Numerical Study of Effective Bond Length for Externally Bonded CFRP Plate under Cyclic Loading

Numerical study of effective bond length for externally bonded CFRP plate under cyclic loads

Raid Daud [1, 2], Lee Cunningham [1], Yong Wang [1]

[1] School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, UK

[2] Department of Civil Engineering, Al-Nahrain University, Iraq

raid.daud@postgrad.manchester.ac.uk

ABSTRACT

The reliability of bond is crucial to the performance of concrete structures strengthened with externally mounted CFRP plate. This paper presents a detailed description of a finite element model constructed using ABAQUS 6.10-1, to simulate the behaviour of CFRP-to-concrete bonded joints in single shear pull out tests. Nonlinear finite element analysis with the cohesive surface approach for single shear pull out tests was investigated and validated against existing test results (monotonic and post-fatigue) in order to demonstrate the accuracy of the model. The influence of bond length for different carbon fibre plate stiffness on the ultimate load as well as the de-bonding strain for the post-fatigue analysis was investigated and then compared with existing analytical models. The numerical results suggest that existing analytical models can be non-conservative in estimating the FRP effective bond length in the post-fatigue load regime.

Keywords: *Post-fatigue; Effective bond length; CFRP*

1. Introduction

Recent research has shown that repetitive loading may lead to degradation of bond behaviour between carbon fibre reinforced plate (CFRP) and concrete, Harries and Aidoo [1]. Thus, catastrophic failure may occur at a much smaller load than that adopted for static design. The main focus of this study is to understand the effect of the CFRP plate bond length on the ultimate load capacity and de-bonding strain in a post-fatigue loading regime through detailed finite element (FE) simulation. The effective bond length (Le) may be defined as the active bond zone required to transfer the tension in CFRP plate to the concrete via interfacial shear stresses, Khalifa et al. [2]. Using the commercially available software ABAQUS [3], a 3D FE model of single shear pull-out tests was developed and then validated against the author's experimental results. The experimental work consisted of a series of six specimens subjected to monotonic loading and other six specimens subjected to fatigue loading. The fatigue load specimens were loaded until an interfacial slip of 0.4 mm was reached then monotonic loading was applied until failure. The specimens consisted of 50 x 500 mm CFRP plate and a concrete substrate with dimensions 150x200x500 mm. A 300 mm length of CFRP was bonded to the concrete substrate, whereas a 40 mm (notch) was left unbonded near the loaded end to avoid sudden localised failure, adopting a similar set-up to previous researchers, Yao et al. [4]. This paper describes the FE model and compares the numerical load-slip curves with existing experimental data. Additionally the strain profile for both monotonic and post-fatigue tests with the current analysis is investigated. Further to this post-fatigue analysis is conducted to estimate the effective bond length for different CFRP plate stiffnesses and a comparison made with existing analytical models.

2. Finite element model

The simulation model is constructed using the general finite element software ABAQUS. Fig. 1 shows the structure to be modelled. Two different element types (soild, shell) have been used to model the different materials. For the concrete substrate, the three dimensional eight-node linear brick elements with reduced integration and hourglass control (C3D8R) were adopted. For the CFRP plate, linear three dimensional four-node doubly curved general purpose shell elements with reduced integration and hourglass control were used, these account for the finite membrane strains with five degrees of freedom per node (S4R5).

The adhesive joint was modelled using the cohesive surface approach. This technique represents the surface interaction properties by selecting the concrete surface as a master surface and the CFRP surface as a slave surface to assign a contact pair. Fig.1 shows the support conditions in the single shear pull out test, the concrete substrate facing was restricted in the X, Y, Z directions to prevent movement in the direction of loading to simulate the real case. Further details of the modelling procedure can be found in Daud et. al. [5].

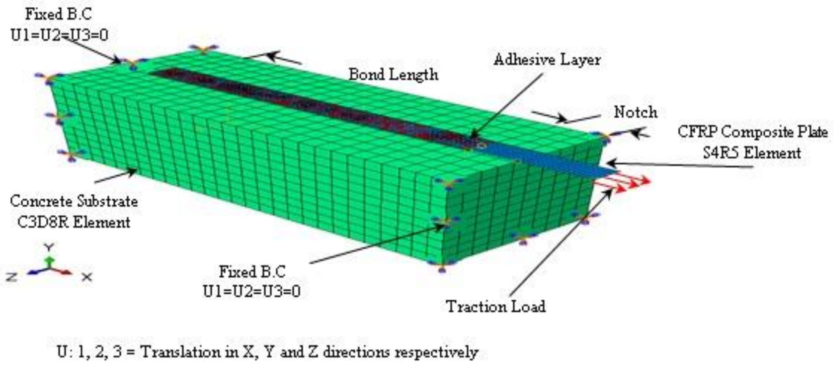
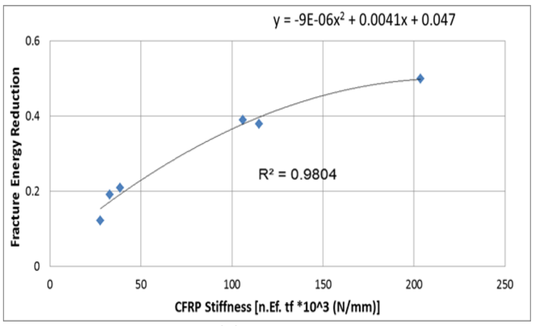


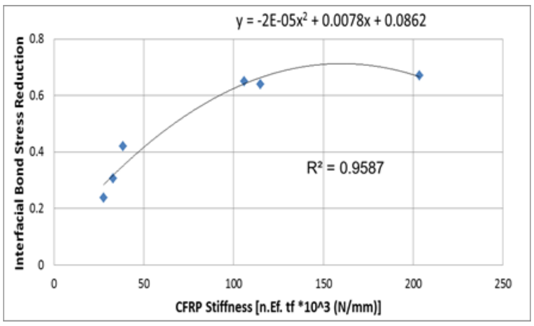
Fig.1: Specimen characteristics and the test configuration for the single shear pull-out test

3. Interfacial bond stress and fracture energy

In the experimental series conducted by the author, Daud [6], the post-fatigue interfacial bond stress-slip relationship showed that both the ultimate bond strength and fracture energy reduces with increase in CFRP plate stiffness for the range of the concrete compressive strengths tested (22.6 MPa - 52.8 MPa). These results indicated that the post- fatigue bond stress-slip relationship is more sensitive to plate stiffness compared to the concrete compressive strength. These reductions are due to cyclic loading history, whereby each single shear pull-out test was subjected to load cycles until 0.4 mm slip between the CFRP and concrete substrate was reached. From the experimental series, the relationship between the CFRP plate stiffness with the ultimate bond strength reduction and the fracture energy degradation are deduced and shown in Fig.2 (a) and (b), respectively. The fracture energy degradation is calculated as a difference between the monotonic and post-fatigue fracture energy. Also, the fracture energy was estimated by measuring the area under the bond-slip curve. Numerical simulations were then implemented to validate the current interfacial bond stress- slip model, as will be discussed in the next section. This experimental data is needed in the cohesive surface approach to define the interaction properties between the CFRP plate and concrete.



(a)



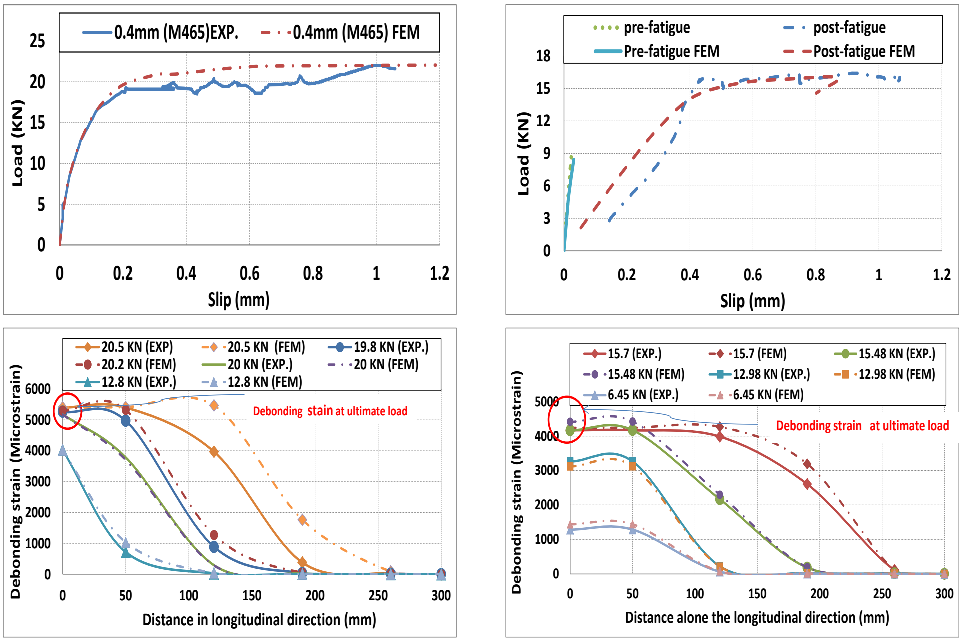
(b)

Fig.2: (a) Experimental interfacial bond stress reduction CFRP stiffness relationship (b) Experimental fracture energy reduction CFRP stiffness relationship

4. Validation of the finite element results

Figure 3 shows the comparison between the numerical results and their corresponding experimental results for representative specimens (0.4 mm M46J), respectively. These results are given in the form of strain distribution along the middle of the bonded CFRP and load slip curves.

The favourable comparison indicates the validity of the numerical models in capturing the test results for both the monotonic and post-fatigue cases through the entire behaviour of the single shear pull out test.

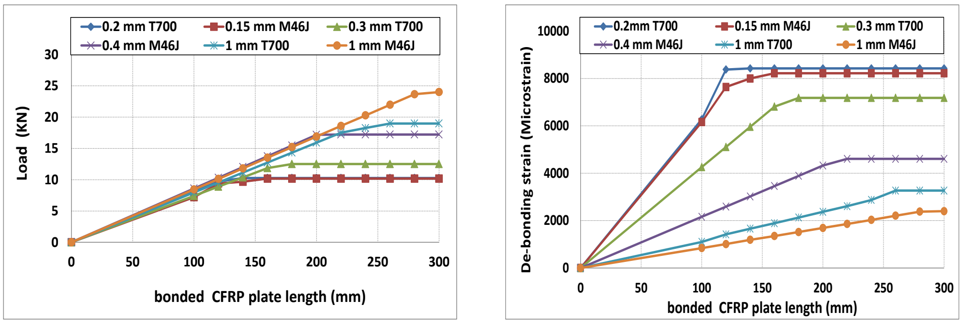


(a) Monotonic test (b) Post-fatigue test

Fig.3: Representative comparisons between numerical and experimental load-slip relationships and stain distribution along CFRP plate (0.4 mm M46J)

5. Effect of bond length based on FE post-fatigue analysis

The effects of bond length on the de-bonding strain and ultimate load are studied for the six post-fatigue single shear pull-out test specimens (i.e. different CFRP plate type and different thicknesses) and then compared with Chen and Teng's [7] analytical model. Fig.4 demonstrates the effect of bond length on the ultimate load and de-bonding strain for six different CFRP plate stiffnesses ($E_f t_f$).



(a) (b)

Fig.4: Effect of bonded CFRP plate length. (a) Ultimate load; (b) De-bonding strain

A comprehensive study of the effect of variations in length on the bonded CFRP plate was conducted. During this study, separate analyses were performed at 100 mm to 300 mm lengths, at intervals of 20 mm. It can be seen that the ultimate load and de-bonding strain increases with increasing bond length until an effective bond length (Le) is reached, beyond which an extension of the bond length cannot increase the ultimate load and de-bonding strain. The effective length ranges from 140 mm for specimen (0.2 mm T700) to 280 mm for specimen (1 mm M46J). Fig. 5 shows a plot of effective length against CFRP stiffness. It is clear that the effective length increases linearly with $\sqrt{E_f . t_f}$ in a similar way to the behaviour predicted by the analytical model proposed by Chen and Teng [7].

However, the values predicted by the analytical model show a significant difference and potential non-conservatism with the current post-fatigue FE effective length results. This is largely because the Chen and Teng's [7] analytical model was based on experimental data obtained from monotonic tests. Hence, the anchorage designs of an externally bonded plate have to consider the effective bond length limit in the fatigue and post-fatigue regime in practice in order to mobilise full tensile strength of the CFRP plate.

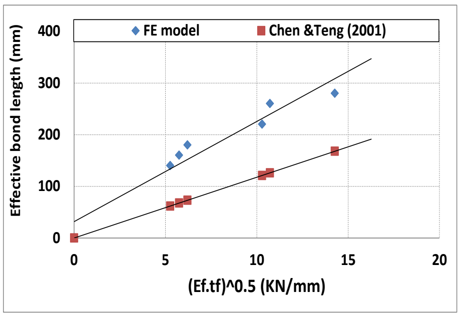


Fig.5: Effect of bonded CFRP plate stiffness on effective bond length

6. Conclusions

- The surface cohesive based model can adequately describe the bond between the CFRP plate and the concrete.
- The experimentally obtained reductions of interfacial bond stress and fracture energy due to previous cyclic loading have been input as interaction properties in the post-fatigue numerical model.
- The post-fatigue numerical study has highlighted the CFRP plate stiffeness influence on the effective bonded length, the specimen with CFRP plate stiffness = 27.67 kN/mm the effective length = 140 mm while the specimen with CFRP plate stiffness =203.5 kN/mm the effective length = 280 mm.
- Chen and Teng's [7] analytical model shows non-conservatism in estimating the post-fatigue FE effective length results for the range of specimens investigated.
- In practice, the anchorage design of externally bonded CFRP plates needs to consider the effective bond length limit for the fatigue and post-fatigue loading regimes.

Acknowledgments

Our thanks to "*The Higher Committee for Education Development in Iraq*" for funding this research. Sincere thanks are expressed to *School of Mechanical, Aerospace and Civil Engineering* of the University of Manchester for providing the facilities to undertake this research.

References

[1] Harries KA, Aidoo J. Debonding- and fatigue-related strain limits for externally bonded FRP. *Journal of Composites for Construction*; 2006, 10 (1):87–90.

[2] Khalifa, A., Gold, W. J., Nanni, A., & MI, A. A. Contribution of externally bonded FRP to shear capacity of RC flexural members. *Journal of Composites for Construction*, 1998, *2*(4), 195-202.

[3] ABAQUS Theory Manual, User Manual and Example Manual, Version 6.10, Providence, RI. 2011.

[4] Yao, J Teng, J. G.; Chen, J. F. Experimental study on FRP-to-concrete bonded joints. *Composites Part B: Engineering*, 2005, 36.2: 99-113

[5] Daud R, Cunningham L, Wang Y. Non-linear FE Modelling of CFRP-Strengthened RC Slabs under Cyclic Loading. Atiner's Conference Paper Series. 2014, CIV2014-0971.

[6] Daud R., "Dynamic behaviour of reinforced concrete slabs strengthened externally with two-way FRP sheets subjected to cyclic loads" PhD. Thesis, University of Manchester, 2015, (in progress)

[7] Chen, J. F., Teng, J. G. Anchorage strength models for FRP and steel plates bonded to concrete. *Journal of Structural Engineering*. 2001, *127*(7), 784-791.