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The quasi-static cyclic behaviour of CFRP-to-concrete bonded joints: An experimental study and a damage plasticity model

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ABSTRACT

In reinforced concrete structures strengthened using externally bonded fibre reinforced polymer (FRP) laminates, the performance of the bonded interface is vital to the performance of the strengthened structure. Extensive research has been carried out to study the behaviour of FRP-to-concrete bonded interfaces under quasi-static monotonic loading. However, only limited work has been done on understanding the behaviour of such bonded joints under quasi-static cyclic loading, which is a key issue to be addressed in modelling the long-term performance of carbon FRP (CFRP)-to-concrete bonded joints. This paper presents an experimental and theoretical study aimed at investigating and modelling the behaviour of CFRP-to-concrete bonded joints under quasi-static cyclic loading. A series of CFRP-to-concrete single lap shear pull-off tests were carried out under both quasi-static monotonic and cyclic loading. A thermodynamically consistent damage plasticity model where the damage parameter is defined as a function of the ratio between dissipated and total interfacial fracture energy was then proposed for modelling the constitutive behaviour of the CFRP-to-concrete bonded interface under quasi-static cyclic loading. The function to define the damage parameter was calibrated using the test results. Proposed model was then used to predict the bond-slip and load–displacement behaviour of the single lap shear pull-off tests. Results were compared with the experimental results and the prediction from two of the other existing models. Compared to the existing numerical models, the proposed model showed a better agreement with the test results.

1. Introduction

Flexural strengthening of reinforced concrete (RC) structures by externally bonded (EB) fibre reinforced polymer (FRP) laminates to its soffit has become an increasingly popular retrofitting method for RC structures. The effectiveness of such EB FRP strengthening methods depends on the interfacial shear stress transfer mechanism of the FRP-to-concrete bonded interface [1,2]. Therefore, understanding the behaviour of FRP-to-concrete bonded interfaces under mode II loading (i.e., under interfacial shear stress) is of critical importance in determining the performance of RC structures strengthened with EB FRP laminates.

Many studies have been carried out on understanding and modelling the interfacial failures in FRP-to-concrete bonded joints under quasi-static monotonic loading [3–5]. However, much less work has been done to understand the behaviour of such bonded joints under quasi-static cyclic loading. Many of the RC structures strengthened with EB FRP laminates are likely to be subjected to fatigue cyclic loading (e.g., bridge girders), thus understanding and modelling the behaviour of FRP-to-concrete bonded joints under cyclic loading is of importance for the design of EB strengthening systems for RC structures. Cyclic actions would accelerate the nucleation and coalescence of the micro-cracks at the regions with concentrated stress. Those micro-cracks finally develop into a continuous crack and lead the failure of the bonding interface. Therefore, how to predict the progress of the interface damage under cyclic/fatigue loading is of great importance to the long-term performance of FRP retrofitting of RC structures.

A bond-slip model, which depicts the relationship between the local interfacial shear stress and the relative slip between the two adherents, is commonly used to model the constitutive behaviour of the FRP-to-concrete bonded interfaces [3] and also [6,7] FRP-to-steel bonded interface under mode II loading. Different bond-slip models with different levels of sophistications have been proposed [5,6]. Among them, the bi-linear bond-slip model with a linear ascending branch followed by a linear descending branch has been the most widely used owing to its simplicity. In such

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models, damage evolution was defined using a scalar damage variable which varies from a value of 0 at the initiation of damage to a value of 1 at the full interfacial damage. This damage scalar variable was defined assuming interfacial behaviour is characterized by damaged elasticity and any plastic deformations of the interface were ignored [8].

Experimental studies on FRP-to-concrete bonded joints under quasi-static cyclic loading showed non-zero residual slip (i.e. slip at zero interfacial shear stress) when local interfacial shear stress is unloaded to zero [9,10]. In addition, bond-slip behaviour under quasi-static cyclic loading showed remarkable hysteresis loops, indicating inelastic deformations occurred during the quasi-static cyclic loading. Based on these experimental observations, several analytical bond-slip models have been proposed for FRP-to-concrete bonded joints under quasi-static cyclic loading [9,11,12]. Except for Ko and Sato's model [9], the other existing models assumed bi-linear bond-slip behaviour, as commonly assumed in FRP-to-concrete bond-slip models under quasi-static monotonic loading. The essential difference between the different bond-slip models proposed for quasi-static cyclic loading is in the approach used to define the damage parameter under quasi-static cyclic loading. In the most advanced of these models [11,12], damaged parameter is either related to the ratio between inelastic and total fracture energy [11] or negative slip increments (i.e. reversal of the residual slip at zero shear stress) [12]. With the definition of damage parameter in [11], a negative slip may occur at zero interfacial stress during unloading at higher damage values, thus resulting in an increase of the total energy during the loading unloading process. This is essentially caused by taking the energy dissipated to degradation of the stiffness into account twice while defining the damage parameter. Carrara and De Lorenzis's model [12] assumes negative shear stresses are not possible under the assumption that friction and interlocking are negligible. With this assumption, Carrara and De Lorenzis [12] assumes that once the interfacial shear stress becomes zero during the unloading process, slip value will start to reduce while maintaining interfacial shear stress at a zero value. However, this assumption does not agree with the existing experimental results of FRP-to-concrete bonded joints under quasi-static cyclic loading [10,13], where clear negative values of the shear stresses are observed.

Against this background, this paper presents an experimental and theoretical investigation into the behaviour of CFRP-to-concrete bonded joints under quasi-static cyclic loading. Results from a series of single lap pull-off test (called pull-off tests hereafter for brevity) of CFRP-to-concrete bonded joints under both quasi-static monotonic and cyclic loading are presented and discussed first. A numerical model in which the damage parameter due to the quasi-static cyclic loading is defined by the ratio between the energy dissipated in the damage process and the total fracture energy as obtained by the bond-slip relation is proposed. Numerical results from the proposed model are compared with the test results.

2. Materials and testing method

2.1. Sample details and material characteristics

In total seven pull-off samples were prepared and tested as a part of an ongoing research work at the University of Queensland structures laboratory. Nominal dimensions of the samples are given in Fig. 1a. Concrete cylinder tests were carried out according to AS 1012.9:2014 [14] to determine the concrete strength at 28 days and at the time of pull-off tests. The mean value of the 28-day compressive strength of concrete was 49.7 MPa with a coefficient of variation (COV) of 4.4% (based on 3 cylinder tests). The mean value of the concrete compressive strength tested from cylinders (6 cylinders) along with the pull-off test was 64.4 MPa with a COV of 4% at 6 months from concrete casting.

Normal modulus CFRP pultruded plates (Sika CarboDur S512) with 50 mm width and 1.2 mm thickness were employed in this test. The elastic modulus of the CFRP pultruded plates in the fibre direction was determined through testing (by measuring the strain of the free length of the CFRP plate during pull-off tests) to be 165 GPa. A 1.3 m long CFRP plate was employed to minimize any effect due to misalignment of the CFRP plate and the centre of the actuator.

Sikadur-30 adhesive was used to bond the CFRP plate to the concrete substrate. The ultimate tensile strength of the adhesive was determined as 25.3 MPa through adhesive tensile coupon tests carried out according to ASTM D638-14 [15]. For all samples, the start of the bonding area was 50 mm away from the support end of the concrete block (Fig. 1a), as recommended by [4] to avoid the edge effects. The gap between the CFRP and the concrete block in the front was prefilled with silicon to avoid adhesive leaching into the gap so that gap dimensions were better controlled. The bonding area (50×300 mm) on the surface of the concrete block was roughened by needle gun to expose the coarse aggregates (except M1, which was grinded with a sand grinder). Then the dust on the surface was further removed by compressed air. The overall test set-up and sample detail can be seen in Fig. 1a. Out of the seven samples tested, three were tested under quasi-static monotonic loading (named M1, M2 and M3) and the other four were tested under quasi-static cyclic loading (C1, C2, C3, C4). Before bonding the CFRP plate to the concrete block, voids within the roughened area were filled with the adhesive from the same batch used to bond the CFRP plate. The thickness of the adhesive layer was controlled to be 1 mm by placing 1 mm thickness aluminium tabs beside the bond area while using a roller to squeeze the excessive adhesive. The bonded sample was stored in the laboratory environment for at least two weeks before testing.

2.2. Testing procedures and measurements

The test rig used for pull-off tests is shown in Fig. 1a. Before test, the sample and the actuator were carefully laser-level aligned using the mounting hole in the strong wall as reference. In all samples, axial strains at the top of the CFRP plate were measured and calculated using a 3D digital image correlation (DIC) system (VIC-3D) (shown in Fig. 1b). Two 35 mm focal lens, together with two Grasshopper GRAS-50S5M cameras were used to capture the testing image at 2448×2048 resolution. Lightening (provided either by two LED spot lights or GS Vitec: Multi-led LT-V9 according to the test light condition) of the test was carefully tuned to minimize the focus deviation. Speckle pattern (1mm diameter) of this test was prepared with a prefabricated rubber stamp. For Sample C4, 21 strain gauges were attached along the bonding length and two LVDTs were employed at the loaded end and far end respectively to verify the measurement from DIC. To keep the simplicity, results from this sample will not be discussed in the following sections. For all samples, two strain gauges were attached to top and bottom sides of the CFRP plate within the un-bonded length at 100 mm distance away from the loaded end to measure the elastic modulus of CFRP plate.

The axial strain of the CFRP plate at any point within the bond length was taken as the mean strain value obtained from five points on the CFRP plate along the transverse direction (width direction). Meanwhile, the interfacial slip and shear stress at different locations were calculated from the strain values using the equations given in [16].