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Prediction of the interfacial shear stress of externally bonded FRP to concrete substrate using critical stress state criterion

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ABSTRACT

This research focuses on the development of a fracture mechanics based-model that predicts the debonding behavior between FRP composites and reinforced concrete beams. The maximum transferable load for FRP composite externally bonded to concrete substrate was expressed as a function of material properties and the fracture energy. Fracture energy for FRP pull-off test was determined with the maximum interfacial shear stress and the corresponding slip. The interfacial shear stress and the corresponding slip are predicted based on a proposed criterion that shear stress failure initiates adjacent to the FRP-concrete bond interface. With the application of the elasticity theory, the corresponding slip of FRP bond system and the interfacial shear stress are obtained. Comparison between the experimental FRP pull-off tests and those predicted by the new model showed good agreement.

1. Introduction

For the past few decades externally bonded fiber reinforced polymer (FRP) composites are used for strengthening existing reinforced concrete structures. In general, the performance of strengthened FRP concrete structures depends on the bond strength at adhesive–concrete interface. Many failure modes [1] have been proposed to understand the behavior of FRP strengthened structures. As such several experimental works on the bond joint has been carried out using single pull-off test, where the strength of the bond is calculated as the maximum transferable load [2–4]. Based on experimental works [5], it was inferred that for an effectively executed bond joints, the debonding failure occurs at a certain depth in concrete substrate from the adhesive–concrete interface. Therefore, bond strength may be expressed as a function of strength of the concrete.

The adhesive–concrete bond interface is typically considered as the critical portion of the system subjected to the interfacial shear stress. Considerable studies are carried out on the interfacial behavior of the bond joint to predict its capacity. Relationship between local slip and shear stress is not simply linear till complete debonding occurs. Therefore bi-linear and non-linear models are developed through experimental studies and analytical solutions [6–8] to capture the debonding characteristics. For non-linear models, classical form of the Popovics' expression [9] was successfully used by many researchers [10–14]. The maximum interfacial shear stress and the corresponding local slip are the key parameters for both the empirical and analytical models. These values are generally obtained in empirical forms from the regression analysis. Some authors tried to develop expressions for those as a function of concrete compressive strength, where adhesive thickness was neglected [10,15,16]. Adhesives used can be of considerable thickness, and its effect could be of an important factor to predict the bond joint behavior [17,18].

In this study, the maximum transferable load is determined theoretically by proposing a failure criterion where the stress state on a small element in concrete substrate is limited to the tensile strength of concrete. The interfacial fracture energy, the maximum shear stress, and the corresponding local slip need to be evaluated as intermediate parameters to determine the maximum transferable load. The interfacial fracture energy of the bond joint is estimated using Popovics' expression. The maximum interfacial shear stress and the corresponding local slip are approximated by developing an analytical solution considering the effect of the adhesive thickness. A parametric study to determine the failure depth in concrete substrate is carried out to verify the proposed criterion. The predicted maximum transferable loads are compared with the experimental results available in literatures. In addition the interfacial fracture energy predicted in this work is compared with the existing models.

2. Load transfer in bond joint

2.1. Stress state criteria for debonding in pull-off test

For the bond system of FRP-to-concrete, single pull-off test is widely adopted due to its simplicity and ability to examine the bond behavior under shear stress. In the test, mechanical properties

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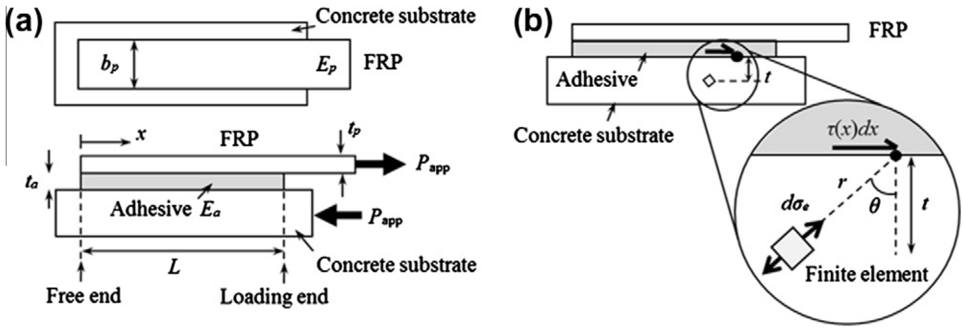

Fig. 1. Sketch of pull-off test for FRP-to-concrete bond joint. (a) Plan and side views; and (b) differential stress on the concrete substrate element.

of FRP, concrete substrate, and adhesive are considered as important parameters. In this paper, thickness and tensile young's modulus of elasticity are denoted as t and E with subscripts p for FRP and a for adhesive (Fig. 1a). Also, the shear modulus of adhesive G_a is used. FRP strip with the width b_p is attached along the bond length L on concrete substrate surface. For the ease, the edges of the bond length are denoted as the free end and the loading edge, which are far from and close to the loading point, respectively.

The applied load P_{app} at the end of FRP is transmitted to concrete substrate through adhesive by the interfacial shear stress with the distribution function of $\tau(x)$ along the bond length. In general, it can be agreed that the debonding actually is initiated with concrete fracture. During FRP debonding, Brosens [19] noted that the failure occurs at a certain depth into concrete substrate. Yao et al. [5] reported, through experimental studies, that thin concrete layer attached to the debonded FRP strip and confirmed that its thickness is in the range of 1–5 mm. Thus, it is assumed that the initial fracture in FRP debonding occurs in concrete substrate elements below the bond interface at depth t and away from the loading end at distance d. For concrete full strength, the stress state of the small element should not exceed its tensile strength f_t, and it can be simply proposed as

$$\sigma_{e,d} \leqslant f_t, \tag{1}$$

where $\sigma_{e,d}$ = the stress state in the element of concrete substrate at depth t from the interface and distance d from the loading end. The tensile strength of concrete in the unit of MPa can be obtained from ACI code [20] as a function of the cylindrical compressive strength f_c' (MPa) as:

$$f_t = 0.7 f_c'^{0.5}. \tag{2}$$

2.2. Stress state in concrete substrate induced by interfacial shear stress

The elasticity theory derives the stress state on an element in the material subjected to a horizontal load parallel to the surface. The expression for the differential stress state, denoted $d\sigma$, is obtained as follows [21];

$$d\sigma = \frac{2dH}{\pi r}\sin\theta, \tag{3}$$

where dH = the differential horizontal force on the material surface; r = the radial distance from the load applying point to the considered element; θ = the angle measured from the vertical line to the radial line with the loading point as the origin in clockwise positive. For the validity of the application of 2-D mechanics of materials and elasticity theory, it is assumed that FRP sheet is subjected to only axial forces and the shear stress in plane strain condition. For pull-off test, the expedient concentrated horizontal load at a point is assumed as $\tau(x)dx$. By the force, a differential stress, $d\sigma_e$, is induced and perpendicularly to a plane of a square finite element in concrete substrate shown in Fig. 1b. The differential stress on the element, $d\sigma_e$, induced by load at any point along the bond length can be given by:

$$d\sigma_e = \frac{\tau(x)dx}{\pi t}\sin 2\theta, \tag{4}$$

where θ = the angle measured from the vertical line of x position to the radial line in clockwise positive. It is noted that the positive differential stress means tensile stress.

On the same element, the infinite number of the differential stresses with different magnitudes and directions are superimposed due to consecutive horizontal loads on the concrete substrate surface. For the critical tensile stress state, all differential stresses are transformed with the Mohr's principle on a certain plane, denoted as the critical plane. On an element at distance d from the loading end and at depth t, the critical normal stress $\sigma_{e,d}$ is expressed as

$$\sigma_{e,d} = \int_0^L \frac{\tau(x)}{2\pi t}(1+\cos 2\theta_1)\sin 2\theta_2 dx, \tag{5}$$

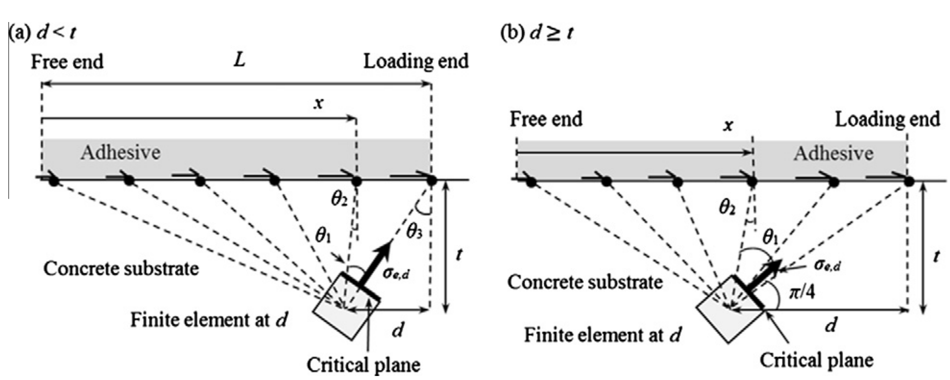

Fig. 2. Transformed stress on a critical plane of concrete element. (a) Case $d < t$; and (b) case $d \geqslant t$.