1st Latin-American Workshop on Structural Health Monitoring
LATAM-SHM 2023
December, 5-8 2023

FBG BASED STRAIN MONITORING SYSTEM TO ASSESS LOAD DISTRIBUTION AND DIFFERENTIAL SETTLEMENTS IN A 33-STORY BUILDING: THE CONSTRUCTIVE LIFE CYCLE BEHAVIOR

Esteban Paniagua-García[a], Javier E. Penagos-Congóte[b] , Carlos A. Blandón-Uribe[b], Carlos A. Riveros-Jeréz[c], Jorge Aristizabal[d] and Julián Sierra-Pérez[a]

[a]Grupo de Investigación en Ingeniería Aeroespacial, Escuela de Ingenierías
Universidad Pontificia Bolivariana
Medellín, Antioquia, Colombia
e-mail: esteban.paniaguag@upb.edu.co,

[b] Departamento de Ingeniería Civil, Universidad EIA
Envigado, Antioquia, Colombia,

[c] Facultad de Ingeniería, Universidad de Antioquia
Medellín, Antioquia, Colombia,

[d] Área Ingenieros Consultores
Medellín, Antioquia, Colombia.

Key words: FBG sensor, Differential settlements, Civil structure, Reinforced concrete building

Abstract. Civil structures are prone to axial shortening, overloads, differential settlements, structural damage, and some other events that make the structure to behave different than expected. Those conditions need to be assessed to maintain the building safe, nevertheless, there are not affordable and reliable technologies to evaluate the structure integrity at any moment. In this work, a low-cost monitoring system for strain, loads, and differential settlements is implemented in a 33-story building structure, aiming to get knowledge on its behavior over the construction and operational life cycle. The work is addressed from the FBG-based sensor conception and its experimental and numerical validation, as well as it is discussed the installation method in the real construction environment. The sensor is mechanically and thermally sensitive, hence, it allows to account for strain variations from both thermal and mechanic sources. It is embedded in all 32 building columns before concrete pouring, and connected in a fiber optics network to a common acquisition site. The data collection during the construction period were carried with some minor interruptions. Data analysis techniques are used to evaluate each individual column and the whole structure. Load distributions and trends are identified and compared with the construction binnacle during that period, associating column strains with concrete pouring of any particular structural element and its location, as well as pointing changes not associated with any constructive load. The monitoring system presented some damages due to heavy constructive activities, however, it still allows to constantly monitor the structural behavior, which makes the building reliable in future events that may require structural analysis.

1 INTRODUCTION

Recent advancements in Structural Health Monitoring (SHM) primarily concentrate on bridges. This emphasis is attributed to the inherent flexibility of bridges and their lack of redundancy. Consequently, numerous field implementations have been conducted to investigate the effectiveness of various sensor configurations and strategies for modal identification and damage detection, as documented by Rizzo et al. [1]. It can be stated that these developments have undergone adequate calibration, demonstrating good performance. This success is partly attributed to the substantial ambient and forced excitation sources with large magnitudes that commonly affect bridge structures.

However, even in favorable conditions, it is challenging to differentiate between structural response variability due to environmental conditions and structural degradation [2]. Consequently, it is widely recognized that changes in elastic modulus values associated with varying temperatures, for example, are commonly ignored during field testing, leading to significant deviations in response prediction [3]. Therefore, economic constraints have motivated the development of low-cost robust systems that work in a synchronized manner to account for environmental disturbances always present during field measurement [4, 5].

In contrast to bridge structures, the implementation of vibration-based frameworks implies challenges for buildings because of their inherent redundancy and rigidity. Moreover, the magnitude of available excitation sources varies significantly, resulting in building responses primarily governed by static loading conditions. As a result, certain structural degradation processes in buildings are not detectable when relying on vibration-based frameworks, as noted in studies by Han et al. [3] and Sivasuriyan et al. [6].

The use of static-based frameworks in the structural assessment of buildings involves multiple-source information collected from different types of sensors and highly depends on the structural condition to be monitored. For instance, differential settlements in tall buildings constitute a long-term process, where the structural damage caused to the structural elements involved is first observed in non-structural elements. Although this affirmation significantly depends on the severity of the differential settlements experienced by the structure, monitoring the process is still challenging due to the influence of several parameters that are not properly understood.

In reinforced concrete buildings, the increment in vertical load involves additional challenges due to the differential shortening of columns. The differences in the stress level and associated vertical deformations highly depend on the level of vertical load affecting stress distribution in beams. It is desirable a methodology to account for all factors related to the creep shortening of columns. However, field measurements and experimental results report significant differences in the predicted values of vertical deformation in columns. Although improvements in prediction models have been reported, environmental factors remain the primary source of error and, therefore, it must be considered to predict column long-term deformation accurately [7, 8, 9].

Differential settlement in reinforced concrete buildings implies a long-term coupled mechanism involving soil settlements and the shortening or elongation of columns. Since this coupling process adversely affects the load transfer mechanism, monitoring the process becomes more challenging as the level of vertical load in columns increases. Therefore, static-based frameworks are best suited for differential settlement prediction if the number of instrumented columns allows comparative analysis of shortening/elongation measurements among all the instrumented elements.

A strain-based monitoring procedure for predicting differential settlements in buildings was schematically represented and thoroughly explained by [10]. The main idea behind this procedure is that columns suffering from differential settlements will elongate while neighboring columns will shorten. Based on the concept of local measurement in static-based methods, several studies have been conducted to study the performance of fiber optic sensors in civil infrastructure. However, properly accounting for degradation processes is still challenging, especially in concrete structures where creep and shrinkage are strongly related to column shortening. In addition, multi-year timescales are needed to monitor differential settlements [11].

Among the most widely used fiber optic sensors in SHM applications, Fiber Bragg Grating (FBG) sensors have shown advantages and have been successfully implemented in civil infrastructure [12, 13]. However, the importance of adequately protecting FBG sensors to withstand harsh construction conditions and aggressive environmental factors has been reported as one of the main issues of the technology.

In addition, inadequate handling during construction compromises the durability of FBG sensors, and the small size increases the possibility of fracture during installation [14]. Although structural elements or even small-scale structures have successfully been instrumented, practical implementations are greatly restricted due to the limitations accounting for all the parameters affecting the deformation process. As a result, there is a need for real-scale experiments to develop FBG monitoring systems that consider the construction variables during the system's installation and operation, allowing long-term measurements.

This paper presents the development of a FBG monitoring sensor to continuously assess the structural behavior of reinforced concrete buildings. The paper briefly discusses the procedure challenges faced for its installation in reinforced concrete building, from the beginning of the construction process. The main features of the monitoring system are its affordability, its compact design to withstand harsh construction conditions, and the possibility to measure temperature variations inside the instrumented columns. Practical implementations are presented, showing the system's performance .

2 SENSOR DEVELOPMENT

Directly incorporating sensors into a structure offers a unique solution for monitoring long-term variation processes. Embedded FBG sensors have been used to monitor the structural performance of newly constructed and existing structures. However, it has been reported the construction and environmental variables that adversely affect the performance of the deployed system [14, 15, 16].

Embedded FBG sensors in concrete structures have been tested in controlled environments to demonstrate their potential for damage detection in reinforced concrete structures [12, 17]. Also, practical applications are limited in the number of sensors due to economic constraints [10] or, in other cases, are mainly restricted to places where controlled experiments can be conducted [11]. The importance to protect the FBG sensor to withstand harsh construction practices has motivated the development of integrated FBG sensors.

The choice of material utilized in the embedding procedure is aimed at mitigating error measurements due to its potential for creep[18]. The installation phase means a significant challenge to integrated FBG sensors due to possible partial damage or failure, as reported by Capova et al. [19]. Thus, the embedding material needs special attention to withstand the embedding process as well as the construction process to ensure long-term operation [20, 21]. Practical implementations coincide in concluding the significant temperature influence on strain measurements [10, 22].

Experimental evidence has confirmed that strain measurements vary between bare and packaged Fiber Bragg Grating (FBG) sensors. Consequently, it is advisable to employ materials with negligible differences in stiffness to mitigate errors. However, it's important to note that this approach introduces a potential source of error related to mismatches that could arise from variations in concrete resistance in real-world applications.

As noted earlier, prolonged strain measurements in concrete columns are notably influenced by fluctuations in temperature. Furthermore, the phenomena of creep and shrinkage play a crucial role in strain measurements and are closely interconnected with temperature variations. Similar temperatures are expected inside and outside the concrete column, but there exists a lag in the temperature variation between these two locations, making internal temperature measurements highly recommended.

The transducer developed in this study consists of a 60 mm diameter cylinder that contains an epoxy block connected to a concrete block, adopting the two-FBG array that allows simultaneous measurement collection of temperature and strain via optical fiber. A representation of sensor placement is shown in Fig 1. The sensor is designed to be placed axis-wise near to the cross-section centroid of a column.

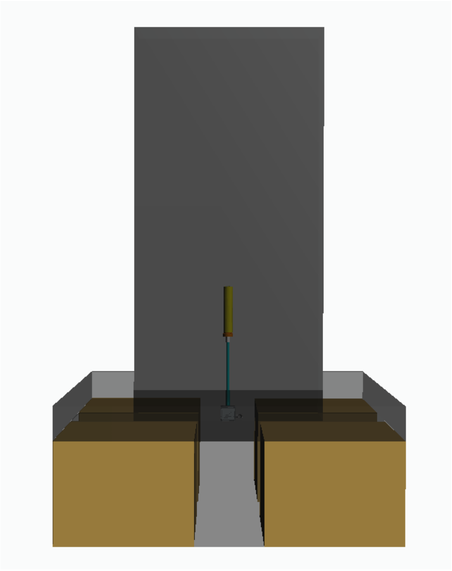

Figure 1: FBG packaged sensor and its installation scheme [23].

3 PRACTICAL IMPLEMENTATION

One of the main challenges on the use of monitoring systems in structures is the installation stage. Therefore, a pilot instrumentation program was carried out to install prototype sensors in the basement columns of a 33-story reinforced concrete building, during the construction stage. The structural design of the building consists of a system of columns and beams that compose moment-resistant frames. Fig 2 shows the building's column distribution in the basement floor.

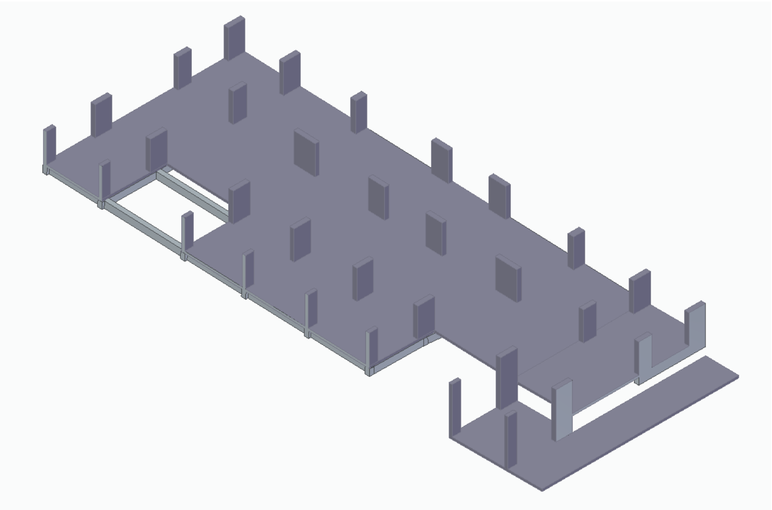

Figure 2: Building's ground level view.

The instrumentation premise consisted of installing sensors in all 32 columns at the basement without interrupting the construction process. Therefore, the sensor positioning had to be time efficient to guarantee a low installation cost.

The acquisition system consists of a sm130 optical sensing interrogator from Micron Optics, it has 4 optical channels that support a range of 1,510 to 1,590 *nm*. It means that in terms of sensing, the 32-columns structure is to be divided into four groups of eight columns. Hence, each sensing channel have a wide range between sensor wavelengths to guarantee lecture reliability.

The instrumentation network implemented in the building consists of 202 *m* of cabling that covers the 17.8 *m* by 41 *m* plant of the building and connects each sensor with the acquisition system. Each one of the 32 columns was instrumented with one sensor, which measured, in real-time, the state of elongation/shortening for the basement floor of each column at the location of the sensor.

The sensors could only be installed when the head of the foundation pile was cast and the overlapping steel connected to the steel reinforcement of each column. When the building contractor advanced in placing the reinforcing steel, the sensors had to be installed simultaneously.

Each sensor was introduced parallel to the longitudinal reinforcing steel of the element and was located as close as possible to the centroid of the geometric cross-section of each column. Additionally, in height, it was located at least forty centimeters from the upper face of the head of the pile to avoid measuring the local strain distortion effects at the base of the column. Each sensor was anchored and tied to the steel stirrups to ensure its stability, alignment, and position during the casting process in columns (Fig 3).

To protect the fiber optic cable and sensor connector, a 1/2 *in* conduit was installed on each sensor and connected to a 4 *in* × 4 *in* junction box. The box was entirely sealed to prevent the concrete paste to get inside it and the final formwork sheet was fixed in place.

After installing all sensors in the columns, they were connected to the central acquisition equipment using optic fiber cables routed through ducts. Adopting system's security measures was a critical activity, such as the protection of the cable and connector after first opening the junction box. A communication campaign was carried out to make the work staff aware of the system and its fragility despite it was always covered and protected by the pipe system. Nev-

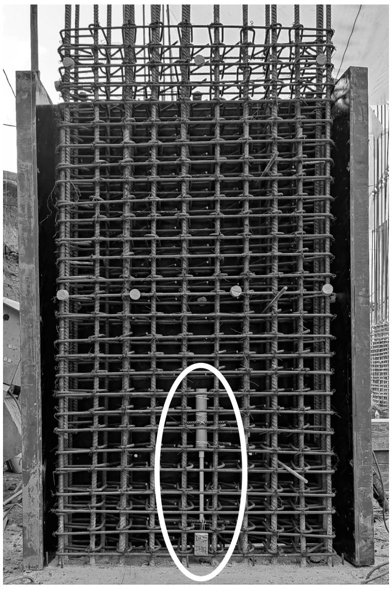

Figure 3: Installed sensor before and after concrete pouring.

ertheless, during the months that the instrumentation procedure lasted, there was significant traffic from the construction team around the sensors and along the connection ducts.

Additionally, construction operators used the column's surroundings as temporary storage of materials, equipment, and heavy tools. This situation significantly increased the risk of damage to the optical fiber cables of installed sensors. Despite the awareness and training of the personnel regarding sensors and the fragility of the optical fiber, during the process, some sensors were lost due to the construction operator's activities. The damage to the sensors revealed the importance of leaving visible marking of the ducts underground so the construction crew is aware of the cables.

4 RESULTS

After completing the connection process of the sensors to the acquisition equipment, several tests were carried out to evaluate the operation of each sensor and the stability of the data acquisition equipment.

The strain and temperature data captured by each sensor is collected by the system at $1Hz$ to be processed, as the strain had to be corrected to consider the effect of temperature change. This acquisition frequency is sensitive to capturing noise, hence, a rolling mean is applied to the data to reduce the noise. A thermal correction algorithm was implemented for each column taking into account variables such as the thermal delay time compared to the mechanical signal, the column size, and its location. These last two are significantly affected by the differential sun irradiation during the day depending on the building side.

Fig 4 depicts the raw lecture, thermal signal and corrected signal for a 1500 mm x 400 mm column, over seven days of continuous measurement. It is to be noted that the thermal response is delayed in time, and it is to be considered at the thermal correction process. The correction applied to the data resulted in strain (ϵ) variation smaller than 2.5 $\mu\epsilon$, which is related to significantly low axial loads. This is in accordance with the construction binnacle during that week, as no additional loads were applied to the column in that period of time.

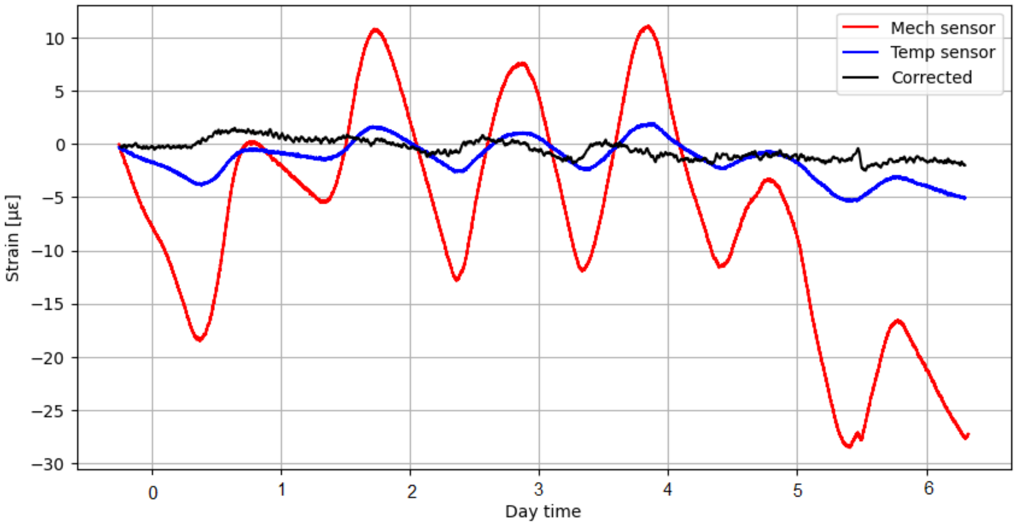

Figure 4: Raw data collected from one column during seven days.

Data obtained from a column is shown in Fig 5 for a period of 16 days after the acquisition system was installed at the site. The results show that the strain data, after thermally corrected, has a good potential of being useful to identify variation patterns that could describe normal structure functioning or possible anomalies. The data is being processed to attempt strain-force calibration for the different sensors and to identify load pattern variations during the construction process and during the service life of the building. Long-term measurements are being taken during the construction stage.

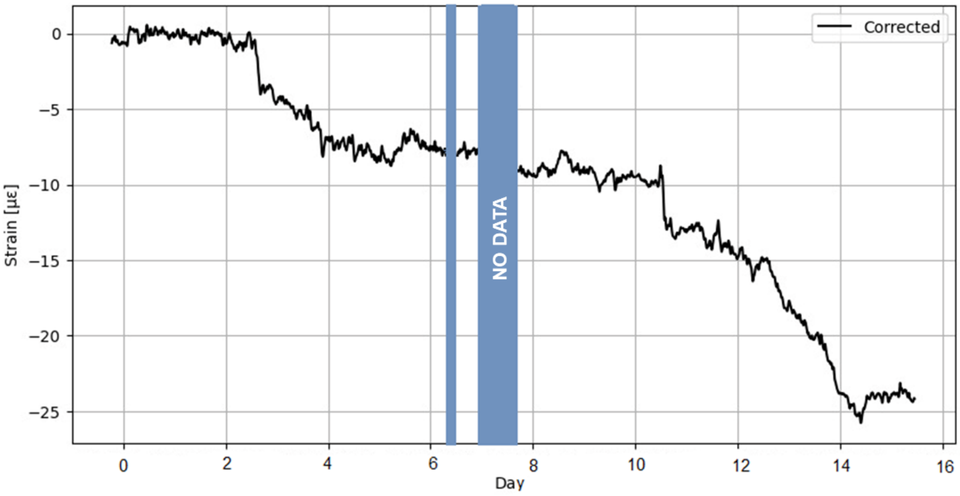

Figure 5: Strain variation for pilot column.

5 CONCLUSIONS

A low-cost Fiber Bragg Grating (FBG) sensor was designed to monitor variations in load distribution within the columns of reinforced concrete structures. The sensor was specifically deployed in the basement columns of a thirty-three-story building. To facilitate data collection, the sensors were interconnected with a central acquisition system using fiber optics communication cables. Continuous data acquisition commenced upon the completion of the first-floor columns during the overall construction process.

Strain and temperature readings from the sensor were consistently recorded once all sensors were interconnected. The assessment of the system revealed that, with the exception of some sensors that had to be disconnected, only two sensors incurred damage from the construction crew due to the substantial activity around the sensors and cabling ducts. This outcome demonstrates a high success rate, considering the delicate nature of fiber optic connections and the challenging conditions imposed on the sensors during the casting of the columns. However, an additional four sensors suffered damage in the later stages of construction, revealing the importance of adapting the protocol to ensure a durable marking of the ducts' location underground until the completion of the construction work.

REFERENCES

[1] P. Rizzo and A. Enshaeian, "Challenges in bridge health monitoring: A review," *Sensors*, vol. 21, p. 4336, jun 2021.

[2] E. Figueiredo and J. Brownjohn, "Three decades of statistical pattern recognition paradigm for SHM of bridges," *Structural Health Monitoring*, vol. 21, pp. 3018–3054, mar 2022.

[3] Q. Han, Q. Ma, J. Xu, and M. Liu, "Structural health monitoring research under varying temperature condition: a review," *Journal of Civil Structural Health Monitoring*, vol. 11, pp. 149–173, oct 2020.

[4] S. Komarizadehasl, F. Lozano, J. A. Lozano-Galant, G. Ramos, and J. Turmo, "Low-cost wireless structural health monitoring of bridges," *Sensors*, vol. 22, p. 5725, jul 2022.

[5] R. Lu and J. Judd, "Field-deployable fiber optic sensor system for structural health monitoring of steel girder highway bridges," *Infrastructures*, vol. 7, p. 16, jan 2022.

[6] A. Sivasuriyan, D. S. Vijayan, W. Górski, Ł. Wodzyński, M. D. Vaverková, and E. Koda, "Practical implementation of structural health monitoring in multi-story buildings," *Buildings*, vol. 11, p. 263, jun 2021.

[7] P. P. Torres, E. Ghorbel, and G. Wardeh, "Towards a new analytical creep model for cement-based concrete using design standards approach," *Buildings*, vol. 11, p. 155, apr 2021.

[8] C. M. Blanc, A. O. Sánchez, and I. F. Navarro, "Analytical characterisation of axial shortening due to creep of reinforced concrete columns in tall buildings," *Engineering Structures*, vol. 228, p. 111584, feb 2021.

[9] C. Zhang, Z. Zhu, S. Zhu, Z. He, D. Zhu, J. Liu, and S. Meng, "Nonlinear creep damage constitutive model of concrete based on fractional calculus theory," *Materials*, vol. 12, p. 1505, may 2019.

[10] B. Glisic, D. Inaudi, J. M. Lau, and C. C. Fong, "Ten-year monitoring of high-rise building columns using long-gauge fiber optic sensors," *Smart Materials and Structures*, vol. 22, p. 055030, apr 2013.

[11] M. Pereira and B. Glisic, "A hybrid approach for prediction of long-term behavior of concrete structures," *Journal of Civil Structural Health Monitoring*, vol. 12, pp. 891–911, jun 2022.

[12] A. Amaya and J. Sierra-Pérez, "Toward a structural health monitoring methodology for concrete structures under dynamic loads using embedded FBG sensors and strain mapping techniques," *Sensors*, vol. 22, p. 4569, jun 2022.

[13] L. Hong-Nan, R. Liang, J. Zi-Guang, Y. Ting-Hua, and L. Dong-Sheng, "State-of-the-art in structural health monitoring of large and complex civil infrastructures," *Journal of Civil Structural Health Monitoring*, vol. 6, pp. 3–16, apr 2015.

[14] A. Rahmatian, T. B. Roy, A. Mofidi, A. Bagchi, and M. Nokken, "Long-term performance monitoring of GFRP-reinforced concrete beams using sensor-mounted supplemental rebars under harsh environmental conditions," *Journal of Civil Structural Health Monitoring*, vol. 9, pp. 293–306, apr 2019.

[15] X. Feng, Y. Han, Z. Wang, and H. Liu, "Structural performance monitoring of buried pipelines using distributed fiber optic sensors," *Journal of Civil Structural Health Monitoring*, vol. 8, pp. 509–516, jun 2018.

[16] M. A. Caponero, D. Dell'Erba, and C. Kropp, "Use of fibre optic sensors for structural monitoring of temporary emergency reinforcements of the church s. maria delle grazie in accumoli," *Journal of Civil Structural Health Monitoring*, vol. 9, pp. 353–360, may 2019.

[17] J. Yang, P. Hou, C. Yang, and N. Yang, "Study of a long-gauge FBG strain sensor with enhanced sensitivity and its application in structural monitoring," *Sensors*, vol. 21, p. 3492, may 2021.

[18] H. Yang, Y. Huang, Z. Zhou, and J. Ou, "Long-term performance of packaged fiber bragg grating sensors for strain monitoring inside creep medium," *International Journal of Smart and Nano Materials*, vol. 13, pp. 42–63, jan 2022.

[19] K. Čápová, L. Velebil, and J. Včelák, "Laboratory and in-situ testing of integrated FBG sensors for SHM for concrete and timber structures," *Sensors*, vol. 20, p. 1661, mar 2020.

[20] R. H. Scott, S. Chikermane, M. Vidakovic, B. McKinley, T. Sun, P. Banerji, and K. T. Grattan, "Development of low cost packaged fibre optic sensors for use in reinforced concrete structures," *Measurement*, vol. 135, pp. 617–624, mar 2019.

[21] V. Matveenko, N. Kosheleva, and G. Serovaev, “Strain measurements by FBG-based sensors embedded in various materials manufactured by different technological processes,” *Procedia Structural Integrity*, vol. 37, pp. 508–516, 2022.

[22] N. de Battista, R. Harvey, and N. Cheal, “Distributed fiber optic sensor system to measure the progressive axial shortening of a high-rise building during construction,” in *IABSE Symposium - Engineering the Future*, 2017.

[23] L. Montoya, “Con monitoreo de salud estructural buscan disminuir riesgo de edificios “enfermos”.” Revista Universitas Científica ISSN: 2462-8662 (online), 2022.