Thermal behaviour of a concrete cable-stayed bridge in Algeria

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Abstract

The Salah Bey Viaduct located in the city of Constantine, Algeria, is a cable-stayed bridge with a total length of 756 m and a 259 m main span. Its two pylons have a total height of 130 m and the deck is a prestressed box-girder 3.75 m high with large lateral cantilevers.

A comprehensive structural health monitoring system was set up during construction, including a large number of sensors and covering different aspects, as the weather conditions or the static, dynamic and seismic structural behaviours.

Since the environmental conditions in Constantine involve large daily and seasonal thermal amplitudes, this paper has the purpose to characterize these thermal variations and to analyse its structural effects.

Keywords: Cable-stayed Bridge; prestressed concrete bridge; structural health monitoring, thermal behaviour.

1 Introduction

The Salah Bey Viaduct crosses the Rhumel gorges, connecting two urban areas of Constantine, the third largest city in Algeria.

This viaduct, designed by the Danish consultancy COWI and built by the Brazilian group Andrade-Gutierrez, has been in service since July 2014.

A broad structural health monitoring system (SHMS) of the viaduct was deployed, according to the project's technical specifications [1], in order to monitor bridge performance and, therefore, an early detection of potential anomaly. This system includes the monitoring of weather conditions, static, dynamic and seismic structural behaviour, as well as a component related to durability and *in situ* study of the time-dependent behaviour of concrete.

Since the environmental conditions in Constantine have large daily and seasonal thermal amplitudes and the sensitivity of cable-stayed bridges to temperature variations [2], it is interesting to characterize the viaduct's thermal behaviour and analyse the structural effects of these thermal variations.

For this purpose, after a brief description of the viaduct, the environment temperatures as well as the temperatures measured in different structural elements are presented and related with other variables measured in the structure like vertical displacements, joint displacements, rotations, strains and forces in stay-cables.

2 Description of the Viaduct

The Salah Bey Viaduct is a cable-stayed structure consisting of a single deck, continuous along its development, with a total length of 756 m.

The viaduct is an asymmetrical pre-stressed reinforced concrete structure consisting of two pylons, six piers and nine spans, three of which are suspended, with a main span 259 m long (Figure 1).

The deck, carrying four traffic lanes, has a box-girder cross section, 27.13 m with and 3.75 m high, with large lateral cantilevers. The deck has diaphragms extending to the lateral cantilevers, spaced 7 m each other.

A central cable plane, made by 64 stays in a modified fan system, suspends the deck. The stays rods are anchored in the deck with a longitudinal spacing of 7 m, always in sections with diaphragm.

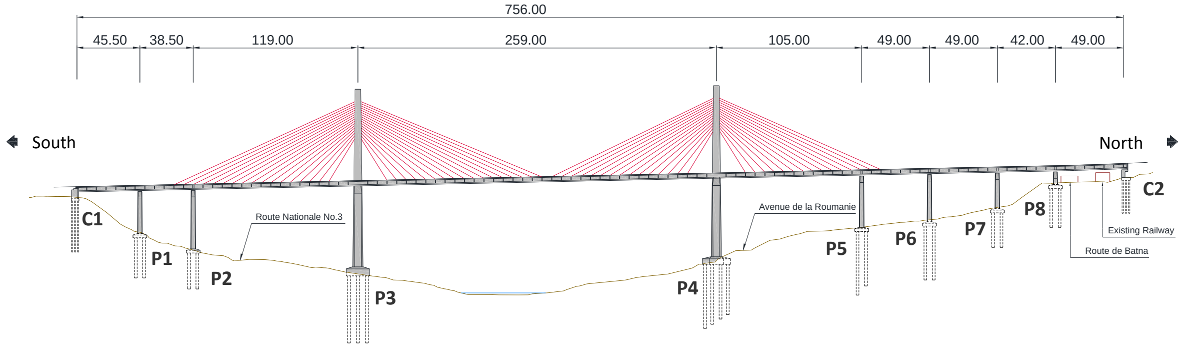

Figure 1. Elevation of the Salah Bey Viaduct

The pylons are single shaft concrete reinforced with a total height of 127 m (P3) and 130 m (P4), with 65 m above the deck (Figure 2). On each side of pylon P3 17 stays are anchored, while on pylon P4 only 15 stays are anchored.

The pylons, piers and abutments are supported by 2.0 m and 0.80 m diameter piles.

3 The SHM System

3.1 General

The viaduct's structural health monitoring system was set up during construction and includes the monitoring of weather conditions, static, dynamic and seismic structural behaviours. A study of the *in situ* time-dependent behaviour of concrete and corrosion monitoring have been carried out.

The following sections outline the focus of this paper being the weather conditions and structural behaviour monitoring system described.

In order to design the SHM system a detail finite element model was developed, taking into account the construction sequence and the time-dependent behaviour. This model was validated by static and dynamic tests and is used for prediction of the experimental values.

Figure 2. General view of the Salah Bey Viaduct

3.2 Weather monitoring

Weather monitoring is performed by a Vaisala Weather Transmitter WXT520, placed at mid-span section of the main span. This device measures wind speed and direction, atmospheric pressure, precipitation, temperature and relative humidity.

The temperature and the relative humidity inside the box-girder are measured by a Vaisala HMP155 sensor.

3.3 Monitoring of the static behaviour and temperature inside concrete

The monitoring of the viaduct static behaviour includes the measurement of several quantities in different structural elements (Figure 3):

- vertical displacements in 13 sections of the deck, through hydrostatic levelling system;
- rotations in the deck and pylons, with 12 gravity referenced servo inclinometers;
- strains in three sections of the deck and one section of pylon P3, using vibrating-wire strain gauges (23) and fibre Bragg grating sensors (22);
- axial forces in 12 stay-cables, using mono strand force cells (installed by Freyssinet).

A detailed study of the temperature inside the concrete was carried out in one section of the pylon P3 (S1) and in one section of the deck (S3). 21 thermistors were embedded in these sections, as presented in Figure 4 for section S3.

In addition, the temperatures inside the concrete are measured by the thermistors integrated in the 23 vibrating-wire strain gauges and by 18 fibre optic temperature sensors placed near the fibre optic strain sensors.

The acquisition, processing and transmission of the values measured by the installed equipment is carried out automatically. The static acquisition is performed by 4 Dataker DT80G loggers associated with several channel expansion modules (Figure 3).

Fiber optic sensors require the use of a specific acquisition unit. In this case, a FiberSensing FS2200XT unit was used, allowing four channels with a 100 Hz acquisition frequency.

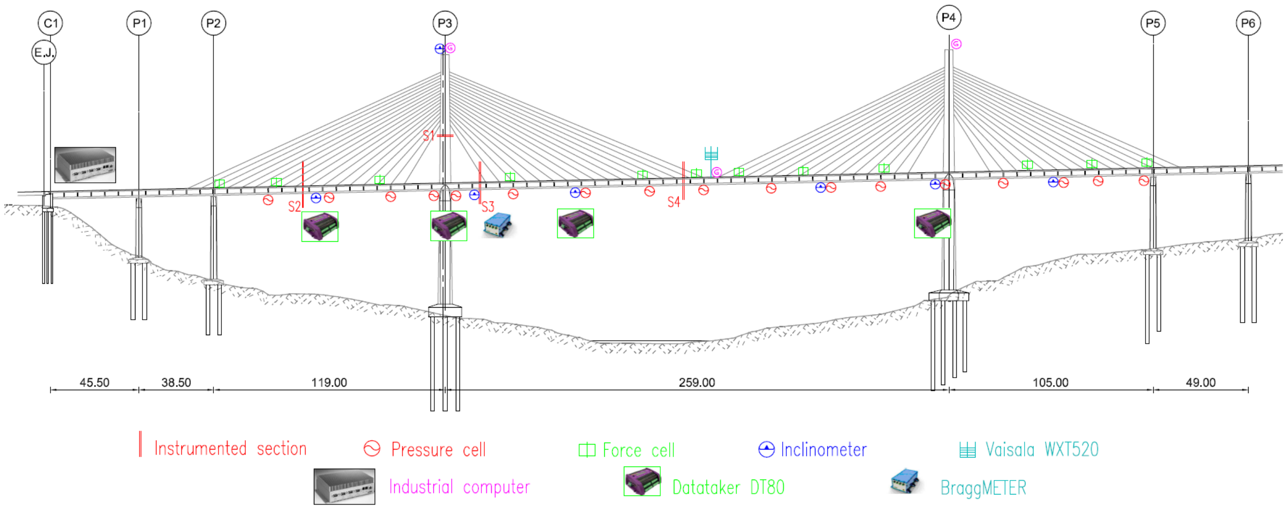

Figure 3: Static monitoring system

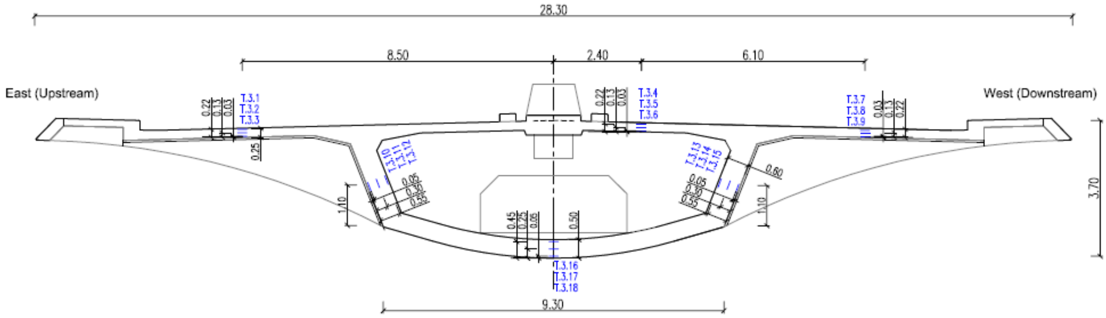

Figure 4: Instrumented section S3

3.4 Monitoring of the dynamic behaviour

The dynamic component of the monitoring system includes 38 uniaxial accelerometers, two triaxial accelerometers, 6 horizontal displacement sensors and 4 bidirectional inclinometers, placed as presented in Figure 5. This system provides, by one hand, daily extraction of fundamental modal parameters and, by the other hand, monitoring of the bridge seismic behaviour.

The wide dispersion of sensors, along with the high sampling frequency required, led to the choice of a modular system Q series of Gantner Instruments. The data is acquired continuously, with a sampling frequency of 250 Hz. The binary record file size is around 220 MB per hour.

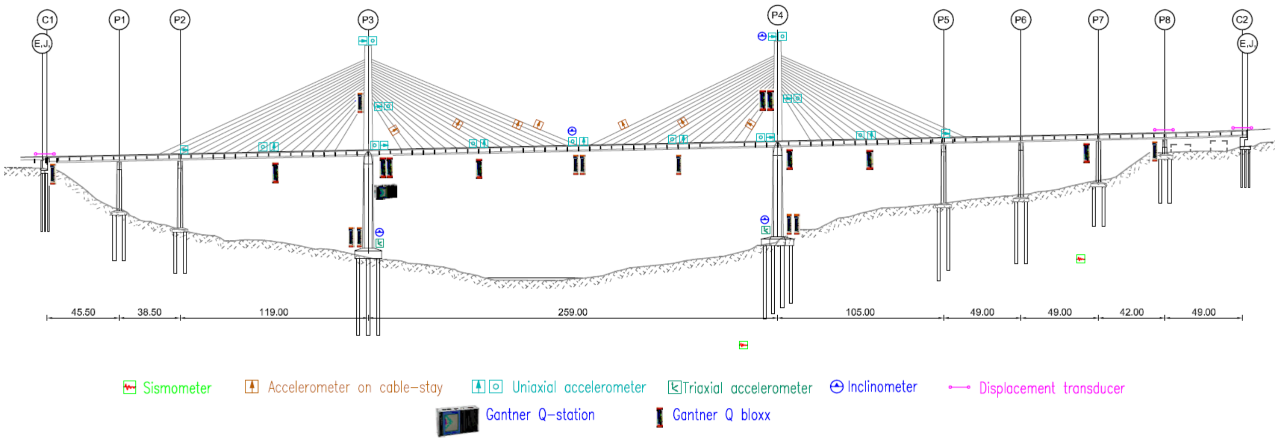

Figure 5. Dynamic monitoring system

The distributed data acquisition units are connected to a backbone fibre optic LAN and thereby to the internet. Two industrial computers were also installed to manager the data acquisition, processing and transmission.

4 Measured temperature

4.1 Ambient temperature

The ambient temperatures measured during almost four years with an hourly frequency on the deck (T.ext) and inside the box-girder (T.int) are showed in Figure 6. The seasonal variation is quite clear, with a temperature range of around 40°C outside the deck and 30°C inside the box-girder.

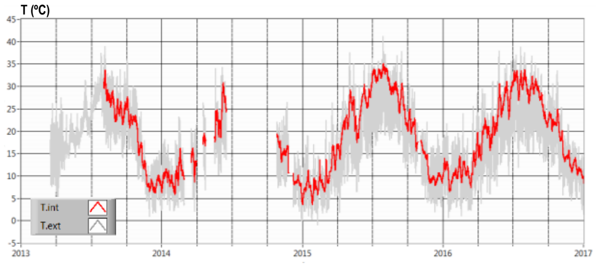

Figure 6. Air temperature on the deck (T_{ext}) and temperature inside the box-girder (T_{int})

The significant daily temperature variations, only perceptible in the previous figure, are evidenced in Figure 7. In fact, the diurnal temperature variation achieved 20°C, although on most days it is between 5°C and 15°C, as displayed in the right-hand histogram.

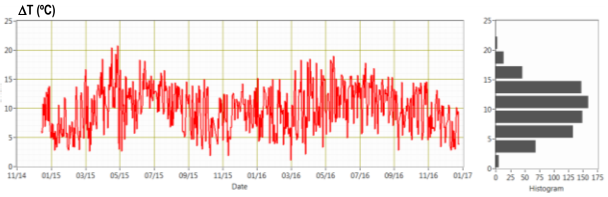

Figure 7. Diurnal temperature variation

4.2 Temperature inside the concrete

In order to characterize the evolution of the temperature inside the concrete, Figure 8 presents the average of the temperatures measured on an hourly basis by the 12 thermistors placed in section S1 (pylon P3) and by the 18 thermistors installed in section S3 (deck) were recorded.

Despite the huge quantity of data, this figure shows the expected correlation between temperatures measured in concrete and ambient temperatures, in particular with air temperatures measured inside the box-girder.

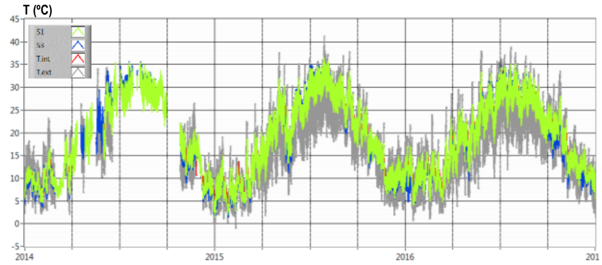

Figure 8. Temperatures measured inside the concrete of a pylon (S1) and of the deck (S3)

To explore in more detail the thermal behaviour of the bridge, Figure 9 presents two extracts of these temperatures: the first from a summer month (July 2015); the second from a winter month (January 2016).

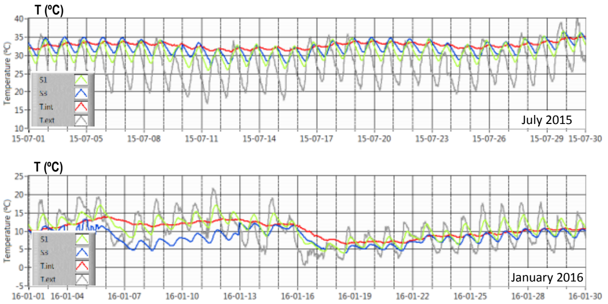

Figure 9. Temperatures measured in concrete during a mouth of summer and winter

The differences between the four curves displayed are clear. However, the focus goes to the evolution of the temperatures measured inside concrete: both S1 and S3 curves are generally closer to the temperature inside the box-girder (T_{int}); the pylon is more sensitive to outside temperature (T_{ext}); during summer, concrete temperature remains high even through the night.

Finally, with the purpose of illustrating the evolution of the thermal gradients caused by daily temperature variations in the cross-section of the deck, Figure 10 shows the temperature across the different elements of the section, during a summer day at four moments with 6 hours intervals. As expected, the gradients are more accentuated in the thicker elements, as the webs and the bottom slab, in which thermal gradients higher than 3°C were recorded.

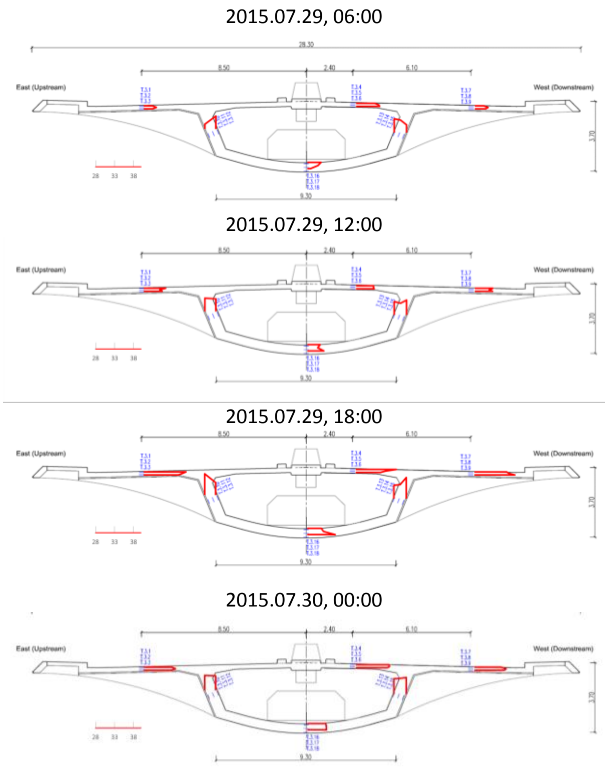
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Figure 10. Evolution of the thermal gradients in the cross-section of the deck during a summer day

5 Structural effects of the temperature variations

5.1 General

The values measured by the SHM system over time allow detecting the thermal effect in the different monitored structural parameters and makes possible the identification of any structural changes, as damages. It can also be useful to anticipate possible new functionality requirements, as the need of larger ranges of displacements in supports or expansion joints.

For detecting changes in the features, a statistical process control tool was applied to time histories of the different measured parameters. For this purpose, the technique Multiple Linear Regression (MLR) was used. The aim is to reproduce the part of variance in measured parameters that is associated with changes in environmental and operational conditions [3].

Assuming that the variation of the measured values in the structure results from temperature changes, the relationship between the dependent variable y (observed values) and the explanatory variables x can be expressed by:

$$y = A_0 + \sum_1^n A_i\, x_i + \varepsilon \qquad (1)$$

The ambient temperature, the temperature inside the box-girder, the section averages temperatures and the temperature gradients in the four instrumented sections were considered as explanatory variables.

As the structural effects of the temperature variations are present in the different measured parameters, only a part of the acquired information was selected for presentation.

5.2 Displacements at abutments

Four magnetostrictive position sensors, two in each side of both abutments, are monitoring the expansion joints openings at both abutments. The measured values are presented in Figure 11.

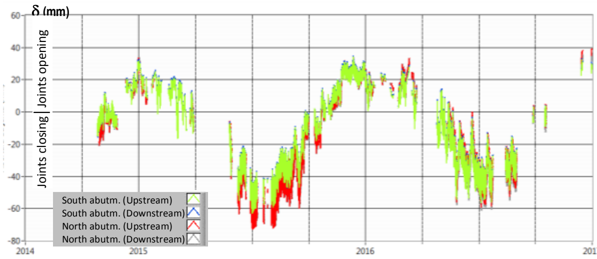

Figure 11. Displacements at abutments

The expected and strong temperature influence in these displacements, quite clear in this figure, is emphasised in Figure 12. In fact, this figure relates displacements measured in the south abutment with the average temperature simultaneously measured inside the concrete (section S3).

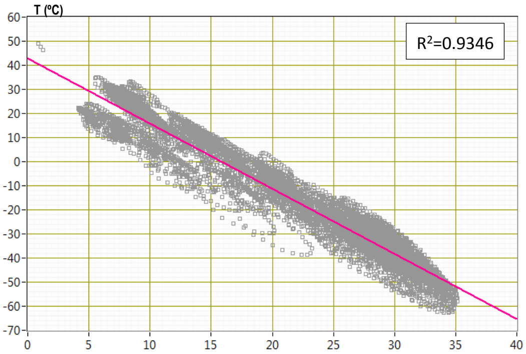

Figure 12. Displacements at south abutment vs. average temperature in section S3

The good correlation between these two variables is stressed by the representation of the line resulting from the regression carried out, which led to a coefficient of determination of 0.9346.

However, it should be noted that temperature is not the only influence on these displacements. In fact, if the aforementioned regression is used to remove the temperature effects of the measured displacements, the remaining values indicate a tendency for a progressive opening of the expansion joints (Figure 13). The numerical model used predicts displacements of 26 mm at South abutment and of 32 mm at North abutment, by the end of the 2nd year in service, which is accordance with the experimental values present in Figure 13.

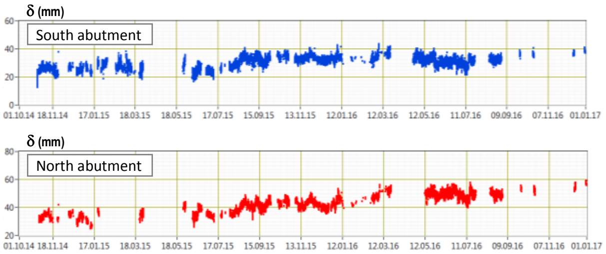

Figure 13. Displacements at abutments after elimination of temperature effect

5.3 Deck vertical displacements

The vertical displacements measured since october 2014 at the mid-span sections of the three suspended spans are presented in Figure 14. In order to emphasize the seasonal effects in the evolution of these displacements, only the values measured at 6:00 am were used.

The clear influence of the seasonal temperature variation in these displacements is particular visible in the main span, where the displacement from summer to winter achieved 50 mm.

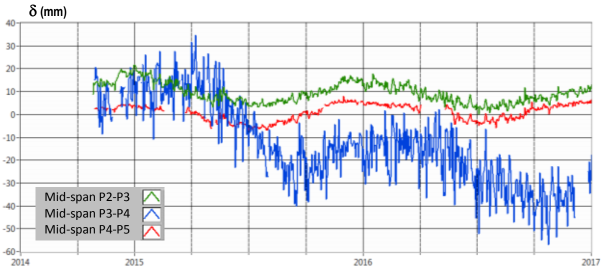

Figure 14. Vertical displacements of the deck

Removing the temperature effect, the remaining displacements shows a strong tendency for the descent of the main span, in contrast with the stability of the side spans (Figure 15). The total displacement of the main span predicted by the time-dependent numerical model for this period is about 50 mm, slightly higher than the experimental value (45 mm).

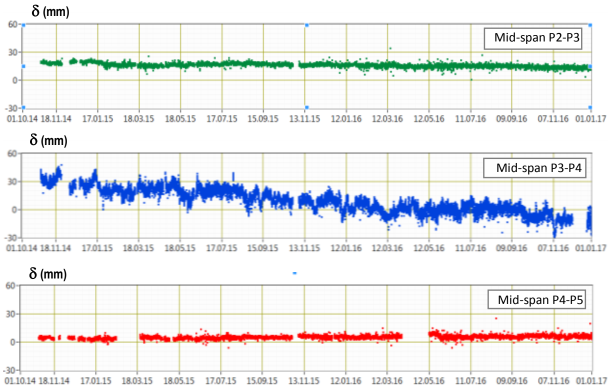

Figure 15. Vertical displacements of the deck after removing the temperature effect

5.4 Cable forces

The forces values in the cables are very important in cable-stayed bridges. The impact of temperature variations in those forces is illustrated in Figure 16, where the evolution of the forces in the longest cables is presented.

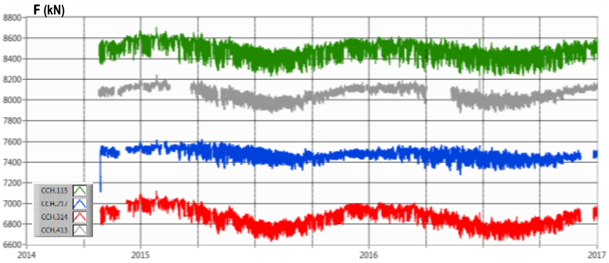

Figure 16. Forces evolution in the major stay cables

This impact is exemplified in Figure 17, where the force in the stay-cable 314 (connected to pylon P3 and central mid-span) is related with the air temperature measured simultaneously. The linear regression between these two variables led to the line displayed in the figure and to a coefficient of determination of 0.8569.

The forces evolution in the two longest cables after removing the temperature effects is presented in Figure 18 and suggest a very slight tendency for a cables tension loss, in accordance with the values predicted by the time-dependent numerical model of the viaduct (-67 kN for CCH.217 and -28 kN for CCH.314).

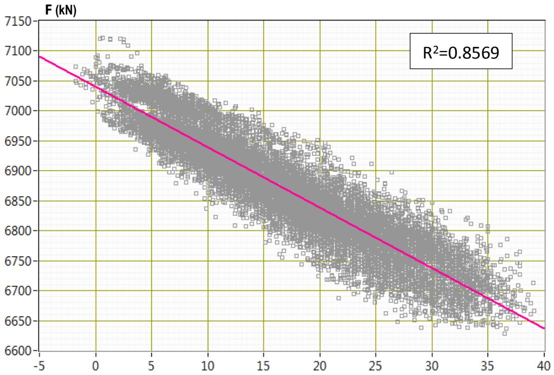

Figure 17. Force in stay 314 vs. air temperature

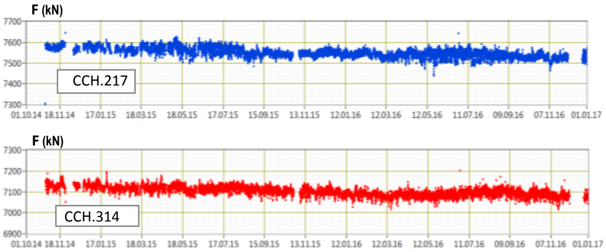

Figure 18. Force in central stay cables 217 and 314 after elimination of temperature effect

5.5 Modal parameters

The dynamic monitoring system has been operating since October 2014. In order to allow an effective and real-time structural identification, based on ambient vibration measurements, an integrated method was developed using the Stochastic Subspace Identification technique (SSI) and cluster analysis [4].

The modal parameters of the vertical and torsion modes were identified from the measurements of 10 vertical accelerometers; the transverse modes from the transverse accelerations acquired by 11 transducers; and, finally, the values measured by 8 longitudinal accelerometers were used for the identification of the longitudinal modes.

The evolution from October 2014 to December 2016 of the natural frequencies of the identified transverse modes are presented in Figure 19. In the same way, Figure 20 includes the time history of the natural frequencies of the vertical modes.

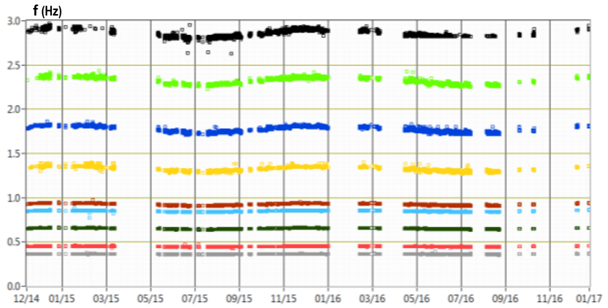

Figure 19. Time history of the natural frequencies of transversal modes

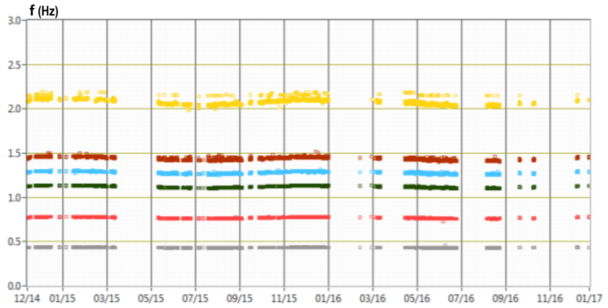

Figure 20. Time history of the natural frequencies of vertical modes

The seasonal effect of frequency variations is clear in these three figures, increasing for higher order vibration modes. To quantify the correlation between natural frequencies and air temperature, Figure 21 presents the coefficients of determination obtained from the linear regression carried out for each vibration mode. It can be seen that only the longitudinal mode is not significantly affected by temperature variations.

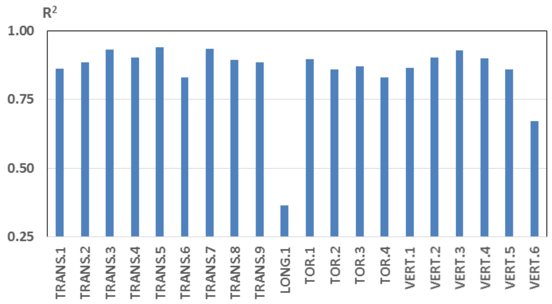

Figure 21. Natural frequencies vs. temperature inside deck (T_{int})

6 Conclusions

The extensive structural health monitoring system installed in the Salah Bey Viaduct provides a significant information about thermal and structural behaviour of this cable-stayed bridge.

The information analysed allowed to characterize the wide daily and seasonally temperature range in Constantine (Algeria), as well as the impact of the temperature in the bridge static behaviour and on the dynamic parameters, namely in its natural frequencies. Correlations were established between air temperatures, concrete temperatures and structural parameters, as vertical and horizontal displacements, cable forces and natural frequencies.

The knowledge of the viaduct's thermal behaviour is essential for an adequate comprehension of the data provided for the SHM system, and, thus, to the early detection of possible anomalies.

7 References

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