In Situ Measurement of Stress Losses in Unbonded Tendons of Post Tensioned Flat Slabs

Avaliação "in loco" das perdas de protensão de cordoalhas engraxadas em lajes planas

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Abstract

This paper presents the results of "in situ" measurements of stress losses in unbonded tendons of post tensioned flat slabs. These flats slabs have approximately 350 m² in area and are 17 centimeter thick. They are part of a 16 story high hotel building. Load cells were employed to measure the forces in the tendons; they were placed in the vicinity of the active and the passive anchorages. The forces in the tendons were monitored from the time of their straining up to 170 days afterwards. The measurements reveal a frictional coefficient μ equal to 0.0528, a very close value to the one prescribed by NBR 6118 of 0.05. The stress loss due to the anchorage of the tendons was of 5.17% of the initial stress. The results indicate also that the remaining force near the passive anchorage is larger in relation to the value measured in the vicinity of the active one. The total stress loss measured so far (170 days) corresponds to 14 % of the initial post-tensioning stress.

Keywords: post-tensioning flat slabs, unbonded tendons, stress losses.

Resumo

Este trabalho apresenta os resultados de um estudo sobre as perdas de protensão, medidas "in loco", de cordoalhas engraxadas em lajes planas. Essas lajes planas, com 17 centímetros de espessura e 350 m² de área, fazem parte de um edifício para fins hoteleiros de 16 pavimentos. As forças de protensão foram medidas por células de carga colocadas nas proximidades da ancoragem ativa e da ancoragem passiva. As medidas de forças foram feitas desde a protensão até idades de 170 dias após esse instante. Os resultados revelam um coeficiente de atrito μ igual a 0,0528 bastante próximo ao valor apresentado pela norma brasileira NBR 6118: 0,05. Nas perdas pela acomodação da ancoragem os valores apurados foram bastante similares e em termos médios, essa perda correspondeu a 5,17% da força inicial de protensão. Os valores de força medidos mostram também que a perda de tensão na cordoalha, próximo à ancoragem passiva, é menor em relação à perda na ancoragem ativa. Até a idade de 170 dias, verificou-se uma perda média de 14% da força inicial de protensão.

Palavras-chave: concreto protendido, lajes planas, cordoalhas engraxadas, perdas de protensão.

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1. Introduction

Buildings with post-tensioning flat slabs with unbonded tendons are designed and built in the United States since 1950's. Initially, the tendons were greased and wrapped up in paper. Afterwards it was developed an anticorrosive protection formed by a polyethylene tube of high-density and special grease involving the tendons. In Brazil, according to Loureiro [1], the use of unbonded tendons in post-tensioning started in 1997, when Belgo Bekaert began to produce these tendons. Since then, this new technology has become very popular. This post-tensioning system is most advantageous in flat slabs without beams, or when the number of beams is a minimum. This type of design simplifies significantly the formwork as well as reduces material consumption and working force. It also facilitates the placing of the reinforcing bars and casting the concrete with respect to construction systems having beams which is more laborious due to the interferences of reinforcement at the beam-column joints. These post-tensioning flat plates have smaller thickness and allow great flexibility in locating electrical ducts and pipes as well as partitions. These facts explain the increasing use of these systems in commercial and residential buildings.

Figure 1 – Main façade of the hotel building

Unbonded tendons are commonly used with post-tensioning as in this study. The post-tensioning process promotes an early evaluation of the slab strength since the highest stresses the slab will be subjected to occur right after stretching the tendons. Generally this operation is executed when the concrete is still young and, therefore, has not reached the total strength it was designed for. Thus, the post-tensioning procedure constitutes a kind of load test for these slabs.

In this scenario, the main goal of this paper is to present the test results of a study, accomplished by Soares [2], of the post-tensioning stress losses, measured "in situ", on unbonded tendons in flat slabs. These slabs are part of a hotel building, under construction, in the metropolitan area of Belo Horizonte, Brazil. The forces were measured in the tendons, at the proximities of the active and passive anchorages, from the time of post-tensioning to 170 days afterwards. A comparative study of the measured stress losses to predicted values prescribed by the Brazilian code NBR 6118 [3] and found in the literature is also included in the analysis.

It is worth mentioning that, in Brazil, there is no prescribed procedure and is not common to evaluate, "in situ" and along the time, stress losses in tendons. The contribution of this paper comes in this direction.

2. Materials and experimental procedures

2.1 Characteristics of the flat slabs

For the analysis of the stress losses in the tendons, a hotel building under construction in the city of Belo Horizonte was chosen. The building is 16 stories high. The first floor holds the hotel reception and administrative area; the next three levels are for car parking. The hotel rooms are located from the 5th to 15th floors (repetitive floor plan) while the building technical facilities are placed on the top floor. Figure 1 shows the main façade of the building.

All slabs in the building are post-tensioned with unbonded tendons. The first three are waffle slabs and are not analyzed herein. The other ones are 17 centimeter thick flat slabs. The investigated tendons are located in floors 10 to 15. Figure 2 illustrate the repetitive floor plan (5th to 15th level). The external ceramic brick walls are 12 centimeter thick while the internal ones are dry walls.

The measurements were taken on same tendon (cable 2A) of floors 10 to 15. Load cells were installed in openings, 30 cm wide by 100 cm long, left in the flat slabs. These openings were located in the proximities of the active and passive anchorages. Figure 3 presents the location of cable 2A as well as of the openings. The tendon profile is shown in figure 4.

Cable 2A designed post-tensioning force was equal to 140 kN. The corresponded elongation, after anchoring the tendons, was set to 130 mm. During the post-tensioning procedure in each slab, cable 2A was always the last one stretched. This way no stress loss due to consecutive tensioning occurred in this cable.

2.2 Concrete

The concrete mix was designed to reach 80% of the 28-day characteristic compressive strength at the time of post-tensioning. The concrete specified 28-day characteristic compressive strength was equal to 30 MPa. Brazilian CP V type cement was employed, with

a content of 356 kg/m^3. The water/cement ratio was 0.46. For the necessary workability, a plasticizer TEC MULT 44, produced by RHEOTEC, was used. The initial concrete compressive test results indicated that the strength reached the expected values at the age of 7 days. This timing also matched well the construction schedule. Therefore, the chosen date for post-tensioning the tendons was, on average, 7 days after the concrete was cast.

2.3 Unbonded tendons

The unbonded tendons, manufactured by the Belgo Bekaert, have a nominal diameter of 12.7 mm and are made of Brazilian CP 190 type steel. The tendon complete stress-strain relationship was determined in laboratory. The load corresponded to 1% elongation averaged 181 kN and the mean modulus of elasticity reached 204 GPa.

2.4 Tendon force measuring devices and procedures

Load cells, produced by ALPHA instruments, were used to measure the forces in the tendons. These cells are commonly employed in scales for heavy loads as well as in elevator cables. They are easy to install and to monitor. Figure 5 shows the load indicator connected to the cell already attached to the tendon inside an opening left in the slab.

Figure 2 – Repetitive floor plan (5th to 15th level)

The load indicator and cell came certified by IMETRO, the Brazilian institute for standards. They were installed according to the manufacturer's instructions. Two different load cells were attached to the same tendon (cable 2A): one near the active anchorage and the other in the proximities of the passive one. Initially a pre-load stretching the tendon was applied by the hydraulic jack and sized by the cells. The tendon was then elongated to its initial post-tensioning force which was also measured by the load cells. This load corresponded to the first recorded reading. Forces measurements were also taken at the anchoring the tendons right after the hydraulic jack removal as well as several times afterwards. The load recording dates were up to 14 days (366 hours) for cable 2A in floors 10 to 14 and up to 170 days (4086 hours) in the case of 15th floor.

3. Test results and analysis

3.1 Immediate stress losses due to friction

Immediate stress losses due to friction are developed along the tendon during its stretching at the instant of post-tensioning. Table 1 shows the results of tendon forces measured in the proximities of the active and passive anchorages at that instant in each slab. The difference between these forces corresponds to the loss due to friction. The analysis of these results reveals very distinct values for these force losses. Possible alterations in the tendon profile during casting may be one of the factors which cause these differences in the measured values.

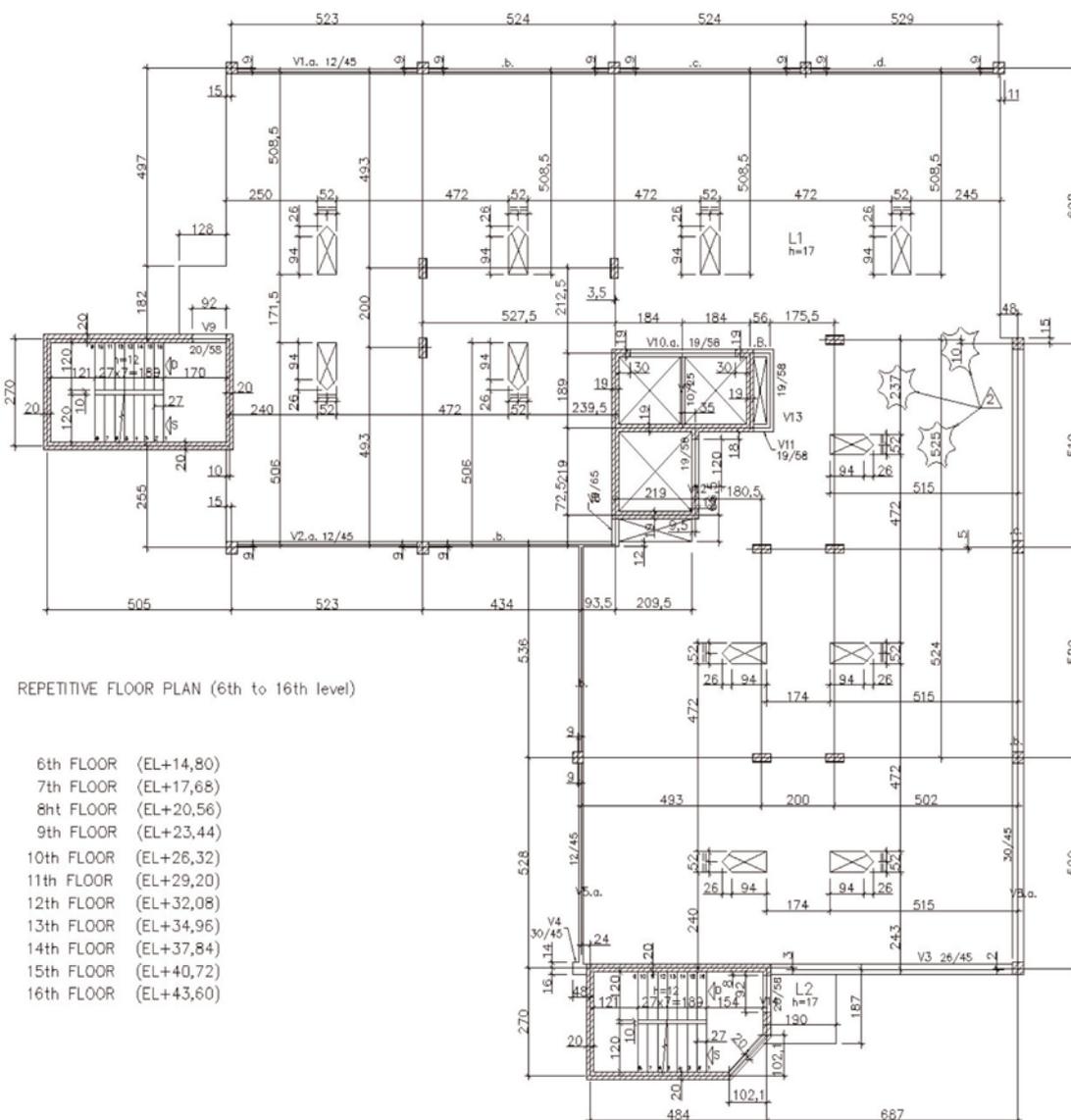Figure 3 – Tendon distribution in the repetitive floor plan

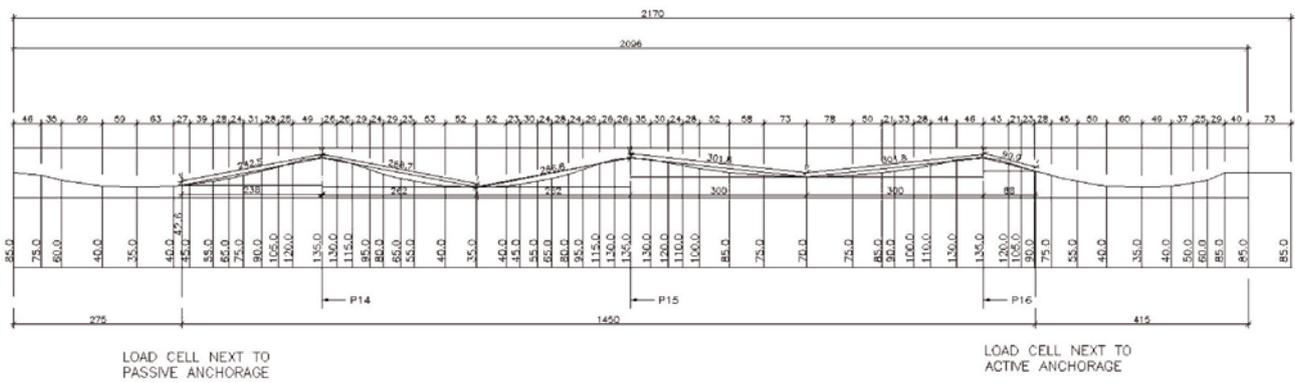Figure 4 – Profile of cable 2A

Figure 5 – Load indicator connected to the cell already attached to a tendon inside an opening left in the slab

Table 1 – Immediate friction losses when stretching the tendons to their initial post-tensioning force

Floor	Tendon force near the active anchorage (kN)	Tendon force near the passive anchorage (kN)	Tendon force difference (kN)	Friction coefficient μ (1/radians)
10	136,20	129,95	6,25	0,0910
11	143,85	142,25	1,60	0,0217
12	143,75	140,35	3,40	0,0464
13	141,55	140,50	1,05	0,0144
14	137,20	131,20	6,00	0,0866
15	138,75	134,75	4,00	0,0566
Mean value	140,22	136,50	3,72	0,0528

Brazilian code NBR 6118 [3] presents in chapter 9 an equation for estimating the immediate loss due to friction in post-tensioning concrete structural elements. The equation is given by:

$$\Delta P_{(x)} = P_i \cdot \left[1 - e^{-(\mu \Sigma \alpha \, + k x)} \right]$$ (1)

where,
P_i is the initial post-tensioning force;
x is the distance, in meters, between sections at which ΔP is determined;
$\Sigma \alpha$ is the sum of the angles, in radians, due to intended curvatures in the cable profile between the measuring sections;
μ is the friction coefficient between the tendon and the high-density polyethylene sheathing (1/radians); and
k is the wobble coefficient due to unintended curvatures in the tendon.

In the lack of experimental data, NBR 6118 suggests using k = 0.01μ. The tendon manufacture (Belgo [4]) specifies a value for the friction coefficient μ between 0.06 and 0.07. NBR 6118 [3], on the other hand, suggests 0.05 in the lack of experimental data.
Table 1 also presents values for the friction coefficient calculated with equation 1. In this calculation, k was set equal to 0.01μ. The distance between the measuring points (load cells) was equal to 14.07 meters and 0.3757 radians was the sum of the angles (Σα) due to intended curvatures in the tendon profile. The mean calculated value for the friction coefficient was smaller than the one prescribed by the manufacture equal to 0.07. With respect to the Brazilian code NBR 6118 there was no difference: 0.0528 versus 0.05.
A comparison between the design initial post-tensioning force (140 kN) and an estimated value based on the force measured by the load cell near the active anchorage is shown in Table 2. This estimated force was calculated using equation 1 with a friction coef-

Table 2 – Estimated tendon force at the hydraulic jack at the time of post-tensioning

Floor	Tendon force near the active anchorage (kN)	Friction coefficient μ (1/radians)	Estimated tendon force at the hydraulic jack (kN)	Design initial post-tensioning force (kN)
10	136,20	0,0910	138,50	
11	143,85	0,0217	144,40	
12	143,75	0,0464	144,95	
13	141,55	0,0144	141,90	140,00
14	137,20	0,0866	139,40	
15	138,75	0,0566	140,15	
Mean value	140,20	0,0528	141,55	

Table 3 – Immediate tendon force losses due to anchorage take-up

| Floor | PRÓXIMO À ANCORAGEM ATIVA | | | | |
	Tendon force near the active anchorage (kN)	Tendon force right after anchorage take-up (kN)	Tendon force loss (kN)	Percentile of tendon force loss (%)	Tendon return length (mm)
10	136,20	128,40	7,80	5,73%	3,70
11	143,85	135,90	7,95	5,53%	3,33
12	143,75	135,00	8,75	6,09%	2,93
13	141,55	137,50	4,05	2,86%	1,59
14	137,20	129,60	7,60	5,54%	3,62
15	138,75	131,40	7,35	5,30%	4,10
Mean value	140,20	132,95	7,25	5,17%	3,21

ficient µ determined for each floor and **k** equal to 0.01µ. In this case the distance between the measuring sections was of 4.15 meters and the sum of the angles (Σα) due to curvatures in the tendon of 0.1471 radians. The analysis of the results shown in table 2 reveals good correlation between the average value for the estimated force at the hydraulic jack and design initial post-tensioning force.

3.2 Immediate losses due to anchoring the tendons

Table 3 shows the results of measured forces near the active anchorage at the instant of post-tensioning and right after anchoring

the tendons. The difference between these forces represents the immediate loss due to anchorage take up. The percentiles of this force loss as well as the return length of the tendons due to slippage are also presented in the table. The tendon return length was calculated as described in appendix A.

The analysis reveals similar results for the force losses with the exception of floor 13 in which the calculated value was significant smaller. The mean force loss corresponded to 5.17% of the initial straining value. This finding is in good agreement with suggested values found in the literature for this loss (Lyn and Burns [5]). The average cable return length equal to 3.21 mm is significantly smaller

Table 4 – Comparative study of tendons elongation

Floor	Estimated tendon force at the hydraulic jack (kN)	Tendon force loss due to anchorage take-up (kN)	Tendon remaining force at the active anchorage right after anchorage take-up (kN)	Estimated tendon elongation (mm)	Design tendon elongation (mm)	Actual tendon elongation (mm)	Percentage difference between actual and design tendon elongation (%)	Percentage difference between actual and estimated tendon elongation (%)
10	138,50	7,80	130,70	133,34	130,00	136,00	4,41 %	1,95 %
11	144,40	7,95	136,45	139,21	130,00	133,00	2,26 %	-4,67 %
12	144,95	8,75	136,20	138,96	130,00	130,00	0,00 %	-6,89 %
13	141,90	4,05	137,85	140,64	130,00	131,00	0,76 %	-7,36 %
14	139,40	7,60	131,80	134,47	130,00	128,00	-1,56 %	-5,05 %
15	140,15	7,35	132,80	135,49	130,00	130,00	0,00 %	-4,22 %
Mean value	141,55	7,25	134,30	137,02	130,00	131,33	---	---

than 7 mm prescribed by the tendon manufacturer (Cauduro [6]). Based on the estimated value for the initial straining force at the hydraulic jack (table 2) and on the tendon tension loss shown in table 3, the remaining force at the active anchorage right after anchoring the tendons can be evaluated. This remaining force, whose value for each floor is presented in table 4, is equal to the difference between the other two. With this force the tendon total elongation can be determined. This elongation was calculated considering a tendon initial total length of 21.0 meters, a cross-sectional area of 1.01 cm^2 and a value of 204 GPa for the steel modulus of elasticity. Table 4 also shows a comparison between this determined elongation with respect to the design estimated one and to the actual value measured "in situ" right after anchoring the tendons. The analysis of these results shows differences smaller than 10 % in the elongation values. According to Brazilian NBR 14931 [7], there is no need to stretch once more tendons, whose elongations are within the interval of ± 10 % of the predicted values.

3.3 Time dependent losses

A comparative study of the remaining average force in tendons along the time, near the active and passive anchorages, considering all slabs monitored (floors 10 to 15) can be seen in table 5 and figure 6. These results show larger remaining force values next to the passive anchorage. The analysis also unveils that the difference between the forces next to the passive and active anchorages stayed constant up to 14 days (336 hours) with a mean value of 0.65 kN. At that time, the average remaining force in the tendons next to the active anchorage was equal to 125.45 KN, which corresponded to a total stress loss of 10,52 % in relation to the mean initial straining value of 140.20 KN. In the proximities of the passive anchorage the mean total loss was smaller 8.04 %.

Figure 7 presents the remaining forces, after anchorage take-up, in cable 2A at the 15th floor 15 in the proximities of the active and passive anchorages. These results also show larger remaining force values next to the passive anchorage. The analysis unveils that

the difference between the forces next to the passive and active anchorages decreased with time to a value of 0.45 kN after 170 days (4086 hours). At that time, the average remaining force in cable 2A next to the active anchorage was equal to 117.15 KN, which corresponds to a total stress loss of 15.06 % in relation to the initial stretching value of 138.7 KN. In the proximities of the passive anchorage this total loss was smaller 12.72 %.

The usual lump sum design estimate for post-tensioning loss is in the order of 20 % of the initial force value. In this study a total loss of 14 % was already reached 170 days after straining. With this result we can not estimate if the usual lump sum for the total post-tensioning loss will exceed or not 20 % of the initial straining force. Tendon force measurements along a significant longer period of time are still necessary.

4. Conclusions

This paper presented the results of "in situ" measurements of stress losses in unbonded tendons of post tensioned flat slabs. These flats slabs have approximately 350 m^2 in area and are 17 centimeter thick. They correspond to the repetitive floor plan (10th to 15th level) of a hotel building, under construction, in the city of Belo Horizonte. In each slab, the monitored tendon was always the last one strained. Load cells were employed to measure the forces in the tendons; they were placed in the vicinity of the active and the passive anchorages. The forces in the tendons were monitored from the time of their straining up to 170 days afterwards. The main conclusions of the study are:

• Very distinct values were found for the force losses due to friction. Possible alterations in the tendon profile during casting the slabs may be one of the factors which cause the differences in the measured values. Based on the test results, an average value for the friction coefficient of 0.0528 was determined. This mean value is smaller than the one suggested by the manufacture of 0.07; on the other hand is very close to the prescribed one by NBR 6118 of 0.05.

Table 5 – Average remaining tendon forces – (floors 10 to 15)			
Instant	Average tendon remaining force next to the ctive anchorage (kN)	Average tendon remaining force next to the passive anchorage (kN)	Force difference (kN)
Right after anchorage take-up	132,95	133,70	0,75
48 hours after that	131,20	132,20	1,00
72 hours after that	130,95	131,55	0,60
144 hours after that	128,60	129,35	0,75
200 hours after that	126,75	127,20	0,45
336 hours after that	125,45	125,80	0,35
Mean value	-----	-----	0,65

Figure 6 – Average remaining tendon forces after anchorage take-up – (floors 10 to 15)
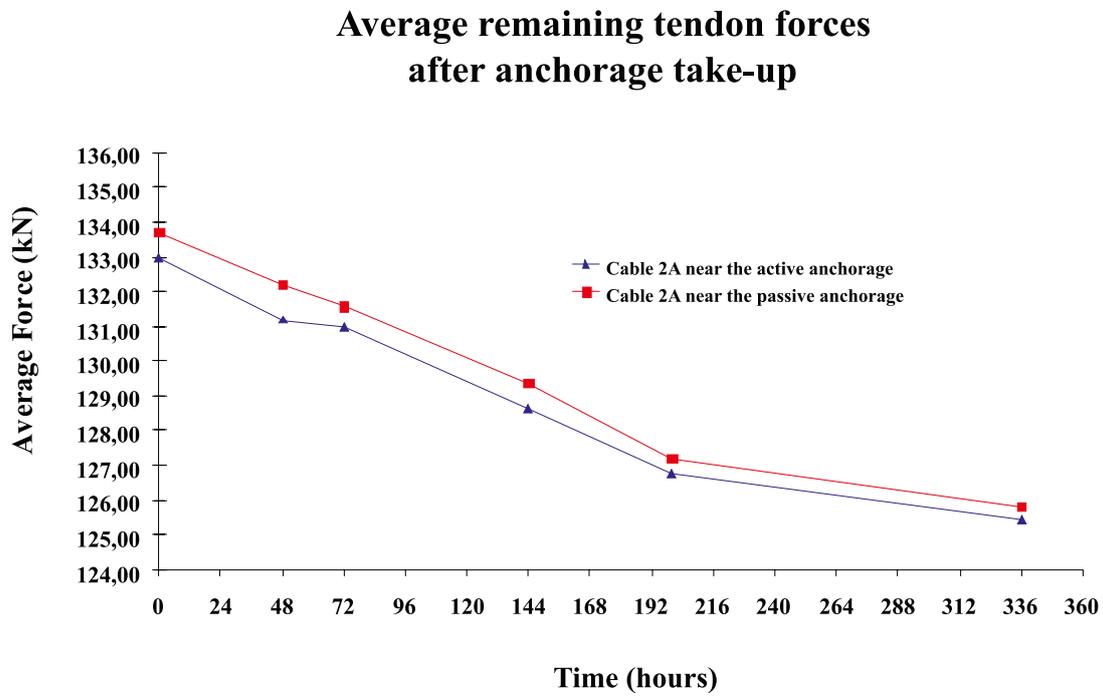
Figure 7 – Remaining tendon force after anchorage take-up – (15th floor)
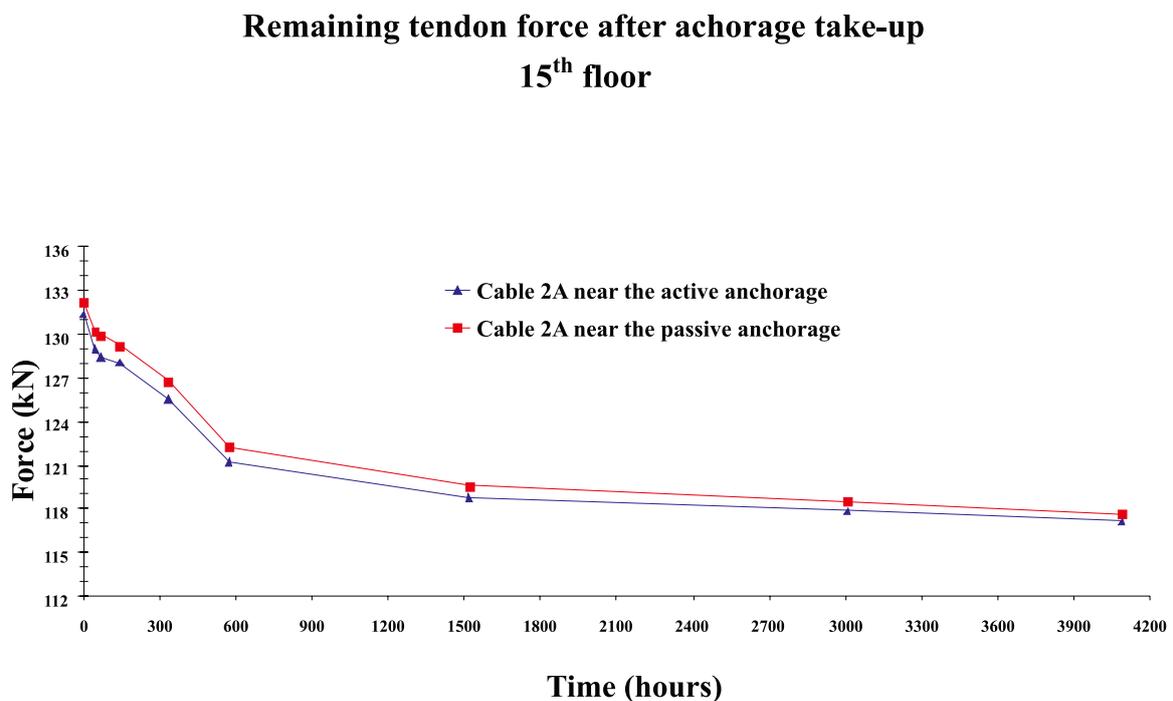
- Very similar results were obtained for the stress losses due to anchorage take-up. The average value for this immediate loss corresponded to 5.17% of the initial post-tensioning force.
- The evaluation of the average tendon return length, right after anchorage take-up, unveiled a value of 3.21 mm, significantly smaller than 7 mm prescribed by the tendon manufacturer.
- Until 14 days after straining, the average tendon total force loss (floors 10 to 15) corresponded to 9.25 % of the initial post-tensioning force.
- The results showed that approximately 14 % of the initial post-tensioning force was already lost till 170 days after straining.
- The results also unveiled larger remaining tendon forces in the proximities of the passive anchorage in relation to the active one.

5. Acknowledgments

6. References

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Appendix A – Determination of the tendon return length

The tendon return length right after anchorage take-up was determined on the linearization of equation 1 as suggested by Collins and Mitchell [8]. Thus that equation becomes:

$$P_{(x)} = P_i.(1 - \mu\Sigma\alpha - kx)$$

(2)

The distribution of the force $P_{(x)}$ along the length of cable 2A at the 10th floor is given by:

Figure 8 – Distribution of the force right after anchorage take-up along the length of cable 2A at the 10th floor
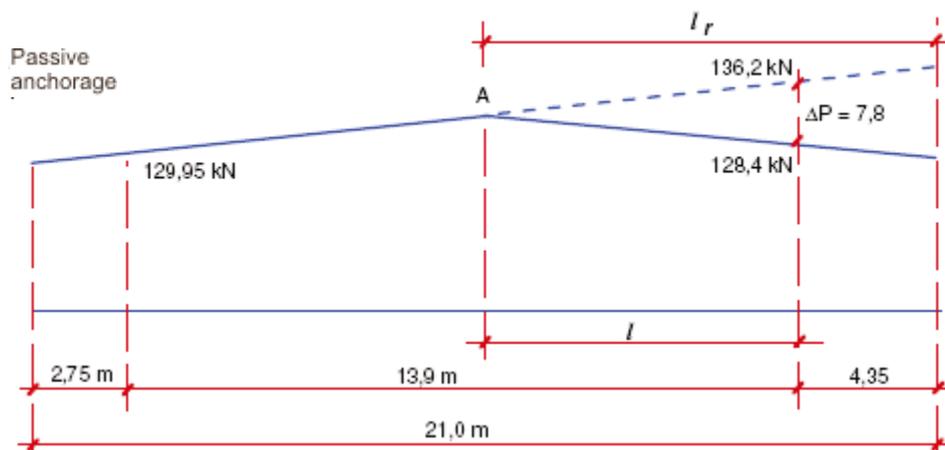
The length *l*, in the figure, is equal to:

$$l = \Delta P/2p \text{, with } p = \frac{136.2 - 129.95}{13.9} = 0.45 \, kN/m \text{ and, thus,}$$

$$l = 7.8/2.0.45 = 8.67 \, m \text{ .}$$

The total length *l*ᵣ affected by the tendon return is equal to **13.02 m (8.67 + 4.35)**. With this, the cable return length, considering the tendon cross-sectional area of 1.01 cm² and a value of 204 GPa for the steel modulus of elasticity, is given by:

$$\delta = \frac{pl_r^2}{A_p E_p} = \frac{0.00045 \cdot 13020^2}{1.01 \cdot 20400} = 3.7 \, mm$$

The same procedure was used for cable 2A in the 14th and 15th floor. The obtained values were *3.62* and *4.10* mm respectively. For the other floors, the above procedure led to values of length *l* larger than *16.65* m *(13.9 + 2.75)*, indicating that the whole cable was affected by the return. For these cases, the adopted procedure, employing cable 2A of the 11th floor as an example, was:

$$p = \frac{143.85 - 142.25}{13.9} = 0.115 \ kN$$

Figure 9 – Distribution of the force right after anchorage take-up along the length of cable 2A at the 11th floor
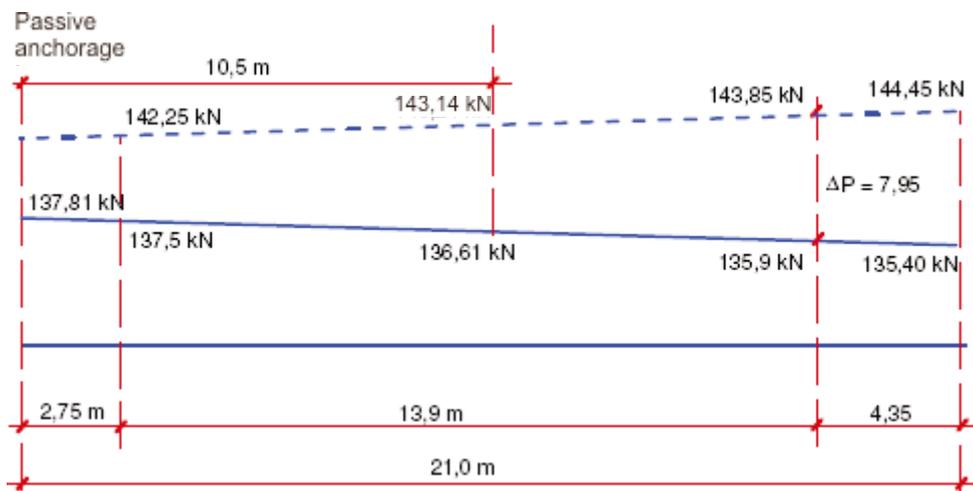
$$\delta = \frac{\Delta P_{médio} l_r}{A_p E_p} = \frac{\left(\dfrac{143.14 - 136.61}{2}\right).21000}{1.01 \ . \ 20400} = 3.33 \ mm$$

The same above procedure was employed for cable 2A in the 12th and 13th floor. The obtained values were *2.93* and *1.59* mm respectively.