CARBON-FIBER REINFORCED POLYMER USED IN THE REINFORCEMENT OF RECTANGULAR OPENINGS IN THE WEB OF REINFORCED CONCRETE BEAMS

E. E. Matar
Escale Engenharia, São Paulo, Brazil

ABSTRACT: After the first fifteen years of the 21st century, the predictions made around 2000 about repair and reinforcement of concrete structures have been confirmed: from books and scientific articles to the service execution of such a specialty, including several products launched by the chemical industry, the evolvement of the subject is evident.

As concrete has been the most used material throughout the world for decades, there are lots of structures made of that material in need of repair and reinforcement. The current standards for concrete prescribe strict rules to increase the durability of the future works, which did not occur in the past.

Repair and reinforcement of concrete structures is a multidisciplinary theme, and it involves studies related to: structure mechanics, chemistry, physics, environment and new materials, for example. Due to their special characteristics, the carbon-fiber reinforced polymers (CFRP) were introduced in this context to solve the problem of existing structures affected by earthquakes. Because of their performance and practicability, the use of CFRP was extended to the wrapping of low-resistance concrete columns, bending and shear reinforcement of beams, bending reinforcement of slabs and reinforcement of openings in beams and slabs.

Due to the short time available to execute engineering works nowadays, sometimes it is not possible to foresee the openings that will be necessary in the structures, to pass facilities or to have access for future maintenance. Thus it is often necessary to make an opening in the reinforced concrete structure already made, and the reinforcement with CFRP has been chosen to solve the problem. One of the main advantages of such a reinforcement in those openings is that it can be applied in most cases – and it is ideal to be so – before the opening is made, because it will be loaded as the opening is being made, and so eventual cracks can be avoided and props are spared.

In such a context, the present article deals with the reinforcement of rectangular openings in the web of reinforced concrete beams. Those openings change the values of resistant shears, of the concrete and of the shear reinforcement (stirrups), and so CFRP stirrups sometimes have to be applied both before and during the execution of the opening, to add an additional resistant shear to the beam.

We want to prove that the previous application of reinforcements – the ones practicable before the execution of the opening – contribute to the effectiveness of the solution; we also seek the ideal arrangement of the CFRP stirrups so as to optimize the reinforcement.

This paper seeks for a simple way to design CFRP when openings in structures: beam webs and even slabs.

1 INTRODUCTION

1.1 *Repair and reinforcement of concrete structures*

Concrete structures, without a maintenance schedule, are not forever. Nowadays the new design and construction codes have specifications to guarantee 50 years, or more, of good health to concrete. Besides, we have a lot of about-40-year-old concrete structures that show many pathologies we have to fix to keep design security factors.

Corrosion of the steel reinforcement, concrete sections damage and non-conformity in the support parts are some of the problems we find in old concrete structures.

As to bridges we can also have: structural modification due to enlargements, repairs due to accidents, design or construction errors to be fixed and beam or slab openings for maintenance purposes.

1.2 *Carbon-fiber bridge reinforcement*

From prestressed cable problems to steel reinforcement addition, including opening reinforcement in

slabs or beams, the external CFRP has been applied on concrete bridges with very good results.
First used in Japan to protect building columns against earthquake effects, the CFRP reinforcement application has been extended to many other structural cases.
In every case in which you have designed steel reinforcement in the structure, now you can apply a CFRP strip at the construction site.

2 THE MATERIAL CFRP

2.1 *Carbon-fiber cloth*

The most commonly used CFRP is the in situ composite material formed by the carbon-fiber cloth (CFC) with epoxy resin impregnation. Experience shows that CFC has better performance than bonded carbon laminates and it is only exceeded, in performance but not in economy, by the laminates used in the Near Surface Mounted (NSM).
CFC has the following properties:

Weight 300 gf/m³
Thickness 0,172 mm
Final Tensile Stress 3500 MPa
Elastic Modulus 266 GPa
ε_{fu} = 12500 µstrain

2.2 *Epoxy resin*

The resin added to the CFC that shows the best final tensile stress composite is the epoxy resin. It has the following properties:

Final Tensile Stress 60 MPa
Elastic Modulus 3,5 GPa

2.3 *Composite material for structural reinforcement*

The CFC and epoxy resin are prepared in situ with hand-lay up process. A good application is got with 40% of CFC and 60% of epoxy.
The composite material with CFC and epoxy resin has the following properties obtained from theoretical rules or from lab tests:

Thickness 0,38 mm (one layer)
Elastic Modulus 125 GPa
Final Tensile Stress 1225 MPa (deformation limited to 9800 µstrain)

Notice that the elastic modulus is near half the CFC value. This must be taken into account when calculating final tensile stress = 125 x 9,8 = 1225 MPa.
That limit of deformation is compatible with the limit of the steel deformation and it allows us to use up to six layers of CFC in the reinforcement strips.

2.4 *The tensile concrete zone*

Except when it is used to confine column sections, the CFRP reinforcement works, as a stirrup or a bending strip, bonded to the concrete tensile zone.
Even cracked, the concrete continues to contribute to the effective stiffness of the structures, due to tension stiffening. RIZKALLA & HWANG have proposed a constitutive relationship for reinforced concrete.
The model was based on a large experimental program to determine the behavior of concrete segments reinforced in two directions and loaded in pure membrane tension, varying: concrete cover, concrete thickness, percentage of steel and spacing between transverse reinforcement.
The constitutive diagram before cracking ($\varepsilon < \varepsilon_{cr}$) is linear:

$$\sigma = E \times \varepsilon$$

While, after cracking ($\varepsilon > \varepsilon_{cr}$), is:

$$\sigma = \sigma_{cr}\, e^{-1000\times(\varepsilon-\varepsilon cr)}$$

One advantage of the CFRP reinforcement is that the epoxy resin used to impregnate the CFC and to bond it to the concrete penetrates into the tensile concrete zone, and, as classical studies have shown, improves the tension resistance.

2.5 *Adherence composite-concrete*

In order to make CFRP perform as it must, we have to have perfect adherence composite-concrete.
In the case of the CFC and epoxy resin specified in this paper, the result got was 3,0 MPa in adherence test, which is greater than the 1,4 MPa required by ASTM.

2.6 *Increase in service inertia*

Another advantage of CFRP application is the increase in service inertia.

Table 1. Increase of inertia because of CFRP.

Inertia(m³)	CFC layers	Increase of inertia
1,61E-05	0	1,00
2,69E-05	1	1,68
3,69E-05	2	2,30
4,62E-05	3	2,88
5,49E-05	4	3,42

As we can see, in Table 1, a single layer of reinforcement increases in 68% the cracked inertia.

3 RECTANGULAR OPENINGS IN THE WEB OF REINFORCED CONCRETE BEAMS

3.1 *Why do beam webs open?*

Structural openings not foreseen in the original design can be necessary to allow maintenance access or to pass a utility duct. The opening can be made in a slab or beam web; it can be a circular or a rectangular opening.

This paper presents the behavior and the design of rectangular openings in the web of reinforced concrete (RC) beams.

3.2 *Reinforcing before opening*

The openings will be executed in a structure loaded, at least with dead load. Therefore there will be a dynamical problem. LEVIN & VERSHININ (2008) shows that it can happen stress amplification in the structure.

When the problem is to introduce failure in a loaded system one must also be careful of collapse (ASHBY & JONES 2007). Considering that the RC fracture toughness varies from 10 to 15 MN $m^{-3/2}$ and that the CFRP fracture toughness varies from 32 to 45 MN $m^{-3/2}$, it is better to apply a CFRP reinforcement before making the RC structure opening.

3.3 *CFRP contribution to shear strength*

PELEGRINO & MODENA (2006) have taken experimental and analytical studies of the CFRP contribution to shear strength.

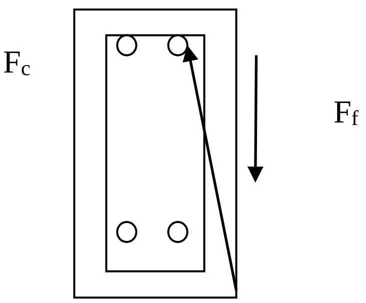

Figure 1. Forces acting on the cross section of a beam at failure. F_f is the force acting on the CFRP and F_c is the force acting on the concrete rod.

The authors discovered the importance of the interaction between the CFRP externally bonded and the internal steel. In their research they have found out that although many codes overestimate the CFRP contribution to shear resistance, the sum of resistant shear forces from concrete, steel and CFRP reaches positive results.

3.4 *Rectangular web opening beams experimental program*

El-MAADDAWY & El-ARISS (2012) have tested 16 RC beams with rectangular web openings. Such beams had the following characteristics: concrete C20, CA50 steel, cross section 8,5 x 40 cm and d = 35 cm. All RC beams had 4 ϕ 16 mm of longitudinal CA50 reinforcement.

The authors studied openings with three different sizes, without any and with one or two CFRP layers, as well as a beam without any opening.

Through the theoretical code calculation, the paper mentioned above came to the same value to reinforcement as the experiment results showed.

Using NBR 6118 code and computer processing (ANSYS©) we are going to come to an adequate approximation to determine that tested reinforcement.

The CA50 steel stirrup area would be A_{sw} = 2,55 x 32 / 35 = 2,33 cm² / m.

Between the beam support on the left and the beginning of the opening (distance, 0,15 m, and total opening length, 0,50 m) we could have:

A_{tot} = 2,33 cm² / m x 0,15 m + (0,50 / 2) x 2,33 = 0,93 cm²

It was considered that:

- between the beam support on the left and the beginning of the opening there are no stirrups, only CFC;
- half of the stirrups in the opening region will be (CFC equivalent) between the beam support on the left and the beginning of the opening.

For the above calculation, because of the opening, we do not consider the concrete collaboration.

So, for A_{tot} = 0,93 cm², the equivalent CFC stirrup would be: (0,93/2) x (5000/1,15) = b_f x 0,038 x (12250/1,4), resulting b_f = 6,10 cm.

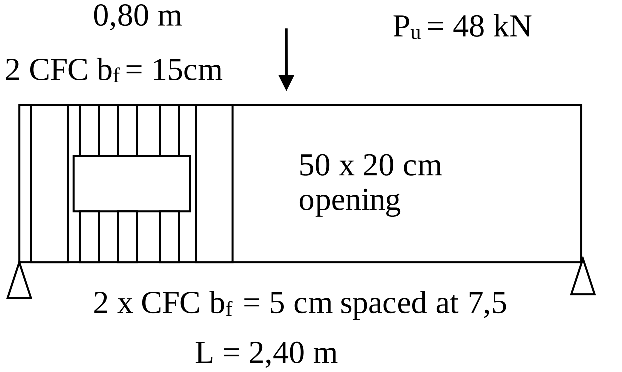

Figure 2. Specimen S2-500 x 200, one of the 16 RC beams, studied in the paper mentioned.

On the other hand, if we process this beam in ANSYS we find a shear force peak of 299 kN near the opening, which will result in 3,05 cm² CA50.

So, for A_{tot} = 3,05 cm², the equivalent CFC stirrup would be: (3,05/2) x (5000/1,15) = b_f x 0,038 x (12250/1,4) resulting b_f = 19,94 cm.

If we take the means 19,94 and 6,10 we come to 13 cm, very close to the 15 cm used in the test and proven below by ACI.

The ACI code verifies a CFRP shear reinforcement in a beam opening by calculating the shear force contribution of chords and corners. Both the tested values and our calculated values will be verified.

According to ACI, the concrete contribution is:

ρ = 4 x 2 cm² / (8,5 x 40) = 0,0235

$V_c = 5{,}35 \times (20 \times 0{,}0235)^{0{,}33} \times (350/800)^{1{,}33} \times (85 \times (350-200))$

V_c = 16666 N

3.5 *Chord-shear failure*

For tested values:

A_{fb} = 2 x 50 x 0,38 = 38 mm²

$k_1 = (20 / 27)^{0{,}67} = 0{,}818$

$L_e = 23300 / (1 \times 0{,}38 \times 125000)^{0{,}58} = 45$ mm

k_2 = (0,8 x 100 – 45) / (0,8 x 100) = 0,438

k_v = (0,818 x 0,438 x 45) / (11900 x 0,0125) = 0,108

$\varepsilon_{fe,b}$ = 0,004 <= 0,75 x 0,0125 = 0,0094

$\varepsilon_{fe,t}$ = 0,108 x 0,0125 = 0,0014 <= 0,004 = 0,0014

$V_{f,chords}$ = 1 x 38 x 125000 x 0,004 x (80 / 75) + 1 x 38 x 125000 x 0,0014 x (80 / 75)

$V_{f,chords}$ = 20267 + 7093 = 27360 N

3.6 *Corner-shear failure*

For tested values:

A_{fb} = 2 x 150 x 0,38= 114 mm²

k_2 = (0,8 x 400 - 45) / (0,8 x 400) = 0,859

k_v = (0,818 x 0,859 x 45) / (11900 x 0,0125) = 0,213

$\varepsilon_{fe,c}$ = 0,213 x 0,0125 = 0,0027 <= 0,004 = 0,0027

$V_{f,corners}$ = (1 x 114 x 125000 x 0,00213) / 2

$V_{f,corners}$ = 15118 N

The total analytical shear capacity will be:

$V_n = V_c + \min(V_{f,chords}, V_{f,corners})$

V_n = 16,67 + min (27,36 ; 15,11)

which attends the design value.

3.7 *Comparing the proposed approximation with ACI*

The approximate solution proposed here, which simply replaced the nonexistent CA50 stirrups in the opening region, and was calculated without any concrete collaboration, by CFPR reinforcement, came to a low CFC width (6,1 cm). That seems to happen because of the proximity between the opening and the beam support; ANSYS processing shows stress concentration there.

If we use the concentrated shear force given by ANSYS we would arrive to 19,94 cm CFC width. The results show that if we detail the ANSYS processing, we will come to a very close result.

Then, we will have a way to predict the opening reinforcement and not only to verify it according to ACI code.

4 RECTANGULAR OPENINGS IN SLABS

As a development of this paper, rectangular openings in slabs have been studied.

VASQUEZ & KARBHARI (2003) tested 6 x 3,2 x 0,18 m slabs with central 1 x 1,6 meter openings.

The authors commented that “cutouts were formed after casting of slabs to simulate field condition” and that “the CFRP strips were bonded on prior to the cutout being made.”

Slabs were loaded to failure and the tests showed that the CFRP reinforcement led to the slab with cutouts behaving as the one without opening.

Next we show that by simple designing the reinforcement through replacing the cut steel by equivalent CFC, we come to a value bigger than the one shown below, but smaller than that one applied in the test.

Total cut steel in the opening: 9 ϕ 16 mm = 18 cm² (9 cm² on each side of the opening)

Equivalent to the reinforcement applied, in the test, on each side of the opening: 16 cm².

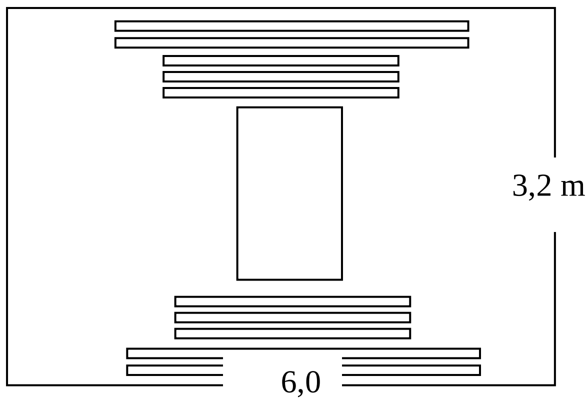

Figure 3. Concrete slab with opening, reinforced with CFRP.

ANSYS processing of that slab with opening gave us:

mx = 125,46 kN.m/m (maximum value)

which results in 16,73 cm² of CA50 steel on each side of the opening.

There is already 9,00 cm² of CA50 steel on each side, so the reinforcement needed would be equivalent to 16,73 - 9,00 = 7,73 cm².

This value is less than the 9,00 m² obtained with the simple designing way (substitution) but greater than the 16,00 m² applied in the tests.

Therefore, the refinement of the computer process improves the procedure to determine the forces, and then we can design the reinforcement accurately.

5 REAL MODELS OF BEAM WEBS AND SLABS WITH OPENINGS IN ABAQUS©

Towards a simple way to design CFRP reinforcement, structures will be processed with a kind of software for modeling, like ABAQUS©. RC slabs and beam webs will be modeled for detailing how concrete, steel and CFC work under those conditions.

When you use such software you can model your structure realistically with several materials represented by their constitutive equations.

In the case of CFRP reinforcement in structural opening we will model: compressive concrete, tensile concrete, CA50 steel and CFC plus epoxy.

6 CONCLUSIONS

A very used material for maintenance, recovery and reinforcement of bridge structures, the CFRP has also been used for the reinforcement of beam and slab openings. Because of its versatility, CFC bonded and impregnated with epoxy resin must be applied, as early as possible, before opening the beam web or the slab.

One of the advantages of such early reinforcement is to protect the structure against dynamic effect and collapse when making the opening.

The CFC stirrups and strips that could not be applied early will be applied after the opening is made.

The method to calculate the amount of CFRP reinforcement to be applied in the edges and inside the opening, is to get elastic shear forces, normal forces and moments from a adequate computer model, and to calculate CA50 steel reinforcement according to normal codes and then to transform it into CFC stirrups and strips.

Future studies using modeling softwares, like ABAQUS©, will detail how concrete, steel and CFRP work in structure opening.

7 REFERENCES

ASHBY, M. F. ; JONES, D. R. H. Engenharia de materiais, uma introdução a propriedades, aplicações e projeto. Rio de Janeiro: Elsevier, 2007.

ACI 440. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute, Michigan, 2008.

AGARWAL, B. D.; BROUTMAN, L. J.; CHANDRASHEKHARA, K. Analysis and performance of fiber composites. New Jersey: John Wiley& Sons Inc., 2006.

ALVES, M.; MATOS, H. S. C. Mechanics of solids in Brazil. São Paulo: Brazilian Society of Mechanical Sciences and Engineering, 2007.

ASTM D 4541. Standard test method for pull-off strength of coatings using portable adhesion tester. Pennsylvania: American Society for Testing and Materials, 1993.

CASADEI, P.; NANNI, A.; IBELL, T. Experiments on two-way RC slabs with openings streghthened with CFPR laminates. Center for Infrastructure Engineering Studies, University of Missouri-Rolla, CIES-03-39.

CHRISTENSEN, R. M. Mechanics of composite materials. Florida: Krieger Publishing Company, 1991.

DA SILVA, R. C.; GIONGO, J. S. Modelos de bielas e tirantes aplicados a estruturas de concreto armado. São Carlos: EESC–USP, 2000.

EL-MAADDAWY, T.; EL-ARISS, B. Behavior of concrete beams with short shear span and web opening strengthened in shear with CFRP composites. Journal of Composites for Construction, American Society of Civil Engineers, v. 16, n. 1, p. 47-59, 2012.

FIB-CEB-FIP. Externally bonded FRP reinforcement for RC structures. Bulletin 14. Switzerland: FIB, July 2001.

FIB-CEB-FIP. FRP Reinforcement in RC structures. Bulletin 40. Switzerland: FIB, September 2007.

FUSCO, P. B. Estruturas de concreto: solicitações tangenciais. São Paulo: Editora Pini, 2008.

HYER, M. W. Stress analysis of fiber-reinforced composite materials. New York: Mc Graw Hill, 1998.

KARMAN, J. B. Manutenção incorporada à arquitetura hospitalar. Brasília: Ministério da Saúde, Secretaria de Assistência à Saúde, 1995.

LEONHARDT, F. Construções de concreto. Verificação da capacidade de utilização. Rio de Janeiro: Ed. Interciência, 2012. v. 4.

LEONHARDT, F. Construções de concreto. Princípios básicos sobre a armação de estruturas de concreto armado. Rio de Janeiro: Ed. Interciência, 1983.v. 3.

LEVIN, V. A. & ZINGERMAN, K. M. A class of methods and algorithms for the analysis of successive origination of holes in a pre-stressed viscoelastic body. Finite strains. Communications in Numerical Methods in Engineering, n. 24, p. 2240-2251, 2008.

MACHADO, A. P. Reforço de estruturas de concreto armado com fibras de carbono. São Paulo: Ed. Pini, 2002.

MEHTA, P. K. & MONTEIRO, P. J. M. Concrete microstructure, properties and materials. 3. ed. New York: Mc Graw Hill, 1988.

NBR 6118. Projeto de estruturas de concreto. Rio de Janeiro: Associação Brasileira de Normas Técnicas (ABNT), 2000.

PALIGA, C. M..; CAMPOS FILHO, A.; REAL, M. V.; DINIZ, S. M. C. Métodos de análise de confiabilidade aplicados a vigas de concreto armado reforçadas com PRFC. Teoria e Prática na Engenharia Civil, n. 17, p. 57-66, Maio 2011.

PELEGRINO, C.; MODENA, C. Fiber-reinforced polymer shear strengthening of reinforced concrete beams: experimental study and analytical modeling. ACI Structural Journal, American Concrete Institute, p. 720-728, September-October 2006.

PLATT, G.; BASTOS, I.; ROCHA, M.; HENDERSON, N.; MOURA NETO, F. Modelagem computacional em materiais. Rio de Janeiro: Ed. Ciência Moderna Ltda., 2010.

PROENÇA, S. P. B. Sobre modelos matemáticos do comportamento não linear do concreto: análise crítica e contribuições. 1988. Tese (Doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, 1988.

PYRZ, R. Micromechanics of composites. In: DE BORST, R. & SADOWSKI, T. (orgs.) Lecture notes on composite materials: current topics and achievements. Dordrecht: Springer, 2009. p. 77-97.

RIZKALLA, S. H. & HWANG, L. E. Effective tensile stress-strain characteristics for reinforced concrete. Winnipeg: University of Manitoba.

TITA, V. Projeto e fabricação de estruturas em material composto polimérico. São Carlos: Universidade de São Paulo, 2011.

VANALLI, L.; PACOLLA, R. R.; Coda, H. B. A simple way to introduce fibers into FEM models. Communications in Numerical Methods in Engineering, n. 24, p. 585-603, 2008.

VAN LANGENDONCK, T. Cálculo de concreto armado. Rio de Janeiro: Ed. Científica, 1959.

VASQUEZ, A.; KARBHARI, V. M. Fiber-reinforced polymer composite strengthening of concrete slabs with cutouts. ACI Structural Journal, American Concrete Institute. p. 665-673, September-October 2003.