IBRACON Structures and Materials Journal
Revista IBRACON de Estruturas e Materiais
ISSN 1983-4195 ismj.org

ORIGINAL ARTICLE

Investigation of an alternative system for monitoring strains in reinforced concrete structures

Investigação de um sistema alternativo para o monitoramento de deformações em estruturas de concreto armado

Fernanda Petry Pes[a]
Marcelo Maia Rocha[a]
Paula Manica Lazzari[a]

[a]Universidade Federal do Rio Grande do Sul, Programa de Pós-graduação em Engenharia Civil, Porto Alegre, RS, Brasil

Received 04 March 2023
Revised 11 May 2023
Accepted 12 June 2023
Corrected 27 March 2024

Abstract: In civil engineering, variations in material properties together with the application of different construction techniques and environmental conditions may not be fully considered in structural designs, which could lead to structural damages. Structural Health Monitoring (SHM) makes it possible to follow the behavior of a structure, allowing the evaluation of its conditions and the investigation of its damages and need for interventions. However, SHM is not commonly applied yet due to its high instrumentation cost and the complexity of its procedures. Therefore, the present work aims the development of a low-cost strain measurement system for reinforced concrete structures composed of strain gages, amplifiers, signal converters, and microprocessors. Thus, an easy-to-use and low-cost data system composed of an AD620 amplifier module and an ADS1115 converter was built. Additionally, to facilitate field instrumentations, a steel plate with strain gages arranged in a full Wheatstone bridge was also built. The evaluation of the system was conducted by lab testing a column, four-point bending tests of four beams, and the field monitoring of two columns in a residential building during construction. The results showed that the proposed system performed satisfactorily, being able to accurately measure the strains in reinforced concrete structures.

Keywords: instrumentation, low-cost equipment, strains, reinforced concrete.

Resumo: Na construção civil, as variações nas propriedades dos materiais juntamente com as diferentes técnicas construtivas e condições do ambiente, podem não ser totalmente consideradas no cálculo estrutural e ocasionar danos nas estruturas. O Monitoramento da Integridade Estrutural (MIE) possibilita acompanhar o comportamento estrutural, avaliar as condições da estrutura e inclusive investigar o acontecimento de danos e das possíveis necessidades de intervenções. No entanto, o MIE ainda é pouco implementado devido ao alto custo de instalação e complexidade de operação. Desta forma, o presente trabalho busca desenvolver um sistema de medição de deformações em estruturas de concreto armado através de extensômetros, amplificadores, conversores de sinais e de microprocessadores de baixo custo. Assim, foi construído um sistema de aquisição de dados de baixo custo e relativa facilidade de operação, composto pelo módulo amplificador AD620 e o conversor ADS1115. Ainda, para facilitar a instalação de extensômetros em campo, foi desenvolvida uma placa de aço com extensômetros fixados, formando uma ponte de *Wheatstone*. Para avaliar o sistema, foram realizados ensaios de compressão em um pilar, ensaios de flexão à quatro pontos em vigas, além do monitoramento de pilares de um edifício residencial em fase construtiva. Através da elaboração deste estudo, encontraram-se resultados favoráveis à utilização dos sistemas propostos, obtendo-se as deformações das estruturas de concreto armado.

Palavras-chave: instrumentação, equipamento de baixo custo, deformações específicas, concreto armado.

How to cite: F. P. Pes, M. M. Rocha, and P. M. Lazzari, “Investigation of an alternative system for monitoring strains in reinforced concrete structures,” *Rev. IBRACON Estrut. Mater.*, vol. 17, no. 3, e17308, 2024, https://doi.org/10.1590/S1983-41952024000300008

Corresponding author: Fernanda Petry Pes. E-mail: fernandappes@gmail.com
Financial support: This study was financed by the Civil Engineering Graduate Program (PPGEC) of the Federal University of Rio Grande do Sul (UFRGS) and by the Brazilian governmental research institution (CNPq).
Conflict of interest: Nothing to declare.
Data Availability: none.
This document has an erratum: https://doi.org/10.1590/S1983-41952024000300011

1 INTRODUCTION

Concrete is the second most applied resource in the world (water is the first) and is massively applied by designers, builders, construction workers, and others involved in construction processes. This considerable acceptance of such material worldwide and its increasing use in Brazil is related to several aspects, such as the availability of its components, ease of use, and cost efficiency [1]. New methods and techniques in engineering allied to technological advances in concrete have allowed the construction of slender and bolder structures [2]. However, due to the variations that can occur in the properties of concrete, which are a function of many variables and conditions, the development of methods to verify the performance of concrete elements becomes increasingly relevant [3].

In structural design, it is common to consider a structure with rigid supports and subjected to uniformly distributed loads. However, this may not be the most realistic situation since differential displacements may happen in the foundations and concrete cracking may modify the loading configuration and the structural response in columns and even in the entire structure. Also, constructive effects that are less common or difficult to simulate are conditions that tend to induce different configurations of internal forces in the structures. And the taller a building is, the more significant these effects become, proportionally increasing the internal forces on the first floors. Therefore, structural monitoring becomes a valuable tool for understanding the real behavior of a structure and to improve its quality control [4].

Structural Health Monitoring (SHM) can be used to evaluate the behavior of existing structures and those still under construction, to verify the results of the analytical and numerical models used in the design phase, and to assess the onset of damages and deterioration processes. SHM requires the development of data systems capable of measuring and processing signals from sensors placed on structures to provide a reliable response in terms of structural behavior [5]. Nevertheless, SHM is a tool that is not much applied in construction yet due to the high costs associated with instrumentation and the complexity of the required operations [6].

Some representative cases from the literature that can illustrate the importance of SHM can be briefly mentioned herein. For instance, Ye et al. [7] monitored the stresses in the floating platform of a 245m-tall building in China. Osman and Malak [8] evaluated the structural behavior of the Makkah clock tower during the construction phase and for service conditions by instrumentation with strain gages. Glisic et al. [9] observed differential displacements throughout ten years of monitoring a high-rise building in Singapore. Gao et al. [10], monitored the strains of a 335m-tall building, also simulating its construction process through the Finite Element Method.

Considering the importance of the development of low-cost solutions easier to implement and use and that would allow the evaluation of structures during their construction phases and service conditions, this work investigates a proposed technique for monitoring strains in reinforced concrete (RC) structures. More specifically, strains in RC beams and columns were measured through a developed data system that is going to be shown in detail in the next sections.

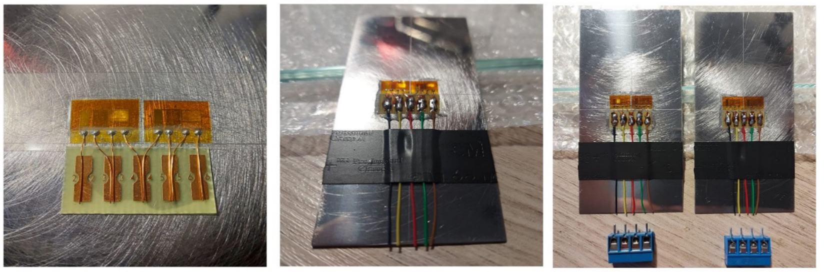
2 MATERIALS AND EXPERIMENTAL PROGRAM

This section presents the experimental program that was conducted in two phases for the master's thesis by Pes [11]. The first phase consisted of the development and calibration of the instruments at the Laboratory of Tests and Structural Models (LEME) of the Federal University of Rio Grande do Sul (UFRGS). The second phase applied the developed methodology in two columns of a residential building.

The development of a practical system was sought for the instrumentation of strain gages in the field, where handling and installation of sensors tend to be difficult, or even not feasible sometimes, to obtain the typical small strains of reinforced concrete columns. Since strain gages are quite sensitive sensors, requiring careful handling and time during the instrumentation process, steel plates measuring 50mm x 100mm x 0.5mm instrumented with strain gages were developed to speed up the instrumentation of two columns in a residential building under construction. Moreover, considering that commercial data systems tend to be quite costly and dependent on computers, complicating their use in certain harsh conditions in the field, a low-cost and more practical measurement device was developed for data acquisition.

2.1 Making of the instrumented plate

A steel plate with four strain gages arranged in a full Wheatstone bridge was made to facilitate the instrumentation of structures in the field. The strain gages used were of the *Excel Sensores* brand, a double 90º-rosette model with side-by-side PA-06-125TG-350LEN foils. Therefore, two of these sensors had to be applied on each plate to complete the full bridge connection. The fixation of the strain gages started by marking the central axes of the plates, followed by a surface regularization with sandpaper followed by cleansing with acetone. Next, the sensors were glued to the plates and their terminals soldered to data wires. Figure 1a shows the sensors already fixed to one steel plate. Figure 1b shows the wires soldered to the sensors, while Figure 1c shows blue connectors (KRE type) positioned for soldering to the data wires that are connected to the data system.



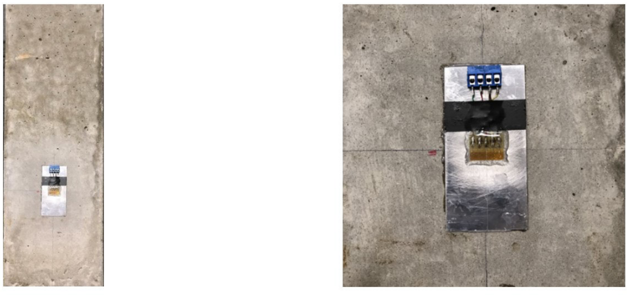
(a) Sensors glued to the plate (b) Soldered wires (c) Positioning connectors

Figure 1. Installation of strain gages on a steel plate.

After soldering the connectors to the wires, the sensitive areas were protected with epoxy resin. The plates were then ready to be used to monitor structural elements by simply, once again, regularizing the surfaces with sandpaper, cleansing them with acetone, and gluing them with epoxy adhesive. Figure 2 shows one finished plate.

Figure 2. Instrumented plate.

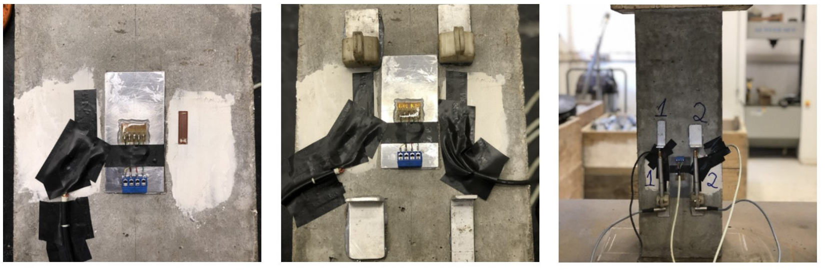
A simple compression test of a 205mm x 205mm x 600mm concrete column was conducted in the lab to evaluate the performance of the proposed method based on instrumented plates. The compressive strength of the concrete (f_{ck}) of 35 MPa was determined by testing two cylindrical specimens and finding an average compressive strength of 38.3 MPa. Kyowa concrete strain gages, type KFG-20-120-C1-CC, and displacement transducers (LVDTs) were used for the determination of the control strain readings of the column. Naturally, the longitudinal displacements measured with the LVDTs had to be converted to strain measurements. The instrumentation of the column started by installing one instrumented plate on its concrete substrate. A fast-drying *Poxipol* brand epoxy adhesive was used for that intent. Figure 3 shows a view of the instrumented plate already installed in the column.



(a) Plate installed in the column (b) Closer view, showing reference axes

Figure 3. Column with the instrumented plate.

Next, the process continued with the instrumentation of the column with two strain gages for concrete, each on each side of the plate. Figure 4a shows the column with the instrumented plate at the center and, on the right, a strain gage for concrete already in place, but not yet soldered to wires, neither protected with insulating tape. On the left, there is another strain gage for concrete, but already finished and ready for measurements. Next, the supports for the LVDTs were attached, as shown in Figure 4b. Figure 4c shows the concrete column with all the sensors ready for testing. In summary, at the end of the instrumentation of the column, there was an instrumented plate placed 20cm from the base of the column and, on each side, there was one LVDT and one protected strain gage for concrete.



(a) Strain gages installed (b) LVDT supports (c) Instrumented column

Figure 4. Instrumenting concrete column for testing of the proposed plate.

2.2 Development of the data system

The data system was developed using an Arduino UNO, an AD620 amplifier module, and an ADS1115 converter. The data obtained were differential voltage values between A+ and A- that were amplified and converted to a digital signal. A code for Arduino, which is presented in Figure 5, was employed to digitize the signal measurements.

ADS1115_4Channels | Arduino 1.8.10

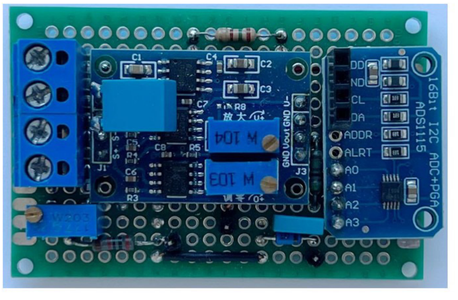
Arquivo Editar Sketch Ferramentas Ajuda

ADS1115_4Channels §

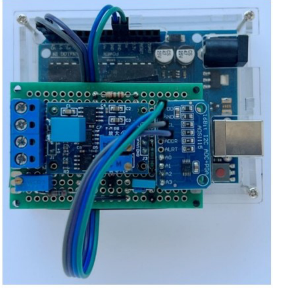
```
#include <Wire.h>
#include <Adafruit_ADS1015.h>

// Acquisition variables
   uint16_t CA, CB;     // data from ADS115
   char     line[14];             // formatted output
   long     t0, t;                // time from internal clock

// ADS1115 instance
   Adafruit_ADS1115  ads(0x48);  //

void setup(){

// Setup serial (only for debugging)
   Serial.begin(230400);
   while (!Serial){delay(100);}

// Setup ADS1115
   ads.begin();
   ads.setGain(GAIN_ONE);

   delay(1000);
   t0 = millis();
}

void loop(){
     if (Serial.available() > 0){
          String NS = Serial.readString();
          int    N  = NS.toInt();

          for (int i = 0; i < N; i++){

               CA = ads.readADC_Differential_0_1();
               CB = ads.readADC_Differential_2_3();


               t  = millis() - t0;

//             sprintf(line, "%91d %6d %6d %6d %6d\n",
//                                t,   CA, CB);
               sprintf(line, "%6d %6d\n", CA, CB);

               Serial.print(line);
               delay(200);
               }
          }
}
```

Figure 5. Arduino code (adapted from Rocha [12]).

Figure 6a shows the AD620 amplification board connected to the ADS1115 converter, where the potentiometer W104, connected in parallel with a 150-ohm resistor, adjusts the system gain, while the potentiometer W103 adjusts the reference voltage. In addition to these two potentiometers that compose the AD620 amplifier, another one was added to balance the Wheatstone bridge on the instrumented plate so that the initial measurement could be set to zero. Thus, the voltage would be set to a value near 1V so that, when the bridge voltage would vary due to strains, the voltage increases would remain within the system limits, i.e., from 0 to 4V. The system supply voltage was 5V, with a gain set to 330 times that value. It was also necessary to add a Schottky diode, allowing only positive current, to protect the ADS1115 input connector since the AD620 module output could result negative, at -5V, which would burn the converter. Finally, a code programming via Arduino IDE based on the differential mode was used to get a 16 bits resolution. Figure 6a shows the amplifier and the converter, while Figure 6b shows how they were connected to the Arduino UNO. Then, the system could be connected to a power supply, which could simply be a USB port of a notebook computer.



(a) AD620 amplifier module and ADS1115 converter

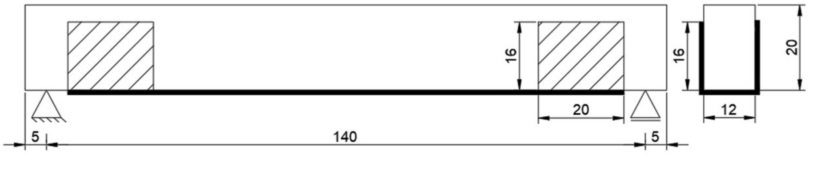


(b) Overall view of the system

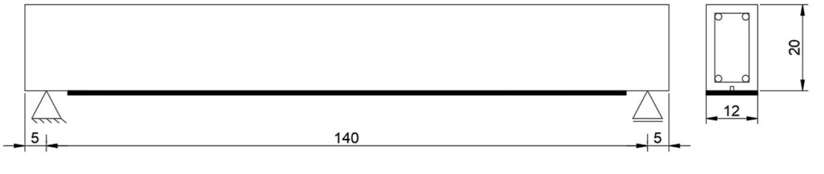
Figure 6. Data reading system.

2.3 Methodology for calibration

Four-point bending lab tests were carried out with the developed system to calibrate the instrumented plate. The reinforced concrete (RC) beams used in the tests had a characteristic compressive strength of 25 MPa, measured 200mm x 120mm x 1500mm, and were provided by a precast concrete company for Tirado's master's thesis [13], where different anchorage methods for Fiber Reinforced Polymers (FRP) were studied. Therefore, additionally, to the control beam specimen, composed only of reinforced concrete, other beams strengthened with PRF, i.e., carbon laminates, were also used in the tests. Additional details about these beams and their PRF strengthening systems, such as properties, dimensions, etc., can be found in that thesis [13]. The beams were identified as VT2, VA1, VA2, and VD1. The beam VT2 was made of reinforced concrete only. The beams VA1 and VA2 were characterized by presenting a strengthening system composed of PRF laminate on the bottom surface and PRF U-loops anchorages at their ends, as illustrated in Figure 7a. Beam VD1, as can be seen in Figure 7b, presented a PRF laminate also on the bottom surface, but with anchorage strengthening at the ends in grooves (EBRIG - Externally Bonded Reinforcement in Grooves).



(a) U-loop anchorages (beams VA1 and VA2)

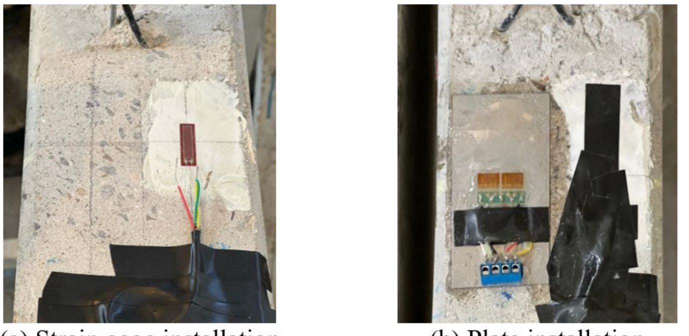


(b) EBRIG anchorages (beam VD1)

Figure 7. Strengthened beams tested – dimensions in cm.

Five cylindrical specimens were tested to find the average compressive strength of the concrete as 26.2 MPa. Additional three specimens were also tested to find the modulus of elasticity of the concrete as 25 GPa. Also, strain gages for concrete were applied on the top surfaces of the beams at midspan for strain measurements.

The instrumentation of the beams began with the installation of strain gages directly on the concrete surface, as shown in Figure 8a. The sensors used were of the Kyowa brand, type KFG-20-120-C1- CC. Then, the instrumented plates were fixed to the beams after regularization, cleansing, and marking of the concrete surfaces. A fast-drying *Poxipol* brand epoxy adhesive was then used to bond the plates to the beams. Figure 8 shows the installation steps for the strain gage and the instrumented plate, side by side, for the instrumentation of one of the beams tested.



(a) Strain gage installation (b) Plate installation

Figure 8. Sensors installed in a beam.

The surface of some of the beams presented pronounced irregularities during the instrumentation process and, thus, an additional procedure had to be carried out to level up the concrete surfaces with the plates by using a structural adhesive. Sikadur-32 with ASTM D-695 compressive strength of 60 MPa in 24 hours and 80 MPa in 7 days was therefore used for this intent. Figure 9 shows the sensors installed at the midspan of one of the beams.

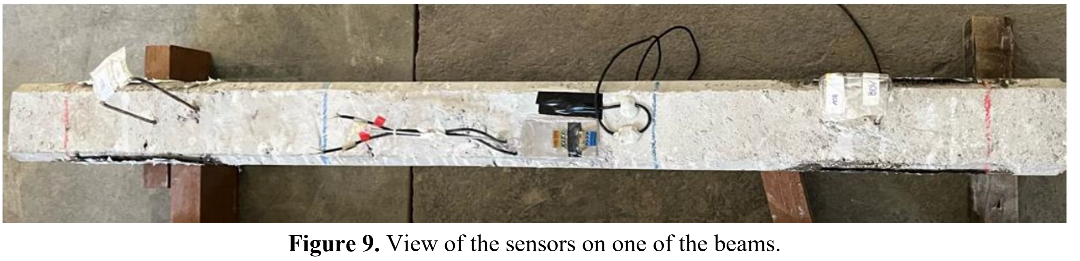


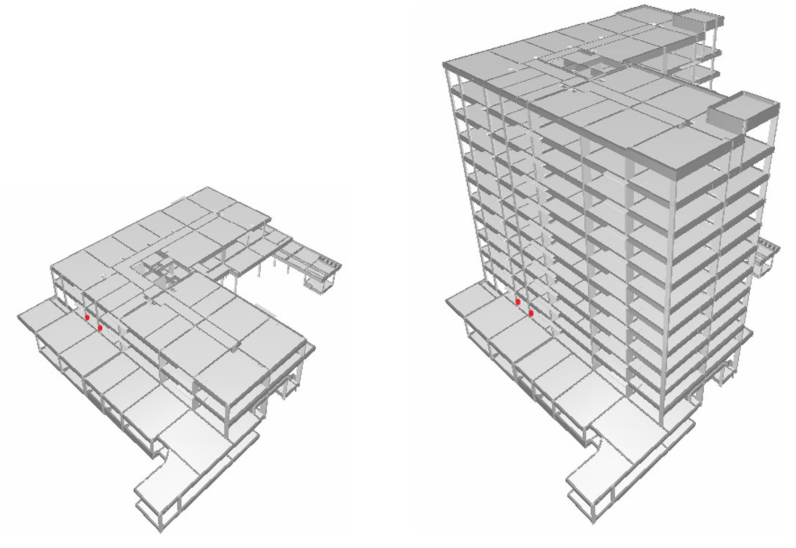
Figure 9. View of the sensors on one of the beams.

Four tests were conducted to measure the strains of the beams by applying loads until rupture in a universal hydraulic press available in the lab. The instrumented plate was connected to the data system developed in this work for all tests. The other sensors were connected to the data system usually used in the lab, which consisted of two modules of an HBM equipment *QuantumX* MX840B controlled through *Catman Easy* software. Figure 10 shows the test setup for the four-point bending tests, with the control sensors connected to the *QuantumX* system, on the left, and the built instrumented plate connected to the developed data system on the right.

2.4 Installation of the measurement system in a residential building

The software CAD/TQS was used to analyze the studied structure, a 38.45m-high residential building with 12 floors located in the city of Porto Alegre, RS, Brazil. The reinforced concrete structure was designed with a characteristic compressive strength of 35 MPa. Figure 11a shows the constructive stage of the structure, when the 3rd floor was finished, which was the stage chosen to install the instrumented plates on the two columns highlighted in red. Therefore, monitoring the structure considered the strains caused by the dead load of the structure and masonry walls from the 4th floor upwards. Figure 11b shows the entire structure when the monitoring was complete.

Figure 10. Test setup.



(a) 3D model of the structure up to the 3rd floor (b) Complete 3D model

Figure 11. 3D model highlighting the instrumented columns.

The instrumented plates were installed on the smaller faces of columns P26 and P31 on the first floor of the building, as highlighted in red in Figure 12. The cross-section of column P26 measured 25cm x 45cm, while column P31 was 25cm x 41cm.

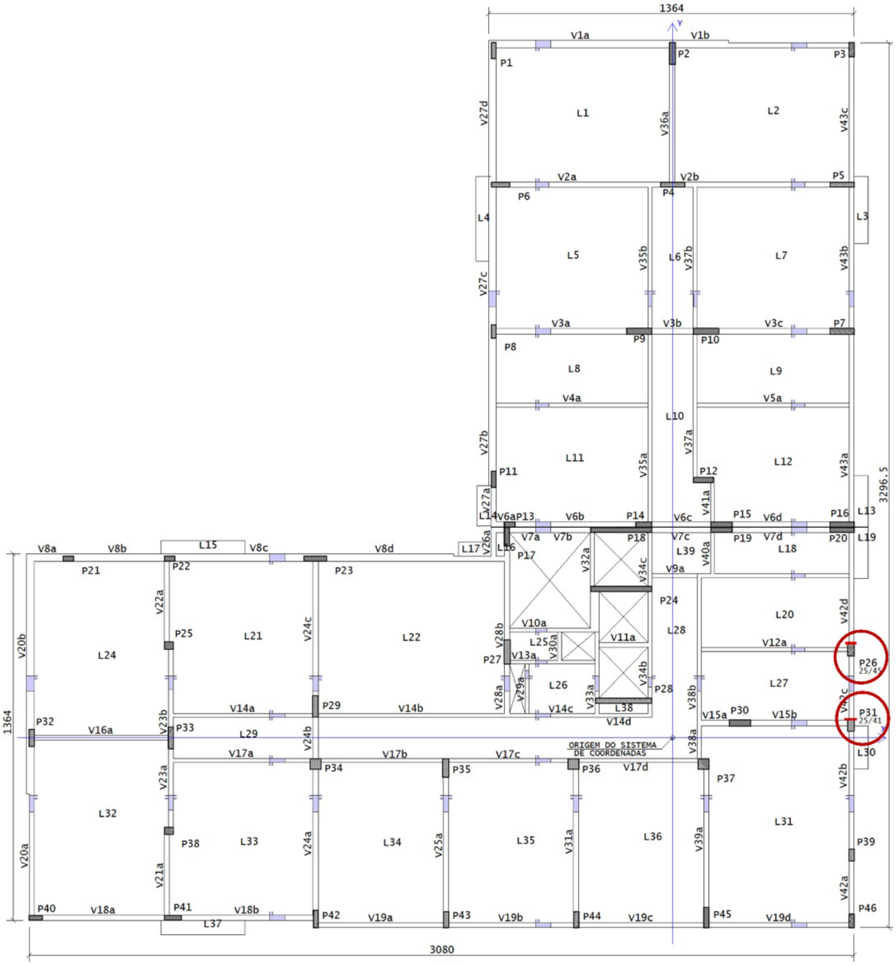


Figure 12. Indication of the two monitored columns (measures in cm).

Since at the ends of the columns, the stresses tend to be heavily nonuniform, the instrumented plates were installed at 1m from the floor. Moreover, the structural analysis pointed out that the moments at that position would be negligible and therefore not affect the measurements.

The installation of the instrumented plates on the columns followed the same procedure used in the lab. Figure 13a shows columns P26 and P31 with plates installed. Figure 13b shows the plates protected with a Styrofoam cover protection against impacts as well as sunlight. Figure 13c shows the proposed data system connected to one of the instrumented plates. As mentioned before, the measurements took place after connecting the system to a laptop computer.

(a) Plates installed (b) Protecting the plates (c) Data system connected

Figure 13. Installation of instrumented plates on two building columns.

2.5 Measurement System Costs

The cost involved to build one instrumented plate and to assemble one data system unit was a key factor to be considered during the development of this work. The cost to build one plate instrumented with strain gages amounted to approximately US$18.00, which was not much different from commercial alternatives since they use the same materials. However, its use was of fundamental importance for the objectives of this work, facilitating instrumentations of reinforced concrete elements in the field. Regarding the costs involved in the building of the data system, an amount of approximately US$54.00 was expended, generating a significant economic advantage when compared to available commercial alternatives. Additionally, the unit built was easy to manage and completely portable.

3 RESULTS AND DISCUSSIONS

The results are presented and discussed below in the same sequence used in the previous section, i.e., from the lab tests to the measurements taken in the field.

3.1 Lab test of the instrumented plate in RC column

A lab test in a reinforced concrete (RC) column subjected to simple compression was carried out to evaluate the behavior only of the instrumented plate. Concrete strain gages (SG1 and SG2), displacement transducers (LVDT 1 and LVDT 2), and the plate were connected to the lab data system, which was composed of two modules of the HBM *QuantumX* MX840B equipment. *Catman Easy* software was used to control the data measurements at a frequency of 2Hz. Loads were applied continuously up to 50% of the theoretical ultimate load in a hydraulic universal press. Figure 14 shows the instrumented column positioned in the press ready for testing and the wires connecting the sensors to the data system.

Figure 14. RC Column with sensors connected to the *QuantumX* MX840B data system.

Figure 15 shows stress vs. strain diagrams obtained from the sensors after finishing the lab test of the column. As can be seen, the response was quite similar among all the sensors and, therefore, the instrumented plate performed as expected, showing satisfactory behavior.

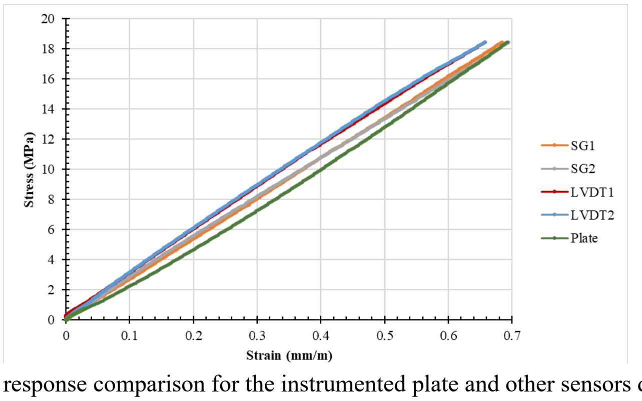


Figure 15. Stress vs. strain response comparison for the instrumented plate and other sensors during the column lab test.

3.2 Tests with the instrumented plate and the data system

The data system developed was used to determine the strains of four reinforced concrete (RC) beams in lab tests and the strains of two RC columns of a residential building under construction, as described previously. The lab tests of the beams were conducted to calibrate and validate the developed data system so that the measurements in the field could also be accomplished.

3.2.1 Strains of the RC beams

Four-point bending tests in four reinforced concrete (RC) beams were carried out with simultaneous readings from a strain gage (SG1) fixed directly on the concrete substrate of the beams and from the instrumented plate. The strain gage SG1 was controlled by the *QuantumX* MX840B data system available in the lab, while the instrumented plate was controlled by the data system developed in this work. The readings were taken at a 5Hz sampling rate, i.e., five readings per second. Figure 16a shows beam VT2 ready for testing in the press and Figure 16b shows its failure mode after the test was concluded.

(a) VT2 ready for testing

(b) Failure mode of VT2

Figure 16. Four-point bending test of beam VT2.

During the tests, it was quite important to verify whether the data system could be able to handle the very small values of strains that typically occur during the elastic response of this kind of test, since that would also be the case of the columns to be monitored in a building afterward, with strains that typically range from 0.018 mm/m to 0.14 mm/m. Figures 17 to 20 show the strains obtained with strain gage SG1 and with the instrumented plate for the four beams so that the responses obtained with the two data systems could be compared. Additionally, it is highlighted in the diagrams the elastic response of the beams, where can be seen that both methods corroborate one another. Also, it is observed a good post-cracking response.

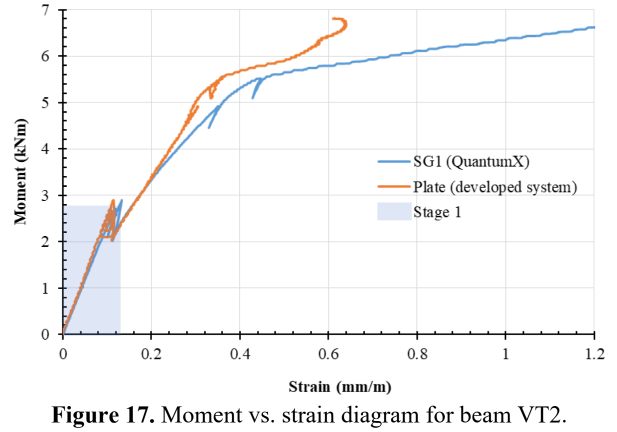


Figure 17. Moment vs. strain diagram for beam VT2.

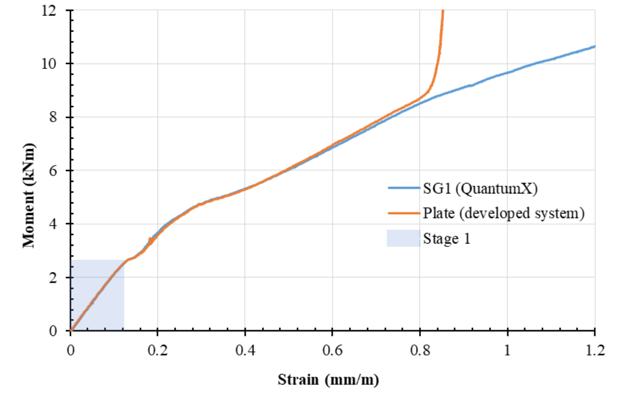


Figure 18. Moment vs. strain diagram for beam VA1.

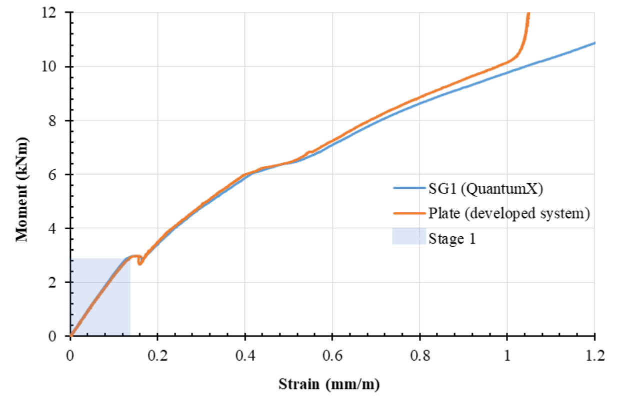


Figure 19. Moment vs. strain diagram for beam VA2.

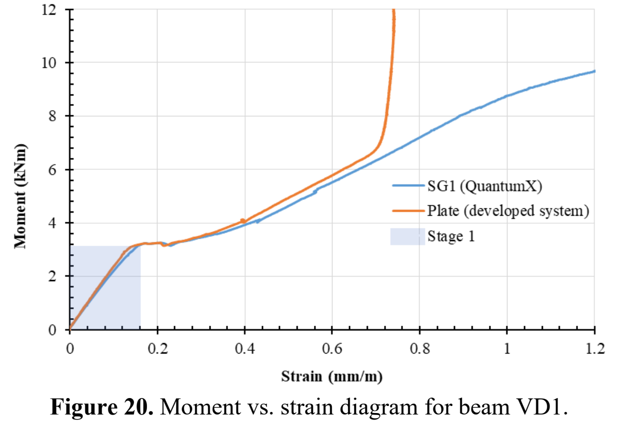


Figure 20. Moment vs. strain diagram for beam VD1.

Figure 21 shows the relationship between the measured values for the beams obtained with the developed data system with the values obtained with the *QuantumX* MX840B, which was available in the lab. The digital values of the proposed data system are represented using their LSB (Least Significant Bit) and, therefore, the diagrams obtained represent the calibration curves for each one of the beams. The strains obtained for these diagrams were limited to a maximum of 0.1 mm/m so that the calibration curves would result as linearly as possible. Moreover, the strains that were estimated for the building columns to be monitored afterward would be also near to this value.

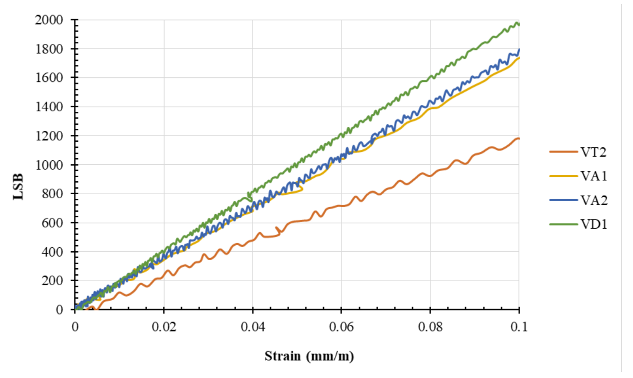


Figure 21. Calibration curves of the beams.

A single general calibration curve to transform the readings from the developed data system into strains was obtained by simply averaging the four curves through linear regression, with the result shown in Figure 22. More specifically, a maximum enveloping curve was found through a linear function for the response of beam VD1, while a minimum curve was obtained with a linear function for beam VT2. These curves served as calibration for the measurements of the columns that were conducted later in the field.

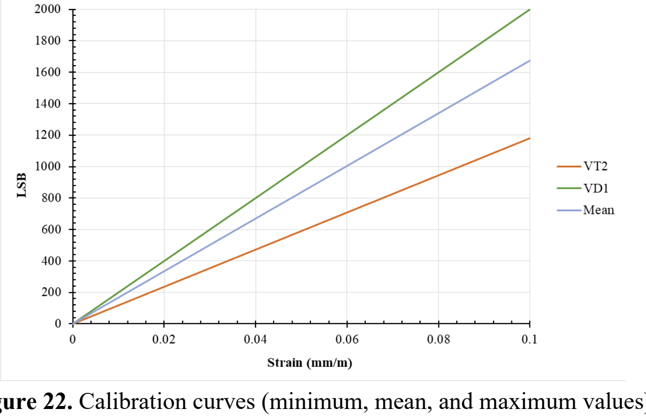


Figure 22. Calibration curves (minimum, mean, and maximum values).

A final verification had still to be conducted. It was necessary to check whether the calibration obtained with the beams involved the same range of stresses and strains typical to RC columns. Then, a stress vs. strain diagram was plotted with the responses given by the strain gages (PSG1 and PSG2) from the first lab test on an RC column and with the responses from the strain gages fixed on the concrete substrate of the beams. It was observed that, for strain levels of approximately 0.1 mm/m, the column and the beams responded similarly, as can be seen in Figure 23.

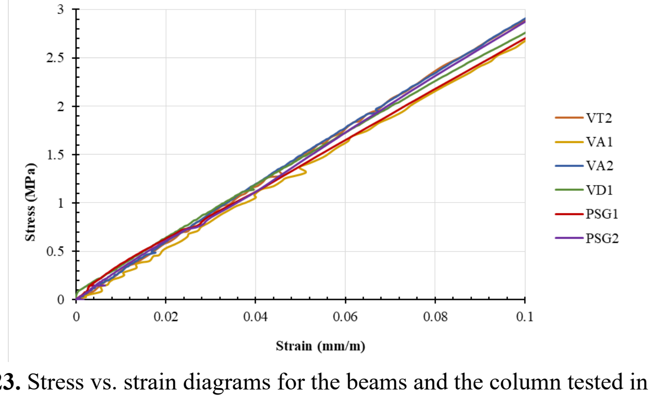


Figure 23. Stress vs. strain diagrams for the beams and the column tested in the lab.

3.2.2 Strains in the columns of a residential building

Measurements were conducted with instrumented plates fixed to columns P31 and P26 of the 30.52m-high residential building chosen for monitoring during a period of five months when the last floor was finished (Figure 24).

Figure 24. Monitored residential building under construction.

According to the estimated loads found with the software CAD/TQS, it can be observed in Tables 1 and 2 the load increments found for columns P31 and P26 along the addition of each floor. Therefore, after casting the eleventh floor, the total dead load that column P26 received was 520kN, while column P31 received 392kN. Considering the loads from the fourth to the ninth floors, masonry dead loads were also added to agree with the schedule followed in the construction. The strains found analytically were calculated considering a modulus of elasticity of 33 GPa and the loads for each floor are given in Tables 1 and 2. It is important to highlight that the loads considered in the numerical model were not factored in.

Table 1. Loads and strains of column P31.

Floor	Date	Numerical Model Load		Analytical Strain (mm/m)	Experimental Strain (mm/m)			Temp. (°C)
		Own weight (kN)	Own weight + Masonry (kN)		Maximum	Mean	Minimum	
4	07/04/22	49	57	0.017	0.016	0.013	0.011	19
5	07/20/22	98	106	0.31	0.029	0.024	0.020	20
6	08/05/22	147	155	0.046	0.043	0.036	0.030	22
7	08/23/22	196	204	0.060	0.047	0.039	0.032	23
8	09/08/22	245	253	0.075	0.037	0.031	0.026	16
9	09/26/22	294	302	0.089	0.066	0.056	0.046	17
10	10/10/22	343	-	0.101	0.087	0.073	0.060	21
11	10/26/22	392	-	0.116	0.102	0.085	0.070	26

Table 2. Loads and strains of column P26.

Floor	Date	Numerical Model Load		Analytical Strain (mm/m)	Experimental Strain (mm/m)			Temp. (°C)
		Own weight (kN)	Own weight + Masonry (kN)		Maximum	Mean	Minimum	
4	07/04/22	65	73	0.020	0.002	0.002	0.001	19
5	07/20/22	130	138	0.037	0.009	0.007	0.006	20
6	08/05/22	195	203	0.055	0.038	0.032	0.026	22
7	08/23/22	260	268	0.072	0.049	0.041	0.034	23
8	09/08/22	325	333	0.090	0.009	0.008	0.006	16
9	09/26/22	390	398	0.107	0.083	0.070	0.058	17
10	10/10/22	455	-	0.123	0.082	0.069	0.057	21
11	10/26/22	520	-	0.140	0.090	0.075	0.062	26

Figures 25 and 26 show the strains obtained analytically and those measured experimentally by converting the voltage readings from the monitoring with the previously shown calibration curves. The measurements took place right after the casting of the slabs on each floor. The measurements that occurred at the beginning of September were not considered in the diagrams because of a detected abnormal and erratic behavior probably due to the seasonal temperature variation that may have affected the data or the system's power supply at that time. It was also noticed throughout the measurements, that the notebook's USB power supply voltage varied from 4.5V and 4.9V, which may have affected the data acquisition. Nevertheless, the diagrams show the linearity of the acquired data, giving reliability to the measurement system developed.

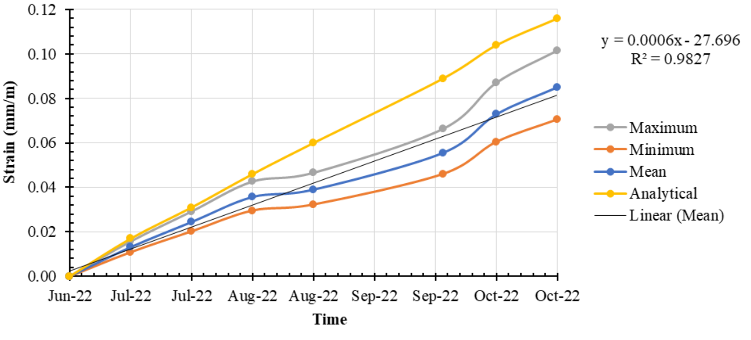


Figure 25. Strain vs. time diagram for column P31.

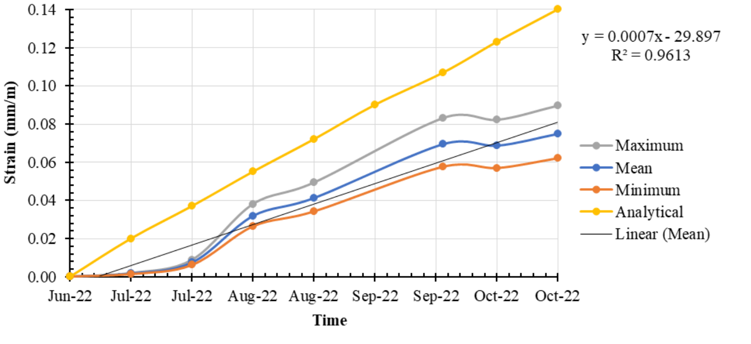


Figure 26. Strain vs. time diagram for column P26.

4 CONCLUSIONS

The lab test conducted in the reinforced concrete (RC) column with the developed instrumented plate behaved as expected, showing robustness and reliability in the measurements. As for the bending tests on RC beams with the developed data system, which was composed of the instrumented plate, the AD620 amplifier module, and the ADS1115 converter, a highly efficient response was obtained for strains of up to approximately 0.2 mm/m, for all beams. After that value, the readings for beam VT2 were lost probably due to a detachment of the instrumented plate from the concrete substrate or even a failure in the strain gages of the plate. Nevertheless, the measurements of beams VA1, VA2, and VD1 were quite satisfactory up to strains of about 0.8 mm/m, far exceeding the elastic limits of the beams. Regarding the strains measured in the columns of the building with the developed data system, it was verified that there was a response mostly compatible with the analytical estimates. However, more columns would have to be instrumented for a better evaluation of long-term monitoring. When evaluating the costs of building the proposed system, a significant economic advantage was found when compared to the costs of the available commercial data systems. Moreover, due to the risk of theft, misplacements, and damages typical of field measurements, developing reliable, low-cost systems becomes quite important. Finally, the next step in this investigation could be the use of low-cost sensors combined with nowadays available communication networks to allow remote monitoring of structures.

ACKNOWLEDGEMENTS

This study was financed by the Civil Engineering Graduate Program (PPGEC) of the Federal University of Rio Grande do Sul (UFRGS) and by the Brazilian governmental research institution (CNPq).

REFERENCES

[1] T. Andrade, “Tópicos sobre durabilidade do concreto,” in *Concreto: Ensino, Pesquisa e Realizações*, G. C. Isaia, Ed., São Paulo, Brazil: IBRACON, 2005, ch. 25, vol. 1, pp. 753–792.

[2] F. A. Torrico, “Análise teórica e experimental do comportamento de pilares esbeltos de concreto de alta resistência, considerando a ductilidade,” Ph.D. dissertation, Escola Eng. São Carlos, Univ. São Paulo, São Carlos, Brazil, 2010.

[3] A. Lorenzi, J. L. Campagnolo, and L. C. P. Silva Fo., “Application of artificial neural network for interpreting ultrasonic readings of concrete,” *Int. J. Mater. Prod. Technol.*, vol. 26, pp. 57–70, Feb. 2006.

[4] K. A. R. Nahum and D. R. C. Oliveira, “Monitoramento de pilares em edifícios altos de concreto armado,” *Rev. IBRACON Estrut. Mater.*, vol. 3, no. 2, pp. 179–194, Jun. 2010.

[5] L. O. Santos, “Monitoramento e ensaio de pontes,” in *VII Congr. Brasil. Pontes Estrut.*, Rio de Janeiro, Brazil, May 2014, pp. 1–14.

[6] A. C. Galante and R. F. Garcia, “Sistema de aquisição de dados de sensores de baixo custo baseado no Arduino,” in *Congr. Brasil. Agricult. Prec.*, São Pedro, Brazil, 2014, pp. 1–6.

[7] X. W. Ye, Y. Q. Ni, and Y. X. Xia, “Distributed strain sensor networks for in-construction monitoring and safety evaluation of a high-rise building,” *Int. J. Distrib. Sens. Netw.*, vol. 8, no. 9, pp. 685054, Sep. 2012, http://dx.doi.org/10.1155/2012/685054.

[8] A. Osman and C. Malak, “Evaluating the stresses in a supertall structure: field monitoring and numerical analysis,” in *SMAR 2017-4th Int. Conf. Smart Monit. Assess. Rehabil. Civil Struct.*, Zurich, Switzerland, Sep. 2017, pp. 1–8.

[9] B. Glisic, D. Inaudi, J. M. Lau, and C. C. Fong, “Ten-year monitoring of high-rise building columns using long-gage fiber optic sensors,” *Smart Mater. Struct.*, vol. 22, pp. 055030, Apr. 2013, http://dx.doi.org/10.1088/0964-1726/22/5/055030.

[10] F. Gao, H. Zhou, H. Liang, S. Weng, and H. Zhu, “Structural deformation monitoring and numerical simulation of a supertall building during construction stage,” *Eng. Struct.*, vol. 209, pp. 110033, Apr. 2020, http://dx.doi.org/10.1016/j.engstruct.2019.110033.

[11] F. P. Pes, “Investigação de uma técnica alternativa para monitoramento de deformações em estruturas de concreto armado,” Master thesis, Prog. Pós-Grad. Eng. Civil, Univ. Fed. Rio Grande do Sul, Porto Alegre, Brazil, 2022.

[12] M. M. Rocha. “PEC00144.” GitHub. https://github.com/mmaiarocha/PEC00144 (accessed Jun. 12, 2023).

[13] L. H. B. Tirado, “Estudo da ancoragem de polímeros reforçados com fibras (PRF) em vigas de concreto armado submetidos à esforços de flexão,” Master thesis, Prog. Pós-Grad. Eng. Civil, Univ. Fed. Rio Grande do Sul, Porto Alegre, Brazil, 2022.

Author contributions: FPP: conceptualization, writing, data curation, formal analysis, and methodology; MMR and PML: conceptualization, formal analysis, methodology and supervision.

Editors: Vladimir Haach, Guilherme Aris Parsekian.