Deformation monitoring and model updating: three case studies on the Paris Metro

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Abstract

The Paris Metro is among the densest and most extensive public transportation networks in the world. It comprises several kilometers of viaducts, with some of them dating back to the very beginning of the 20th century. These exceptional assets combine the problematics of highly strategical infrastructure, very frequently loaded civil works, and heritage buildings all together. Thus, their management involves innovative assessment methods. Structural Health Monitoring (SHM) by means of deformation measurements contributes to this management and has been frequently applied to the viaducts in the last years, in combination with advanced modeling of the structures. Three practical case studies are presented. The relative displacement of a bearing device, because of the temperature variations on one viaduct, has been monitored for one year, and the measurements have been used to quantify precisely the frictional behavior of the device, through optimization methods applied to a strongly non-linear model. To assess the effect of an upgrade of the rolling stock, a one-kilometer portion of viaduct comprising 42 spans has been monitored with continuous strain measurements. The model updating, based on the results of load testing, enabled the precise determination of the real effect of the trains braking. The Austerlitz Viaduct over the river Seine is one of the most iconic civil works of the network. It has been continuously monitored since 2010 with a set of optical strand strain sensors. Massive data analysis tools have been developed to process the measurements.

Keywords: Structural Health Monitoring, Model Updating, Data Analysis, Asset Management, Civil Infrastructure

Received: 5th December 2024. Revised: 11th February 2025. Accepted: 25th February 2025.

1 Introduction

The RATP (Régie Autonome des Transports Parisiens) oversees 250 km of railway lines on the metro network, including 7.2 km of metal truss viaducts, built between 1900 and 1906 on lines 2, 5, and 6. These viaducts support an intense traffic of around 700 trains every day and are assets of critical importance for the economy of the city. They are also part of the historical heritage of Paris and deserve specific management and maintenance actions.

One part of this management is to use Structural Health Monitoring (SHM) to get an accurate and continuously updated knowledge of the real mechanical behavior of the structures (Cartiaux et al., 2023). Indeed, the variety and the age of the building techniques and materials used for the viaducts induce difficulties to assess their structural health and load capacity with a classical simulation from numerical models. Some input from in-situ measurements is required, to give conclusions from models which fit at best the reality of the structural behavior. In addition, the implementation of SHM as a permanent system allows to detect changes in this behavior, and eventually, to be alerted in case of anomalies.

The application of SHM on the historical viaducts of the Paris Metro is presented in this contribution with three case studies. First, we focus on the behavior of a specific element of the viaducts at a local scale, by assessing the friction behavior of bearing devices, and establishing a link with a strongly non-linear model. Secondly, a large model describing a whole 950 m long viaduct is studied in combination with numerous strain measurements acquired on its supports, on both masonry and cast-iron piles, to check the capacity of the asset to bear a new type of trains. Finally, we describe the SHM operation active since 2010 on the Austerlitz viaduct, an iconic work spanning the river Seine with a single isostatic truss arch.

2 Friction on a bearing device

In 2015, a vertical crack appeared at the top of one masonry pillar of the station Quai de la Gare, on the line 6. The pillar was reinforced by external steel rebars to stop the extension of the crack. However, its origin had to be investigated, to avoid the risk of similar defects on other pillars. One hypothesis was an excessive friction force from the bearing device of the iron truss span supported by the pillar.

To check this hypothesis, the horizontal relative displacements of the bearing device have been monitored continuously over one full year, along with the temperature acting on the span (Fig. 1).

Figure 1. Picture of the bearing device equipped with relative displacement sensors

The displacement sensor was a Keyence GT2-H50 device with a measurement range of 50 mm and a resolution of 0.5µm. It was fixed horizontally on a dedicated rigid support linked to the top part of the bearing device, and its measuring head was in contact with the bottom part. Additional displacement sensors with a shorter range (Keyence GT2-P12) were installed vertically at the four corners of the bearing device, to check vertical displacement and rotations, which appeared as negligible compared to the horizontal displacement.

Temperature effects on the sensors did not interfere significantly with the analysis, because they were negligible also, compared to the range of the horizontal movement of the bearing device during the phases of sliding.

The measurements have been compared to the results of a theoretical model of the friction. This model describes a stronlgy non-linear phenomenon: the displacement switches from sliding to bonding (and backwards) in relation with the variations of the temperature, according to the values of two different friction factors (dynamic for sliding and static for bonding). The friction force is deduced from these factors and from the permanent vertical load, given as an assumption. In addition, the model takes into account the elastic shear deformation of the bearing device, along with the bending of the piers (Fig. 2).

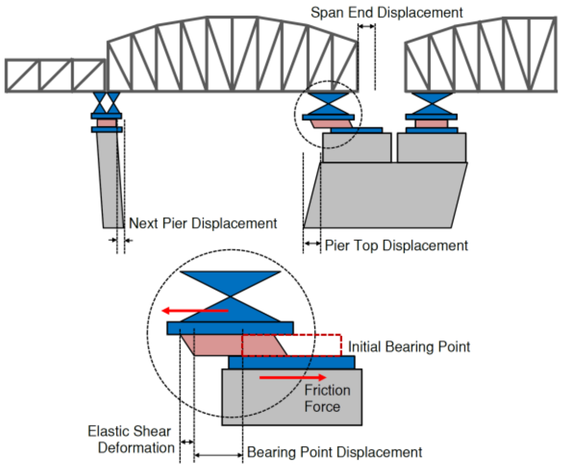

Figure 2. Schematic view of the friction model

Three model parameters are tuned to make the model prediction fit the measurements: the two friction factors, and the dilatation length of the span, that is the distance between the bearing device and the next fixed point for thermal dilatation. It appeared that the latter varied during the year, with a longer distance in summer, due to stronger interaction with the nearby station Quai de la Gare. A rolling regression defined on two-weeks non-overlapping windows was devised for this parameter estimate. As a result of this optimization process, the model prediction has a very good match with the measurements on site (Fig. 3)

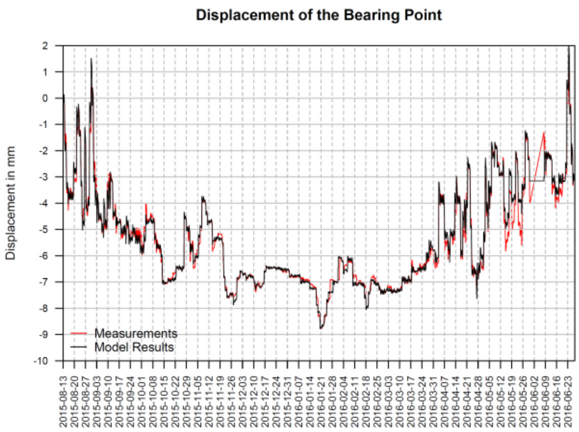

Figure 3. Comparison of the measured displacement (red) and model prediction (black) with one year of data

As a conclusion, the friction factors were far above their nominal values, with a static value of 0.47 and a dynamic value of 0.42. Thus, the friction force from the bearing device was confirmed as the origin of the crack, and similar bearing devices on the viaduct were preventively replaced.

The fitting of the friction parameters on this strongly non-linear model is a mathematical endeavor which triggered the development of new methods. The detailed formulation of the mathematical problem and its solution have been published by Bensoussan et al. (2021).

3 Viaduct of the Line 6

The Metro Line 6 runs over ground for the most part of its length, with three long viaducts including two crossings of the river Seine. The coaches used on this line, dating back to the 1970's, are currently being replaced by newer trains with a higher capacity. Thus, the viaducts, in service since 1909, must be checked for updated traffic loads, especially for the case of emergency braking with strong horizontal loads.

A continuous 950 m long part of the viaducts is chosen to assess the effects of braking loads with an approach combining SHM and modelling. The purpose is to introduce a set of parameters deduced from in-situ measurements, into an exhaustive model which will be used afterwards to check the future braking loads. Both modelling and SHM need to cover a long part of the viaduct, because the main unknown result is the length of the zone on which the braking loads are distributed, through the effect of track-structure interaction and relative rigidity of spans and piles (Cartiaux et al., 2021).

3.1 SHM system and load test

The SHM system installed in 2017 includes 136 optical strands (OS) strain sensors set on masonry and cast-iron piles of the viaduct to assess vertical strain due to load and bending, along with 11 accelerometers and 36 temperature gauges. A set of 19 Expert Data Acquisition Systems (EDAS) are distributed along the viaduct to gather all the sensors with wired connections (Fig. 4).

Figure 4. Under the viaduct of the Line 6: vertical OS sensors are set on the masonry piles and protected by half-pipes. EDAS are installed at the top of selected piles.

The SHM operation on the viaduct comprises three different parts and purposes:

1. Check the number of spans which participate in the balancing of the braking loads: the continuity of the viaduct through the tracks distributes the load over a length and on a quantity of columns that was not known,

2. Process the strain measurements acquired during two nights of load tests (in May 2018) to update a model of the whole viaduct, allowing to predict the distribution of the braking load on the piles under the effect of the future rolling stock,

3. Keep the viaduct under surveillance for the whole transition period and assess the real effects of the new trains. Thus, the SHM system is still operating after seven years.

Since 2017, a few maintenance operations have been required to keep the whole system operational. Most of them were consequences of vandalism, and not sensor defects. For example, the fixation plates of 16 OS were replaced in 2022, although the sensors themselves were operating well and were left in place without a replacement. Only seven OS among 136 have been replaced once: six in 2020, and one in 2022.

During the load tests of May 2018, trains of the older generation were driven on the viaduct to test several configurations of normal or emergency braking, acceleration, and drive-by cases at usual speed. Accelerometers set inside the coaches give the acceleration of the train in the longitudinal direction, which is taken as an input for the braking (or acceleration) load applied to the model, along with the location of the train on the viaduct.

3.2 Model updating

The model covers the whole viaduct, including three stations with a doubled row of columns and some monumental pillars with high rigidity (Fig. 5). The study included 42 spans, even if not all of them were instrumented.

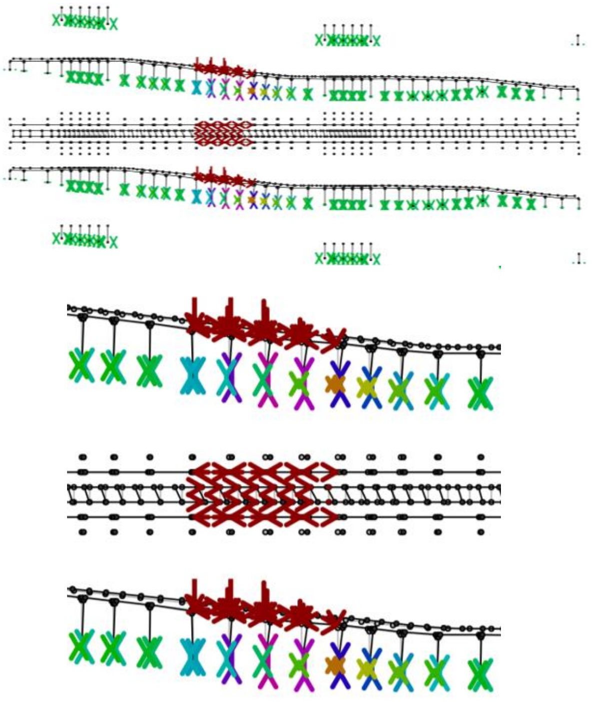

Figure 5. Schematic view of the model of the viaduct with one braking load case. Whole model (top) and detail (bottom). Colored symbols on the columns represent the strain.

The following longitudinal rigidity parameters are updated to make the model prediction match the measurements:

- Young Modulus of cast-iron and two different masonry stones,
- Longitudinal stiffness of bearing devices, split into two groups (fixed or not),
- Longitudinal stiffness of the span truss structures, split into two groups (current track or inside a station),
- Longitudinal stiffness of tracks,
- Track/structure interaction, with two different values along the viaduct, on two zones separated by the middle station Chevaleret.

The latter is the most significant one for the model updating. A total of ten different load test cases were considered, each one recorded as a 15 second signal at 50 Hz sampling rate on 120 sensors. Thus, the total number of observed measurements for the updating process is 900,000.

The model updating is performed by a classical least-square method. Although the model covers a large quantity of elements, the philosophy of the process is to keep it as simple as possible to focus on the effects of longitudinal braking and vertical descent of load on the pillars. Thus, a heavy finite element model is avoided, and the updated model only considers the longitudinal stiffness of the multiple elements as a complex series of elastic springs, which allows a description of the whole viaduct as a single square stiffness matrix of order 846. Thanks to the fast computation of this matrix, according to a set of updated parameters, and its application to the ten load cases, it is possible to proceed efficiently to the optimization with a comprehensive grid of values for the set of model parameters.

The whole process of model updating is managed by a single R script and takes not more than a few hours (on an office laptop of average performance). Figure 6 displays the result by comparing the measured and predicted strain on two columns for one case of emergency braking.

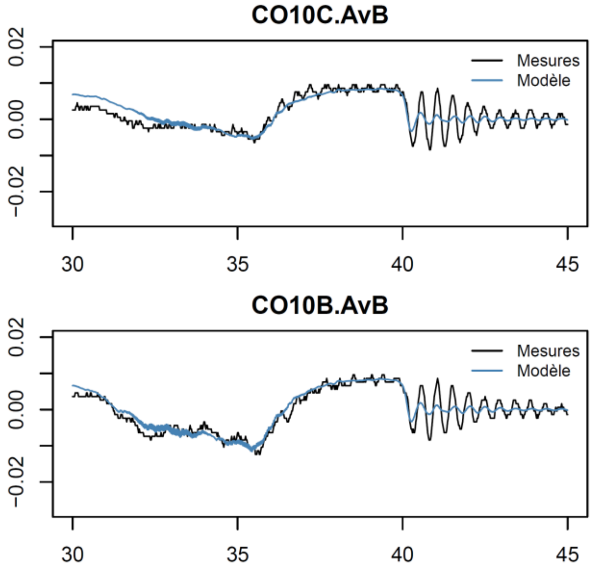

Figure 6. Comparison of measured (black) and predicted (blue) vertical strain for two sensors. Time in seconds, strain in mm/m.

To control the efficiency of the model, dynamic effects are not considered. Thus, the free vibrations of the viaduct after the braking are poorly predicted. This is because the mass accelerated by these vibrations includes some spans of the viaduct, and not only the mass of the train. However, this poor prediction is not an issue for the purpose of the study, which focuses on the response of the viaduct during the braking itself, before the free vibrations. Here, the updated model predicts highly accurately the strain deduced from the braking acceleration measured in the train (between seconds 35 and 40 on Figure 6).

Once the model is updated, the newer trains are simulated with conventional braking load cases. The descent of loads on each column is then checked and compared to the resistance of the columns and their foundations. According to this simulation, the longitudinal displacement at the top of the highest iron-cast columns does not exceed 2.6 mm in the most conservative case of emergency braking.

This study gives evidence that the braking loads are distributed on a large amount of columns along the viaduct, and that the three stations are acting as fixed spots, which finally reduces the descent of loads on each individual column. No specific reinforcement works are needed for the rolling stock upgrade.

4 Austerlitz Viaduct

Spanning the river Seine near to the Austerlitz station on the line 5, the Austerlitz viaduct stands as a masterpiece of civil engineering of the early 20th century. Built in 1903, it is a single 140 m long span composed of mild steel truss arches, deck and hangers. The arches are isostatic with three hinges, at both abutments and at the key (Fig. 7).

Figure 7. Austerlitz Viaduct

4.1 SHM system

Since 2010, the viaduct has been monitored by a set of 18 OS sensors on various elements: arch members, hangers, deck members, bracing truss elements, abutment cantilevers. In addition, the relative displacement of four specific joints is monitored as well. Two additionnal OS were also added in 2015 on one hanger. In 15 years of operation, only one sensor defect has been recorded: one OS was replaced in 2020. This maintenance came along with an upgrade of the EDAS, since the former hardware had become obsolete, while still operating well.

The SHM data management combines two different modes of measurements, both available for all the sensors:

1. The static mode is a permanent data acquisition with a fixed period of one point

every ten minutes. It aims at assessing the effect of the temperature on the structure, and detecting long-term variations of the strain under the effect of dead loads,

2. The dynamic mode is triggered by the variations of any strain signal, when its range exceeds a defined threshold within a short period of time (4 seconds buffer). Each dynamic record is a short signal of around 30 s sampled at 100 Hz, available for all the sensors, even those which did not trigger the record. Such a signal is called an “event” and the dynamic data is organized as a series of events. Each event is usually related to the passage of one train on the viaduct, or two trains in opposite directions.

Since every passage of a train on the viaduct triggers one dynamic record, the number of events is above 500 every day. These events constitute a rich database from which various information and indicators relative to the health of the structure are derived.

4.2 Cycle range counting

The first indicator is the range of the strain in each monitored element under the effect of the trains. This range is directly linked to the stiffness of the structure, and an increase in similar loading conditions would be a clear sign of damage. A statistical overview of the strain range for long periods is given as the result of a Rainflow cycle counting applied to each event and merged for regular periods of one day. This representation allows a quick assessment of the stability of the effects of the train loads, by checking horizontal patterns on the resulting map, as shown on Figure 8 for a period of 41 months (2020-2024).

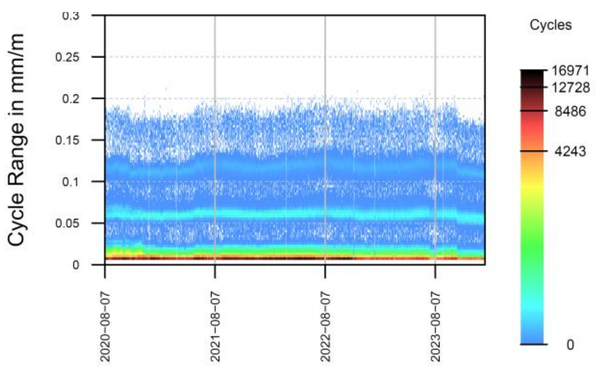

Figure 8. Strain range in a bracing element, displayed as cycle counts each day

On this example, the heat map resulting from the cycle counting shows horizontal rays, which represent the range values with the most occurrences every day. The first one, near to 0, counts the many free vibrations of the element. The second and third ones, respectively around 0.06 mm/m and 0.12 mm/m, are related to trains in each direction, with stronger effects for the trains passing on the track located on the same side than the monitored bracing element. Interestingly, we notice a sudden gap with a slight diminution of the range for the last three months: this is related to works on the nearest station, inducing a reduced speed for every train, and thus lower vibrations, lower dynamic amplification, and so, lower ranges.

4.3 Massive spectral analysis

Another indicator is related to the free vibrations of the structure. Indeed, the characteristics of the vibrations are directly related to the stiffness and mass of the structure, and constitute its mechanical signature, independently from the applied loads. Some change in the characteristics of the vibrations through time, like a decrease in their frequencies, would be the sign of a loss of stiffness, usually related to damage.

The common practice for vibration analysis on civil structures is to use measurements from accelerometers or velocimeters. However, in the case of the Austerlitz viaduct, the strain sensors are sensitive enough to record the vibrations in terms of strain variations in the truss elements, instead of point displacement and its derivatives. Thus, we can use the strain data to perform the usual vibration analysis and check the stability of modal frequencies of the structure through a massive spectral analysis.

The whole dynamic dataset is analyzed by applying a Fast Fourier Transform on the signal, on 10 seconds rolling Hann windows for each event. The results from all the events of each day are then summed, for each Fourier coefficient. Finally, we can display a synthetic view of this spectral analysis at the scale of several years of monitoring, as a heat map like the one showing the strain range. The frequency of vibrations stands as Y-axis and the spectral density is released through a color scale. Again, the stability of the mechanical behavior of the structure is checked by assessing horizontal patterns in the frequency distribution. Figure 9 gives the result for the same bracing element for 41 months.

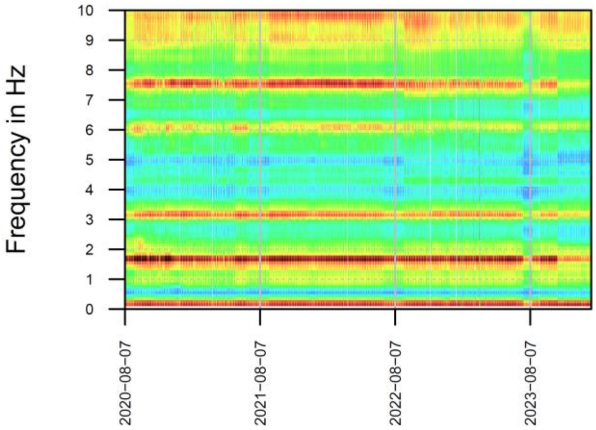

Figure 9. Vibration frequencies of a bracing element, displayed as spectral density each day

On this example, clear horizontal patterns show a good stability of the spectral density, and thus of the vibration frequencies. Four main modes are identified, at 1.7 Hz, 3.1 Hz, 6.1 Hz, and 7.6 Hz. Their frequency remains very stable for the 41 months, including for the last three months with the reduced speed: the speed of the trains does not affect the vibration frequencies, which are in relation to the mechanical state of the structure. However, the intensity of the vibrations decreases for this period: this is visible as a change in the colored pattern, with colder (diminished spectral content) patterns for the last three months.

The results of the spectral analysis have also been used to check models of the structure or of some of its elements. As an example, in 2015, the strain measurements on one hanger were analyzed to assess its residual tension, by comparing the frequency of the first bending mode of the hanger in situations with or without the load of the train. As a conclusion, despite of significant vibration amplitude, the hanger had no loss of tension.

4.4 Alert management system

Since the strain data is sent and released in real time, it is also used to manage alerts in case of unusual situations in terms of strain in the different elements of the structure.

The first alert mode is instantaneous: based on the past measurements, dynamic thresholds values are set at the maximum strain range yet recorded on a fixed rolling window of 4 seconds. This mode aims to identify extreme loads or sudden strain variations right at the time when they happen.

The second alert mode is released once a day and results from a statistical analysis of the ranges of all the events recorded in the last 24 hours. The alert thresholds are set as pairs of values: a strain range S and a quantity of events N. The alert is sent if more than N events had a range above S in the last 24 hours, for each sensor. This mode aims to check, every day, whether the tail of the distribution of strain cycle ranges remains stable. If we observe more events of higher range, and that it is confirmed for several consecutive days, it is an early sign of a stronger response of the structure to the live loads, potentially linked to damage.

5 Conclusion

The three different case studies show how various SHM solutions can reveal useful information on the mechanical behavior of historical railway viaducts, with practical applications for their management and maintenance.

The monitoring of the displacement of one bearing device for a full year allowed us to assess experimentally its real friction factors, by analyzing the bonding and sliding sequences in relation with the variation of the temperature, by means of a strongly non-linear model. In conclusion, the excessive values of the friction factors, compared to the nominal ones, explained the growth of a vertical crack in the masonry of the support and triggered the decision of replacing this type of bearing devices in full knowledge of the facts.

On the 950 m long viaduct of line 6, a numerical model, coupled to strain measurements on the cast-iron and masonry columns, allowed a fine assessment of the effects of the train braking on the whole viaduct. This has been used to anticipate the descent of loads from a new rolling stock with higher capacity, and to check that no reinforcement works were required on this viaduct, which opened in 1909.

The Austerlitz viaduct benefits from a long lasting SHM service, still operating since 2010. A sample of various structural members of the bridge is equipped with Optical Strand long-basis strain sensors. Each train rolling on the viaduct triggers a record of short duration on all sensors, which releases the response of the structure to the loads. This response is further analyzed by means of different processing tools, to assess the stability of the mechanical characteristics of the viaduct: statistical analysis of main features of each signal, massive cycle counting and spectral analysis, and automatic alerts in case of abnormal behavior.

Acknowledgements

The authors are grateful to RATP Infrastructures and Mr Rudinger for permitting the release of these case studies.

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