SMAR 2017 – Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

SMAR 2017

Cyclic response of FRP-to-concrete adhesive joints: effect of the shape of bond-slip model

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ABSTRACT: Although the strengthening of reinforced concrete (RC) structures using externally bonded fiber-reinforced polymers (FRPs) have been widely accepted as an excellent technical solution for structural strengthening, only few studies have been conducted to understand and predict the behaviour of FRP-to-concrete bonded joints under cyclic loadings. This paper summarizes the results of a theoretical study aimed at investigating the effect of the shape of bond-slip models on the behaviour of the FRP-to-concrete bonded interfaces under cyclic loading. Two bond-slip model shapes, one with a linear descending branch and another with an exponential descending branch were used in this study. Evolution of damage for each bond-slip model was defined using the existing test data on Carbon FRP (CFRP)-to-concrete bonded joints under cyclic loading. These bond-slip models were then used to predict the behaviour of a CFRP-to-concrete bond joint subjected to cyclic loading. The results are then compared with the experimental results from a CFRP-to-concrete single shear pull off test under cyclic loading.

1 INTRODUCTION

Fiber-Reinforced Polymer (FRP) materials are widely employed as a well-established technique intended at upgrading/retrofitting structural members in existing members, such as concrete beams and columns (Napoli and Realfonzo, 2015), wooden floor beams (Shober et al., 2015) and masonry panels (Martinelli et al., 2016). Many studies have been carried out on flexural strengthening of RC beams using externally bonded FRP plates (Hollaway and Leeming 1999) and design guidelines have been developed. The behaviour of the FRP-to-concrete bonded interface is of critical importance to the performance of strengthened RC beams using externally bonded FRP laminates. Therefore, many studies have been carried out to investigate the bond behaviour of FRP-to-concrete bonded joints (Smith and Teng 2002, Yao et al. 2005, Lu et al. 2005). However, such studies are mostly focused on the behaviour of FRP-to-concrete bonded joints under quasi-static monotonic loading, and only handful of studies so far focused on the behaviour of such bonded joints under cyclic loading, mainly experimentally (Ko and Sato 2007, Carloni et al., 2012) and, more recently, also theoretically (Martinelli and Caggiano 2014, Carrara and De Lorenzis 2015).

Bond-slip models are commonly used to model the constitutive behaviour of the FRP-to-concrete bonded interfaces (Lu et al. 2005). Such bond-slip models describe the relationship between interfacial shear stresses and slips. All the existing analytical models to describe the constitutive behaviour of FRP-to-concrete bonded interfaces under cyclic loading have adopted bi-linear bond-slip relationship as the envelop curve (Martinelli and Caggiano 2014, Carrara and De Lorenzis 2015). While bi-linear bond-slip model were shown to provide a simple yet accurate results for modelling the behaviour of FRP-to-concrete bonded joints under quasi-static cyclic loading, when modelling behaviour under cyclic loading, the rate of damage which is related to the shape of the softening branch of the bond-slip curve may have a significant effect and such effects. However, no study has been carried out so far to study the effect of the shape of the bond-slip curve on the behaviour of FRP-to-concrete bonded joints under cyclic loading.

Against this background this paper presents a study aimed at investigating the effect of the shape of the bond-slip curve on predicting the behavior of FRP-to-concrete bonded joints under quasi-static cyclic loading. Two bond-slip model shapes, one with a linear descending branch and another with an exponential descending branch were used in this study. Evolution of damage for each bond-slip model was defined using the existing test data on Carbon FRP (CFRP)-to-concrete bonded joints under cyclic loading. These bond-slip models were then used to predict the behavior of a CFRP-to-concrete bond joint subjected to quasi-static cyclic loading. The results are then compared with the experimental results from a CFRP-to-concrete single shear pull off test under quasi-static cyclic loading.

2 SUMMARY OF THE EXPERIMENTAL RESULTS

Several single lap shear pull-off specimens were prepared and tested at the University of Queensland Structures laboratory. Nominal dimensions of the specimens are given in Figure 1.

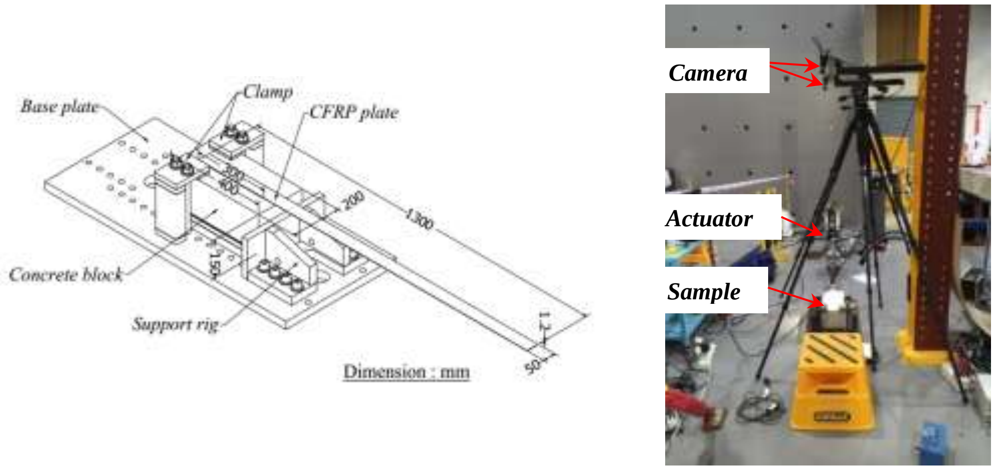

Figure 1. Test rig configuration and Photograph during the test

For all tests, the load was applied using a 100 kN capacity MTS servo-hydraulic actuator. Both monotonic and cyclic tests were carried out at a displacement rate of 0.05 mm/min. In the monotonic test, the sample was loaded up to full debonding of the plate, whereas in the quasi-static cyclic test it was unloaded to zero force at predefined displacement intervals (Table 1).

Table 1 The loading scheme of all samples

Cyclic step	1	2	3	4	5	6	7	8
Max. displacement	0.020	0.035	0.042	0.071	0.127	0.184	0.448	0.523

The load-carrying capacity of the specimens M1, M2 and M3 were 25.5kN, 28.1kN and 26.6kN respectively. Conversely, specimen C1 resulted in ultimate loads of 26.4kN. The analyses proposed in the present paper focus on the cyclic test C1, which is considered for validating the theoretical model whose formulation is outlined in the following section.

3 OUTLINE OF THE THEORETICAL MODEL

Martinelli and Caggiano (2014) formulated simplified theoretical model intended at modelling the cyclic response of FRP strips glued to brittle substrates, made of materials such as concrete or masonry. Specifically, it was based upon the following key assumptions:

- the crack develops at the FRP-to-concrete interface in (pure shear) "mode II";
- the analytical expression of the monotonic softening branch of the bond-slip relationship is described by assuming an analytical expression (either exponential or linear in shape);
- stiffness degradation in the unloading stages depends upon the actual value of the "fracture work" developed in each interface point;
- “small” displacements are assumed at the interface and axial strains possibly developing in the concrete substrate are neglected.

The four assumptions listed above lead to defining the general equations for the mechanical behaviour of FRP strips glued to a brittle substrate (Fig. 2). They are derived by writing the classical “equilibrium”, “compatibility” and “(generalised) stress–strain” relationships, in both monotonic and cyclic response.

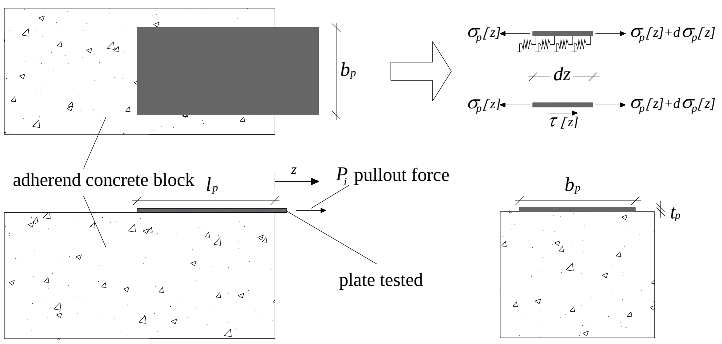

Figure 2. Single-lap shear test of a FRP-to-concrete bonded joint.

The bond-slip equations for the adhesive behaviour can be expressed through two alternative bond-slip laws (even though under the simplified hypothesis of mode II response). The first one is given by the following negative exponential law:

$$\begin{cases} \tau[z] = -k_E s[z] & \text{if } s[z] \le s_e \\ \tau[z] = -\tau_0 e^{-\beta(s[z]-s_e)} & \text{if } s[z] > s_e \end{cases} \tag{1}$$

where k_E is the tangential bond stiffness in pre-peak response of the interface shear-slip relationship, *s[z]* the shear slip at the considered *z* abscissa, $s_e = \tau_0/k_E$ represents the elastic slip value, τ_0 is the shear strength, while β is the exponential parameter of the post-peak τ-s relationship. Then, a linear softening interface model can be alternatively defined by means of the following expressions:

$$\begin{cases} \tau[z] = -k_E s[z] & \text{if } s[z] \le s_e \\ \tau[z] = -\tau_0 + k_S\left(s[z]-s_e\right) & \text{if } s_e < s[z] \le s_u \\ \tau[z] = 0 & \text{if } s[z] > s_u \end{cases} \tag{2}$$

being k_S the negative stiffness in the post-peak branch and $s_u = \tau_0/k_E + \tau_0/k_S$ the ultimate slip.

The unloading/reloading stiffness is modelled within the framework of Fracture Mechanics (FM) theory by considering, for each point of the adhesive interface, the fracture work w_{sl} and the corresponding fracture energy in "mode II" G_f^{II}. The fracture work, w_{sl}, developed during the sliding fracture process, controls the evolution of damage. Specifically, the variable $w_{sl}[s]$ represents the "inelastic portion" of the enclosed area of the τ-*s* curve in the range *[0-s]* (Fig. 3). Moreover, since a unique bond-slip law is assumed throughout the bond length, the value of G_f^{II} is uniform and depends on the physical parameters involved in the two expressions (1) and (2).

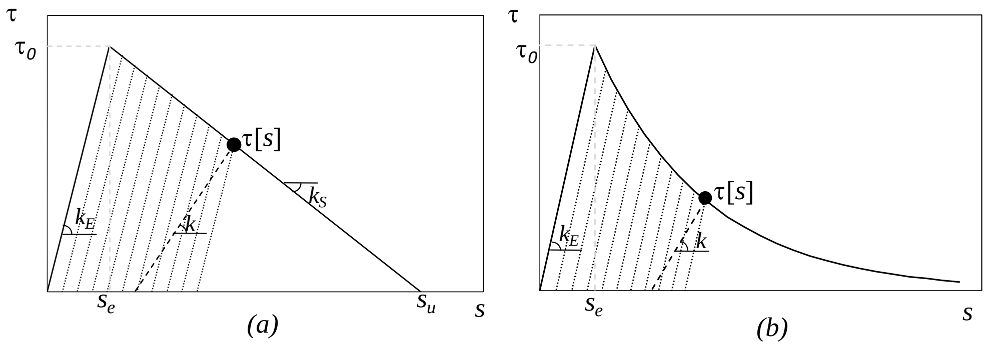

Figure 3. Fracture work spent as defined in eq. (6): (a) linear and (b) exponential softening branches.

Finally, the damage parameter *d* can be defined in each point of the adhesive interface:

$$d = \xi^{\alpha_d}, \text{ with } \xi = \frac{w_{sl}}{G_f^{II}}, \quad (4)$$

where α_d controls the shape of the damage curve and the loading/unloading stiffness *k* is related to the elastic one through the following relationship:

$$k = k_E(1-d). \quad (5)$$

A Finite Difference (FD) procedure was developed for the governing equation under both monotonic and cyclic actions. Details about formulation and implementation of that procedure are omitted herein for the sake of brevity; interested Readers may refer to Martinelli and Caggiano (2014).

4 COMPARISONS

The numerical procedure outlined in Section 3 is employed for simulating the response observed in the test C1, whose experimental results are summarized in Section 2. Specifically, the average value of fracture energy $G_F^{II}=0.723$ *N/mm* determined on the three monotonic tests is considered in the following numerical analyses. Moreover, based on the literature, a value $s_u=0.20$ mm is assumed in eq. (2) and, hence, the maximum bond stress $\tau_0=7.23$ *MPa* is derived accordingly. Furthermore, a value $k_E=400$ *N/mm*^{3} is assumed, both in eq. (1) and (2) for the slope of the elastic branch of both bond-slip law, which are, then, both fully identified.

Figures 4 and 5 show the comparison between experimental results and numerical simulation in terms of force-slip curved measured at the loaded end. The former demonstrates that the assumed linear-exponential bond-slip law results in a highly accurate simulation of the experimental test, whereas a slightly stiffer response is predicted by the bi-linear law in the first part of the non-linear branch. However, both simulations lead to sufficiently accurate predictions of both ultimate displacement capacity and number of cycles leading to complete debonding.

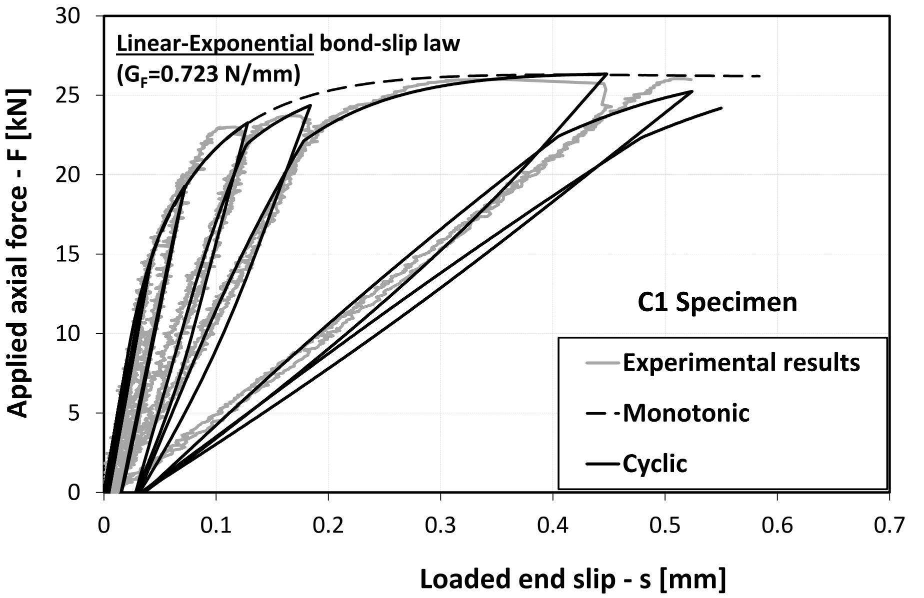

Figure 4. Force-slip response: Experimental vs Numerical results (Linear-Exponential bond-slip law)

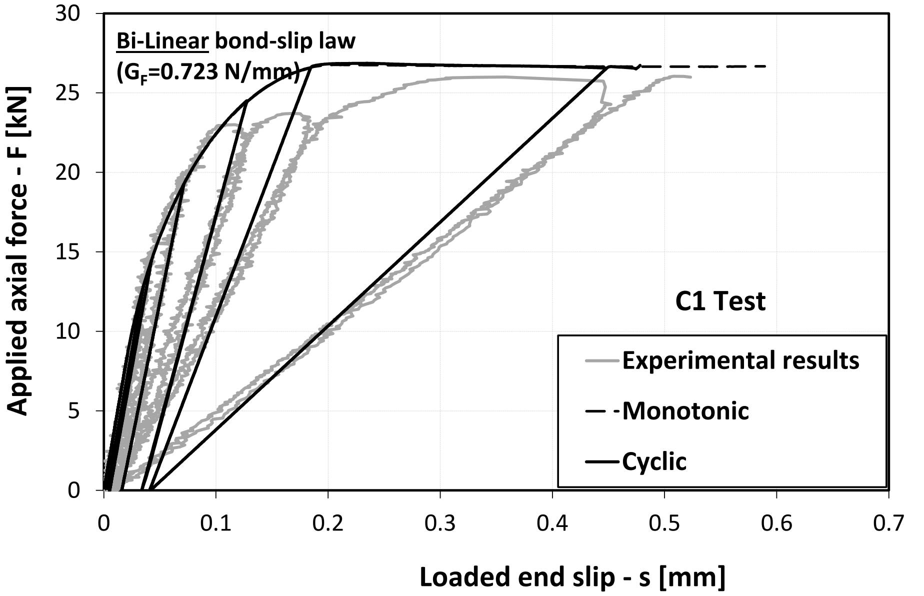

Figure 5. Force-slip response: Experimental vs Numerical results (Bi-Linear bond-slip law)

Furthermore, Figures 6 and 7 proposes and even more challenging validation based on the comparison of axial strain distribution, either experimentally measured or numerically determined, throughout the bond length at the eight load reversals corresponding to the maximum slip value for each cycle. Specifically, the former proposes the results obtained by adopting the linear-exponential bond-slip load, whereas the latter is based on the bi-linear law. Once again, both comparisons are satisfactory in terms of matching between experimental measures and numerical predictions. However, the linear-exponential law showed a better accuracy, especially in the softening range (e.g. Step #8 in Figures 5 and 8).

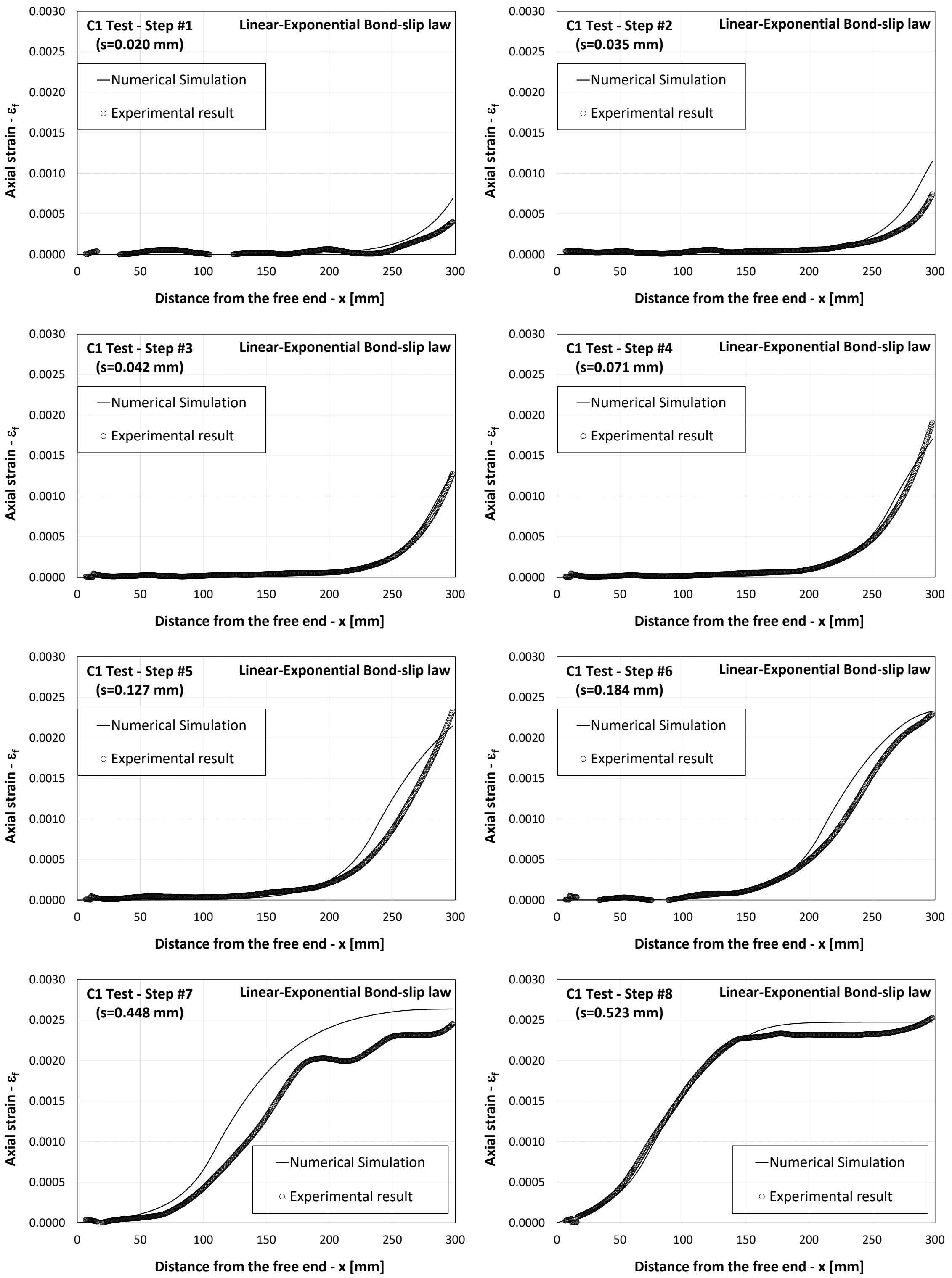

Figure 6. C1 Test: Experimental vs Numerical results (Linear-Exponential bond-slip law)

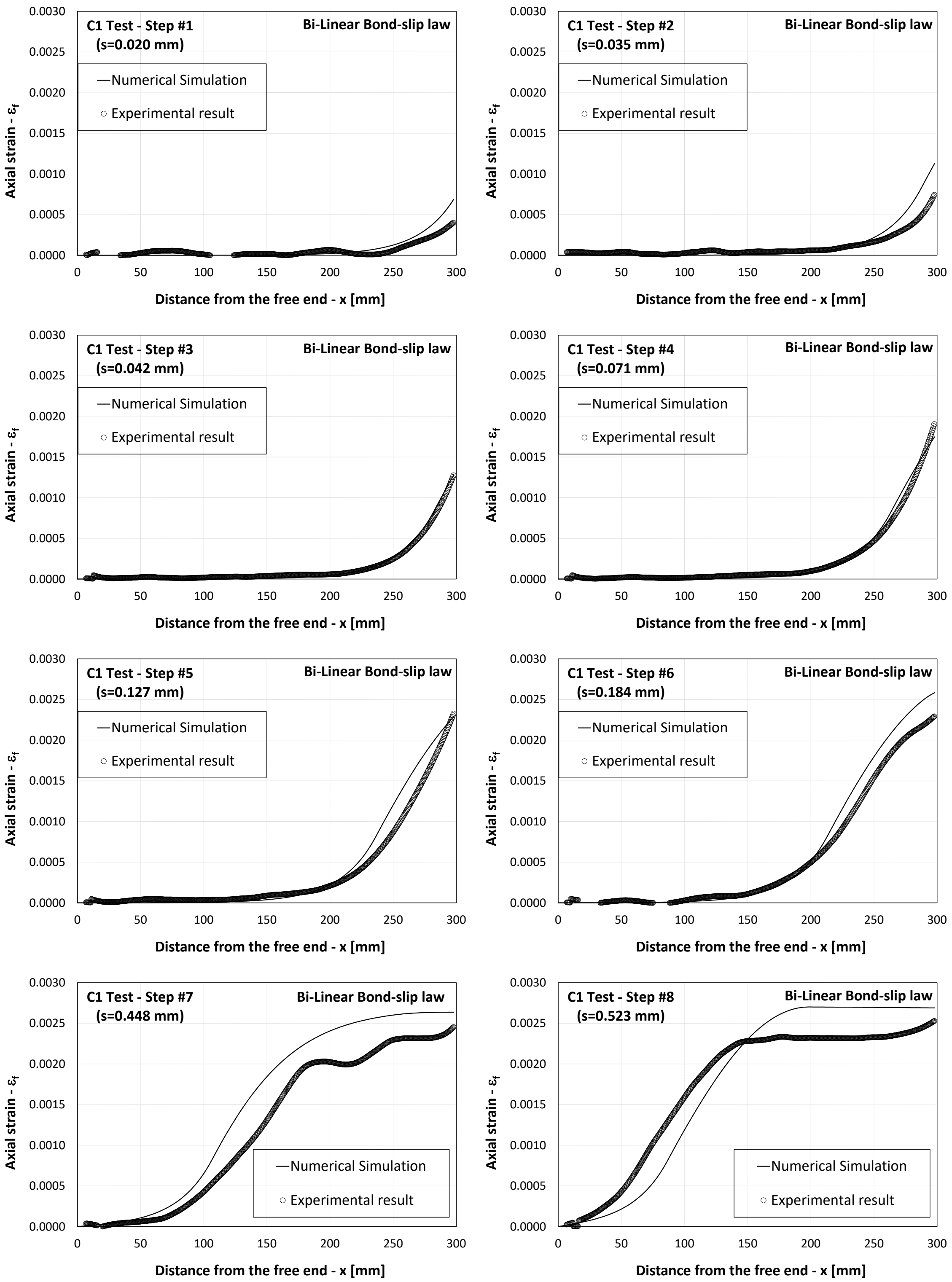

Figure 7. C1 Test: Experimental vs Numerical results (Bi-Linear bond-slip law)

5 CONCLUSING REMARKS

This paper has presented a study investigating the effect of the shape of bond-slip curves on the behaviour of CFRP-to-concrete bonded joints subjected to quasi-static cyclic loading. After summarising the experimental results obtained on both monotonic and cyclic tests carried out on CFRP strips, a numerical procedure has been employed to simulate the cyclic tests.

Two different bond-slip models, a bi-linear model with linear ascending and softening branches and a linear-exponential model with a linear ascending branch and an exponential softening branch were used to investigate the effect of the bond-slip curves on the behaviour of CFRP-to-concrete bonded joints under quasi-static cyclic loading.

The linear-exponential law proved to be slightly more accurate in reproducing both force-slip relationship and axial strain distribution throughout the interface at various stages of the cyclic response. Nevertheless, both bond-slip models led to accurate predictions of the load-displacement behaviour as well as the interfacial strain distributions. Moreover, they both provided a good estimate of the number of cycles resulting in complete debonding under cyclic actions, which is probably the most relevant response quantity in term of macroscopic response of the FRP-to-concrete interface.

Further studies are currently under way with the aim to investigate the relationship between the main structural parameters, among which the shape of the bond-slip law, and the resulting cyclic performance of FRP-to-concrete interfaces, which, in principle, could be described through consistent fatigue curves.

6 REFERENCES

Carrara, P., and De Lorenzis L. (2015). "A coupled damage-plasticity model for the cyclic behavior of shear-loaded interfaces", *Journal of the Mechanics and Physics of Solids*, 85, 33-53.

Carloni, C, Subramaniam, KV, Savoia, M, and Mazzotti, C, 2012, Experimental determination of FRP-concrete cohesive interface properties under fatigue loading, *Composite Structures*, 94, 1288–1296.

Hollaway, L, and Leeming MB. 1999. Strengthening of reinforced concrete structures using externally-bonded FRP composites in Structural and Civil Engineering. Cambridge, England : Woodhead Publishing Limited.

Ko, H, and Sato, Y. 2007. Bond stress-slip relationship between FRP sheet and concrete under cyclic load, *ASCE Journal of Composites for Construction*, 11(4):419-246.

Lu, X. Z., Teng, J. G., Ye, L. P. and Jiang, J. J. 2005. "Bond–slip models for FRP sheets/plates bonded to concrete". Engineering Structures, 27(6), 920-937.

Martinelli, E. and Caggiano, A. 2014. "A unified theoretical model for the monotonic and cyclic response of FRP strips glued to concrete". Polymers, 6(2), 370-381.

Martinelli, E, Czaderski, C, and Motavalli, M. 2011. Modeling in-plane and out-of- plane displacement fields in pull-off tests on FRP strips, *Engineering Structures*, 33: 3715-3725.

Martinelli, E, Perri, F, Sguazzo, C, and Faella, C. 2016. Cyclic shear-compression tests on masonry walls strengthened with alternative configurations of CFRP strips. *Bulletin of Earthquake Engineering*, 14(6): 1695-1720.

Napoli, A, and Realfonzo, R. 2015. RC columns strengthened with novel CFRP systems: An experimental study, *Polymers*, 7 (10), 2044-2060.

Schober, K-H, Harte, AM, Kliger, R, Jockwer, R, Xu, Q, and Chen J-F. 2015. FRP reinforcement of timber structures. *Construction and Building Materials*, 97: 106–118.

Smith, S. T. and Teng, J. G. (2002a). "FRP-strengthened RC beams. I: review of debonding strength models". Engineering Structures, 24(4), 385–395.

Yao, J., Teng, J. G. and Chen, J. F. (2005). "Experimental study on FRP-to-concrete bonded joints". Composites Part B: Engineering, 36(2), 99-113.