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OPTIMIZED DYNAMIC DESIGN RULES FOR HIGH-SPEED BRIDGES BY USING DIGITAL TWIN

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Abstract

Dynamic behaviors of bridges on high-speed railway are often the main criteria in bridges design. It has a huge impact on the technical choices and thus on the building cost. In the European Union, civil engineers rely on the Eurocode standards which defines the dynamic constitutive law for bridge designing. Those laws were based on the results of the European research program ERRI with few experimental test results. Therefore, to guarantee the structural safety, the design rules are disadvantageous that implies the design of oversized bridges and thus extra building costs.
In the interest of improving the safety of the infrastructure and optimizing the cost, SNCF Réseau realized a research program in a two-step approach. Firstly, it has carried out a great monitoring campaign of its bridges on the high-speed railway network. This experimental campaign consists of measuring the acceleration and the dynamic displacement of the deck under train traffic. Secondly, we create a digital twin of measured bridges by modeling them with an in-house software for dynamic solution. An important number of measurement data were used to correct the simulation of the digital twin. In the end, through the digital twin of bridges, we were able to refine the dynamic constitutive law of bridges by extracting the adjusted values like the damping coefficient or the structural stiffness from the numeric model.

Keywords: Digital Twin, Dynamic Bridge Behavior.

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1 MOTIVATION OF THE PROJECT

The consideration of dynamic effects is often critical for the design of rail bridges, particularly for high-speed. As the speed of a train increases on a bridge, the effects of the loading on the bridge intensifies compared to the corresponding static values. Thus, the deflection, bending stresses and similar effects due to torsion and shear stresses are higher than the static values. Annex A2 of Eurocode 0 [4] presents the deformation and vibration checks for railway bridges. The points to be checked in the dynamic calculations are the deck twist, the vertical deflection, the transverse and longitudinal displacements of the deck and the uplift of the bearings. In addition to these criteria, the limitation of the vertical accelerations of the bridge must be considered. This criterion is one of the most important safety parameters for ballasted bridges. Excessive acceleration can lead to reduce the interlocking of the ballast and consequently to reduce the friction at the interfaces between sleepers/ballast and ballast/deck. Under these conditions, the bearing of the track by the ballast is no longer guaranteed, increasing the risk of track buckling in warm weather.

These excessive accelerations are due to resonance effects between the bridge and the regularly spaced loads of the rolling stock. This phenomenon was detected at the opening of the first high-speed line in France. The passage of TGVs at 250 km/h caused excessive vibrations destabilizing the ballast on several structures. One of bridges caused a track buckling. After this incident, studies and laboratory tests were undertaken by the European Railway Research Institute (ERRI) to determine a permissible vertical acceleration limit for bridges on high-speed railway. The results of the tests [4] indicated that unfavorable dynamic behavior of the ballast occurred at deck accelerations exceeding 7 $m \cdot s^{-2}$. The current regulatory limit for the design of new structures has been limited to 3.5 $m \cdot s^{-2}$ by EN 1990 [5].

To determine the accelerations of bridges under rail traffic, it is necessary to identify the parameters that dominate the dynamic response. The boundary conditions of the deck, the skew, the span, the mass, the stiffness, and the damping must all be carefully considered to be relevant in the dynamic simulations. Damping is particularly important because it characterize how the energy dissipated and thus how the amplitudes of the oscillations are reduced. But damping is difficult to quantify and depends on many parameters (materials, support conditions, type of structure, etc.).

The critical damping coefficient expressed in percentage can be deduced from the acceleration measurements made at mid-span of the structure. In free oscillation, when the load is no longer present on the bridge, the oscillations decrease, and this decreasing rate can be used to determine the damping. However, this parameter has a large dispersion because it depends on the stresses, and it is therefore necessary to carry out numerous measurements to deduce a reliable value. In the absence of sufficiently numerous data, the statistical values indicated in the Eurocode 1991-2 must be used. These values come from tests carried out in the framework of the work of committee D 214 [4], the number of exploitable results was very limited, and no results could be obtained in the vicinity of resonance speeds given the danger of the phenomenon for traffic. The laws used for damping are therefore very conservative and have a very important impact on the design cost of rail bridges.

Therefore, SNCF has initiated a major test campaign in order to obtain more relevant data, particularly in the vicinity of the resonance speed. To do this, new measurement methods have been developed to adapt to the strong constraints on railway, particularly on high-speed railway. Numerous tests have been carried out on the entire network, and more than a hundred structures have been instrumented by SNCF since the first high-speed railway was put in use.

Finally, the tests were compared with the results of numerical simulations and helped to create digital twins of the bridges, facilitating in the future the verification of the dynamic compatibility of new rolling stock.

2 MONITORING CAMPAIGN OF BRIDGES

The railway infrastructure of SNCF has around 30 000 railway bridges with a span greater than 2 m. The monitoring campaign could be limited to a subset of bridges. They are selected in order to have a panel of bridges covering the different kind of bearing, numbers of spans, numbers of tracks and the rolling stock.

Bridge type	Number
Masonry bridge	12 000
Filler beam bridge	7 000
Reinforced or prestressed concrete slab bridge	5 000
Modern metal or composite steel/concrete bridge	4 000
Old metal bridge	2 000

Table 1: Distribution of bridge types in the French railway network.

Instrumentation of bridges was to measure the vertical acceleration and dynamic displacement of the deck at its mid-span while a train was traveling. Measure should be sampled at 108 Hz at least which is the Nyquist frequency of 2 axles at the highest speed. The maximum speed on the French railway network is 350 km/h (97.2 m/s) and the minimal distance between 2 axles in bogie is 1.8 m, which gives a frequency of 54 Hz.

There are many constraints in the high-speed infrastructure. Access to the tracks is highly controlled, and installation the measuring equipment can require halting the train running which strongly increases the cost of the monitoring campaign. The sensors should be installable from underneath the bridge without having an impact on the gauge below.

2.1 Acceleration measurement

For measuring the acceleration, we used the wireless MEMS accelerometer G-Link-200 from Lord Microstrain. They were mounting on magnetic base to be installed directly upon metallic surface. In the case of reinforced concrete deck, a steel plate was preinstalled on the lower side if the deck.

Accelerometers were configured with a sampling rate of 4 096 Hz, a measurement range of 8g, a low-pass filtering at 800 Hz, and no high-pass filter. Acceleration recording were manually triggered.

2.2 Displacement measurement

The digital book [1] presents several instruments used in civil engineering to measure the displacement of the deck. For the dynamic displacement, there is 4 ways to measure it:

- A rod made in a material with a low thermal expansion coefficient (often rod in Invar) is fixed under the bridge on one side and connected on the other side to an instrument which records the displacement. The instrument can be a rotating drum with an arm to graph the displacement (“Jules Richard” mechanical fleximeter) or a displacement sensor like a LVDT.

It's an affordable solution but its installation and use are quite constraining because the area under the measurement point must be free of traffic during the record. It cannot be used if the measurement point is over a river.

- A motorized theodolite tracks a retroflector on the bridge and records its rotations. The displacement is computed by triangulation.

  Unlike the first solution, there are very few constraints on the installation et use. But equipment able to measure the position of a reference at 108 Hz are expensive. Moreover, the accuracy depends strongly on the distance from the bridge because the displacement is computed by triangulation.

- A laser emitter installed outside the bridge (fixed reference) points to an instrument able to track the laser beam (Flexigraph LASER) fixed on the deck. Inside the instrument, there is a light-sensitive sensor able to move. The instrument centers the sensor on the laser beam and records the movement which corresponds to the displacement of the deck.

  Like the motorized theodolite, the use has few constraints, and the displacement is directly recorded. However, the installation can be cumbersome because the equipment is heavy and must be strongly fixed to the deck. Because of the equipment size, it cannot be installed where the gauge below the deck is limited.

- Railway bridges have sometime a concrete beam next to the deck called heavy shoulder. They are installed for protecting the deck against vehicle collisions and are independent of the deck. The vertical displacement of the deck can be measure by measuring the distance between the deck and the heavy shoulder with a distance sensor as shown in figure 1.

  It a low cost, easy to install and easy to use solution. But not all bridges have heavy shoulders, and because we monitor bridges on highspeed line there are constraints for accessing to heavy shoulders from tracks. Another problem is the heavy shoulders have the same bridge support as the deck. They vibrate during the passage of trains bringing measurement errors. We use a laser distance sensor from ACUITY.

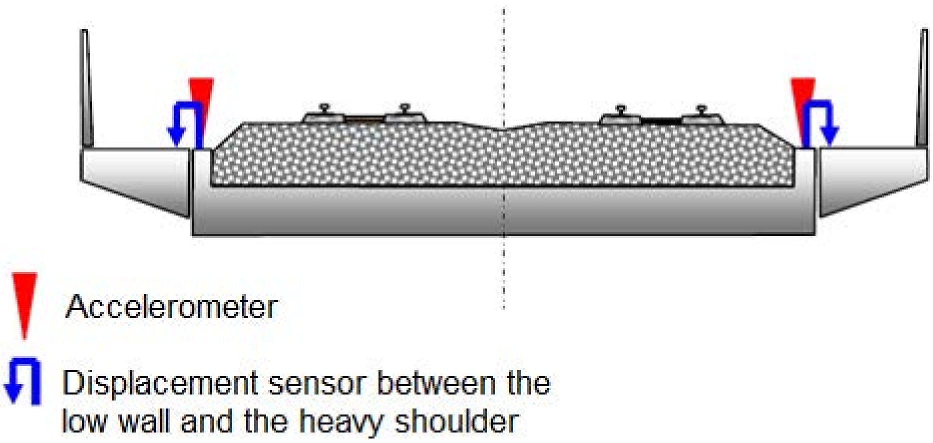
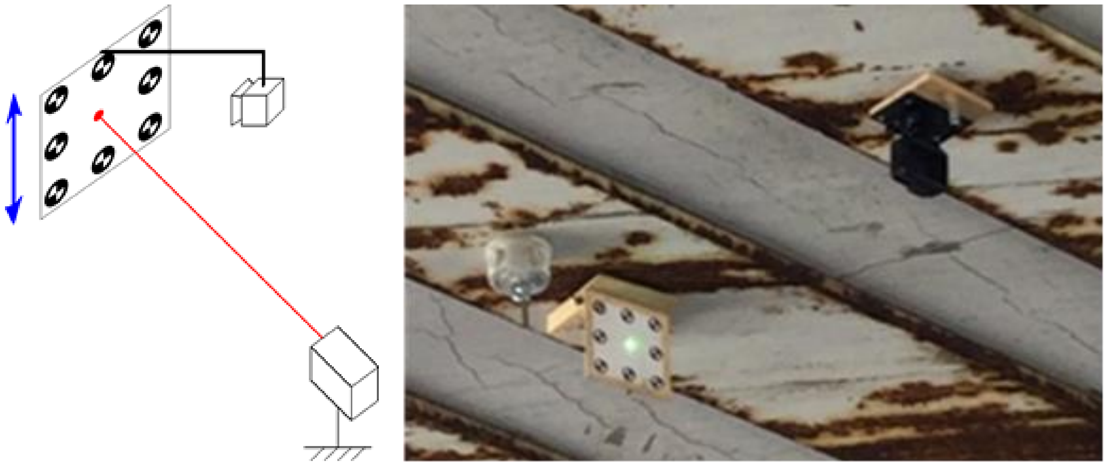


Figure 1: Layout of the sensors when measurement is taken from heavy shoulders

The first 3 measurement system cannot be used because there are expensive and/or not practical. The last one can be used for just a subset of bridges which contains mainly metal bridges. For those reasons, we had to develop an instrument which is easy to install, to use and ideally cheap [2]. The solution created works on the principle to track a laser beam on a normalized target with a camera. The target and the camera are installed on the deck. The laser emitter is outside the bridge for creating a fixed reference.



(a) (b)

Figure 2: Schema of the system tracking (a) and photo of the system installed under a bridge deck (b)

On the target, 8 beacons are printed, including one that represents the origin. When the deck moves, the beacons move relative to the laser dot of the emitter. The camera records the displacement of the dot relative to the beacons.

Figure 3: Processed image from the video with the laser dot position

Then the video is processed to extract the position of the dot relative to the beacons thanks to an in-house software (figure 5). Its algorithm is presented figure 4.

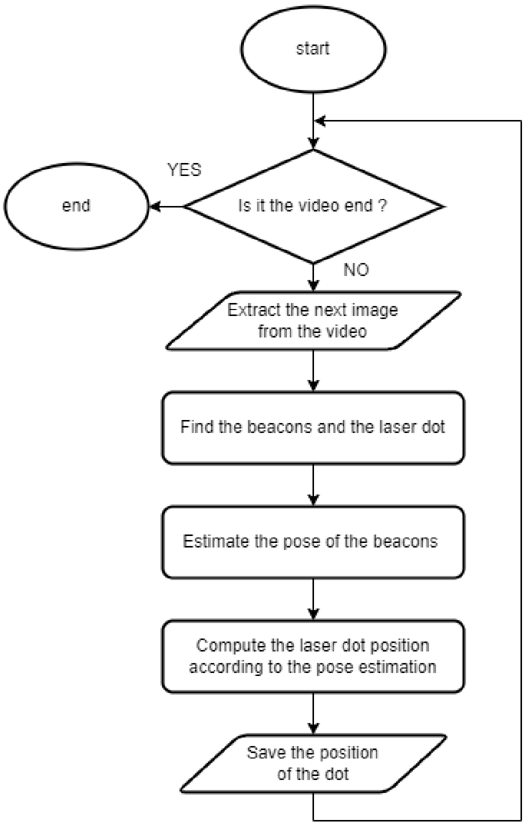


Figure 4: Algorithm for extracting the displacement from the video

For detecting the beacons, the contrast of the image is improved, and threshold is applied to keep the darkest pixels. Then a blob detection is applied on the black pixels. The beacon representing the origin is recognized by finding the beacon which has more black pixels. For detecting the laser dot, we apply a threshold to keep the brightest pixels then we apply a blob detection on the white pixels. The beacons on the target form a square of 80 mm by 80 mm. We compute the homography matrix (pose estimation) between their real positions and their position on the image. The matrix is used for computing the real position of the laser dot on the target.

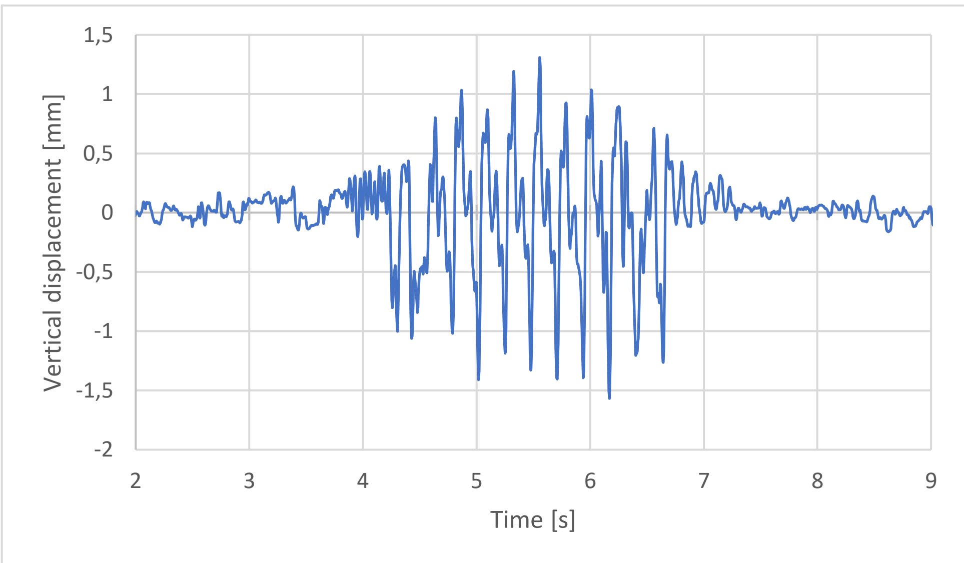


Figure 5: Resulting graph of the vertical displacement of a deck

The system is very inexpensive. We use a simple laser pointer. For the camera, we use an action camera because there are cheap, small, wireless, and able to record a video at a framerate higher than 110 Hz. We used a GoPro Hero 5 recording at 240 frame per second with a resolution 720×1280 pixels. The target and the camera were mounted on magnetic bases to be installed like the accelerometers. The camera was manually triggered.

3 EXTRACTING OF THE DYNAMIC CHARACTERISTICS

For each deck and train travels, we have an acceleration and a displacement signal. the following dynamic characteristics to be compared to the numerical simulation:

- The absolute maximal displacement
- The 1st natural frequency of the unloaded deck
- The damping of the unloaded deck
- The absolute maximal acceleration

On the acceleration signal, we firstly apply high-pass frequency with a cut-off frequency of 0.5 Hz to remove the constant component in the signal. In the free vibration period, we extract the 1st natural frequency by applying a Fourier transform.

For computing the damping coefficient, we use the Logarithmic Decrement method by selecting local maximal values in the free vibration period, or the Peak-Picking method by selecting the 1st natural frequency and computing the Q-factor (bandwidth of the peak at -3 dB). We keep the lowest value of both. the Peak-Picking method is more robust than the Logarithmic Decrement method when the structure is a little excited, but the 1st frequency must be well separated from the 2nd one. The Logarithmic Decrement method is less sensitive in this case, but the free vibration period must be clearly visible (for vibrations less than 0.3 m/s^2, damping is strongly underestimated. Figure 6 shows the signal processing.

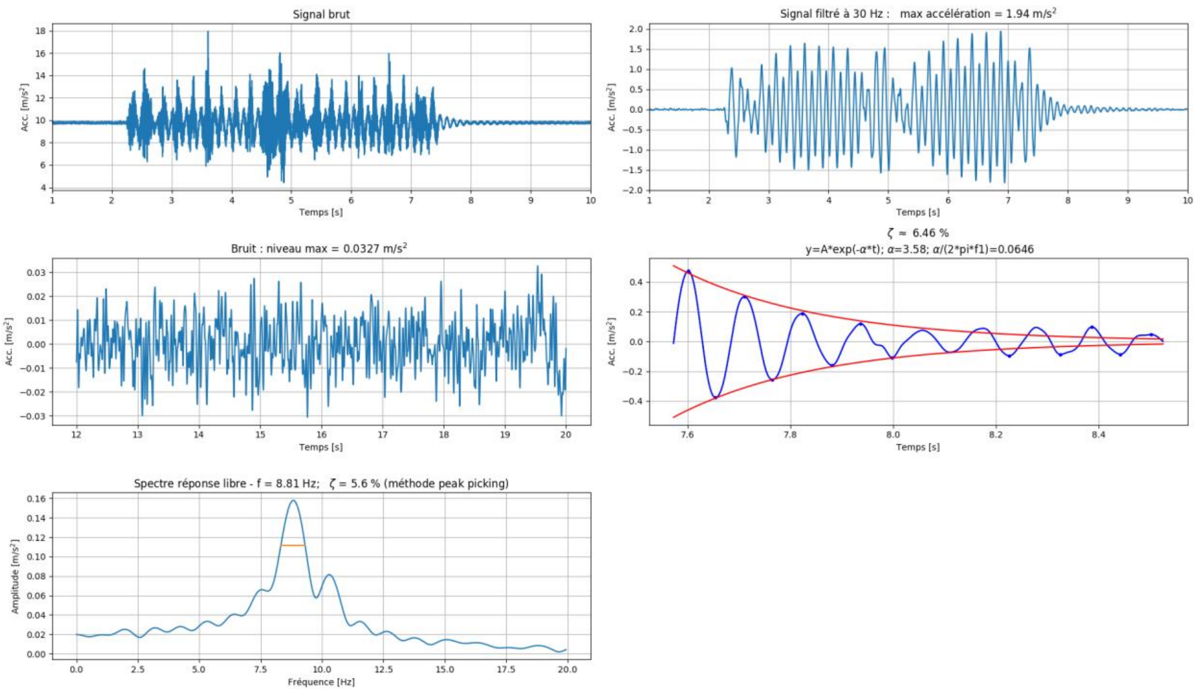


Figure 6: Result from the signal processing for a reinforced concrete slab bridge with a 12 m span under a TGV MU at 282 km/h

For extracting the absolute maximal acceleration, we apply a low-pass filter with a cut-off frequency at 30 Hz. We extract the absolute maximal acceleration in the signal, excluding isolated peaks because they don't contribute to destabilize the ballast (figure 13 shows a peak which is excluded).

On the displacement signal, we remove the constant component by applying a high-pass frequency with a cut-off frequency of 0.5 Hz and a low-pass filter with a cut-off frequency at 30 Hz. Then we extract the absolute maximal displacement.

After the processing, we have a table with the dynamic characteristics for each deck like the table 2. There are compared the numerical simulation and used for fitting our digital twins of bridges.

Train	Speed [km/h]	Displacement [mm]	Acceleration [m/s²]	Natural frequency [Hz]	Damping [%]
TGV SU	281	2.0	1.8	8.9	4.1%
TGV SU	293	2.0	2.2	8.9	5.3%
TGV MU	282	2.1	1.9	8.9	5.6%
TGV SU	283	-	1.8	8.8	5.2%
TGV MU	285	-	2.1	8.9	3.9%
TGV MU	291	-	2.1	8.9	3.9%
TGV US	293	2.1	2.1	8.8	3.9%
TGV	240	-	0.9	9.8	2.5%
TGV	262	-	1.2	-	-
TGV	272	-	1.1	-	-

Table 2: Results for a reinforced concrete deck on the high-speed railway.

For each measure, we note the kind of train. The speed of the train is estimated from the acceleration signal or displacement signal knowing the kind of train. A peak in the forced vibration period corresponds to the passage of a bogie. Dividing the distance between 2 bogies by the duration between 2 peaks gives the speed of the train.

4 MEASURES AND COMPARAISON WITH SIMULATIONS

The measurement campaign concerned all types of rail bridge (metal, composite, concrete, filler-beam) in proportion to their number on the network. Figures 7 to 9 show critical damping and maximal acceleration for different kind of bridges.

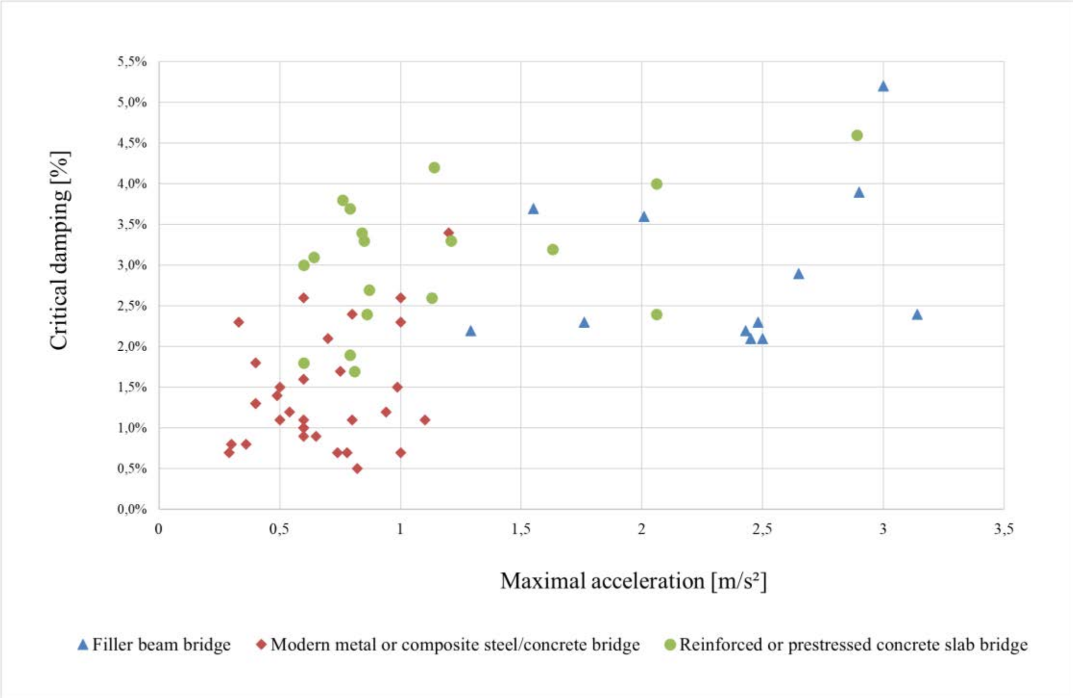


Figure 7: Critical damping according to the maximum acceleration for different kind of bridges

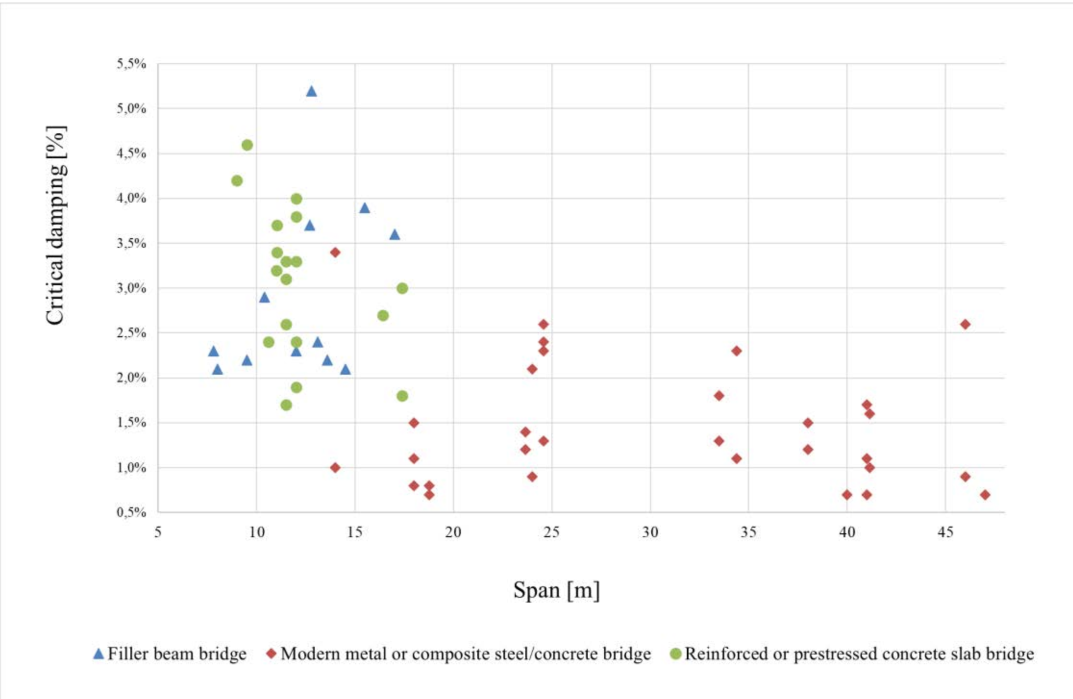


Figure 8: Critical damping percentage according to span for different kind of bridges

Metal and composite bridges have a critical damping around 0.75% which is higher by 50% than the value of 0.5% recommended by the Eurocodes for those kinds of bridges. For the concrete slab bridges or filler beam bridges, minimal values of damping correspond to ones from the Eurocodes.

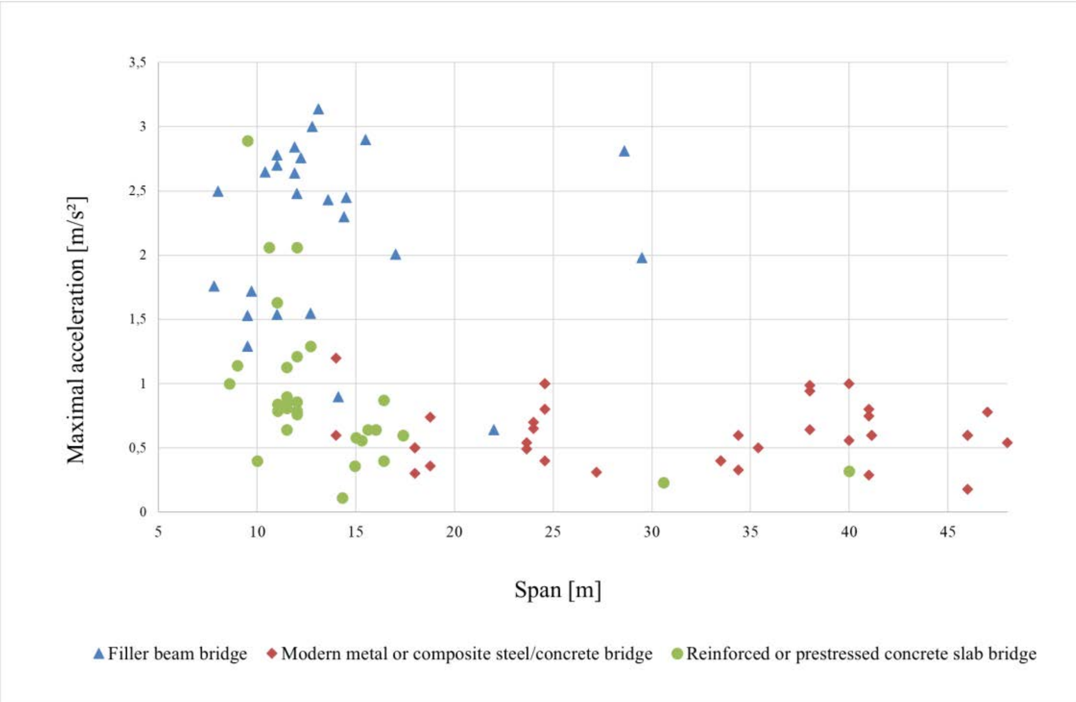


Figure 9: Maximal acceleration according to the span for different kind of bridges

The results confirmed that the most sensitive structures in terms of dynamics are the short, very slender structures with a high-speed traffic. Decks with coated girders and isostatic concrete slabs carrying a single track are the most sensitive. These kinds of structures became scarcer on new high-speed lines. Thus, instrumentation was mostly carried out on the oldest high-speed line designed before the advent of dynamic rules. On this line, the encased girder bridges were mainly reinforced to meet the regulatory criteria, however some reinforced concrete structures were kept as is and present a significant slenderness which is very interesting for studying the dynamic behavior of bridges.

As an example, figures 10 to 14 below illustrate the comparison between the different measurements carried out on an isostatic reinforced concrete slab bridge with a span of 12 m and a natural frequency of 8.8 Hz equal to twice the exciting frequency of the high-speed train which is 4.4 Hz. The exciting frequency is equal to the train speed (296 km/h) by the distance between the train bogies (18.7 m).

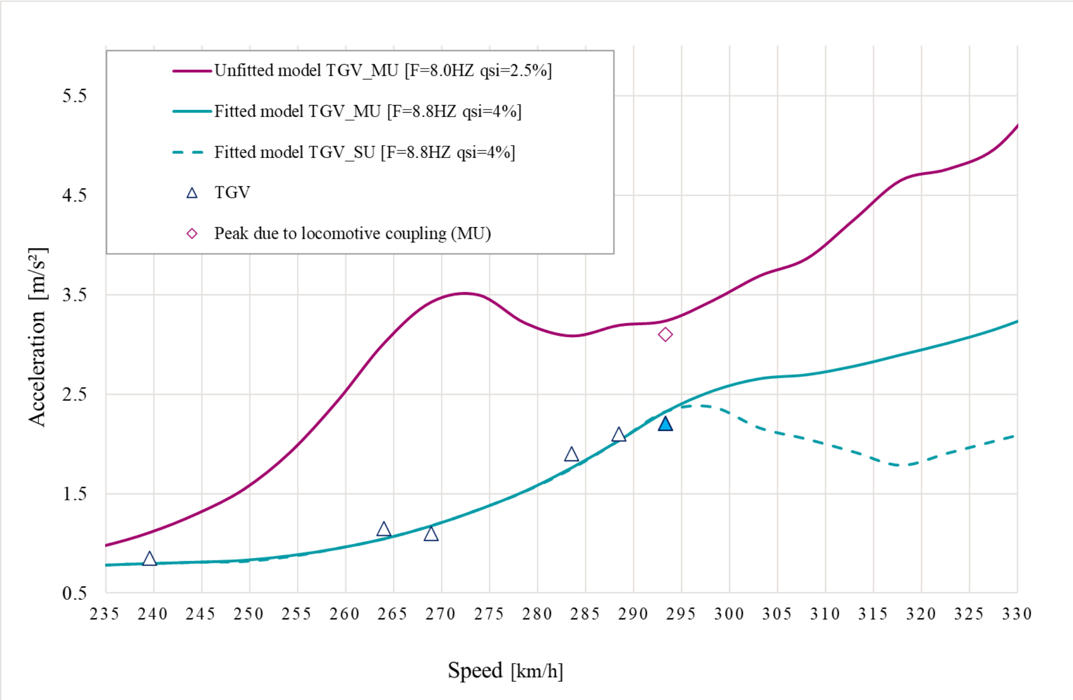


Figure 10: Comparison of the acceleration between measurement results and the digital twin

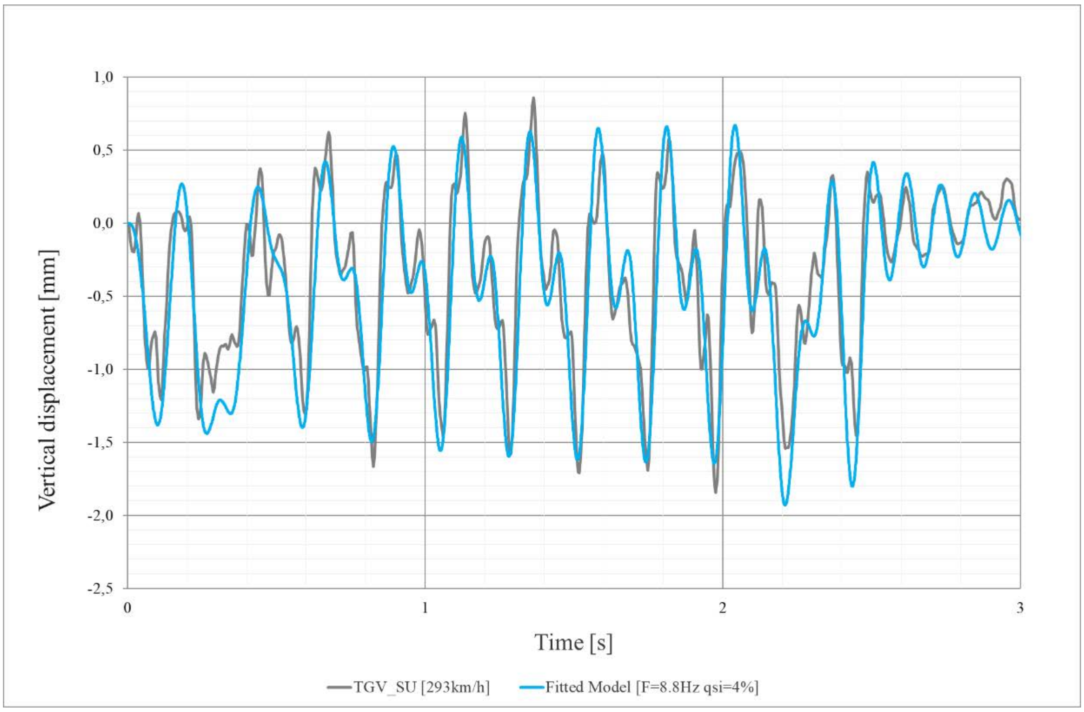


Figure 11: Comparison of the vertical displacement between measurement results and the digital twin TGV SU at 293 km/h

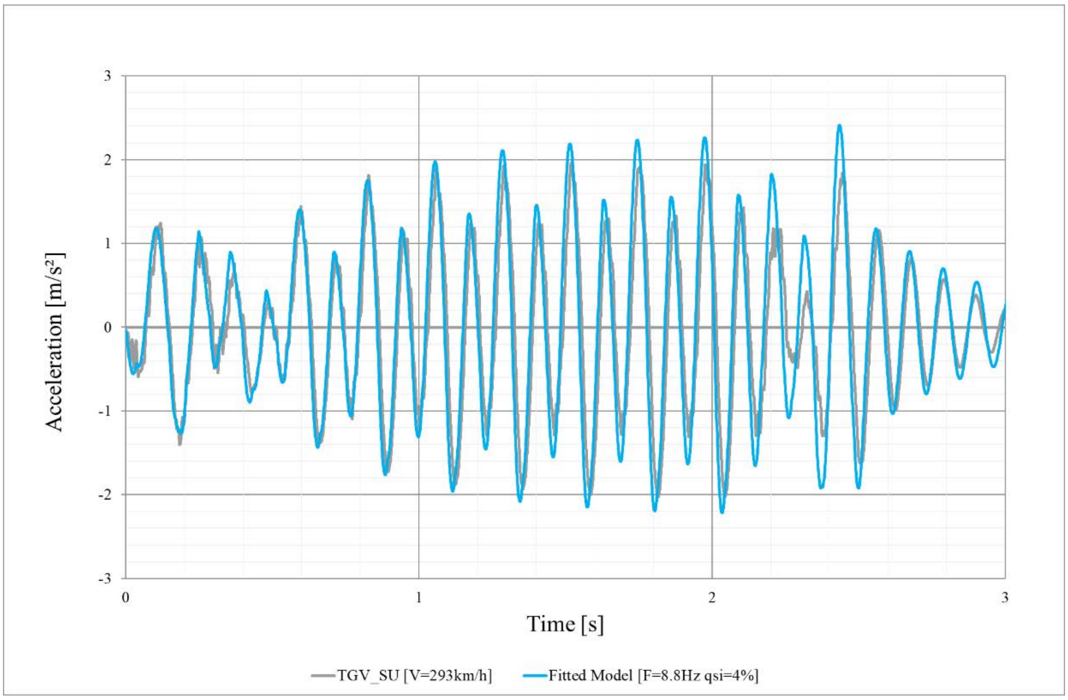


Figure 12: Comparison of the acceleration between measurement results and the digital twin for TGV SU at 293 km/h

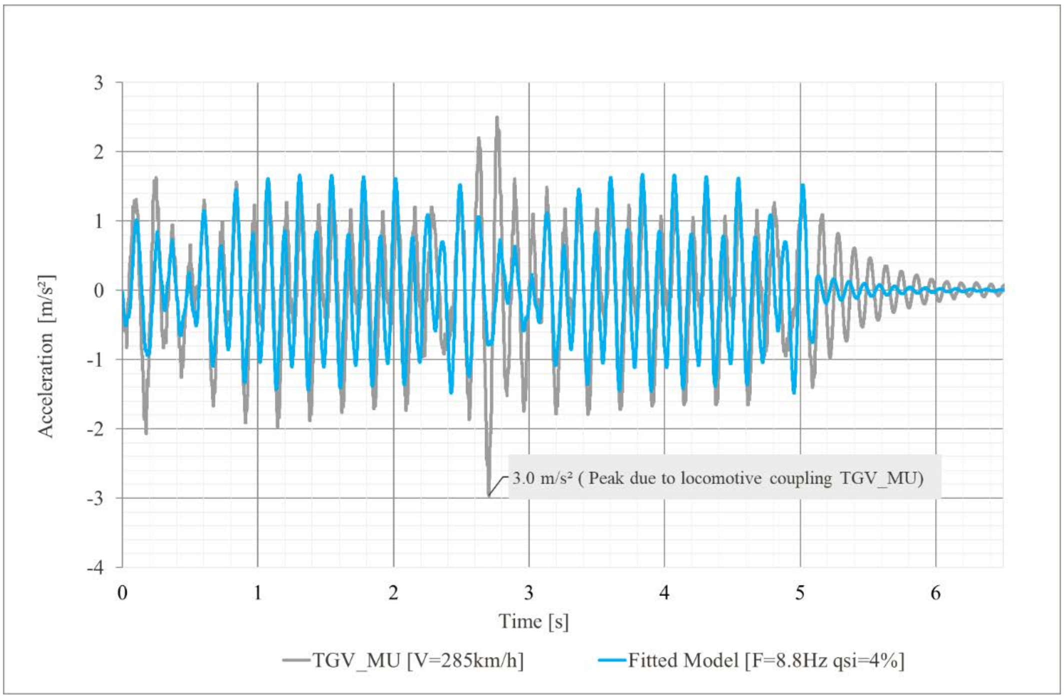


Figure 13: Comparison of the acceleration between measurement results and the digital twin for a TGV MU at 285 km/h.

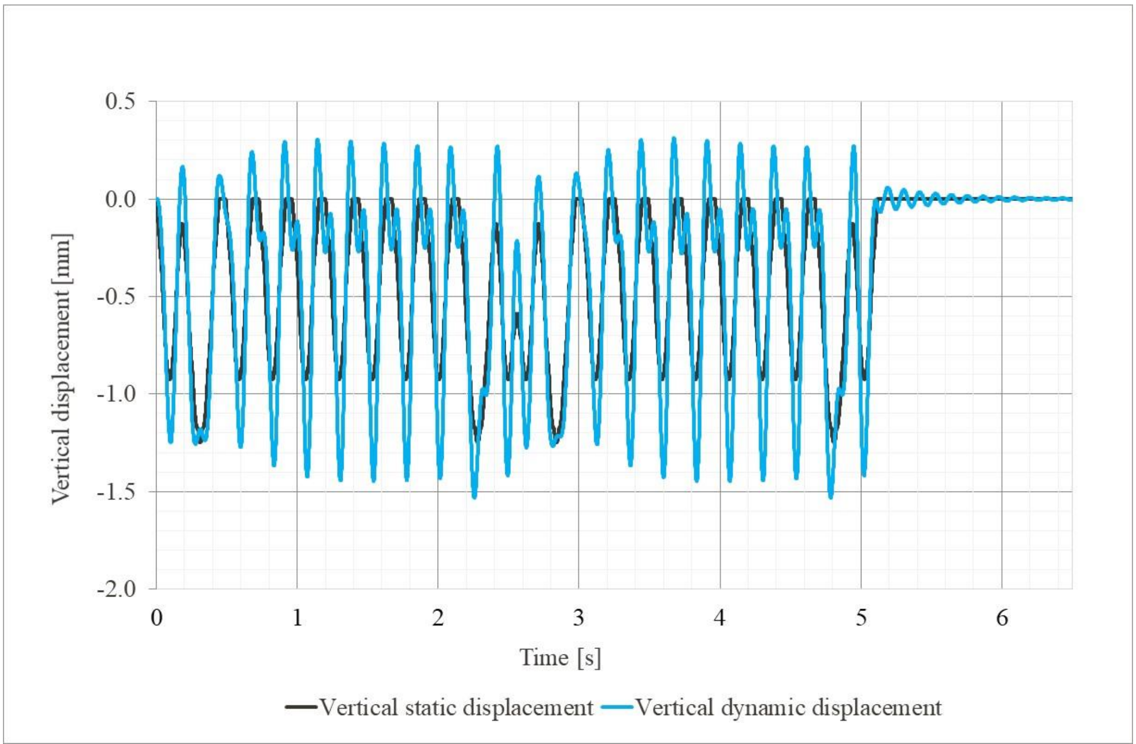


Figure 14: Comparison between the static and the dynamic vertical displacement for digital twin for a TGV MU at 285 km/h.

It can be noted that there is a very good correlation in acceleration and vertical displacement between the results of the measurements and the simulations of a TGV Simple Unit (TGV SU). The first natural frequency (8.8 Hz) corresponds to the one for a model with the stiffness of an uncracked concrete section. The critical damping is higher than the one recommended by the Eurocodes. However, in the figure 13, there is an acceleration peak caused by the coupling between 2 locomotives in a TGV Multiple Unit (TGV MU). The deck bends more under the overload of bogies of the 2 locomotives. The vertical displacement and the acceleration are close to values from a model with the stiffness of a cracked concrete section (figures 9 to 13). In this case, the 1st natural frequency is 8.0 Hz.

5 CONCLUSION

The monitoring of high-speed was like the monitoring presented in the article [5]. The keys differences on the monitoring part were that we instrument a greater number of bridges. And besides the measurement of the acceleration, we measure the vertical displacement. It required the development of a new measuring tool adapted to the constraints in the railway environment. It has been the subject of a patent [2].

Results of instrumentations and numerical simulations show that for concrete and coated beam constructions, the deck stiffness is almost always underestimated. The cracking assumptions adopted by the Eurocodes are relevant for verifications under heavy loads at low speeds (freight wagon at 22.5 tons per axle travelling at 100km/h) however they are too pessimistic in most cases studied for verifications under light loads at high speeds (fast train at 17 tons per axle travelling at 320km/h).

Similarly, the damping values obtained from the measurements are higher than those recommended by the Eurocode [4]. The latter are too pessimistic, especially for composite bridges whose span values lead to a very low damping in the order to 0.5%. This value leads to oversize the structures and thus extra costs of construction. Consequently, a statistical analysis of all the data from the tests is underway to define optimized design rules.

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