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► **To cite this version:**

Alexandra Labrousse-Ansiaux, Sylvain Magne, Veronique Marty-Dewynter, Stéphane Rougeault, Jonathan Boussoir, et al. Fiber Bragg grating extensometers for reliable health monitoring applications in civil engineering. Proceedings of SPIE, the International Society for Optical Engineering, 5502, SPIE, pp.72, 2004, 10.1117/12.566515 . cea-04186582

HAL Id: cea-04186582

<https://cea.hal.science/cea-04186582>

Submitted on 31 Aug 2023

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Fiber Bragg grating extensometers for reliable health monitoring applications in civil engineering

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ABSTRACT

This paper describes the laboratory tests and field trial on the Saint-Jean bridge (Bordeaux, France) of both FBG extensometers (long and short-gage) and associated instrumentation, in the context of its industrial transfer.

Keywords: Health Monitoring, Civil Engineering, Extensometer, Optical Fiber Sensor, Fiber Bragg Grating

1. INTRODUCTION

Most civil engineering structures have been built in the 50's and 60's. They suffer from climatic conditions, corrosion, traffic, high loading, etc. In Europe, National Authorities and the European Commission promote Health Monitoring concepts, instrumentation of existing structures and help in the design of new durable structures with higher performance. The structure monitoring concept aims at assessing the structural integrity to anticipate degradation and failure modes and to optimize maintenance planning for further structural intervention and rehabilitation operations. Health monitoring is also a question of security and cost savings for both maintenance and equipments. Besides the classical instrumentation (LVDTs, strain gauges and vibrating wires), many civil engineering structures have already been equipped by Optical Fiber Sensors, mainly Fiber Bragg Gratings (FBG) and multimode fiber extensometers (white light interferometry) [1]. The FBG technology is useful in many industrial sectors, from the composite industry, transportation means, to electro-nuclear applications [2]. Civil Engineering [1] is surely one of the industrial sectors of the greatest interest because of immediate market share, regarding the wide potential application area (historical monuments, box-girder bridges, cable-stayed bridges, dams, large buildings, tunnels, ...) [3]. Besides simple health monitoring (micro-cracking, impact detection, post-seismic damage evaluation) applications are numerous: in-situ concrete curing process monitoring and pre-stress determination, repair using epoxy-bonded carbon fiber reinforced panels, steel corrosion detection, load rating, Weight-In-Motion and vehicle counting identification.

The Optical Measurement Laboratory of the CEA-List is actively working in the field of Fiber Bragg Grating (FBG) sensors and systems since 1992 [4]. As the principle of these sensors relies on spectral signatures, they enable wavelength multiplexing, the measurements are independent from intensity fluctuations, and they do not need any recalibration procedures after any disconnections. Furthermore, their cabling procedure is quite simple since FBG sensors may be connected in series along a single fiber or in star network if needed. An optical switch is often incorporated into the acquisition unit to address several lines under a parallel arrangement, multiplexed in a time-sharing approach. Such a matrix sensor network is able to gather all the relevant information about the structural behavior of large structures. In

the context of health monitoring, the CEA-List has also made some field tests in the framework of European projects (STABILOS, COSMUS) [4], as well as in previous national programs (Electricité de France), notably on large concrete samples to test the sensor reliability of the strain transduction under compressive conditions. The European Community and the French ministry of Industry have also supported a non-exclusive industrial transfer of FBG extensometers and measurement system technology for civil engineering applications to a French SME, Hydrolog.

2. FIBER BRAGG GRATING CEA-PROPRIETARY INSTRUMENTATION

It is a multi-parameter sensor system gathering not only temperature and strain data but also displacement, force, pressure, humidity, angle,... if an appropriate transducing mechanism is used. The fiber optic sensing technology presents many assets for the civil engineering sector: quasi real-time and remote sensor operation, ease of cabling, data sorting and acquisition, electromagnetic and lightning immunity. Moreover they can be fixed onto or embedded into concrete structures while casting, or incorporated into reinforcing elements such as steel cables or tendons [3].

The CEA has patented a long-length gage extensometer (LGE) design in which the fiber sensors are pultruded into a composite bar [5]. Longgage extensometers made by the pultrusion process are several meter long. The composite material used is glass-epoxy (50% glass, 50% epoxy). The experimental value of its equivalent Young modulus was found about $40 \text{ GPa} \pm 1 \text{ GPa}$, compatible with concrete of similar stiffness. This extensometer concept is particularly useful to provide a wide strain analysis over a large structure span, and follow very large crack openings or displacements. A dedicated test bench has been built specifically to check the strain-to-force behavior of the extensometer. It is based on a steel box terminated by two anchors. A load sensor is placed at the interface between anchor and box edge to measure the axial force, then correlated to the wavelength shift in order to get the strain response vs load (see Fig. 1, a 1.2 m long LGE in its test bench). Alternatively, Short-Gage Extensometers (SGEs, see Fig.2) have been developed, which can work either under compression or under traction up to 0.25 % in strain. They are useful to complete the strain information by providing a more localized information. The SGEs are composed of a 20-cm long central steel bar (protected by a plastic sleeve) which is used for transduction and two anchors which design depends on whether the extensometer is embedded into or fixed onto concrete. Both kinds of extensometer need to be compensated by a temperature sensor of similar constitution, integrated in the same optical line as the FBG extensometers one. The temperature compensation procedure is automatically performed by subtracting the wavelength shift of each extensometer to that of its associated temperature sensor.

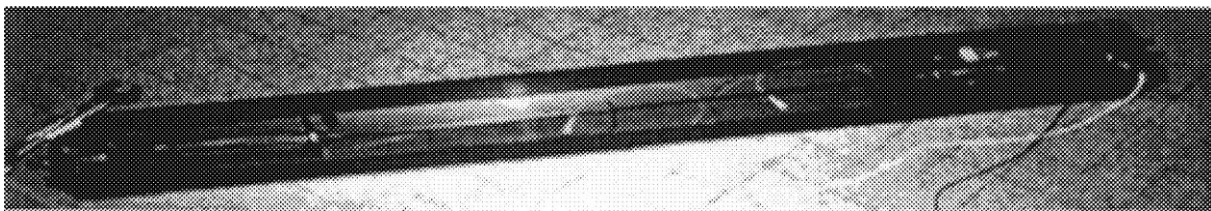


Fig. 1: Long-Gage Extensometer (LGE). Courtesy of CEA

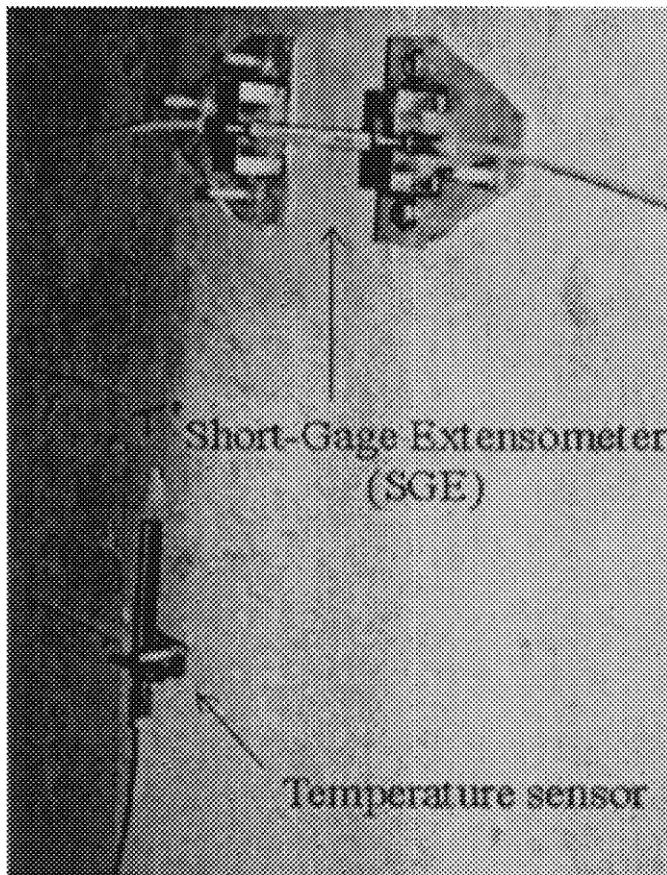


Fig. 2: Short-Gage Extensometer (SGE) and its temperature sensor for self-compensation. Courtesy of CEA

The optoelectronic readout system developed by the CEA has already been described in [6]. For civil engineering applications the sample frequency is 0.5 Hz (for one given optical line). It changes to 0.125 Hz for each line (among four parallel lines). This system is very easy to handle by civil engineers, as there is no need for them to be familiar with optics. Furthermore, it is perfectly suitable for long-term health monitoring of large civil engineering structures because it may address typically 32 to 64 sensors, or more according to the optical switch capability.

3. EXPERIMENTAL RESULTS OF SGE STRAIN MEASUREMENTS ON CONCRETE SAMPLES

The main features of an extensometer are to make sure that the strain experienced by the fiber is conformable to the strain of the structure and the low intrusivity. Finally, it must be robust and withstand rough civil engineering handling. In this context, concrete cylindrical samples instrumented with 2 SGEs were tested in compressive conditions [7]. The compression and traction resistance of the concrete cylinders ($\varnothing = 25$ cm and 50 cm high) were respectively measured as 49.6 MPa and 4.14 MPa. The Young modulus of the concrete was 37.9 GPa. A crescent charge in compression from 0 N to 1 200 kN (± 1.5 %) by step of 100 kN was applied to the samples. Figure 3 shows the measured strain for each sensor versus the calculated strain $\epsilon = F / S.E$, where F is the press charge, E the Young modulus and S the surface of the cylinder.

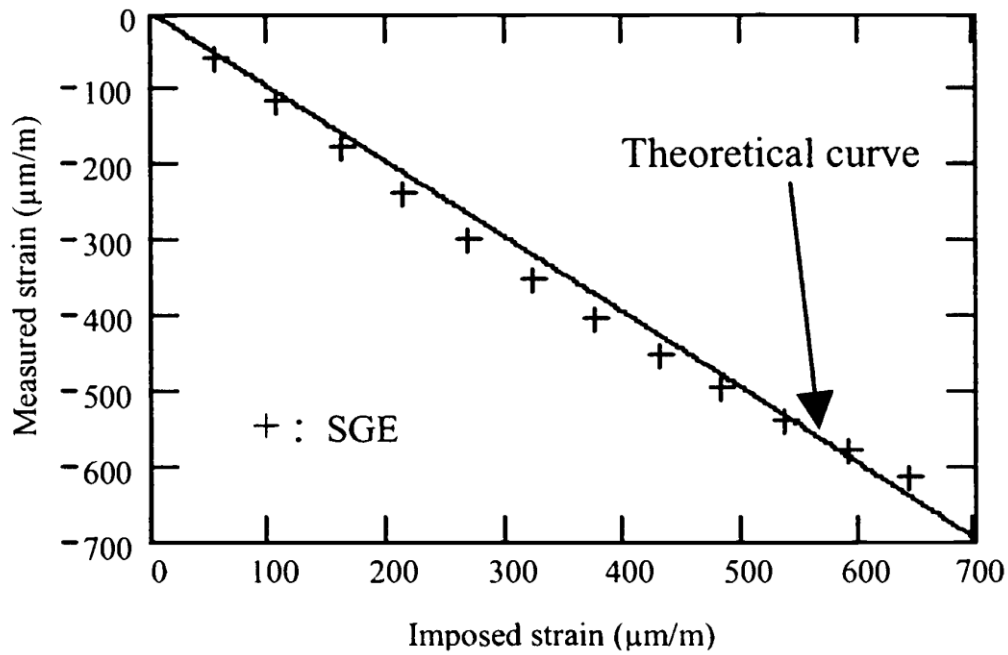


Fig. 3: Measured strain versus calculated strain for the 2 SGEs (concrete sample)

The SGEs response shows a good linearity in compression from 0 $\mu\text{m/m}$ to -700 $\mu\text{m/m}$ and is close to the theoretical curve (see Fig. 3). A cyclic loading test was performed in order to check the robustness of the SGEs and to verify the proper return-to-zero (RTZ) behavior. Ten loading cycles were applied to the samples from 0 N to 1000 kN with a fast RTZ. The RTZ point is reached with a precision of 1 % Full Scale and the strain measurement shows good repeatability (see Fig. 4).

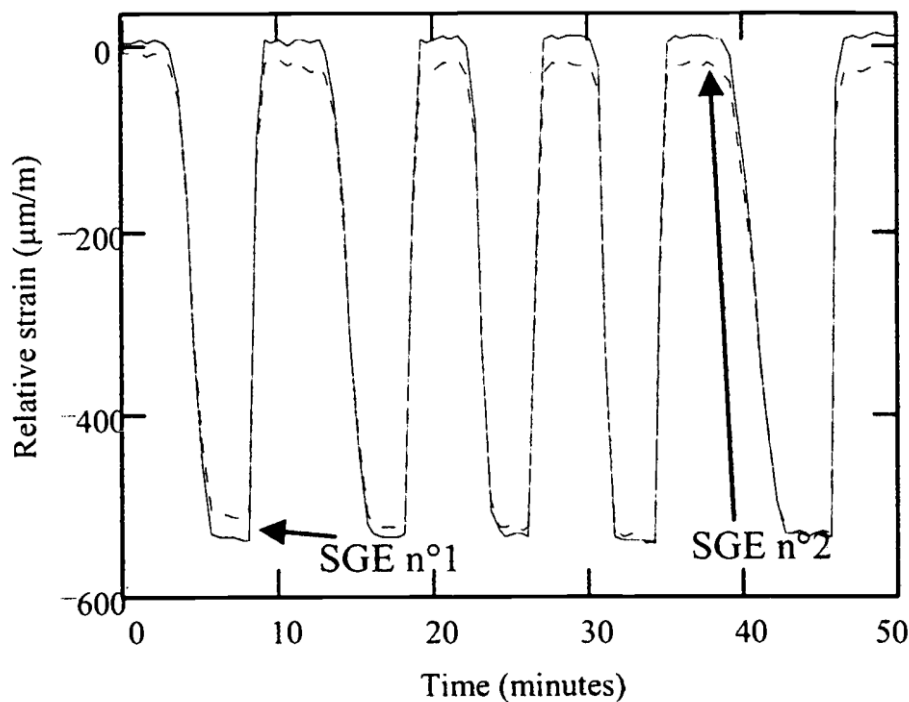


Fig. 4: Kinetics of load and unload tests for the 2 SGEs (concrete sample)

4. FIELD TEST OF FBG EXTENSOMETERS INSTRUMENTATION IN THE ST-JEAN BRIDGE (FRANCE)

The Saint-Jean bridge is a 474-meter long bridge, built in 1964 in Bordeaux (France). It is made of three parallel pre-stressed concrete box girders tunnels. Thermal expansion issues were not taken into account for its design, leading to cracks appearing few years after completion due to thermal overstress. Moreover, the Saint-Jean bridge is a very important transportation knot as the traffic is expected to grow with the city of Bordeaux gaining more and more economical importance. Therefore, the assessment of its structural integrity and check-in of its thermo-mechanical behavior turn out to be key points. The field trial took place within the scope of an industrial transfer of the FBG extensometer instrumentation to the French SME Hydrolog, supported by the European Community and the French ministry of Industry. The sensors and acquisition unit were implemented into the central tunnel of the bridge. Eleven FBG extensometers were fixed onto the concrete surface, inside the central tunnel. Six SGEs and five LGEs were connected to four optical lines and were either horizontally fixed onto the wall (1.5 m high) or fixed onto the floor parallel to the bridge. The LGEs and SGEs were placed onto large crack openings, onto box-girder junctions (with no apparent crack) or onto plain concrete. Each line incorporates a temperature sensor to allow the temperature compensation of each extensometer response.

A previous standardized loading of the bridge has been performed on October 29, 2001 with the assistance of the Bordeaux Authority (Communauté Urbaine de Bordeaux), in the purpose of correlating its mechanical reaction to the loading conditions. A very good correlation was observed between the sensors' responses and the progression of the trucks on the bridge. The measured crack-opening accuracy was about $\pm 1 \mu\text{m}$. All the details of the experimental protocol and results can be found in [6]. Then the optoelectronic equipment has been operating for the first four months of 2002. The sampling period was 1 measurement/hour. The strain data show the evolution of the thermo-mechanical behavior of the structure correlated to its thermal expansion of the concrete material on which loading-induced strain was superimposed. Each line measurement took 15 minutes (averaged over 450 measurement points). The strain data exhibited amplitude variations in strain due to day-night temperature variations (about $150 \mu\text{m/m}$). We observe a very good correlation between the temperature evolution and the thermal-apparent strain of the structure (see Fig. 5). So it was possible to extract pure mechanical-induced strains by inferring a strain-to-temperature coefficient during the calibration procedure (about $35 \mu\text{m/m}/^\circ\text{C}$).

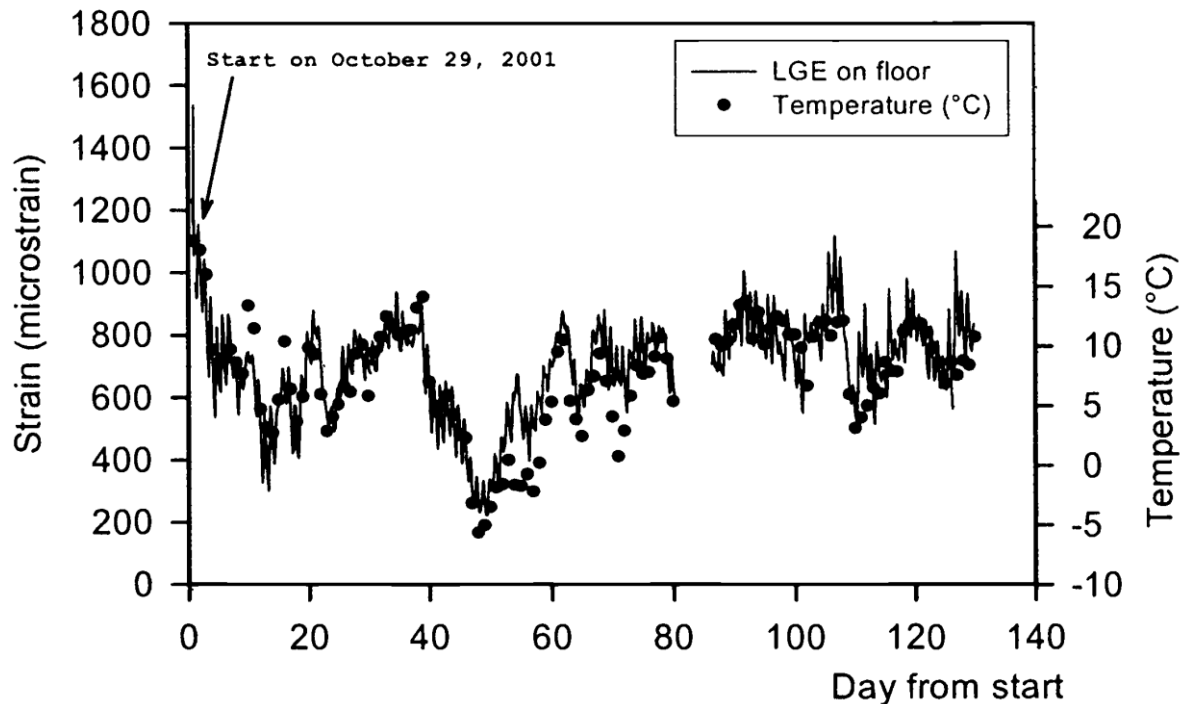


Fig. 5: Strain and temperature data gathered during field test on the Saint-Jean Bridge (France)

5. CONCLUSION

The CEA-List has developed a FBG based instrumentation for strain measurements well suited for civil engineering applications. Compressive tests on instrumented concrete samples show the high reliability, robustness and measurement repeatability of this instrumentation. Within the scope of an industrial transfer to the French SME Hydrolog, this instrumentation was installed on the Saint-Jean Bridge (Bordeaux) (see Fig. 6) to perform tests under standardized loading of the bridge conditions and a several months real-time acquisition of its thermo-mechanical behavior. The reliability and userfriendliness could also be checked under typical civil engineering conditions. The thermo-mechanical behavior of the bridge structure was clearly detailed in the strain data (accuracy # 1 $\mu\text{m/m}$). We showed a very good correlation between the temperature and the long-term strain averaged over transportation loading. Such fiber optic sensor system provide essential information on the thermo-mechanical behavior of the structures to assess their integrity. Such instrumented structures are the first step toward Smart Structures Concept or more precisely to Adaptive Structures Concept. Even if the definition of smart structures is not so obvious [8], we can briefly defined them as structures able to automatically correct themselves for their perturbation or wrong behavior. Actuation must also be implemented. Active control is the main application of Adaptronics in Civil Engineering, originally dedicated to anti-seismic systems with the Kyobashi Seiwa Building in Japan [9] and also used now to actively control the vibrations of bridges (Kurushima Bridge in Japan, Viaduc de Verrières in France, etc). Numerous applications of active control can be foreseen: aerodynamic control of structures under construction, improvement of stability, of safety and comfort for workers during construction and for users, noise, vibration and fatigue reduction, rehabilitation, etc. FBG sensors turn out to present numerous assets to play the role of the sensitive organ in a civil engineering adaptive structure. Due to the important size of most civil engineering structures (dams, large

buildings, power plants, tunnels, etc), a huge amount of sensors is required setting issues of cost, weight, bulk and handling. FBG-based sensing techniques are attractive for enabling remote, long-gage multi-point measurements of a large panel of parameters with the same logging unit and fibers are well-suited for insertion into cables. Despite the fact that the cost of the optical instrumentation and sensors (which basic components are standardized by the Optical Telecommunication market) is still higher than its electronic counterpart, the multiplexing capability of numerous sensor types, and the gain in maintenance costs (simplification in cabling and data handling) make this optical technology actually competitive.



Fig. 6: The Saint Jean Bridge (Bordeaux, France). Courtesy of CEA

ACKNOWLEDGMENTS

We would like to thank the European Community (EEC), the French Ministry of Industry (ANVAR), the Departmental Division of Equipment (DDE) and the Aquitaine Region for their support in the transfer of the FBG instrumentation, and the Urbanism District of Bordeaux (CUB) for their help during the field test on the Saint-Jean bridge. We would also like to thank Y.H. Rimbaud from the DDE and J. Vilaldach from the CUB for their kind attention and help all along this project.

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