# BOND BEHAVIOR OF CARBON LAMINATE STRIPS INTO CONCRETE BY PULLOUT-BENDING TESTS

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**SUMMARY**
During the last years it has been investigated a reinforcing technique based on introducing carbon laminate (CFRP) strips into saw cuts made on the concrete cover of the element to be strengthened. The CFRP is fixed to concrete element using epoxy adhesive. Comparatively to the techniques that glue the CFRP to the external surfaces of the concrete element, the one proposed in the present work has the advantages of mobilize high percentage of the tensile strength of this composite, prevent the peeling phenomenon and add an extra protection against fire and vandalism acts. To characterize the bond behavior of the CFRP strips to concrete, pullout-bending tests were carried out. The influence of the concrete strength and the embedment length was analyzed in the experimental campaign. In the present work the tests performed are described and the results obtained are presented and discussed.

## 1. INTRODUCTION

In the last decade, conventional materials (steel and concrete) are being replaced by fiber reinforced polymer (FRP) materials on the strengthening of concrete structures. These materials are available in the form of unidirectional strips made by pultrusion, and in the form of sheets or fabrics made by fibers in one or at least two different directions, respectively. Carbon (C) and glass (G) are the main fibers composing the fibrous phase of these materials (CFRP and GFRP), while epoxy is generally used on the matrix phase. Wet lay-up (sheets and fabrics) and prefabricated elements (designated by laminates) are the main types of FRP strengthening systems available in the market. The significant demand of FRP in last years on the structural repair and strengthening is due to the following main advantages of these composites: low weight, easy installation, high durability and tensile strength, large deformation capacity, electromagnetic permeability and practically unlimited availability in FRP sizes, geometry and dimensions (CEB-FIP, 2001).

The FRP laminates and sheets are generally applied on the faces of the elements to be strengthened, designated by externally bonded reinforcing technique (EBR). The research carried out up to now has revealed that this technique cannot mobilize the full tensile strength of the FRP materials, due to the peeling phenomenon (Juvandes, 1999; Dias, 2000). Besides, the reinforcing performance of FRP materials can be negatively affected by the effect of freeze/thaw cycles (Toutanji and Balaguru, 1998) and decreases significantly when submitted to high and low temperatures (Pantuso *et al.*, 2000). EBR systems are also susceptive to vandalism acts.

To overcome these drawbacks some attempts have been done, a promising one is the near surface mounted (NSM) FRP rods, based on the concept of embedding glass and carbon FRP rods into grooves made on the concrete cover of the elements to be strengthened (De Lorenzis *et al.*, 2000). The bond performance of this technique has been extensively analyzed in last two years (De Lorenzis and Nanni, 2002). This technique was used in some practical applications (Warren, 1998; Alkhrdaji *et al.*, 1999; Hogue *et al.*, 1999; Tumialan *et al.*, 1999), and several benefits were pointed out.

With the same purpose, Blaschko (1999) and Barros *et al.* (2000) have proposed a strengthening technique where strips of CFRP laminates were bonded into slits made on the concrete cover. High level of reinforcement efficiency was registered on the strengthening of concrete columns (Ferreira, 2001) and beams (Barros and Fortes, 2002). The peeling was prevented, the tensile strain on CFRP laminates has attained values near its ultimate strain, and large deformability was assured on the failure of the elements tested, revealing that high levels of ductility were guaranteed (Fortes *et al.* 2002).

To develop a numerical model that can predict, with high accuracy, the nonlinear behavior of concrete structures reinforced with this last reinforcing technique, it seems important to know the bond behavior of the interface laminate-adhesive-concrete. To fit this purpose an experimental research campaign was developed, carrying out pullout-bending tests with a configuration similar to the one proposed by RILEM (1982).

The present work describes the tests carried out, and presents and analyses the main results obtained. To simplify the designation, the strip of CFRP laminate will be named by *cutin* in this work.

## 2. MATERIAL CHARACTERIZATION

### 2.1 Concrete

To assess the influence of the concrete quality on the bonding behavior of the *cutin*, the three mix compositions included in Tab.1 were produced for attaining 35, 45 and 70 MPa of average compression strength. This table includes the average compression strength (fcm) and the corresponding standard deviation (in brackets) registered in sets of more than three cylinder specimens (150 mm diameter and 300 mm high) for the series tested. Each concrete strength class is composed by three series of different *cutin* embedment length, La, (40, 60 and 80 mm), leading to a total of nine series, each one composed by three beams, with a generic designation of fcmXX_LaYY, where XX represents the concrete strength class and YY the *cutin* embedment length. In preliminary pullout-bending tests the specimens were failed by concrete shear, since it was not applied conventional reinforcement. To avoid this kind of failure, 60 kg/m$^3$ of hooked ends Dramix® ZP305 steel fibers (1998) were used.

*Tab.1 Mix compositions and average compression strength of the concrete of the series tested.*

| Designation of the series | Concrete class strength [MPa] | *Cutin* embedment length [mm] | Composition [kg/m$^3$] | | | | | $f_{cm}$ (1) [MPa] |
|---|---|---|---|---|---|---|---|---|
| | | | FS | CS | CA | C | W | |
| fcm35_La40 | | 40 (La40) | | | | | | 34.5 (6.94%) (2) |
| fcm35_La60 | 35 (fcm35) | 60 (La60) | - | 745 | 943 | 350 | 210 | 33.0 (4.24%) |
| fcm35_La80 | | 80 (La80) | | | | | | 37.2 (1.50%) |
| fcm45_La40 | | 40 (La40) | | | | | | 46.2 (0.53%) |
| fcm45_La60 | 45 (fcm45) | 60 (La60) | - | 627 | 1049 | 400 | 200 | 41.4 (2.32%) |
| fcm45_La80 | | 80 (La80) | | | | | | 47.1 (1.65%) |
| fcm70_La40 | | 40 (La40) | | | | | | 69.9 (0.87%) |
| fcm70_La60 | 70 (fcm70) | 60 (La60) | 427 | 419 | 848 | 500 | 150 | 70.3 (8.24%) |
| fcm70_La80 | | 80 (La80) | | | | | | 69.2 (7.47%) |

Obs.: FS – Fine Sand (0-3mm); CS – Coarse Sand (0-5mm); CA – Coarse Aggregates (0-15mm); C – Cement Secil 42.5 type I; W – Water; in series fcm70 it was applied 7.8 l/m$^3$ of Rheobuild1000 super plasticizer (MBT Portugal); (1) at the age of testing the pullout-bending specimens; (2) standard deviation.

## 2.2 CFRP laminates

The strips of CFRP laminate (*cutins*) were provided in rolls, produced by S&P® and distributed by Bettor MBT® Portugal. The *cutins* were cut from CFRP laminates with the trade mark of *MBrace LM* (1999) that, according to the supplier, have the following main properties: width ($w_f$) of 100 mm; thickness ($t_f$) of 1.4 mm; characteristic tensile strength ($f_{fk}$) greater than 2200 MPa, characteristic Young's modulus ($E_{fk}$) of 150 GPa and ultimate tensile strain of 14 ‰.

From twenty measures it was verified that the thickness and the width of the *cutins* furnished were 1.385±0.003 mm and 9.339±0.094 mm, respectively. In the following of this document it was assumed 1.39 mm and 9.34 mm for the thickness and width of the *cuttins*.

To evaluate the tensile strength and the Young's modulus of the *cuttins*, uniaxial tensile tests were carried out in a servo-controlled test machine (Instron series 4208), according to the recommendations of ISO 527-5 (1997). From the results obtained (Cruz *et al.*, 2001) with three specimens the values of 158.3±2.6 GPa, 2739.5±85.7 MPa and 17.0±0.4 ‰ for the Young's modulus, tensile strength and ultimate tensile strain, respectively, were determined, which are higher than the values indicated by the supplier.

## 2.3 Epoxy adhesive

To bond the *cutins* to concrete it was used an epoxy adhesive with the trade name of *MBrace laminate adhesive* (2000), furnished by Bettor MBT® Portugal. According to the supplier the flexural tensile strength and the Young's modulus were 30 MPa and 8.15 GPa, respectively. To check this data it was carried out uniaxial tensile tests (Cruz *et al.*, 2001), according to the recommendations of ISO 527-3 (1997). From the results obtained it was determined a Young's modulus of 5.0 GPa and a tensile strength ranged from 16 MPa to 22 MPa. The relative wide range of the tensile strength can be justified by the erratic occurrence of voids, detected on the fracture surface of the specimens tested, which can also justify the relative lower value of the Young's modulus (Cruz *et al.*, 2001).

# 3. SPECIMENS AND TESTING CONDITIONS

At the age of 28 days the specimens were taken out from the water tank of the curing room for making slits of 15 mm depth and 3.3 mm width (see Fig.1), where the *cutins* will be inserted. The *cutins* were bonded into slits after the specimens have been eight days in the natural environment of the laboratory, in order to assure a proper concrete drying. In Block B (see Fig.1) the *cutin* was fixed to concrete along an embedment length of 325 mm, and in Block A the *cutin* was bonded to concrete using three embedment lengths (40, 60 and 80 mm) for analyzing the influence of this parameter on the bond behavior. To assure stable tests the LVDT2 (see Figs.1 and 2), of 5 mm displacement range and 2 μm of accuracy, was used to control the test, using a displacement rate of 5 μm/s. The LVDT2 measured the slip at the loaded end, while LVDT1 registered the slip at the free end. On the *cutin*, at the symmetry axis of the specimen, it was applied a strain gauge (see Figs.1 and 2) for evaluating the strains, and therefore, the stresses and the pullout load induced on the *cutin*. The pullout load was also determined from the forces measured on the load cells LC1 and LC2 (50 kN of maximum load bearing capacity with an accuracy of 0.5%), placed on the supports of the specimen, and taken the value of the bending internal arm (distance from the point contact of the steel hinge to the axis of the CFRP laminate). It was verified that these two procedures have given similar results of the pullout load, except on series fcm35_L80 where the differences were not marginal, maybe due to deficiencies on the gluing procedure of the strain gauges.

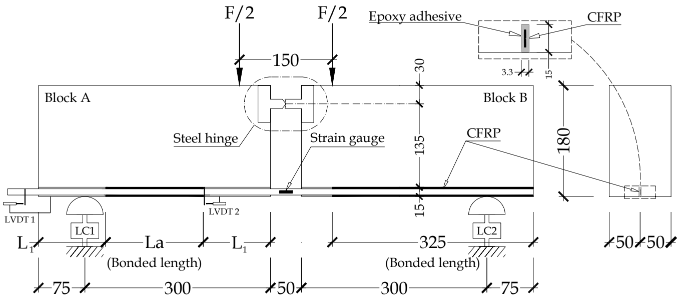


*Fig.1 Specimen of the pullout-bending tests.*

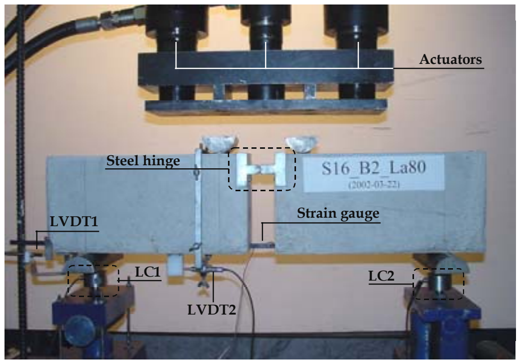


*Fig.2 Layout of the pullout-bending tests.*

## 4. RESULTS

Figs.3, 4, 5 include the bond stress-slip relationship obtained for the three series of concrete class strength considered. In fact, the bond stress is an average bond stress since it was evaluated dividing the pullout load by the bonded area, $2\times(w_f+t_f)\times La$. In this approach it was assumed that the slip and the bond stress are constant throughout the embedment length, in spite of the authors are aware that this distribution is highly nonlinear (Focacci *et al.*, 2000; De Lorenzis and Nanni, 2002).

Analyzing the curves depicted on Figs. 3-5 it is observed that, after a short linear branch, the response become nonlinear, due to the nonlinear behavior of the epoxy adhesive (Cruz *et al.*, 2001). The peak load has occurred for a slip in the range of 0.25 mm to 0.8 mm. After peak, the load decay decreases with the increment of the slip, describing a nonlinear softening branch. The higher load decay in the beginning of the softening might be associated to local failures of the adhesive, and to the loss of bonding between adhesive and *cutin*, and adhesive and concrete. After a slip in between 1 mm and 2 mm, the load decrement with the increment of the slip is much lower, showing a significant residual bond stress due to frictional mechanisms amongst concrete-adhesive-*cutin*.

Tab.2 includes the average values of the main results obtained with the data registered on the tests. In this table, $G_f$ is the energy dissipated in the slip fracture mode, designated by fracture energy, considered as the area under the curve bond stress-slip up to a slip of 5 mm, $\varepsilon_{fmax}$ is the maximum strain read during the test, $\varepsilon_{fu}$ is the ultimate tensile strain obtained on the uniaxial tensile tests with *cutin* specimens (17 ‰), and $\delta_{Fmax}$ is the slip at peak pullout load.

*Tab.2 Average values of the main parameters evaluated.*

| Parameter | La40 | | | La60 | | | La80 | | |
|---|---|---|---|---|---|---|---|---|---|
| | fcm35 | fcm45 | fcm70 | fcm35 | fcm45 | fcm70 | fcm35 | fcm45 | fcm70 |
| $F_{max}$ (kN) | 15.0 (5.8%) | 15.5 (2.0%) | 15.7 (8.8%) | 22.8 (8.7%) | 19.9 (3.7%) | 18.9 (5.8%) | 22.4 (5.0%) | 26.4 (4.2%) | 25.6 (6.2%) |
| $\tau_{max}$ (MPa) | 17.5 | 18.1 | 18.3 | 17.7 | 15.5 | 14.7 | 13.0 | 15.4 | 14.9 |
| $G_f$ (MN/mm) | 48.3 (11.4%) | 53.3 (12.6%) | 51.5 (12.5%) | 43.9 (4.8%) | 38.4 (12.7%) | 41.9 (6.3%) | 38.4 (7.1%) | 43.0 (3.9%) | 48.4 (6.7%) |
| $\varepsilon_{fmax}/\varepsilon_{fu}$ | 42.1 | 43.5 | 44.0 | 64.0 | 55.8 | 52.9 | 62.1 | 73.9 | 71.6 |
| $\delta_{Fmax}$ (mm) | 0.29 (21.5%) | 0.27 (26.8%) | 0.32 (10.5%) | 0.49 (5.8%) | 0.46 (8.8%) | 0.40 (10.0%) | 0.65 (16.0%) | 0.84 (30.6%) | 0.74 (3.0%) |

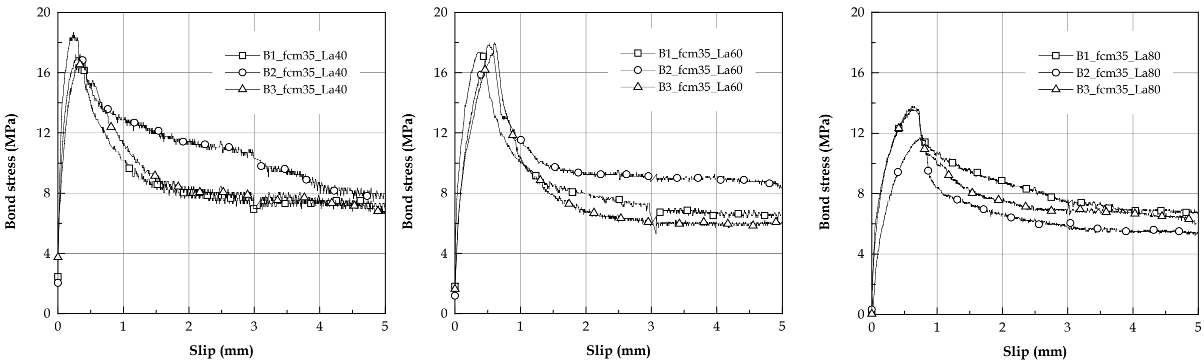


*Fig.3 Bond stress-slip relationship for series of concrete class strength of 35MPa (fcm35).*

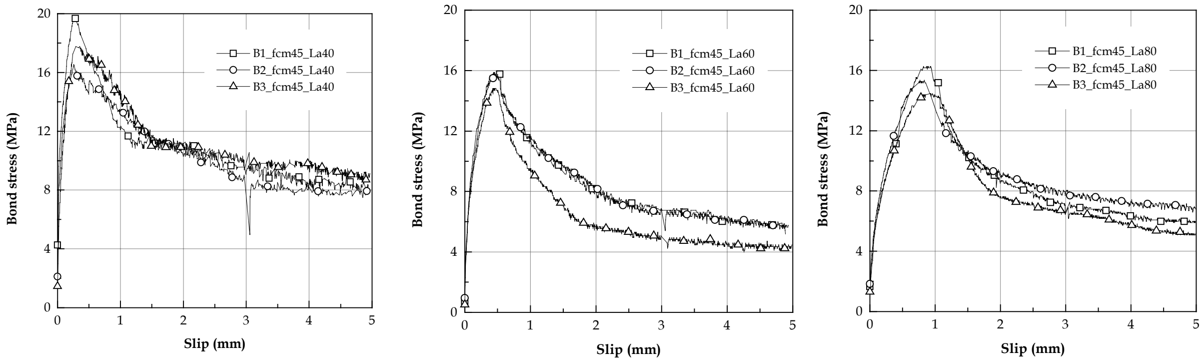


*Fig.4 Bond stress-slip relationship for series of concrete class strength of 45MPa (fcm45).*

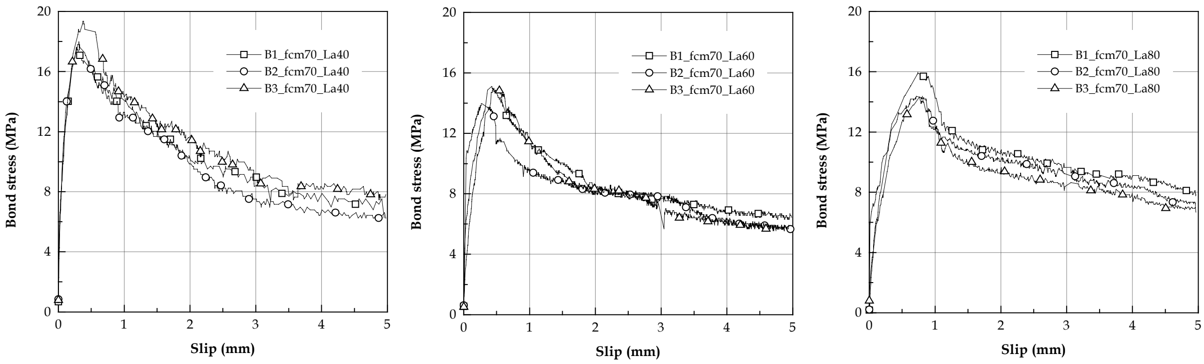


*Fig.5 Bond stress-slip relationship for series of concrete class strength of 70MPa (fcm70).*

Fig.6 shows the influence of the embedment length (La) on the: bond strength (maximum bond stress, $\tau_{max}$), fracture energy ($G_f$), ratio between maximum stress and tensile strength on the *cutin* ($\sigma_{fmax}/f_{fu}$), and displacement at maximum bond stress ($\delta_{Fmax}$). From these results it can be verified that $\tau_{max}$ has a tendency to decrease with La, $G_f$ did not reveal any prone, and $\sigma_{fmax}/f_{fu}$ and $\delta_{Fmax}$ have increased significantly with La, mainly from La=60 mm to La=80 mm. It seems that, from an embedment length between 100 and 120 mm, the tensile strength of the *cutin* will be attained.

Fig.7 shows the influence of the concrete class strength on the $\tau_{max}$, $G_f$, $\sigma_{fmax}/f_{fu}$ and $\delta_{Fmax}$. From these results it can be verified that concrete class strength has marginal influence on these parameters.

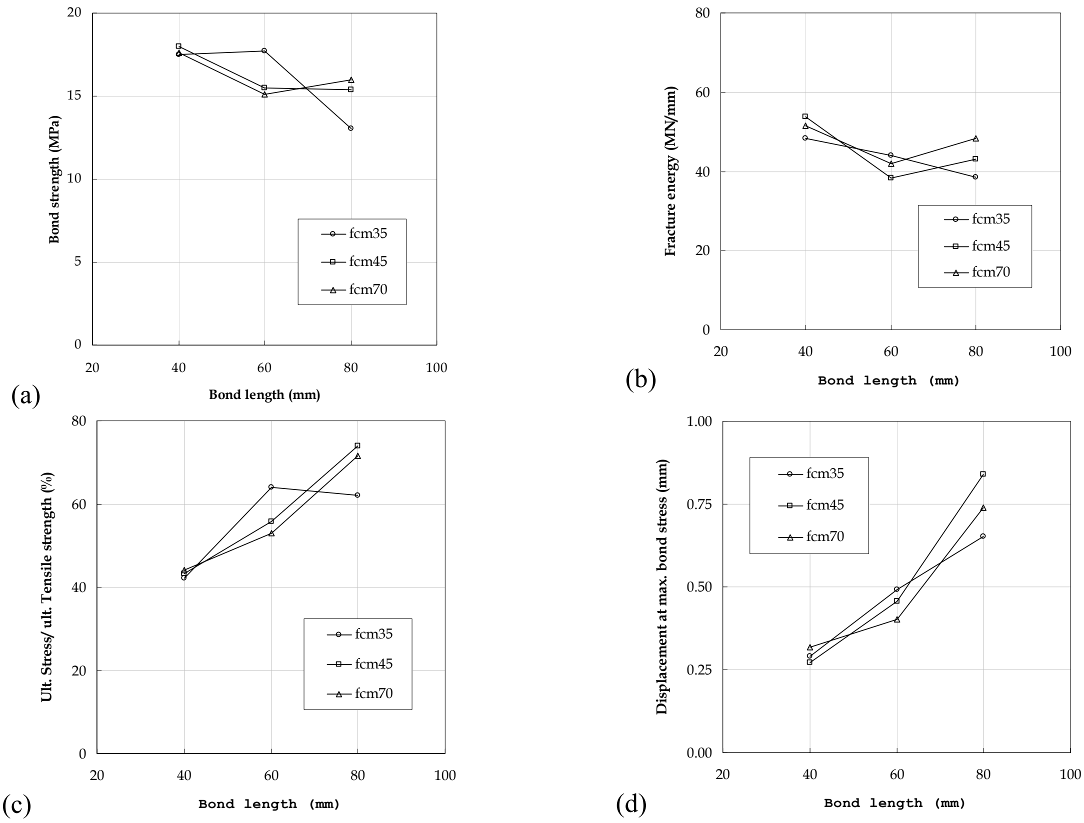


*Fig.6 Influence of the bond length on the bond strength (a), fracture energy (b), cutin tensile ratio (c) and peak displacement (d).*

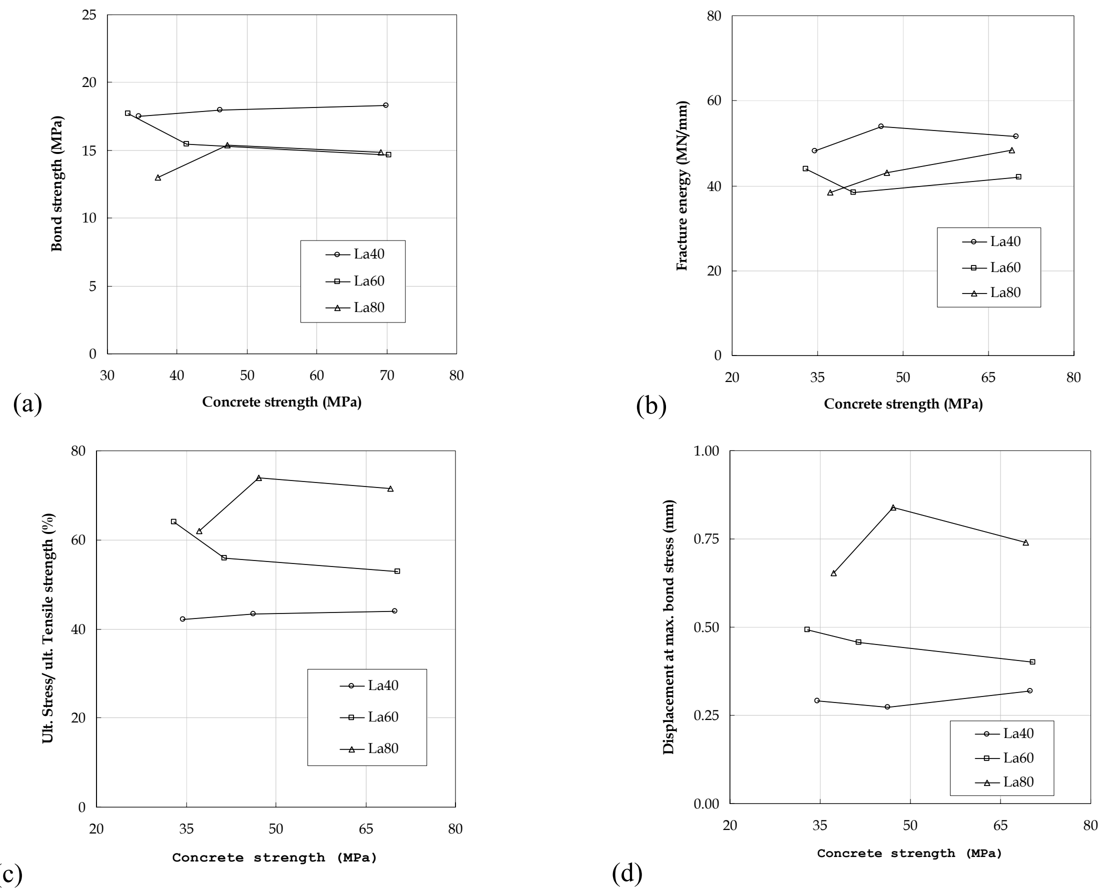


*Fig.7 Influence of the concrete strength on the bond strength (a), fracture energy (b), cutin tensile ratio (c) and peak displacement (d).*

## 5. CONCLUSIONS

To assess the bond performance of the strip of CFRP laminate (*cutin*) to concrete, pullout-bending tests were carried out. The influence of the embedment length (La) and the concrete class strength (fcm) was analyzed, testing series with La=40, 60 and 80 mm, and fcm=35, 45 and 70 MPa. From the results obtained the following comments can be pointed out:

- The pullout load increased with the embedment length of the CFRP laminate;
- The bond strength ($\tau_{max}$) revealed a tendency to decrease with the increment of the embedment length, but it is significantly higher than the values obtained using externally bonded CFRP and near surface mounted FRP rods reinforcing techniques;
- The fracture energy ($G_f$) did not reveal any clear prone with the embedment length;
- The ratio between the maximum tensile stress registered on cutins and its tensile strength ($\sigma_{fmax}/f_{fu}$) increased with the embedment length, showing that, for an embedment length between 100 mm and 120 mm the *cutin* tensile strength might be attained;
- The displacement at peak pullout load ($\delta_{Fmax}$) increased with the embedment length, mainly from La=60 mm to La=80 mm;
- The influence of the concrete class strength on $\tau_{max}$, $G_f$, $\sigma_{fmax}/f_{fu}$ and $\delta_{Fmax}$ was marginal.

In a next paper, the data registered on the tests performed will be used for defining a local bond-slip relationship for this kind of reinforcing technique.

## 6. ACKNOWLEDGEMENTS

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