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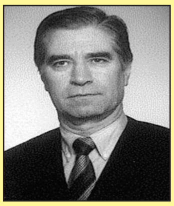
Strengthening of reinforced concrete structures in bending with CFRP systems

Estruturas de betão armado reforçadas à flexão com sistemas de CFRP





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Abstract

Experimental works regarding flexural strengthening of RC structures with externally bonded unidirectional carbon-fiber-reinforced systems (CFRP) have been carried out in the Structural Laboratory (LABEST) of Faculty of Civil Engineering of Porto University (FEUP). The paper presents two of these works, one refers to RC slabs specimens and other to RC beams specimens. The results are exposed, analysed and discussed in order to obtain conclusions about the behaviour of RC structures strengthened with CFRP composite systems. These studies confirmed that the resistance of RC structures can be significantly increased from applying externally bonded CFRP.

Keywords: reinforced concrete, bending strengthening,CFRP systems, external end anchorage systems.

Resumo

No Laboratório de Estruturas (LABEST) da Faculdade de Engenharia da Universidade do Porto foram realizados vários programas experimentais sobre o reforço à flexão de estruturas de betão armado por intermédio da colagem externa de sistemas compósitos de CFRP (polímeros reforçados com fibras de carbono) unidireccionais. Neste trabalho serão apresentados dois, um realizado sobre faixas de laje e o outro sobre vigas. Os resultados obtidos são analisados e interpretados, referindo-se as principais conclusões sobre o comportamento dos elementos estruturais ensaiados tendo em vista avaliar a viabilidade do reforço com CFRP de elementos de betão armado à flexão. Estes estudos asseguram que a colagem de CFRP permite aumentos significativos na capacidade resistente de elementos de betão armado à flexão.

Palavras-chave: betão armado, reforço à flexão, sistemas de CFRP, mecanismos exteriores de fixação.

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1 Introduction

Concrete structures are designed for a given period of useful life, during which they must show adequate levels of safety, functioning and durability. However, it is frequently verified that the safety levels may not be satisfactory because there are errors, either at the level of conception/design, construction or use, that cause the appearance of damage and consequently a decrease in performance of the concrete structures. There are also some situations wherein it is necessary to adapt the structure to new functions that can lead to an increasing of loads. Furthermore, the design codes are introducing more severe clauses to face up certain effects of the actions which had not been considered previously. The safety of a structure may also be put into cause due to the effect of accidental actions (ex.: fire and earthquakes) or the ageing of materials.

It is in this context that the rehabilitation and the strengthening of the concrete structures have played a relevant role in the last years, becoming an important part in the activity of the building construction (Bakis et al. [1]). To face up this situation it has been necessary to develop new strengthening techniques with fast and simple application, that will minimize the effects in the constructions' architecture and using light materials with high mechanical and durability characteristics. The application of externally bonded CFRP systems appears as a solution that guarantees these premises (Meier [2], ACI [3] and FIB [4]).

The FRP composites were developed during the 20th century with the aim of creating materials capable of overcoming the drawbacks exhibited by the use of traditional materials. They are the result of a principle of heterogeneity and they are formed by two components. One of them, the fibers, presents a high strength, a high modulus of elasticity and has the form of a filament with a small diameter. The second component, the matrix, is soft and has synergetic characteristics, being relatively ductile, it wraps up completely the first component permitting a good transfer of tensions between the interlaminated fibers and in the plan. From the association of these two components (fibers+matrix) it results the composite material reinforced with fibers. These materials present properties with interest to engineering such as high strength-to-weight and stiffness-to-weight ratios, good corrosion resistance as well as the possibility of presenting directional properties at a structural level that may change according to the design (Juvandes [5]).

From the different fibers available in the market, the systems reinforced with carbon fibers (CFRP) present characteristics that best fit to requirements of the strengthening of concrete structures. Generally, the CFRP system used in the externally bonded technique is formed by three main components, this is, the CFRP itself, the adhesive of the concrete-CFRP interface and the primer used for the concrete surface preparation. The commercial forms of the CFRP system may be classified in two main groups: the prefabricated system (laminates) and the in situ cured system, being the latter either unidirectional (sheets) or multidirectional (fabrics). Due to the arrangement of the fibers in the composite the unidirectional orientation of the fibers gives to the CFRP the maximum strength and stiffness in the longitudinal direction. The first system is supplied under the form of prefabricated profiles and its mechanical and physical characteristics are granted by the producers. The adhesive is a material different from the composite, being generally of the epoxy type. The second system (sheets or fabrics) consists in the application of bundles of continuous fibers, in a dried or preimpregnated condition, with epoxy adhesive previously spread over the surface to be reinforced. The adhesive (saturation resin) is used to impregnate the reinforcing fibers, fix them in place by polymerization, and also provides adhesion between the wet-lay up composite and the concrete subtract.

The principal aim of this work is to present the experimental investigation carried out in LABEST in order to evaluate the structural behaviour of concrete elements in bending (slabs and beams) reinforced with externally bonded unidirectional CFRP systems, namely the in situ cured system (sheets) and the prefabricated system (laminates). Two different studies developed in LABEST are presented, which will enable to evaluate: the performance of the models under the viewpoint of limit states (service and ultimate); the performance of the additional anchorage systems for CFRP; the advantages and drawbacks of the products and techniques used (Juvandes [6] and Dias [7]).

2 Description of the strengthening technique

The application of the CFRP systems essentially involves three tasks: i) the preparation of the surface to guarantee that the concrete substrate has good bond conditions; ii) the bonding of the CFRP composite reinforcement; iii) the quality control before, during and after the application. Figure 1 includes the main phases of the strengthening of RC structures with externally bonded CFRP systems (FIB [4]).

3 Experimental program with slabs

Taking into consideration the proposal of a Portuguese Roadway Authority (JAE) to study the viability of strengthening the deck of "Nossa Senhora da Guia" Bridge situated in Ponte de Lima - North of Portugal (Costeira Silva et al. [8]), an experimental program on reduced-scale models of the bridge deck (scale 1/2.5 behaviour of RC slabs) was carried out to evaluate the efficiency of strengthening technique with externally bonded CFRP systems.

The experimental program is based on bending tests on four series of reinforced concrete slab specimens. Two series are just RC specimens used as reference, one with the minimum reinforcement (series MIN) and the other with

Figure 1 – Steps of the CFRP application using the externally bonded reinforced technique

- **SURFACE PREPARATION**
  - **Concrete**
    - Remove the superficial cement paste, roughen surface and round corners
    - Quality control: strength, unevenness, flaws and corrosion......repair if needed
    - Concrete should be dry and without residues
  - **CFRP**
    - Cut to size, clean surface and check for flaws
- **CFRP EXTERNALLY BONDED REINFORCEMENT APPLICATION**
  - **Precured system (Laminate)**
    - Primer (optional) and putty application (if need be)
    - Adhesive application on the concrete
    - Adhesive application on the CFRP
    - CFRP application (squeezing out extra adhesive)
  - **In situ cured system (Sheet)**
    - Primer and putty application (if need be)
    - Resin application
    - CFRP application
    - Resin application (CFRP impregnation)
- **QUALITY CONTROL (BEFORE, DURING AND AFTER APPLICATION)**
  - On the supplied materials (standard testing CFRP and adhesive/resin)
  - On the application conditions (environmental conditions)
  - During the application (CFRP position, fiber direction, bond and voids)
- **FINISHING (OPTIONAL)**
  - Painting, shotcrete,....(for e.g. aesthetics, U.V. and fire protection)

a double amount of steel reinforcement (series N). These series are compared with specimen series strengthened with externally bonded CFRP systems. The RC slabs were strengthened with two different unidirectional CFRP systems: the prepreg sheets in situ cured (Replark 20 – series M(1), MBrace sheet C1-20 – series M(2)) and the prefabricated laminate (Carbodur S512 – series L(3), MBrace laminate LM – series L(4), INEGI laminate – series L(5)). The strengthened specimen series (M and L) were designed to have a similar behaviour to the RC specimen of series N, in terms of loading capacity.

3.1 Slab specimens

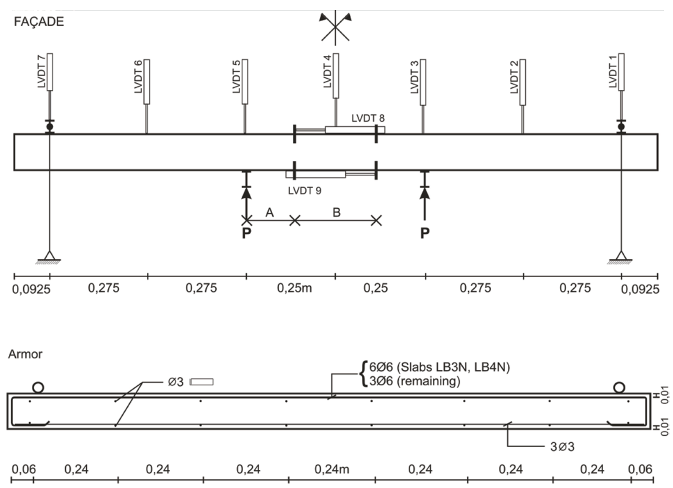
The slab specimens had a width of 45 cm, a depth of 8 cm and a length of 180 cm. The series MIN specimen contained 3ϕ6 rebars as tensile reinforcement, which corresponds to the minimum reinforcement, considered similar to the one that exists in the deck per meter of width ($\rho_s \cong$ 0.20% ÷ 0.25%). The analysis of the structural forces, resulting from the design loads set out in the RSA [9], concluded that it is necessary to increase the load bearing capacity to twice the currently available (Oliveira and Figueiras [10]). The

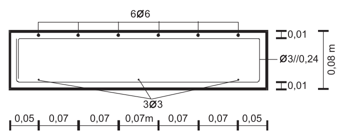
Table 1 – General information about slab models

Slabs	Series	Specimen	ρ_s^{min} (%)*	Strengthening criterion Material	ρ(%)**	Comments
	MIN	LA1M LA2M LE1M LE2M	0.25	without strengthened		RC series with 3ϕ6
	N	LB3N LB4N	0.25	Additional 3ϕ6	0.25	RC series with 6ϕ6
M (sheet)	M(1) - crack. M(1)	LA3R LB1R LC3R LC4R	0.25	Replark 20	0.09	Series pre-craked then strengthened Series strengthened
M (sheet)	M(2)	LD1BM LD2BM		MBrace C1-20	0.09	Series strengthened
(laminate)	L(3) - crack. L(3)	LA4S LB2S LC1S LC2S	0.25	CarboDur S512	0.11	Series pre-craked then strengthened Series strengthened
(laminate)	L(4)	LD3BL LD4BL	0.25	MBrace LM	0.13	Series strengthened
(laminate)	L(5)	LE3I LE4I	0.25	INEGI	0.13	Series strengthened

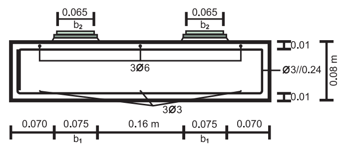
$^*\rho_s^{min} = A_{s,3\phi6} / A_c$; $^{**}\rho_s = A_{s,3\phi6} / A_c$ and $\rho_{CFRP} = A_{CFRP} / A_C$ (%)

Figure 2 – General information about slabs models

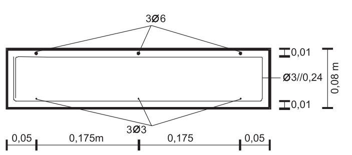




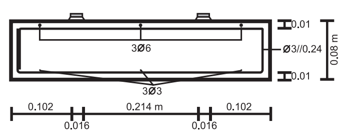
N series (6ϕ6)



M series (3ϕ6 + 2 strips of sheet with 2 layers: 7.5 cm and 6.5 cm)



MIN series (3ϕ6)



L series (3ϕ6 + 2 strips of laminate with 1.6 cm)

Table 2 – Properties of concrete and steel used

<table>
<tr><th rowspan="3"></th><th rowspan="3">Slab specimens</th><th colspan="7">Concrete</th><th>Steel</th></tr>
<tr><th colspan="3">28 days</th><th colspan="4">Slab test date (j days)</th><th rowspan="2">ϕ
f_{sym}
f_{sum}
(MPa)</th></tr>
<tr><th>f_{cm}^{cil} (MPa)</th><th>E_{cm} (GPa)</th><th>f_{ctm} (MPa)</th><th>f_{cm}^{cil} (MPa)</th><th>E_{cm} (GPa)</th><th>f_{ctm} (MPa)</th><th>$f_{ctm,p}$ (MPa)</th></tr>
<tr><td>Concreting A</td><td>LA1M
LA2M
LA3R
LA4S</td><td>50.3
(C45/55)</td><td>40.9</td><td>3.5</td><td>59.5
59.5
60.2
60.3</td><td>44.5
44.5
44.7
44.8</td><td>4.2
4.2
4.2
4.2</td><td>-
-
3.8
3.7</td><td rowspan="3">ϕ3
330.3
464.6

ϕ6
635.6
684.9</td></tr>
<tr><td>Concreting B</td><td>LB1R
LB2S
LB3N
LB4N</td><td>51.6
(C45/55)</td><td>36.9</td><td>3.6</td><td>61.6
61.8
58.0
60.0</td><td>40.3
40.4
44.7
44.8</td><td>4.3
4.3
4.1
4.2</td><td>4.0
3.9
-
-</td></tr>
<tr><td>Concreting C</td><td>LC1S
LC2S
LC3R
LC4R</td><td>56.3
(C50/60)</td><td>36.8</td><td>3.8</td><td>65.6
65.7
65.8
65.5</td><td>39.7
39.7
39.8
39.7</td><td>4.5
4.5
4.5
4.5</td><td>3.8
3.9
3.7*
3.5*</td></tr>
<tr><td>Concreting D</td><td>LD1BM
LD2BM
LD3BL
LD4BL</td><td>45.0
(C40/50)</td><td>34.4</td><td>3.6</td><td>49.0
49.3
49.2
49.0</td><td>35.9
36.0
36.0
35.9</td><td>3.9
3.9
3.9
3.9</td><td>3.2
3.4
4.2
4.1</td><td>ϕ3
330.3
464.6</td></tr>
<tr><td>Concreting E</td><td>LE1M
LE2M
LE3I
LE4I</td><td>45.2
(C40/50)</td><td>36.5</td><td>3.6</td><td>47.9
47.9
50.2
50.2</td><td>37.9
37.6
38.5
38.5</td><td>3.8
3.8
4.0
4.0</td><td>-
-
4.0
4.0</td><td>ϕ6
555.0
602.0</td></tr>
</table>

(value) – concrete classification by strength (concrete class). * Without pre-drilling.

series N specimen contained 6ϕ6 rebars in order to simulate the strengthened slab situation in a RC sample.

The specimen geometric characteristics for the strengthened series M and L were evaluated to have the same load bearing capacity as the series N specimen. Using the design criterion proposed by Rostasy (is described in Juvandes [6]), the maximum deformation of the CFRP was limited to 8‰ in order to account for the possible occurrence of premature collapse and to control the steel strain in service. For each series of strengthened specimens with CFRP (series M and L), two models were pre-loaded (pre-cracked) prior the application of the CFRP systems. General information on specimens and test set-up are illustrated in Figure 2 and Table 1 (Juvandes [6] and Dias [7]).

3.2 Materials properties and characterization of concrete-adhesive-CFRP interface

To characterize the properties of the concrete at 28 days of age (tensile strength, modulus of elasticity and com-

Table 3 – Properties of the CFRP systems

CFRP systems		Main properties			
Type	Materials	Tensile strength (MPa)	Young's modulus (GPa)	Ultimate strain (‰)	Thickness (mm)
Replark 20 (14)	Primer Resin Sheet	- 29.4 3400	- - 230	- - 15	- - 0.111
MBrace Sheet C1-20 (15)	Primer Resin Sheet	12 50 3700	0.7 3 240	30 25 15	- - 0.111
CarboDur S512 (16)	Adhesive Laminate	20-30 2800	8-12.5 160	30-60 17	2-3 1.2
MBrace Laminate LM (15)	Primer Adhesive Laminate	12 - 2200	0.7 7 150	30 - 14	- - 1.4
INEGI Laminate (17)	Primer Adhesive Laminate	80 22.8 2400	3.4 5.1 160	- - 15	- - 1.4

Figure 3 – “Pull-off” test set-up

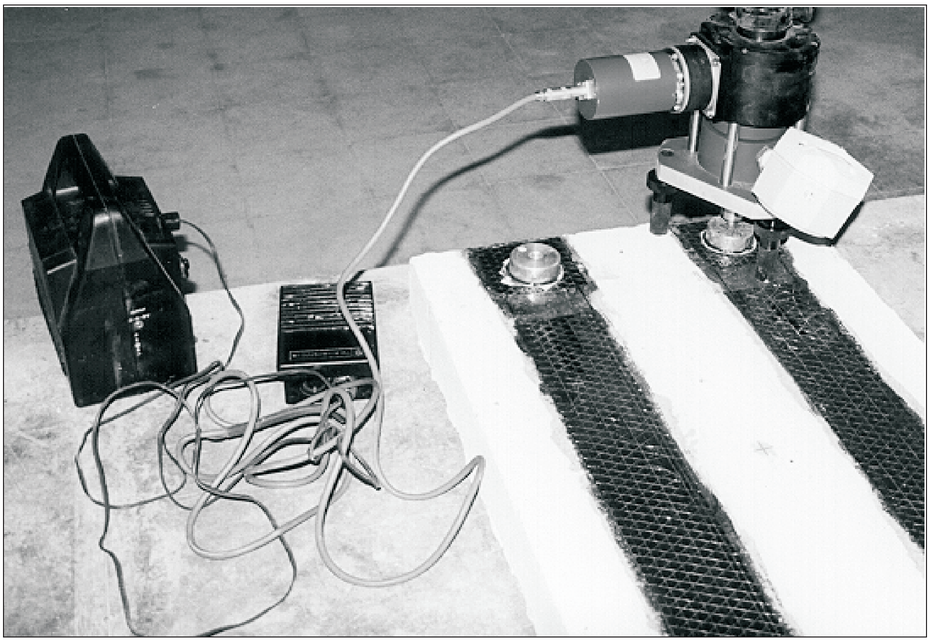
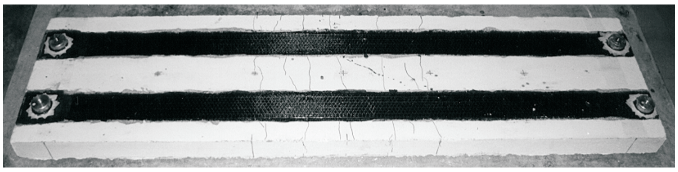
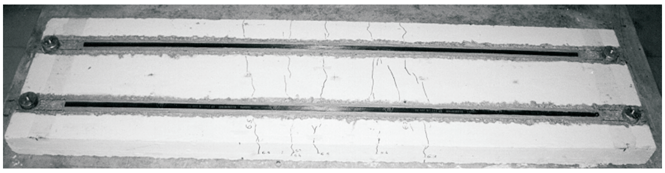


Figure 4 – Flexural strengthening with CFRP using externally bonded reinforcing technique

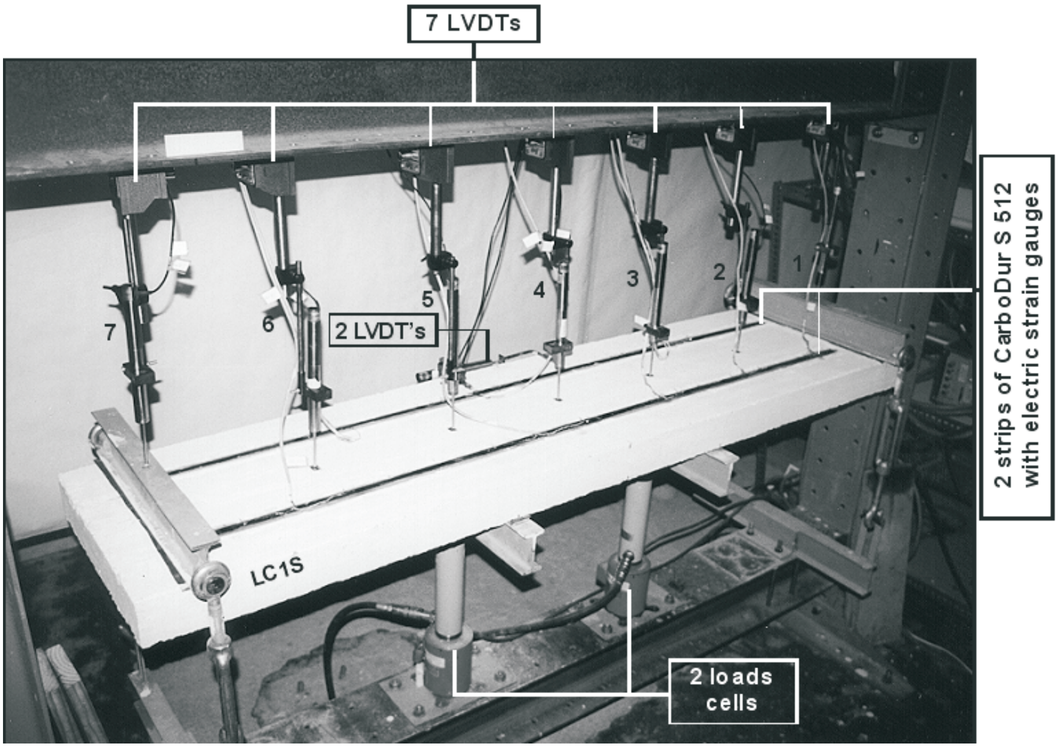


Final aspect of a slab strengthened with CFRP ("in situ" cured system)



Final aspect of a slab strengthened with CFRP (prefabricate system)

Figure 5 – Test set-up of slabs



pression strength), tests, according to NP-ENV206 [11], were carried out. The modulus of elasticity and compression strength of concrete were obtained from uniaxial compression tests with cylinder specimens of 150 mm diameter and 300 mm height and cubes 150/150/150 mm. The concrete tensile strength was obtained from flexural tests with prisms 150/150/525 mm. The main properties of the concrete at the date of testing the models were evaluated considering the properties of the concrete at 28 days age and the equations of Model Code 1990 [12]. The slab specimens tested had steel bars with 3 mm (smooth) and 6 mm (ribbed) and their properties were assessed with uniaxial tensile tests. Table 2 presents the average values for the concrete and steel properties experimentally evaluated.

According to the manufacturers, the CFRP systems used in this experimental program had the properties indicated in Table 3.

In order to evaluate the bond conditions of the CFRP-concrete interface, pull-off tests were carried out (Juvandes [6] and Dias [7]). The type of pull-off tests performed consists in measuring the tensile load to pull one steel plate bonded to the concrete surface, with a diameter of 50 mm. The bond strength value, $f_{ct,p}$, is obtained dividing the ultimate tensile load by the surface of the steel plate.

Figure 6 – Criterion of pre-cracking

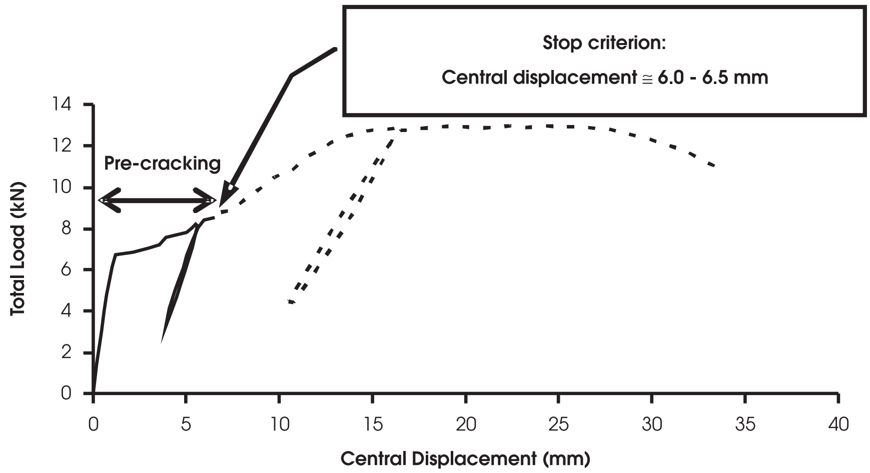


Table 4 – Results from each pre-cracking slab specimen

Slabs specimens		Initialized cracking F_{crack} (kN)	Initialized cracking δ_{crack} (mm)	Stabilized cracking F_{scrack} (kN)	Stabilized cracking δ_{scrack} (mm)	s_m (cm)
M(1) - crack.	LA3R	6.33	1.07	7.96	6.51	10.3
	LB1R	8.07	1.23	10.22	6.45	11.8
L(3) - crack.	LA4S	7.80	1.17	10.06	6.10	13.6
	LB2S	10.27	1.33	11.50	6.40	11.2

To limit the bond surface of the steel plate area, a partial core was made. In Figure 3 the pull-off test set-up can be observed. The average values of bond strength ($f_{ctm,p}$) are presented in Table 2. These results are higher than the limit (1.4 MPa) recommended by the ACI Committee 440 [13] for strengthening of RC members with externally bonded FRP reinforcement.

3.3 Application of the CFRP systems

3.3.1 CFRP prepreg sheet

Surface treatment started with mechanical grinding of the concrete surface layer in order to remove the superficial laitance and contamination, followed by an air jet to eliminate dust. A layer of primer was applied to guarantee the best adherence at the concrete-adhesive-composite interface. Two strips of CFRP sheet, composed of two layers, were glued on the tension face of the slab specimen by epoxy resin.

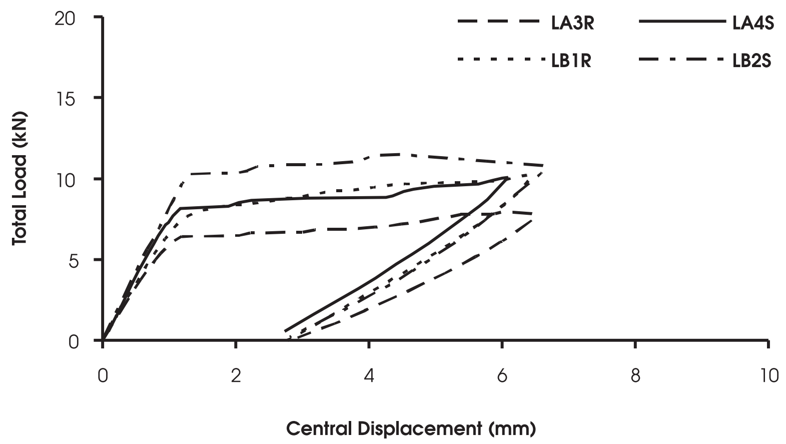
3.3.2 CFRP laminate

The concrete surface with uniform roughness that is required to bond this system was obtained by means of a 'needle hammer' and an air jetting. A layer of primer was applied over the specimens of the concrete surface, strengthened with MBrace and INEGI laminate systems. After these steps, the two strips of CFRP laminate were glued on the tension face of the slab specimen by epoxy adhesive.
Figure 4 illustrates two slab specimens strengthened with CFRP composite systems using externally bonded reinforced technique (slab specimens strengthened after pre-cracked).

3.4 Description of the tests and presentation of the results

The experimental program consisted of two types of four-point bending tests. In the first (test type I), four slab specimens (LA3R, LB1R, LA4S and LB2S) were loaded to produce

Figure 7 – Total load *vs* central displacement responses of pre-cracking slabs (type I)



a specific level of cracking. In the second test (test type II), all slab specimens were loaded up to failure. To register the cracks and see the failure modes of CFRP, the specimens were tested upside down. The test set-up is illustrated in Figure 5, where it can be seen the instrumentation of the test slabs: LVDTs (linear variable displacement transducers) to record the displacements; two load cells applied under the specimens to measure the load during the test; electric strain gauges glued to the composite (sheet or laminate) in order to measure the strain distribution along its length.

3.4.1 Pre-craking test (type I)

The strengthening of an existing structure often involves concrete in a cracked state. Thus, prior to the application of the strengthening material, four models of slab samples (LA3R, LB1R, LA4S and LB2) were loaded in order to reach a stage of stabilized cracking (Dias [7]). The test criterion, obtained in total load vs central displacement response of the LAM1 slab, is presented in Figure 6 which corresponds to a maximum value of the central displacement of 6.0 to 6.5 mm (about five times the central displacement at the beginning of cracking).

After the test type I (pre-cracking), the four models exhibited, basically, flexural cracks in the central zone of the slabs. Table 4 shows for each pre-cracked model the load (F) and corresponding displacement at mid span (δ) at the beginning of cracking and at stabilized cracking moment, as well as, the average crack spacing (at the end of test type I). The pre-cracked specimens were first loaded to produce a state of stabilized cracking, then (after unloading - see Figure 7) the CFRP system was bonded (see Figure 4) and finally the specimens were tested up to failure (test type II).

3.4.2 Test up to failure (type II)

Table 5 shows, for each model tested, the main results in terms of limiting states (service and ultimate): load at the beginning of cracking (F_{crack}), maximum load (F_{max}) and corresponding displacement at mid span (δ_{max}), the average crack spacing (s_m - test type I and s_{um} - test type II) as well as the types of failure observed.

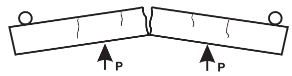
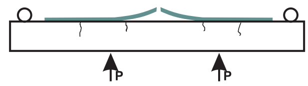
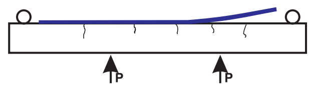
In terms of service it is to be noted that the load at the beginning of cracking (F_{crack}) shows higher values in the strengthened specimens, decreasing progressively through the specimens of the N and MIN series. All slab specimens followed a typical crack pattern of flexural members. The first flexural crack occurred at the midspan of the beam between the applied loads (pure bending zone). Under further increase in the load, news cracks emerged at each slab shear span. The pattern of cracking shown by the slab specimens, suggests that the average distance between cracks (s_m) reaches its maximum value for the models of the MIN series. Specimens of the series N, M and L exhibit similar values for crack spacing.

In terms of ultimate limiting state it is to be noted that the CFRP strengthened slabs exhibited a significant increase in the maximum load (more than double) and in the corresponding displacement at mid span. As far as failure modes are concerned, in the models reinforced with the prefabricated system there was only one type (early peeling of the CFRP), while in the models strengthened with the in situ cured system, two types of failure occurred (rupture of the CFRP and premature failure caused by peeling). The RC models without CFRP (models of the series MIN and N) failed by yielding of the steel tension reinforcement.

3.5 Analysis of results

To carry out a more direct comparative analysis of the various series of slab specimens, through the total load vs central displacement diagram, the loads are normalized in order to consider the effect of the parameters such as geometry and

Table 5 – Main results from each specimen tested

Slabs			Service		Ultimate			
Series	Strengthening	Specimens	F_{crack} (kN)	s_m (I) (cm)	F_{max} (kN)	δ_{max} (mm)	s_{um} (II) (cm)	Modes of failure
MIN	-	LA1M	6.74	-	13.02	20.9	9.9	
		LA2M	7.20	-	13.40	20.0	9.7	
		LE1M	6.66	-	12.51	18.3	8.5	
		LE2M	6.78	-	12.49	25.6	8.7	
N	3ϕ6	LB3N	7.30	-	29.20	22.7	6.8	steel yielding
		LB4N	7.60	-	28.60	22.6	6.2	
M	M(1)	LC3R	10.60	-	39.10	39.3	6.3	
		LC4R	10.60	-	31.30	32.3	6.4	
	M(1) - crack.	LA3R	*	10.3	31.78	39.1	6.6	CFRP rupture
		LB1R	*	11.8	36.26	36.5	6.8	
	M(2)	LD1BM	8.04	-	28.22	32.1	6.4	
		LD2BM	8.59	-	27.03	24.9	7.3	
L	L(3)	LC1S	11.00	-	34.10	31.9	6.4	
		LC2S	11.40	-	37.70	30.6	6.3	
	L(3) - crack.	LA4S	*	13.6	30.60	29.3	6.7	
		LB2S	*	11.2	33.46	25.1	6.6	CFRP peeling
	L(4)	LD3BL	8.79	-	33.13	35.5	7.5	
		LD4BL	8.02	-	32.33	41.4	7.9	
	L(5)	LE3I	7.59	-	30.76	31.0	6.7	
		LE4I	7.29	-	31.95	38.6	6.9	

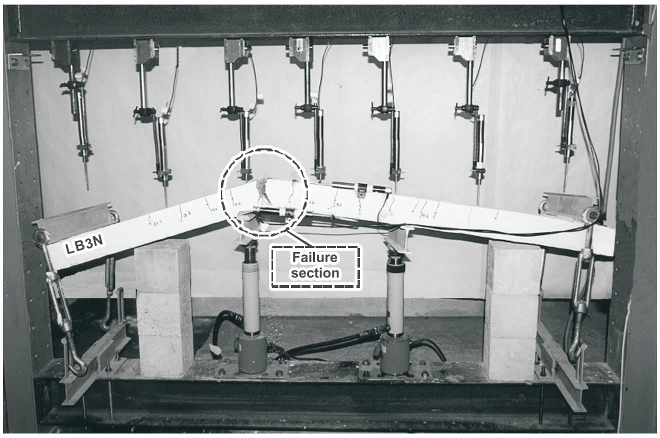
*The cracks of pre-cracked specimens reopened when these specimens were loaded up to failure (test type II).

the type of concrete of the specimens (Juvandes [6] and Dias [7]). Considering the geometry initially established (b = 0.44 m and h = 0.08 m) and for a class C45/55 concrete, the average curves of the total load vs central displacement are presented in Figure 9 for the series MIN, N, M (M (1) and M (2)) and L (L (3), L (4) and L (5)).

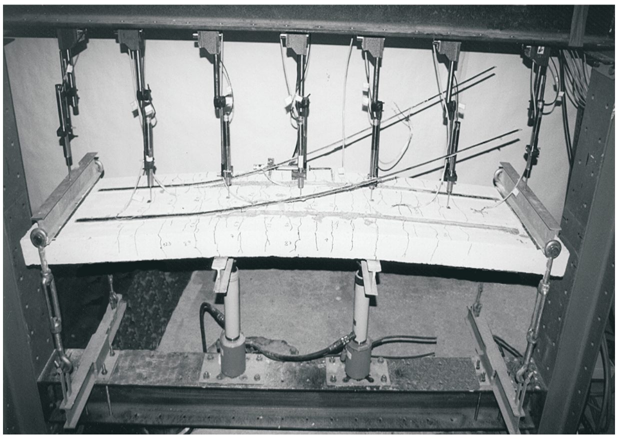
The specimens externally strengthened with composite material show three main stages of behaviour (Juvandes [6]), namely: the phase of uncracked concrete, the phase of cracked concrete and the phase of yielding of the reinforcing rods. It is noticeable that after the reinforcing rods yielded, only the composite contributed to the increase of flexural capacity, hence the appearance of the straight line in the final part of the graphs of the strengthened specimens (linear behaviour of the unidirectional CFRP composite). Comparing the series MIN, M and L, it can be seen that along with an increase in ultimate bearing capacity, the reinforcement permitted an increase in the initial cracking load, a significant gain both in terms of rigidity and the maximum displacement at rupture.

Table 6 shows the parameters used to quantify the gains measured in terms of ultimate bearing capacity and ductility. In average terms, the models strengthened with CFRP show higher values of maximum load (F_{max}) and maximum displacement (δ_{max}) than those of the specimens of MIN series (2.34 and 1.14 times more, respectively). In the particular, for series M(2) the gain in resistance was a little lower than in the rest of the strengthened specimens, since an undesirable premature failure occurred (debonding of the concrete-primer interface).

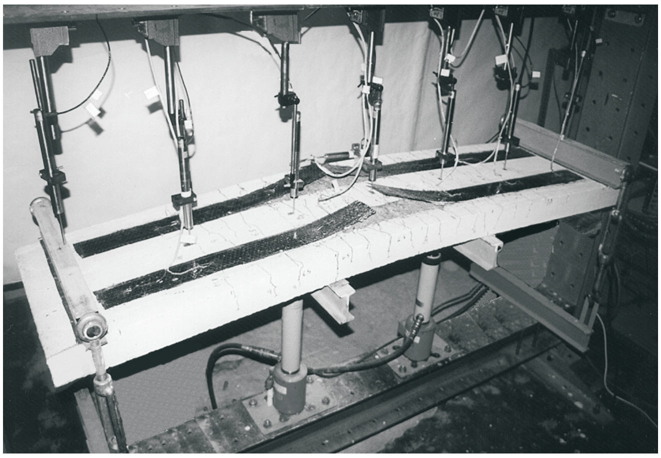
Figure 8 – Failure modes observed for series MIN, N, L and M



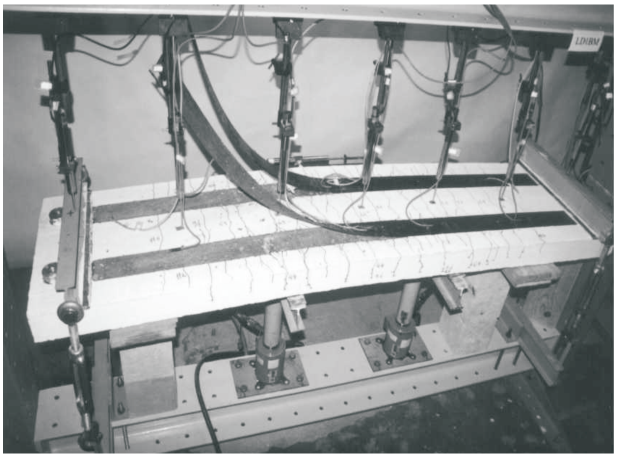
MIN series and N series – Steel yielding



L series – CFRP peeling



M series – CFRP rupture



M series – CFRP peeling

Table 6 – Average results of the ultimate bearing capacity

Series	F_{max} (kN)	F_{max} / $F_{max,\ MIN}$	F_{max} / $F_{max,\ N}$	δ_{max} (mm)	δ_{max}/l	s_{um} (cm)
MIN	14.2	1.00	0.49	29.7	1/54	9.2
N	28.9	2.04	1.00	27.7	1/58	6.5
M(1)	34.5	2.43	1.19	35.8	1/45	6.4
M(2)	29.8	2.10	1.03	28.5	1/56	6.9
L(3)	33.4	2.35	1.16	31.3	1/51	6.4
L(4)	34.9	2.46	1.21	38.5	1/42	7.7
L(5)	33.8	2.38	1.17	34.8	1/46	6.8

Figura 9 – Curvas médias carga total *vs* deslocamento central das quatro séries de faixas de laje

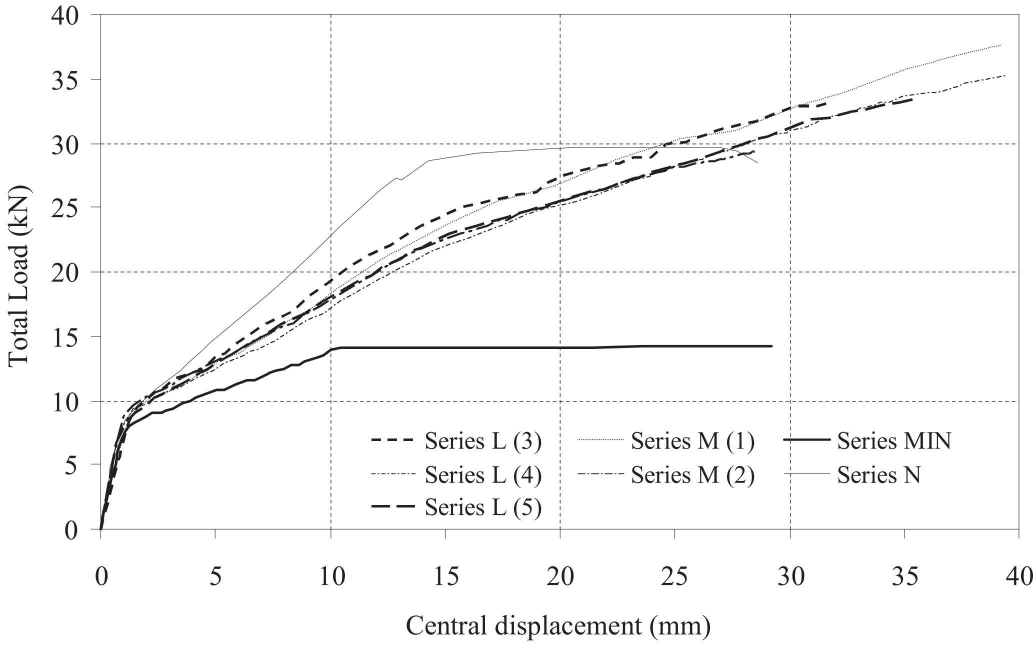


Table 7 – Average results of the ultimate bearing capacity: effect of pre-cracking induced in concrete

Series	F_{max} (kN)	δ_{max} (mm)	s_{um} (cm)
M(1)	34.5	35.8	6.4
M(1) - crack.	35.5	37.8	6.7
L(3)	33.4	31.3	6.4
L(3) - crack.	32.0	27.2	6.6

The series M and L, compared with the series N of RC, in average terms, have a maximum load 1.15 times higher and a maximum deformation of 1.21 times more (Table 6). Moreover, it can also be seen from Figure 9, that the CFRP strengthened specimens have reduced rigidity in service, greater ultimate strength and a greater maximum displacement at rupture than those of series N.

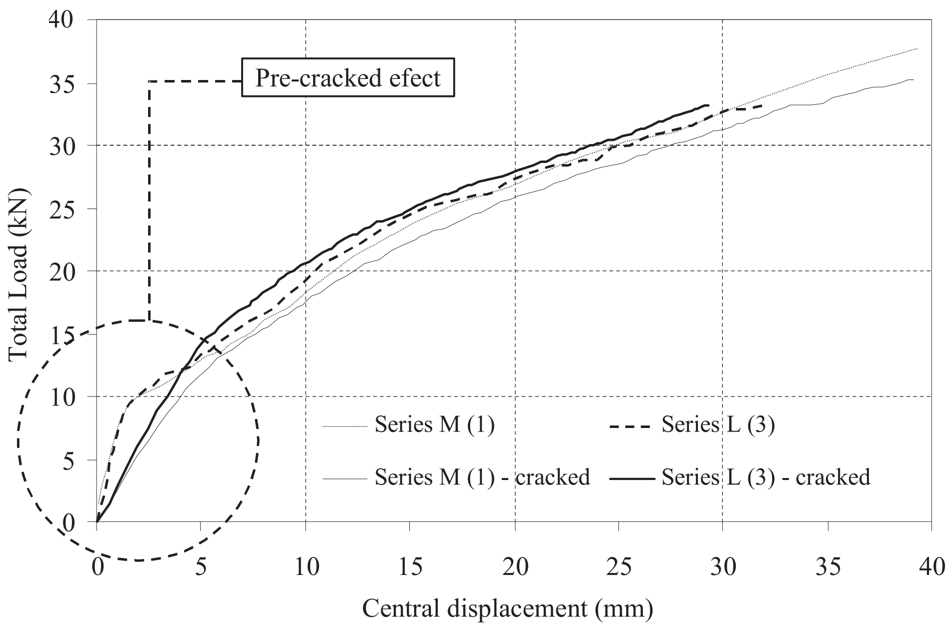
Figure 10 shows a graph of specimens behaviour, which only differ in terms of being pre-cracked (series M(1)-crack. and L(3)-crack.) or not pre-cracked (series M(1) and L(3)). It can be concluded from a comparative analysis that there is a natural loss of initial rigidity for the pre-cracked specimens in service behaviour. In terms of the load-bearing capacity and ultimate deformation, the values are practically the same for both series.

For these specimens, Table 7 includes the average values of the maximum load (F_{max}) and corresponding displacement at mid span (δ_{max}), and the average distance between cracks after the test (s_{um}). In the terms of this parameters it can be seen that the specimens with or without pre-cracking reinforced by externally bonded CFRP systems had the same performance.

Figure 11 shows the patterns of cracking for the four series tested (Juvandes [6] and Dias [7]). The specimens of the series N, M and L have very extensive patterns of cracking. These specimens showed 6.4 cm to 7.7 cm average crack spacing (Table 6). Less extensive cracking has occurred in the slabs of series MIN that showed the largest average crack spacing.

Table 8 presents the performance levels of the CFRP (series M and L) in terms of the maximum average values obtained for the strain (ε_{max}^{CFRP}), tensile stress (σ_{max}^{CFRP}

Figure 10 – Total load vs central displacement responses (effect of pre-cracking induced in concrete)



) and shear stress in the concrete-adhesive-CFRP interface ($\tau_{max}^{interface}$). Occurrence of premature failure (peeling) observed in models strengthened with CFRP laminates, is directly related to the exhaustion of concrete's adherence capacity ($\tau_{max}^{interface} \cong f_{ctm,p}$). This fact corresponds to low performance of the composite, which was on average of 62%. In the specimens strengthened with a CFRP sheet, with the exception of the models LD1BM and LD2BM (with a deficient application of the strengthening), the composite failed with the observed maximum average values of strain ε_{max}^{CFRP} less than the ultimate strain indicated by the supplier (15‰); in spite of that the specimens strengthened with a CFRP sheet produced a high average performance (74%) when compared with the ones observed for those with CFRP laminates.

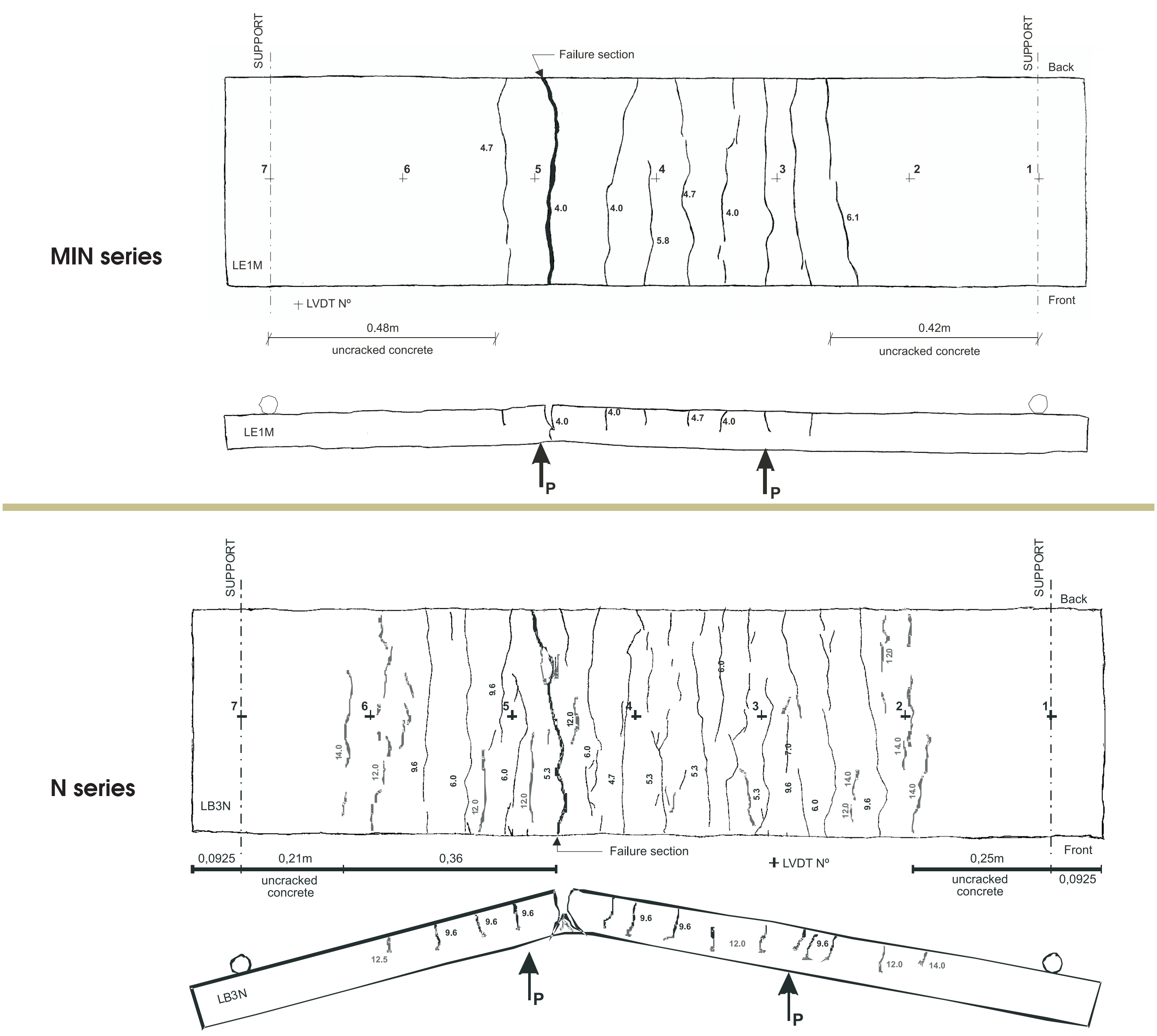
4 Experimental program with beams

The work already carried out has confirmed that it is difficult to obtain efficient use of the CFRP by reaching failure of the composite simultaneously with concrete crushing. This happens because premature failure occurs along the concrete-adhesive-CFRP interface, which culminates with the peeling phenomenon.

The extremity of externally applied CFRP flexural reinforcements creates a structural discontinuity, which involves some un-favourable mechanisms of stress transfer at the interface, namely, the concentration of normal and shear stress (Costeira Silva [18]). Several other researchers (Neubauer and Rostasy [19]) concluded that anchorage zones should deserve special attention. For example, in RC beams strengthened by addition of steel plates the use of mechanical anchorage systems is essential to prevent end premature failure (peeling effect) and, simultaneously, to increase ductility and load bearing capacity of the beam. The addition of these anchorage systems creates compression forces normal to the plane of the connection, with beneficial effects considering the peeling mechanisms that are formed in the interface.

The second study carried out in LABEST is based on an experimental program comparing the flexural behaviour of two groups of RC beams. One group refers to a simply reinforced concrete beam (taken as reference). The other group includes five reinforced beams, with similar load capacity through use of two externally bonded unidirectional CFRP systems: strips of wet lay-up CFRP sheets (MBrace Sheet C1-20) and laminate strips of CFRP (MBrace Laminate HM). For each tested system, two strengthening solutions were analyzed for bending, differentiated by the addition or absence of external end mechanisms in the anchorage zones of the composite. The aim of this study is to compare the behaviour of the unstrengthened beam and the beams strengthened with CFRP, specially to show the effect of different anchorage systems on the efficiency of CFRP strengthening, in terms of limiting states (service and ultimate) and failure modes.

Figure 11 – Patterns of cracking for series MIN, N, L and M

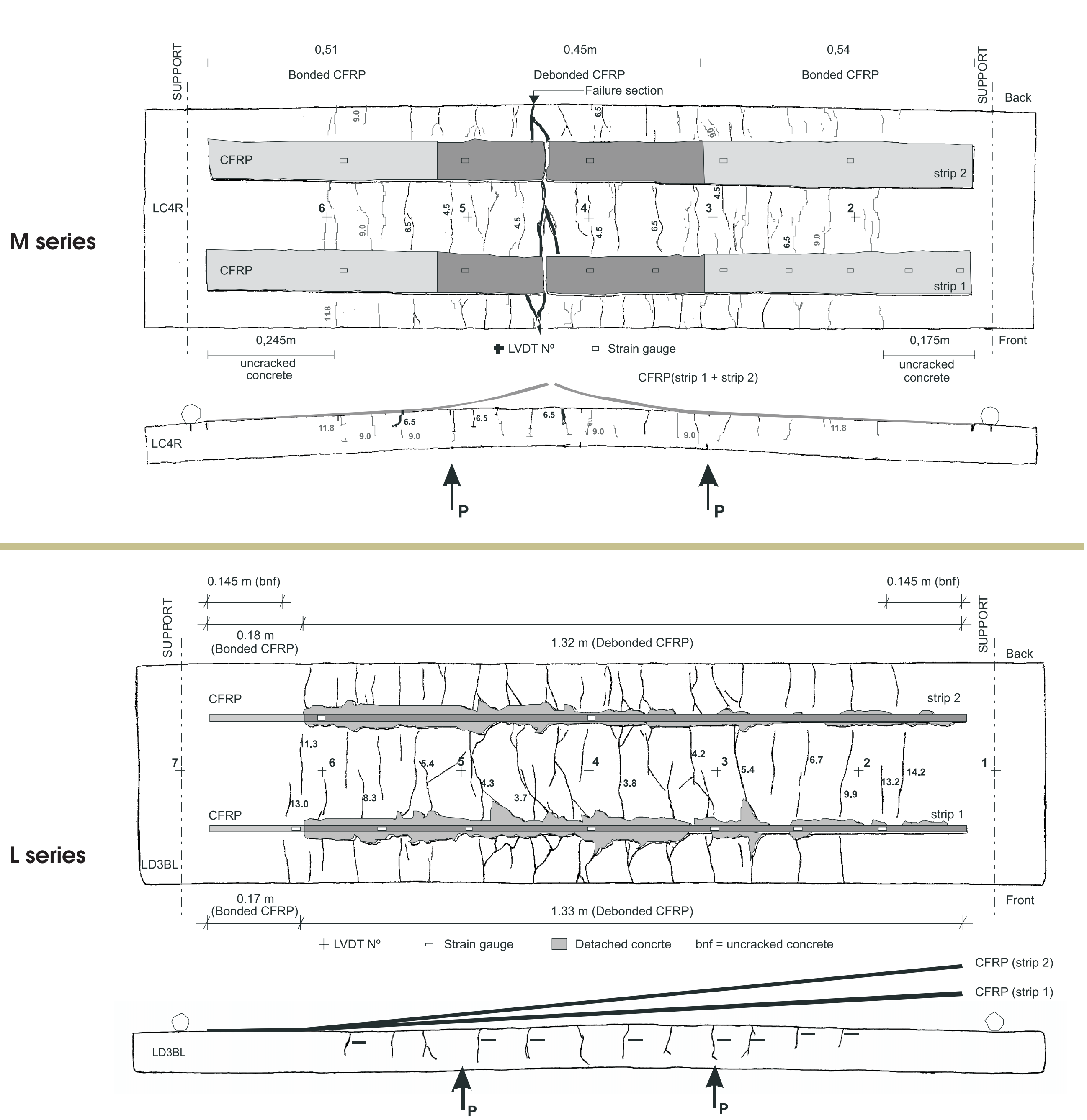


4.1 Beam models

This experimental program involved the conception of six models of RC beams designated by V1 to V6. One was the reference model (beam V1), two were strengthened with CFRP sheets (beams V2 and V3) and the remaining three were retrofitted with CFRP laminate (beams V4, V5 and V6). The beams presented a cross section of 0.12x0.18 m^2 being longitudinally reinforced with 2ϕ8 in the bottom face and 2ϕ6 in the top face. The possibility of premature failure by shear was prevented through the use of vertical stirrups ϕ6 every 0.10 m.

The amount of CFRP reinforcement was considered in order to provide reinforced models with a load capacity approximately 50% greater than that of the reference beam (not strengthened). In terms of design criterion, the maximum allowable CFRP strain is limited to include the possible occurrence of premature collapse and to control the steel strain in service. For this purpose, considering the criterion proposed by Rostasy (described in Juvandes [6]) and the producers recommendations (Bettor MBT Portugal [15]), the maximum strain was limited to 7.5‰ in the case of the CFRP sheets and to 5.5‰ in the case of the CFRP laminates. For the case of sheets,

Figure 11 – Patterns of cracking for series MIN, N, L and M (cont.)



the CFRP presented two overlaid layers 7 cm wide and for the case of CFRP laminate a strip 2 cm wide was considered. Figure 12 illustrates, for each strengthened beam (V2 to V6), the flexural reinforcement and respective geometry, as well as, the longitudinal external fixing mechanisms of the composite considered in the strengthened beam with the system in situ cured (sheet) and in the strengthened beam with the prefabricated system (laminate) (Dias[7]).

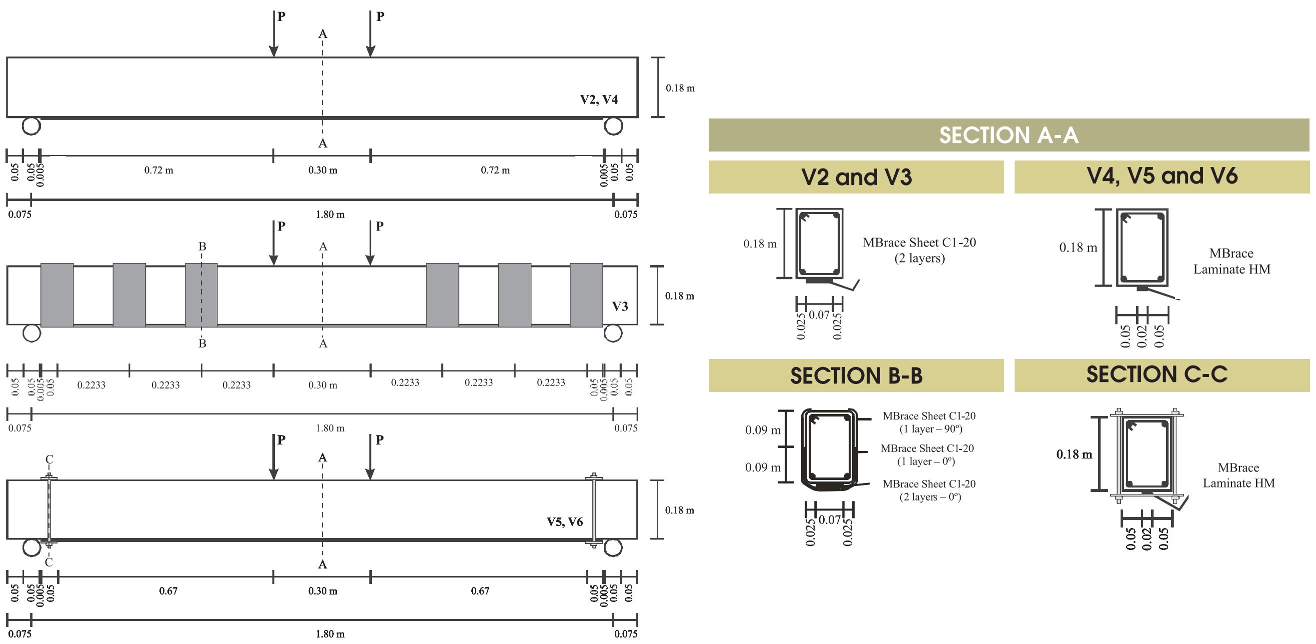
In the case of strengthened beams with the CFRP sheets (beam V3) the external fixing mechanisms were executed with CFRP sheets. First, a layer of 30 cm long and 10 cm wide was applied with fibers oriented at 0º (the same orientation as the longitudinal retrofitting). After, a second layer was over-

Table 8 – Performance levels of CFRP and the concrete-adhesive-CFRP interface

Séries	ε^{CFRP}_{max} (‰)	σ^{CFRP}_{max} (MPa)	$\sigma^{CFRP}_{max} / \sigma_u$* (%)	$\tau^{interface}_{max}$ (MPa)	$f_{ctm,p}$ (MPa)
M (1)	10.2	2352.0	69.2	1.8	3.6
M (1) - crack.	11.6	2661.1	78.3	1.7	3.9
M (2) **	7.3	1748.4	47.3	1.3	3.9
L (3)	10.8	1731.0	61.8	4.2	3.8
L (3) - crack.	9.4	1508.0	53.9	2.8	3.8
L (4)	10.0	1499.3	68.1	3.5	4.2
L (5)	9.4	1505.6	62.7	3.3	4.0

* Tensile σ_u -see Table 3; ** This series was not considered.

Figure 12 – Beams strengthened with CFRP



lapped with 52 cm long and 10 cm wide, with fibers oriented at 90º. Figure 13 shows the solution considered for the "anchorages" executed with CFRP sheets. The choice of position and quantity of the "anchorages" was established considering the model of a truss and the widening of bonded surface. In the case of beams V5 and V6 strengthened with the laminate system, steel "anchorages" were applied at the ends of the composite, based on the experimental work of Deuring [20]. Figure 13 presents a detail of this external fixing mechanism.

4.2 Materials properties and characterization of concrete-adhesive-CFRP interface

Table 9 includes the main properties of the concrete (at 28 days and at the date of beam testing: 200 days), steel bars and the CFRP systems used: MBrace Sheet C1-20 and MBrace Laminate HM. The values of the concrete and steel

Figure 13 – External fixing mechanisms adopted

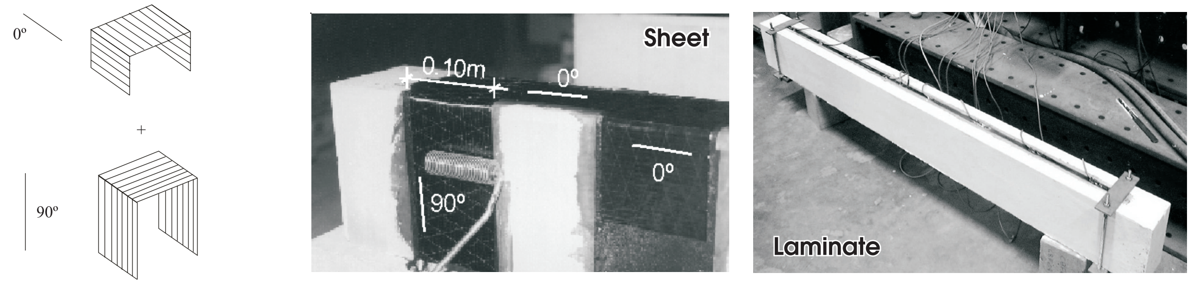


Table 9 – Properties of the materials

Concrete					
Age	**f_{cm}^{cub} (MPa)**	**f_{cm}^{cil} (MPa)**	**E_{cm} (GPa)**	**f_{ctm} (MPa)**	**$f_{ctm,\ p}$ (MPa)**
28 days	41.4	36.7	28.5	2.9	-
200 days	47.7	41.0	31.1	4.2	4.0
Steel					
Diameter		**f_{sym} (MPa)**		**f_{sum} (MPa)**	
ϕ6		555		602	
ϕ8		533		543	
CFRP					
Type	**Material**	**Tensile strength (MPa)**	**Young's modulus (GPa)**	**Ultimate strain (‰)**	**Thickness (mm)**
MBrace Sheet C1-20 (15)	Primer	12	0.7	30	-
	Resin	50	3	25	-
	Sheet	3700	240	15	0.111
MBrace Laminate HM (15)	Adhesive	-	7	-	-
	Laminate	2200	200	11	1.4

properties were obtained using a similar procedure described in section 3.2.
Pull-off tests were performed to evaluate the bond conditions of the CFRP system to the concrete. Figure 14 shows the pull-off test that was performed with one steel plate bonded to the beam V3 (beam strengthened with the in situ cured CFRP system). The average value of bond strength ($f_{ctm,p}$) obtained in pull-off tests was 4.0 MPa (Table 9). This result is higher than the limit (1.4 MPa) recommended by the ACI Committee 440 [13] for strengthening of RC members with externally bonded FRP reinforcement.

4.3 Aplication of the CFRP systems

The application procedure of CFRP systems (sheet and laminate) was similar to the described in section 3.3. Furthermore, the basic steps present in Figure 1 were applied (Dias [7]).

4.4 Test set-up

The test set-up used consisted in submitting the specimens (simply supported) to four-point static bending tests up to failure. The distance between supports was 1.80 m

Figure 14 – "Pull-off" test set-up

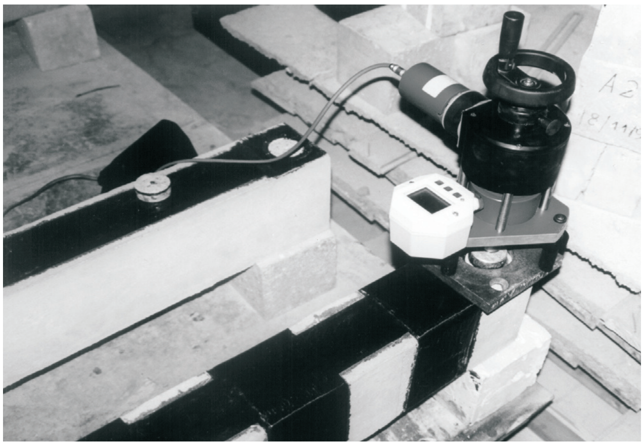
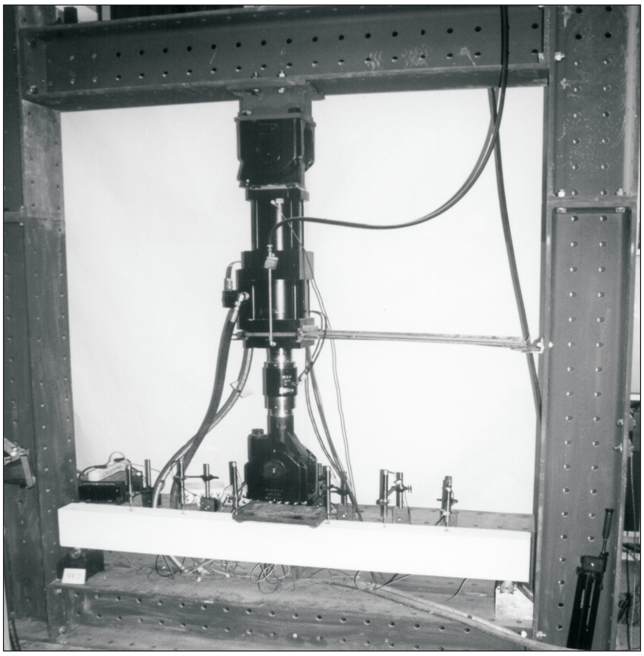


Figure 15 – Test set-up of beams



and the applied loads were 15 cm from each side of the middle beam (Figure 12). The test set-up can be observed in Figure 15.
The reference beam (V1) was loaded up to failure with a deformation speed of 0.6 millimeters per minute. The strengthened beams were loaded initially up to 15 kN at a speed of 0.025 kN per second. Then the beam was submitted to a cyclic load (60 cycles) between 5 and 15 kN at a frequency of 1 Hz. The limits of the cyclic load correspond to 15% and 45% of the predictable load of failure of strengthened beams. Subsequently, the beams were loaded up to failure with a speed of deformation of 0.6 millimeters per minute. Instrumentation of the tested beams consisted of a load cell, LVDTs (linear variable displacement transducer) and electric strain gauges glued to the composite along its length.

4.5 Results and discussion

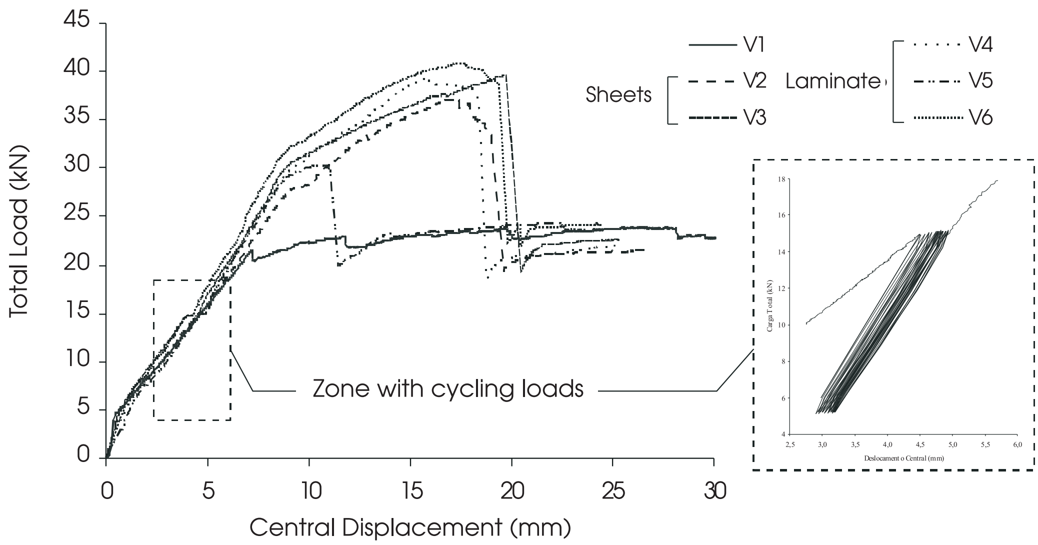
For each tested model, Table 10 shows the main results in terms of load at the beginning of cracking (F_{crack}), load at the reinforcement steel yielding (F_{sy}) and corresponding displacement at mid span (a_{sy}), maximum load (F_{max}) and corresponding displacement at mid span (δ_{max}). The relations between the reference beam (V1) and the strengthened beams, in terms of the measurements previously referred to, are also presented. Figure 16 shows the behaviour of the specimens, in terms of total load vs central displacement.
It should be noted that, in terms of service, the load at the beginning of cracking (F_{crack}) shows higher values in the strengthened specimens (exception for beam V4). The presence of additional reinforcement in the strengthened beams caused average increase of 39% of the load corresponding to the reinforcement yielding compared to the reference beam. The cyclic load test in the strengthened beams could have contributed for a larger displacement at mid span (corresponding to the yielding of steel) than the reference beam (see detail in Figure 16).
In average terms, strengthened beams (V2 to V6) present a maximum load 1.57 times higher than for non strengthened beam. When external fixing mechanisms are used (V3, V5 and V6) the bearing maximum capacity is a little larger, with the exception of beam V5 (detachment of the laminate at the interface with the adhesive). Considering the displacement values at mid span, δ_{max}, illustrated in Table 10 it may be concluded that the retrofitting of beams with CFRP introduced a smaller maximum deformation in relation to the non retrofitted beam.
Figure 17 illustrates the pattern of final cracking observed in each one of the tested beams. The failure mode for each beam is presented in Table 10. The failure of the reference beam takes place by crushing of concrete. With the exception of the beam V3 where the rupture of CFRP occurred, the strengthened beams reached their maximum bearing capacity when the CFRP peeling happened. In the beams V2, V4 and V6 the failure takes place by CFRP debonding and in some zones the concrete near the CFRP has detached which was not happen on the beam V5. In this beam the failure occurred by detachment of the laminate at the interface with the adhesive (unsatisfactory bonded between the laminate and the adhesive due to use an inappropriate degreaser – without acetone). This fact justifies the low performance of V5 beam. Figure 18 illustrates the failure modes of the tested beams (see also Figure 17).
Table 11 presents for each tested beam the maximum strain observed (ε_{max}^{CFRP}) and the efficiency of the CFRP. Maximum values obtained for shear stress at the concrete-adhesive-CFRP interface ($\tau_{max}^{interface}$) are also present-

Table 10 – Main results from each specimen tested

Properties	Beams					
		Sheet		Laminate		
	V1	V2	V3**	V4	V5**	V6**
F_{crack} (kN)	4.47	5.0	5.36	4.20	5.75	6.40
F_{crack} / $F_{crack,\,V1}$	1.0	1.12	1.20	0.94	1.29	1.43
F_{sy} (kN)	21.18	28.39	29.8	28.75	29.38	31.0
F_{sy} / $F_{sy,\,V1}$	1.0	1.34	1.41	1.36	1.39	1.46
a_{sy} (mm)	7.2	9.2	8.8	9.0	9.1	8.6
a_{sy} / $a_{sy,\,V1}$	1.0	1.28	1.22	1.25	1.26	1.19
F_{max} (kN)	23.87	37.19	39.64	39.22	30.33	40.81
F_{max} / $F_{max,\,V1}$	1.0	1.56	1.66	1.64	1.27	1.71
δ_{max} (mm)*	41.37	17.16	19.74	15.62	10.69	17.35
δ_{max} / $\delta_{max,\,V1}$	1.0	0.41	0.48	0.38	0.26	0.42
Failure modes	Crushing of compressive concrete	CFRP debonding	CFRP rupture	CFRP debonding by adhesive and concrete	CFRP debonding along adhesive/CFRP interface and slipping by the end anchorages	CFRP debonding by adhesive and concrete and slipping by the end anchorages

* Beam V1: value for the failure load; ** Specimens with end anchorages of the longitudinal CFRP.

Figure 16 – Total load vs central displacement responses of the tested beams



ed and compared with the average values of adherence stress ($f_{ctm,p}$) determined through pull-off tests. In all the strengthened beams, with the exception of beam V5, the longitudinal composite reached 50% of its ultimate tensile strength ($\sigma_{max}^{CFRP}/\sigma_u$).

In spite of the reduced number of models tested, results

Table 11 – Performance levels of CFRP and the concrete-adhesive-CFRP interface

Beams		ε^{CFRP}_{max} (‰)	σ^{CFRP}_{max} (MPa)	$\sigma^{CFRP}_{max} / \sigma_u$* (%)	$\tau^{interface}_{max}$ (MPa)	$f_{ctm,p}$ (MPa)
V2	Sheet	8.1	1936.8	52.3	1.1	3.6
V3	Sheet	8.7	2088.0	56.4 - 100	1.6	3.6
V4	Laminate	6.9	1374.0	62.5	2.5	4.4
V5	Laminate	4.1	812.0	36.9	1.1	4.4
V6	Laminate	7.2	1442.0	65.5	2.7	-

* σ_u is the CFRP tensile strength (see Table 9).

obtained suggest that the application of external fixing mechanisms for the flexural strengthening improves the CFRP performance and causes small increase of the bearing capacity as can be seen in Figure 16. It may be concluded that the approach used for external fixing mechanisms in the beam strengthened with the CFRP sheets (V3) caused the rupture of the composite with the observed maximum strain in CFRP of 8.7‰ (the ultimate strain indicated by the supplier is 15.0‰ - see Table 9). On the contrary, for CFRP laminate models (V5 and V6) the composite rupture did not happen as the external fixing mechanisms allowed laminate slipping in the two beams, disabling the efficient use of CFRP. In this case, it may be concluded that is necessary to implement a mechanism that works not only at the ends, but also, discreetly, along the effective length of CFRP on the concrete.

5 Conclusions

From the two experimental programs on the flexural strengthening of RC structures with externally bonded unidirectional carbon-fiber-reinforced systems (CFRP), the following considerations can be drawn:

i) Performance levels of the CFRP strengthening
The technique of strengthening, using external bonding of unidirectional CFRP composites (sheets and laminates) in RC elements (slabs and beams), results in an improvement in load at the beginning of cracking, in service stiffness and in ultimate load-bearing capacity, when unstrengthened models are compared with strengthened ones. In terms of the maximum displacement at rupture that improvement occurred only on the slab specimens.
When the results of two distinct solutions for getting similar loads (simply RC or RC strengthening with CFRP) are compared, it is observed that the simply RC models show greater rigidity, less maximum deflection and less ultimate load-bearing capacity.
Pre-cracking of some specimens led to the reduction of initial rigidity in those models only, their performance otherwise reverting to that of the specimens not cracked in advance. In terms of ultimate limiting state, the behaviour of the strengthened models, with or without pre-cracking, was similar. The pattern of cracking shown by the strengthened specimens, with or without pre-cracking, was similar and their average distance between cracks was lower than the values for the unstrengthened specimens.
In general terms, the CFRP strengthening systems applied in the present work have exhibited good performance. The laminates have overreached the bond capacity of the concrete and the premature failure (peeling) has occurred. In spite of the premature failure by peeling has occurred in some situations, the sheets have conduced to the CFRP rupture. This fact explains the better performance of the sheets than laminates.

ii) The importance of the external fixing mechanisms for the CFRP flexural strengthening
Despite the good results obtained for the strengthened models with CFRP, ways of premature failure are observed (notably peeling) that lead to low levels of strengthening performance, being recommended in this case to apply exterior anchoring methods to avoid the detachment of the CFRP. The external fixing mechanisms for the flexural strengthening used in this work have permitted an increase in terms of deformation capacity and a small increase of the bearing capacity. In V3 beam (sheet) the external fixing mechanisms of CFRP, executed with strips of CFRP sheets (two layers: the first with fibers oriented at 0º and the second with fibers oriented at 90º) and positioned along the beam span, allowed the failure of the CFRP near one of these strips. This fact indicates that the CFRP failure has occurred due the tensile stress concentration phenomenon. The type of external fixing mechanism used with the laminate system proved not to be very efficient because it did not prevent premature peeling of

Figure 17 – Patterns cracking of the tested beams (beams V1 to V6)

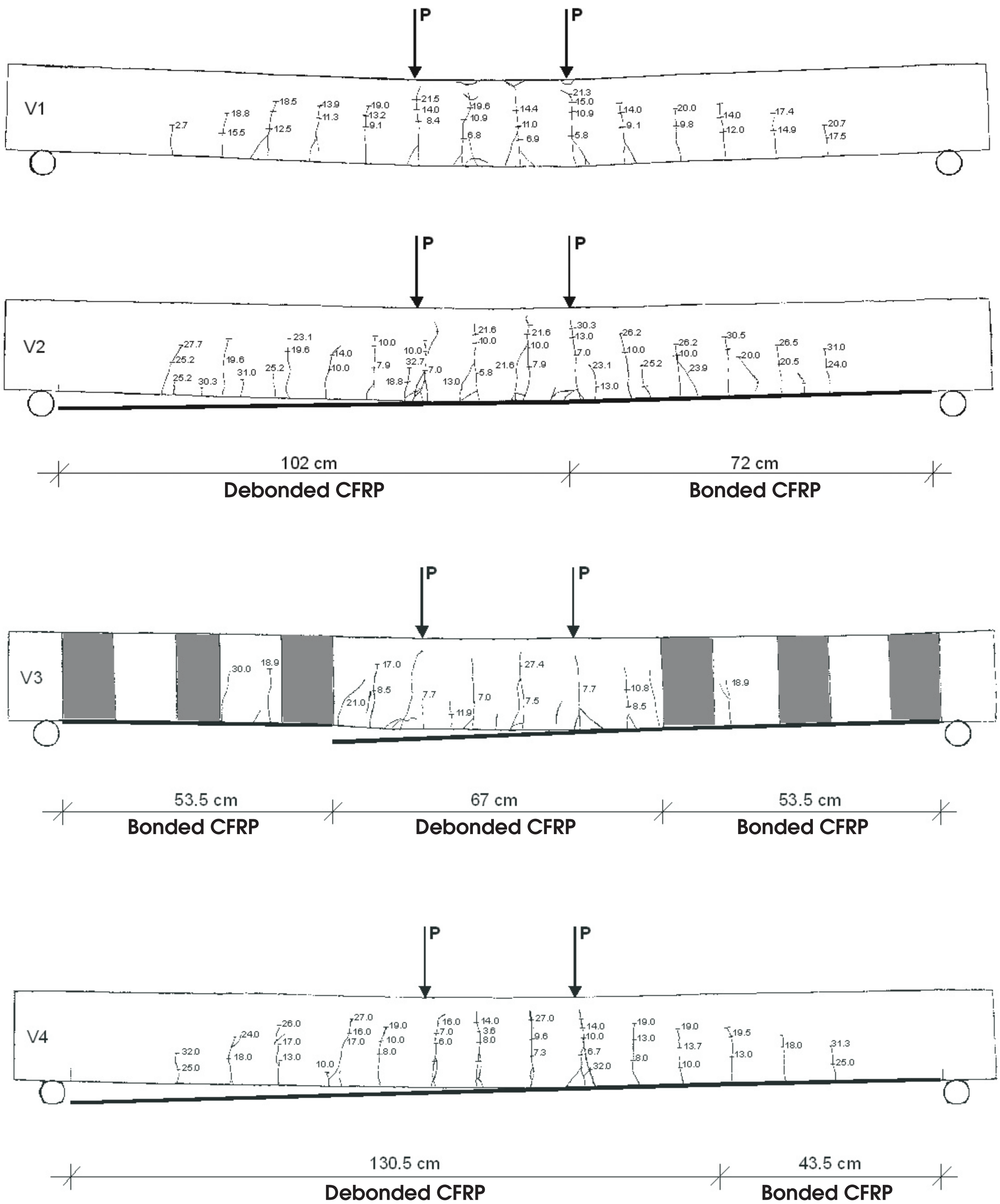
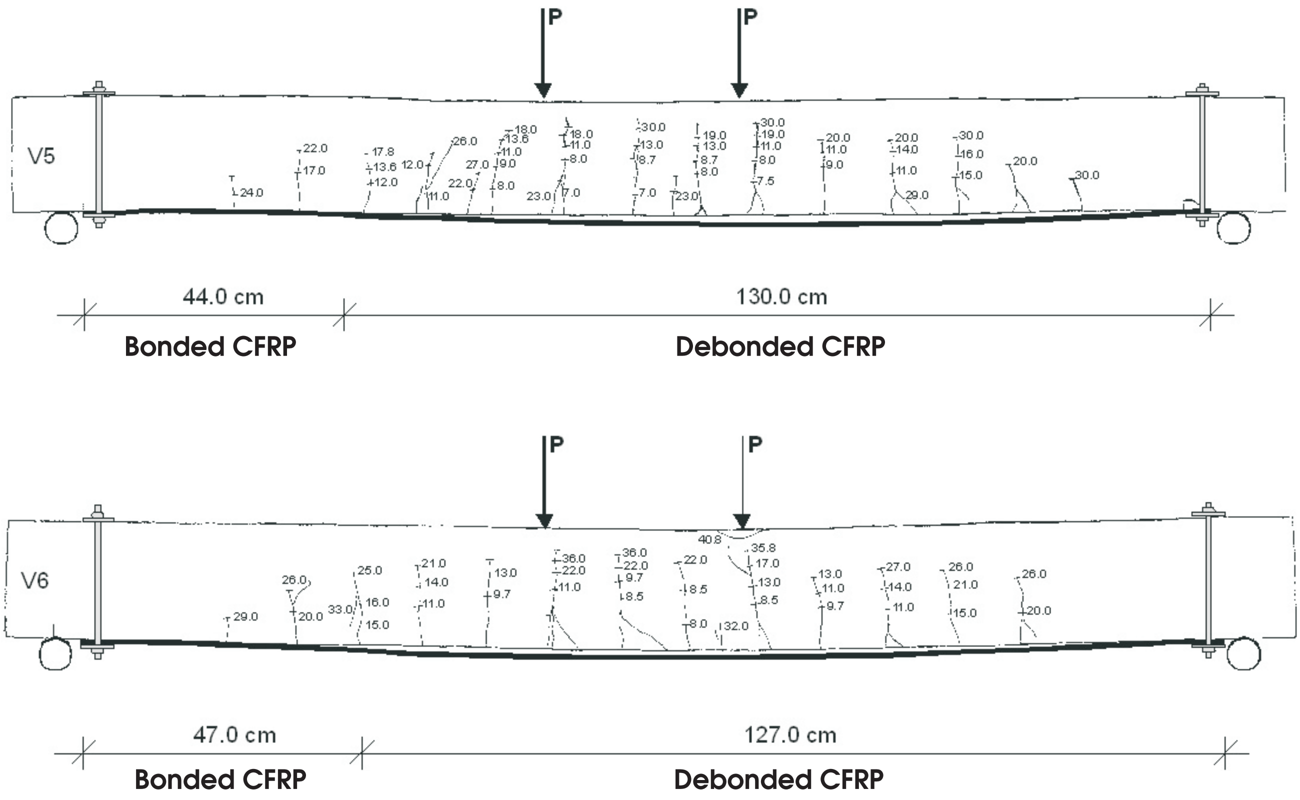


Figure 17 – Patterns cracking of the tested beams (beams V1 to V6) (cont.)



CFRP due to lack of rigidity and appropriate tightening. In this subject, new external fixing mechanisms for the CFRP have been developed in LABEST (Dimande [21]).

iii) Quality control

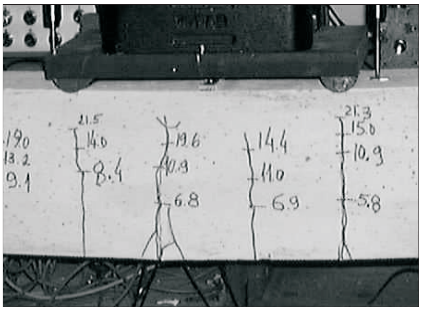
An underprovided application can lead to unsatisfactory results as shown in some slab and beam models tested. In LD-1BM and LD2BM slabs the strengthening work was carried out on concrete surface with a high level of moisture that made impossible a good adherence between the concrete and primer. Consequently the gain in resistance was lower than in the rest of the strengthened slab specimens with CFRP. In beam V5, due to the use of a non specific degreaser in the CFRP system (without acetone) the laminate was not fully clean and its detachment occurred at the interface CFRP-adhesive. Consequently the gain in resistance was lower than in the rest of the strengthened beams specimens with CFRP. These occurrences indicate that it's necessary to make a rigorous quality control in all steps of the CFRP systems application. Therefore the procedures of the quality control process must be included in the technical data of the commercial CFRP systems.

iv) Justification for a design criterion

The design criterion of the CFRP was based on the maximum CFRP strain limitation to the minimum value of: five times the strain corresponding to the yield strength of steel reinforcement (to control the steel strain in service) and 50% of the ultime strain in CFRP (to include the possible occurrence of premature collapse). It seems to be a satisfactory criterion. The strengthened slabs with CFRP reached maximum loads at least two times greater than that of the reference model (non reinforced slab). The strengthened beams with CFRP reached maximum loads at least 1.5 times greater than the reference model (non reinforced beam). As a matter of fact, the quantities of CFRP reinforcement adopted were designed to perform the wanted aims. However, the analysis of the design criterion deserves a greater development in the future, which has already been shown in the contents of the ACI Committee 440 [13] and FIB [4] documents.

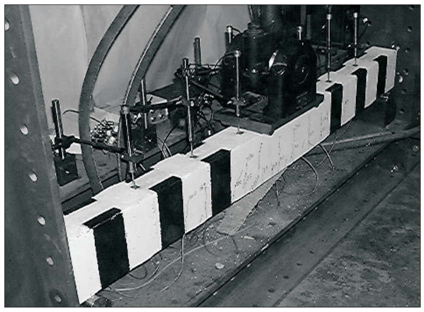
The conclusions of the two experimental programs developed in LABEST, mainly the first, had one immediate consequence: the deck of the "Nossa Senhora da Guia" bridge can be strengthened with externally bonded unidirectional CFRP systems, since they all meet the principal aim, which is double the current load carrying capacity. An experimental strengthening of a slab deck region of this bridge has been carried out and its behaviour has been monitored for the last three years. The results of this work

Figure 18 – Failure modes of the tested beams

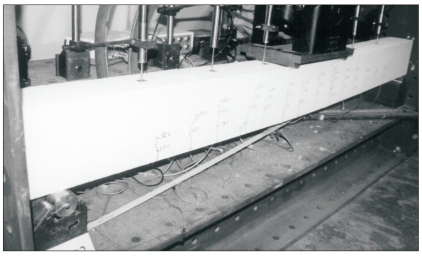


Beam V1

Beam V2

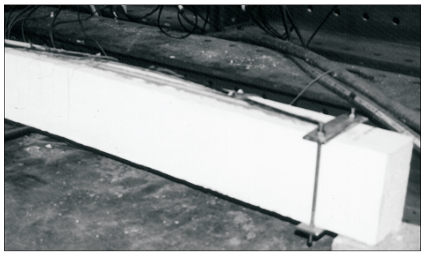


Beam V3



Beam V4

Beam V5



Beam V6

have corroborated the conclusions written in this section (Costeira et al. [22]).

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