FIBRE OPTICS TECHNOLOGY APPLIED TO DYNAMIC TRAFFIC LOAD MONITORING IN MEXICAN BRIDGES

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ABSTRACT

This article discusses fibre optics monitoring on two bridges on the Guadalajara-Colima road in Mexico, beginning with a detailed description of sensor typology and data acquisition methodology.

It also explains how static and dynamic monitoring of real traffic loads is being conducted to “calibrate” the sensors.

The conclusion reached is that simple data collection on the structure does not suffice and that the data recorded are only useful if automatically processed and exploited. Rational criteria based on structural reliability theory must likewise be established to define threshold values for each parameter monitored.

1. INTRODUCTION

The need for preventive maintenance of in-service bridges based on monitoring the actual structural behaviour of the infrastructure may arise for a number of reasons, such as structural ageing induced by increases in overall traffic loads, budget cutting or the institution of stricter user safety requirements.

Bridge maintenance has traditionally been based on routine statutory visual inspections in which a subjective assessment of appearance and physical-chemical criteria prevail.

The difficulty of integrating structural behaviour criteria in infrastructure maintenance programmes has been an obstacle to their use to date. The low cost monitoring technology now in place, however, enables engineers to determine bridge behaviour on wholly objective grounds.

The advantage of monitoring bridges using structural behaviour-related criteria is that urgent maintenance needs can be attended to and possible interventions optimised. In other words bridge monitoring based on behaviour under real traffic loads affords the works supervisor in-service structural information that can be used to establish intervention priorities in bridges with a high risk of incidents or deterioration.

The bridge monitoring programme described below comprised three phases:

- selection of the structures that require follow-up operations

- installation of a static and dynamic monitoring system in those structures for a sorter or longer time horizon

- establishment and record-taking of in-service bridge behaviour under dynamic traffic loads.

A permanent monitoring and record keeping system may be installed for several reasons:

- to ensure that the structure behaves as expected
- to confirm the absence of pathologies
- to extend the service life of the bridge
- to optimise maintenance and repair costs
- to ensure safe in-service performance.

2. MONITORING

Structural systems are designed and engineered to ensure economic use during their expected service life, while meeting predefined aptness and structural safety requirements.

Depending on the actions to which such structures are exposed, they may undergo deterioration due to corrosion, fatigue or abrasion or may even be damaged by exceptional events that reduce their performance to below acceptable limits.

The present case study explored two structures continuously repaired throughout their useful life to correct a type of pathology whose symptoms consist of the appearance of fatigue cracks. These structures had already showed signs of time- and very heavy load-induced deterioration. For reasons of safety, they were monitored based on first order criteria (deformation measurement) to track their behaviour during the construction of two new structures that will replace the damaged bridges.

The two existing bridges are on the stretch of road that connects two Mexican cities, Colima and Guadalajara. They are similarly designed, with a deck consisting of a three-dimensional steel girder (Figure 1) whose nodes are connected to the upper concrete slab with four rectangular tubular profiles. Similarly, these nodes are longitudinally and transversally inter-connected by means of corrugated steel bars.

Figure 1 – Detail of the structure

The first bridge, named "El Tapón", has a single 65-m span, while the second, "El Nuevo", has four spans measuring 18.36, 65.26, 63.82 and 12.56 metres. The pathologies observed during the periodic inspections were damaged profiles, damaged transition joints, cracked welded joints, displaced bearings and section losses in concrete slabs.

In light of these circumstances and because the client expressed an interest in having a permanent monitoring system in place as early as possible to detect flaws, a scheme based on optical fibre sensors was designed.

The deck centreline was divided into instrumentation sections and a node was installed in each (Figure 2). These nodes were optical strands cut to a length of 1.5 m for adaptation to both the top and bottom tubular profiles. Each section was also fitted with a second optical cord secured to the lower longitudinal bars.

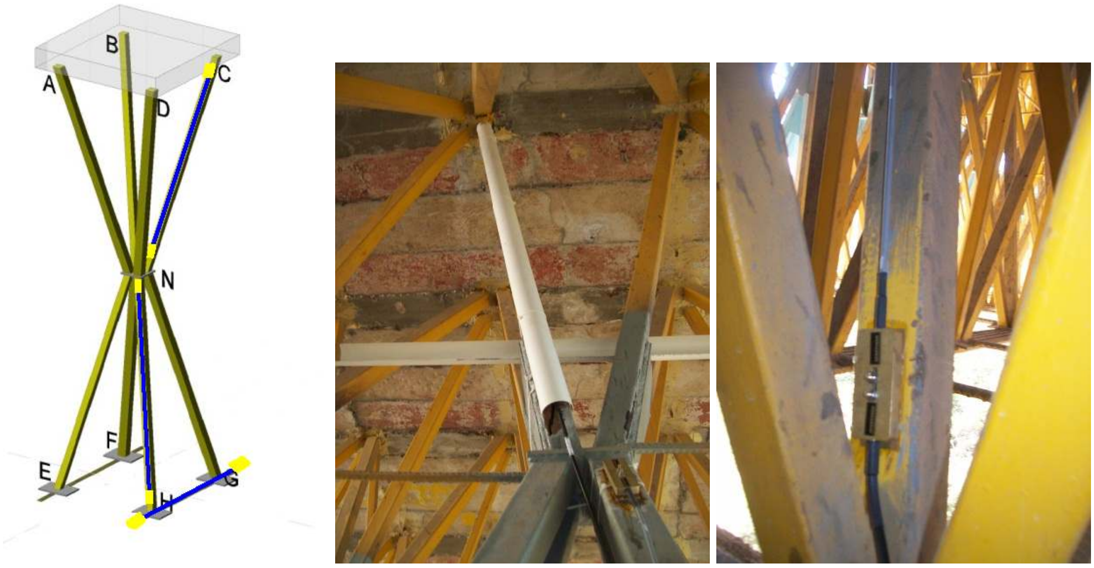

Figure 2 – Detail of optical cord installation

The choice of sensor location was based on structural criteria, for they were installed in the sections with either the highest bending or highest shear stress. These were regarded to be the critical forces acting on the structure able to induce the pathologies observed.

The above instrumentation was supplemented with several optical strain gauges (Figure 3) installed on bearings and joints.

Figure 3 - Optical strain gauge on supports; detail

OSMOS optical fibre sensors based on the measurement of variations in light intensity (optical strands with a long base and strain gauges).

These sensors were chosen for the characteristics described below.

1. The sensor is in permanent contact with the areas of the structure deemed to be most critical.
2. Their very broad measurement base, covering a sizeable proportion of the structure to be monitored, provides a higher quality of information than shorter sensors.

3. They are able to monitor long-term effects.
4. One and the same sensor can record dynamic events even where high frequencies are involved.
5. The same reference is used for static and dynamic records.
6. They are very stable over time, for a number of structures monitored with these instruments have been in service for years with no need for maintenance.
7. They are not subject to electromagnetic interference.
8. The system is parasite-insensitive because transmission is across an optical fibre with no amplification or signal processing.
9. They can be readily installed and maintained.

3. OPTICAL SENSORS

As noted earlier, optical fibre sensors can monitor variations in deformations based on measurements with a very large amplitude. The sensors used in these bridges were specially manufactured for the three-dimensional girder, because the length of its tubular profiles called for a specific instrumental set-up (Figure 4).

The two types of sensors installed in Tapón and El Nuevo Bridges are described in the following item.

3.1. Optical strands

These sensors measure changes in geometric shape. They may be from 1 to 10 m long and come in a wide variety of forms. Despite their long base, they can measure deformation to a precision of 1 micron.

Figure 4 – Installation of optical strands on tubular profiles

3.2. Optical strain gauge

An optical strain gauge is a very high precision displacement transducer based on variations in light intensity. Thanks to its compact design, it can measure a wide range of lengths and displacements of up to 5 mm.

The sensor detects geometric changes with a probe and converts them internally into optical signals. It can record both dynamic and static measurements from the same measuring base over periods of time ranging from a few seconds to several years.

Moreover, these are the same sensors used to measure dynamic effects on the structure generated by traffic loads (Figure 5).

Figure 5 - Optical strain gauge installed on bearings

4. DATA ACQUISITION

The sensors were connected to a standard optical fibre cable to carry the signal for a substantial distance to monitoring stations installed on the bridges, with no need for transformation or amplification. These networked stations were and are the instruments responsible for collecting the measurement readings.

Each station (shown in Figure 6) consists of a data processing and analysis unit and a data acquisition unit. The overall system can be set up remotely with a web server or off-line. A database server establishes a modem connection to all the measuring points and configures and stores all the raw and set-up data.

Figure 6 – Monitoring stations

An independent power system consisting of solar panels was installed on the bridges to ensure permanent monitoring of the structure and a satellite telephone connection.

The system, which is password-protected, delivers immediate, permanent and on-line data visualisation, while speedily processing both the dynamic and static data (Figure 7).

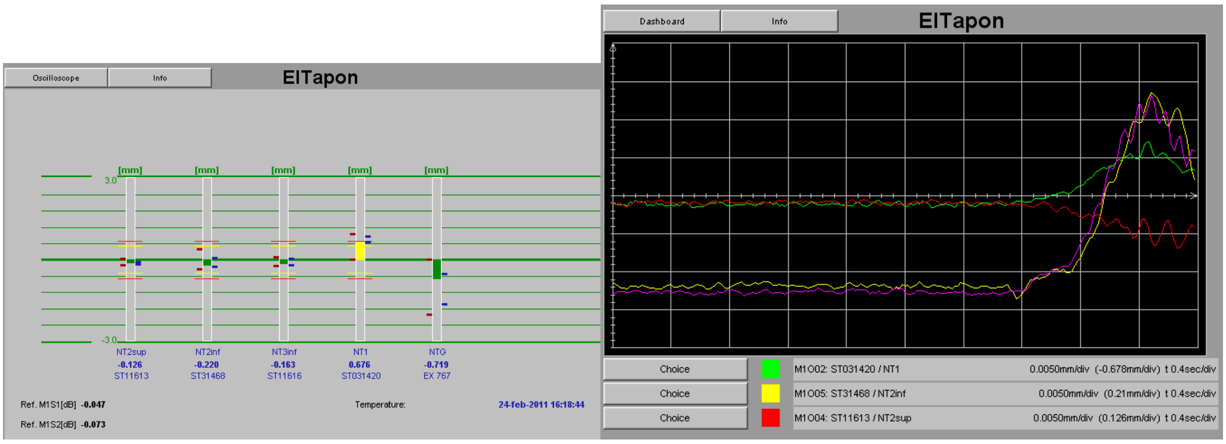

Figure 7 – Real-time display of bridge monitoring results

The state of the structure can be assessed instantaneously with the web display, which includes the instantaneous value for each sensor, along with the daily minimum and maximum and historic peak and trough values.

Data post-processing yields a more detailed analysis of the state of the structure, including the graphs and calculations required to study its static and dynamic behaviour.

5. DYNAMIC AND STATIC STRUCTURE MONITORING

In light of the practical difficulties and the inconvenience to users that interrupting bridge traffic to conduct static and dynamic load tests would have entailed, simplified tests were designed consisting of driving lorries across different areas of the bridges at different speeds.

In the absence of a structural assessment, threshold values could not be established for the data recorded in these tests, which served as structural safety indices for the bridges. The intention is to repeat the trials periodically and compare the values recorded by the optical fibre sensors to the values for the previous trials. The existence of significant differences between any two consecutive trials would in all likelihood be an indication of structural damage in the time lapsing between them. Such damage would have to be located, assessed and repaired, as appropriate, to be able to continue to use the bridge.

The lorry used (Figure 8) reached the target speed in each trial before approaching the bridge and maintained that speed until it was driven off the other end.

Six trials consisted were conducted on each bridge, following the procedure described below.

- A C3 (six-wheel) lorry carrying a 37.85-t load drove along the centre of the carriageway at 10 and 40 km//h.
- A C3 (six-wheel) lorry carrying a 37.85-t load drove along the left side of the carriageway at 10 and 40 and km//h.
- A C3 (six-wheel) lorry carrying a 37.85-t load drove along the right side of the carriageway at 10 and 40 and km//h.

Figure 8 – Lorry before and during the load test

Although highly simplified, this load test gave some insight into the behaviour of the structure and “calibrated” the monitoring system sensors for subsequent assessment of the dynamic behaviour of the structure during its service life.

The parameters measured in this load test were:

1. elastic behaviour
2. amplitude of the weight or intensity readings
3. characteristic period frequency

4. 2nd and 3rd vibration modes
5. impact detection
6. viscoelastic behaviour
7. count (repeating incidents)
8. load reampification rate
9. absolute synchronisation between measuring points
10. detection of exceptionally low frequencies.

The graphs in Figure 9 show the curves plotted by the optical fibre sensors when the test lorry crossed the bridge, and how elastic behaviour, amplitude and vibration damping and modes were analysed from them. Signals obtained from optical sensors with no amplification are noiseless and can therefore be analysed in considerable detail. Moreover, since transmission is optical, all the sensors installed on the bridges can be precisely synchronised to verify whether the same behaviour is recorded in all.

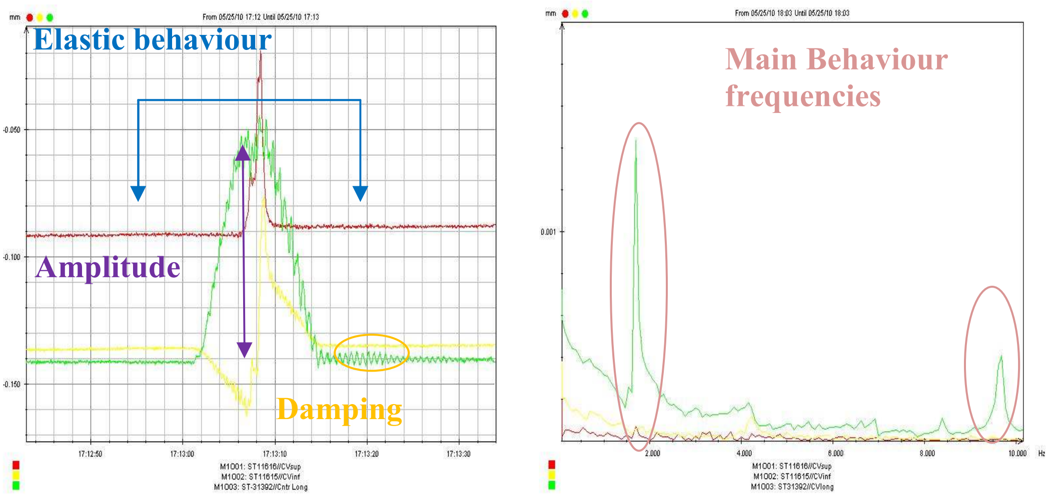

Figure 9 – Dynamic analysis graphs

6. DYNAMIC AND STATIC MONITORING OF IN-SERVICE STRUCTURES

The in-service behaviour of the structures is presently underway, with both static and dynamic measurements taken by the same sensor.

6.1 Long-term, in-service static monitoring

The (Figure 10) deformation record obtained for the structural members is being used to monitor their bending and shear stress behaviour, along with variations in the joints and bearings instrumented.

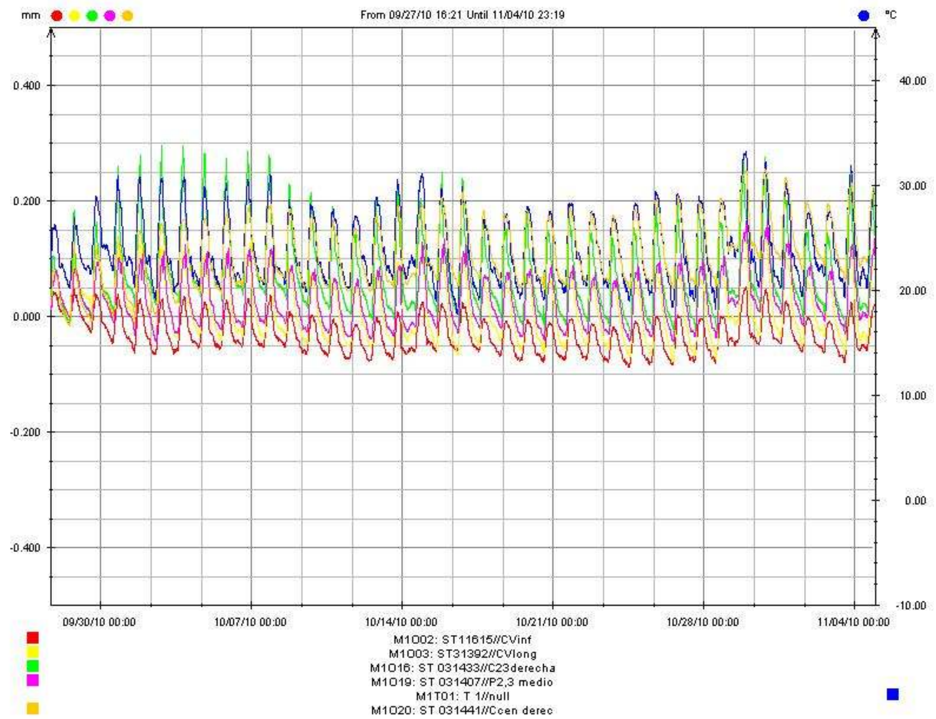

Figure 10 – Graph of deformations measures in the optical strands installed on tubular profiles versus the thermal variations in the structure

The analysis of the static data records (Figure 11) obtained with the monitoring system reveals whether stress builds up in the instrumented members. This in turn will serve to help prevent future damage to the structure. A stress build-up is a symptom of anomalous structural behaviour that could induce future damage or pathologies. Since such build-ups were observed in some of these members, they are presently the object of special monitoring.

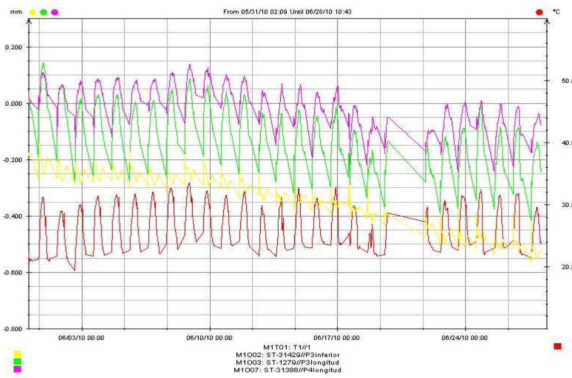

Figure 11 – Graph showing a stress build-up over time in one of the sensors

As noted earlier, the bearings were also instrumented with strain gauges (Figure 12) to verify their behaviour and determine whether their replacement may be in order if they fail to serve the purpose for which they were designed.

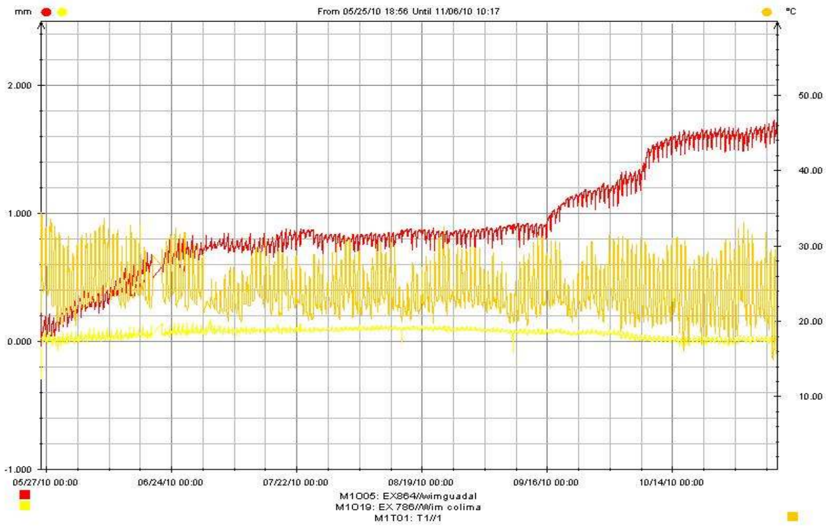

Figure 12 – Data record showing non-elastic deformation in bearings

6.2 Dynamic monitoring of traffic loads on the bridges

With a view to obtaining the fullest possible information on the in-service behaviour of the structures studied, their dynamic behaviour under daily traffic loads is also being monitored.

The actual loads are being compared to the load test findings.

In addition, the monitoring system has been fitted with a web camera (Figure 13) to assess the actions subjectively and relate them to the instrument readings for readier estimation of the maximum amplitude generated, the main frequencies, vibration modes, elastic behaviour and damping.

The figure below is an example of the actual deformations taking place in the instrumented members under the loads simultaneously depicted by the web camera.

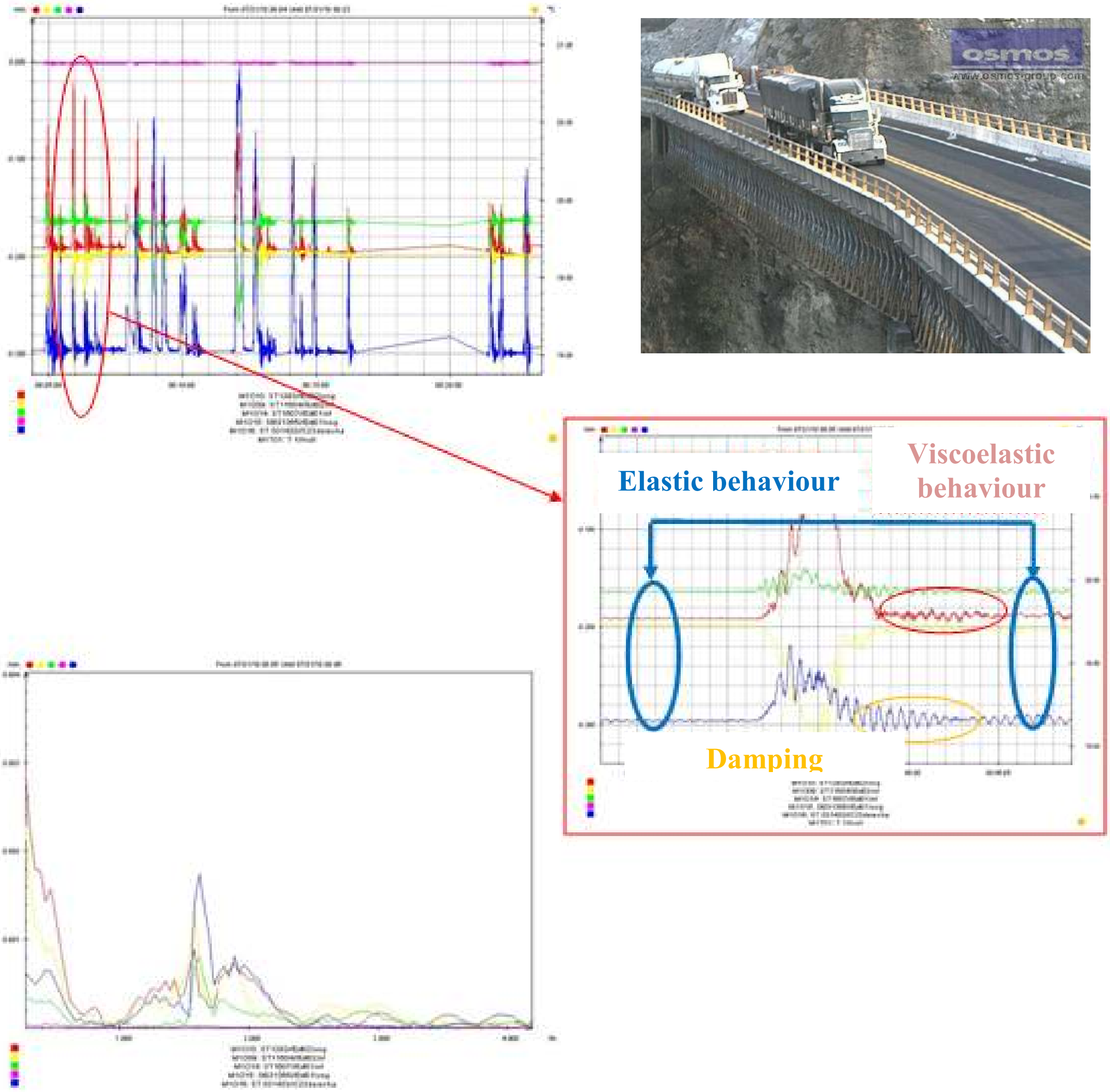

Figure 13 – Load monitoring data record and web camera

7. CONCLUSIONS

Monitoring systems are available today for the analysis of structural behaviour under in-service loads.

Instrumenting with optical strands is one such readily installable system able to provide the precise first order (stress and deformation) data required to conduct preventive structural monitoring.

Furthermore, independent communication and power systems can also be deployed to ensure that all the information can be obtained in real time. Structural engineers can presently draw on tools based on theoretical modelling, such as the optical fibre monitoring described on Tapón and El Nuevo Bridges, that contribute to more accurate estimations of structural safety. This is of particular interest in times when both construction and maintenance budgets are subject to considerable cutbacks.

Mere data acquisition on a structure does not suffice. Such information is only useful if it can be automatically processed and exploited. Rational criteria based on structural reliability theory must be established to define threshold values for each parameter monitored with optical fibre sensors. If one of the values measured exceeds that threshold, the system should automatically set off a real-time alarm, enabling worksite managers to immediately adopt any necessary measures to mitigate risk.

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