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Prediction of the bond–slip law in externally laminated concrete substrates by an analytical based nonlinear approach

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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 the FRP in strengthening of the 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 article introduces a simplified analytical method to define the bond–slip law of the FRP–concrete interfaces. The advantage of this procedure is that the model is developed only based on boundary conditions and therefore can be applied to any type of the adhesively bonded joints. Subsequently, the bond characteristics obtained from the proposed model is compared with the experimental results and the previous models. A modified single lap shear test set-up is adopted during the experiments. In addition, a new relationship is proposed for determination of the fracture energy corresponding to antisymmetric in-plane shear mode. Analytical analysis indicates that the interfacial fracture energy increases for the samples with thicker bondline or lower FRP-to-concrete width ratio.

1. Introduction

Failure in adhesively bonded joints occurs in several ways, namely substrate failure, FRP delamination or failure in bond between two adherends. In structures strengthened with fibre reinforced polymer (FRP) materials, interfacial debonding typically governs the critical failure mode. The bond failure may affect the total integrity of the structure considering that the ultimate capacity and desirable ductility of the strengthened structure may not be achieved. The possible failure pattern in strengthened flexural or shear members is a complicated phenomenon regarding the interfacial behaviour in externally bonded (EB) joints [1]. Concerning this issue, extensive experimental [2–10] and theoretical investigations [11–13] have been carried out and classified in the literature to address the bond behaviour between the FRP and concrete substrate.

A large number of researches have been conducted to investigate the effects of different parameters on the fracture mechanics in adhesively bonded joints [14–21]. These factors are mainly; the height of the free concrete edge [20], loading offset [20], bonded length [4], FRP width [22], concrete compressive strength [3], and concrete composition [21]. Despite these researches, still very little investigation has been done to study the effects of bondline thickness on the bond between the FRP and concrete. The interfacial shear stresses were studied in the experiments carried out by Barnes and Mays [18] on steel-to-concrete bonded joints considering different thicknesses for steel plate and adhesive. Results showed that the shear stress was characterised over the bondline with an exponential profile and the increase in adhesive or plate thickness leads to lower peak stress level and subsequently higher bond capacity [18].

Lopez et al. [23] performed beam tests to determine the bond characteristics of FRP-to-concrete bonded joints. The concrete strength and adhesive thickness varied between 20–60 MPa and 2–3 mm, respectively. They found that load carrying capacity of the joints varies with the changes in concrete compressive strength and adhesive thickness. For the low-strength concrete, failure is more likely to happen in the concrete while for higher strength concrete, it occurs in the weakest part which is the concrete–adhesive interface. Therefore, thicker bond can help to redistribute the stresses and increase the load capacity of the joint. Considering the failure patterns, concentrated shear and normal stresses contribute to the transverse adhesive failure in samples with high concrete strength. Since the behaviour of the FRP is different from steel plates, the results of the former experiments, Barnes and Mays [18], cannot be developed to the FRP-to-concrete bonded

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joints and in the later tests, Lopez et al. [23], the variation of the adhesive thickness was limited (between 2 and 3 mm).

Several analytical approaches have been presented to achieve a comprehensive understanding about the bond–slip constitutive law between the FRP and concrete. Oehlers [24] identified the generic debonding mechanisms which occurs in FRP strengthened reinforced concrete beams and slabs under flexural, shear and axial loads and categorised them into flexural intermediate crack (FIC), plate end (PE), critical diagonal crack (CDC), and shear intermediate crack (SIC) debonding regarding the place where the crack occurs. Based on nonlinear fracture mechanics analysis, Chen and Teng [25] proposed a relationship to predict the ultimate bond strength and effective bond length for steel and FRP plates bonded to concrete. Reviewing the anchorage strength models in accordance with an extensive experimental data, Lu et al. [26] provided predictions for the bond strength and the strain distribution in the FRP plate employing a meso-scale finite element model in conjunction with a fast Fourier Transform smoothing procedure.

The bilinear local bond–slip model is employed to express the interfacial shear stress and load–displacement response in a closed-form analytical format at each loading stage [27]. Seracino et al. [28] presented an analytical model using a simplified linear-softening interface bond–slip relationship to calculate the debonding resistance and critical bond length in externally bonded (EB) plates and also near surface mounted (NSM) strips. This model is a function of geometric and material properties through which the debonding failure plane and confinement ratio is considered [28]. Nonlinear micromechanics-based finite element method has been applied to develop theoretical models for the normal and shear stress distribution along the bondline beneath the adhesive/concrete interface [29]. To propose three separate bond–slip relationships, the interaction between the interfacial normal stresses and local bond strength were considered [29]. Ulaga and Vogel [30] obtained shear stress of the interface assuming the modified Coulomb failure criterion. Based on the mechanical bond analysis, Ulaga and Vogel [30] proposed a bilinear stress–slip relationship.

This paper introduces a new differential equation method to estimate the local and global strain profile of the adhesively bonded joints. Further a continuously differentiable function is presented for deduction of bond stress along the interface. Generally, the bond–slip models reported in the literature have been derived using the experimental results, or by indirect analytical approaches based on the regression of experimental data, or by finite element analysis. Therefore, the results of the bond–slip relationships are scattered due to the variation and precision of data and cannot be extended to different types of the FRP processing techniques. For analytically or numerically derived models the majority of the existing bond stress models apply sophisticated factors determined based on test data which can vary from one experiment to the other. Hence, 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 adherends. These aspects of the proposed model contribute to overcome the instability of the bond stress function and application of the proposed model to different types of FRP manufacturing techniques.

In the majority of literature, the single lap shear test set-up has been adopted to investigate the bond performance in adhesively bonded joints. According to the FRP–concrete interface fracture mechanism, the slip value is quite small and any error in test set-up can lead to variation in the results. Therefore to overcome such problems, this paper also presents the results of the experimental series through which a modified single lap shear (MSLS) test set-up has been utilised. The experimental series investigate the effect of bondline thickness and FRP/concrete width ratio on the interfacial behaviour of pultruded laminates.

2. Outline of the experiments

Concrete blocks with dimensions of 150 mm in width, 150 mm in height and 300 mm in length were cast using maximum 14 mm crushed coarse aggregates. Mean concrete compressive strength (f'_{cm}) of the blocks was 40.4 MPa with a slump of 80 mm. Details of the samples are shown in Fig. 1. In this research, the bondline thickness and FRP width are studied through *Series IV* and *V*, respectively (Table 1). Three repeated specimens were cast for each combination of test variables in order to achieve reliable results. The results mentioned are a part of a comprehensive experimental program to investigate the bond behaviour between the FRP and concrete.

SikaCarboDur-S1214 and Sikadur-30 were used as unidirectional carbon fibre laminate and epoxy resin which their properties are presented in Tables 2 and 3, respectively. The tensile properties of the laminates were obtained from tensile tests on five FRP coupon samples with loading rate of 2 mm/min based on ASTM: D3039. A modified single lap shear (MSLS) test set-up (Fig. 1) is used in this research by which the slip between the FRP and concrete is monitored with more accuracy. In MSLS test set-ups, the relative slip between the FRP and concrete substrate is measured directly at the loaded end with one LVDT which is mounted onto the concrete. Six 10 mm-length strain gauges were applied on the top surface of the CFRP laminates (Fig. 1 and Table 4) to monitor the strain distribution in the interface during the experiments. More information about the MSLS test set-up is available in [31]. The load was applied to the samples under displacement control condition by an actuator in a 0.2 mm/min rate. In order to distribute the load evenly over the FRP width, FRP plate was tightly held between two grip plates and the load was applied to the grips. Samples were subjected to an 8 kN initial load and then released and finally loaded until the failure.

3. Experimental results

Table 5 summarises the experimental results for two series of the tests. In this table, the slip (S_{max}) when the load reaches its maximum value is presented. The ultimate global slip (S_u) is assumed the slip after which the load response of the joint drops suddenly. For all of the samples the most dominant failure pattern was debonding of a thin layer of concrete beneath the bondline

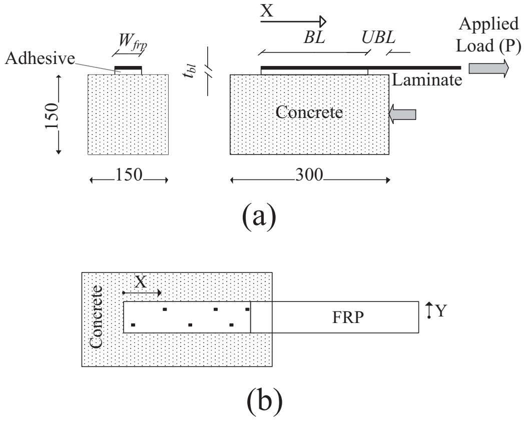

Fig. 1. (a) Geometry of the concrete blocks and (b) position of the strain gauges (dimensions in mm).