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Carbon fiber reinforced polymer (CFRP) inserted in different configurations of the tensile zone retrofitting with microconcrete containing steel fibers to the strengthening of beams

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ABSTRACT. It is researched, in this study, the strengthening technique known as Near Surface Mounted (NSM), which consists of the insertion of laminates of Carbon Fiber Reinforced Polymer (CFRP) into notches in the covering concrete structures. In the strengthening in beams, the tensile zone is found damaged for several reasons (cracking and corrosion, for instance), which demands, in the practice of engineering, its preliminary retrofitting. It should be considered that the good performance of the material used in this retrofitting is fundamental for a higher efficiency of the strengthening. Therefore, it is proposed a methodology that consists of the reconstitution of the tensile zone of the beams with a cement-based composite of high performance (CCAD), which acts as a substrate for the application of CFRP and as an element for the transfer of efforts to the part strengthened. The retrofitting of this tensile zone was performed only in the shear span, as well as throughout of the zone with a view to evaluating the influence of this aspect on the performance of the beams. The CCAD, produced from Portland cement, steel fibers and microfibers, was evaluated using the Rilem (2002), showed to be able to delay the cracking. Tests performed in the beams with the tensile zone retrofitting by CCAD and strengthening using the technique NSM showed the efficiency of the proposed methodology.

Keywords: retrofitting, tensile zone, cement-based composite, strengthening, CFRP.

Polímero reforçado com fibras de carbono (PRFC) inserido em diferentes configurações do banzo tracionado reconstituído por microconcreto com fibras de aço para o reforço de vigas

RESUMO. Estuda-se nesta pesquisa a técnica de reforço conhecida como Near Surface Mounted (NSM), que consiste na inserção de laminados de Polímeros Reforçados com Fibras de Carbono (PRFC) em entalhes no concreto de cobrimento de estruturas. No reforço de vigas, o banzo tracionado encontra-se frequentemente danificado por razões diversas (fissuração e corrosão, por exemplo), o que exige na prática da engenharia sua prévia recuperação. Considerando-se que o bom desempenho do material dessa recuperação é fundamental para maior eficiência do reforço. Nesse sentido, propõe-se aqui uma metodologia que consiste na reconstituição da face tracionada de vigas com um compósito cimentício de alto desempenho (CCAD) que sirva como substrato para aplicação do PRFC e também como elemento de transferência de esforços à peça reforçada. A reconstituição desse substrato tracionado foi executada apenas no vão de cisalhamento, bem como ao longo da extensão do banzo com vistas a avaliar a influência desse aspecto no desempenho das vigas. Produzido à base de cimento Portland, fibras e microfibras de aço, o CCAD, avaliado usando-se conceitos da Rilem (2002), demonstrou ter condições de retardar a fissuração. Ensaios realizados em vigas com o banzo reconstituído pelo CCAD e reforço pela técnica NSM demonstraram a eficiência da metodologia proposta.

Palavras-chave: reconstituição, banzo tracionado, compósito cimentício, reforço, PRFC.

Introduction

The strengthening of structural elements of reinforced concrete with carbon fiber reinforced polymer (CFRP) has become ever more widely known due to characteristics such as the high tensile strength and corrosion resistance, low weight, and ease and speed in application. However, in many countries such as Brazil, there is still no specific standardization on the issue. Professionals use the foreign standards, recommendations of catalogs from the manufacturers of products of CFRP and the results of existing researches.

The issue becomes even more delicate, because in most case studies of engineering, the parts of reinforced concrete need to be restored even before their strengthenings.

Retrofitting the reinforced concrete beams has been considered by many researchers. In recent years much research has been performed about bending and shear retrofitting of reinforced concrete beams with different materials such as steel plates, FRP and high performance fibre reinforced cement-based composite (Ferrari, Hanai, & Souza, 2013; Moatasem, Fayyadh, & Abdul, 2014; Hamdy, Afefy, & Hussein, 2015).

In this regard, according to Ferrari, Hanai, and Souza (2013), the preliminary retrofitting of the tensile zone of reinforced concrete beams (as indicated in Figure 1) with a cement-based composite of high performance (CCAD), based on steel macro and microfibers, prevents the quick spread of critical crack at the edge of the strengthening and delays the early detachment of the blanket of CFRP. Such procedure is extremely interesting for the increase in stiffness of the part, in its load capacity and for a greater use of the resistant properties of the strengthenings.

Also according to the author, the presence of a material of higher resistance to cracking in the tensile zone of the beams, promotes a better distribution of the cracks with smaller openings along the length of the strengthening.

Based on such already existing considerations, the present study complements the study of the proposal initially made by Ferrari et al. (2013) and applied here to the strengthening through the Near Surface Mounted (NSM) technique, performed at the tensile zone and retrofitting the beams by the CCAD.

Thus, in this study the tensile zone of the beams is retrofitting with a CCAD that functions as a transition layer between the CFRP and the beam in a way to allow a better performance to the strengthened beam.

In this sense, it is proposed in this study a methodology that consists of the retrofitting of the tensile zone of beams with a cement-based composite of high performance (CCAD) that serves as layer for the application of the CFRP and also as an element for the transfer efforts to the part that will be strengthened. The retrofitting of the tensile zone was performed to the part that will be strengthened. The retrofitting of this tensile zone was performed only in the shear span of the beam, as well as throughout the entire extension of the tensile zone with a view to evaluating the influence of this aspect on the performance of the beams. To evaluate the effect of the total or partial retrofitting of the tensile zone, a beam was retrofitting in the entire tensile zone and other beam had only the shear span.

Material and methods

Development of the CCAD

Composites analyzed

Six different cement-based composites were analyzed. They are formed from the variation in the volume of steel microfibers and fibers as indicated in the Table 1. The steel fiber specified by the letter 'A' has 25 mm in length and terminal hooks. On the other hand, the steel microfiber specified by the letter 'C' is not yet produced for commercial purposes and has 13 mm in length only, terminal hooks and 0.75 mm in diameter, as are the fiber type A. For each group, five composites with the same characteristics were molded. The composites were stored at + 20°C and humidity of 95% until preparation for testing.

In order to produce the cementitious matrix of microconcrete the following materials have been used: Portland cement of high early strength and density of 3.15 g cm^{-3}, medium sand with a finemess modulus of 2.60 and an apparent specific gravity of 2.70 g cm^{-3}, and a maximum aggregate size of 10 mm and a particle density of 2.78 g cm^{-3}. A superplasticizer that acts as a dispersant of the cementitious material has also been used and all composites had 0.5% of superplasticizer by weight of cement. The cement consumption for the microconcrete was 443 kg m^{-3}.

Table 1. Composites analyzed.

Cement matrix	Group	Composites	Fiber volume	Fiber type
Microconcrete (M)	1	CPM1A1C	1 + 1%	A + C
	2	CPM1A1.5C	1 + 1.5%	A + C
	3	CPM1A2C	1 + 2%	A + C
	4	CPM1.5A1C	1.5 + 1%	A + C
	5	CPM1.5A1.5C	1.5 + 1,5%	A + C
	6	CPM1.5A2C	1.5 + 2%	A + C

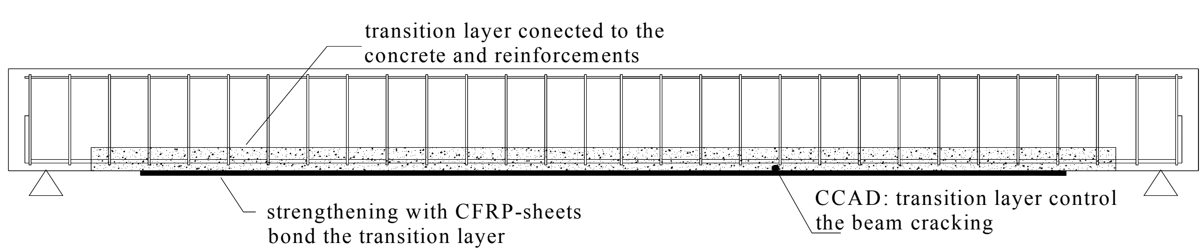

Figure 1. Beam previously recovered with CCAD and then strengthened with CFRP (Ferrari et al., 2013).

Three-point bending test configuration

In order to evaluate the tensile strength of the CCAD, the three point bending test of prismatic specimens with central notch, as recommended by the RILEM TC 162-TDF (Rilem, 2002), has been applied. In the Figure 2, it is observed the general configuration of the test that was conducted under control of the crack mouth opening displacements (CMOD – crack mouth opening displacement) using, for this purpose, an electrical extensometer of the clip gauge type.

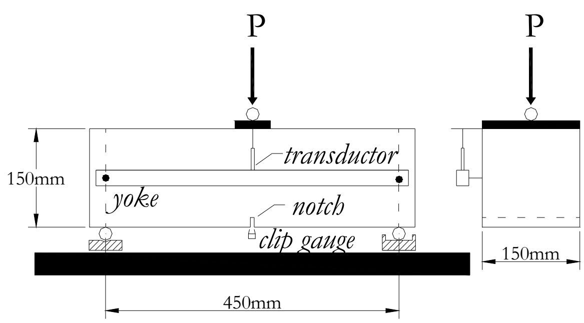

Figure 2. General setup of the three point test of prismatic specimens.

Results of the three-point bending tests: loads, strengths and P-CMOD curves

In order to determine the flexural toughness of the composites, the recommendations prescribed by the work group of the RILEM TC 162-TDF (Rilem, 2002) have been followed. The Table 2 shows the average values of loads and strengths calculated based on these recommendations. These values were extracted directly from the mean curve that is representative of the group.

Table 2. Loads and strengths calculated according to Rilem (2002).

Composites	Loads (kN)				Strengths (MPa)				
	F_L	F_M	$F_{R,1}$	$F_{R,4}$	$f_{fct,L}$	$f_{eq,2}$	$f_{eq,3}$	$f_{R,1}$	$f_{R,4}$
CPM1A1C	12.2	13.0	11.4	1.0	3.6	3.5	2.4	3.4	0.3
CPM1A1.5C	12.0	15.2	12.1	2.7	3.5	3.8	2.5	3.6	0.8
CPM1A2C	14.4	18.9	15.9	1.8	4.1	4.9	3.0	4.5	0.5
CPM1.5A1C	12.8	18.5	16.0	2.4	3.7	5.0	2.4	4.6	0.7
CPM1.5A1.5C	15.2	20.7	17.5	1.3	4.3	5.3	3.6	5.0	0.4
CPM1.5A2C	11.0	15.6	13.7	3.2	3.2	4.4	2.9	4.0	1.0

F_L: maximum load of offset within the interval of vertical displacement (δ) equal to 0.05 mm; F_M: maximum load of the composite; $F_{R,1}$ and $F_{R,4}$: residual loads corresponding to the displacements δ_{R1} = 0.46 mm and δ_{R4} = 3.00 mm; $f_{fct,L}$: stress corresponding to F_L; $f_{eq,2}$ and $f_{eq,3}$: equivalent flexional tensile strengths; $f_{R,1}$ and $f_{R,4}$: residual strengths.

In the Figure 3, the behavior of each composite is compared based on the P-CMOD. The curve used to each composite is the curve of intermediate behavior, which can be representative of the other curves of the group.

All composites presented an initial behavior characterized by a linear stretch, where the cement matrix is presented in full. In this behavior phase it is highlighted the performance for the composites CPM1A2C, CPM1.5A1C and CPM1.5A1.5C, characterized by higher stiffness, higher values of loads applied until the matrix cracking (F_M) and higher strengths ($f_{fct,L}$). As special focus, it is emphasized the values obtained for the composite CPM1.5A1.5C. The behavior of this composite is also emphasized in relation to other composites, after the matrix cracking, when it is noticed the existence of a stretch with horizontal plateau (Figure 2) due to the contribution given by the fibers and microfibers.

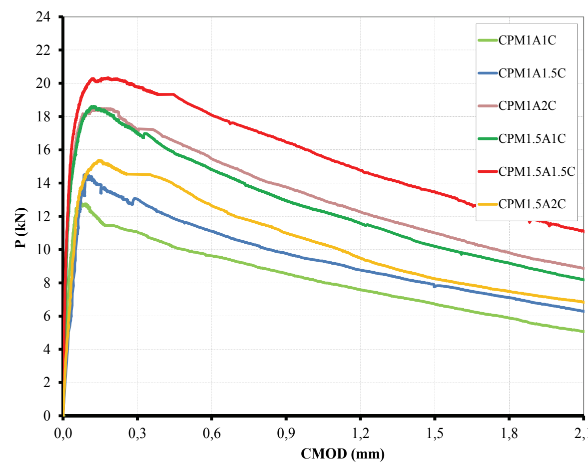

Figure 3. P-CMOD curves of the composites.

Reinforced concrete beams

Characteristics

Eight beams were molded with cross section of 170 x 350 mm, length of 3600 mm and free span of 3200 mm. The lower longitudinal reinforcement was composed of two CA-50 steel bars with 12.5 mm in diameter and the upper reinforcement of two CA-50 bars with 6.3 mm in diameter. The stirrups were formed by steel bars with 6.3 mm in diameter with a uniform spacing of 120 mm. The beams were divided into four groups and their characteristics are described in the Table 3.

Table 3. Characteristics of the reinforced concrete beams.

Groups	Beams	Characteristics
A	VA1 VA2	Beams of reference without strengthening.
B	VB1 VB2	Beams strengthened with two sheets of CFRP
C	VC1 VC2	Beams in which the region of concrete of the tensile zone was removed in the entire extension of the span and subsequently reconstituted with the composite CPM1.5A1C and strengthened with two sheets of CFRP
D	VD1 VD2	Beams in which the region of concrete of the tensile zone was removed only in the extension of the shear span and subsequently reconstituted with the compositeCPM1.5A1C and strengthened with two sheets of CFRP

The beams of the group A, without strengthening, are references for other beams that were strengthened. The beams of this group were sized with low rate of longitudinal reinforcement so that the ultimate limit state could be characterized by the excessive strain of the reinforcement without breaking the compressive zone.

The beams of the group B were strengthened through the insertion of two sheets of CFRP into notches performed in the covering concrete of the reinforcement. On the other hand, beams of the group C and D were subjected to a removal process of concrete from the tensile zone and the retrofitting with the composite CPM1.5A1C. In the Figure 4, it is showed the region of the tensile zoned that was retrofitting and strengthened on the beams.

The only difference between the group C and D is related to the extension of the region of concrete removal of the tensile zone. In the group C, this removal was performed in the entire extension of the span of the beams, while in the group D, it was restricted only to the region of the shear span of the beams.

Another aspect to be mentioned is in relation to the depth of 80 mm used for the concrete removal of the tensile zone. This measure was used based on the recommendations of Ferrari et al. (2013), i.e., for allowing partial exposure of the reinforcement of the stirrups and, therefore, a greater connection between the concrete of the beam and the cement-based composite.

Reconstitution of the tensile zone of the beams and application of the strengthening

Fourteen days after concreting, markings for the regions to be removed from the tensile zone of each beams were performed. This removal was done mechanically with hammer drill and concluded with club hammer, flat chisel and pointed chisel. In order to remold the tensile zone from the beams of the groups C and D, it was applied the composite CPM1.5A1C.

It is important to mention that despite the best responses obtained with the composite CPM1.5A1.5C, the CPM1.5A1C was the composite applied in the reconstitution of the tensile zone of the beams, solely because of the low supply of steel microfibers, which is not commercially available and was produced on request for the present research.

The exposed surface of the concrete of the tensile zone received a cleaning with air jet, followed by water to remove all dust accumulated. It was sought to keep the surface of the concrete dry, however, saturated.

The composite was applied using two wooden formworks in plastic-coated plywood positioned on the two sides of the beams. The composite was manually inserted inside these formworks (Figure 5). In order to characterize the cement-based composite, six cylindrical specimens (100 x 200 mm) were molded.

The strengthening was performed on the beams eight days after the remolding of the tensile zone. The notches were made with the help of a cutting disc, seeking to keep them with an opening of 5 width and 18 mm depth. It was used a two-component epoxy resin, of brand name Sikadur 30, for fixing the sheets in the notches.

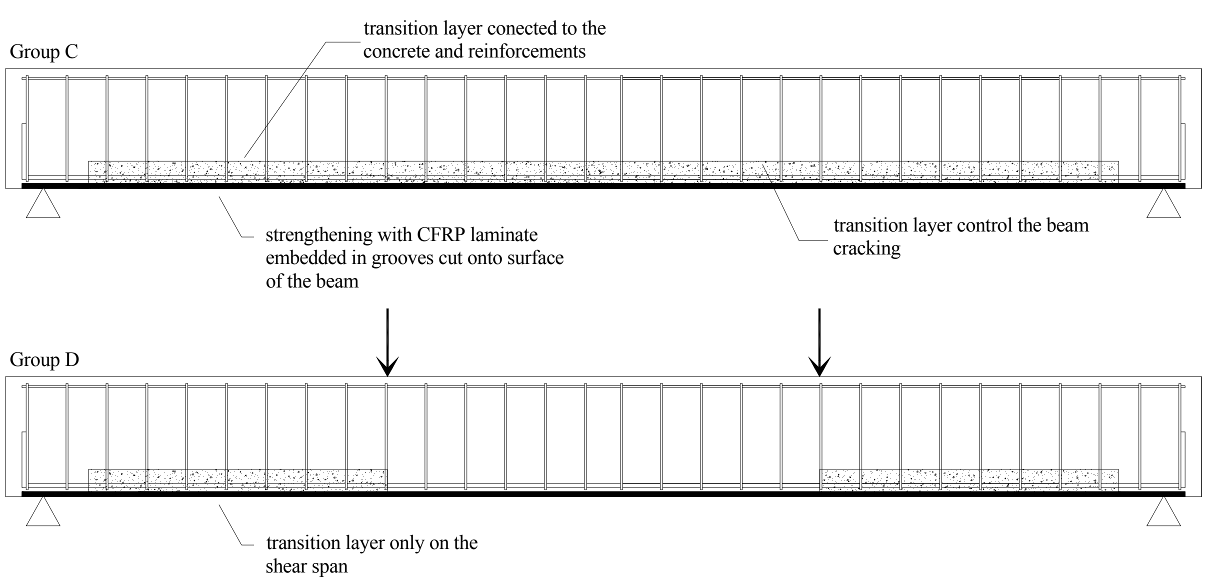

Figure 4. Beams of the groups C and D.

Figure 5. Removal and reconstitution of the tensile zone of the beams of the groups C and D.

The resin was applied firstly inside the notches and then on the two sides of the sheets. The sheets were subsequently inserted into the notches and the excessive resin was removed according to the procedures indicated in the Figure 6.

Figure 6. Procedures to apply the strengthening on the tensile zone of the beams.

Test configuration and instrumentation

The test setup was mounted in the Laboratory of Structures at Engineering School of São Carlos, as indicated in Figure 7. The load was applied through an actuator servo hydraulic (Instron with 500 kN of nominal capacity), able to control the intensity and the speed of loading as well as the displacements (rate of 0.005 mm s^{-1}). Transducers were used in order to measure the vertical displacements of the beams. For monitoring the specific deformations of the concrete, reinforcement and the strengthening, strain gauges (Vishay Micro-Measurements) with resistance of 120.0 OHMS and 12 mm length have been used.

Material properties

For the concrete used on the beams, average values equal to 31.5 and 2.9 MPa; and 40 GPa were obtained for the compressive strength (Associação Brasileira de Normas Técnicas [ABNT], 2007), tensile strength by diametral compression (Associação Brasileira de Normas Técnicas [ABNT], 2011) and for the modulus of elasticity (ABNT, 2007), respectively. As to the cement-based composite applied in the remolding of the tensile zone, the following average values were obtained: 48.0 (ABNT, 2007) and 4.6 MPa (ABNT, 2011); and 33 GPa (NBR 5739, 2007).

The sheets of CFRP (brand name Fita de MFC) were subjected to uniaxial tensile tests according to the recommendations of the American Society for Testing and Materials (ASTM, 2008), being obtained a behavior perfectly linear until the rupture and the average values of 1,363 MPa, 10.9‰ and 118 GPa, for the tensile strength, ultimate strain and modulus of elasticity, respectively.

Results and discussion

For reasons of deficiency in the planning, concerning the safety of the tests, no beams were tested until the failure. The tests were interrupted when the specific strain of the steel achieved the value of 10‰.

The beams of the group A had their behavior as expected, i.e., excessive strain of the longitudinal reinforcement and strain of the concrete of the superior chord up to the limit of 3.5‰. Such beams presented a picture of cracking of large aperture and of spread beyond the half of the beam height.

The beams of the other groups presented great amount of cracks, but with smaller openings when compared to the beams of reference. Cracks with smaller openings were observed in the beams of the group C when compared to the groups A and B (Figure 8). Although, in greater quantity, the cracks in the beams of the group C many times were initiated but were not spread. This effect is due to the control exerted by the cement-based composite in the formation and development of the cracks.

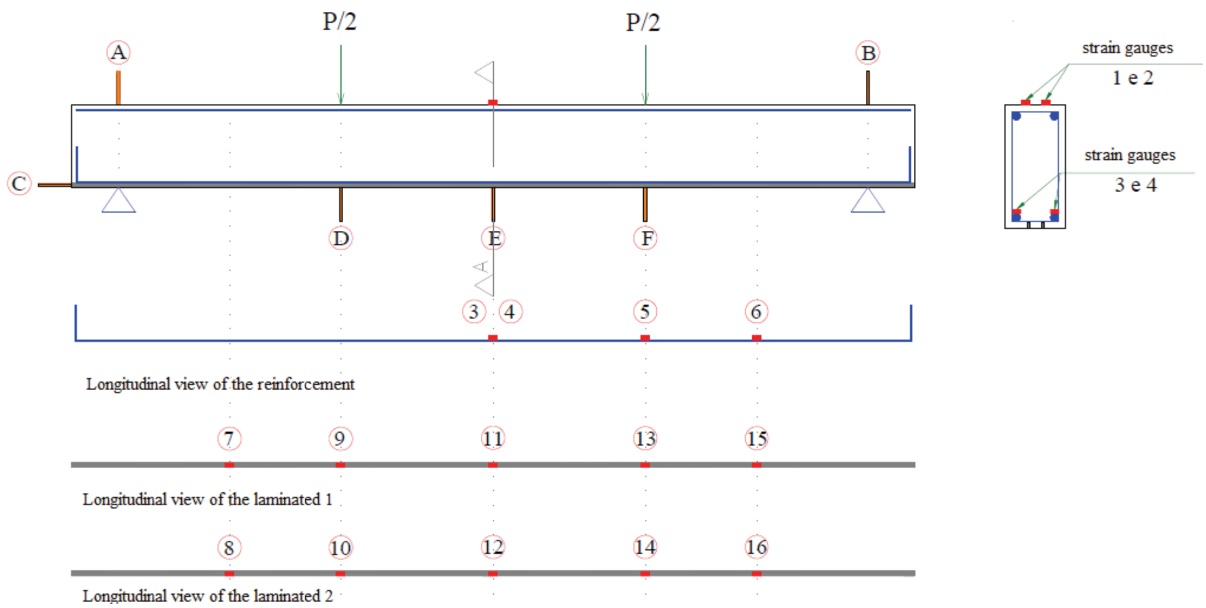

Figure 7. Schematic of the beams and positioning of the transducers and extensometers.

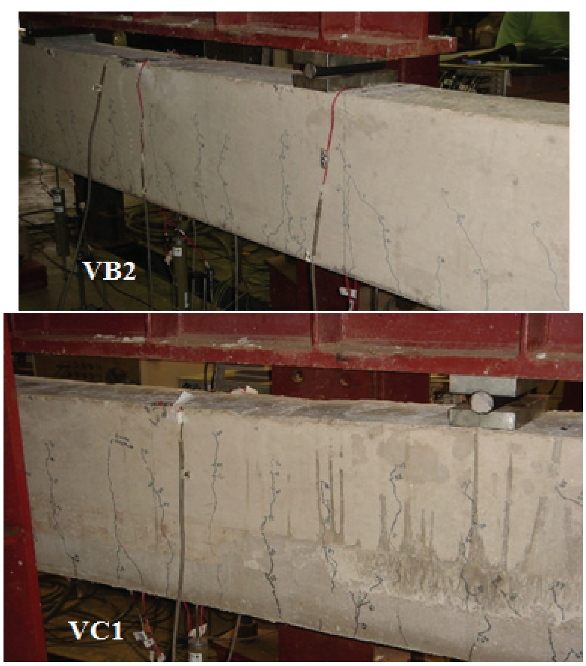

Figure 8. Cracking in the beams of the group B and C.

Loads and vertical displacement

The loads of cracking (P_f) and the maximum load supported by the beams (P_u) until the interruption of the test are indicated in Table 4. The only group with increase in load of cracking was the group C, in which is the result of the presence of the cement-based composite to control of the formation and spread of cracking.

With regard to maximum loads, the strengthened beams presented significant increases in relation to the reference beams, ranging between 40 and 67%. Among the strengthened beams, it is observed that the VC1 has maximum load 11% higher than the beam VB2 and 14% higher than the VD1. These indices show that the presence of the cement-based composite in the entire extension of the span improves the load capacity of the part.

Table 4. Loads of cracking and maximum loads supported by the beams.

Groups	Beams	P_f (kN)	P_u (kN)**	Increases (%)	
				P_f	P_u
A	VA1	32.0	88.9	-	-
	VA2	27.0	79.5		
B	VB1*	18.0	99.2	-39	18
	VB2	21.0	126.5	-29	50
C	VC1	35.0	140.3	19	67
	VC2	39.0	136.9	32	63
D	VD1	23.0	123.0	-22	46
	VD2	23.0	117.2	-22	40

*Through improper execution of the notch, part of the laminate remained exposed. Thus, the results for such beam will not be considered; **Values of maximum load referring to the strain of 10‰ of the reinforcement.

In terms of loads, it is observed that the best responses among the strengthened beams were those obtained by the beams of the group C, which denotes the significant influence of the presence of the cement-based composite along the entire extension of the tensile zone of the beams.

In the Figure 9, it is presented the behavior load *versus* vertical displacement each beams. After the cracking, it is noticed a distinction in the behavior among the beams, having the strengthened, a greater stiffness in relation to the beams of reference, highlighting mainly the performance of the beams of the group C. The beams of the group B and D presented similar behaviors. Aspect in which denotes that the presence of the cement-based composite only in the shear span did not alter significantly the stiffness of the beams.

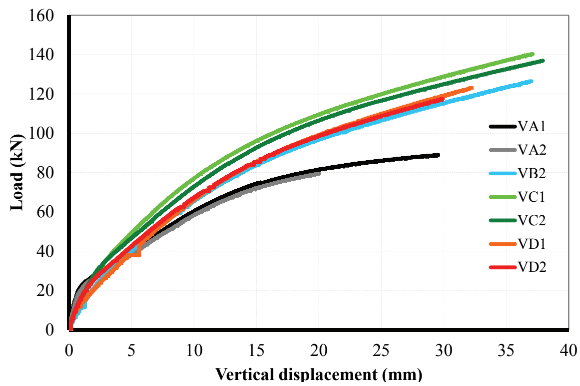

Figure 9. Evolution of the vertical displacement of the beams in the middle of the span *versus* load.

The highlighted behavior of the beams of the group C in relation to the other beams, both in terms of stiffness and load capacity, is the result of the retrofitting of the tensile zone by the CCAD. Such behavior revealed by the Figure 9, indicates that the material CCAD contributed to delay the beginning of the cracking of the beam and to reduce the opening and the spread of the cracking.

In the Table 5, there are the comparisons of the values of loads supported by each beams for the maximum vertical displacement allowed (span/250 = 12.8 mm), considering the limit state of service. Highlighted is the load capacity of the beams of the group C, achieving an increase of up to 30% in relation to the reference beam and of up to 16% in relation to the strengthened beam. Thus, it is verified that the beams of the group C, both for the ultimate limit state and for the limit state of service present the best load capacity.

Table 5. Loads supported by the beams for the limit state of service.

Groups	Beams	P* (kN)	Increase (%)
A	VA1	69.1	-
	VA2	66.8	
B	VB2	76.5	13
C	VC1	88.5	30
	VC2	84.8	25
D	VD1	78.0	15
	VD2	78.0	15

*P: load corresponding to the vertical displacement of 12.8 mm in the middle of the span.

Strain in the laminate

In Figure 10, it is showed the strain progress in the laminate registered in the middle section of the span of each beam. The maximum strains registered in the strengthening, ranged between 8.0 (beam VD2) and 9.6‰ (beam VC2), reaching, therefore, 88% of the maximum capacity of strain of the CFRP sheets, which is of 10.9‰.

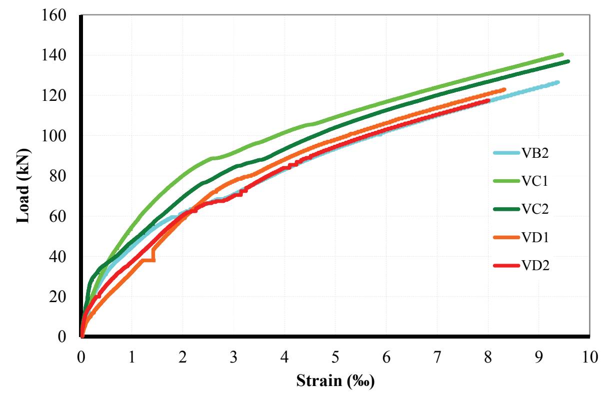

Figure 10. Evolution of the strains of the strengthening in the middle of the span versus load.

Conclusion

In the present study, it was employed the technique of flexural strengthening NSM, by which strips of sheets of CFRP were inserted into notches performed on the tensile zone of reinforced concrete beams. Some of these beams had their tensile zone previously removed and reconstituted through the application of a cement-based composite of high performance. The following conclusions were, thus obtained:

It was possible to develop a cement-based composite with the addition of conventional steel microfibers and fibers in order to potentiate a greater contribution of the cement matrix for the composite strength and for the improvement of the transfer mechanism of stresses from the matrix to the fibers;

The developed composite presented a behavior of pseudo strain-hardening, because, with the cracking of the matrix, the transfer of stresses was facilitated, firstly, by the steel microfibers that, in great amount in the matrix, conditioned the progress of the cracks with the increase of the level of loading;

Comparatively to the beam that was only strengthened, it was verified that the complete reconstitution of the entire tensile zone of the beams provided increase of load capacity and increase of stiffness due to the reduction in the opening of the cracks and consequently to a better use of the sheets of strengthening;

The presence of the material CCAD in the tensile zone that was completely reconstituted provided a better use of the resistant capacity of the flexural strengthening with sheet of CFRP;

The partial reconstitution of the tensile zone did not significantly improve the beam stiffness, and not even the load capacity, when compared to the beam that was only strengthened. For the history of loadings in which the beams were subjected, the cracking in the span central zone was more pronounced than the cracking that occurred in the shear span.

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