Extended Abstract

"Building strengthen design with pre-stressed CFRP laminates."

1. Introduction

The rehabilitation and strengthening of structures are two of the biggest challenges of sustainability of civil engineering. Of all the existing strengthening techniques, this paper will highlight an emerging one that is based on the exterior bonding of pre-stressed CFRP laminates.

This type of system mobilizes a higher resistance capacity, that the passive reinforcement solutions cannot operate, which is why there has been an increasing development of these solutions. It manages to hoist a significant extension, so early on, and therefore are gains of around 50% in resistant capacity. Other advantages of this system are: ease of application, little need for equipment in the construction site and the possibility of using the building during the strengthening. Their low resistance to fire and its high cost prevent this technique to be applied on a wider scale.

This research is divided in four main sections. The 1st part of this document is the descriptive memory, where was made an overall assessment of the structure, about its geometry and its residual resistant capacity. There were also defined in this part, the materials to be used and the significant security checks. The 2nd part concerns to the calculation memory, it identifies the used criteria for the design and later on, there were presented the calculations for the most representative structural elements. The 3rd and 4th parts are related to the specifications and drawings, respectively, although properly attached to the two above mentioned documents, will not be addressed in this summary.

2. Analysis of the Existing Structure

The analysis of the existing structure is a key step in any building project and ideally this type of information should be acquired from the original design project of the structure. Yet the strengthening interventions sometimes occur in buildings whose design is inaccessible. So the structure should be characterized by proper instrumentation means and tests, carrying out its survey geometry, mechanical properties of the materials and structural pathologies.

The quantification of the resistance of structural elements constitutes an important chapter in this kind of intervention, whether it allows to measure if the resistant capacity of the elements is enough to the new load level. The permanent, and variable loads considered in the original project were estimated using RSA.

In a project of rehabilitation and / or strengthening of a structure, there are four key stages:

- Diagnostic phase;
- Decision phase;
- Design stage;
- Implementation phase.

This paper will focus primarily on the third phase of the list, *Design Stage,* although it derives from the previous ones, and none of them can be deleted in an appropriate project.

2.1. Geometry of the Structure

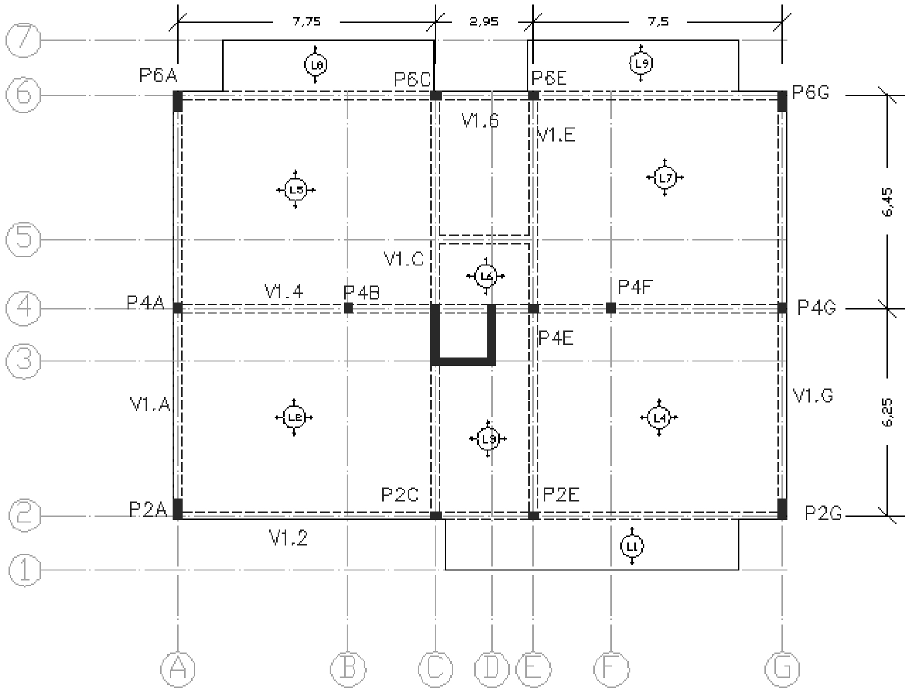

Figure 1: Slab - type of the building.

Presented in the following table, are all of the overall dimensions of the structural elements that make up the porch.

Table 1: Structural Elements Geometry.

	Structural Elements	*b (m)*	*h (m)*	*c (cm)*
Beams	*Outline Beams (V1.A, V1.6, V1.G e V1.2)*	*0,25*	*0,65*	*3*
	Interior Beams (V1.4, V1.C, V1.E e V1.5)	*0,25*	*0,55*	*3*
Pillars	*P1 (P2A; P6A; P2G; P6G)*	*0,25*	*0,60*	*3*
	P2 (P4A; P4B; P4F; P4G)	*0,25*	*0,35*	*3*
	P3 (P2C; P2E; P6C; P6E; P4E)	*0,35*	*0,25*	*3*
	Slab	*-*	*0,17*	*3*

2.2. Materials

- Concrete: C25/30
- Steel: A500NR SD
- CFRP Laminates:
  - S&P CFK 150/200 - 80x1,2;
  - SIKA CarboDur S624.
- Resin:

- Primary: S&P Resin 50;
- Adhesive Resin S&P 220.

3. Load Definition and Safety Checks.

3.1 Load Definition

The definition of actions for the new use of the structure was carried out according to the criteria recommended by *Eurocode 1: Actions on Structures.*

3.2 Safety Check

The verification of safety to various limits, considered in the legislation, was based on section 6 of *Eurocode 0: Basis of Structural Design.*

Actions defined in chapter 3 will be combined with various probabilities of occurrence. It is therefore necessary to define the most relevant and unfavourable combinations of actions according to the EC_0:

Ultimate Limit State

$$E_d = \sum_{j=1}^{m} \gamma_{gi}.E_{Gik} + \gamma_q.\left[E_{Q1k} + \sum_{j=2}^{n} \psi_{0j}.E_{Qjk}\right]$$

Service Limit State

$$E_d = \sum_{j=1}^{m} \gamma_{gi}.E_{Gik} + \gamma_q.\left[E_{Q1k} + \sum_{j=2}^{n} \psi_{0j}.E_{Qjk}\right]$$

4. Project Criteria

4.1. Deformation Control

The pre-design strengthening criterion adopted was to control the deflection for quasi-permanent combination of actions, according to the values recommended by EC $_2$. Simultaneously it was need to check the tension on the opposite fibres, so they do not reach the medium tensile strength *fctm.* According to EC $_{2,}$ the deflections allowed are:

- Quasi-permanent combination of actions: $\delta_{adm} = \frac{L}{250}$;
- If the deformation affects walls: $\delta_{adm} = \frac{L}{500}$.

In parallel with this criterion was carried out an Ultimate Limit State verification of the structural elements. The model used to determine the expressions of pre - design is shown in Figure 2.

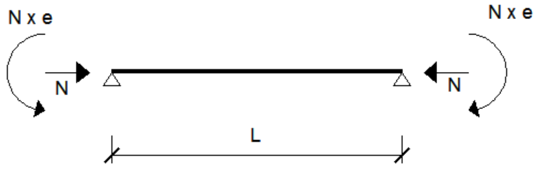

Figure 2: Model of pre-stress pre-design.

There are two possible configurations for strengthen the span of structural elements:

- Strengthening applied on the sides (configuration 1) - available only on beams.

- Strengthening applied on the underside (configuration 2) - is available for beams and slab.

It can also outcome a 3rd configuration resulting from the combination of the above. In the case of negative moment is only possible to strengthen the upper surface of the elements.

The pre-stress design is based on the calculation of the counter - deflection necessary so that the values of the deformation of the elements (figure 3), in a long term, match the ones imposed by the EC_2.

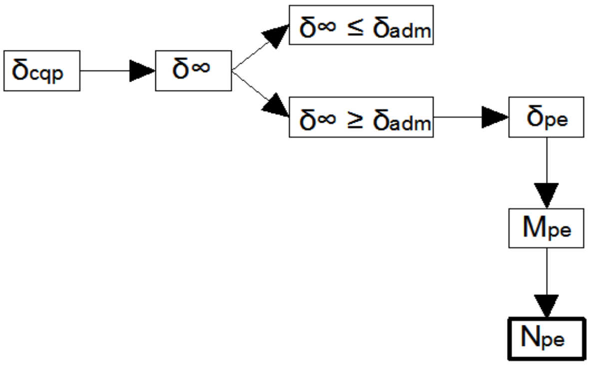

Figure 3: Flowchart of the pre-stress strength calculation, to be applied in the laminates.

The long term deflection for the various structural elements is obtained through the method of global factors.

4.2. Cracking Verification

To verify the limit state of cracking it was tried, at first, to ensure decompression of the conditioning sections ($\sigma < 0$), so that the security would be ensured. Failing this, to successfully fulfill this hypothesis, the following criteria would guarantee that the tensile strain in the most requested fiber of the conditioning section of the elements, was under the average tensile concrete strain ($\sigma < fctm$), following the model in figure 4.

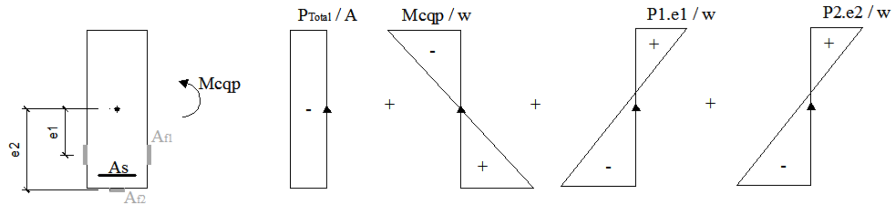

Figure 4: Generic tension diagram, for a concrete section.

$$\sigma = -\frac{P_{Total}}{A} + \frac{M_{cqp}}{w} - \frac{P1.e1}{w} - \frac{P2.e2}{w}$$

For sections that do not meet the above mentioned criteria, namely cracked sections, the crack opening will be calculated, and compared with the recommended levels recommended by EC_2. The maximum aperture of cracks allowed is based on the usefulness of the building and

the environment in which it is inserted. Given the kind of exposure of the building and according to the EC table 7.1N, were adopted as the threshold for the crack opening: wk_{max} = 0.3 mm.
In this chapter, is also relevant to analyze the tensile stresses arising in the fibre opposite the application of the pre-stress.

4.3. Ultimate Limit State

The verification to the ultimate limit state will be done through an iterative method by which the ultimate extensions will be calculated. The resisting bending moment of the element should be calculated according to the simplified rectangular diagram (DRS).

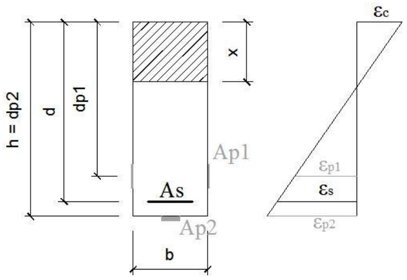

Figure 1: Diagram of extensions in a generic section with strengthening on the lateral and lower surface.

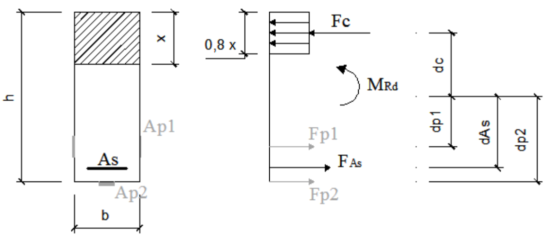

Figure 2: DRS in a generic section with strengthening in the lateral and lower surface.

This iterative method has the basic principle of setting the extension at one end, and go by assigning values to the extent on the other end until it converge to the first set value. This method can be started by setting either the shortening in concrete, or the extension of CFRP laminates, or steel. The calculation of the other extensions will derive from the hypothesis initially admitted. Note also that, as this is a check to the ultimate limit state, the failure hypothesis to admit initially can be one of three possible:

- Failure by crushing of concrete: ε_c = 3.5 ‰;
- Failure by collapse of CFRP laminates: ε_p = 10 ‰;
- Rupture the reinforcing steel: ε_s = ‰ 10 - this event can occur only in elements reinforced laterally.

4.3.1. Effort Redistribution

The possibility of a redistribution of efforts has been exploited mainly in the security check of the beams. This attempt is justified as a way to simplify the assembling process of the strengthening. It was always tried to, in the first instance, strengthen the beams on their side faces, avoiding thereby demolishing masonry walls already built, or chaser the pillars to strengthen the area of negative moment.

4.4 Viability Enhancement by Externally Bonded Reinforcement

The rehabilitation of concrete structures by applying FRP composite systems requires they comply with certain requirements in order to be possible. This analysis is performed based on information gathered in the diagnostic phase, and also on the design requirements set to the desired level of security

5. Design

5.1. Slab

5.1.1. Serviceability Limit State (SLS) - Deformation.

According to the criteria established in chapter 5, the table presented below shows the maximum displacement of each slab panel, and it identifies the panels to verify. The long-term deformation of each panel is determined by applying the global coefficient (K) to its elastic deformation (δ).

Table 2: Maximum deflections in the slab for the quasi-permanent load combination.

Deflections					*δ (EC2)*	
Slab Panel	*δ_{qp} (m)*	*K*	*δ∞ (m)*	*L (m)*	*L/250*	*L/500*
1; 8; 9	-	-	-	*3,2*	*0,0128*	*0,0064*
2	***0,0098***	***7***	***0,0684***	***6,25***	***0,025***	***0,0125***
3	*0,0007*	-	*0,0053*	*2,95*	*0,0118*	*0,0059*
4	***0,0092***	***7***	***0,0642***	***6,25***	***0,025***	***0,0125***
5	***0,0115***	***7***	***0,0772***	***6,45***	***0,0258***	***0,0129***
6	*0,001*	*8*	*0,001*	*2,08*	*0,00832*	*0,00416*
7	***0,0108***	***7***	***0,0725***	***6,45***	***0,0258***	***0,0129***

The solution found for the strengthening of the slab was 3 laminates per meter. The response of the structure to this configuration is shown in the table presented below; the results are confronted with the limits given in $EC_{2.}$

Table 3: Value of the long term deflections, after strengthening (3lam / m).

Slab	*L (m)*	*δ (m)*	*K**	*δ∞ (m)*	*L/250*	*L/500*
Panel 2	*6,25*	*0,0047*	*3,2*	*0,0150*	*0,025*	*0,0125*
Panel 4	*6,25*	*0,0047*	*3,2*	*0,0150*	*0,025*	*0,0125*
Panel 5	*6,45*	*0,0061*	*3,2*	*0,0195*	*0,0258*	*0,0129*
Panel 7	*6,45*	*0,0057*	*3,2*	*0,0182*	*0,0258*	*0,0129*

The parameter K*, was the new global coefficient calculated to the slab, after its strengthening.

5.1.2. Serviceability Limit State (SLS) - Cracking.

According to the criterion in Chapter 5.2, it is necessary to check the crack in the conditioning areas of structural elements. The results obtained for the calculation of stresses in the most conditioning sections of the slab, are presented below.

Table 4: Stress calculation on the conditioning sections of the slab.

Panel	Section	M_{cqp} (kN.m)	P (kN)	e (m)	σ (MPa)	f_{ctm} (MPa)	Wk,máx (mm)
L2/L5	6,25 (1/2 vão)	30	276,6	0,085	-0,28	2,6	-
Apoio	Viga 1.4	70	184,4	- 0,085	10,2	2,6	0,113
L4/L7	6,45 (1/2 vão)	30	276,6	0,085	-0,28	2,6	-

It was also checked the cracking in the transverse direction of the strengthening application, and the deflection registered was inferior to the maximum admissible. Furthermore, the tensions in the areas opposed to the application of the pre-stress were analyzed, which prove to be necessary, the adjustment of the CFRP laminate position. Initially these zones intercepted nil bending moment areas, resulting in tensile stresses higher than $f_{ctm.}$ After the adjustment of the laminates position, they intersected zones with at least 20 kN.m/m of bending moment value, which the resulting stress values were already lower than the average tensile strain of concrete.

5.1.3. Ultimate Limit State.

After calculating the design efforts of the structure, the iterative method of the extensions of the material at failure was carried out to verify the ultimate limit state, as explained in paragraph 5.3 of this document.

Table 5: Resistant bending moment along the span of the reinforced slab (3 lam/m).

Section	εc (‰)	εp (‰)	Fp (kN/m)	Fc (kN/m)	εs (‰)	F_{As} (kN/m)	x (m)	M_{Rd} (kN.m/m)	M_{Ed} (kN.m/m)
Span (L5)	3,5	8,5	392	563	6,4	171	0,0496	**74,9**	**68**

5.2. Beams

This chapter will not treat all the beams individually, only the most demanded beams in terms of efforts will be analyzed, or those that emerge as the most relevant and representative of the structure. Therefore the analyzed beams are: Beam 1.A, Beam 1.6 and Beam 1.4.

Is presented in the following table the justification of the need for strengthening for each of the cases studied.

Table 6: Justification of the need to strengthen the beams studied.

Beam	Span (m)	δ_{cqp} (m)	K	δ_{∞} (m)	L/250 (m)	L/500 (m)
1.A	6,25	0,001423	8	0,01138	0,025	0,0125
	6,45	0,001665	8	0,01332	0,0258	0,0129
1.6	7,75	0,009306	3	0,02792	0,031	0,0155
	7,5	0,008289	3	0,02487	0,03	0,015
1.4	5,13	0,00311	6	0,01866	0,02052	0,01026
	5,15	0,00308	6	0,01848	0,0206	0,01030

In the case of the beam 1.A, it would not be necessary to strengthen in accordance with the design requirements set forth. That does not mean that this element will be neglected, as it may be necessary for other security checks. In the case of other elements, the need is evident.

Beam 1.6

In the case of the beam 1.6, it was found at an early stage that would be necessary to combine the two possible configurations of bonded reinforcement, to be able to generate the necessary counter-deflection to cancel the deformation caused by the quasi – permanent combination of actions. This will apply the maximum amount of reinforcement that this element can endure (1 laminated on each side + 1 laminate on the underside).

Table 7: Calculation of the pre-stress required to beam 1.6.

Span(m)	δ_{adm} *(m)*	δ_{cqp} *(m)*	δ_{pe} *(m)*	δ_{Total} *(m)*	$M_{Lateral\ Laminates}$ *(kN.m)*	$M_{Inferior\ Laminates}$ *(kN.m)*	M_{pe} *(kN.m)*	M_{Total} *(kN.m)*
7,75	*0,0155*	*0,009306*	*0,004877*	*0,004429*	*33,2*	*71,6*	*115,2*	*104,8*
7,5	*0,015*	*0,008289*	*0,004*	*0,004289*	*33,2*	*71,6*	*101,0*	*104,8*

As can be seen by table 7 $M_{Total} < M_{PE}$ for the case of the span of 7.75 m, which means that it was not possible to apply the pre-stress needed to generate the counter - deflection necessary to attenuate the deflection caused by the quasi – permanent combination of loads, and therefore this section will not verify L/500.

Beam 1.4

Table 8: Strengthening calculation for the beam 1.4.

Span (m)	δ_{adm} *(m)*	δ_{qp} *(m)*	δ_{ps} *(m)*	M_{ps} *(kN.m)*	*e1 (m)*	*P1 (kN)*	*Laminates*
5,13	*0,01026*	*0,00311*	*0,00017357*	*5,67*	*0,13*	*43,6*	*1*
5,15	*0,01030*	*0,00308*	*0,00013714*	*4,44*	*0,13*	*34,2*	*1*

According to the table, the strengthening in the lateral area of the beam will be sufficient to cancel the deflection resulting from the quasi-permanent combination of loads.

5.2.1. Ultimate Limit State

For checking the ultimate limit state of bending of beams, it was resorted to the same iterative method used for the slabs. There will be a redistribution of effort, whenever possible, that will ease the strengthening, from the assembling point of view.

After determining the actuating bending moment resulting of the effort redistribution, the sections were verified to their ultimate limit state.

Table 9: Calculation of the resisting bending moment.

Beams	εs *(‰)*	F_{As} *(kN)*	*x (m)*	εc *(‰)*	*Fc (kN)*	$\varepsilon p1$ *(‰)*	*Fp1 (kN)*	$\varepsilon p2$ *(‰)*	*Fp2 (kN)*	M_{Rd} *(kN.m)*	M_{Ed} *(kN.m)*
1.A	*10,0*	*175*	*0,147*	*3,25*	*418*	*7,9*	*242,8*	*-*	*-*	***203***	***168,4***
1.6	*9,14*	*700*	*0,07*	*1,16*	*1176*	*7,51*	*230,7*	*10,0*	*245*	***664***	***441,1***
1.4	*9,04*	*273*	*0,032*	*0,613*	*718*	*7,2*	*220*	*10,0*	*245*	***343***	***249***

εp1 - Extension of CFRP laminate applied on the lateral section;

εp2 - Extension of CFRP laminate applied on the underside of the section.

5.2.2. Serviceability Limit State - Cracking

Similar to what happened to the slab, it was first calculated the decompression in the conditioning sections, followed by the calculation of the crack width for those sections that do not meet the first criterion as shown in table 10.

Table 10: Cracking verification in the studied beams for quasi-permanent combination of actions.

Beam	*Section*	M_{qp} (kN.m)	*P1 (kN)*	*e1 (m)*	*P2 (kN)*	*e2 (m)*	P_{Total} (kN)	*σ (MPa)*	f_{ctm} (MPa)	*Wk,máx (mm)*
1.A	*6,25 (1/2 span)*	*82,6*	*184,4*	*0,18*	*0*	*0,325*	*184,4*	*1,67*	*2,6*	*-*
	Support (P4A)	*145,8*	*0*	*0,18*	*92,2*	*0,325*	*92,2*	*6,01*	*2,6*	*0,125*
	6,45 (1/2 span)	*87,5*	*184,4*	*0,18*	*0*	*0,325*	*184,4*	*1,95*	*2,6*	*-*
1.6	*7,75 (1/2 span)*	*289,6*	*184,4*	*0,18*	*222,8*	*0,325*	*407,2*	*7,95*	*2,6*	*0,0195*
	Support (P6C)	*287,6*	*0*	*0,18*	*0*	*0,325*	*0*	*16,34*	*2,6*	*0,27*
	Support (P6E)	*257*	*0*	*0,18*	*0*	*0,325*	*0*	*14,6*	*2,6*	*0,27*
	7,5 (1/2 span)	*274*	*184,4*	*0,18*	*222,8*	*0,325*	*407,2*	*7,06*	*2,6*	*0,0195*
1.4	*5,13 (1/2 span)*	*137,3*	*184,4*	*0,13*	*222,8*	*0,275*	*407,2*	*1,17*	*2,6*	*-*
	Support (P4B)	*171,7*	*0*	*0,13*	*92,2*	*0,275*	*92,2*	*10,94*	*2,6*	*0,19*
	Support (P4F)	*169,02*	*0*	*0,13*	*92,2*	*0,275*	*92,2*	*10,73*	*2,6*	*0,19*
	5,15 (1/2 span)	*135*	*184,4*	*0,13*	*222,8*	*0,275*	*407,2*	*0,99*	*2,6*	*-*

In parallel with this verification, it was checked, as has been done for the case of the slab, the fibres in the opposing area of the strengthen application and adjust the laminate position whenever relevant in order to obtain a more efficient reinforcement.

5.2.3. Ultimate Limit State – Shear verification

With the increased load of the building, it is necessary to assess the safety of beams to shear. The results are summarized in Table 11.

Table 11: Shear resistance of beams.

Beam	*Asw/s*	*Asw/s (cm2/m)*	*Psd (kN/m)*	V_{Ed} *(kN)*	$V_{Edz.cot(30)}$ *(kN)*	V_{Rd30} *(kN)*
1.6	*φ6 // 0,10*	*5,66*	*98*	*300*	*130,3*	*230,3*
1.A	*φ6 // 0,20*	*2,83*	*49*	*150*	*65,1*	*115,1*
1.4	*φ8 // 0,15*	*6,7*	*108*	*400*	*212,9*	*227,2*

None of the structural elements studied has revealed the need to be strengthened to the ultimate limit state of shear.

5.3. Total Amount of CFRP Laminates Needed

For the strengthening of the 4 storey building, the total amount of CFRP laminates needed is 2117.8 m.

6. Recommendations for Execution

The recommendations presented in this document followed the specifications presented in FIB´s bulletin 14 for:

- Substrate surface preparation;
- CFRP laminates application;
- Carbon fibre sheets application;
- Pre-stress application;
- Bond quality control;
- Corrective actions for bonding defects.

The technique of strengthening contained in this work concerns the use of structural reinforcement in CFRP laminates externally bonded to an existing structure which this document applies to a concrete substrate. The laminate binding to the substrate is achieved by polymerization of a two component epoxy resin, whose specifications and requirements established in sections provided by the manufacturer should be taken into account.