Development of a fibre optic-based patch sensor for monitoring structures

Yago DE SOUZA GOMES[1], **Mohamed SAIDI**[1] **Anna LUSHNIKOVA**[1], **Olivier PLE**[1]

[1] *Université Savoie Mont Blanc, CNRS,* ***UMR CNRS 5271****, INES, LOCIE, Chambéry, 73000, France*

RESUME The number of accidents involving the collapse of civil engineering structures, in addition to the cost of maintenance in the construction industry, has drawn the attention of researchers and builders over the last few years. Therefore, much attention is given to the importance of improving periodic measurements, analysis, and diagnostics of operating structures' integrity, frequently referred to as structural health monitoring (SHM). These monitoring activities were first operated by visual inspections. These methodologies have evolved with the emergence of new tools and devices that are leading SHM towards techniques of remote monitoring based on data transmission networks featuring alarming systems. Nowadays, fiber optic sensors represent a promising solution over existing sensors because of their unique features, such as the versatility for installation and to measure different parameters as well as their immunity to electromagnetic interference. In this project, part of the SENTMI Region project (PSPC Region 2020), an innovative 2D patch carrying weaved optical fibers is being developed in a partnership made by Leon Grosse, Inouid, Brochier Technologies, and the laboratory LOCIE from the University "Savoie Mont Blanc". Each of these partners adds up essential know-how in structural diagnostics in buildings and the construction of civil engineering structures, sensor devices, and optical fibers. The technology is being tested in concrete structures at the laboratory level using methods that include 2D digital image correlation (DIC). The preliminary main results are presented in this paper. Its performance has raised significant prospects over the possibilities for detecting the presence of water, temperature change, and cracks in structures. In particular, the optical sensor is able to detect crack openings of 0.04 mm. The potential applications at the real scale and their respective challenges are also discussed with the goal of pushing the limits of structural health monitoring.

Mots-clefs structural health monitoring, optical fiber sensors, crack detection, digital image correlation

I. INTRODUCTION

Civil engineering is one of the most valuable industries in the world, costing billions every year. A considerable part of this figure is spent on maintenance. In 2021, the Public Works activity reached a turnover of €46.1 billion in France. Maintenance is responsible for €19.4 billion, thus 42.1% of this value (FNTP 2022).

The structures are often subjected to several events that accelerate the process of deterioration, such as earthquakes, rains, hurricanes, mistakes in design or execution, etc. For instance, in France, there are about 250,000 bridges, and according to a report on bridge safety submitted on June 15, 2022, the Senate's Regional Planning and Sustainable Development Committee estimates that between 30,000 and 35,000 structures are in poor structural condition. The Senate initiated this work of assessing bridges' and engineering structures' integrity in France after the Morandi bridge's collapse in Genoa, Italy. In this context, €120 million per year is set to be dedicated to the maintenance of France's national road network (Vie Publique 2022).

For this reason, much importance has been given to the strategies for continuous or regular measurement and analysis of key structural and environmental parameters under operating conditions, for warning of abnormal states or accidents at early stages, also called Structural Health Monitoring (SHM) (Villalba et al., 2013). Traditionally, the assessment of the condition of civil engineering infrastructures was carried out through periodical visual inspections by trained professionals, (Barrias, et al., 2018) which can lead to mistakes due to unprecise and inaccurate diagnostics that depend on each engineer's background among other factors. Nowadays, SHM is going towards techniques in which a great variety of parameters are automatically and remotely measured and treated based on data transmission networks featuring alarming systems that will help in decision-making.

In this context, the SENTMI project (PSPC Region 2020) aims to contribute to the evolution of monitoring techniques and devices, specifically in one of the most recent and promising solutions of this matter: the optical fibers sensors. The SENTMI project is a collaboration between the companies Léon Grosse, Inouid, and Brochier Technologies, and the laboratory LOCIE from Université Savoie Mont-Blanc. Together, these companies combine expertise in sensor development, optical fiber development, and civil engineering construction. The laboratory LOCIE has expertise in structural and energetic diagnostics for buildings.

This paper presents preliminary results on the development of a monitoring technology optical fiber-based for concrete infrastructures as a solution that brings not only reliable measurements of strain, temperature variation, and water presence, but also an easy application, efficient data storage, and warning system.

II. METHODS AND EXPERIMENTAL INVESTIGATIONS

The patches were developed by Brochier technologies, specialized in the weaving of optical fibers, in many different configurations regarding the fibers' diameter, density, and length, among other parameters. They can be, both, embedded in concrete samples or glued on their surface, and connected at two ends by a light source and a detector. The detector, developed by Inouid, uses the AS7261 sensor from ams OSRAM, which is a chromatic white color sensor that provides XYZ color coordinates consistent with the CIE color space as well as the Near Infra-Red spectrum. This detector features wireless communication with computers where an application, also developed by Inouid, allows the management of acquisition and integration time, as well as exporting data in xlsx files. The sensor technology cannot be further explained as patents are pending.

In the LOCIE laboratory, concrete samples were manufactured using cement "performat CEM I 52,5N CE PM-CP2 NF" and prismatic steel formworks of size 10 cm x 10 cm x 40 cm (Figure 1). A mixture of sand (0-6 mm), gravel (4-10 mm), cement performat and water was used. Notch 2cm high, to ensure the location of the crack propagation, is done in the sample. For that, a prismatic piece of wood is placed at the middle point of the samples' length before casting the concrete. A maximum bending moment should be mobilized to open a crack, consequently, three-point bending tests are done. The loading is applied in the middle part of the sample to the upright of the notch. Another specimen size of 15cm x 15 cm x 60 cm, with a different granulometric curve for the concrete, has been built and will be tested, as soon as possible, to analyse size effects.

FIGURE 1. SENTMI sample featuring a notch in the middle, after removing the formwork.

A. Crack detection and measurement

To calibrate the measurement of cracks, the method used consists in using on-surfaces patches and submitting samples to a three-point bending test in which a crack would appear at the region of interest (starting from the notch) where the SENTMI patch was placed. During the test, the crack is followed and measured by a camera through 2D digital image correlation, and this measured crack width is compared to the signal coming from the sensor. The samples were symmetrically placed on two parallel supports and bent via a compression die displacement driven, with a 0.3mm/min rate.

To compare the signal acquired from the SENTMI patch with the phenomenon of crack opening and evolution, the correlation between images was used, with a model NIKON D7000 and 60 mm focal length. This way, the evolution of the crack in the three-point bending test can be followed by setting a reference distance.

Following the recommendations of the DIC Good Practices Guide, from the International Digital Image Correlation Society (2017), in a 2D – DIC, the sample is assumed to be planar and to remain planar throughout the test, and to keep a constant stand-off distance. A speckle pattern was prepared with the application of a background white color painting throughout the region of interest (ROI) and then the application of roughly circular black color speckles at random locations for contrast with the white background.

The frame rate must be commensurate with the highest expected rate of variation of the quantity of interest (QOI). If the displacement between frames is too large, DIC algorithms may fail to locate the subset position in the formed images (International Digital Image Correlation Society, 2018). 5 seconds rate was chosen for these tests, with 1/500 sec exposure time. The images are sized 4928 x 3264 pixels and 300 x 300 dpi resolution. These images were treated using the software GOM Correlate 2018, from where the distances between points were exported in xlsx files.

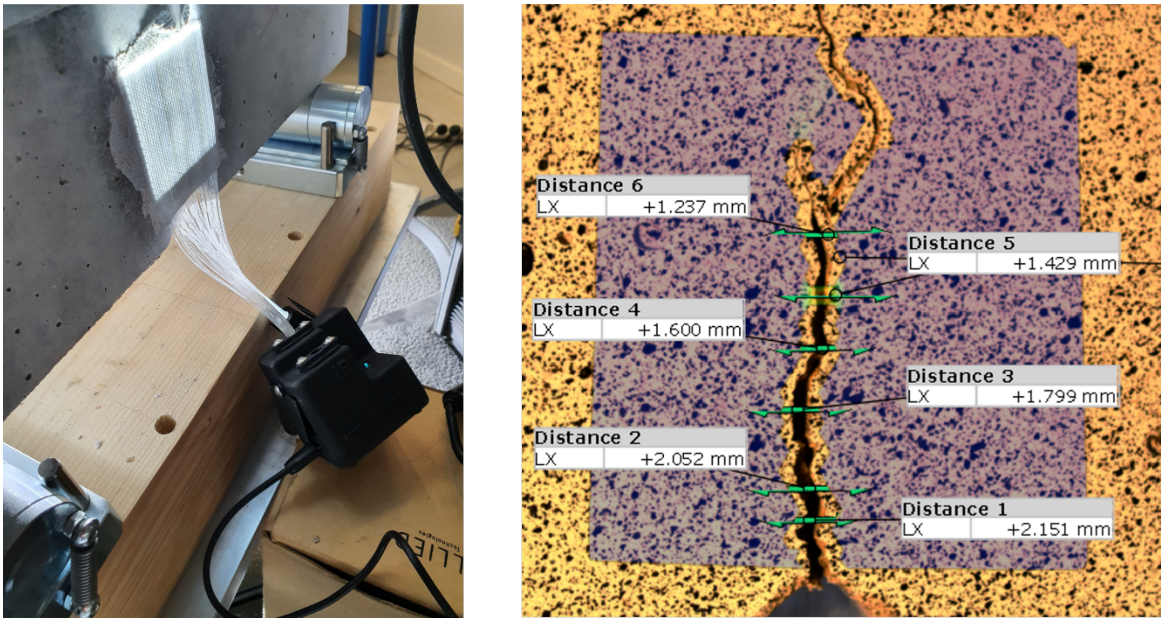


FIGURE 2. Left: SENTMI sensor; Right: 2D DIC performed at GOM Correlate 2018 Software.

B. Water detection

The SENTMI sensor is sensible to the water presence. As the technology relies on the optical phenomenon of the propagation of rays and accounts for the environment around the fibers, it reacts to the change of the medium because of the difference in the direction of propagation of light in water and air.

Embedded and on-surface patches are used in this method where samples are placed in a prismatic box and, during the test, the water level rises and falls linearly while the detector acquires the signal from the patch so the level of water can be compared to the signal. When measured in a dry condition and then submitted to the rise of water level, the sensor responded by lowering the intensity of light, indicating that fewer rays would be reaching the detector.

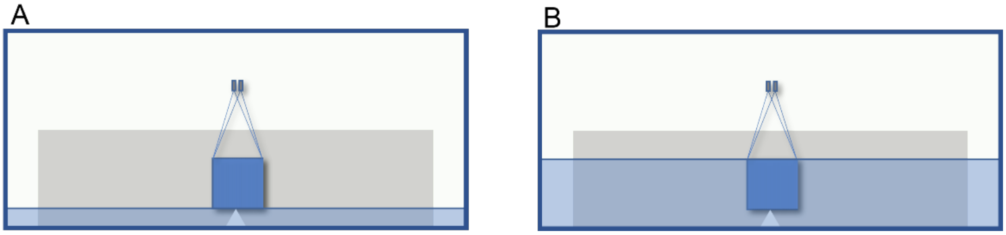


FIGURE 3. Scheme of the test for water detection. A and B represent the moment when the water first interact with the patch and the moment when the patch is totally submersed.

C. Temperature response

For the experimental campaign that aims to monitor temperature variations in concrete structures, the patch was subjected to the application of a temperature gradient within the concrete sample. The embedded patch was positioned having its plane perpendicular to the horizontal plane, thus, perpendicular to the temperature gradient, with the fibers oriented vertically, 2 cm from the surface of the sample on which an infrared lamp was pointing at. The lamp heated the sample at one side while the patch connectors access was positioned at the top surface (Figure 4).

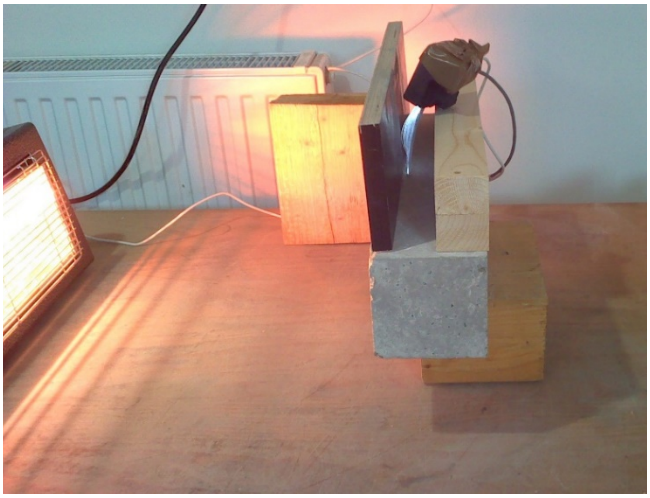


FIGURE 4. Setup for testing the patch response to a temperature gradient normal to the patch surface.

To measure the temperature, a thermal camera from FLIR Systems AB, model E60bx 1.0 was used (Figure 5). It is important to note that the camera is measuring the temperature at the surface level of the sample. Therefore, the distance from the patch to the measured spot on the external surface of the concrete structure must be taken into account.

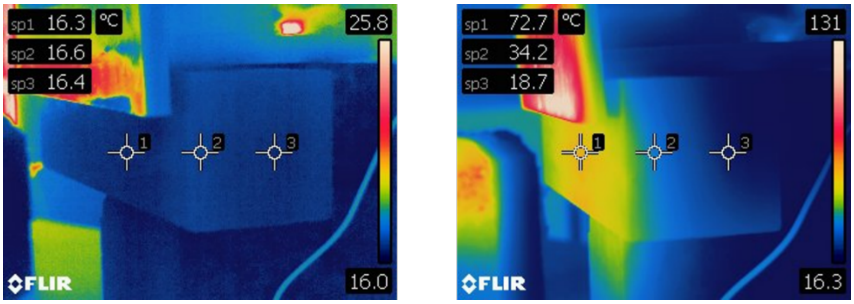


FIGURE 5. Photos by FLIR E60bx 1.0 thermal camera.

III. EXPERIMENTAL RESULTS

A. Crack detection and measurement

The patch measurements of light intensity over time, as well as the crack width measurements from the digital image correlation, after exported, were treated using python, to allow the calibration of the sensor. A linear coefficient of correlation is used for this matter, and it corresponds to the sensor resolution. Then, the light intensity of the sensor is calibrated in function of the opening crack and compare to DIC (Figure 6). Python codes are responsible for finding the best coefficient by systematically trying different options and calculating the error between the two curves. This post-treatment considers the signal of when the crack starts as the value of reference (zero) and then works with the increments of the signal (Figure 6 show results on three tests).

The evolution of the patch configurations performed by Brochier Technologies and optimized on LOCIE concrete samples at Savoie Mont Blanc University allowed the SENTMI sensor to reach interesting results on sensor resolution. The configurations have been narrowed, and the best configurations are reaching a sensor resolution in a 0.04 mm order or higher. For this case, the sensor resolution is defined as the amount of crack width increment necessary to change in one unit the light intensity.

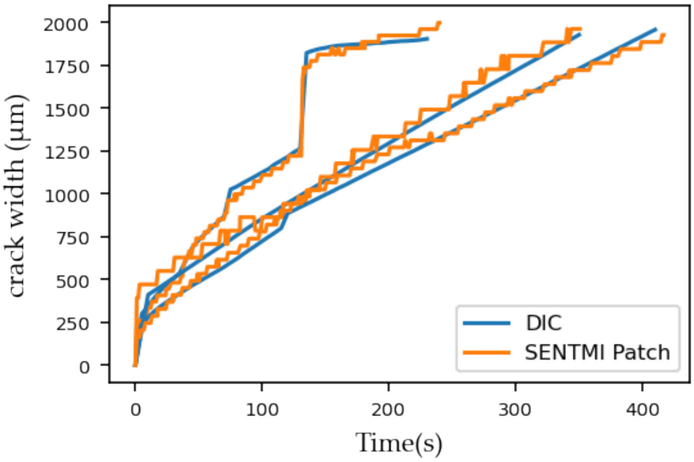


FIGURE 6. Main results of crack measurement. The blue line represents the crack width measured with 2D Digital Image Correlation (DIC), while the orange line represents the SENTMI patch signal.

Figure 6 is comparing the real crack width evolution (in blue) measured by Digital Image Correlation, and the signal acquired by the patch after post treatment (in orange). It is possible to analyse how the SENTMI patch signal follows the crack start and crack evolution by noting that the curves are almost overlapping each other. The crack width curve starts at the moment that the crack appears, that is, with a quick increase, and then this crack evolves slowly and almost constantly but with eventual abrupt increases due to the heterogeneity of the material (rupture of aggregates can cause non-linearities). It is interesting to see how the patch manages to follow these "jumps" in addition to smoother evolutions.

B. Water detection

Signals collected from the patch are compared with the water level between the patch's bottom and top. As the patches used are 5cm high, the blue curve (Figures 7) presents the water level at the patch that is embedded or glued on the sample. To facilitate water infiltration in samples featuring embedded patches, the tests, for those samples, were performed after creating cracks in the sample.

Points A and B represent the moment when the water first interacts with the patch and the moment when the patch is totally submersed, respectively.

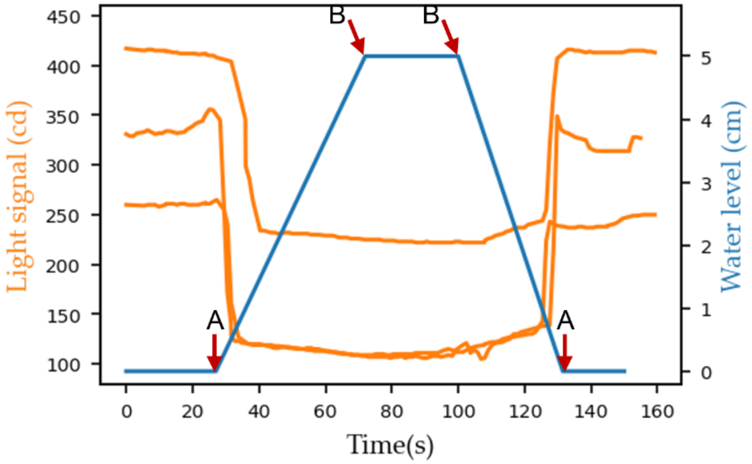


FIGURE 7. **Reaction of patches glued on the samples' surface in function of the water level with three different ranges of light signal**

When the water level rises and reaches the bottom of the patch (point A) the sensor responds by lowering its intensity of light. This behavior is the same for embedded patches and on-surface patches. However, they present different behaviors in the second part of the test, which is the lowering of the water level. The on-surface patches (Figure 7) turn to increase back their light signal when the water level gets lower than the bottom of the patch again (point A), while the water is exiting the box. The embedded patches (Figure 8), on the other hand, keep decreasing their signal, toward stabilization, indicating to be sensible to concrete residual water.

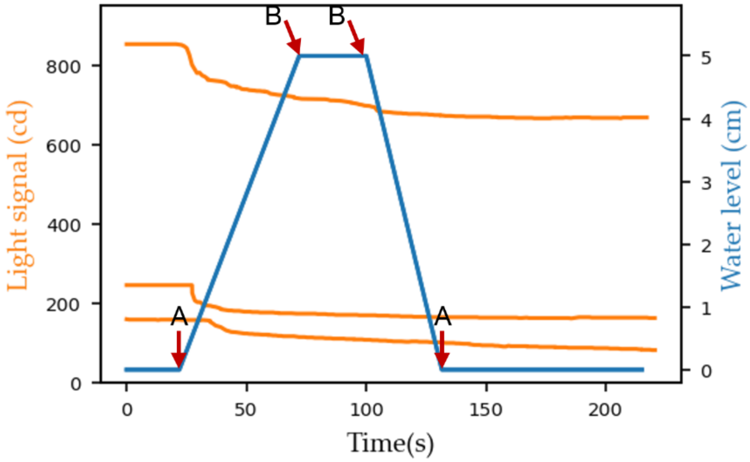
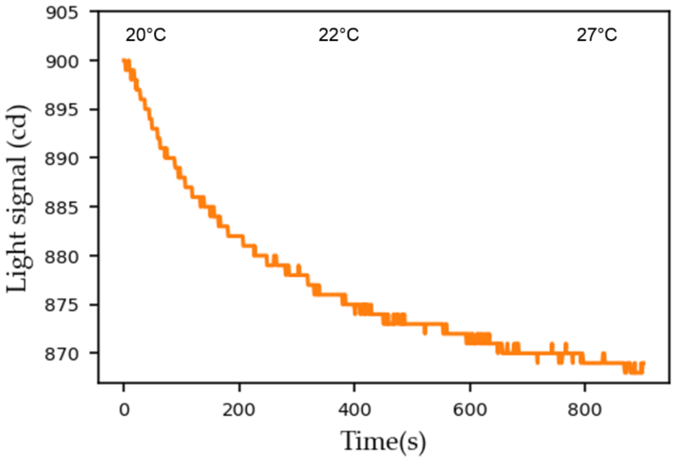
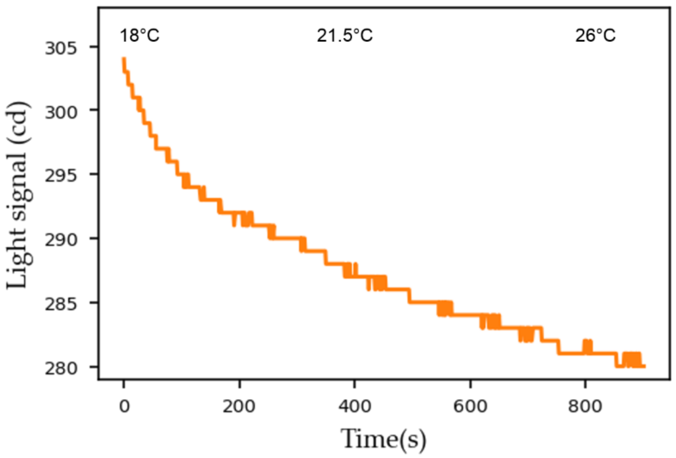


FIGURE 8. **Reaction of embedded patches in function of the water level, with three different ranges of light signal.**

C. Temperature response

The signal of the patch is obtained and stored for 15 minutes while the infrared lamp is heating one side of the concrete sample. The patches embedded in the tested samples have shown to be sensitive to the variation of temperature and responded to the applied temperature gradient by lowering the light signal by 3% to 24% after an increment raging between 7 °C and 11 °C on the sample's surface temperature.





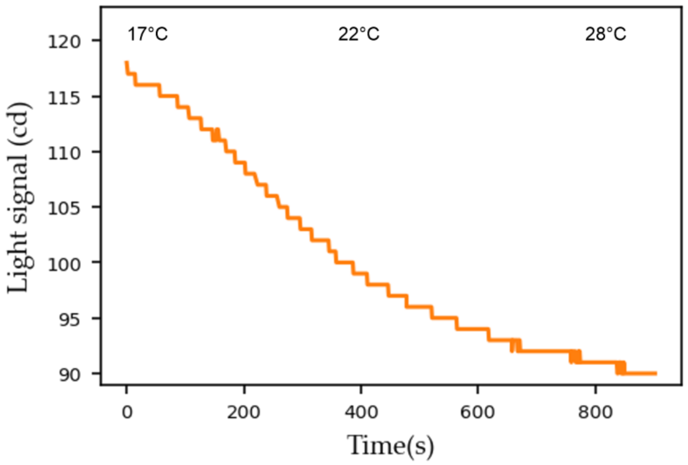


FIGURE 9. Response of SENTMI patches to the applied temperature gradient, with three different ranges of light signal.

IV. DISCUSSION

The response of the patch to an approximately linear heating is, however, not linear. Thus, it rises the importance of an individual pre-calibration of each patch, so that a measurement can be reliable. In other words, one can only determine the temperature within the concrete structure if the curve of temperature related to the spectrum color coordinates for that specific patch is well known.

The difference in the behaviors of embedded patches and on-surface patches when detecting water presence indicates that the on-surface patches seem to be responding to the medium in the box but outside the sample, because of the quick signal increase when the water exits the box. The embedded patches, however, seem to have a response more linked to the degree of saturation of the sample's material, as the signal tends to maintain its value while the sample's interior is still wet.

For water detection and temperature variation detection, the embedded patch seems to be more appropriate in case of capillary rise and heat transfer within the structure, while for crack measurement, this approach (embedded) has a drawback which is the choice of placement. Like for other local sensors, one should know where the crack will appear, which is easy to ensure in the laboratory but not that easy in a real construction, since in the moment of construction, based on the calculated distribution of stresses, we can only predict the most probable locations for cracks. Another concern that is being studied regarding the transition from the laboratory to the construction site is the standardization of the gluing method of patches for cracks detection. For example, the method of implementation must be simple and systematic to avoid risks of error.

V. CONCLUSION

This paper presented the main preliminary results of an innovative fiber optic-based sensor for structural health monitoring, targeting the sensing of water presence and temperature variation within the structures, as well as the measurement of crack width. The sensor, which features a 2D patch carrying weaved optical fibers, is applied on concrete structures at the laboratory level, where different methods are proposed for the study of the response of the patch to different phenomena. Preliminary results are promising, and tests are now in parallel with real-scale tests, as in real constructions structures.

It was shown that the sensor with on-surface patches can follow the crack start and crack evolution in concrete, with a sensor resolution that reaches 0.04 mm. The results of the sensor when submitted to an increase in water level revealed a significant sensibility to the presence of water, with a decrease of signal between 20% and 50% for the embedded patches when the dry concrete becomes saturated. The sensibility of the patch to the change in temperature was also verified, with a decrease of signal between 3% and 24% of the signal after an increasing between 7 °C and 11 °C the samples' temperature.

ACKNOWLEDGEMENT

This work is performed thanks to the financial support of La Région AURA (PSPC 2020), as well as the dedication and teamwork of the participating members Leon Grosse, Inouid, Brochier Technologies, and the laboratory LOCIE from the University "Savoie Mont Blanc, that have been investing their financial and intellectual resources to create a useful tool in the construction industry for a more safe and efficient monitoring system.

REFERENCES

Vie publique (2022). Sécurité des ponts : la dégradation se poursuit malgré les mises en garde du Sénat. Viewed January 10, 2023. https://www.vie-publique.fr/en-bref/285508-securite-des-ponts-une-degradation-qui-se-poursuit

FNTP - Fédération Nationale des Travaux Publics (2022). Les Travaux Publics en chiffres. Viewed January 9, 2023. https://www.fntp.fr/data/secteur-en-chiffres/france/activite

Barrias, A., Rodriguez, G., ... Villalba, S., 2018. Application of distributed optical fiber sensors for the health monitoring of two real structures in Barcelona. *Structure and Infrastructure Engineering* 14, 967–985. doi:10.1080/15732479.2018.1438479

Villalba, S., Casas, J.R., (2013). Application of optical fiber distributed sensing to health monitoring of concrete structures. *Mechanical Systems and Signal Processing* 39, 441–451. doi:10.1016/j.ymssp.2012.01.027

ams OSRAM (2016). AS7261 XYZ Chromatic White Color Sensor + NIR with Electronic and Smart Interface. Viewed 2022. https://ams.com/ams-start

iDICs – International Digital Image Correlation Society (2017). A Good Practices Guide for Digital Image Correlation. Viewed April, 2022. https://idics.org/guide/