engineering structures are subjected to ageing and degradation due to the loss of material properties, exposure to severe environmental conditions, or increases in service loads. Carbon fibre reinforced polymer (CFRP) has become very popular for the strengthening and rehabilitation of structural members because of its excellent material properties, such as high strength-to-weight ratio, high stiffness-to-weight ratio and ease of application in the field. Early research work confirmed that the CFRP can be effectively used in strengthening steel sections [1–5]. However, knowledge of the durability of CFRP systems is very limited, despite its widespread use in strengthening and rehabilitation [6–17].

The strength degradation of CFRP-steel bonded joints occurs due to the diffusion of water through the adhesive layer under normal conditions [18,19]. Further, research to evaluate the bond properties of CFRP-steel interface [10,18,20] has found that the CFRP material properties can be significantly affected by environmental conditions. In addition, galvanic corrosion can result in CFRP material property degradation in certain applications [6–8,10].

Accelerated tests have been successfully used to predict the durability of CFRP-steel strengthening systems [8,14,21–24]. For example, Kim et al. [8] used a direct current (DC) to degrade CFRP-steel bonded joints artificially in sodium chloride (NaCl) solution and showed that the CFRP-steel interface properties are significantly influenced by severe environmental conditions. Kabir et al. [10,25] conducted experiments to study the durability performance of CFRP-strengthened beams and concluded that the environmental conditions tested adversely affected the durability. The above studies suggest that there may be possible material and/or bond degradation in CFRP-steel composite systems under different environmental conditions, and this should be investigated in detail.

Some studies have related to the bond between CFRP-steel interface and failure modes in ambient environmental conditions [26–30]. However, these existing bond-slip models have restricted applicability, because all were developed for non-degraded CFRP-steel systems. Furthermore, the failure modes under severe environmental conditions may differ significantly. Hence, the existing models are not capable of simulating the long-term durability performance of CFRP-strengthened steel composite systems. Therefore, the focus of the present research is the evaluation of failure

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modes and bond characteristics of degraded CFRP-steel systems. Accelerated environmental conditions were used to impose material and bond degradation. The outcomes of this study will be beneficial for the understanding of the durability performance of CFRP-strengthened steel composite systems.

2. Experimental investigation

2.1. Material properties

Five materials were involved in this study: steel, normal modulus carbon fibre (MasterBrace FIB 300/50 CFS), glass fibre, two-part epoxy primer (P3500) and two- part epoxy adhesive (P4500) produced by BASF. The manufacturer-provided material properties are given in Table 1.

2.2. Specimen preparation

The CFRP-steel double strap joints were fabricated by joining two steel segments (25 mm in width and 6 mm thick) together with CFRP sheets as shown in Fig. 1. The width of the CFRP sheet was maintained the same as the steel plate. The bond length of the CFRP varied from 20 mm to 180 mm. The wet lay-up method was used to form the double strap joint. The steel surface was sandblasted to remove any coating material and then cleaned with acetone to remove oil, grease and rust from the surface before bonding. The two steel parts were joined together using a thin epoxy adhesive layer prior installing GFRP/CFRP layers (contribution of this thin epoxy adhesive layer to the joint capacity is negligible). The two-part epoxy primer was then applied to the cleaned, dust-free steel surface. On this primed surface, the two-part epoxy adhesive layer was applied, and pre-cut CFRP sheets were pasted on top of the adhesive layer. A flat roller and a ribbed roller were used to press the CFRP sheets onto the epoxy adhesive to ensure a constant adhesive thickness throughout the specimen and to remove air voids. Once this side had cured for 24 h, the same procedure was followed to apply CFRP on the other side of the steel plates. The specimens were then cured for a minimum of seven days before undergoing environmental conditioning. Foil strain gauges (FLA-6-350-1) were used to measure the strain. Fig. 2 shows the strain gauge positions for the different series of specimens. Specimens with GFRP layers were also fabricated using the same procedure.

2.3. Test parameters

Three parameters were used in this test series to investigate their influence on the performance of the joint capacity and the failure modes. They were (i) CFRP bond length (ii) number of CFRP layers and (iii) effect of GFRP layer. The bond configurations and the exposure durations considered in the experimental program are given in Table 2. Test series 1 and 2 were intended to evaluate the effect of CFRP bond length and the effect of multi-layer CFRP systems, respectively. Test series 3 evaluated the effect of embedded GFRP layers for three different exposure durations.

In the specimen group identification in Table 2, the first two characters represent the number of longitudinal layers used, and the next two letters describe the type of fibre (CF = carbon fibre, GF = glass fibre, GC = both glass and carbon fibre). GFRP was installed as the first layer, on top of steel surface wherever GFRP/CFRP combination was used as a composite. The last character/s represent the exposure condition (CS = control specimen, A = 24 h exposure, B = 48 h exposure and C = 72 h exposure).

2.4. Accelerated corrosion method

An electrochemical method was used to accelerate the degradation process of the CFRP-steel double strap joints. A direct current was applied to the specimens using an integrated system incorporating a rectifier with a built-in ammeter to monitor the current and a potentiometer to control the current intensity. The current density applied to the CFRP was related to the 10% corrosion mass loss of the bonded steel area. The current density was determined using Faraday's law considering the same size of steel area as the bonded CFRP. The direction of the current was adjusted such that the double strap joint specimen served as an anode. A stainless steel bar was positioned in the tank to act as the cathode. The specimen's shorter bond length portion was fully immersed in an aqueous solution of 5% sodium chloride in a plastic tank. The salinity level used here was close to the average salinity found in the world's oceans and is used by most researchers [10,18,31]. A schematic representation and the laboratory test set-up of the accelerated corrosion cell are shown in Fig. 3.

2.5. Instrumentation and loading procedure

Double strap joint specimens were tested in tension to failure at a constant displacement rate of 1 mm/min using an Instron testing machine with a capacity of 100 kN (Fig. 4). Self-locking grips were used at each end of the specimen to minimise the initial slip. Strain, load and displacement readings for each increment were recorded using a data acquisition system.

3. Results and discussion

3.1. Failure modes and failure loads

The failure mode and load of each specimen are shown in Table 3. The failure modes are discussed in detail in Sections 3.1.1–3.1.3. The notations follow the same convention as that described in Section 2.3.

3.1.1. Series 1

Three types of failure modes could be identified in the samples tested in series 1: (i) steel-adhesive interface debonding [32] (also referred as adhesion failure [33]) (ii) mixed mode failure (interface debonding and CFRP rupture) and (iii) CFRP rupture. Specimen 1LCF-20 failed due to steel-adhesive interface debonding. With the increased bond length, the failure mode shifted to mixed mode

Table 1
Material properties.

	Steel	CFRP	GFRP	Epoxy	Primer
Density (kg/m^3)	7850	1807	2540	1100	1080
Elastic modulus (GPa)	210	230	72	–	0.7
Tensile strength (MPa)	530	4900	3400	>17	>12
Yield stress (MPa)	350	–	–	–	–
Ultimate elongation (%)	36	2.1	4.8	–	3