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Retrofit of over-reinforced concrete beams using ultra-high performance steel fiber reinforced concrete

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Abstract

Over-reinforced beams are characterized by sudden failure due to crushing of concrete in compression without yielding of the longitudinal reinforcement. In this paper, it is discussed the application of ultra-high performance fiber reinforced concrete (UHPFRC) as a strengthening material in the compressed region of over-reinforced concrete beams, demonstrating its potential to increase the load bearing capacity and improving the beam's failure mode. Ultra-high performance fiber reinforced concrete is a material with exceptional mechanical and durability properties, appearing as a potential candidate to retrofit applications. In this study, the mechanical properties of the ultra-high performance fiber reinforced concrete were investigated, as well as the interface between concrete and the strengthening layer by means of slant shear tests. Over-reinforced concrete beams were also cast and tested, with two being control specimens and four strengthened beams. The interface between the strengthening layer and the conventional concrete was prepared using sandblasting and application of an epoxy-based adhesive. Steel and concrete strains, deflection behavior and failure load were measured, and the crack pattern and failure mode were observed. The results indicate the efficiency of the strengthening method in terms of load bearing capacity and the need to pay special attention to the shear behavior of the strengthened beam. It is discussed how the retrofit process can influence de shears tresses in the beam and how the shear can cause delamination of the reinforcing layer.
Keywords: Ultra-high performance fiber reinforced concrete, strengthening of structures, composite materials, experimental analysis

Resumo

Vigas superarmadas são caracterizadas por uma ruptura frágil por meio do esmagamento do concreto sem que o aço da armadura longitudinal tenha escoado. Neste trabalho discute-se a aplicação do concreto de ultra alto desempenho reforçado com fibras (CUADRF) para reforço de vigas de concreto superarmadas em sua região comprimida, demonstrando a capacidade que este reforço tem de aumentar a capacidade de carga das vigas e alterar seu modo de ruptura. O concreto de ultra alto desempenho reforçado com fibras é um material com excepcionais propriedades mecânicas e de durabilidade, mostrando-se um potencial candidato para aplicações de reforço. Neste trabalho, primeiramente foram realizados estudos para determinação das propriedades mecânicas do CUADRF e ensaios de aderência para avaliar a capacidade da interface do reforço com o concreto convencional. Posteriormente, foram elaboradas e ensaiadas vigas de concreto superarmadas de controle e reforçadas. A interface entre o reforço e a viga foi preparada por meio de jateamento de areia e aplicação de adesivo estrutural à base de resina epóxi. Nos ensaios, foram medidos a deformação do aço e concreto, os deslocamentos das vigas, a carga de ruptura, além de observados padrões de fissuração e o modo de falha. Os resultados indicam a eficiência do reforço para aumento da capacidade de carga e a necessidade de atenção quanto ao comportamento da viga reforçada em cisalhamento. É discutido como o reforço pode influenciar as tensões de cisalhamento na viga e como o cisalhamento pode causar o descolamento da camada de reforço.

Palavras-Chave: concreto de ultra alto desempenho reforçado com fibras, reforço de estruturas, materiais compósitos, análise experimental

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1 Introduction

Designing reinforced concrete flexural elements always demand special attention to the maximum amount of tensile reinforcement in order to avoid brittle failure. Design codes usually specify maximum ratios of reinforcement for beams, but sometimes higher amounts of steel are used to reduce beam depth while still complying with stiffness requirements. This, however, will lead to reduced deflection in failure, with little or no warning to the building users, which is undesirable.

The failure mode of over-reinforced beams is characterized by compressive failure by crushing of the concrete, instead of the desired failure of steel, which is preceded by a yield plateau. In concrete design, this can be represented by the position of the neutral axis of the cross section, which leads to reduced deformation of steel reinforcement. To improve the failure mode of these beams, it is necessary to introduce a stiff element in the compressive region, effectively reducing the depth of the neutral axis. This can be achieved by introducing steel or higher strength concretes in the top of the beam.

Ultra high performance concrete (UHPC) is a type of concrete developed over the last decades that attracted a lot of attention due to its excellent mechanical properties and durability, achieving compressive strengths higher than 150 MPa, tensile strengths over 8 MPa and negligible permeability. These properties attract lots of attention from researchers and engineers to study different applications for the material, including structurally efficient slender elements, critical elements in bridge and buildings, pre-cast structural connections and strengthening or retrofit of structural elements.

One of the main applications of UHPC is rehabilitation and strengthening of reinforced concrete structures due to its exceptional properties. Cement based materials are usually optimal candidates for retrofit of concrete structures because of the compatibility of the mechanical and physical properties of the strengthening and substrate concretes. Other properties of cement based materials that make it suitable for strengthening purposes are availability of materials and ease of casting, which reduce construction cost.

Development of UHPC occurred in a context of verticalization of urban centers, which demanded improvement of concrete properties to comply with higher buildings loads. Improving concrete properties was only possible because of progress in other areas of material sciences, especially concrete admixtures (CALDARONE, 2009). The main research lines that developed the UHPC, and later the UHPFRC, worked with the idea of creating a dense and strong matrix with fine materials and extremely low water/binder ratios, made possible with high admixture contents (BACHE, 1987; CASAGRANDE, 2017; RICHARD; CHEYREZY, 1995; ROSSI, 1997).

The matrix composition of UHPC is characterized by high cement contents, usually reaching over 800 kg/m³, mineral additions such as silica fumes, fly ash or ground granulated blast furnace slag, fine aggregates smaller than 0,6 mm, water/binder ratios under 0,2 and high superplasticizers contents (BUTTIGNOL; SOUSA; BITTENCOURT, 2017; DE LARRARD; SEDRAN, 1994; DUGAT; ROUX; BERNIER, 1996; FERNANDES, 2011; RICHARD; CHEYREZY, 1995; SHI et al., 2015; WILLE; NAAMAN; PARRA-

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MONTESINOS, 2011). This combination of high amounts of binder and very fine aggregates greatly reduce the porosity of the matrix and the low water/binder ratio ensures a high strength cement paste, while the superplasticizers guarantee good workability for the mixture. The low water content combined with high amounts of binder tend to lead to low hydration degrees, making it possible for the remaining binder to react with water once the matrix cracks, giving the material a regenerative property and reducing its permeability (YU; SPIESZ; BROUWERS, 2014).

The resulting material of this mix is an extremely dense and homogeneous matrix due to the optimal packing of the particles. Particle packing optimization is a design method to improve the mechanical properties of the concrete, and is widely used in UHPC mix design (BROUWERS, 2006; HÜSKEN, 2010; YU; SPIESZ; BROUWERS, 2014). This design method focusses on studying the particle size distribution of the different components of the mixture and finding an optimal combination between them to achieve minimal porosity. It is known that reducing the porosity and increasing homogeneity of the concrete vastly improves its properties, which is essential for UHPC (AÏTCIN, 2004).

Adding fibers to the matrix is essential to increase toughness and ductility of the UHPFRC after cracking. Improvement of tensile properties of UHPC is important in several aspects, such as improving shear resistance, increasing durability and better structural performance in general (LI, 1993). UHPC ductility's is improved by adding fibers to the matrix, creating UHPFRC. Ductility enhancement of cement based materials is directly related to the pseudo strain hardening, which in turn requires the occurrence of multiple cracking. Multiple cracking is characterized by the appearance of multiple parallel small cracks during tensile loading of fiber reinforced concretes. This phenomenon happens because, after cracking, the fibers are capable of transferring higher loads than the matrix through the crack, which leads to the formation of more parallel cracks in the uncracked matrix. This happens until the critical load is achieved, leading to crack localization and fiber pullout, where strain softening predominates until the final failure of the material.

This behavior characterizes what is called pseudo strain hardening in cementitious composites, and is essential for good tensile performance of UHPFRC (and fiber reinforced concretes in general). Optimal use of fibers and maximum performance of fiber reinforced cementitious composites are achieved through the study of micromechanics, which models the concrete matrix, the fiber and the interface to find the best conditions in which pseudo strain hardening can happen. This field of engineering aims to unite material and structural engineering to quantify the micromechanical properties of the components and apply the results in macroscopic scale through analysis of structural behavior of composite materials (KANDA; LI, 1999; LI, 1993; LI; WU, 1992).

UHPFRC's compact matrix, optimized by the particle packing models, has extremely low porosity, and, consequently, permeability (HABEL, 2004; TOLEDO FILHO et al., 2012; YU; SPIESZ; BROUWERS, 2014). Tests indicate a thin UHPFRC layer can have permeability up to 30 times lower than conventional concretes (BRÜHWILER; DENARIÉ, 2008). Thus, the penetration of aggressive agents such as chlorides, sulfides, water, deicing salts or others is extremely reduced, increase the lifespan of such structures, even in severe environmental conditions.

Considering these properties, the use of UHPFRC in structural rehabilitation or strengthening has a great potential. The material's excellent mechanical properties can provide improved load bearing capacity to structures, while the durability properties can spread maintenance interventions further apart. Due to the material's high cost, it's application should be considered in areas where it's properties are most used (BRÜHWILER; DENARIÉ; HABEL, 2005).

Structural strengthening has many different particularities, especially due to the interface between the reinforcing layer and the substrate and the difference in stiffness between the old and new concretes. Since UHPFRC usually has a modulus of elasticity 60% higher than conventional concretes, high stresses may be induced in the strengthening layer. These stresses, however, are easily resisted by the UHPFRC, since its tensile strength is several times higher than the substrate. Besides, UHPFRC presents pseudo strain hardening in tension and is able to accommodate much higher deformations. Finally, according to Habel (2004), UHPFRC presents viscoelasticity in early ages, reducing the chance of cracks after the casting, and its shrinkage is much smaller than conventional concrete, thus making the stresses due to constrained shrinkage less relevant (KAMEN et al., 2009).

As mentioned, the interface has a main role in the study of strengthening of reinforced concrete elements. Several authors studied the bond between UHPC and conventional concretes using classical methods found in the literature, mainly slant shear and diametral compression test of composite cylinders. Such tests are usually done by considering different conditions of the interface to simulate normal use of strengthening, such as water or sandblasting, mechanical damage or notching. Results indicate great performance of the UHPFRC, complying with code performance standards (CARBONELL MUÑOZ et al., 2014; HARRIS; SARKAR; AHLBORN, 2011; LEE; WANG; CHIU, 2007; TAYEH et al., 2012). Even in extreme conditions, such as elements subject to freeze-thaw cycles, the interface still shows good performance in terms of load bearing capacity and durability (CARBONELL MUÑOZ et al., 2014; LEE; WANG; CHIU, 2007). Permeability of the composite structure was also studied, showing that the reinforcing layer has high resistance against the penetration of chlorides, water and air, protecting the substrate from harmful substances (TAYEH et al., 2012). Finally, several studies indicate that the best performing surface preparation method is sandblasting, which produces a rough surface for the application of the strengthening layer (CARBONELL MUÑOZ et al., 2014; HARRIS; SARKAR; AHLBORN, 2011; TAYEH et al., 2012). Other methods also show good results, such as water blasting or notching. It is also common combine different bonding techniques, such as using sandblasting and applying structural epoxy-based adhesives.

Finally, considering the specific case of application of UHPFRC as a strengthening layer in the compressive region of beams, it is possible to find some papers on the effects of this type of strengthening on reinforced concrete beams. Lampropoulos et al. (2016) studied the strengthening of beams by means of numerical analyses, modelling different types of

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beams using constitutive models found in the literature. The authors validate their constitutive models by bending, tensile and compressive tests. Results indicate that strengthening with UHPFRC in the compressive region in regular beams don't improve the load bearing capacity significantly, and that increasing the tensile strength of the UHPFRC does not have an impact on the overall performance of the beam. Buttignol et al. (2018) studies the case of strengthening of reinforced concrete beams in the compressed region analytically, finding that in conventional beams the ultimate state resistance is only slightly affected by the strengthening, while combining two methods of strengthening in the compressive and tensile region can yield increases up to 140% in bending resistance. Granato, Sousa e Soldá (2019) confirm the analyses done by the previous authors using a different analytical method and a numerical analysis, finding significant increase in resistance of over-reinforced beams. The authors also studied those beams experimentally, finding difficulties in the bonding technique of the strengthening layer.

2 UHPFRC mechanical properties

Concretes can be classified as ultra-high performance concretes if they achieve exceptional mechanical or durability properties, with 150 MPa compressive strength usually being adopted as a practical threshold. Different studies, as well as many design codes, indicate that UHPFRC has a linear behavior in compression up to its failure, with a short plastification plateau where there is no increase in resistance before rupture (AFGC-SETRA, 2002; HABEL, 2004; JSCE, 2004; KCI, 2012). Design recommendations follow a bilinear model in compression, with the modulus of elasticity and compressive strength as the main properties.

In tension, the material has to be modelled to represent two different behaviors. With the material still uncracked, its behavior is linear, usually modelled as a bilinear curve. After cracking, UHPFRC is modelled considering through inverse analysis of the curve of stress versus crack mouth opening displacement to obtain the viscous-cohevise model that represents concrete after cracking. After that, this stress versus strain viscous-cohesive model can be used in numerical analyses. For UHPFRC, some authors recommend the use of a bilinear model after fracture for materials with both softening or hardening. An example of a complete stress versus strain curve for UHPFRC is shown in Figure 1.

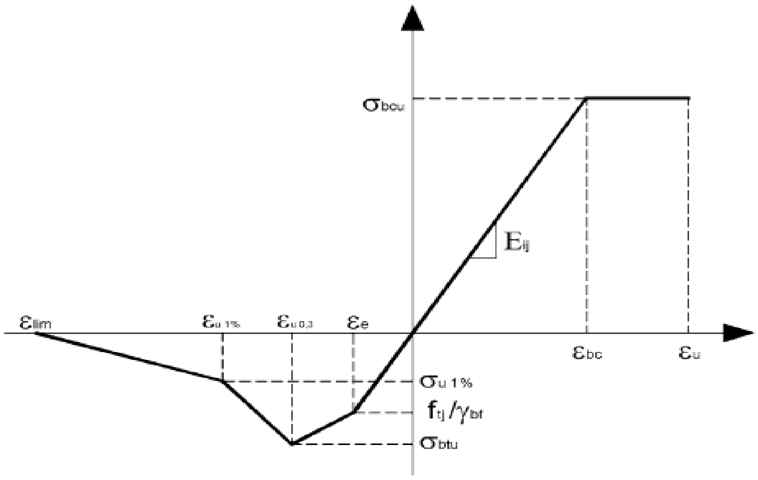

Figure 1 –UHPFRC’s stress versus strain curve (Source: AFGC-SETRA)

3 Analytical model

Analytical models for composite elements such as those found in strengthened or rehabilitated beams are usually not found in usual design codes, especially for UHPFRC composites. However, it is possible to analyze the behavior of composite beams in bending through cross section analysis considering the properties of the concrete substrate, the strengthening layer and possibly the interface bond-slip relation (in case it is not considered to be perfectly bonded). Moment curvature relation and the behavior of structural elements in bending can be reasonably well modelled through cross section analysis with a few assumptions: plane sections remain plane after deformation, the materials behave according to known stress versus strain relations and the cross sections remains in equilibrium. This analyses are commonly used by several authors in studies considering composite beams, yielding good results (FERRIER et al., 2015; HABEL, 2004; YANG; JOH; KIM, 2011, 2010; YOO; BANTHIA; YOON, 2016; YOO; YOON, 2015).

Determination of the moment curvature relation can be done through an algorithm based on the previous assumptions. A generic cross section is shown in Figure 2, where an assumed distribution of deformations is transformed into stresses, and consequently summed to find the forces applied by each material. By an iterative process of assuming a curvature and finding equilibrium, the complete diagram can be determined. The diagram is finished when one of the materials reaches an ultimate deformation.

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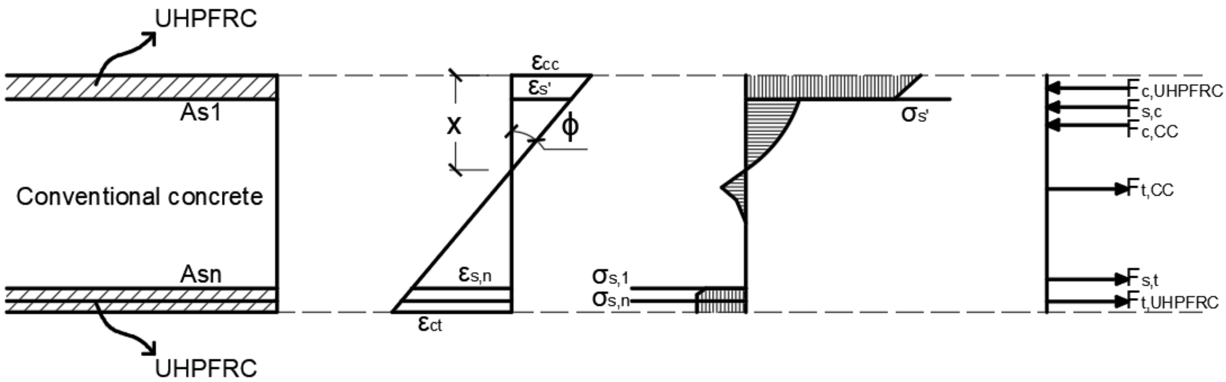

Figure 2 – generic cross section model

4 Materials and methods

In order to analyze the behavior of strengthened over-reinforced beams, six beam specimens were cast, two of them being conventional concrete beams and four strengthened beams. All beams have a 15 x 15 cm cross section, with two 8 mm steel bars on the compressed region and four 16 mm bars at the tension region. It was adopted a concrete cover of 2 cm. The beams were strengthened by replacing the concrete cover in the compressed region by a layer with the same thickness of UHPFRC. To avoid shear failure, stirrups were designed to withstand the expected load with a factor of safety of two. The three-point bending tests were carried out on 1,8 m beams with a span of 1,6 m. The test layout and details of the cross section and stirrups is shown in Figure 4.

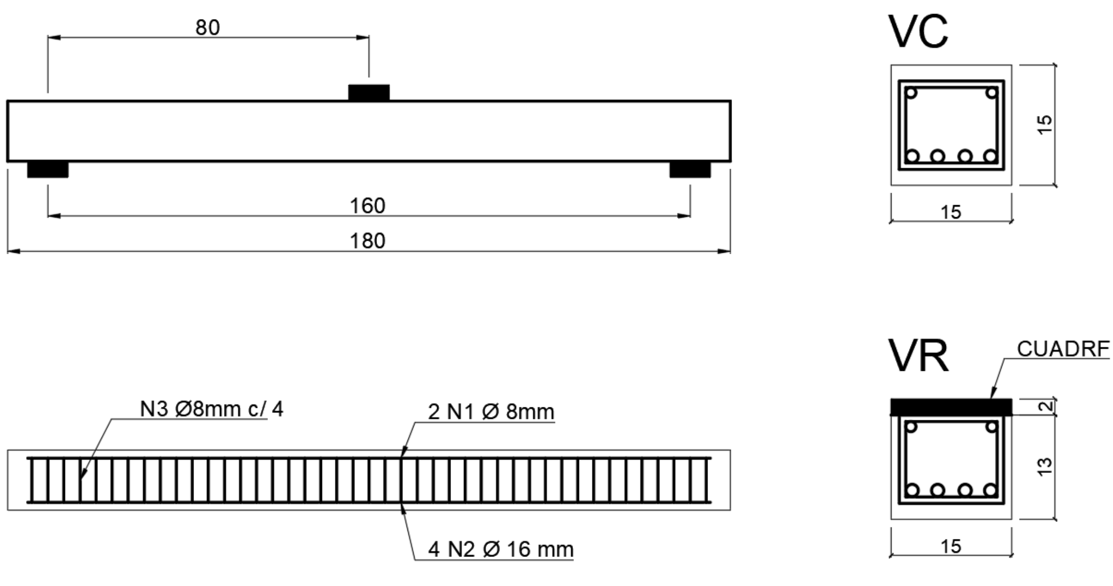

Figure 3 – test layout and cross section

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The strengthened beams were cast in two stages. Firstly, the conventional concrete was cast up to the cover height. One day after casting, the surface was prepared by using a steel brush to remove the weak cement paste on the surface. Eleven days after the casting, the surface was sandblasted to create a rough interface and the UHPFRC was cast. As an additional bonding technique, an epoxy-based structural adhesive was used to improve the reinforcing layer bond performance.

The conventional concrete mix consisted of a 1:2:2 proportion of cement, fine and coarse aggregate. The water/cement ratio was 0,5, with a 1% superplasticizer content to ensure good workability of the mixture and avoid problems with the casting of the densely reinforced beams. Along with the beams, 10 x 20 cm cylinders were cast to evaluate the compressive and tensile strength of the concrete. The UHPFRC mix is given in Table 1, with a steel fiber content of 2% by volume. The steel fibers used were Dramix with 0,2 mm diameter and 13 mm length. To evaluate the mechanical properties of the UHPFRC, 5 x 10 cm cylinders were cast.

Table 1 – UHPFRC mix

Cement	Silica	Sand	Quartz powder	Water	Suerplasticizer
1	0,24	1,17	0,16	0,22	0,07

The tests were conducted at 62 days for VCs and 53 days (substrate concrete) and 43 days (UHPFRC age) for the VRs. All tests were done at the Laboratório de Ensaios Dinâmicos (LabEDin), in Unicamp. Load was applied through controlled displacement of 0,5 mm/min and data was recorded with a set of measuring devices. Strain gauges were glued to the steel bars (2 in the tension bars) and on the concrete in the middle of the span. Three LVDTs were installed equally distributed in the span to measure displacements. The instrumentation is described in Figure 5.

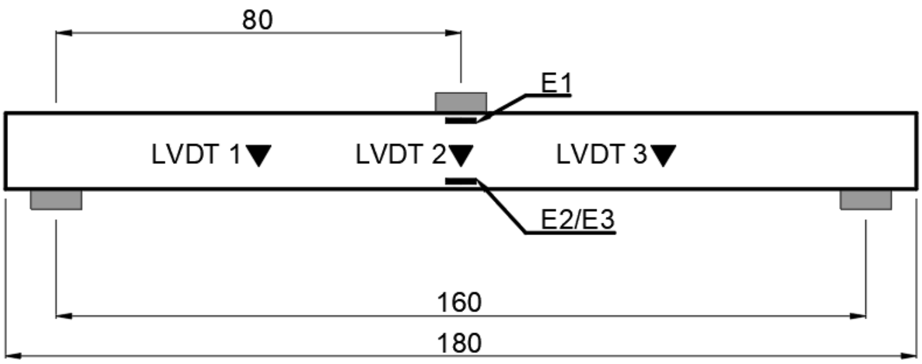

Figure 5 – instrumentation

5 Results

Results of the mechanical properties tests are shown in Table 2. The conventional concrete was cast four times as well as the UHPFRC due to the amount of materials the

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laboratory equipment was able to handle. The properties given are the average over all the specimens, since a small deviation was found between different batches of each concrete.

Table 2 – mechanical properties of the concretes

	CC	UHPFRC
$f_{c,m}\ [MPa]$	39,40	140,0
$E_{ci}\ [GPa]$	27,10	41,46

All tests were performed in a hydraulic press with 1000 kN capacity. The modulus of elasticity was measured with a clip gauge setup in the hydraulic press, acquiring deformation and stress data. The calculations were done considering the tangent elastic modulus up to 30% of the ultimate load. It can be observed that the UHPFRC performs much better than the conventional concrete, with a compressive strength 3,5 times higher and a modulus of elasticity 52% higher.

First, considering the analytical model, it is possible to predict the ultimate moment of the cross section. Using the proposed analytical model, the moment curvature diagram is derived and the ultimate moment and stiffness of the beam are obtained. In Table 3, it is possible to compare those values obtained experimentally and analytically. This shows that the strengthening of over-reinforced beams provides a significant increase in the load carrying capacity and stiffness of the structural member.

Table 3 – comparison between analytical and numerical results

Beam	M_R [kN m] Analytical	M_R [kN m] Experimental	Stiffness [kN m²]
VC	34,1	32,6	$1,14 \times 10^3$
VR	49,6 (+46%)	76,8 (+45%)	$1,50 \times 10^3$ (+32%)

Analyzing the data from the conventional concrete beams (VC), the behavior in the tests is perfectly represented by the models. The expected failure of crushing of the concrete occurs, and the different between the predicted moment versus the observed moment is only 2%. It is also possible to observe the high stiffness of over-reinforced beams and the small ductility, without yielding of the steel. The force versus displacement of the beams can be observed in Figure 6.

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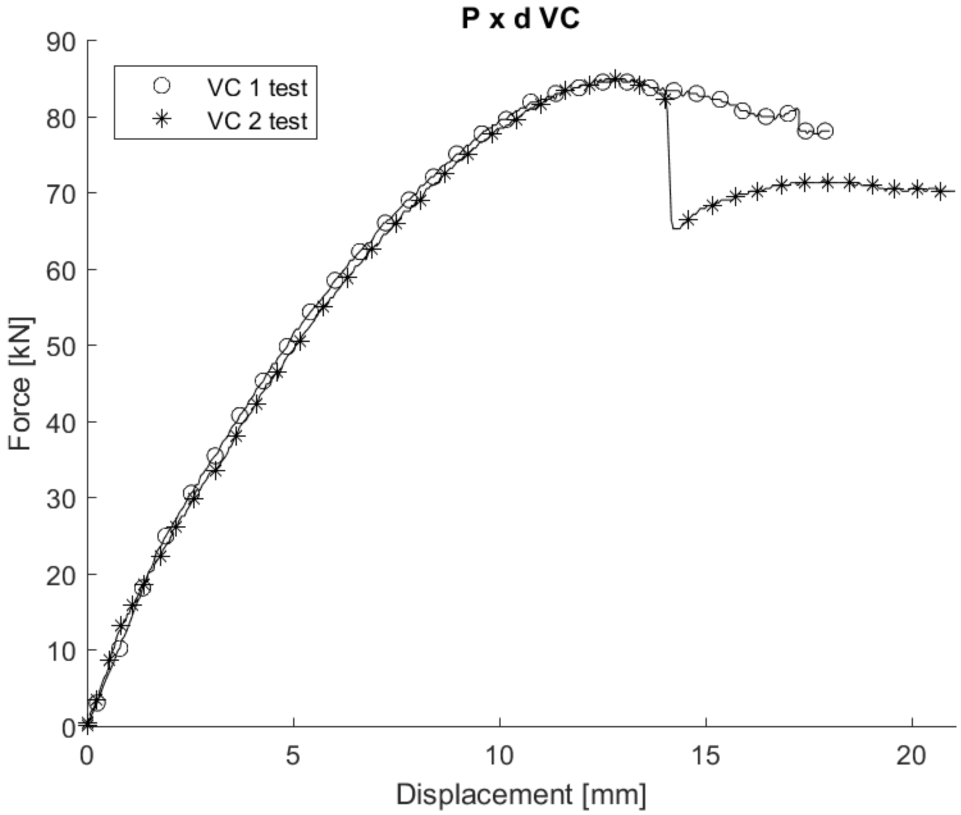

Figure 4 – analyses of the VC tests.

On the strengthened (VR) beams, two distinct behaviors were observed. Firstly, due to the proposed layout of the cross section, irregularities in the casting were very significant in the strengthening layer. Thus, due to difficulties in casting, two beams had sections where the UHPFRC layer had a thickness of 0,5 cm, compared to the desired 2,0 cm. This led to a stress concentration due to the sudden variation in strengthening layer thickness which caused premature failure of the beam. After rupture, measurements were taken on the failed cross section and a model was created to analyze the data. The results were consistent with the data in the tests, finding that the failure was caused by crushing of the UHPFRC in the strengthening layer. After the failure of the strengthening layer, the test was continued and the beam behaved as a conventional concrete beam with a reduced height, achieving a load bearing capacity consistent with analytical predictions of such geometry, until failing again.

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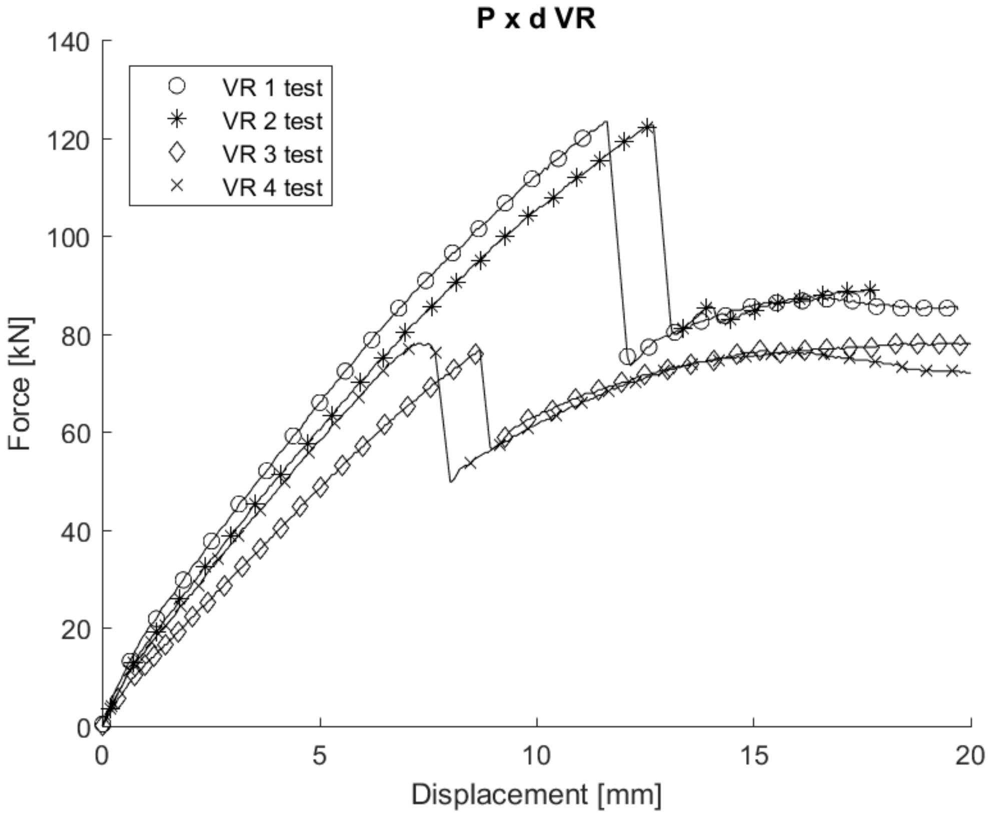

Figure 5 –comparison between all VRs.

The second group of beams did not present the casting issues, showing a behavior closer to expected. The graph of force versus displacement is presented in Figure 8, with the VC beams behavior presented again for comparison. It is clear that the strengthened beams show a much higher stiffness and load bearing capacity, showing the effectiveness of the method. The beams presented a 45% increase in the load bearing capacity and a 32% increase in the stiffness compared to the conventional concrete control beam.

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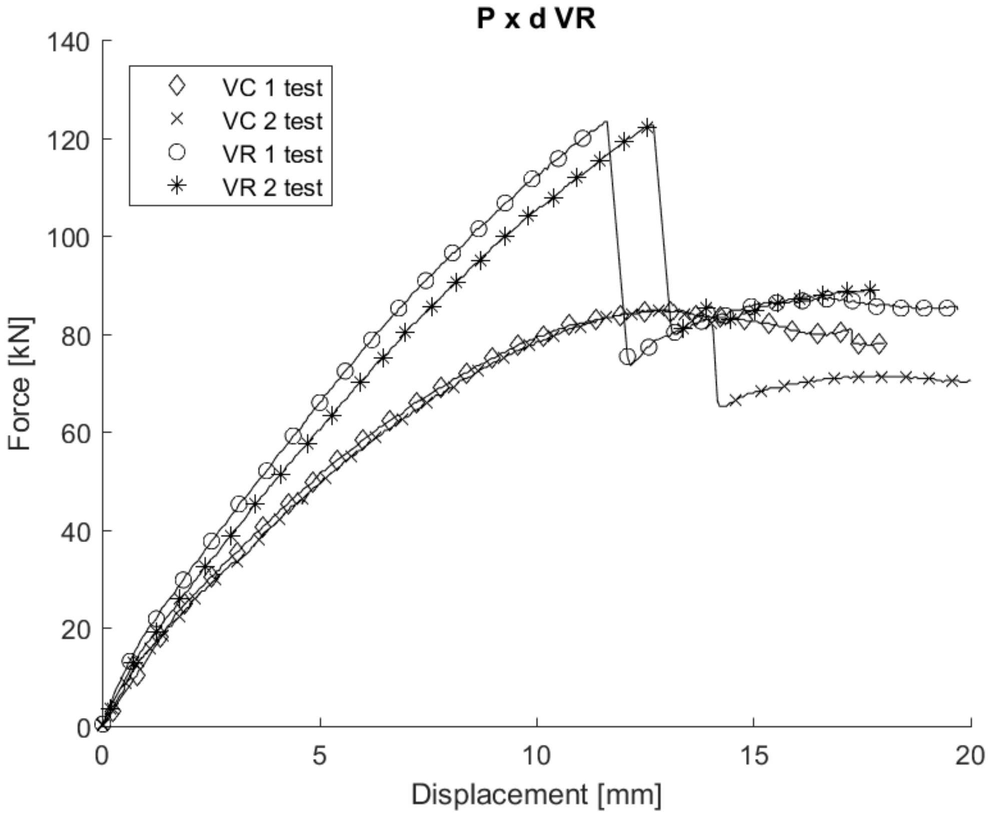

Figure 6 – VR1 and VR2 compared to VC1 and VC2.

However, the beam failed in an unexpected manner. Based on analytical and numerical analyses, the strengthening should increase the ductility of the beam, since the introduction of a stiff element on the compressed region moves the neutral axis closer to the top of beam, increasing the deformation in the steel. This should lead to steel yielding and a larger displacement before failure. During the test, it was observed that the beam behaved as expected until the point of failure, with the strengthening layer behaving monolithically with the beam. However, failure occurred by a sudden debonding of the strengthening layer shortly after yielding of the steel. It was observed that this sudden process started when cracks formed by the bending and shear interaction about one sixth of the span from the load.

In the literature, this phenomenon is described as intermediate crack debonding. Although the specific case of strengthening in the compressed region of beams is not very common, this behavior is observed in other retrofit methods in the tension region. This process happens when an inclined crack reaches the interface between the materials, creating a tendency of vertical displacement between the two materials (TENG et al., 2003). Since the interface usually does not perform well in tension, this process tends to reach the tensile strength of the interface and the materials nearby due to the rapid dissipation of energy, starting an unstable crack propagation near the surface. This is clearly observable

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in the debonded layer, where a thin layer of substrate concrete is still attached after failure (YAO; TENG; LAM, 2005).

This process is further amplified by the adopted geometry of the beam. Analyses indicate that due to the introduction of the presence of a stiff element in the top of the beam, the shear stress has its maximum value closer to the interface. Also, comparing the control and strengthened beams, for the same load, the shear stress is higher on the strengthened beams. Thus, the shear stress reaches a critical point more easily on the strengthened case, and its maximum value is closer to the interface, so the cracks develop faster and in a more critical region.

6 Conclusions

This paper evaluated the application of ultra-high performance concrete as a strengthening material for reinforced concrete beams. The material's main mechanical and durability properties were presented, discussing its suitability as a strengthening material. An analytical model was proposed to investigate the behavior of the composite beams.

Experimental tests were conducted on over-reinforced beams designed in domain 4 according to the Brazilian code. Two control beams and four strengthened beams were tested, where the strengthening was done by casting a 2 cm layer of UHPFRC replacing the cover in the compressed region of the beams. All beams were tested in three-point bending tests. The results indicate that the strengthening method was successful, increasing the load bearing capacity and stiffness significantly. The assumptions for the analytical model were consistent up until the point of failure.

In the tests, an unexpected debonding failure occurred due to the propagation of intermediate cracks resulting from shear-bending interaction. This failure mode consists of an unstable crack propagation near the interface due to stress concentrations and rapid energy release provoked by a crack reaching the interface, leading to a sudden undesired failure of the retrofitted beam. This mechanism is further amplified by the geometry adopted, where shear stresses are amplified and occur near the interface, leading to a faster appearance of cracks in a critical region. Careful design should be done in order to avoid this sudden failure on strengthened over-reinforced beams.

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