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Monitoring of high-rise buildings´ reinforced concrete columns

Monitoramento de pilares em edifícios altos de concreto armado

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Abstract

The structural behavior simulated by computer programs can be very different from reality, once the adapted loading distribution (regular) is far from the real one, and this disparity becomes more significant in high buildings because of vertical and horizontal actions which contribute to the global effects of second order for columns, making accuracy in the calculation of great importance for the stability of the overall structure. In this work are presented loads for a high building simulated using the commercial software CAD/TQS and the loads from the monitoring of 7 columns that received 3 extra bars along their height in two levels before concreting. In the steel bars were set electric strain gages to measure the strains. The data acquisition was performed through 1 module “Spider” that gets and stores the readings. The measurements were executed in periods previously chosen until the end of the structure building, including upper reservoir. The computation loads for the columns were satisfactory when compared to the loads from the strains and characteristic mechanical properties of the materials.

Keywords: *reinforced concrete, columns, stability, buildings.*

Resumo

O comportamento estrutural simulado por programas computacionais pode ser bem diferente da realidade, uma vez que as cargas idealizadas no cálculo não representam fielmente a verdadeira distribuição do carregamento. Essa disparidade torna-se mais significativa em edificações altas, devido às ações verticais e horizontais que contribuem aos efeitos de segunda ordem nos pilares e tornam a precisão no cálculo de grande relevância para a estabilidade global da estrutura. Neste trabalho são comparadas as cargas nos pilares, calculadas com o software comercial CAD/TQS com as cargas observadas pelo monitoramento de 7 pilares selecionados, que receberam 3 barras extras ao longo de sua altura em dois níveis antes da concretagem. Nessas barras foram fixados extensômetros elétricos para medir as deformações ao longo do tempo. A aquisição de dados foi realizada através de um módulo “Spider” que realiza e armazena as leituras. As medições foram executadas em períodos pré-fixados até a conclusão da estrutura, incluída a caixa d’água. As cargas simuladas para os pilares, nesta etapa de carregamento, mostraram-se coerentes com os resultados obtidos pela análise das deformações medidas e dos resultados de ensaios dos materiais empregados na estrutura.

Palavras-chave: *concreto armado, pilares, estabilidade, edifícios.*

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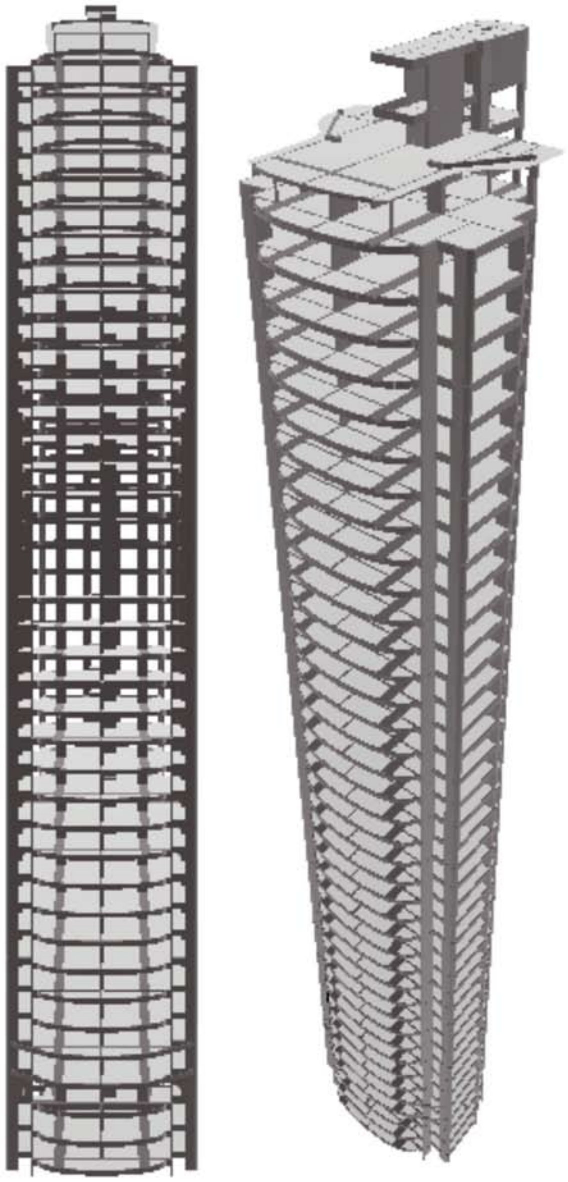
1. Introduction

Due to the shortage and at the high cost of the space in the centers of the large cities, the construction of high buildings has been the main solution found by the companies. In the structural design the considered model is, in general, a non displacement structure and with uniformly distributed load. This situation is not realistic, because the vertical differential displacements in the foundations and cracks in the structure could change the configuration adopted initially in the design calculation so much for the geometry as for the reactions in the columns. Vibrations of machines and equipments are also factors that potentiate the new configurations for stresses in the structures. These unexpected effects are more significant in high structures, due to the great intensity of the loadings turning the structural monitoring an important tool for the real understanding of the structural behavior. This verification becomes more relevant considering that the evaluation of the loading in columns of a building is based on several dimensioning hypotheses, but of difficult verification and thoroughly recognized as high imprecision degree. This is a pioneer work in the North Region of Brazil and it consists in monitoring 7 columns of a residential building with 41 floors, located in a noble neighborhood of Belem city, aiming to compare the experimental normal forces with those provided by the commercial software CAD/TQS applying the Brazilian code's prescriptions, considering the interaction soil-structure, the geometrical non linearity of the structure and the physics non linearity of the material intending to compare the obtained results.

Figure 1 – Views of the building modeled with program CAD/TQS

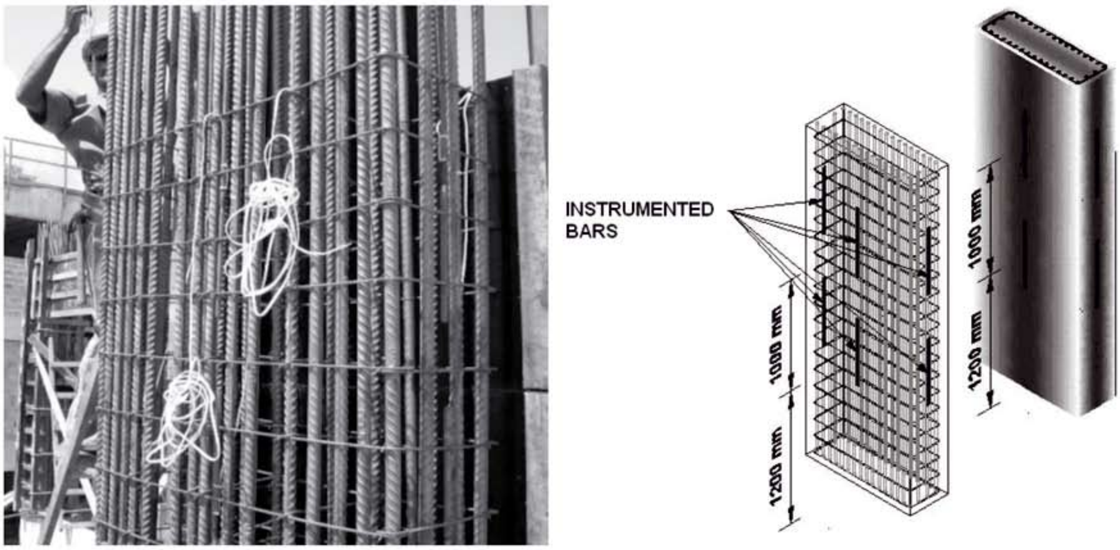


2. Structural analysis

The calculations which were manually done along the last decades nowadays are carried out with tools much more sophisticated that seek to simulate the structural behavior in a more realistic way. To verify part of that structural behavior in a high building in the city of

Figure 2 – Monitored building (left)

Figure 3 – Position of the instrumented bars in the columns



Belém the commercial software CAD/TQS V13 was used in the computational simulation, considering the structural model of the designer, structural elements' cross sections, the materials' characteristic mechanical properties and the Brazilian code's prescriptions [1] where, according to FERREIRA & OLIVEIRA [2], the present calculation process for columns is a great progress for reinforced concrete structural design in its recommendations, turning design stage more rigorous in relation to the durability and generating columns with satisfactory amount of steel reinforced smaller than by its previous version. The aim of the numeric analysis is to verify the normal forces that theoretically act in the columns and to compare them to the observed one from the monitoring of the building. The Figure 1 shows the views of the structure modeled in perspective, front view and superior view.

Some criteria were established for the modeling, as the action of the wind (31 m/s), class of aggressiveness II (urban ambient), maximum diameter of coarse aggregate (19 mm) and of the vibrator (35 mm). The structural model used in the structural analysis was the spacial frame with displacement joints considering the non linearity of the structure and materials.

3. Experimental program

3.1 Characteristics of the building

The monitored building is, at the moment, considered the tallest one in Belém city and the second in the areas Northeast North, being a residential type with 1 ground floor, 2 mezzanine levels, 1 level of leisure area, 34 pattern floor, 2 duplex levels and 1 loft (machines and small barrel), holding a total of 41 floors. The floors have area of 308 m² with 20 columns, and the slabs are ribbed with prestressed bands, with medium height of 170 mm. The pattern floor has 2,970 mm of floor height and the tip height of the building is over 126 meters. Beside of the monitored building there is another building with the same structural characteristics. The Figure 2 shows the ready structures of the buildings with their external and internal masonries.

3.2 Instrumentation of the columns

The employed technique for the columns' monitoring consisted basically in positioning additional instrumented short bars and places them in the existent reinforcement, in the mezzanine floor I. The bars of 600 mm length and 12.5 mm diameter were instrumented with electric strain gages Kyowa Electronic Instruments Co. Ltd, model KFG-5-120-C1-11, and later positioned in the reinforcement bars, before concrete placement, on the 3 faces of the columns and at two levels, so that the first strain gages was placed at 1,200 mm from the superior surface of the inferior slab and the second one positioned to 2,200 mm, as shows the Figure 3. The columns were selected after carried out the structural pre-analysis of the building, being verified the factors judged relevant as the greatest required normal forces and the simplest geometries. The chosen columns were: P9, P10, P12, P13, P14, P15 and P16, totaling 7 columns. The Figure 4 shows the location of the columns in floor plan and the Table 1 presents their main characteristics. In the table *Ac* is the concrete area of the columns cross section and A_s is the sum of the steel longitudinal bars' cross sections with diameter Ø.

3.3 Monitoring system

For the monitoring of the columns it was employed one module Spider 8, 600 Hz, with the aid of one Notebook. The first reading was to reference and it occurred after removing the molds of the columns, the second one was after the concrete placement of the floor of the second pattern floor and, from this reading, the sequence of the

Figure 4 – Low plant of the pattern floor indicating the monitored columns

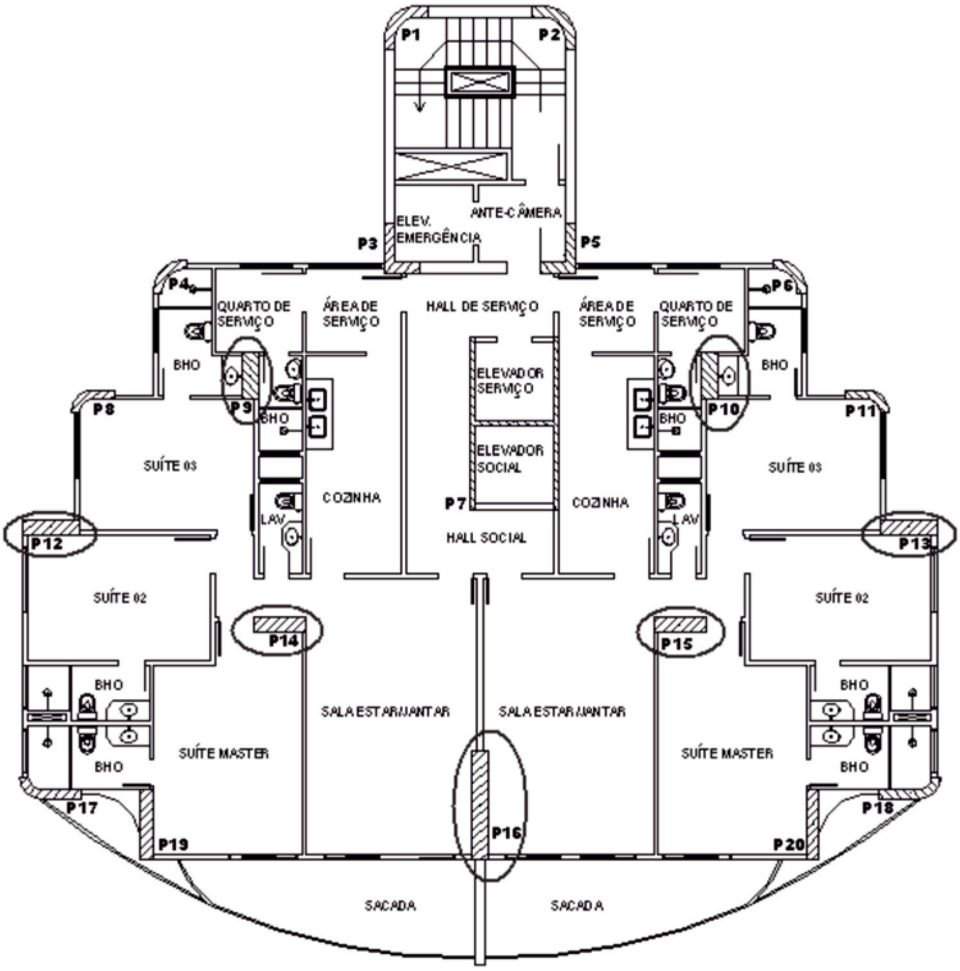


Table 1 – Characteristics of the monitored columns

Column	Section		A_c	Longitudinal Reinforcement steel		A_s
	(mm)	(mm)	(mm²)	(und)	ø(mm)	(mm²)
P9	400	1,100	440,000	36		17,671
P10	400	1,100	440,000	36		17,671
P12	350	1,300	455,000	18		8,835
P13	350	1,300	455,000	18	25	8,835
P14	350	1,200	420,000	38		18,653
P15	350	1,200	420,000	38		18,653
P16	350	2,500	875,000	60		29,452

measurements occurred to each floor placed. The Figure 5 shows the procedure of one of the readings during construction.

4. Results

4.1 Concrete and steel

The concrete and steel are two materials whose behaviors govern the reinforced concrete elements' performance. The stress-strain diagram of the concrete is not linear but presents behavior approximately linear for stresses up to 30 % of its maximum compression resistance. The curve sketch for the concrete was done according to the Brazilian design code [3], using 3 cylindrical specimens with dimensions (100 x 200) mm under axial compression, that were cast during the concrete placement of the columns of the mezzanine I. To determinate the module of elasticity of the concrete were also cast 3 cylindrical specimens with dimensions (100 x 200) mm and monitored with electric strain gages to measure the strains with satisfactory precision in agreement with the Brazilian code [4]. The average strength of compression resistance was of 34 MPa and the average modulus of elasticity was of 36 GPa. The Figure 6 shows the specimens with strain gages. Figure 7 shows the theoretical (according to Brazilian code NBR 6118) and experimental characteristic curves for the concrete.
Nowadays the most used steels in building sites are the hot treated ones, once they are more flexible, stress-strain diagram with well defined yield stress and with moderate resistance to fires. For the tension tests of the steel following the Brazilian code [5], it was used 3 samples of the steel bars added to the columns, with 600 mm length and 12.5 mm diameter. The Figure 8 shows the stress-strain diagrams for the tested samples, from where was obtained the average curve for the calculation of mechanical properties of the same ones, where the yield stress and the strain were 535 MPa and 2.6 ‰ respectively, the failure strength was 713 MPa and the experimental modulus of elasticity was 205 GPa. The value of the modulus of elasticity was admitted equal to the average one from the tested bars.

4.2 Normal forces in the columns

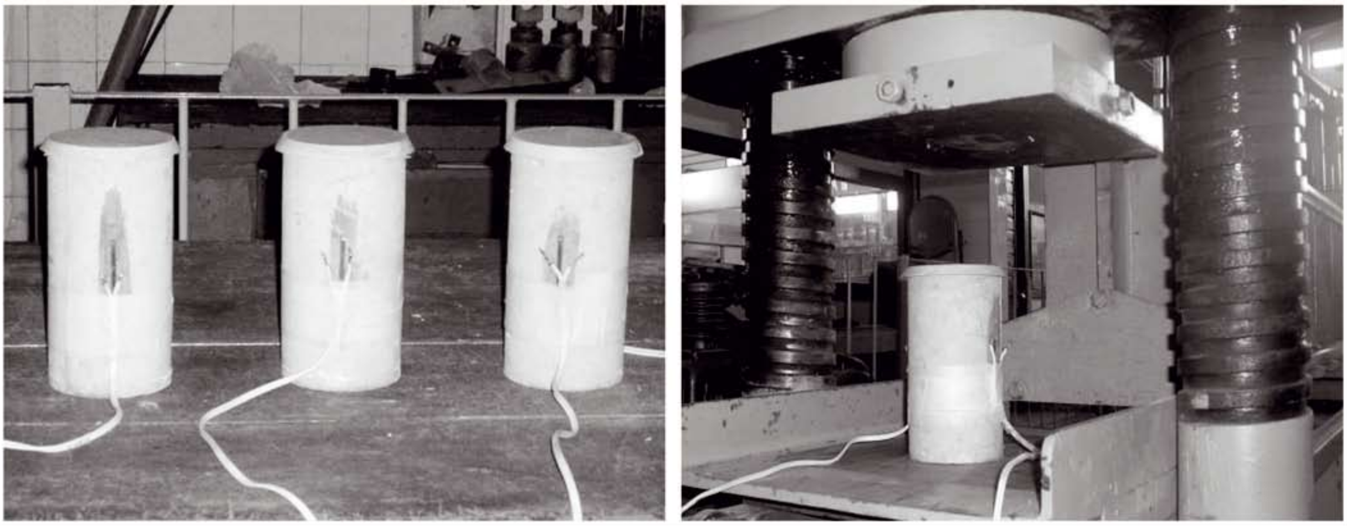
To estimate the normal forces in the columns it was used the characteristic curve of the concrete from axial compression experimental tests of the concrete specimens and the modulus of elasticity of the steel bars tested. In each level of monitored column were considered the flexural-compression effects and the bending moments found were discarded in this analysis due to their low intensities and no simultaneous readings at other columns, beyond they don't change the experimental normal forces since the reinforced was not subject to the tensile stress. The normal forces in the columns can be calculated with the Equation 1.

$$N = (A_c - A_s).f_c + A_s.f_s \qquad (1)$$

where,
N = force in the column;
A_c = total area of the cross section;
A_s = sum of the areas of the longitudinal bars reinforcement;
f_c = concrete stress from the stress-strain curve;
f_s = steel bar stress from the measured strain.
All of the loadings in the floors were considered in factored in the calculations, among them: internal and external walls, sub-floors, self weight of the structure (with reinforcement) and wind loads.

Figure 5 – Monitoring system used in the building

Figure 6 – Specimens instrumented



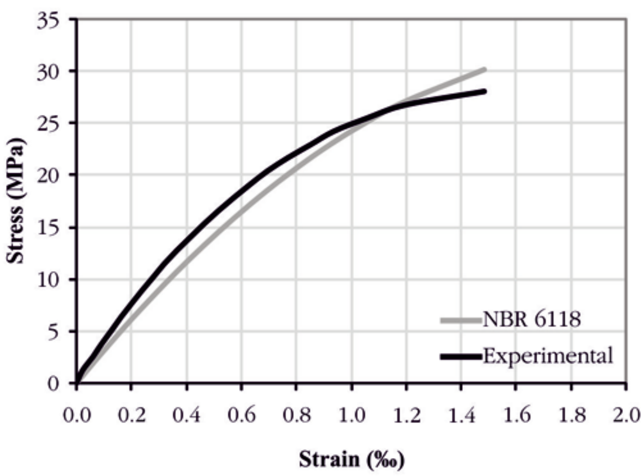
The live load was not considered once the monitoring was carried out without the occupation of the building and without the use of the upper water reservoir. In the Table 2 the measured normal forces are presented with the monitoring of the columns (N_{exp}) and the estimated ones through the modeling of the structure from the program CAD/TQS (N_{proj}). In the Figure 9 are shows 2 diagrams, the first with the average strain used in the calculation of the force in the columns observing the limit strains for compression (2 ‰) and flexural-compression (3.5 ‰) and the second the relation among the forces obtained experimentally and numerically. The Figure 10 shows the progress of the strains in the 3 faces in the two levels of the monitored columns P9, P12 and P14 with the increasing of the number of floors.

5. Conclusions

Results obtained experimentally with the instrumentation of seven columns of a 126 meters height building in the city of Belem are presented and discussed. The experimental curves for strains presented a linear trend with low standard deviation, as expected. The variations along these curves can be due to the action of the wind, loading distribution, still varying, to vertical of differential displacement or even to interferences in the data acquisition system. The average strain found in the columns was of 0.5 ‰, corresponding to 25 % of the strain limits from 2 ‰ to compression and 15 % for the strain to limit of 3.5 ‰ recommended for flexural-compression. The bending moments found computationally were higher than those from calculations with the experimental strains (variation of the speed of the wind, etc.), not being considered significant for the analysis of the presented results.

The estimated values from the program CAD/TQS for the normal forces in the columns P10 and P16 were higher 14 % and 7 %, respectively, than the values found experimentally. For the other columns the estimates were lower 5 %, case of the column P13. Considering that the construction was in loading phase, these values are not the final ones, could vary for more or less depending, mainly, on distribution of the live loads, and internal and external coverings and of the behavior of the foundations.

Figure 7 – Theoretical and experimental stress-strain curves for the concrete



6. Acknowledgements

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Figure 8 – Stress-strain diagram of the steel from the laboratory tension test

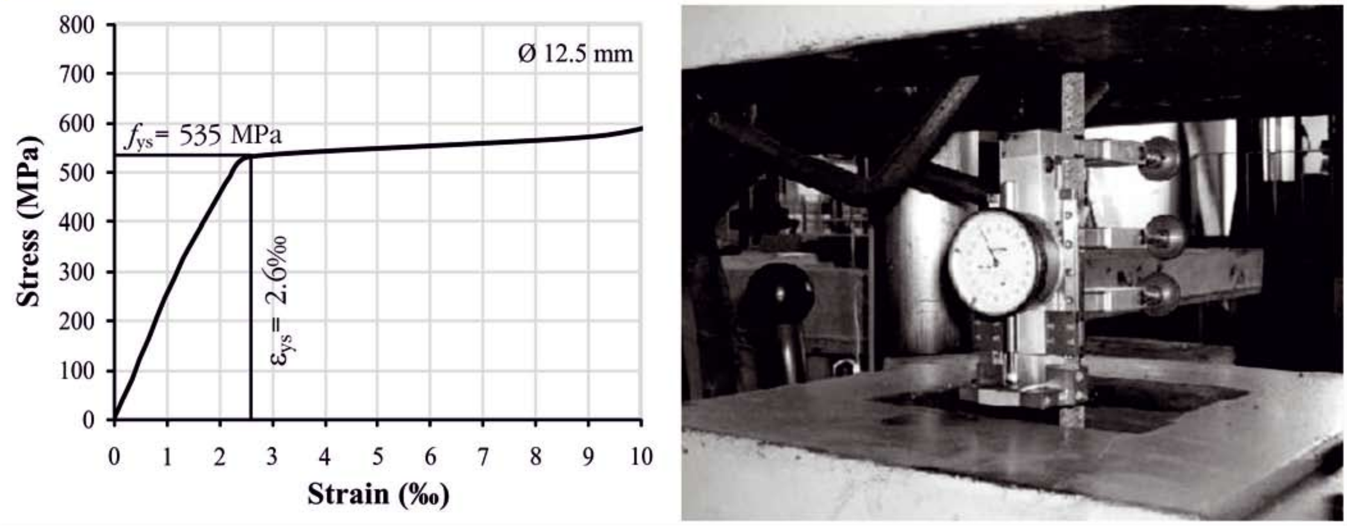

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Table 2 – Normal forces in the columns

Column	Nproj (kN)	Nexp (kN)	Nexp/Nproj
P9	8,691	8,886	1.02
P10	8,169	7,059	0.86
P12	7,266	7,425	1.02
P13	7,263	7,634	1.05
P14	8,485	8,799	1.04
P15	8,099	8,375	1.03
P16	19,210	17,858	0.93

Figure 9 – Average strains and comparison of stresses from the monitored columns

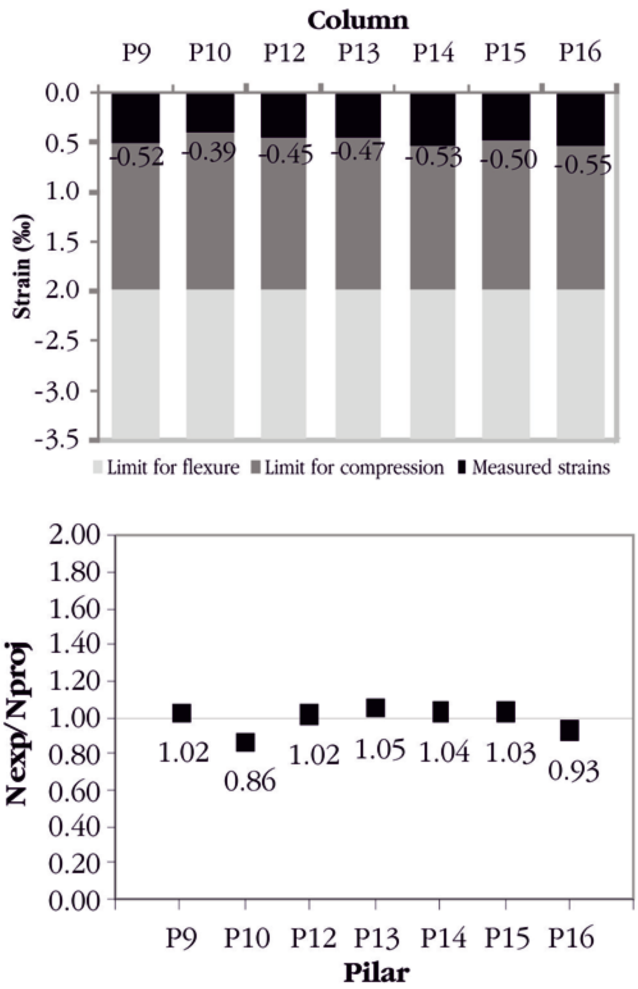

Figure 10 – Reinforcement measured strains of the columns P9, P12 e P14