Structural Engineering International

ISSN: 1016-8664 (Print) 1683-0350 (Online) Journal homepage: https://www.tandfonline.com/loi/tsei20

The Millau Viaduct: Ten Years of Structural Monitoring

Emmanuel Cachot (Civil Eng.), Thierry Vayssade (Civil Eng.), Michel Virlogeux (Civil Eng.), Hervé Lancon (Civil Eng.), Ziad Hajar (Civil Eng.) & Claude Servant (Civil Eng.)

The Millau Viaduct: Ten Years of Structural Monitoring

Emmanuel Cachot, Civil Eng. CEVM, Millau, France; **Thierry Vayssade,** Civil Eng. CEVM, Millau, France;
Michel Virlogeux, Civil Eng. MV Consultant, Bonnelles, France; **Hervé Lancon,** Civil Eng. SITES, Ecully, France;
Ziad Hajar, Civil Eng. EIFFAGE TRAVAUX PUBLICS, Vélizy, France; **Claude Servant,** Civil Eng. EIFFAGE TRAVAUX PUBLICS, Vélizy, France. Contact: claude.servant@eiffage.com

DOI: 10.2749/101686615X14355644770776

Abstract

The Millau viaduct's monitoring and instrumentation system was designed by a team of experts already involved in structural engineering of the bridge. With the client they set objectives and priorities. Data management, system monitoring and maintenance were also examined. After describing the monitiring program, the results are presented for the first few operating years of the structure.

Keywords: Cable-stayed bridge, orthotropic steel box girder, Pylons, instrumentation, long term monitoring, structural behaviour, durability tests, wind effects, temperature assessment

Presentation of the Viaduct

The Millau Viaduct (*Fig. 1*), crossing the turn in Southern France is a multi-span cable-stayed bridge with a total length of 2460 m and 343 m height at the top of the pylons (*Fig. 2*). The deck is 27.75 m wide overall, and is equipped with heavy barriers and wind screens to protect users from side winds. It was constructed in a series of assembly and launch cycles from platforms installed behind the north and south abutments (1743 m on the south side and 717 m on the north).

The deck is a trapezoidal orthotropic steel box-girder 4.20 m high at the centreline and whose deck plate is made from 12–14 mm thick steel plates.

The piers are composed of single box-sections at the bottom, which split into two shafts in the upper prestressed part, and rest on a series of four circular shafts, 4.5 or 5 m in diameter.

Fig. 1: The viaduct (Units: [–])

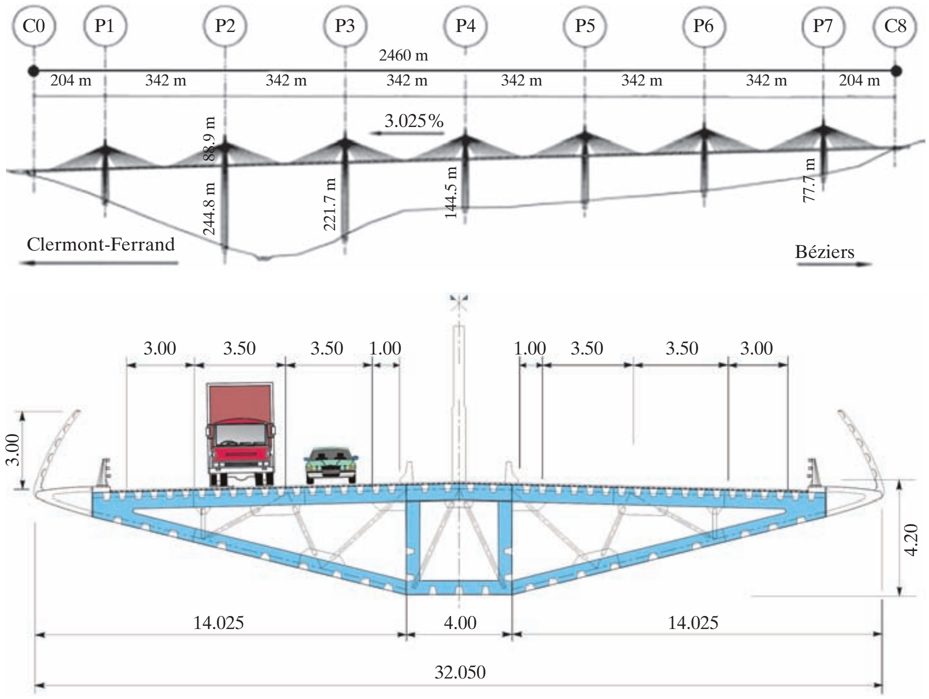

Fig. 2: Longitudinal view and cross-section of the viaduct

The deck is supported by spherical bearings and is stitched to the pier, with vertical prestressing tendons.

Each span is supported by 11 pairs of stays arranged in a half-fan shape and anchored on both sides of the pylons along the deck centreline.

The 87 m high steel pylons in the shape of an inverted Y are orientated longitudinally as extensions of the divided pier shafts.

With these structural characteristics, the viaduct holds the world records for multiple-span cable-stayed bridge length and pier height (P2: 245 m and P3: 221 m).

Monitoring and Follow-up: Project Design and Objectives

As the contracting authority, the French Government fixed the viaduct monitoring and follow-up objectives in the Appendix 10 of the "Concession Specifications", which insists on a 120 year "useful project life", a period of time during which the viaduct must be used as originally planned, receiving the appropriate maintenance and service, without any need for major repairs.

Monitoring was divided into three phases with different objectives: construction, delivery and operation.

The installation of instrumentation equipment during the works was carried out with the aim of optimizing its use in the long term, during the delivery and monitoring phases.

During construction, controls were needed to check the structure's geometry and movements, principally during launching operations to install the deck. The topographical techniques used thus enabled engineers to monitor the viaduct's behaviour and confirm compliance with forecasts based on the original calculations.

On completion of the viaduct, the baseline status was registered, and notably also the structure's reaction to static and dynamic stresses during load testing. This baseline serves as a "zero point” for long-term monitoring and the first stages of maintenance.

During the operational phase, long-term monitoring includes three aspects: specific parameter controls linked to vehicle and passenger safety, checks on structural behaviour and checks on ageing.

The viaduct monitoring was deliberately separated from the control systems designed for traffic safety. Wind speed measurement (which can result in closure of the bridge) uses a channel that is independent of other monitoring information.

Most of the follow-up instruments—sensors, data acquisition modules and networks—are industrial devices, chiefly from the electronics technology sector.

Particular care is needed to manage quantities of data, which must be organized in the early stages of monitoring: codes, recording formats, file formats, file names, and data processing.

Contracting authorities often feel that monitoring should be a long-term process. In the case of Millau Viaduct, a continuous follow-up period was planned for the first years of operation, with dynamic recording of a considerable number of parameters, enabling the viaduct’s reaction in periods of great wind stress to be anticipated. At the end of this period, knowledge of the structure’s behaviour, especially in storm conditions, was complete.

The viaduct also includes provisions for maintenance and monitoring access (all parts of the structure must be accessible for upkeep purposes). Since its opening to traffic, it has had two detailed periodic inspections in 2005 and 2011, in addition to annual inspection visits carried out without any special means apart from the drone (*Fig. 3*).

Structural Monitoring During the Operational Phase

Millau Viaduct’s instrumentation is divided into two separate systems: the static system and the dynamic system. Each system has its own acquisition chain and its own dedicated application (*Fig. 4*).

Several types of measurements were taken:

- Measurement just before opening to traffic, to check compliance of real behaviour with calculated behaviour, and
- Continuous measurement after opening to traffic, to ensure the structure was in good working order and ageing within the expected timeframe.

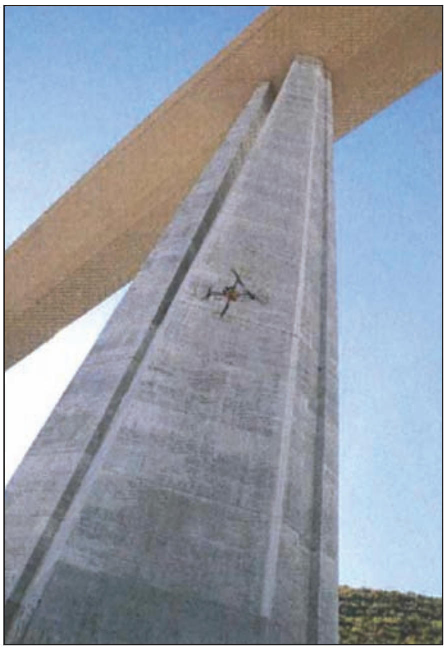

Fig. 3: Drone used for pier section inspection (Units: [–])

The measurements carried out before opening the viaduct to traffic were as follows:

- Dynamic measurements taken by Nantes CSTB :
  - under ambient excitation to determine the principal structure’s vibration modes and frequencies (*Table 1*)
  - under pulsed excitation to measure damping of the first natural vibration modes
- Static measurements under static loads:
  - measurement of deck deformation under a regulatory load induced by 30 trucks weighing around 30 t

Vertical vibration modes	Frequencies calculated	Frequencies measured
4	0.25	0.256
6	0.28	0.293
8	0.321	0.336
10	0.37	0.385
12	0.423	0.433
15	0.474	0.494
17	0.532	0.549
21	0.589	0.604
26	0.639	0.653
28	0.685	0.702
29	0.725	0.748
32	0.766	0.762
34	0.797	0.815
36	0.818	0.833

Table 1: Comparison of frequencies measured and calculated for the first 14 vertical modes of the deck (Units: Hz)

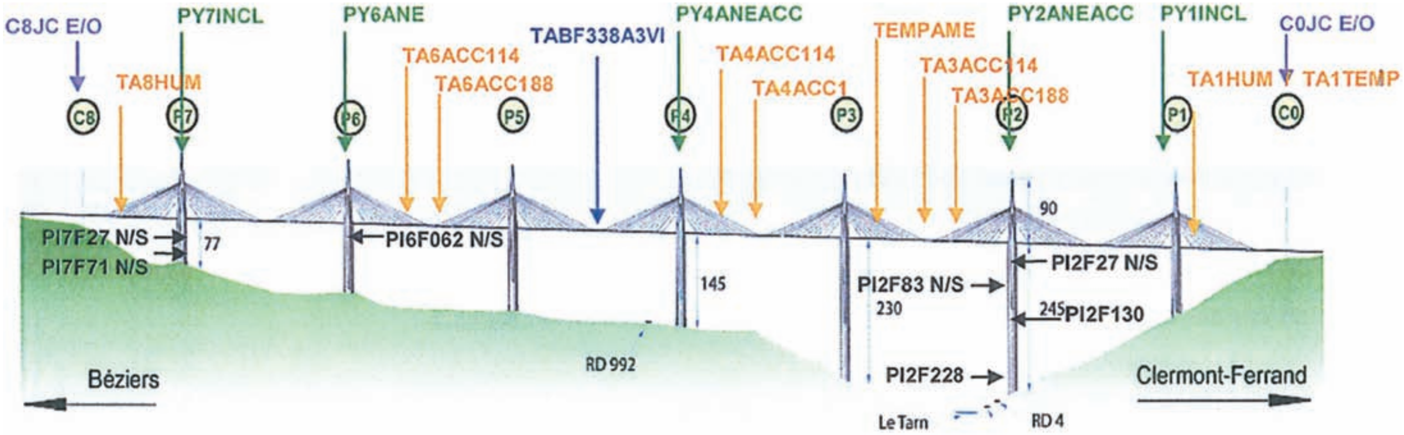

Fig. 4: System layout for viaduct instrumentation acquisition sets (Units: [–])

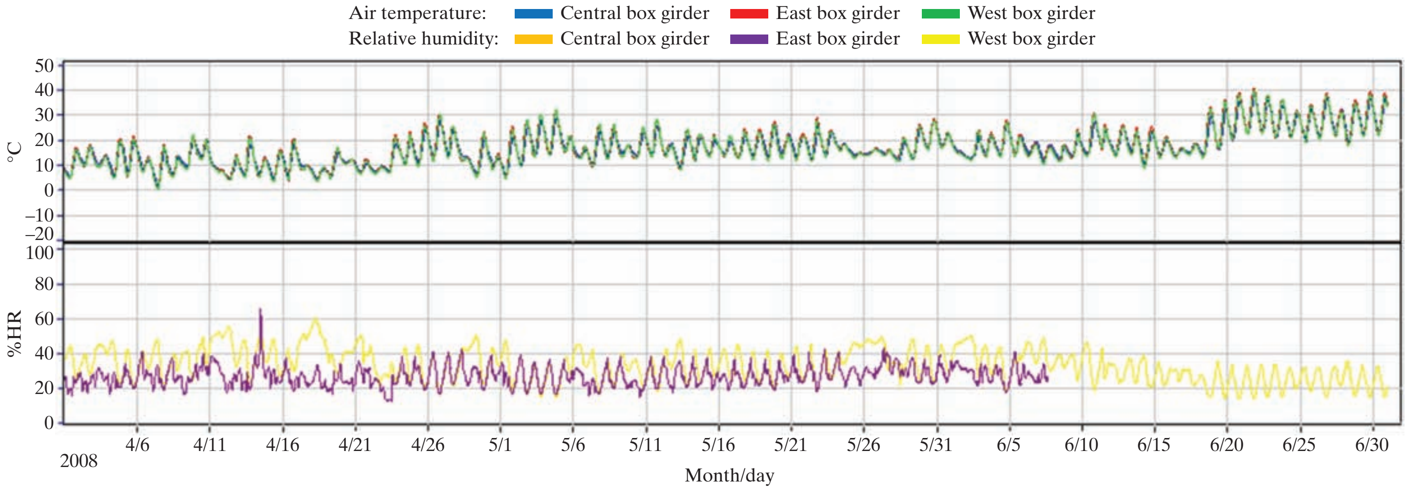

Fig. 5: Deck temperature and relative humidity

Since its opening to traffic, measurements have been taken with the following three fundamentally different aims:

1. The first, and most important, aim is to keep a permanent check on operating conditions, to ensure the viaduct is safe for traffic and users. The viaduct is thus equipped with sensors and specific devices which enable the following to be carried out:
   - Traffic monitoring
   - Wind speed measurement
   - Detection of slippery phenomena
   - Continuous monitoring of the following parameters:
     - opening of extension joints at the abutments
     - average air and deck temperatures
     - relative steel deck humidity (*Fig. 5*)
     - pavement surface temperature

All these measurements can be viewed in real time in the operations control room at Saint-Germain toll station 6 km north of the viaduct (*Fig. 6*).

Fig. 6:Operations control room (Units: [–])

Monitoring of the different values measured is displayed on the screen in digital and graphic form. This display enables vigilance level thresholds to be closely observed. An alert is issued if a predefined threshold is crossed.

2 The second aim is to supervise structural ageing. The viaduct is equipped with instrumentation that enables the following to be monitored:

– Foundations: Height measurements are taken by direct levelling and redundant measurements with an inclinometer, enabling absolute foundation settlement and any differential to be assessed over time (*Table* 2).

– Piers: The end piers P1 and P7 include inclinometric sensors with continuous measurement via the monitoring system. Pier deformation measurements are carried out with extensometers to follow the development of creep in the concrete, and the temperature is measured to assess the effects of transverse thermal gradients.

– Deck: Vertical alignment measurements (of spans and supports) are taken. Deck and air temperatures are measured, as well as air humidity inside the box-girder. Accelerometer measurements are carried out if the wind speed threshold is overtaken.

– Pylons: Geometric measurements are carried out with prisms and inclinometers, as are accelerometer measurements at the top of pylons P2 to P4 if the wind speed threshold is overtaken.

– Cable stays: Monitoring of damping in the six instrumented cable stays on the south side of P3 pylon and of the tension in strands equipped with measuring cells.

– Displacement in expansion joints at the abutments: Each expansion

	December 2006 origin (mm)	November 2007	December 2008	January 2010	October 2010
CO	$s = 0$	+0.4	+1.0	+1.4	+2.2
P1	$s = 0$	–1.3*	+0.1	+0.5	–0.4
P2	$s = 0$	–0.2	–0.4	+0.7	+0.6
P3	$s = 0$	–1.5	–1.2	–1.0	–0.8
P4	$s = 0$	+0.7	+0.5	+1.2	+1.4
P5	$s = 0$	+0.2	–0.2	+1.0	+1.2
P6	$s = 0$	–0.9**	–2.0	–0.8	–0.4
P7	$s = 0$	–1.2**	–1.4	+1.2	+1.7
C8	$s = 0$	–0.1	–0.3	+0.0	+0.1

*Origin 2007 with four guide marks.
**Origin 2008 with four guide marks.

Table 2: Average pier and abutment settlement since 2006

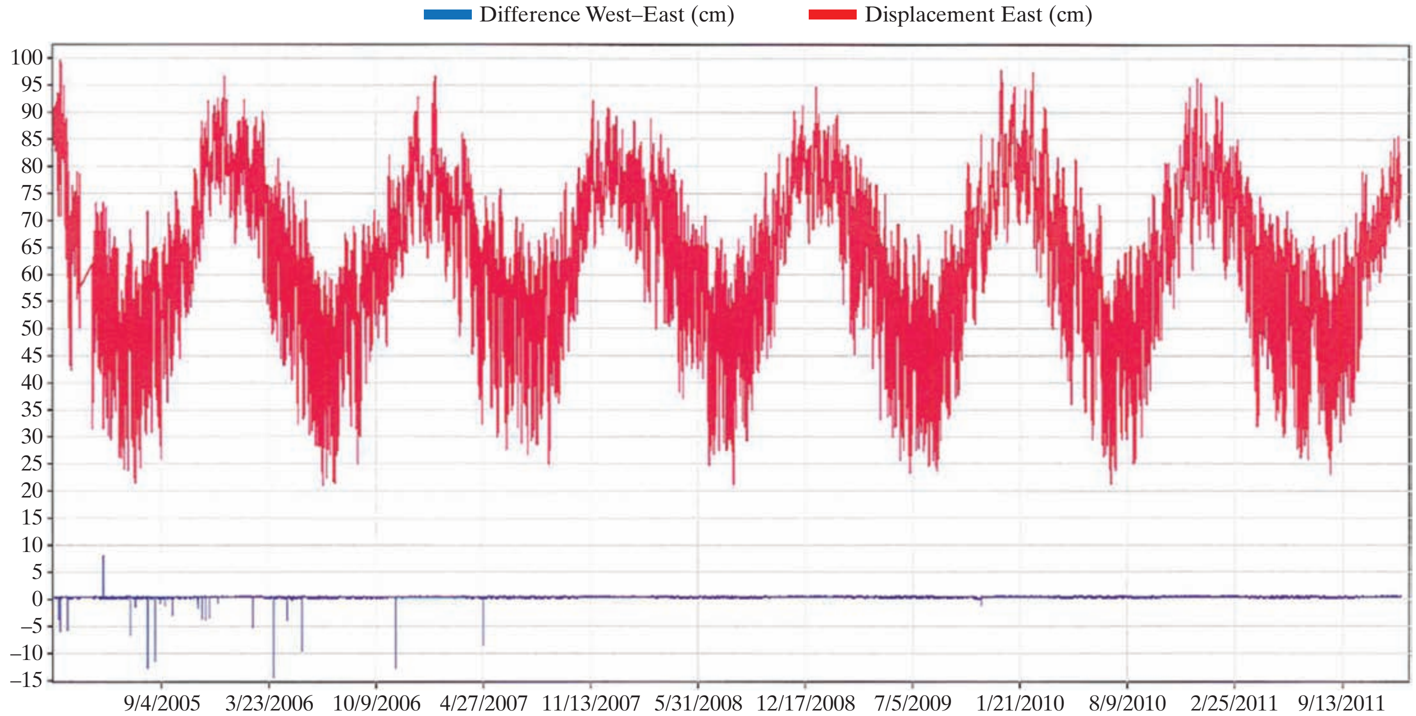

Fig. 7: Evolution of displacements at the abutment (Units y-axis: cm)

joint is equipped with a pair of sensors to monitor deck deformation and displacement in relation to the abutments (*Fig. 7*).

This instrumentation enables the contracting authority and their experts to monitor the viaduct's state of health.

3 The third and last aim is to compare actual viaduct behaviour with the predictions, and ensure compliance with the initial implementation study calculations.

Wind effects

With the participation of Nantes CSTB, strong wind sequences were studied during the Klaus and Xynthia windstorms (24 January 2009 and 28 February 2010, respectively).

These studies confirmed that the results of theoretical calculations carried out by the Greisch design office during the detailed design stage were safe when compared with the results of calculations made on the basis of recordings measured by the different sensors (*Fig. 8*).

Temperature effects

In order to confirm the pertinence of Michel Virlogeux's calculation assumptions about the effects of temperature based on the analysis carried out on Normandy Bridge, the deck was equipped at the construction stage with 27 temperature sensors, in a section located on the P2–P3 span. This was to allow continuous recordings from the viaduct's opening date in late December 2004 and thereafter (acquisition approximately every 30 min).

Analysis carried out on the basis of recordings made over a 7 year period from 2005 to 2011 enabled the deck's theoretical behaviour to be accurately determined: development of the average box-girder temperature, vertical and transversal thermal gradient values for the deck, and concomitance between the two phenomena when statistically analyzed. Similarly, a correlation was established between these values and meteorological data, particularly atmospheric temperature and solar radiation (*Figs. 9 and 10*).

(a) *(b)* *(c)*

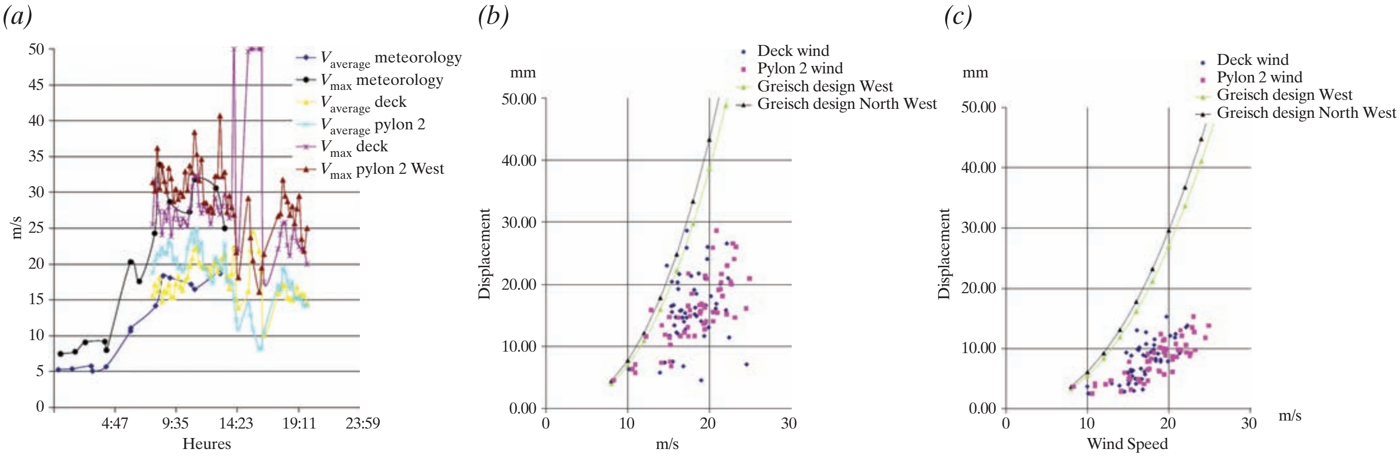

Fig. 8: Legend on next page

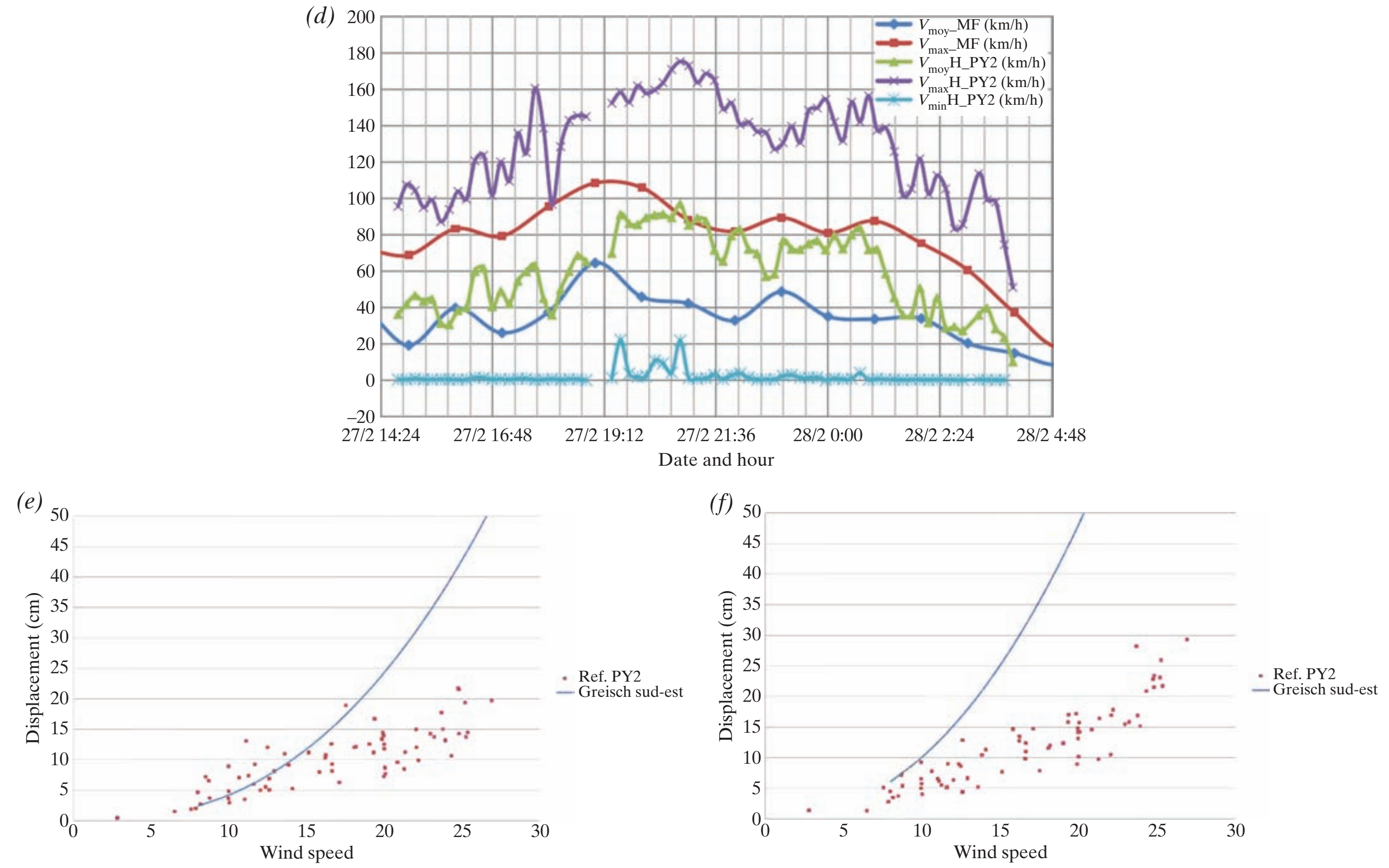

Fig. 8: Comparison of the different measurements and calculations during cyclones Klaus and Xynthia. (a) Cyclone Klaus, wind speed recordings; (b) transversal mode 1; (c) vertical mode 6; (d) wind speeds observed during cyclone Xynthia; (e) transversal mode 3 and (f) vertical mode 4 (Units Fig. 8e and f: y-axis: cm)

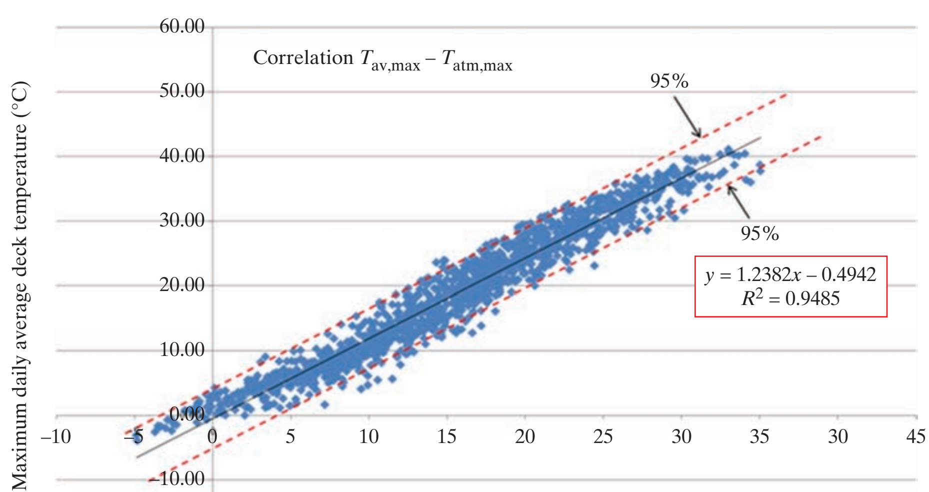

Fig. 9: Correlation between maximum daily average deck temperatures and maximum daily atmospheric temperatures

Concrete tests

Measurements of concrete drilled samples were also planned, in order to monitor sustainability and ageing in the reinforced concrete of the piers simultaneously (carbonation and chloride penetration). The first measurements carried out in 2008 and 2013 on samples taken from the foot and at right angles to the base of pier P2 showed the following:

– The values measured, that is compressive strength, tensile strength by concrete splitting, static Young's modulus (B60), are much greater than those taken into account in the calculations: 75 MPa on average in compressive strength, 7 MPa in tensile strength and an average longitudinal elasticity modulus of 45 GPa.
– Oxygen permeability (according to AFPC-AFREM recommendations) is 4.10^{-17} m^2 on average.
– Chloride content is almost undetectable at any depth given a detection limit equal to 0.005% of concrete mass.

Conclusion

The instrumentation programme deployed from the construction stage to confirm initial calculations and monitor the viaduct's behaviour was much more extensive than the programmes usually set up for cable-stayed, large structures at that time. Having monitored the behaviour of all the viaduct's components during construction (foundations, piers and temporary piers, deck, pylons, cable-stays), the operations involved in the completion and delivery stage enabled basic values to be established, which have since served as benchmarks for monitoring and maintenance during the operation of the viaduct.

Since the viaduct's opening to traffic on 16 December 2004, the monitoring

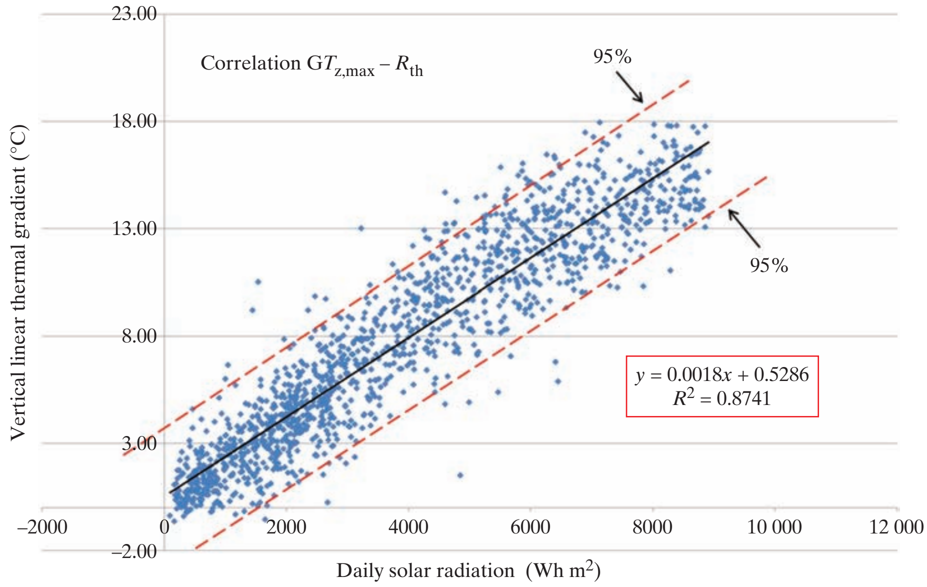

Fig. 10: Vertical linear thermal gradient according to daily solar radiation

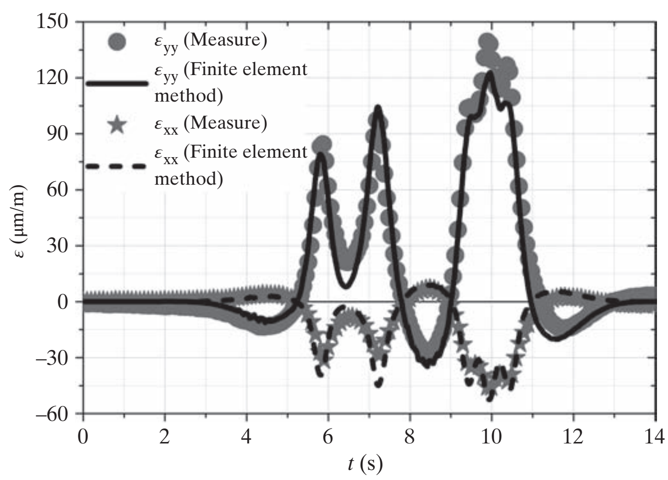

Fig. 11: Comparison of measured and calculated values (ORTHOPLUS Project)

system has thus confirmed that the viaduct's behaviour has remained compliant with the detailed design calculations.

The Millau Viaduct has also contributed to the following research programmes:

1. The «ORTHOPLUS» project, which aims to upgrade the mechanical behaviour of orthotropic deck sections and their coating, so as to optimize their overall lifecycle. Two test campaigns were carried out on Millau Viaduct in October 2009 and October 2010 in order to compare and contrast the results of measurements taken on site with those obtained from 3D calculations using the finite element method (*Fig. 11*).
2. The LCPC (central bridges and roads laboratory) project involving weigh-in motion on instrumented bridges. The aim is to ensure the capacity of systems to measure loads on orthotropic deck structures with satisfactory accuracy and reliability, and thus to supply contracting authorities and operators with information about behaviour under traffic, based on detailed knowledge of the actual loads applied. The data obtained is useful for the structure's monitoring and supervision (*Fig. 12*).

Fig. 12:Weigh-in motion for lorries (Units: [–])

Reference

[1] Virlogeux M, Servant C, Cremer JM, Martin JP, Buonomo M. Millau Viaduct, FRANCE. *Struct. Eng. Int.* 2005; **15**(1): 4–7.