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NUMERICAL SIMULATION OF THE FATIGUE BEHAVIOUR OF FRP STRIPS GLUED TO A BRITTLE SUBSTRATE

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Abstract: This paper investigates the behaviour of FRP strips glued to concrete subjected to the cyclic loads often induced on structures by dynamic actions, such as the ones induced by traffic loads or earthquake events. The study moves from a theoretical model recently formulated by the Authors and capable to simulate the mechanical response of the aforementioned FRP-to-concrete joints. The model formulation, shortly summarised in this paper, is consistent with the general assumptions of fracture mechanics and closed-form expressions are obtained for determining the key fracture-related quantities. Then, a parametric analysis is carried out for investigating the influence of both the cyclic load protocol and the bond length on the resulting cyclic response of the system under consideration. The obtained results unveil that debonding failure under cyclic actions can be described by means of general conceptual tools derived by the theory of fatigue.

1 INTRODUCTION

The use of Fiber-Reinforced Polymer (FRP) materials in strengthening and retrofitting existing constructions is nowadays a common solution in civil engineering [1]. Well-established models are currently available in the international technical and scientific literature for predicting the effect of FRP strengthening on existing concrete members [2]. Moreover, the recent publication of up-to-date structural guidelines have further increased the possibility of adopting these materials in field applications [3][4].

However, it is worth highlighting that, from the very beginning [5], the development of cracking processes possibly leading to debonding of FRP strips Externally Bonded (EB) to brittle substrates has been recognized as one of the issues of main concern [6]. In the last decade, the bond behaviour of FRP strips glued to concrete have been attracting in interest of several research groups. In fact, both experimental tests [7][8] and theoretical studies [9][10] investigated the debonding phenomena occurring at the FRP-to-concrete interface. However, these activities were generally limited to the case of monotonic actions and quasi-static loading processes [6].

Nevertheless, FRPs are have been often employed for enhancing the structural performance of RC members subjected to the cyclic actions possibly induced by either traffic loads or seismic shakings. In fact, few studies about the cyclic behaviour of FRP-to-concrete interface are nowadays available in the literature. Furthermore, they are often limited to empirical observation drawn out of experimental tests. Some of these tests aim to observe the cyclic response under wide oscillations of the applied load or imposed displacements [11]: so that debonding crisis occurs after a few number of cycles (low-cycle fatigue) as it is likely to occur under earthquake-induced actions. Conversely, other researches target the behaviour under cyclic actions of smaller amplitude [12][13]: these are intended at reproducing the conditions of FRP strips under the actions induced by traffic loads.

As for modelling, an empirical bond-slip model intended to simulate the behaviour observed in a series of monotonic and cyclic tests carried out on aramid (A), carbon (C) and polyacetal (P) FRP strips glued on concrete blocks can be found in the literature [14]. It is based on assuming a Popovics-like bond-slip law and seven mechanical parameters need to be calibrated experimentally, as a result of the aforementioned empirical nature of the model under consideration.

More recently, a coupled damage-plasticity model has been proposed for simulating the cyclic behaviour of FRP-to-concrete interfaces under cyclic loads, based on a classical bilinear elastic-softening bond-slip law [15].

In the same period, the Authors followed an alternative approach, based on Fracture Mechanics concepts, for formulating a model capable to simulate the cyclic behaviour of FRP strips externally bonded to concrete [16]. Various bond-slip laws (linear-exponential and doubly exponential, along with the aforementioned bi-linear one) have been considered [16]: one of the most attractive features of the proposed model is that the main physical quantities of relevance in Fracture Mechanics, such as the work pent in the fracture process, are derived in closed-form.

This paper is intended as a further contribution to modelling FRP-to-concrete adhesive joints under cyclic actions: it summarises the aforementioned theoretical model and proposes a parametric analysis intended at investigating the cyclic behaviour and the possible fatigue failure of the aforementioned mechanical systems. Hence, Section 2 outlines the key theoretical assumptions of the proposed model and reports some closed-form expressions of the fracture work which can be derived once having assumed “a priori” an exponential expression for the post-peak branch of the bond-slip law. Then, Section 3 presents the main relevant quantities and summarises the most significant results of a parametric analysis carried out for understanding the fatigue behaviour of FRP-to-concrete joints. Finally, Section 4 remarks the main findings of this study and introduces the future development of this research.

2 FORMULATION AND VALIDATION

The key features of a model capable to simulate the debonding behaviour of FRP strips glued on concrete substrate and subjected to cyclic action are summarised in the following. Details about its numerical implementation are omitted herein for the sake of brevity and can be found in a previous work by the same Authors [16].

2.1 Fundamental assumptions

The model is based on the following fundamental assumptions:

- the cracking process develops at the FRP-to-concrete interface in pure “mode II”;
- the softening branch of the bond-slip law is assumed “a priori” and takes an exponential expression;
- stiffness degradation in the unloading stages depends upon the current value of the “fracture work” spent at each point of the FRP-to-concrete interface;
- “small” displacements are assumed at the interface and the concrete substrate is assumed to be rigid.

2.2 Main equations

The four assumptions listed above lead to defining the equations governing the mechanical problem under consideration. Figure 1 depicts the FRP strip glued to a concrete block and a schematic of axial and shear stresses applied on a segmental element of the former.

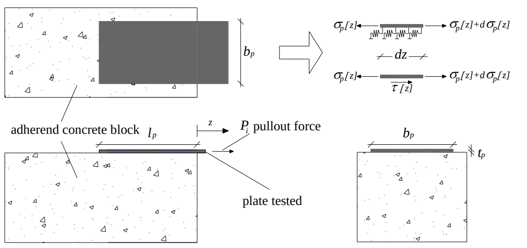

Figure 1: Single-lap shear test of a FRP-to-concrete bonded joint.

Assuming a uniform width and thickness, b_p and t_p, along with a unique bond-slip relationship throughout the adhesive interface, leads to the following equilibrium condition:

$$\frac{d\sigma_p[z]}{dz} = -\frac{\tau[z]}{t_p} \qquad (1)$$

being $\tau[z]$ the interface bond stress and $\sigma_p[z]$ the axial stress in its cross section.

The interface bond-slip law is described by means of the following linear-exponential relationship (Figure 2):

$$\begin{cases} \tau[z] = -k_E s[z] & \text{if } s[z] \le s_e \\ \tau[z] = -\tau_0 e^{-\beta(s[z]-s_e)} & \text{if } s[z] > s_e \end{cases} \qquad (2)$$

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 a parameter of the post-peak τ-s law.

Moreover, the linear elastic behaviour of the FRP strip leads to the following relationship between axial stress and strain:

$$\sigma_p[z] = E_p \varepsilon_p \qquad (3)$$

where E_p is the Young modulus of the composite, whereas the strain field can be calculated by means of the following compatibility condition:

$$\varepsilon_p = \frac{ds[z]}{dz}. \qquad (4)$$

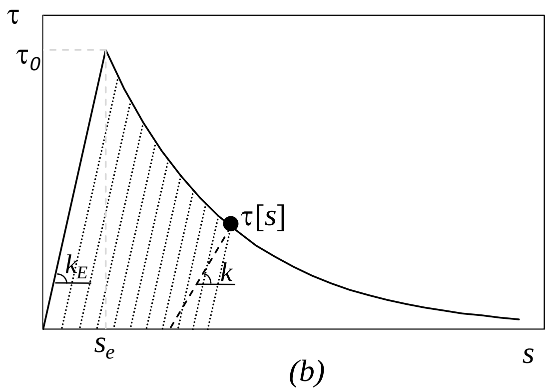

Figure 2: Bond-slip law highlighting the fracture work spent as defined in eq. (6).

Therefore, the following well-known differential equation is obtained by introducing Eq. (4) into (3) and, then, into the equilibrium condition (1):

$$\frac{d^2 s[z]}{dz^2} + \frac{\tau[z]}{E_p t_p} = 0. \qquad (5)$$

The unloading/reloading stiffness is modelled within the framework of 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 accumulated fracture work, w_{sl}, developed during the sliding fracture process, controls the evolution of damage. Particularly, the variable w_{sl} represents the "inelastic portion" of the enclosed area of the τ-s curve in the range $[0\text{-}s]$ (Figure 2). Hence, the work spent in the fracture process can be expressed in closed-form as follows:

$$w_{sl} = \int_0^s \left|\tau[s]\right| ds - \frac{\tau^2[z]}{2k_E} =$$

$$\frac{k_E s_e^2}{2} \cdot \left\{ 1 - e^{-2\beta(s[z]-s_e)} - \frac{2\left[e^{-\beta(s[z]-s_e)} - 1\right]}{\beta s_e} \right\} \qquad (6)$$

and, clearly, $w_{sl} = 0$ for $s[z] = s_e$.

Since a unique bond-slip law is assumed, the value of G_f^{II} is uniform throughout the bond length. It depends on the key parameters involved in Eq. (2):

$$G_F^{II} = \int_0^\infty |\tau[s]| ds = \frac{k_E s_e^2}{2} \cdot \left(1 + \frac{2}{\beta s_e} \right). \qquad (7)$$

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

$$d = \xi^{\alpha_d}, \text{ with } \xi = \frac{w_{sl}}{G_f^{II}} \qquad (8)$$

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:

$$k = k_E (1 - d). \qquad (9)$$

2.3 Model validation

The formulation presented in Section 2 needs to be validated in its soundness and capability to simulate the FRP-to-concrete pull-out behaviour under both monotonic and cyclic conditions. To do so, experimental results obtained from both the aforementioned loading protocols are taken from the scientific literature [14].

The results of some tests carried out on a single ply of Aramid-FRP strips are considered to achieve a preliminary validation of the proposal. Particularly, three equal specimens were tested under monotonic and cyclic actions. They were characterised by an A-FRP strip with relative axial stiffness $E_p t_p = 10.4$ *kN/mm* and width $b_p = 50$ *mm*. Then, the values of the parameters identifying the bond-slip law are assumed as the average value of the results determined by the authors of the paper cited above [14]. Particularly, the values $k_E = 52.22$ *MPa/mm*, $\tau_0 = 2.256$ *MPa* and $G_f^{II} = 0.958$ *N/mm* are assumed in the following numerical simulations.

As for the softening branch, the exponent β in eq. (2) can be consistently derived by the three aforementioned values and taking into account the analytical expression in eq. (7).

Moreover, the unit value is considered for the damage parameter α_d.

Figure 3 compares the results (in terms of force-slip relationship) obtained in the cyclic test referred to as A14 [14] with the corresponding numerical simulations.

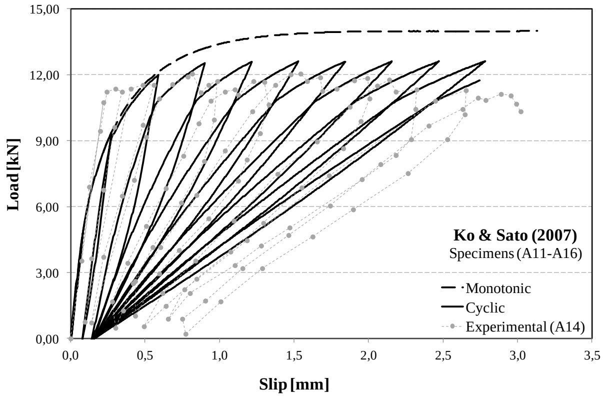

Figure 3: Load-slip response under monotonic and cyclic actions of FRP strips glued on concrete [14].

The agreement between experimental and numerical results is rather satisfactory, especially if it is kept in mind that no fine tuning of the relevant mechanical parameters was performed in this paper, but they were simply assumed in accordance to the values identified by the Authors of the experimental tests [14].

Moreover, a key feature of the proposed model emerges by analysing Figure 3. In fact, although no hysteresis is considered for the unloading/reloading behaviour at the local *material* level by the assumed bond-slip law (Figure 2), a hysteretic response emerges at the global level in the resulting relationship between the applied load and the corresponding slip value at the loaded end of the FRP strip.

The mechanical reason of this peculiar behaviour (clearly observed in the experimental tests, too) has to be sought in the non-uniform value assumed throughout the bond length L by the stiffness k, as a result of the variable value of damage d according to eq. (9). Therefore, the hysteretic response obtained both in experimental tests and numerical analyses has to be regarded as a *structural* effect.

3 PARAMETRIC ANALYSIS

The case analysed in Section 2.4 is considered as the pivot for a parametric analysis intended at better understanding mechanical response and failure mode of FRP-to-concrete joint subjected to cyclic loads.

3.1 Parametric field

The relevant parameters considered in this study deal with either the loading protocol or the system geometry.

As for the protocol, the applied cyclic load is supposed to have a uniform amplitude 2ΔF around a mean value F_m equal to one half of the maximum load F_{mon} obtained in the monotonic loading process and determined as follows [2]:

$$F_m = \frac{F_{mon}}{2} = \frac{\sqrt{2G_F E_p t_p} \cdot b_p}{2} \quad . \tag{10}$$

Based on the values adopted in Section 2.4, F_m= 3.529 kN is assumed. Moreover, the force cycles range between F_{max} and F_{min}:

$$F_{min} = F_m - \Delta F \quad , \tag{11}$$

$$F_{min} = F_m + \Delta F \quad . \tag{12}$$

In this study the value ΔF ranges between $0.15\ F_{mon}$ and $0.45\ F_{mon}$. In other words, the cyclic analyse are conducted by considering:

- a constant mean force F_m;
- a force (and stress) ratio $R=F_{min}/F_{max}$ ranging between 0.053 and 0.538.

More specifically, eight values of ΔF are considered in this parametric study.

As regards the geometry, the parametric analysis is mainly intended to investigate the role of the bond length on the cyclic response of FRP-to-concrete joints. Therefore, three values of L, ranging between 100 mm and 300 mm, are actually analysed.

3.2 Numerical results

The theoretical model summarised in Section 2 is employed for determining the response of the structural systems described in Section 3.1. Particularly, incremental analyses are carried out in displacement control by assuming a value $\Delta s=s_e/10$ as a displacement increment.

A maximum number of 200000 analysis steps is set for the sake of brevity of these analyses; they are mainly intended as a preliminary exploration in the role of some parameters which are expected to play a relevant role in influencing the cyclic response of FRP-to-concrete joints.

The obtained results are firstly reported for the reference case of $L=300\ mm$, as in the case tested in [14]. Hence, Figures 4-11 show the relationship obtained between the applied cyclic force F and the corresponding displacement s_{max} at the loaded end of the FRP-to-concrete joint.

First of all, it is worth highlighting that the analyses of the cases with $\Delta F \leq 0.25F_{mon}$ (Figures 4-6) do not reach the failure within the fixed number of analysis steps. As can be seen in Figure 4, no damage accumulation occurs for $\Delta F=0.15F_{mon}$, even after more than 200000 incremental steps and 10000 cycle reversals simulated in this numerical analysis. As for the other two cases, (namely, $\Delta F=0.20F_{mon}$ and $\Delta F=0.25F_{mon}$, in Figure 5 and 6, respectively), the progressive damage is more apparent than in the previous case, albeit no significant hysteretic response emerges in the load cycles. This is because fracture mainly propagates in the loading branch, while no significant damage is developed in the unloading phase.

A more and more pronounced degradation of the force displacement response is observed for higher ΔF levels. A weakly hysteretic response is actually obtained under the cyclic actions with intermediate amplitude: Figure 7 ($\Delta F=0.30F_{mon}$) is the first one highlighting this peculiarity of the structural response, which is even more evident in Figure 8 ($\Delta F=0.35F_{mon}$).

Moreover, the hysteretic cycles get wider and wider in the case of $\Delta F \geq 0.40F_{mon}$: debonding failure is achieved in these cases after fewer and fewer load cycles. This is typical of a structural behaviour controlled by low-cycle fatigue phenomena developing throughout the FRP-to-concrete interface.

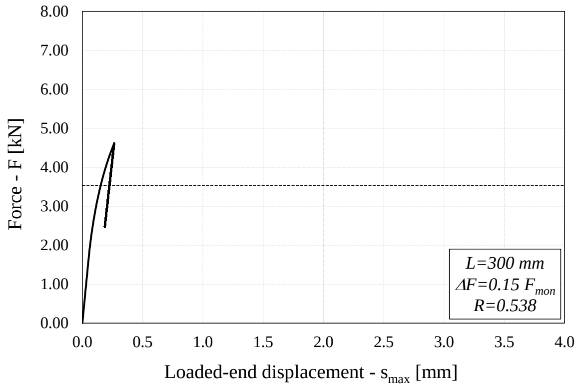

Figure 4: Load-slip curve (L=300 mm, $\Delta F=0.15F_{mon}$).

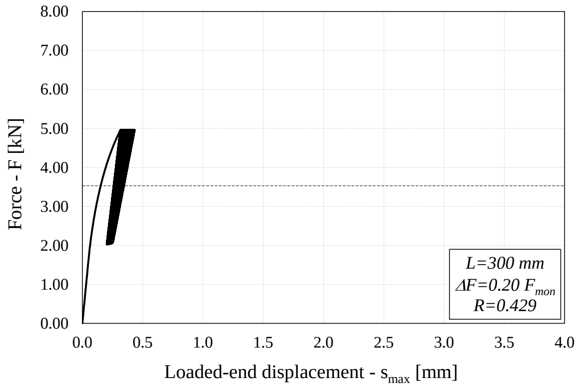

Figure 5: Load-slip curve (L=300 mm, $\Delta F=0.20F_{mon}$).

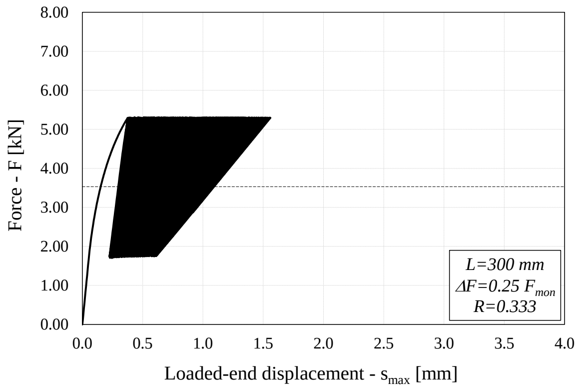

Figure 6: Load-slip curve (L=300 mm, $\Delta F=0.25F_{mon}$).

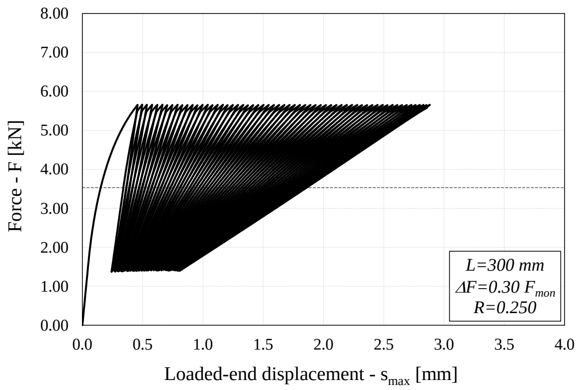

Figure 7: Load-slip curve (L=300 mm, $\Delta F=0.30F_{mon}$).

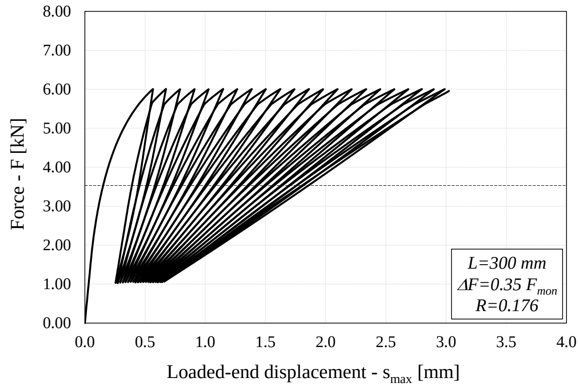

Figure 8: Load-slip curve (L=300 mm, $\Delta F=0.35F_{mon}$).

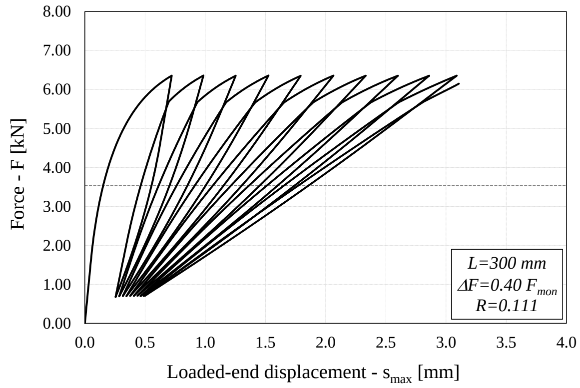

Figure 9: Load-slip curve (L=300 mm, $\Delta F=0.40F_{mon}$).

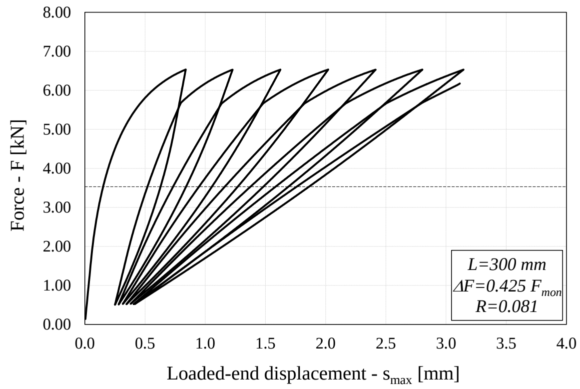

Figure 10: Load-slip curve (L=300 mm, $\Delta F=0.425F_{mon}$).

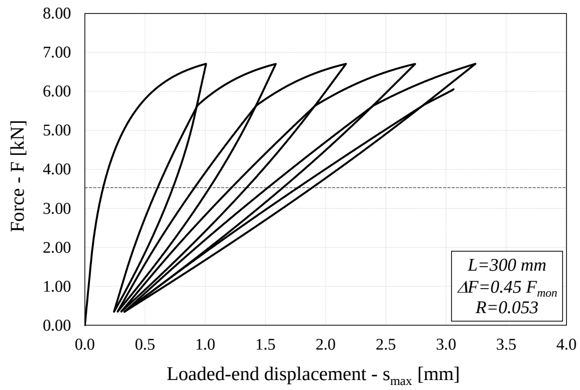

Figure 11: Load-slip curve (L=300 mm, $\Delta F=0.45F_{mon}$).

Furthermore, the role of the bond length can be grasped by analysing Figures 12 and 13 and comparing them to the aforementioned Figure 7. All these three figures refer to a cyclic loading process characterised by $\Delta F=0.30F_{mon}$ (and $R=0.250$), but the bond length L range from 100 to 200 mm. Hence, Figure 12 shows that, as expected, debonding occurs for $L=100$ *mm* after a significantly lower number of cycles with respect to the case of $L=300$ *mm* represented in Figure 7. This number increases significantly for $L=200$ *mm* (Figure 13), albeit remaining lower than the number of reversals observed for the reference case of $L=300$ *mm* (Figure 7).

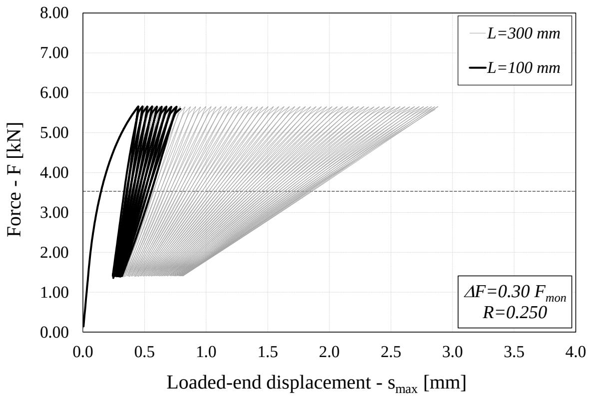

Figure 12: Load-slip curve (L=100 mm, $\Delta F=0.30F_{mon}$).

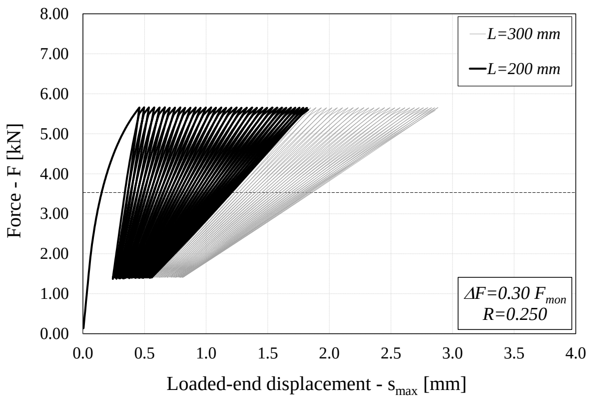

Figure 13: Load-slip curve (L=200 mm, $\Delta F=0.30F_{mon}$).

This observation, whose qualitative extents could have been also figured out based on physical considerations, shed a new light on the mechanical meaning of the bond length in FRP-to-concrete joints. More specifically, although both $L=200$ *mm* and $L=300$ *mm* are longer than the transfer length [2] (being L=100 mm only slightly shorter than that) and, hence, they reach the same strength F_{mon}, a significantly different behaviour characterises the two cases (Figure 13).

Finally, the results reported in the above figures highlight that the concept of transfer length, defined for monotonic loads, needs to be somehow generalised to take into account the effect of cyclic loads. In fact, FRP-to-concrete joints characterised by a given value of the monotonic strength F_{mon}, generally fail under cyclic actions of maximum value F_{max} even significantly lower than the former; however, the longer L, the higher the number of cycles which can be borne.

3.3 Discussion

The structural behaviour simulated for the structural systems under consideration can be regarded in the light of the Theory of Fatigue [17]. Particularly, the well-known Wöhler curve (also known as S-N curve) can be drawn by the results obtained in the three series of numerical analyses carried out for the values of L considered in this parametric study.

First of all, moving from the reference case of $L=300$ *mm*, Figure 14 reports, on the *x*-axis, the number of "cycle reversals" leading to debonding and, on the *y*-axis, the corresponding force amplitude $2\Delta F$. It is worth highlighting once again that, due to the limitation in the maximum number of analysis increments, debonding is actually achieved in the cases of $\Delta F \geq 0.30\ F_{mon}$, and, hence, only the points corresponding to those cases are plotted in the graph.

Figure 14 highlights a remarkable property of the points which, represented in a log-log plane, are aligned on a straight segment and, hence, they can be represented by the following exponential relationship:

$$\frac{2\Delta F}{F_{mon}} = a \cdot (2N)^b \tag{13}$$

where the constants a and b depend on the interface bond-slip law and the bond length; moreover, in principle, they are also influenced by the average stress/force.

The linear shape of the Wöhler curve is

confirmed in both the cases of *L=200 mm* (Figure 15) and *L=100 mm* (Figure 16).

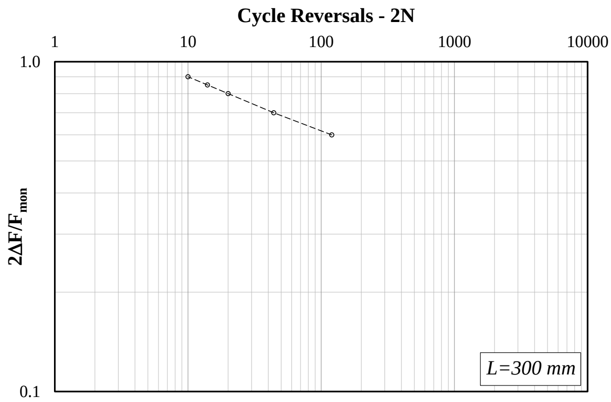

Figure 14: Force amplitude (2ΔF) vs. Cycle reversals at debonding (L=300).

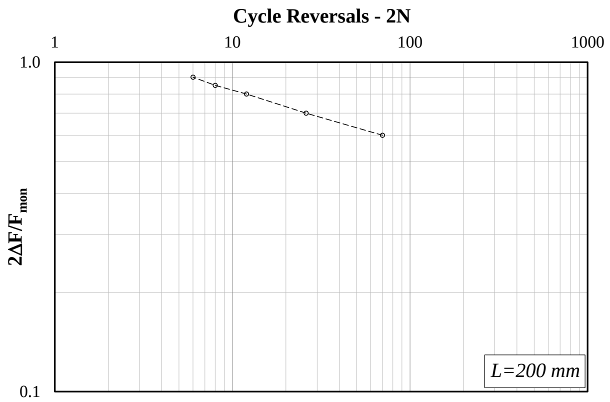

Figure 15: Force amplitude (2ΔF) vs. Cycle reversals at debonding (L=200)

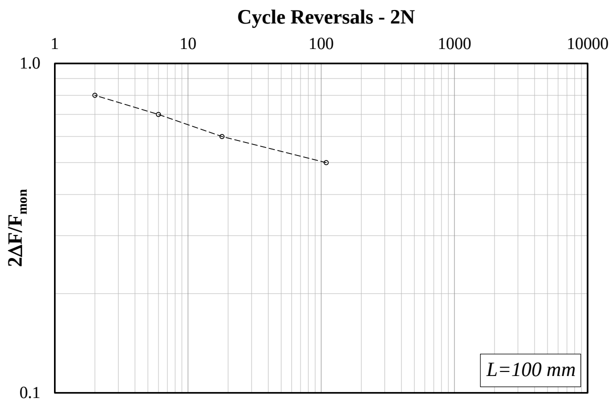

Figure 16: Force amplitude (2ΔF) vs. Cycle reversals at debonding (L=100)

Finally, as a matter of fact, the three curves plotted in Figures 14-16 have almost the same slope, but are shifted in the log-log plane, as lower values of *N* corresponds to the same force amplitude for shorter bond length *L*.

4 CONCLUSIONS

This paper is intended as a contribution to understanding the mechanical behaviour of FRP strips glued to concrete and subjected to cyclic loads. The results of the parametric analysis, proposed herein and based on a theoretical model proposed by the Authors, can be summarised as follows:

- the model under consideration is capable of simulating the cyclic response in a wide range of variation of the relevant parameters;
- as expected, the force/stress amplitude significantly affects the resulting cyclic response of the analysed systems;
- particularly, low-amplitude cycles result in high number of reversals, whereas a progressive reduction in reversals (with significant hysteresis of cycles) is observed for wider cycle amplitudes;
- it is unveiled that the number of cycle reversals can be correlated to the corresponding amplitude by means of a linear curve in the log-log plane, as common in the Theory of Fatigue;
- particularly, the results reported in this paper deals with the so-called low-cycle fatigue ($2N<10^4$) and show that the bond length significantly influences position and slope of the resulting curve.

In the Authors' best knowledge, this remarkable result has not been highlighted yet in the international scientific literature, neither after numerical analyses, nor through experimental tests.

However, this research will be further developed in order to i) validate the model with reference to cyclic tests characterised by various loading protocols, and ii) unveil the relationship between bond-slip law, bond length, relevant FRP properties (e.g. Young's modulus, width and thickness) and the resulting *S-N* curve which describes the fatigue behaviour of FRP-to-concrete joints, both in the low- and high-cycle ranges.

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