Analysis of the use of carbon fiber reinforced polymer bars to reinforce concrete beams

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Abstract. The aim of the present work is to analyze the use of bars made of composite material to act as reinforcement for concrete beams subjected to bending. The analyzed bars are constituted by polymer reinforced with carbon fibers (CFRP), a material that presents linear elastic behavior until rupture. This material has some advantages in relation to steel, such as considerably higher tensile strength in addition to not being susceptible to corrosion caused by environmental conditions. During the development of the work, an article was obtained which demonstrates results of laboratory tests in which the authors used concrete beams subjected to four-point flexure testing and reinforced with PRFC bars. In this work, the same test was simulated using the Atena software, a computer program that performs non-linear analysis for concrete structures, considering the structural cracking. The results obtained by the software were consistent with those obtained in the laboratory. The flexural reinforcement design was performed for a section of concrete beam reinforced with steel and another with CFRP, in addition to having also analyzed a uniformly distributed load that breaks a continuous beam when it is reinforced with steel bars and when it is reinforced with CFRP bars.

Keywords: Reinforced Concrete Structure; Carbon fiber reinforced polymer bar, Nonlinear structural analysis, Atena software

1 Introduction

According to Clímaco [1], in ancient constructions, the most used structural materials were initially stone and wood and later metal alloys. An important advance occurred with the development of the so-called binding materials, which harden in contact with water and made it possible to manufacture concrete, a material that has good compressive strength, but low tensile strength. Since the appearance of concrete, the use of this material in constructions has been expanded, however, it was necessary to find a solution for its limited tensile strength. From this search emerged reinforced concrete, a structural material that associates a component with high tensile strength to concrete, called reinforcement. In general, reinforced concrete structures are composed of concrete with steel reinforcement, however, the environmental actions on this material can start the corrosion process of the reinforcement, thus reducing its tensile strength. In order to avoid this process, it is possible to adopt some preventive measures, such as establishing coverings on reinforced concrete parts and limiting the opening of cracks in these elements. According to Rafi et al [2], new non-metallic materials have been introduced as reinforcement of concrete structures in order to avoid the problem of corrosion that can occur in steel bars. These new non-metallic materials are fiber reinforced polymer (FRP) bars, such as aramid, glass and carbon fibers. This work aims to present the use of carbon fiber reinforced polymer bars (CFRP) as reinforcement in concrete elements instead of conventional steel bars. A free demo version of a nonlinear analysis software based on finite elements called Atena [3] (Advanced Tool for Engineering Nonlinear Analysis) was used to try to reproduce the four-point bending tests for concrete beams reinforced with CFRP bars in a study developed by Rafi et al [2]. The design of the bending reinforcement for a reinforced concrete beam section was also performed considering the case in which the reinforcement is composed of steel bars and the case in which CFRP bars are used. In addition, the uniformly distributed loading that breaks the most stressed section of a concrete continuous beam was verified when three steel bars with 10 mm diameter are used for flexural reinforcement and when three CFRP bars with the same diameter are used for this same end.

2 Fiber reinforced polymer bars

According to Nanni et al [4], one of the characteristics of fiber reinforced polymer bars is the elastic linear stress-strain ratio until failure. When compared to steel bars, fiber reinforced polymer bars have higher tensile strength, but lower maximum deformation and modulus of elasticity. Concrete structures reinforced with steel bars present the possibility of redistributing bending moments because this material presents a level of plastic deformations after reaching its yield stress. This means that the steel does not break when its yield strength is reached. When this tension is reached, this material still acquires a certain resistance and starts to deform in a plastic regime until it reaches its final deformation. The fact that fiber-reinforced polymer bars present an elastic linear stress-strain relationship until failure does not allow, therefore, the possibility of redistribution of bending moments in concrete elements reinforced with this type of bars.

In this work, a demo version of the Atena software was used in an attempt to reproduce the results of the experiments carried out by Rafi et al [2] for four reinforced concrete beams submitted to four-point bending tests. These authors studied the bending behavior of two concrete beams reinforced with polymeric bars reinforced with carbon fibers (CFRP) and used two similar beams but reinforced with conventional steel bars to compare the results. Each beam had a rectangular section of 12 cm x 20 cm and length of 2 m. In the beams reinforced with CFRP bars, two longitudinal CFRP bars with 9.5 mm in diameter on their lower face, two longitudinal steel bars with 8 mm in diameter on their upper face and steel stirrups with a diameter of 6 mm distributed were used every 10 cm. For comparison with conventional reinforcement, two beams were also built with the same upper longitudinal reinforcement and stirrups, but changing the bars on the lower face to two steel bars with a diameter of 10 mm. The CFRP bars were constituted by a fraction of 60% of the volume formed by continuous carbon fibers and bisphenol epoxy vinyl ester resin, presenting a tensile strength of 1676 MPa and a modulus of elasticity of 135.9 GPa. A texture was added to the surface of the bars through the treatment of these surfaces in order to improve the adhesion between the reinforcement and the concrete. The beams were subjected to four-point bending tests and both those reinforced with CFRP bars and those reinforced with steel bars showed a similar crack pattern. The CFRP bars showed good adhesion to the concrete, with no sign of failure due to adhesion and no slippage being recorded during the tests. The beams reinforced with CFRP bars broke due to concrete crushing, while the beams reinforced with steel bars broke after the tensioned reinforcement reached its yield. The maximum tensile stresses in the CFRP bars were 80% to 90% of their tensile strength and developed an adhesion stress greater than 85% of that originating from the steel bars. After cracking, beams reinforced with CFRP bars had a higher deflection than beams reinforced with steel bars, however, after the steel reached yield, the deflection rate of beams reinforced with this material was higher than those reinforced with CFRP bars.

3 Nonlinear Analysis

Simulations of the four beams submitted to the tests described in the previous section were carried out using the Atena software. The concrete beams reinforced with CFRP bars were named BRC1 and BRC2, while the beams reinforced with steel bars were identified as BRS1 and BRS2. The compressive strength of the concrete after 28 days was 47 MPa for beam BRS1, 45 MPa for beam BRS2, 43 MPa for beam BRC1 and 42 MPa for beam BRC2. The modulus of elasticity considered for concrete was the value calculated from NBR 6118:2014 [5] for E_{cs}. The characteristics of the reinforcement bars are presented in Tab. 1 and the results obtained by the authors during the laboratory tests can be observed in Tab. 2.

Table 1. Characteristics of reinforcement bars

Bar Type	Diameter (mm)	Ultimate strength (MPa)	ultimate strain	Modulus of elasticity (GPa)
CFRP	9,5	1676	0,0145	135,9
Steel	10	530*	0,0048	201
Steel	8	566*	0,0049	194
Steel	6	421*	0,0041	200

* Steel yield stress

Table 2. Results obtained in the tests by Rafi et al [2]

Beam	Beam cracking load (kN)	Beam Breaking Load (kN)	deflection at rupture (mm)	Fail mode
BRS1	7,8	41,9	29,16	Steel yielding
BRS2	7,5	40,1	27,78	Steel yielding
BRC1	7,1	88,9	35,26	Shear compression
BRC2	7,1	86,5	35,50	compression

The Atena software considers the cracking of concrete through its fracture energy, which was calculated in this work from the work of Hillerborg et al [6]. This method considers that the crack starts its propagation when the concrete tensile strength is reached and from that moment onwards, the stress continues to decrease until reaching zero as this gap increases to the width of w_1. The method proposed by these authors calculates the fracture energy (G_f) according to equation (1):

$$G_f = \int_0^{w_1} \sigma . dw = \frac{f_{ct}.w_1}{2}. \quad (1)$$

In equation (1), f_{ct} is the tensile strength of concrete and in this work the f_{ctm} value was considered, indicated by NBR 6118: 2014 [5] for the analysis of crack opening. Parameter w_1 is the width of the crack opening whose stress reaches zero value. According to Hillerborg et al [6], this width is in the order of 0.01 mm to 0.02 mm. In the present work, the value of 0.01 mm was used for w_1. The configuration of the tested beams can be seen in Fig. 1.

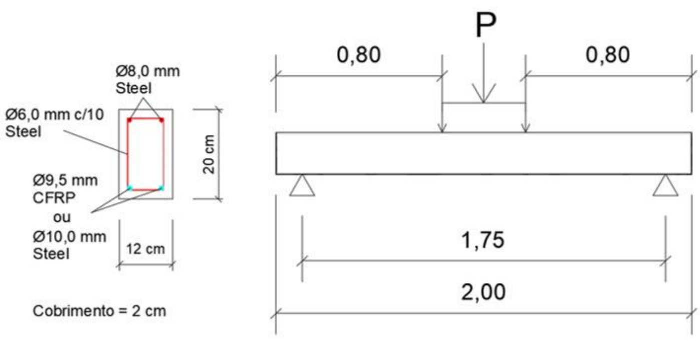

Figure 1. Tested beam configurations

The results obtained by the nonlinear analysis performed in Atena software for the four beams can be seen in Tab 3.

Table 3. Results obtained in Atena for the tested beams

Beam	Crack load of the beam at Atena (kN)	Load on beam analyzed in Atena (kN)	Load deflection analyzed in Atena (mm)	Maximum tension in the longitudinal tensile reinforcement at Atena (MPa)	Failure mode in Atena
BRS1	12,5	42,5	7,0	530	Steel yielding
BRS2	12,5	40	6,0	525,5	Steel yielding
BRC1	10	90	29,0	1340	Not identified
BRC2	10	85	27,0	1218	Not identified

The demonstration of results referring to maximum principal stresses in the bars, crack opening, vertical support reactions and minimum principal stresses in concrete from Atena for beam BRC1 can be seen in Fig. 2. Because a demo version was used, the image of the values of the maximum principal tensions in the bars do not present good visual quality and to solve this problem, the captions referring to each of the images that make up the figure in question were inserted.

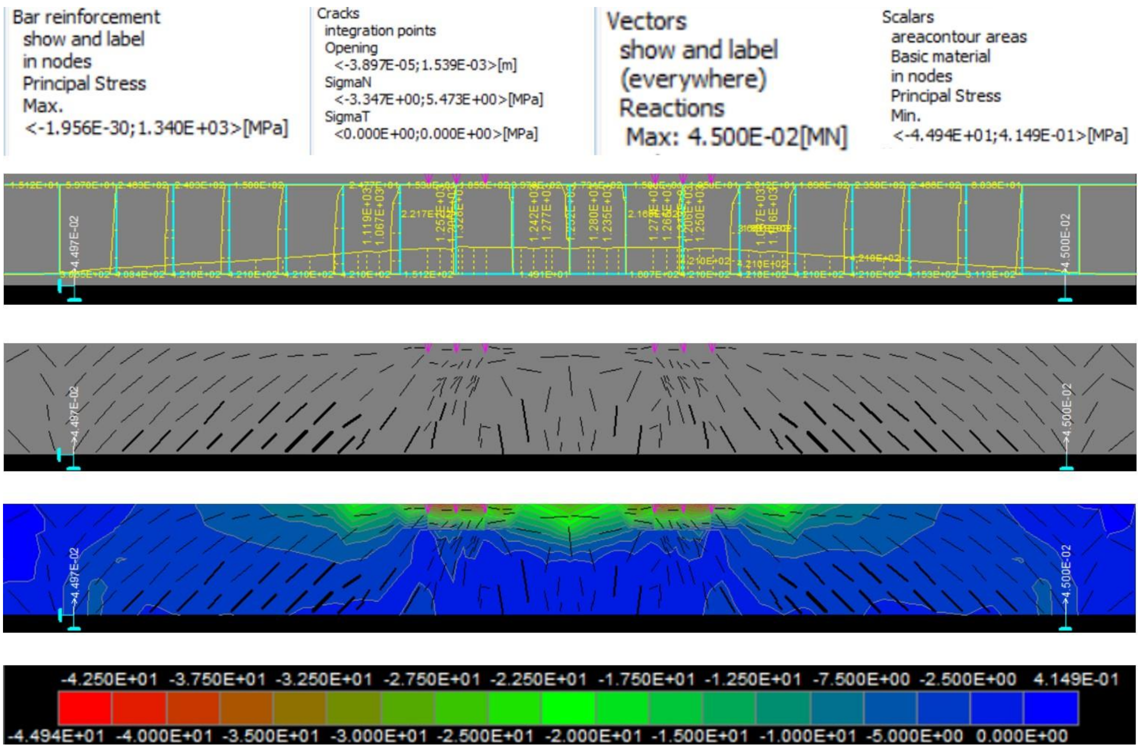

Figure 3. Results regarding crack opening, minimum main stress in concrete, maximum main stress in reinforcement and vertical support reactions for load increase of 90 kN obtained in the BRC1 beam simulation

Analyzing the results, it is possible to see that, in relation to the loads that caused the beams to crack, for the models simulated in Atena referring to all beams, this load was in the range of the same order of magnitude as that obtained by the authors during the laboratory tests. For the maximum deflection recorded in the beams, the models referring to beams BRS1 and BRS2 presented values considerably lower than those obtained in laboratory tests. The beam BRS1 presented for its maximum deflection calculated in Atena a value of 24% of that obtained in the laboratory, while the BRS2 presented a value of 21%. As for beams BRC1 and BRC2, the maximum deflection results obtained in the simulations were closer to those recorded in the laboratory. Beam BRC1 had a maximum deflection of 82% of that recorded in the laboratory and beam BRC2 a value of 76% of that obtained in the laboratory. The maximum stresses recorded in the reinforcements during the analyzes carried out at Atena were consistent in relation to the values obtained in the laboratory tests by Rafi et al [2]. For beam BRS1 the value of 530 MPa was recorded in the longitudinal tensile reinforcement, which represents the yield of the steel, thus confirming the failure mode of the beam recorded in the laboratory. For beam BRS2 the maximum stress in the longitudinal tensile reinforcement was 525.5 MPa, that is, a value very close to 530 MPa, also according to the failure mode recorded in the laboratory. Regarding beams BRC1 and BRC2 the maximum stresses calculated in the CFRP bars were 80% of the resistance stress in beam BRC1 and 72.7% of the resistant stress in beam BRC2. In laboratory tests, the authors recorded values between 80% and 90% of the tensile strength for these beams. Regarding the failure mode, in the simulations carried out at Atena, the beams BRS1 and BRS2 presented rupture according to what was verified in the laboratory. However, for beams BRC1 and BRC2 the same did not occur. The main compressive stresses and main deformations in concrete obtained at Atena are located in ranges below the limits for this material, not indicating rupture by compression of the concrete as recorded in the laboratory tests. It is also possible to observe that some main stress and strain values exceed the limits for concrete, however, this only occurs in regions very close to the application points of the loads and, therefore, this was not interpreted by the beam breaking through the concrete, but that these values occurred due to the high stress concentrations generated close to the loads

4 Flexural reinforcement design

Two concrete beams subjected to bending were designed, the first being reinforced with steel bars and the second reinforced with CFRP bars. A beam with a cross section of 15 cm x 30 cm, useful height (d) of 26.5 cm, concrete with compressive strength of 30 MPa and element under internal conditions of environmental exposure was considered. A bending moment of 32.2 kN.m was considered, referring to twice the value of the minimum bending moment, calculated according to NBR 6118:2014 [5]. The calculation of the flexural steel reinforcement was performed according to this same standard, while the flexural reinforcement composed of CFRP bars was designed in accordance with the North American Standard ACI 440-2015 [7], as there is not at present a regulatory standard in Brazil that establishes guidelines for the design of concrete structures using reinforcement composed of materials other than steel. The ACI 440-2015 Standard [7] establishes calculation guidelines for reinforcement composed of fiber reinforced polymer bars from the failure mode considered in the structure (reinforcement failure or failure by concrete). These failure modes depend on the reinforcement rate (ρ_f) that is present in the section compared to the balanced rate (ρ_{fb}) of reinforcement. When $\rho_f > 1{,}4\rho_{fb}$ the design is given considering the rupture through the concrete and when $\rho_f < \rho_{fb}$, the calculation is performed considering that the cross-section ruptures due to failure of the reinforcement. Steel with a tensile strength of 500 MPa and CFRP bars with a tensile strength of 2070 MPa were considered, as indicated by ACI 440-2015 [7]. Tab. 4 shows the reinforcement areas (steel or CFRP) necessary to resist the bending moment in question.

Table 4. Bending reinforcement

Material	Reinforcement (cm²)
Steel	3,08
CFRP $\rho_f > 1{,}4\rho_{fb}$	1,50
CFRP $\rho_f < \rho_{fb}$	1,15

5 Uniformly distributed loading that breaks a continuous reinforced concrete beam subjected to bending

In this section, the analysis of the uniformly distributed loading that breaks the most loaded cross-section to the bending of a concrete continuous beam was performed when this section is reinforced with three steel bars of 10 mm in diameter and when it is reinforced with three bars of 10 mm in diameter of CFRP. The continuous beam analyzed can be seen in Fig. 2.

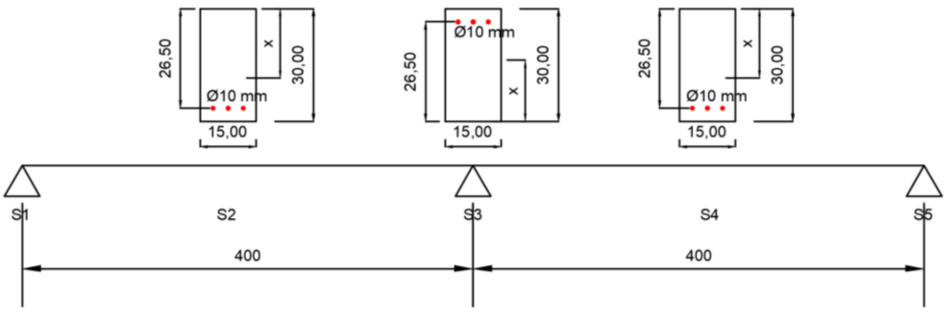

Figure 2. Continuous beam analyzed

To exemplify the redistribution of forces that can occur in hyperstatic concrete structures reinforced with steel bars, a simplified calculation of the plastic rotation capacity for the cross section S3 was performed, which is the most loaded for bending, in order to allow the structure to reach the rupture with a load greater than that for which it was dimensioned. The calculation of the plastic rotation capacity was based on the moment-curvature diagram adapted from Buchaim [8] and presented in Fig. 3.

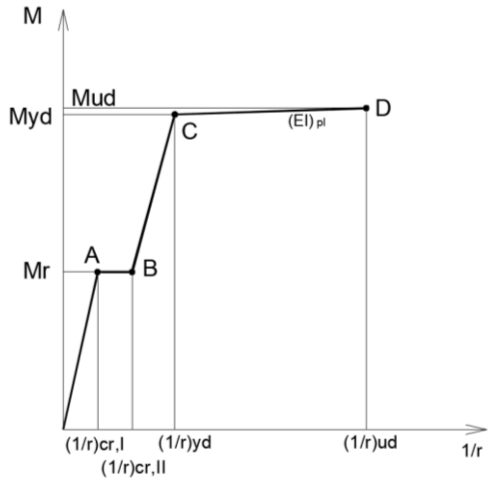

Figure 3. Moment-curvature diagram adapted from Buchaim [8]

In this diagram, M_r is the cracking moment, calculated according to NBR 6118:2014 [5], M_{yd} the section bending moment in ELU, M_{ud} the section's final bending moment, considering the increase in steel strength after yielding, $(1/r)_{cr,I}$ the curvature of the cross=section at the instant the part reaches its cracking bending moment, immediately before the cracking occurs, $(1/r)_{cr,II}$ the curvature of the cross-section at the instant the part reaches its cracking bending moment, immediately after the cracking occurs, $(1/r)_{yd}$ the curvature of the section at the instant the steel yielding is reached and $(1/r)_{ud}$ the curvature of the section at the instant the section reaches its final bending moment.

The calculation of the uniformly distributed load that breaks the most stressed cross-section of the analyzed continuous beam when it is reinforced with CFRP composite bars was performed according to ACI 440-2015 [7] for the reinforcement ratio referring to three longitudinal bars with 10 mm diameter in section. The reinforcement ratio considered is greater than $1{,}4\rho_{fb}$, that is, the calculation followed from the consideration that the cross-section reaches rupture due to concrete failure. Tab. 5 presents the result of the uniformly distributed loading that breaks the most stressed cross-section to the bending of the beam analyzed when it is reinforced with the two different types of longitudinal reinforcement considered.

Table 5. Uniformly distributed loading that breaks the most stressed section for beam bending continues to be analyzed

Reinforcement	Load kN/m
Steel	16,90
CFRP	18,35

6 Conclusion

The non-linear analysis performed with the demo version of the Atena software showed that the loads that caused the beams to collapse had the same order of magnitude as the beams tested in the laboratory. Beam BRC1 had a maximum deflection of 82% of that recorded in the laboratory and beam BRC2 a value of 76% of that obtained in the laboratory tests. The maximum stresses obtained in the CFRP bars through the simulations carried out in Atena were 80% of the shear stress for beam BRC1 and 72.7% of the shear stress for beam BRC2. In laboratory tests, the authors recorded values between 80% and 90% of the tensile strength for these beams. The failure mode of beams BRC1 and BRC2 in the laboratory tests carried out by Rafi et al [2] was through compression failure of the concrete. This failure mode was not identified in the simulations carried out with Atena, since the main compressive stresses and main deformations in the concrete obtained in the simulations are located in value ranges below the limits for this material. The loads obtained in Atena that caused all beams to crack showed consistency with the loads that caused these beams to crack in the laboratory tests. For beam BRS1 the value of 530 MPa was recorded in the longitudinal tensile reinforcement, which represents the yield of the steel, thus confirming the failure mode of the beam recorded in the laboratory tests. For beam BRS2 the maximum stress in the longitudinal tensile reinforcement was 525.5 MPa, that is, a value very close to 530 MPa, also according to the failure mode recorded in the laboratory. The beams with longitudinal tensile reinforcement composed of conventional steel bars, when simulated in Atena, presented maximum deflections considerably lower than expected according to the results obtained in laboratory tests. The design of bending reinforcement for the cross-section of a reinforced concrete beam subjected to a bending moment referring to twice the value of the minimum bending moment calculated according to NBR 6118:2014 [5] demonstrated that, for the case studied, the steel reinforcement resulted in values higher than those found considering the calculation presented in ACI 440-2015 [7] for CFRP reinforcement. In relation to the uniformly distributed load that breaks the cross-section that is most stressed to the bending of the continuous beam analyzed, when it is reinforced with three longitudinal bars of steel or CFRP, it resulted in similar values. This demonstrated that despite the tensile strength of CFRP bars (2070 MPa) being much higher than the tensile strength of steel (500 MPa), this last material allows a design capable of providing ductility to a concrete structure, enabling a design in which these structures redistribute loads when the reinforcement of a given section reaches the yield stress. This load redistribution allows the structure to break with a load greater than that for which it was designed considering a linear elastic analysis.

References

[1] J.C.T.S. Clímaco, Estruturas de concreto armado. Elsevier, 2016.

[2] M. M. Rafi, A. Nadjai. A, F. Ali. F, Experimental testing of concrete beams reinforced with carbon FRP bars. Journal of Composite Materials, p. 2657-2673, 2007.

[3] Advanced Tool for Engineering Nonlinear Analysis. 2D v5 DEMO. Cervenka Consulting, Disponível em: https://www.cervenka.cz/download/.

[4] A. Nanni, A. De Lucca, H.J. Zadeh, Reinforced concrete with FRP bars: Mechanics and Design. Taylor & Francis Group, 2014.

[5] Associação Brasileira de Normas Técnicas. Projeto de estruturas de concreto: Procedimento. São Paulo, 238 p, 2014.

[6] A. Hillerborg. M. Modéer. P-E. Petersson, Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research, p. 773-782, 1976.

[7] American Concrete Institute. Guide for Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer (FRP) Bars, 2015.

[8] R. Buchaim, A influência da não-linearidade física do concreto armado na rigidez à flexão e na capacidade de rotação plástica. 2001. Tese apresentada à Escola Politécnica da Universidade de São Paulo para obtenção do título de Doutor em Engenharia (Doutorado em Engenharia de Estruturas) - Universidade de São Paulo, São Paulo.