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Influence of bond stress-slip relationship on bond strength prediction

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ABSTRACT: The study of the bond stress-slip relationship of FRP (fibre reinforced polymer) adhered to concrete has been a key point to understand the bond behaviour of externally bonded reinforcement (EBR) and near surface mounted (NSM) systems. Researchers have made an effort to determine bond-slip relationships through experimental and analytical/numerical methods, although they have not obtained univocal results.
The area under the bond stress-slip relationship, representing the fracture energy, is one of the main parameters to make bond strength predictions. The fracture energy may be divided in two parts: elastic and softening contribution. These parts act both in a different way in predicting the failure load and the effective transfer length.
In this paper the influence of the shape of the bond stress-slip relationship on the prediction of the bond strength and transfer length is investigated. Hereby, a comparison is made between the bilinear bond stress-slip relationship (linear elastic ascending branch-linear softening branch) and the elastic-exponential bond stress-slip relationship (linear elastic ascending branch-exponential softening branch).

INTRODUCTION

Researchers have studied and characterized the bond behaviour of EBR and NSM systems by means of the bond stress-slip relationship, which describes the stress transfer at the bond interface and characterizes the bond strength (anchorage capacity). Experimental bond stress-slip relationships can be influenced by the test set-up and instrumentation. To reduce these alterations, the area under the bond stress-slip relationship (fracture energy) is used as a global parameter in the bond strength prediction. Considering fracture mechanics models, the theoretical maximum bond force in the EBR system for an FRP-concrete interface with sufficiently long bond length is, Bronsens et al (1998), Dai et al (2005):

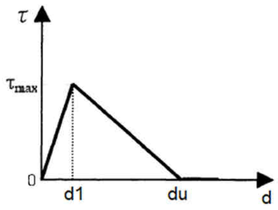
$$P_{max} = b_f \sqrt{2E_f t_f G_f} \quad (1)$$

where:
b_f: FRP width, E_f: FRP Young's modulus, t_f: FRP thickness, G_f: Fracture energy

Implementing (1) , bond stress-slip relationships with the same fracture energy provide the same prediction. Fracture energy is usually formed by two parts: pre-peak ascending branch (G_e-Elastic) and post-peak descending branch (G_s-Softening). In order to evaluate the effect of elastic and softening fracture energy contributions on the bond strength prediction, a parametric study based on the bilinear (Yuan et al, 2001) and exponential (Pan et al, 2014) closed form bond stress-slip relationships has been done. This work also looked into the influence of FRP thickness and stiffness on the transfer length and maximum bond strength.

GENERAL τ-s BEHAVIOUR

Bilinear and exponential bond stress-slip relationships are described by means of the following parameters: the shear strength (τ_{max}), the slip (d_1) corresponding to τ_{max}, the ultimate slip (d_u) and the power (β). The constitutive relationships and the related fracture energy parts G_e and G_s are given in Fig.1 and Table 1.



$0 \le d \le d_1$

$\tau = (\tau_{max}/ d_1)\, d$

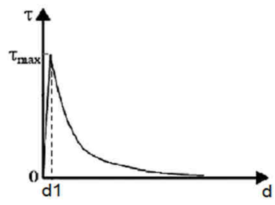
$d_1 \le d \le d_u$

$\tau = (\tau_{max}/ (d_u - d_1))\,(d_u - d)$

$d \ge d_u$

$\tau = 0$

Bilinear



$0 \le d \le d_1$

$\tau = (\tau_{max}/ d_1)\, d$

$d_1 \le d \le d_u$

$\tau = \tau_{max}\, e^{-\beta\,(d - d1)}$

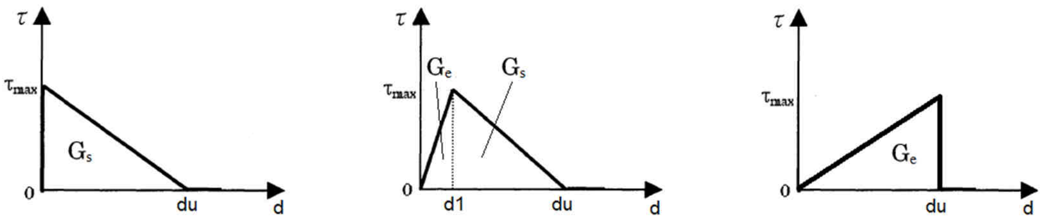
Exponential

Figure 1. Bilinear and Exponential bond stress-slip relationships

Table 1. Parameters and fracture energy

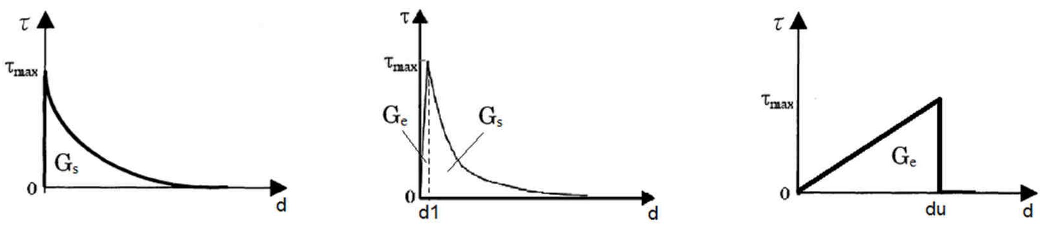
Type	Parameters	G_e	G_s	$G_f = G_e+G_s$
Bilinear	τ_{max}, d_1, d_u	$(\tau_{max}\, d_1)/2$	$(\tau_{max}\,(d_u - d_1))/2$	$(\tau_{max}\, d_u)/2$
Exponential	τ_{max}, d_1, β	$(\tau_{max}\, d_1)/2$	τ_{max} / β	$\tau_{max}\,(d_1/2+\beta)$

Keeping constant the total fracture energy (G_f=0.4N/mm), the maximum shear stress (τ_{max}=4MPa) and the ultimate slip (d_u=0.2mm) different shapes of the bilinear and exponential bond stress-slip relationships are obtained through different d_1 values (0, 0.02, 0.04, 0.08, 0.1, 0.12, 0.16, 0.18, 0.2).



$d_1 = 0$ $\quad$ $0 \le d_1 \le d_u$ $\quad$ $d_u = d_1$

Figure 2. Bilinear bond stress-slip relationships



$d_1 = 0$ $\quad$ $0 \le d_1 \le d_u$ $\quad$ $d_u = d_1$

Figure 3. Exponential bond stress-slip relationships

The tension transfer process (Fig.4) for these bond stress-slip relationships may be described by means of 6 steps:

1) $\tau(x) < \tau_{max}$, $d(x) < d_1$ starting application load, shear stresses are in elastic field (I)
2) $\tau(L) = \tau_{max}$, $d(L) = d_1$ elastic limit is reached
3) $\tau(L) < \tau_{max}$, $d(L) > d_1$ bond length is involved by elastic (I) and softening (II) zones
4) $\tau(L) = 0$, $d(L) = d_u$ softening limit, maximum bond strength
5) $\tau(L) = 0$, $d(L) > d_u$ starting debonding zone (III)
6) $\tau(0) = \tau_{max}$, $d(0) = d_1$ bond length completely beyond elastic stage (I)

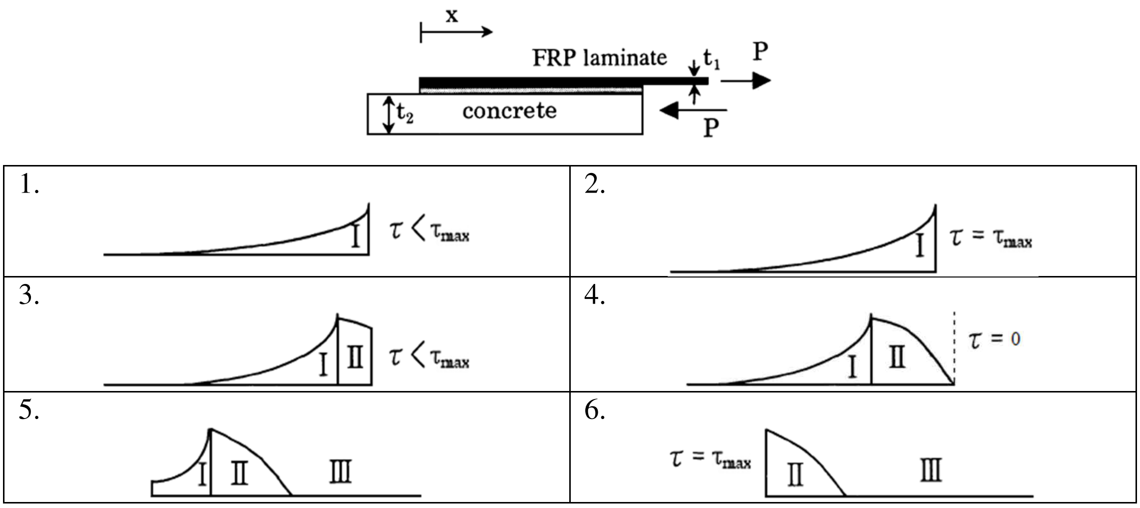


Figure 4. Shear stress distribution, Yuan et al (2001)

Looking at the shear stress distribution, the elastic (P_e) and softening (P_s) bond strength contributions can be calculate:

$$P_t = P_e + P_s = b_f \int_{L_e} \tau \; dx + \; b_f \int_{L_s} \tau \; dx \qquad (2)$$

L_e: bond length in elastic zone (I)
L_s: bond length in softening zone (II)

To investigate the influence of the shape of the bond stress-slip relationship (Figs.2 and 3), a parametric study is conducted varying d_1 and considering predefined properties for the FRP and the concrete as given in Fig.1 and Table 2.

Table 2. FRP and concrete properties

FRP			Concrete		
Thickness (t_f) *mm*	Width (b_f) *mm*	Stiffness (E_f) *MPa*	Thickness (t_c) *mm*	Width (b_c) *mm*	Stiffness (E_c) *MPa*
0.1	100	230000	60	300	32500

BILINEAR τ-s RELATIONSHIP

Considering the bilinear bond stress-slip relationship as reported in Fig.2, the influence of d_1 on the bond strength and effective bond length is shown in Fig.5. The following observations are made:

- the bond capacity increase with available bond length, yet reaching a maximum at the so-called effective bond length,
- the effective bond length increase with d_1, whereas the maximum bond strength remains the same,
- for limited bond length, the bond strength is more sensitive to higher values of d_1

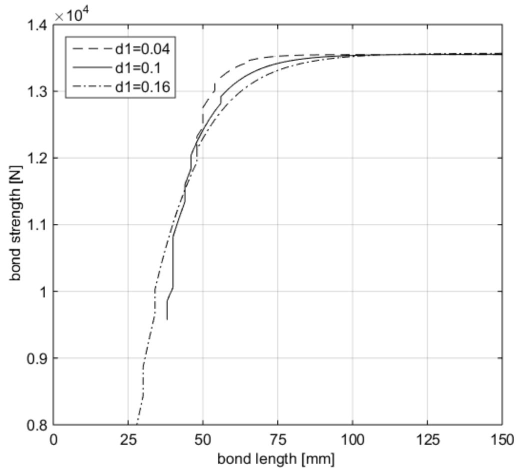


Figure 5. Bond strength along the bond length, for different d_1 (bilinear model)

To understand the effect of the bond stress-slip relationship on the bond strength prediction, Fig.6 shows the interaction between the fracture energies (Elastic and Softening) and the bond strength contributions.

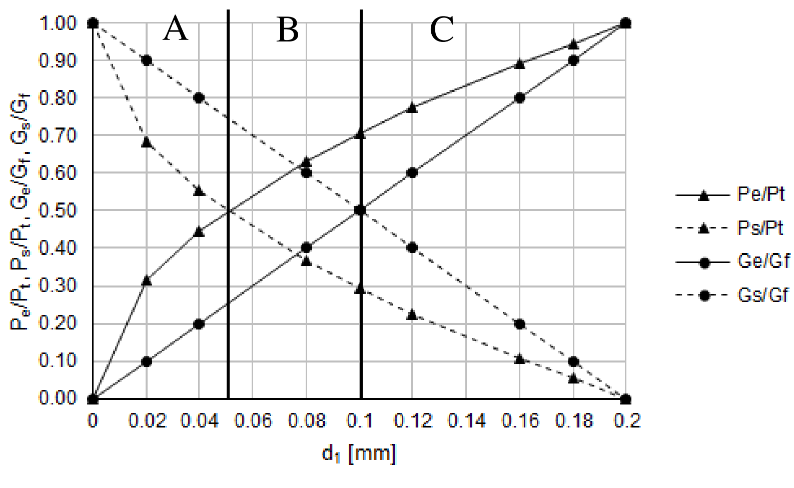


Figure 6. Relationship between fracture energy and the bond strength contributions (bilinear model)

In Fig.6, three different sectors are identified:
A) $d_1 \leq 0.05$mm: the softening fracture energy (and bond strength) is bigger than the elastic one. At $d_1=0.05$, G_e/G_f and G_s/G_f provide the same bond strength contributions P_e/P_t and P_s/P_t, but G_s is three times bigger than G_e.
B) $0.05<d_1 \leq 0.1$mm: softening fracture energy is still bigger than the elastic one. The elastic bond strength contribution starts being higher than the softening part. At $d_1=0.1$, $G_e= G_s$ but $P_e=2.3\ P_s$.
C) $d_1>0.1$mm: elastic fracture energy (and bond strength) is bigger than the softening one.

Using a definition of "efficiency" as the capability of the system to reach the maximum result with the minimum effort, leads to the following observation. Elastic fracture energy has higher efficiency. Indeed, P_e/P_t is always greater than G_e/G_f. The efficiency of the elastic energy is balanced by the "inefficiency" of the softening stage. Indeed, the sum of the elastic and softening bond strength contributions remains constant for the bilinear model.

EXPONENTIAL τ-s RELATIONSHIP

Considering the exponential relationship of Fig.3, the influence of d_1 on the bond strength and effective trasfer length is shown in Fig.7. The maximum bond strength prediction is obtained with $d_1=0.1$, and symmetrical values of bond strength are found with respect to $d_1=0.1$.

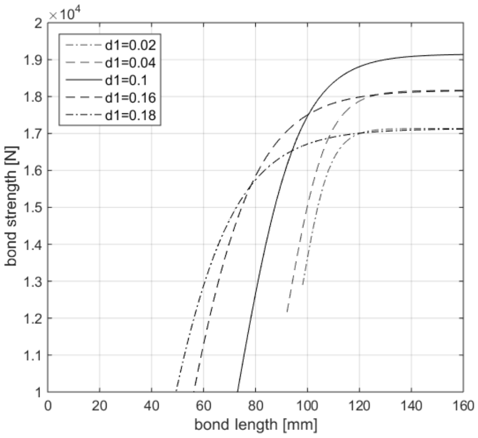


Figure 7. Bond strength along the bond length, for different d_1 (exponential model)

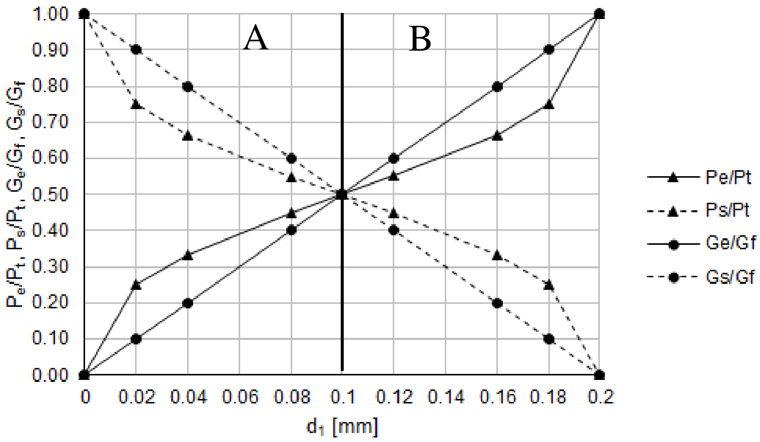


Figure 8. Relationship between fracture energy and maximum bond strength contributions (exponential model)

In Fig.8, two different sectors are identified:
A) $d_1 \leq 0.1$mm: softening fracture energy and bond strength are bigger than the elastic ones. At $d_1=0.1$, G_e/G_f and G_s/G_f provide the same bond strength contributions P_e/P_t and P_s/P_t.
B) $d_1>0.1$mm: elastic fracture energy is bigger than the softening one. Elastic bond strength starts being higher than the softening part.

In this case the elastic fracture energy is only "efficient" for d_1 values lower than 0.1. Again, there is a balanced behaviour between elastic and softening bond strength (efficient or inefficient) for each d_1 value. One has to remind that, unlike the bilinear bond stress-slip relationship, the bond strength prediction changes depending on the d_1 value. To understand the bond strength behaviour in exponential and bilinear model, normalized values of P_s and P_e are shown in Fig.9.

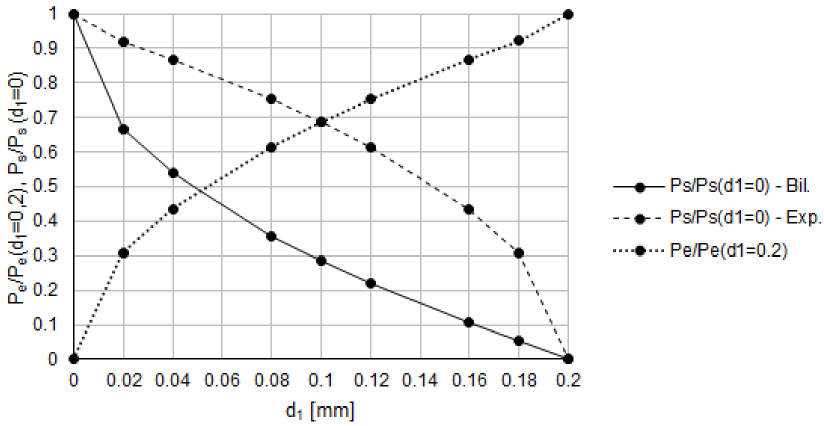


Figure 9. Softening bond strength contributions in bilinear (Bil.) and exponential (Exp.) systems

COMPARISON BETWEEN BILINEAR AND EXPONENTIAL τ-S RELATIONSHIPS

As anticipated, the bilinear and exponential bond stress-slip relationship can lead to different results in terms of bond strength prediction and bond transfer length. At $d_1=0.1$, the exponential bond strength reaches a value 1.4 times greater than the bilinear bond strength (Fig.10).

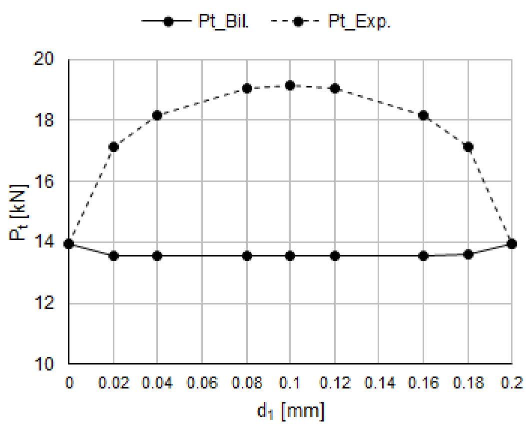


Figure 10. Bond strength prediction in bilinear (Bil.) and exponential (Exp.) systems

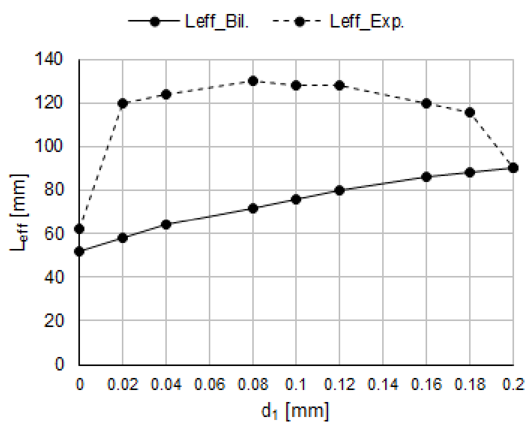


Figure 11. Effective transfer length in Bilinear (Bil.) and Exponential (Exp.) systems

The effect on the effective transfer length is reported in Fig.11, here at d_1=0.1 the L_{eff}_Exp (exponential model) is 1.7 times bigger than the L_{eff}_Bil (bilinear model). Looking at Figs.10 and 11 the increase of the bond strength P_t_Exp related to the increase in bond transfer length.
To evaluate the influence of FRP Young's modulus and FRP thickness on the bond strength and L_{eff}, d_1=0.02 has been fixed. The results are shown in Figs.12-15.
A change of FRP thickness from 0.1mm to 1mm leads to an increase of the bond strength and effective transfer length with a factor 3. In addition, the bond strength and effective transfer length increases 2.2 times when the FRP Young's modulus shifts from E_f=50GPa to E_f=250GPa.

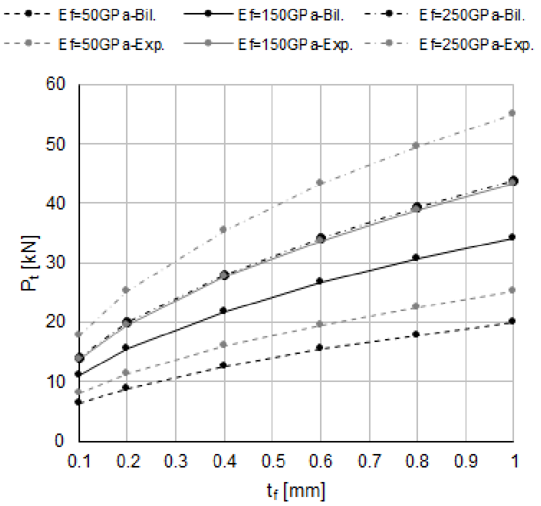


Figure 12. Bond strength as a function of FRP thickness and FRP Young's modulus (E_f)

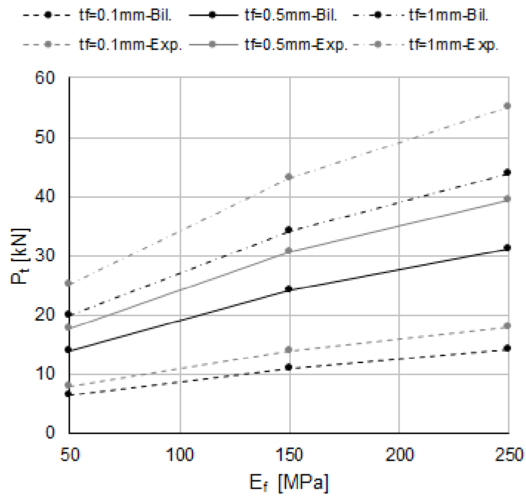


Figure 13. Bond strength as a function of FRP Young's modulus and FRP thickness (t_f)

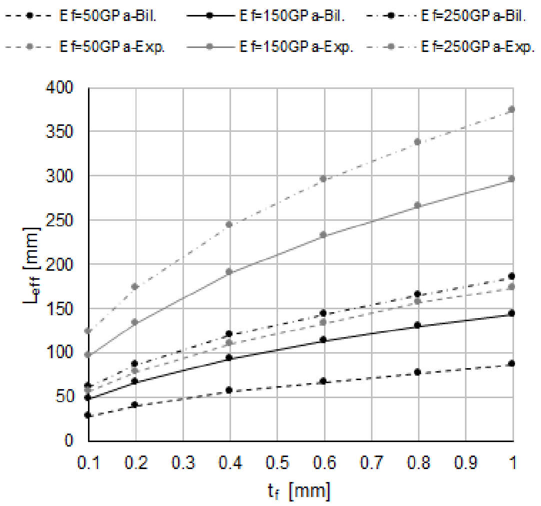


Figure 14. Effective transfer length as a function of FRP thickness and FRP Young's modulus (E_f)

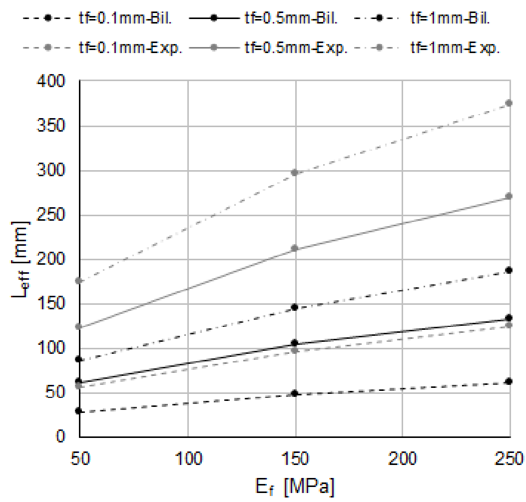


Figure 15. Effective transfer length as a function of FRP Young's modulus and FRP thickness (t_f)

As can be noted from Figs.12-15, the influence of the FRP thickness and FRP Young's modulus on P_t and L_{eff} is not linear proportional. In Figs.16 and 17 the not-proportional behaviours of the bond strength and effective transfer length as a function of t_f are shown, by considering the slope of Figs.12 and 14. A similar result is obtained for the influence of E_f.

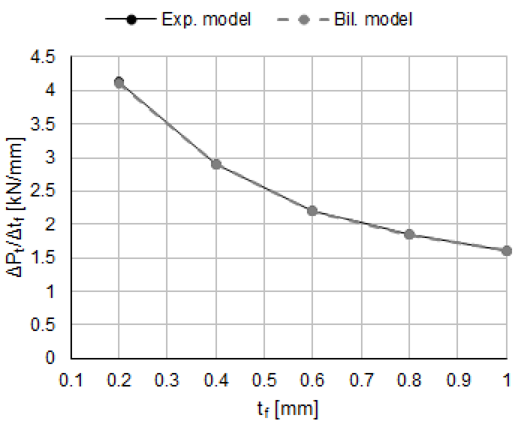


Figure 16. $\Delta P_t/\Delta t_f$ as a function of FRP thickness (E_f=150MPa)

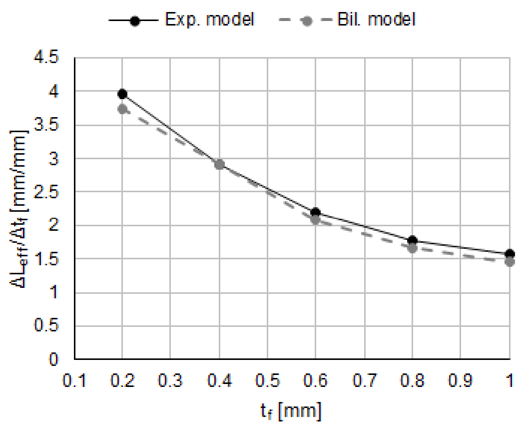


Figure 17. $\Delta L_{eff}/\Delta t_f$ as a function of FRP thickness (E_f=150MPa)

CONCLUSIONS

This work has focused on the shape of the stress-slip relationship in order to evaluate the influence of the τ-s relationship on the bond strength prediction and the effective transfer length. From this parametric study, the following main conclusions can be drawn:

1) Evaluating the bond strength by only considering the fracture energy may be inadequate.
2) For given values of G_f and τ_{max}, the bond strength based on exponential model is sensitive to d_1 value whereas the bilinear model provides the same prediction.
3) For the bilinear model, the elastic fracture energy allows to obtain higher higher bond strength contributions applying lower energy rates. For the exponential model, elastic fracture energy appears only efficient when d_1<0.1mm
4) The exponential bond stress-slip relationship provides (at d_1=0.1mm) a maximum bond strength 1.4 times greater the bilinear relationship. This value needs an effective transfer length 1.7 times higher than the bilinear system.
5) The increase in bond strength and effective transfer length with FRP thickness is not proportional, and tends to reduce for higher FRP thickness values.

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