Traffic and Temperature Effects Monitoring on Bridges by Optical Strands Strain Sensors

François-Baptiste CARTIAUX [1], Patrice PELLETIER [1], Jorge SEMIAO [1]
[1] OSMOS Group, Paris, France

Contact e-mail: cartiaux@osmos-group.com

ABSTRACT: Knowing the actual effects of traffic and temperature on a bridge and its consequences in terms of stress cycles in the bridge structure is of great value in the scheme of a resilient asset management. A solution is proposed in the case of different types of road bridges in Europe, based on continuous strain monitoring by the mean of Optical Strands sensors and of dedicated analysis tools provided by OSMOS Group.

The choice of performing continuous strain measurements on critical parts of the bridge is discussed, as a relevant solution in order to provide the control of the actual effects of traffic and temperature on the structure and the assessment of the structural elements in terms of strain and stress, both under the effects of the live loads and over the long term.

As the monitoring device is conceived as a permanent solution for these bridges, the accumulated data over several months allow a statistical analysis of the effects of heavy traffic and relevant anomaly detection from several criteria at different time scales: dynamic behavior, stability of the response to temperature changes, long-term stability under the effects of the dead load after thermal correction.

The monitoring of bridges through continuous high-sampled strain measurements over long periods as proposed by OSMOS is an integrated solution which answers to several different problematics, both for the daily management through detection of overweight vehicles, and for the long-term assessment through lifespan estimation and anomaly detection.

1 INTRODUCTION

The structural health monitoring of works, buildings, infrastructures, and industrial equipment is in full expansion.

A McKinsey study in October 2017 estimated that US$3.7 trillion needs to be invested in economic infrastructure each year to 2035 in order to support current growth rates (McKinsey Global Institute, Bridging Infrastructure Gaps, 2017).

At the same time that our infrastructures are significantly growing, the world is hit by waves of natural disasters, year after year. As an example, in 2017, according to Swiss Re (2018), the financial losses from earthquakes, hurricanes, floods, wildfires amounted to 337 B$US.

In parallel, the major part of the infrastructures (including bridges) have been built during the last century with life-limited materials and processes. Sized and built to last on average 80 years, many bridges are now at the end of their lifetime and are therefore at risk.

It is believed that the combination of three elements:

- Colossal amounts of aging infrastructures;

- Huge losses of infrastructures due to natural disasters and climate change; and

- Massive need for new infrastructures;

combined with the newly to be introduced SHM regulation will drive the need for monitoring systems (climate, structural health, geotechnical, weather, etc.) to record high figure (over ten billion US$ business by 2022).

More specifically, the lifetime's duration of the infrastructures, such as bridges, is impacted by two factors which are usually not considered in the design of the works:

- An ever-increasing pollution and the multiplication of natural, climatic extreme events (earthquakes, floods, violent winds, etc.)

- The intense traffic and growing number of trucks, and their respective weight

Thanks to the development of digital sensing technologies, telecommunications and the algorithmic processing of data in real time, it is today possible to supplement the visual inspections by a continuous monitoring, in real time, using intelligent sensors, and data acquisition & transmission systems, and a treatment by algorithms of the mass of data being collected.

This allows us to provide to the manager of bridges a "Toolbox" to manage the flow of trucks in function of their weight, so as to optimize the service while checking the safety of the works (weigh-in-motion augmented by deformation information) and to streamline the maintenance required for the works.

The Monitoring System should ideally be conceived as an integrated part of the Life Cycle Management of the bridges, and thus installed at an early stage during or after the construction. However, continuous monitoring is relevant for existing structures as well, even old ones, but we have to keep in mind that structural behavior may also be influenced by events that have taken place prior to the installation of the Monitoring System. In this last case, the comparison of the actual behavior as recorded by the Monitoring System with the theoretical one from the design enables to precisely assess the global effect of these past events.

If there is an evolution, after starting the monitoring, that progresses through time, the OSMOS solution with Optical Strands will detect such evolution and provide information to the asset manager and engineer. If there were changes in the behavior of the structure that evolved through time but stabilized before the start of monitoring then alternative and analysis solutions must be sought to understand that past behavior.

Monitoring assets can provide a base for preventive & predictive maintenance. With today's state of technology we can match the various data & information collated with specific events to enable building (on a local and/or regional basis) Big Data for our structural asset owners. Through Big Data we can develop predictive analysis for improving the safety of people and optimizing maintenance, repair, and rehabilitation.

In summary we offer the following innovative holistic approach including continuous and Real Time Data Monitoring; Data Analysis and Interpretation using Algorithms; Machine Learning and Artificial Intelligence, Preventive and Predictive Analysis; and Integrated Intelligent Data Management System.

Figure 1. Schematic of braided fiber optics (left) and light flux in the Optical Strand (right)

2 OPTICAL STRAND TECHNOLOGY

The Optical Strand system is based on high-precision sensors that measure deformations between two points with micrometric resolution. OSMOS has harnessed optical-waveguide technology to allow measurements of structural changes. The OSMOS measuring system is based on the principle of intensity modulation with analog attenuation measurement, which was selected following an examination of all fiber-optic techniques of detecting changes in shape and position. This technique provides extremely stable and reliable solutions with an optimized price/performance ratio and minimized requirements for electronic and mechanical components.

The Optical Strand comprises three braided optical fibers (Figure 1). Any change of length (tension or compression) of the pre-tensioned sensor causes a proportional attenuation of the light in the optical fiber according to the micro bending principle (Figure 1). The Optical Strand is the active part of the measuring system. Each end of the optical strand is in a splice-box that is used to mount the optical strand. One end of the optical strand is connected (spliced) to an optical link cable, which transports the measured information to an opto-electronic converter. At the other end of the optical strand, splicing together two fibers forms an “optical short circuit”. Connecting the sensors to a normal fiber-optic cable allows transporting the information of the measurement signal over long distances without conversion or amplification of the optical signal. The optical strand is insensitive to electromagnetic noise, works without any additional electrical energy, and therefore reaches a very high level of reliability and safety during its operation.

The main advantage of these sensors is that they operate without dead time and are synchronized. The dynamic events can thus be monitored with a measurement frequency of up to 100 Hz, which makes it possible to carry out a continuous recording and to detect dynamic phenomena such as vehicle passages on bridges, earthquakes, shocks, etc. If no dynamic event occurs, a measurement point is created every one to 60 minutes. A static measurement is thus obtained, representative of the behavior of the structure over the long term.

3 CASE STUDIES

Three case studies of application of the Optical Strand technology are detailed in this paper. These are three road bridges in Europe (locations are confidential).

3.1 Pre-stressed concrete box girder Highway Bridge

This seven spans highway bridge is monitored to prevent the effects of prestress losses and global ageing of the box girder deck. The criterion which have been assumed significant for this purpose is the longitudinal bending of the spans, which is checked at mid-span.

Two longitudinal Optical Strands are set on each span on the lower slab of the box girder in order to continuously monitor the longitudinal strain where it is maximal in tension under the effects of the loads. In addition, two longitudinal Optical Strands are set under the upper slab at mid-span of one of the seven spans, to check the variations of the compression strain and the height of the neutral axis. The global monitoring system consists in sixteen Optical Strands and four temperature gages.

The stability of the mechanical behavior of the bridge deck is checked through different criteria. All of them are deduced from the continuous strain measurements and obtained through different analysis types at different time scales.

The first criterion is the variation of the strain under long-term effects like settlements or prestress losses: the kinetics of these evolutions is monitored through their incidence in terms of bending of the spans. In order to distinguish these effects from the usual strain variations due to the temperature on the bridge, a correction of the effects of the temperature is performed by statistical means. The correlations between temperature and strain, both measured with six points every hour, enable to deduce an empiric law which links temperature to strain for every one of the locations where the sensors are set. Then, the residual strain obtained after subtracting the strain due to temperature is due to long term effects only, and thus a relevant assessment of the long-term evolutions is possible.

The second criterion is the effect of the live loads due to the traffic on the bridge. Around 20 heavy vehicles are automatically recorded each day as the strain variations they induce in the bridge spans exceed a predefined threshold. A statistical analysis of the strain amplitudes due to these vehicles is performed over the long term in order to assess the evolution of the response of the structure to the live loads. Any significant increase of the amplitudes due to similar live loads would be the consequence of a loss of rigidity of the structure. This continuous assessment of the effects of live loads enables to check that the bridge is not overloaded as well.

The last criterion is the dynamic behavior of the bridge. Live loads induce vibrations of the bridge deck which are recorded by the Optical Strands as strain variations (Figure 2). Because the sampling rate of the measurement is 100 Hz, vibration frequencies up to 50 Hz are theoretically available from the measurements. In practice, a spectral analysis up to 10 Hz only is more than enough for most of bridge types in order to identify the first vibrations modes, which are the most important in terms of mass.

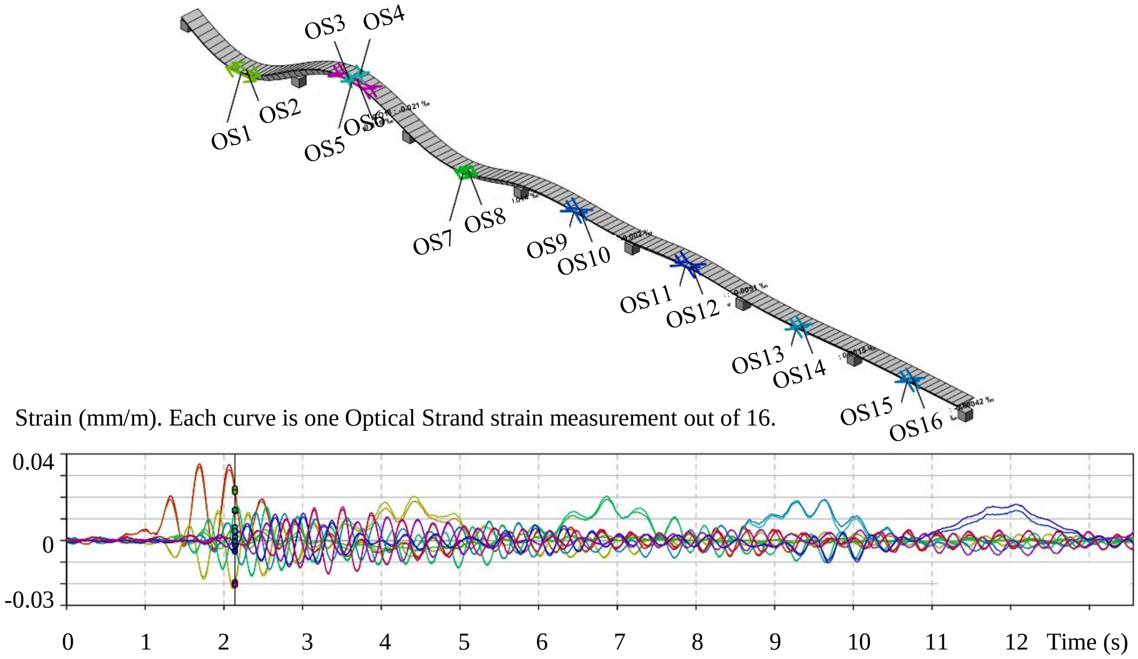

Figure 2. Screenshot of vibrations induced in the bridge deck under the effect of one heavy vehicle.

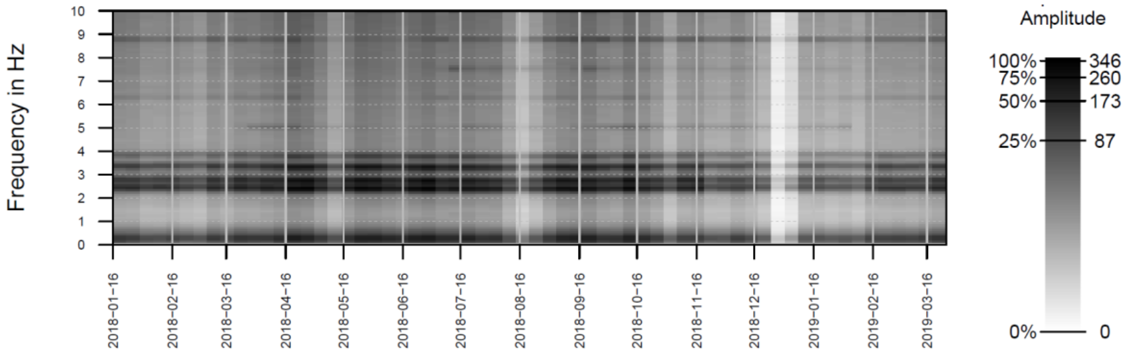

Figure 3. Massive time-frequency analysis over more than one year. Horizontal black patterns on the chart show the vibration frequencies which are the most significant and correspond to vibration modes of the structure. They are supposed to keep their horizontality: Any gap or drift in these patterns would be a sign for structural change due to damage or ageing. Conclusion: The main vibration frequencies are in the range 2.4 Hz to 3.8 Hz and remain stable along the monitoring period.

This spectral analysis is performed for every dynamic record corresponding to the 20 daily passages of heavy vehicles, which enables to follow the potential evolutions of the dynamic behavior on long-term time frequency diagrams, at the scale of several months or even years (Figure 3). A change in the main frequencies or a significant increase in the vibration intensity over long periods of time is an additional way to assess the ageing and defects of the structure.

The three monitoring criteria listed here-above are then combined in order to get a synthetic stability index which gives the global assessment of the mechanical behavior of the bridge deck at every sensor location, for each one of the spans. This enables a relevant comparative analysis from one span to another in order to identify the problematic ones and to prioritize inspection and reinforcement works.

3.2 *Reinforced concrete cantilever Road Bridge*

This three spans reinforced concrete bridge stays over a river in midtown and carries a busy two lanes street. The central span is an isostatic span supported by two cantilever bearings. The bridge is monitored by eight Optical Strands and four local extensometers on the cantilever joints. Four Optical Strands are at mid-span of the central span and the four other ones are on the upper side of the deck just above the two piers, where some vertical cracks have been observed.

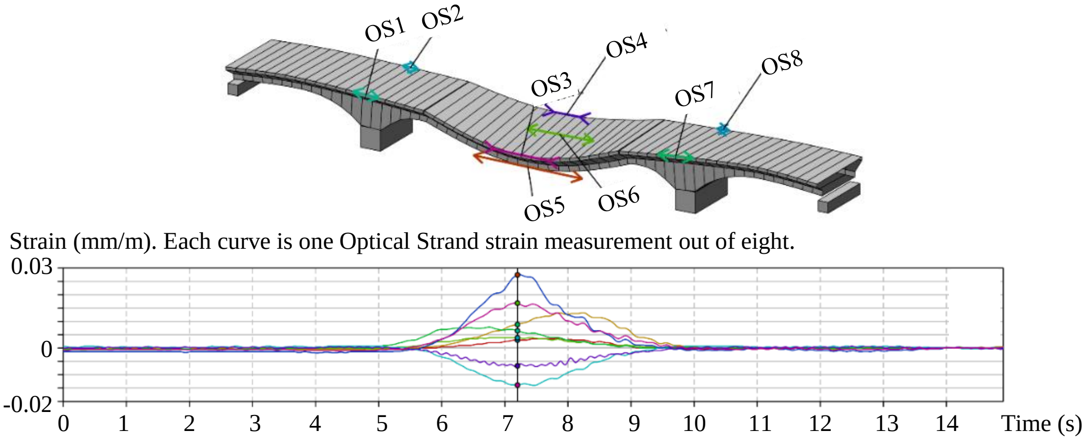

Figure 4. Screenshot of the longitudinal strain measurements and of the reverse model results under the effect of a heavy vehicle: 3D representation of the deflection.

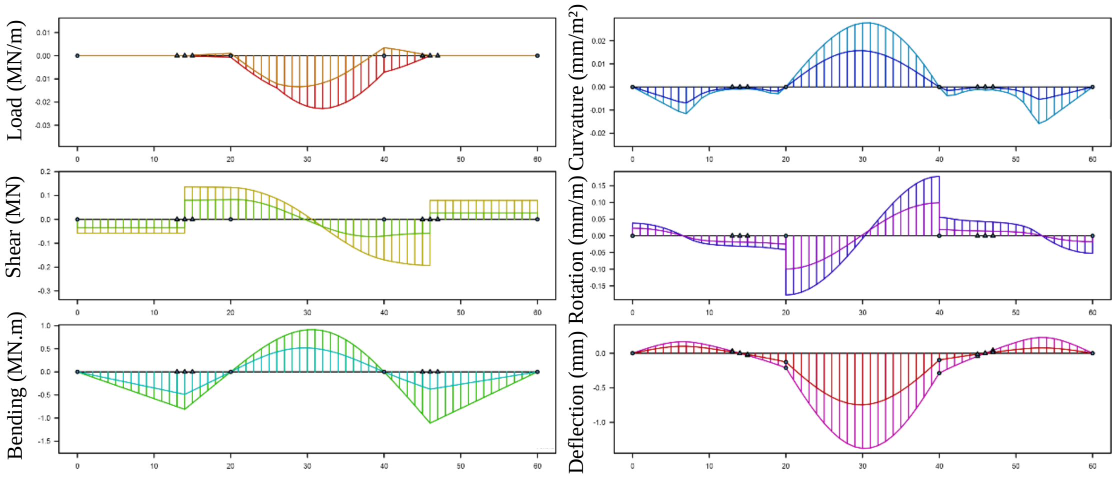

Figure 5. Screenshot of the reverse model results under the effect of a heavy vehicle: load, shear, bending, curvature, rotation and deflection on the 60m long bridge deck for one measurement timestamp.

Both long term effects and live loads effects are monitored on the bridge. Long-term measurements corrected from the effects of the temperature enable a relevant assessment of the crack evolutions. In the case of the live loads, the shape of the recorded variations of strain and joint openings enables to assess the state of the cantilever joints (free or blocked).

A reverse modelling of the bridge is performed in order to deduce quantities which cannot be directly measured like dynamic deflections (Figure 4) and internal forces in the bridge deck, like the shear force in the cantilever (Figure 5). Such a reverse modelling has already been used in other cases like the concrete pylon of the Seyssel cable-stayed bridge (Cartiaux et al., 2017). The model is called reverse because its inputs are the measurements taken on field and the outputs are the estimated loads, deflections and internal forces. This is different from classical design models which will use loads as an input data. This is also different from model parameter identification: the properties of geometry, material and bearing conditions are assumed here and loads are deduced from them. We notice that in the case of a load test, the combination of loads and measurements can be used for parameter identification.

3.3 Composite highway overpass with Weigh-In-Motion solution

A new Bridge Weigh-In-Motion (B-WIM) solution has been implemented by OSMOS since May 2018 on this highway overpass. The bridge is a composite deck with two main steel beams and a concrete deck slab, which supports two traffic lanes in opposite directions. It has two symmetrical 28m long spans. This solution called WIM+D^{TM} relies on strain measurements on specific elements of the bridge span by the mean of Optical Strands.

Compared to previous B-WIM techniques, the novelty of the OSMOS WIM+D^{TM} solution is to radically separate the estimation of Gross Weight and Axle Weight.

Gross Weight is obtained from sensors which measure global effects on main elements, where it is easier to smooth vibration effects and to get accurate influence lines (Figure 6). Meanwhile, the number of sensors required for this estimation whatever the transverse location of the vehicle is reduced to the number of main longitudinal elements of the bridge deck, usually two or four only.

The speed of the vehicle is computed as well, by checking the time gap between measurements from the sensors dedicated to the Gross Weight estimation and additional sensors located on a next span.

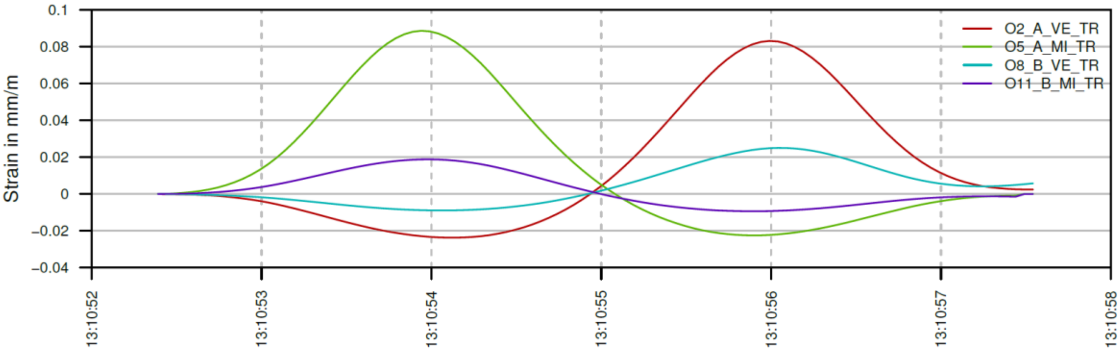

Figure 6. Strain data used for the gross weight estimation. Each curve is one Optical Strand strain measurement on one of the two main beams and one of the two spans of the bridge. After smoothing, we recognize influence lines of the main bending from which we can deduce the gross weight of the vehicle.

The Axle Weight is obtained from additional sensors which are sensitive to local effects, like the bending of the deck slab. Only one Axle Weight Sensor is required for each traffic lane over the bridge, which is typically two sensors on usual road bridges. The local effect recorded by the Optical Strands enables to distinguish the axles and estimate the axle weight. Details about the methodology and accuracy test results are documented in Cartiaux et al. (2019).

The raw data is sent to the OSMOS cloud every few seconds. The WIM+D^{TM} algorithm performs the data analysis on the cloud and releases comprehensive Passage Data Sheets for every single truck over the bridge on a Web Interface named Safe WIM+D^{TM} within a 1 min average delay (Figure 7).

Transit ID :	4832671
Time :	2018/10/22 at 11:31:29 UTC
Maximum Strain (mm/m) :	0.0788
Gross Weight (tons) :	51.6
Number of Axles :	5
Speed (km/h) :	51.4
Direction :	N–S
Plate :	**XX000XX**
Confidence Level :	0 1 2 3 4 4 Reliable Result with good similarity to the load test cases

ID : 4832671

Figure 7. Typical results as displayed on the web interface after 1min delay.

In addition to the weight, speed, and axle configuration information deduced from the strain measurements, the WIM+D^{TM} solution can also include a camera with advanced Optical Character Recognition (OCR) in order to identify the plate of vehicles exceeding a set threshold in terms of effects on the bridge, combined with an automatically triggered video recording.

4 PERSPECTIVES FOR LONG-TERM ASSET MANAGEMENT

As we have seen on the three case studies described above, the continuous strain monitoring of bridge structures over long durations by the mean of Optical Strands enables several types of data analysis in order to assess the mechanical response of the bridge to the loads:

- Response to the variations of the temperature, assessment of blockings, gradient effect etc,

- Long-term evolution under the effect of the dead loads, once the effects of the temperature are automatically corrected,

- Statistical analysis of the strain cycles under the effects of the live loads, detection of changes in the amplitude of the response (and, if relevant, fatigue analysis, especially for steel bridges),

- Massive time-frequency analysis for the assessment of the dynamic behavior,

- Estimation of non-measurable quantities through reverse modelling,

- Estimation of exact weight and configuration of the heavy vehicles in the case of road bridges.

All these different purposes can be fulfilled with one single integrated Monitoring System and a reasonable number of long basis Optical Strands strain sensors. The Monitoring System shall also include additional sensors for the environment conditions (temperature, humidity, and wind) or for other relevant quantities (accelerometers, tiltmeters).

The high quantity of acquired relevant data enables the use of advanced statistical methods in order to get a very synthetic final information from the different parameters listed above. This information is given for each monitored location on a single bridge and for each asset of a wide infrastructure. This includes two main features:

- A Stability Index which gives the information “is anything going on or not, and how fast?” as a single score, on a scale from A to F for example, with daily updates. This enables the prioritization of inspection and maintenance works,

- Smart Alerts which are computed by the mean of stationarity tests on multi-dimensional sets of data: any significant rupture in the data set will induce an alert, which enables early anticipation of critical evolutions or defects.

5 CONCLUSION

Continuous strain monitoring of bridges at 100 Hz sampling rate over durations of several months or years gives a very large amount of data, which can all be useful for the structural assessment of infrastructures. The challenge of Structural Health Monitoring for Structural Asset Managers is to get a synthetic relevant information out of gigabytes of raw data.

OSMOS addresses this challenge through a holistic approach which combines several different criteria in order to perform anomaly detection and anticipation. Strain measurements by Optical Strands are the main – but not unique – input of this analysis because they are the nearest to the actual response of the material under the effects of the loads.

By taking advantage of a very efficient data management system, combining different structural criteria at different time scales, using advanced statistical methods and machine learning, OSMOS solutions will provide relevant synthetic information for an efficient structural asset management system.

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