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Mixed mode fracture characterization of GFRP-concrete bonded interface using four-point asymmetric end-notched flexure test

Qinghui Liu [a], Pizhong Qiao [a,b,*]

[a] State Key Laboratory of Ocean Engineering, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

[b] Department of Civil and Environmental Engineering, Washington State University, Sloan Hall 117, Pullman, WA 99164-2910, USA

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A combined analytical and experimental study using an asymmetric end-notched flexure specimen under four-point bend loading is conducted to characterize the fracture of glass fiber reinforced polymer (GFRP)-concrete bonded interface. Both the classic composite (rigid joint) and interface deformable (flexible joint) bi-layer beam models are used to calculate the compliance and energy release rate (ERR) of the proposed four-point asymmetric end-notched flexure (4-AENF) specimen. The validity and accuracy of the models are obtained by comparison with the numerical finite element results. The results show that the flexible joint model predicts more accurately the compliance and ERR compared with those of rigid joint model in 4-AENF specimen due to the attribute of crack tip deformation. Moreover, the calculated ERR by the flexible joint model can be reduced to that of the rigid joint one when the specimen is properly sized. Then, the designed 4-AENF specimens are utilized to characterize the fracture toughness of GFRP-concrete bonded interface. To overcome the obstacle of low tensile strength and cracking behavior of concrete and prevent the premature fracture of concrete substrate before debonding of bonded interface takes place, a reduced section scheme is adopted and the steel bars are used to reinforce the concrete substrate beams. An aluminum beam with different thickness is bonded to the thin GFRP layer so as to change the stiffness of the composite GFRP/aluminum substrate, resulting in different fracture mode mixities. The fracture toughness values of GFRP-concrete bonded interface under three different mode ratios are obtained. The proposed 4-AENF specimen and data reduction procedures for interface fracture toughness evaluation can be used to effectively characterize mixed mode and mode-II dominated fracture of hybrid material bonded interface.

1. Introduction

Fiber reinforced polymer (FRP) composites have been increasingly used in civil engineering for strengthening, retrofitting and repairing of traditional concrete structures as well as new constructions (e.g., FRP-concrete systems) due to their high specific strength, high specific stiffness, high flexibility in design and superior environmental durability [1–4]. Although satisfactory performance (such as, stiffness and strength) has been achieved by use of FRP materials, there is a concern about reliable performance of bonded interface, which is susceptible to debonding [5,6]. To assess this type of failure modes, fracture mechanics-based approaches have been widely employed, in which the energy release rate (ERR or G) or stress intensity factor (SIF or K) is predicted and compared with its critical value G_c or K_c [7,8]. However, for the bi-material interface of FRP and concrete, G_c is a function of fracture mode ratios. Thus, fracture tests have to be conducted to obtain fracture toughness values over a wide range of mode mixities. In the present work, determination of the mixed mode and mode-II dominated fracture toughness of FRP-concrete bonded interface is addressed.

To characterize the fracture behavior of bi-material interface, beam-type fracture specimens are most widely used. The mixed mode bending (MMB) specimen is very popular for determination of mixed mode envelops, and it has been adopted as a standard by ASTM [9]. However, this standard is limited to FRP composites with high tensile strength. The single leg bending (SLB) [10], asymmetric double cantilever beam (ADCB) [11], and asymmetric end notched flexure (AENF) [12] specimens are all good choices for bi-material bonded interface fracture toughness determination

* Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China.

E-mail addresses: qiao@sjtu.edu.cn, qiao@wsu.edu (P. Qiao).

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over a different range of mode mixities. Even though ERR can be obtained from the above three typical fracture specimens under different mode mixities, only one crack initiation value can be obtained at a time per specimen because of rapid debonding growth. To overcome the above difficulty, crack steady types of specimens, such as four point end notched flexure (4-ENF) [13], tapered end notched flexural (TENF) [14,15], single contoured cantilever beam (SCCB) [7], and over-leg bending (OLB) [16,17] specimens, were proposed. It has to be mentioned that due to the fact that only bending moments exist within the zone in front of the interface crack tip for the 4-ENF specimen, it was usually deemed that the conventional composite bi-layer beam theory (rigid joint model) would give the same ERRs as those of semi-rigid joint and flexible joint models [18,19].

For fracture characterization of FRP and concrete bonded interface, usually peel test [20–24], shear test [24–28], and combination of the two test methods [6,29,30] were adopted due to the low tensile strength of concrete. The peel test is usually used to measure interface fracture toughness under mode-I loading. Ye et al. [21] and Giurgiutiu et al. [23] tested the fracture toughness of FRP and concrete bonded interface using the peel test based on the linear elastic fracture mechanics. However, usually large deformation existed in the un-bonded portion of FRP as shown by Kimpara et al. [22] and Lorenzis and Zavarise [31], and the linear elastic fracture mechanics is thus not suitable for evaluation of ERR of FRP-concrete bonded interface. To overcome the above obstacles, Kimpara et al. [22] obtained the ERR of FRP-concrete bonded interface using the area method and membrane peeling method. The shear tests are usually used to obtain the mode II fracture behavior of FRP-concrete interface [25,26]. However, different shear test set-ups can lead to significantly different test results. Moreover, majority of existing shear tests were concerned with predictions of ultimate load and effective bond length [27]. Considering that the fracture mode is usually mixed in practical application, the effect of combined pulling and peeling on FRP-concrete interface debonding was studied by Pan and Leung [30] using a novel experimental set-up, from which a new theoretical model for debonding analysis was proposed. Recently, the bond behavior of FRP and concrete under mixed-mode I/II loading was experimentally investigated by Ghorbani et al. [6], and the FRP was loaded at different angles with respect to the concrete substrate in order to experience mixed-mode I/II loading. The results showed that the bond strength would decrease or increase over the control specimen when the interface experiences mode I component of loading in the form of normal out-of-plane tensile or compressive stresses, respectively.

It can be seen from the existing studies that the beam-typed specimens have seldom be used to measure fracture toughness between FRP and concrete due to low tensile strength and cracking behavior of concrete materials. Moreover, the above mentioned 4-ENF specimen is usually used for characterization of symmetric sublayers with identical material [13,32–34]. The 4-AENF specimen was first proposed by Qiao et al. [8] to characterize mixed-mode fracture behavior of Carbon FRP-concrete bonded interface. The critical loads for crack initiation and crack arrest and corresponding critical energy release rates were obtained. However, the concrete beam substrate easily failed in tension before the interface propagation took place in their test. To overcome the difficulties of low tensile strength of concrete, a reduced section scheme, similar to the I-section proposed by Yoshihara [33] to prevent bending failure in mode II fracture toughness measurement of wood, is adapted in this study.

In this study, the fracture behavior of GFRP-concrete bonded interface is analytically and experimentally studied using the four-point asymmetric end-notched flexure (4-AENF) specimen. First, both the rigid joint and flexible joint models are used to calculate the compliance and energy release rate (ERR) of the proposed 4-AENF specimen. Then, validity and accuracy of the models are obtained by comparing the results of the two joint models and finite element analysis (FEA). Finally, the designed 4-AENF specimens are utilized to experimentally characterize the fracture toughness of GFRP-concrete bonded interface. To overcome the obstacle of low tensile strength and cracking behavior of concrete and prevent the premature fracture of concrete substrate before the bonded interface takes place, a reduced section scheme is adopted and the steel bars are used to reinforce the concrete substrate beams. Three groups of specimens with different thickness of aluminum plates are considered to achieve three different fracture mode I/II mixities, under which the crack initiation and arrest loads and corresponding fracture toughness values are obtained.

2. Analysis of 4-AENF specimens

A four-point asymmetric end-notched flexural (4-AENF) specimen with an interface delamination length a and a clear span of L loaded by $P/2$ at the two corresponding points with distance d from the left and right supports as shown in Fig. 1 is considered. Following the same procedure provided in the literature [34], the concept of crack-tip element proposed by Davidson et al. [35] is adopted, in which a cracked bi-layer beam lies along the interface of top beam 1 and bottom beam 2 with thickness h_1 and h_2 and width b_1 and b_2, respectively. Each substrate layer may be composed of two or more layers with different materials. The configuration in Fig. 2 illustrates a crack-tip element, where the cracked and uncracked portions join, in which the generic loads are applied as already determined by a global beam analysis. In Fig. 2, N_{i0}, Q_{i0}, and M_{i0} ($i = 1, 2$) are the applied axial forces, transverse shear forces, and bending moments at the crack tip in sub-layers (or substrates) 1 and 2, respectively; N_i, Q_i, and M_i are the internal axial forces, transverse shear forces, and bending moments in sub-layers 1 and 2, respectively; N_T, Q_T, M_T are the total resultant applied axial force, transverse shear force, and bending moment of the bi-layer beam system about the mid-plane of the layer 2. According to the Timoshenko beam theory, the stress resultants and displacements of each sub-layer can be expressed as [18,36]

$$N_i = A_i \frac{du_i}{dx}, \quad M_i = D_i \frac{d\phi_i}{dx}, \quad Q_i = B_i\left(\phi_i + \frac{dw_i}{dx}\right) \tag{1}$$

where u_i, w_i and ϕ_i are the displacements in the x_i and z_i directions and rotations of the sub-layer i of the middle plane, respectively; A_i, B_i and D_i are the axial, transverse shear, and bending stiffness of layer i, respectively.

2.1. Rigid joint model

First, the classic composite bi-layer beam theory (rigid joint model), assuming that after deformation the cross-section at the crack-tip remain in one plane and is perpendicular to the mid-plane of the virgin beam, is adopted here. By substituting the corresponding expressions of moments and shear forces into Eq. (1), the rotations and deflections in different portions of the cracked bi-layer beam are obtained as follows. for $-a \le x \le -a + d$:

$$\begin{aligned} \phi_1 &= \int \tfrac{M_1}{D_1} dx = -\tfrac{\alpha P}{4D_1} x(x + 2a) + c_1 \\ w_1 &= \int (\tfrac{Q_1}{B_1} - \phi) dx = -\tfrac{\alpha P}{2B_1} x + \tfrac{\alpha P}{12D_1} x^2 (x + 3a) - c_1 x + c_2 \end{aligned} \tag{2}$$

for $-a + d \le x \le 0$:

$$\begin{aligned} \phi_1 &= -\tfrac{\alpha P d}{2D_1} x + c_3 \\ w_1 &= \tfrac{\alpha P d}{4D_1} x^2 - c_3 x + c_4 \end{aligned} \tag{3}$$