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INTERFACIAL STRESS ANALYSIS OF ADHESIVELY BONDED JOINTS

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ABSTRACT

To attain a suitable strengthening system for concrete structures, adequate stress distribution between externally bonded fibre reinforced polymer (FRP) materials and the substrate is required. With the growing application of FRP in the strengthening of structures and in order to be able to sufficiently model the strengthened structure behaviour, the need for a generic bond relationship is increasing. Hence, this research investigates the bond between concrete substrates and the FRP composites through an analytical approach. The model is developed for the estimation of the local and global strain profile by which the interface shear stress along the bonded length is determined. In addition, by proposing continuously differentiable nonlinear functions, the relative slip between two adherents is derived. The accuracy of the proposed relationship is verified by comparing the experimental and analytical results.

KEYWORDS

FRP, concrete, bond-slip law, analytical model, boundary condition.

INTRODUCTION

Interfacial debonding between two adhesively bonded elements is the critical failure mode since it has an important role on the performance of strengthened structures. Regarding the brittle behaviour of interfacial fracture, the ultimate capacity or ductility expectations of strengthened structures can not be achieved. The interface behaviour, in the literature, is characterised by the bond strength and more importantly the local shear stress-slip profiles which is called the local interface law.

Depending on the methods, the existing analytical models may be classified into three major categories; empirical-based models (Chen and Teng 2001; Guo et al. 2005; Savoia et al. 2003; Seracino et al. 2007), elasticity theory-based models (Bizindavyi and Neale 1999; Dai et al. 2005; De Lorenzis et al. 2001; Taljsten 1997) or fracture mechanics-based models (Liu and Wu 2012; Ueda and Dai 2005). Empirical-based models are mainly derived from the regression of the experimental data while elasticity theory-based models use the basic governing equations of the joints. The principles of the fracture mechanics are employed to simulate the bond response in fracture mechanics-based models.

Several methods have been employed to reduce the inconsistency in the bond-slip relationships obtained from the experimental results. However, the proposed models are determined based on the factors which are not available in the literature or empirically verified. Therefore they can not be extended to different types of the FRP processing techniques.

Dai et al. (2005) model, as a robust formulation of the interface behaviour, applies an exponential function to predict the relationship between the FRP strain and the slip at the loaded end. The advantage of Dai et al. (2005) model in compare with other relationships is that the bond behaviour is determined based on the properties and geometries of the joint. In addition, the bond-slip relationship can be derived by the magnitude of loads and slip at the loaded end which are available in most of the literature.

The drawback of Dai et al. (2005) model is that it is applicable to the joints with very stiff adhesive layer. By studying the effect of adhesive shear stiffness on the maximum shear stress, Dai et al. (2005) model leads to higher maximum shear stresses when the shear stiffness of the adhesive increases. However, it is shown that increasing the shear stiffness of the adhesive contributes to transfer more shear stresses to the substrate and more rapid fracture (Abdel Baky et al. 2012). In addition, some parameters such as fracture energy, *A* or *B*, are derived based on the regression of the experimental results. Therefore for design purposes, the experimental data is not available and it is hard to find parameters *A* and *B*.

In order to provide a simple and sound analytical model to capture the fundamental features of the interface behaviour, this paper introduces a new method for derivation of the bond-slip law in adhesively bonded joints. For this, the local and global strain profile is modelled by differential equation method based on boundary conditions of the joint. Continuously differentiable function is presented for deduction of bond stress along the interface. Exclusive features of the present investigation are that the bond characteristics are developed only based on boundary conditions of the joints and determined in accordance with the values of applied load at each stage and properties of the adherent. Therefore, the proposed model contributes to overcome the instability of bond stress function application of the proposed model to different types of FRP manufacturing techniques.

METHODOLOGY

The strain profile of FRP-to-concrete joints along the bonded length consists of different stages (Figure 1). During the initial stage, the slip between the FRP and the concrete substrate linearly increases by the applied load. Then, micro-cracks start to propagate through the interface until the formation of the macro-crack. By formation of the macro-crack, the load carrying capacity of the joint does not increase and the length of bond through which the interfacial shear stresses are transferred to the substrate can be defined as the effective bond length, L_{eff}.

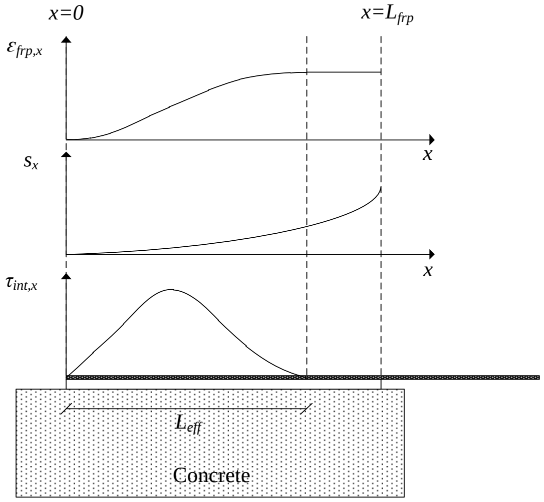


Figure 1. Strain, slip and shear stress profiles

Based on Figure 1, strain distribution along the bonded length of FRP can be characterized as a third degree polynomial function

$$\varepsilon_{frp,x} = \frac{ds_x}{dx} = Ax^3 + Bx^2 + Cx + D \tag{1}$$

s_x is the slip between the FRP and concrete as a function of position. x is the coordinate along the bond length where $x = 0$ corresponds to the free end and $x = L$ represents the loaded end of the laminate. A, B, C and D are constant values which are defined as followed. Along the bonded region, the FRP strain on the detached parts of the laminate remains constant. When the effective bond length is reached, any increase in load leads to a rapid shifting of the unbonded region to the end of the FRP. Based on these conditions, Eq. 1 can be solved based on sets of boundary conditions.

Considering the above mentioned stages, the boundary conditions for the interface can be expressed as (Figure 1):

$$\varepsilon_{frp,x} = 0 \qquad \text{when} \qquad x = 0 \tag{2}$$

$$\frac{d\varepsilon_{frp,x}}{dx} = 0 \qquad \text{when} \qquad x = 0 \tag{3}$$

$$\varepsilon_{frp,x} = \varepsilon_0 \qquad \text{when} \qquad x = L_{eff} \tag{4}$$

$$\frac{d\varepsilon_{frp,x}}{dx} = 0 \qquad \text{when} \qquad x = L_{eff} \tag{5}$$

ε_0 and L_{eff} are the strain at the loaded end and the effective bond length, respectively. Solving Eq. 1 for boundary conditions 2 to 5 gives:

$$\varepsilon_{frp,x} = \frac{ds_x}{x} = -\frac{2\varepsilon_0}{L_{eff}^3}x^3 + \frac{3\varepsilon_0}{L_{eff}^2}x^2 \qquad \text{for} \qquad 0 < x < L_{eff} \tag{6}$$

$$\varepsilon_{frp,x} = \varepsilon_0 = \frac{F}{E_{frp}A_{frp}} \qquad \text{for} \qquad L_{eff} < x < L \tag{7}$$

where E_{frp} and A_{frp} in are modulus of elasticity and the cross section of the FRP, respectively. The interfacial stress along the bond length, $\tau_{int,x}$, can be obtained from the following differential equation:

$$\tau_{\text{int},x} = \frac{1}{E_{frp}t_{frp}} \cdot \frac{d^2 s_x}{dx^2} \tag{8}$$

W_{frp} represents the width of the FRP. Differentiating Eq. 6 and substituting into Eq. 8 gives

$$\tau_{\text{int},x} = \frac{9F}{W_{frp}L_{eff}^2} \cdot \left[x(1 - \frac{x}{L_{eff}}) \right] \tag{9}$$

At each point, the slip can be determined by differences between the integration of strain for FRP laminate and concrete;

$$s_x = u_{frp,x} - u_{c,x} \tag{10}$$

$$u_{frp,x} = \int \varepsilon_{frp,x} dx \tag{11}$$

$$u_{c,x} = \int \varepsilon_{c,x} dx \tag{12}$$

$u_{frp,x}$, $u_{c,x}$ and ε_c are the displacement of FRP, the displacement of the concrete and the strain in the concrete block, respectively. Since the axial stiffness of concrete is large, the slip in concrete can be neglected. Therefore based on Eqs. 11-12 and 6-7, the local slip of the joints can be determined by

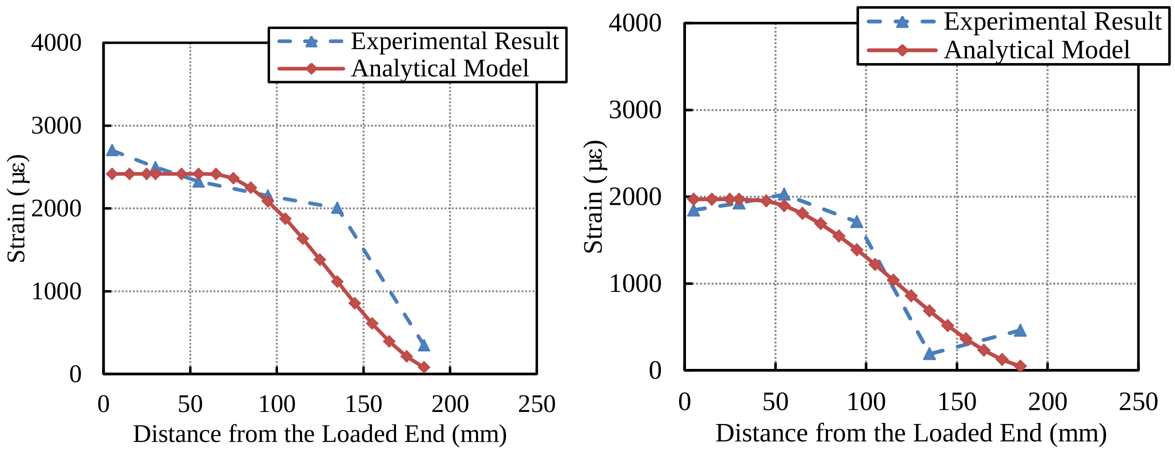
$$s_x = \frac{\varepsilon_0}{L_{eff}^2}x^3 - \frac{\varepsilon_0}{2L_{eff}^3}x^4 \tag{13}$$

$$s_x = \varepsilon_0 x - \frac{\varepsilon_0 L_{eff}}{2} \tag{14}$$

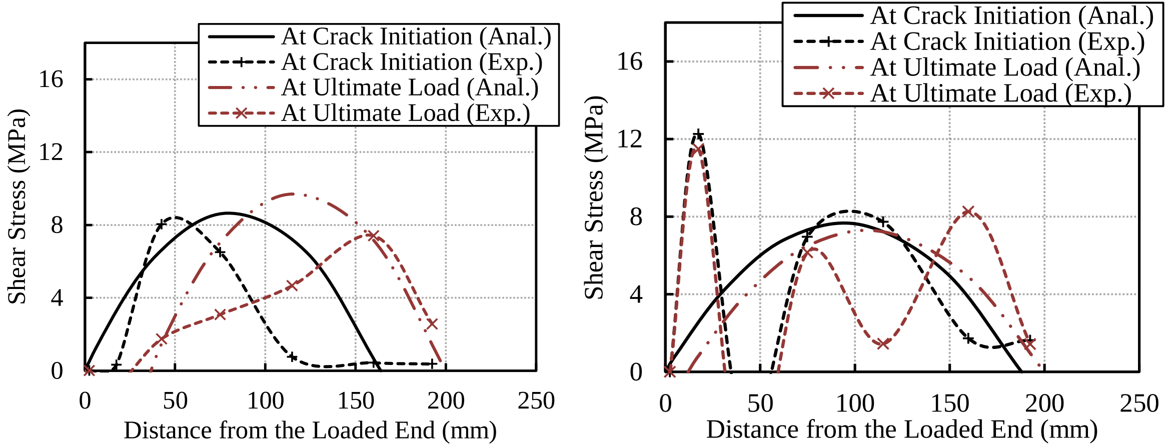
The model which is proposed in this research is solely determined based on boundary conditions of the joint and all of parameters are known. Therefore, the proposed model can predict the interface behaviour of all kinds of joints manufactured by different processing techniques (wet lay-up, pultruded, VARI or HVBO).

VALIDATION OF THE MODEL

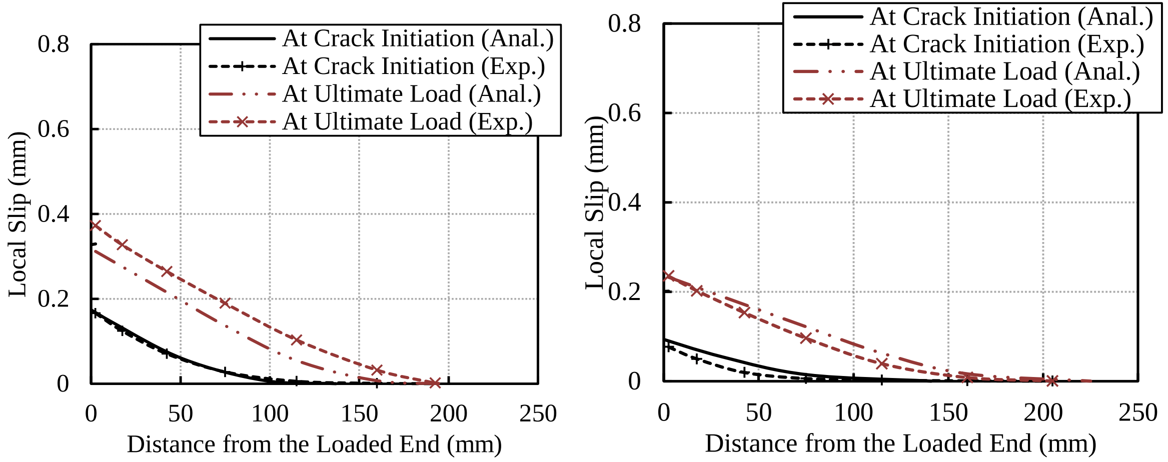
This section evaluates the ability of the proposed model to predict the interface behaviour. It presents a comparison between the analytical results based on the proposed method and the test data obtained from modified single laps shear tests reported in (Gravina et al. 2013; Hadigheh et al. 2013a; Hadigheh et al. 2012; Hadigheh et al. 2013b). The validation is carried out by evaluation of different characteristics of the joints, such as the strain, shear stress and slip profiles (Figure 2).



(a) Pultruded sample (b) VARI sample



(c) Pultruded sample (d) Wet lay-up sample



(e) Pultruded sample (f) VARI sample

Figure 2. Comparison between proposed models and single lap shear test results for (a & b) strain profile, (c & d) shear stress, and (e & f) local slip profile

Figure 2 represents the FRP strain at the level of ultimate load. Shear stresses and local slips are studied at the loading level at which the interfacial crack starts to propagate over the bond length. The analytical results obtained from Eqs. 6 to 14 are in good agreement with experimental observations. Although some deviation exists between the experimental and analytical results, the shear stress and local slip profiles are predicted well for both initial and ultimate stages of loading. This variation is due to the effects of external parameters such as, local stresses at the loaded end of the FRP (Yao et al. 2005).

The proposed analytical approach can estimate the bond stress and its distribution over the FRP constantly and smoothly. The crack starts at the loaded end and propagates toward the free end during different stages of loading and finally leads to FRP debonding. In the models suggested in the literature, a constant shear stress is assumed along the bonded region after the initiation of macro-crack. However, experimentally-observed distributions of the shear stress of the joints at different loading levels reveal that the magnitude of maximum shear stress, τ_{max}, changes along the bondline. The predicted shear stress profile of the specimens in Figure 2 shows that the model which is proposed in this research is able to successfully capture the variation of the stress profile along the FRP.

CONCLUSIONS

An analytical approach was developed to analyse the interfacial stresses of externally bonded joints. Since the model was characterised solely based on boundary conditions of the joints, it can be applied to any type of the FRP processing techniques. Based on the strain profile, bond-slip relations were proposed in which the interfacial behaviour was characterized considering values of the applied load at each stage and the properties of the adherent regardless of the strain measurements on the FRP. Comparison between analytical models and experimental data indicated that the proposed relationships can significantly estimate the interface behaviour of FRP-to-concrete bonded joints.

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