23rd Australasian Conference on the Mechanics of Structures and Materials

2014

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Publication details

Zhang, HW & Smith, ST 2014, 'Numerical simulation of FRP-to-concrete interfaces incorporating frictional resistance of debonded plate', in ST Smith (ed.), *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*, vol. I, Byron Bay, NSW, 9-12 December, Southern Cross University, Lismore, NSW, pp. 397-402. ISBN: 9780994152008.

NUMERICAL SIMULATION OF FRP-TO-CONCRETE INTERFACES INCORPORATING FRICTIONAL RESISTANCE OF DEBONDED PLATE

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ABSTRACT

This paper presents a bond stress-slip model for fibre-reinforced polymer (FRP)-to-concrete bonded interfaces that explicitly incorporates frictional resistance arising from the debonded plate. The bond stress-slip model is incorporated into a partial interaction model for the analysis of FRP-to-concrete joints and an FRP-strengthened reinforced concrete (RC) slab. The partial interaction model enables debonding initiation and propagation to be analysed in the joint, while parametric studies demonstrate the influence of key variables such as the level of frictional resistance and the length of bonded plate. A frictional resistance stress at ultimate is finally determined for an FRP-strengthened RC slab based on test strain data.

KEYWORDS

Anchorage, debonding, friction, FRP, partial interaction model.

INTRODUCTION

Externally bonded fibre-reinforced polymer (FRP) composites can be used to strengthen or repair reinforced concrete (RC) structures, however, the FRP can debonding in a brittle manner at strains much lower than its strain capacity (e.g. Bank 2006, Hollaway and Teng 2008). Upon debonding, the plate separates from the concrete substrate and for all intents and purposes the load carrying capacity of the FRP is lost. There, however, are situations in which frictional resistance may be induced between the debonded FRP and the concrete substrate before complete separation of the FRP. Three situations are presented herein:

(i) Long bond lengths that are well in excess of the effective bond length will be subjected to propagating debonding cracks. In this case, there may be frictional resistance induced from the debonded portion of plate while the remainder of the plate is still undergoing debonding. Once the debonding crack has reached the unloaded plate end, the complete plate separates and hence all load carrying capability of the FRP is lost.

(ii) FRP-strengthened flexural members will be subjected to bending and they also contain long bond lengths in excess of the effective bond length. As debonding in slabs generally initiates away from the plate end, debonded regions will remain in contact with the slab as the slab bends and until the remaining bonded plate has fully debonded to the ends of the plate.

(iii) Upon the installation of anchorage devices (e.g. FRP anchors) to FRP-to-concrete bonds, frictional resistance between the interfaces during debonding exists due to the clamping action provided by the anchorage devices. Following complete debonding and anchor failure, the plate then loses its load carrying capability

Bond stress-slip models have been developed over the years in order to quantify the strength and behaviour of FRP-to-concrete interfaces (e.g. Lu et al. 2005). Such models are generally calibrated from test results arising from single- and double-lap FRP-concrete shear tests. A valid assumption in the development of the models from first principles is the existence of zero frictional resistance between the FRP and concrete upon debonding. Semi-empirical models that are calibrated from test results may, however, implicitly contain a frictional resistance component (e.g. Teng et al. 2003).

This paper presents a bond stress-slip model for FRP-to-concrete bonded interfaces that incorporates frictional resistance. The bond stress-slip model is then incorporated into a partial interaction model for the analysis of FRP-concrete bonds in joints and slabs. Parametric studies are performed on FRP-to-concrete joints for key variables of frictional resistance and plate length. A value of frictional resistance for an FRP-strengthened RC slab is finally determined.

BOND-SLIP MODEL INCORPORATING FRICTIONAL RESISTANCE

Figure 1 shows a bi-linear bond slip model that has been modified to include frictional resistance. In this model, τ_{max} = maximum shear stress (MPa), s_o = slip (mm) at τ_{max}, s_{max} = slip (mm) at zero shear stress, and τ_f is the frictional resistance (MPa) provided by the debonded plate. For the case of $\tau_f = 0$, s_{max} represents initiation of plate debonding. For the case of $\tau_f > 0$, plate debonding is assumed to initiate where the descending portion of the shear stress-slip response intersects the constant friction line (i.e. point A).

The shear stress and slip values provided in Figure 1 have been calibrated from a single-lap FRP-to-concrete joint test result provided in Zhang (2013). For this joint (i.e. specimen CNL-250-1), a wet lay-up plate was formed from three layers of carbon fibre sheet (i.e. nominal sheet thickness per layer = 0.131 mm), the plate length and width were 250 mm and 50 mm, respectively, and the width of the concrete block was 200 mm. The concrete compressive cube strength was 47 MPa while the elastic modulus, ultimate stress and strain at rupture of the FRP were 227.5 GPa, 2,978 MPa, and 13,413 με, respectively.

Owing to a lack of recorded test data, τ_f is not able to be directly calibrated. In addition, there is no slip limit imposed on the model. In reality there may or may not be a slip limit although its calibration can be left for future studies. Another assumption with this model is that τ_f is independent of plate force.

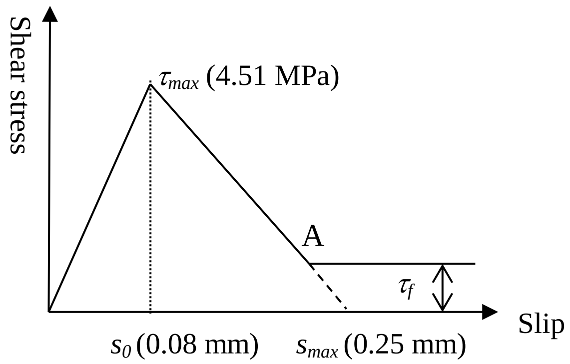

Figure 1. Bond stress-slip model that incorporates friction

PARTIAL INTERACTION MODEL

The details of a partial interaction model are provided in Zhang (2013) and they are not repeated in detail here due to space limitations. In summary though, the modelling approach involves discretising a FRP-to-concrete joint into a series of elements. Constitutive models for the concrete and FRP materials are incorporated as well as a bond stress-slip relationship for the FRP-to-concrete bonded interface. The solution procedure is iterative, where a certain slip at the loaded joint end is assumed and then equilibrium and compatibility are enforced along the length of the joint while a suitable level of load to match the assumed slip is determined. Suitable boundary conditions are also enforced and complete load-slip, load-strain and load-stress responses can be generated by incrementing the slip.

PARAMETRIC STUDIES

The results of parametric studies are provided in this section in order to examine (i) magnitude of frictional resistance, (ii) plate length, and (ii) strain, stress and slip distributions. In this last case, particular attention will be focused on the debonding phenomenon in general. In all three cases, the results are expressed in terms of the load-slip response at the loaded end of the joint. The same control joint geometry used in Zhang (2013) (i.e. CNL-250-1) is considered herein as the default joint parameters unless noted otherwise.

Magnitude of Frictional Resistance Stress

Figure 2 shows the influence of frictional resistance as it is varied from 0 MPa to 1.5 MPa in 0.25 MPa increments. At t_f = 0 MPa, the peak load reaches a plateau. The plateau arises from the bonded plate length being well in excess of the effective bond length and the existence of zero frictional resistance. According to Chen and Teng's (2001) theory, the effective bond length for this particular joint is 120 mm. As the frictional resistance is increased, the load and slip are increased. These increases are important for strength as well ductility and deformability purposes. The load-slip responses are bi-linear in nature and the branching point of the second portion corresponds to the initiation of debonding. With a friction of 1.5 MPa, the maximum load and slip are increased to 28.19 kN and 1.03 mm, respectively, compared to 16.20kN and 0.77 mm for the case without friction. This represents increases in load and slip of 74 % and 34 %, respectively.

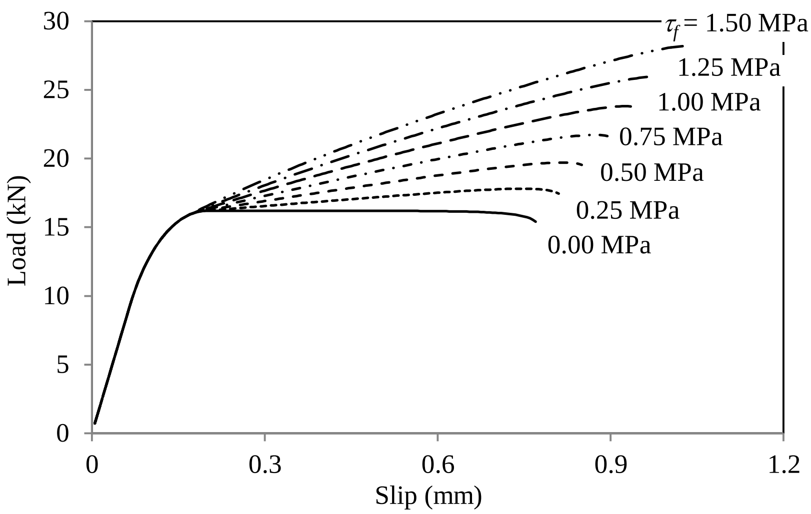

Figure 2. Load-slip responses arising from varying frictional resistance

Varying Plate Length incorporating Frictional Resistance

The influence of plate length is commonly considered to be a fundamentally important parameter in FRP-to-concrete bonds (e.g. Chen and Teng 2001). In this section, the influence of variable plate length is therefore considered in the presence of frictional resistance. For the sake of the study, the plate length is varied from 150 mm to 450 mm in 50 mm increments and the frictional resistance is equal to 0.75 MPa. This friction value represents the average of the values investigated in Figure 2. Figure 3 shows that as the plate length is increased, the load and slip also increase. The increase in load is understandable owing to the presence of friction. The increased slip is also understandable owing to the propagation of the debonding cracks in the longer length of the plate. The load and slip increase by 62 % and 323 %, respectively, as the plate length increases from 150 mm to 450 mm. These represents substantial increases and such long plate lengths would not be uncommon in an FRP-strengthened flexural member.

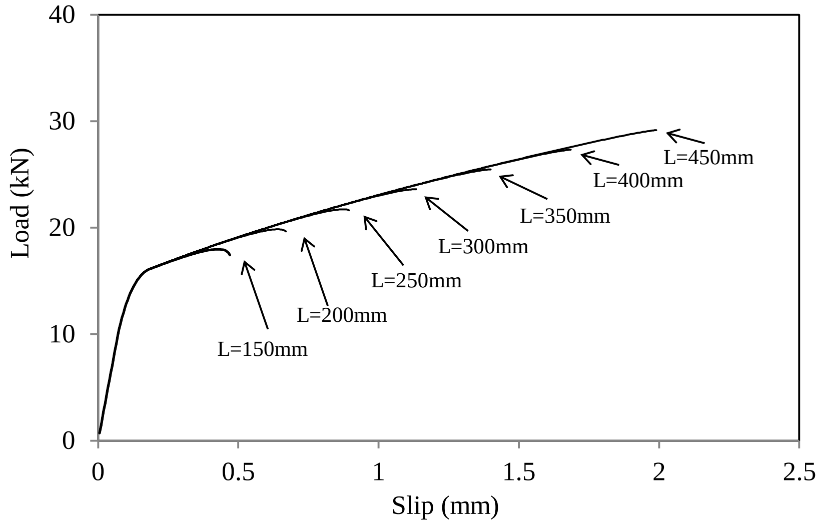

Figure 3. Load-slip responses arising from varying plate length

Strain, Stress and Slip Distributions, and Debonding Process

The debonding process is investigated by considering a plate of 350 mm bonded length and a frictional resistance of 0.3 MPa. This value of friction is derived from the analysis of an FRP-strengthened RC slab in the following sub-section. The key results provided herein though are (i) load-slip response (Figure 4a), (ii-iv) strain, stress and slip distributions along the plate length (Figures 4b-4d, respectively). In Figure 4b, the debonding strain is calculated from the debonding force, P_{db}, divided by the cross-sectional area, A_{frp}, and Elastic Modulus of the FRP plate, E_{frp}. The four sets of results are related to one another by the 13 data points identified in Figure 4a. Three data points are singled out, namely points 1, 3 and 13.

- Point 1: Represents the end of the linear region of the load-slip response. The slip at the loaded bonded end reaches s_0, and the bond stress reaches τ_{max}. The behavior of the load-slip response and strain, stress, slip distributions are identical, with or without frictional resistance.

- Point 3: The plate starts to debond from the concrete and the slip reaches the slip at Point A in Figure 1. The strain at the bonded loaded end is very close to the debonding strain of a joint without the inclusion of friction. The stress at the bonded loaded end, however, reduces to the level of the assumed friction (i.e. 0.3 MPa).

- Point 13: The plate fully debonds from the concrete surface and hence all load carrying capacity of the FRP is lost.

For the results corresponding to points 4 to 12, the plate strain increases linearly in the debonded region. Since the assumption is that the friction is the same for different levels of load, the slopes of the strain curves are the same. As opposed to the case without inclusion of friction, the shear stress does not reduce to zero as the plate debonds from the concrete. It instead reduces to the level of the assumed friction stress and then remains constant in the debonded area. The overall shape of the slip distributions do not noticeably vary between the cases with and without friction.

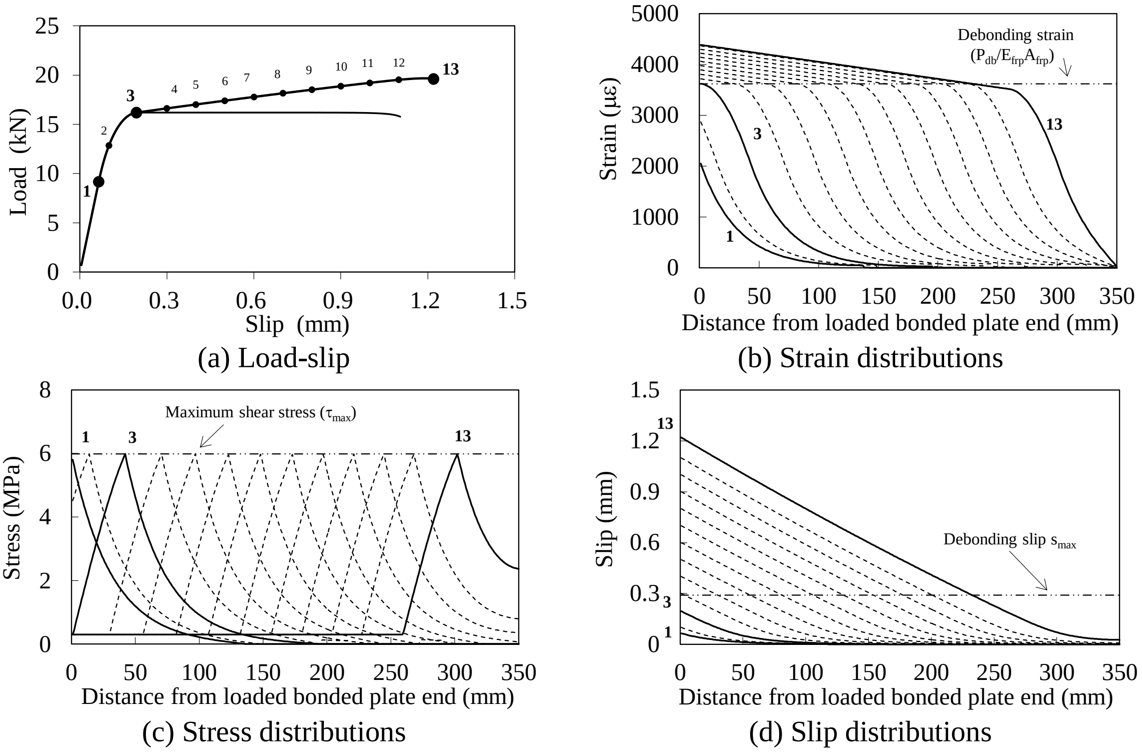

Figure 4. Debonding process of FRP-to-concrete joints considering friction

INVESTIGATON OF FRP-STRENGTHENED RC SLAB

Slab S2.1 provided in Smith et al.'s (2013) study is investigated herein to determine the level of frictional resistance arising from an FRP-strengthened RC slab. The simply-supported slab was 400 mm wide by 150 mm deep and subjected to four-point bending. The concrete compressive cube strength was 39.9 MPa and the slab was reinforced with 10 mm diameter steel bars. The wet lay-up formed FRP plate was made from three layers of the same carbon fibre sheet used in control joint CNL-250-1. The total length and width of FRP plate were 2,200 mm and 100 mm, respectively.

A joint model of 1100 mm plate length was developed and analysed using the partial interaction model. This bond length is half of the length of the FRP plate used in the slab test. The test slab strains recorded from strain gauges applied to the FRP plate are presented in Figure 5. Five different load levels of simulated strains are also shown in this figure, namely (i) 11.05 kN (concrete crack initiation, P_{cra}), (ii) 20.03 kN, (iii) 30.63 kN (onset of reinforcement yielding, P_y), (iv) 36.54 kN (maximum load, $P_{max,1}$), and (v) 33.83 kN (maximum deflection, $P_{f,1}$).

Simulated strain distributions based on a friction stress of 0.3 MPa adequately fit the tested strain results at ultimate. The simulated results capture both the linear ascending trend of strain in the debonded area and the strain profile in the bonded area at the highest load level. The simulations, however, fail to capture the strain distribution at lower load levels. This may be due to the curvature of the slab and gradual formation of concrete cracks that influence the strain distribution. Prior to complete plate debonding, the debonded region is long and hence the model is able to capture the strain distribution well as it is influenced by frictional resistance. Even though the simulated strains only really match at peak load, this represents an important tool for design engineers of which the ultimate load carrying capacity of the slab is required.

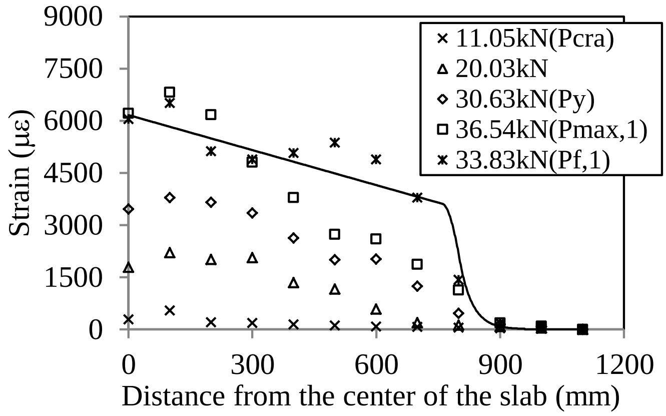

Figure 5. Comparison between test and prediction for an FRP-strengthened RC slab

CONCLUSIONS

This paper has reported an FRP-to-concrete bond stress-slip model that explicitly includes frictional resistance arising from plate debonding. The model was then incorporated into a partial interaction model in order to analyse FRP-to-concrete joints. Parametric studies were performed to understand the influence of the key variables of friction and plate length. Strain, stress and slip distributions were then generated in order to understand the debonding process. Finally, plate strain results arising from an FRP-strengthened RC slab were compared with model predictions. In this case, a friction stress of 0.3 MPa was found to compare well the test results at ultimate load.

Future work can consider to investigate the dependency of frictional resistance to applied load, as well as friction arising from the application of anchorage devices to FRP-to-concrete bonded interfaces.

ACKNOWLEDGEMENT

Southern Cross University is acknowledged for providing facilities with which to conduct the numerical simulations contained in this paper.

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