Numerical Study on the Influence of Geometry and Mode – II Fracture on the Behaviour of Concrete – CFRP Interface

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Abstract. In the present work, a numerical simulation using the finite element method is performed to study the behaviour of the concrete–CFRP interface. The bond between concrete and CFRP is modelled using interface elements with initial zero thickness and non-linear fracture mechanics. The corresponding constitutive law presents an initial linear ascending branch, until the value of the cohesion is reached, followed by an exponential descending branch.

The three parameters used to define the interface behaviour, namely the cohesion, stiffness and fracture energy in mode-II, are obtained from a parametric study and compared with experimental results from shear lap tests [1].

From this study and according to several authors, it is possible to conclude that the interface behaviour is influenced by both mechanical and geometrical properties, such as reinforcement width. In particular, it is observed that, depending on the relationship between the cohesion and interface stiffness, the elastic branch of the interface bond-slip law can assume a significant role. This applies both to soft adhesives, as they present a reduced interface stiffness, and to high cohesion interfaces. In these cases, the contribution of the elastic branch should not be neglected and the use of an adequate model is recommended.
1 INTRODUCTION

In the last few decades we have witnessed an increasing use of externally bonded CFRP sheets or laminates for the strengthening of concrete structures. Much research has been done related within this topic and now existing models can accurately predict the increase in strength of the structure. Yet, experimental studies show that traditional failure modes, including rupture of the CFRP or crushing of the concrete, are seldom observed, implying that the success of this strengthening technique relies mainly on the interfacial bond behaviour between concrete and CFRP. Thus, proper understanding of the stress transfer mechanism at the concrete–CFRP interface is essential, such that both the failure modes and strength increase may be correctly predicted.

In the present study, the finite element method is used to analyze the behaviour of the interface between concrete and CFRP. The results are compared with experimental results [1].

2 EXPERIMENTAL STUDY

The experimental study was performed by [1], and consisted of shear lap tests as shown in figure 1. These authors studied the mode II end debonding of CFRP plates bonded to concrete by varying the plate width and bonded length. Two plate width’s (50 and 80 mm), and four bond length’s (50, 100, 200 and 400 mm) have been considered for a total number of eight specimens.

![Figure 1: Experimental setup [1].](image-url)
Concrete specimen dimensions were 150 x 200 x 600 mm, with mean compressive strength $f_{cm} = 52.6$ MPa, mean value of elastic modulus $E_{cm} = 30700$ MPa, Poisson ratio $\nu = 0.227$ and mean tensile strength $f_{ctm} = 3.81$ MPa.

The composite plates were CFRP Sika Carbodur S, width 50 and 80 mm wide and 1.2 mm thick. From tensile test performed by the authors, a mean elastic modulus $E_p = 195200$ MPa was obtained. CFRP plates have been bonded to concrete by using a 1.5 mm thick layer of two-component Sikadur-30 epoxy adhesive. From tensile tests, mean strength 30.2 MPa and mean elastic modulus $E_a = 12840$ MPa have been obtained for the adhesive.

3 NUMERICAL STUDY

A numerical simulation using the finite element method is performed to study the behaviour of the concrete – CFRP interface. The bond between concrete and CFRP is modelled using interface elements with initial zero thickness and non-linear fracture mechanics. In order to define the concrete – CFRP interface, the constitutive law presented in figure 2 is adopted. This constitutive law is defined by an initial linear ascending branch, until the value of the cohesion is reached, followed by an exponential descending branch. The three parameters used to define the interface behaviour, namely the cohesion ($c$), stiffness ($k_{int}$) and fracture energy in mode-II ($G^{II}_f$) will be presented ahead.

![Figure 2: Constitutive law adopted for the concrete – CFRP interface [2].](image)

First, in order to evaluate the cohesion, the tangential stresses are calculated from experimental results with equation 1. Values of $c = 11$ MPa and $c = 14$ MPa are obtained respectively for plates width’s of $b = 80$ mm and $b = 50$mm. Note that, already at this point, is possible to see an increase of the cohesion with decreasing plate width.

$$\tau(x) = \frac{\Delta e(x)}{\Delta x} \cdot E_f \cdot t_f = \frac{\epsilon_n - \epsilon_{n+1}}{x_n - x_{n+1}} \cdot E_f \cdot t_f$$  \hspace{1cm} (1)

In order to get a first evaluation of the remaining parameters that defines the interface, equation 2 is used. This equation is proposed by [3] and as the particularity of considering the elastic behaviour contribution in the ultimate bond strength.
Results from specimens with plate width $b=80$ mm for various load levels are presented in figures 3, 4 and 5. For these specimens the following parameters were identified: $c=11$ MPa; $G_F^{II}=0.40$ N/mm and $k_{int}=500$ MPa/mm. We can see that there is a good agreement between numerical and experimental results.

Figure 3: Numerical and experimental strains in CFRP plates for plate width $b=80$mm and $F=8$ KN.

Figure 4: Numerical and experimental strains in CFRP plates for plate width $b=80$mm and load $F=22$ KN.
Results from tests with plate width $b=50$ mm are reported in figures 6, 7 and 8. Parameters for these specimens are: $c=14 \text{ MPa}$; $G_F^{II}=0.27 \text{ N/mm}$ and $k_{int}=500 \text{ MPa/mm}$.
Once more, a good agreement can be observed between experimental and numerical results, even for load levels very close to the ultimate load. Results were presented only for three load levels of each specimen, other intermediate load levels are available in [4].

From these results some remarks can be drawn. When plate width increases, cohesion value drops. This implies that cohesion may depend on a geometrical parameter such as plate width. The fracture energy also suffers variation when plate width increases, but in this case, as plate width increases fracture energy also increases.

Based on these results it was possible to establish the following relation between cohesion and reinforcement width. This relation is valid for concrete elements within the same level of compressive strength and with the same reinforcement thickness.
In which:

\[ \frac{c^a}{c^b} = \sqrt{\frac{b_f^b}{b_f^a}} \]

\[ c^a \] – cohesion of element a;

\[ c^b \] – cohesion of element b;

\[ b_f^a \] – reinforcement width of element a;

\[ b_f^b \] – reinforcement width of element b.

A possible explication for the variation of cohesion with plate width is the fact that strain and stress distributions in CFRP may not be uniform across its width [5], [6]. A larger plate width will allow a better stress distribution along the CFRP width, lowering the peak bond stress value.

If this possibility is correct, and since this paper presents a plane stress analysis, an equivalent value for the cohesion (equivalent cohesion, \( c' \)) can be obtained considering the same area in both cases, as presented in figure 9. The smaller the reinforcement plate width the closer this equivalent cohesion will be to the real value.

The same line of thought applied for the fracture energy in mode-II, seems contradictory: in some cases fracture energy tends to drop when plate width decreases whereas the opposite occurs in some other cases [4].

Some authors [7], [8], [9] and [10] suggest that cohesion is not only a material parameter but is also affected by geometrical conditions such as reinforcement width. In [1], the authors conclude that the dependence of interfacial parameters on plate width is much more complex than suggested by existing prediction formulas, and that a more complex analysis is necessary.
There are few studies focusing on the influence of plate width, mainly due to the difficulty to measure displacements across the reinforcement width, with the use of traditional strain gauges. Yet, recent studies, [4] and [5], with the help of new techniques that allow to measure the full displacement field of the specimens, show that the strain and stress distribution in CFRP may not always be uniform across its width. These kind of experimental studies, supported by further numerical simulations in three dimensions are necessary for a complete comprehension of this phenomenon.

Interface stiffness, as expected, does not change with plate width variations since this parameter is essentially dependent on the properties of the adhesive layer between concrete and CFRP, and also surface preparation. Although, interface stiffness is the least important parameter on interface behaviour, its influence will increase as the value adopted is smaller. This is related to the prominence of the elastic regime in the interface behaviour, which is also the case for high values of cohesion [3]. In [2], the author suggests that the contribution of the elastic branch will gain special importance for values smaller than 1000 MPa/mm, which is the case for the present study.

Other authors, [11] and [12], suggest that bond strength can be raised by the use of soft adhesives as they present a reduced interface stiffness, including values between 140 MPa/mm and 1000 MPa/mm.

In this study, the value adopted for the interface stiffness of 500 MPa/mm suggests that the contribution of the elastic branch should not be neglected, this is why equation 2 is used, and the results are satisfactory.

4 CONCLUSIONS

In the present study, a numerical simulation using the finite element method is performed to study the behaviour of the concrete-CFRP interface, in particular the influence of reinforcement width. The bond between concrete and CFRP is modelled using interface elements with initial zero thickness and non-linear fracture mechanics. The corresponding constitutive law presents an initial linear ascending branch, until the value of cohesion is reached, followed by an exponential descending branch. The three parameters used to define the interface behaviour, namely the interfacial stiffness ($k_{int}$), cohesion ($c$) and fracture energy in mode-II ($G_{FII}$), are obtained from a parametric study and compared with experimental results from shear lap tests. The numerical results show good agreement with experimental results and the following conclusions can be drawn:

- The elastic branch of the interface bond-slip law can assume a significant role depending on the relationship between cohesion and interface stiffness. This applies to adhesives that present reduced interface stiffness and to high cohesion interfaces. In these cases, the use of equation (2) is recommended, since it takes into consideration the elastic branch contribution to the ultimate bond strength.
• Experimental and numerical results indicate that cohesion tends to assume smaller values as larger are the reinforcement width.

• Admitting that stress distribution is not uniform along reinforcement width, a larger plate width will allow a less uniform stress distribution along the CFRP width, lowering the average peak bond stress value. This means that in plane stress analysis, an equivalent cohesion should be adopted in order to correctly simulate the interface behaviour.

• Experimental studies, in which techniques that allow measuring the full displacement field of the specimens are used, supported by numerical simulations in three dimensions, are necessary for a complete understanding of the influence of reinforcement width on the interface behaviour.

REFERENCES


