First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Monitoring and Evaluation of Structural Safety of Railway Bridges

W. S. ASSIS[1], A. P. C. NETO[2], R. MONTOYA[3] and T. N. BITTENCOURT[4]

[1] Federal University of Alagoas, Maceió, Brazil
[2] Polytechnic School of the University of São Paulo, São Paulo, Brazil
[3] Vale, Vitória, Brazil
[4] Polytechnic School of the University of São Paulo, São Paulo, Brazil

ABSTRACT: The degradation of structural elements of railway bridges is a concerning problem. Usually, it results from factors such as aging and deterioration of materials, increased traffic load, environmental attack, and sometimes even from poor design, bad detailing or construction. In this context, in many situations it is important to evaluate safety and develop strategies for repairing and service. These strategies are associated with the structural elements conditions which can be compromised due to different degradation processes. It is fundamental to find out whether these processes are in early or advanced stages and to investigate the causes for this deterioration in order to mitigate them or, in order circumstances, tolerate them. For this purpose, structural monitoring features have been increasingly used in the analysis of such existing structures.

In this paper, an application case of structural monitoring techniques to railway bridges is described. The information necessary to quantify and qualify the safety and serviceability responses of these structures is gathered. Measurements have been obtained during different and controlled train passages, and a network of sensors consisting of strain gages, displacement transducers, accelerometers and fiber optic sensors have been employed. The interpretation of the obtained data has allowed the evaluation of the bridge elements which is crucial for the characterization of the structural safety with respect to traffic loads and vibration.

1 INTRODUCTION

One of the most important characteristics of the rail transport system is its ability to carry large volumes and masses with high energy efficiency, especially when it involves the displacement made medium and large distances. Often, the railway infrastructure requires the construction of bridges in remote locations in which to carry out inspections and maintenance does not always occur with appropriate frequency. Combining these factors with the increasing demands of business and the goods carried, the bridges are subjected to degradation, which often is only alleviated when, for security reasons, the exploitation is restricted. Internationally, it appears that the costs associated with restricted use are increasingly high (Marecos, 2008).

In this scenario, the structural monitoring assumes increasing relevance, which through the use of sensors and non-destructive equipment, coupled with an analysis of the structural system, enables a periodic or continuous evaluation of the integrity and safety of the monitored structures (Thakkar, 2006). In Brazil, some research projects are being developed in order to assess the safety and serviceability of selected railway bridges, employing structural monitoring resources. In the next items, will be describe the application of monitoring techniques in a railway steel bridge used by Vale, a Brazilian mining company, within a research project in development, presenting a discussion of results and conclusions of the work conducted.

2 STRUCTURAL MONITORING OF THE SUAÇUÍ RIVER BRIDGE

2.1 Purpose of monitoring

The goal of monitoring performed on the Suaçuí River Bridge is to gather the information needed to quantify and qualify the response of the structure about their safety as well as provide background information for planning and carrying out actions such as: detailed inspections of the structure; theoretical studies on the behavior of the structure and its elements through numerical simulation; decision-making regarding the maintenance and define strategies to strengthen or replace structural components (Bittencourt, 2009).

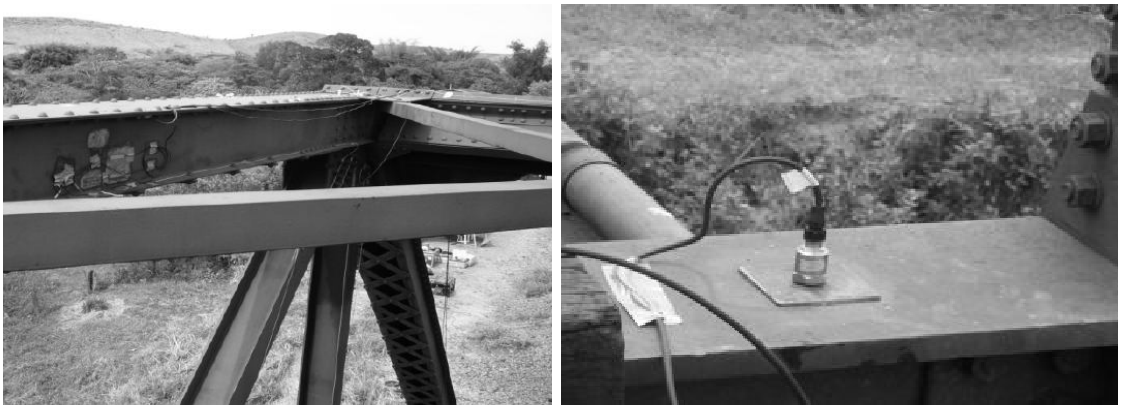
2.2 Structural description

Located in the Vitória-Minas railway, in Baguari, Brazil, the Suaçuí River Bridge, shown in Figure 1, is a metallic bridge constructed in the 40's and has a span of 41 meters and height of 7,8 meters. Its superstructure is made of two Warren truss supported at the ends by metallic structural bearings. The trusses are interlinked in its lower region by transverse floor beams, with approximately 4,5 meters long, and stringers that connects to transverse floor beams. Over the stringers are supported the wooden sleepers, and over these, the rails. Nodal connections are made of riveted steel plates.

Figure 1. General view of the Suaçuí River Bridge.

2.3 Instrumentation plan

In Suaçuí River Bridge, 24 elements were instrumented, including truss bars, transverse floor beams, stringers and structural bearings. The sensor network installed was composed by 25 conventional sensors (measuring strains and displacements), 4 piezoelectric accelerometers and 4 fiber optic strain sensors. The railway track giving access to the bridge was instrumented with a system of transducers for measurement of wheel loads and detection of passage of axles, consisting of strain gages installed properly. Some of the sensors are presented in figure 2.



(a) (b)

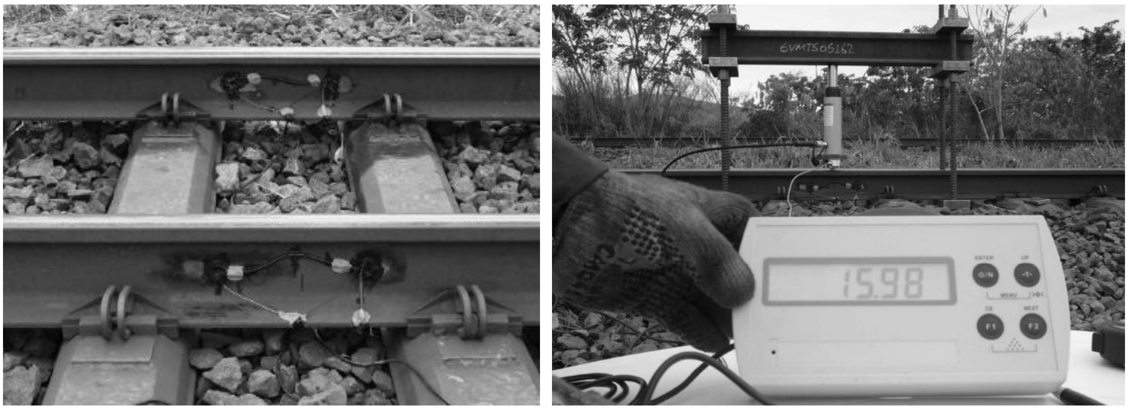
Figure 2. Strain gages and fiber optic sensors installed in the top chord (a) and accelerometer in the transverse floor beams.

The main activities related with the placement of the equipment and also the local monitoring were executed by a group of Structural and Materials Laboratory (LEM) from the Department of Structural and Geotechnical Engineering of Polytechnic School of the University of São Paulo (EPUSP). The installation and measurement of fiber optic sensors was conducted by technicians of the Lupatech company.

2.4 Static load field test

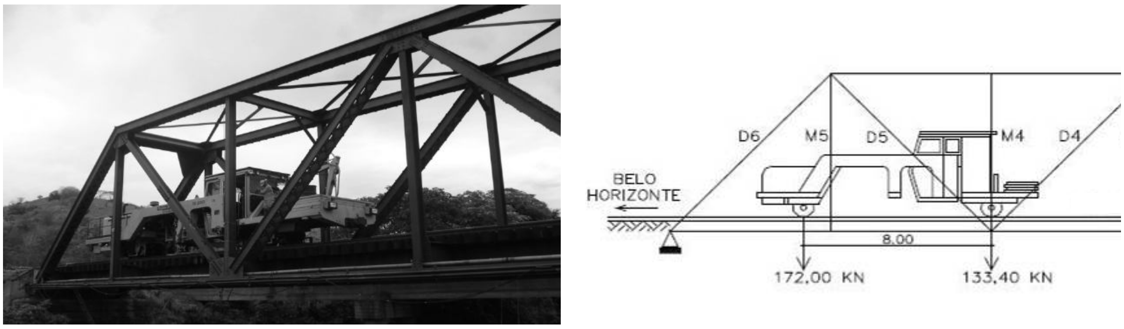
According to the monitoring project, the strain measurement in several pre-determined points on transverse floor beams was carried out with a machine Plasser, being considered ten loading cases. Subsequently, the experimental values were compared with results of numerical model of the bridge.

The use of the machine Plasser occurred at 23th September 2009, and before the start of the measurements, the vehicle wheel loads were determined using a special arrangement of strain gages installed in one of the rails, previously calibrated, as shown in Figure 3. Axle loads were estimated by taking twice the value of the load wheel, for each axle. Figure 4 illustrates the Plasser machine positioned on the floor beam under the vertical M4 of the bridge.



(a) (b)

Figure 3. Special arrangement of strain gages for measure of wheel loads (a) and his calibration (b).



(a) (b)

Figure 4. Plasser machine in the bridge during monitoring operations, with front axle on the vertical M4 (a) and his correspondent scheme (b).

The strains of primary interest were those obtained before the vehicle reach the bridge (reference readings) and those found at each stop in the positions of interest (readings for the deformed structure). This procedure, referring to taking reference readings, was adopted as standard for all measurements, with all sensors. In each situation of interest, the final value of the measured quantity was found by subtracting the value of reference of the original value.

2.5 Quasi-static and dynamic load field tests

The pass of a train called Viliato, consisting of locomotive and four wagons (Figure 5) had been object of monitoring at 23th September 2009. This train passed through in four different nominal speeds (5 km/h, 14 km/h, 25 km/h and 35 km/h). The measurements in the speed of 5km/h correspond to a quasi-static solicitation of the bridge structure and allow comparisons with the correspondent computational model. The weighing of axles was held at this speed, while in the other speeds the wheel load transducer was used only for detection of the axles of the train, allowing, once known distances between axles of the locomotive, to estimate the effective speeds during the passages of composition. Measurements at different speeds of 5 km/h were performed to analyze the dynamic behavior of the structure.

The crossing of passenger trains and freight trains empty and loaded was monitored on 23 and 24th September 2009. Were considered normal operating conditions at the track and, in some cases, was requested that the trains crossed the bridge at speeds previously established, performing the measurement of strains, displacements and accelerations.

(a) (b)

Figure 5. Viliato train in the bridge during monitoring operations: locomotive (a) and wagons (b).

3 OBTAINED RESULTS

The main results of strains, displacements, wheel loads and accelerations obtained during monitoring of the bridge, when the passage of trains, are presented below in the form of tables and charts, being performed comparisons between experimental values and results provided by the computational model.

The results of acceleration measurements have been studied and are presented in terms of analysis in the time and frequency domains, allowing understand the dynamic behavior of the bridge during the passage of trains.

3.1 Strains and displacements

The strains measured during the pass of the Plasser machine were relatively small. The absolute value of higher strain, $99x10^{-6}$ m/m, tracting the structural element, occurred in one of the stringers (VL1 - sensor E1-S1-L1i), representing a stress of 7.9% of the yield stress of steel profiles used in the structure. Figure 6 is shown the location of some strain gages installed.

When the passage of the Viliato train, the measured strains in the structure, for quasi-static case (moving at 5 km/h) and for the other situations (14 km/h 25 km/h and 35km/h), were also relatively small. The absolute value of higher strain, $142x10^{-6}$ m/m, tensile strain, was also provided by the sensor E1-S1-L1i, representing a stress of 11.2% of the yield stress of steel profiles.

In the numerical simulation of the bridge was used the SAP 2000, a commercial software based on the finite element method. The mechanical and geometric properties of the steel profiles were made according to the results of physical characterization tests and inspections of the bridge. An illustration of the generated model is shown in Figure 7

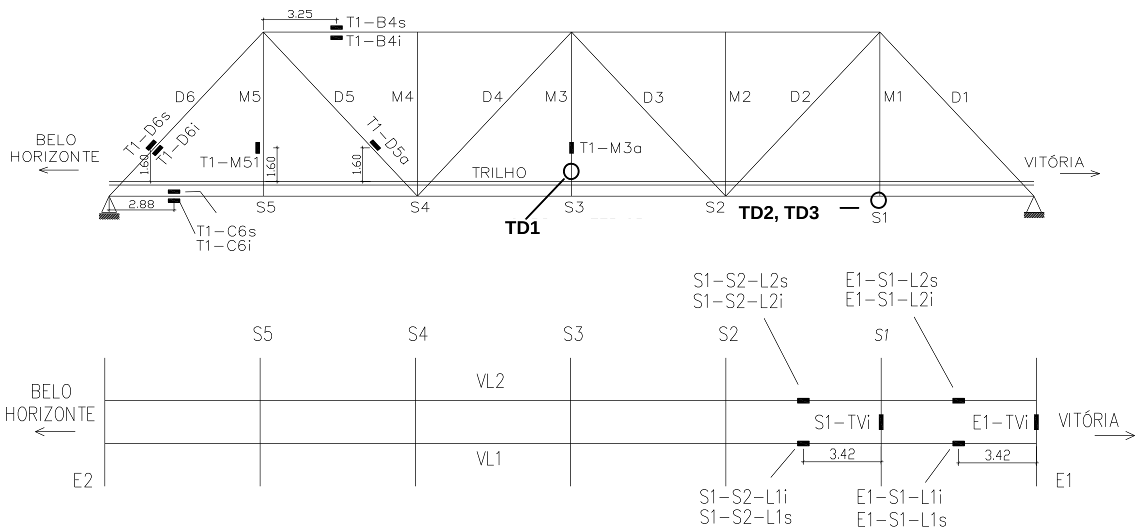


Figure 6. Location of some strain and displacement sensors installed on the bridge.

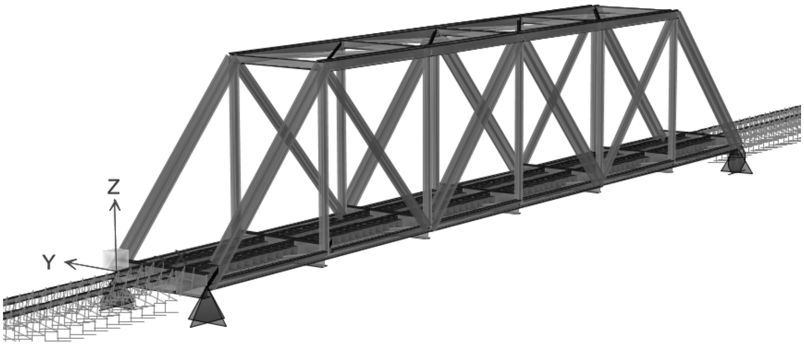


Figure 7. Perspective view of the computational model developed to the Suaçuí River Bridge.

From the modeling, was obtained the highest values of strain and displacement at points where the strain sensors and displacement transducers were positioned, for comparison with the experimental results.

Through the study of the strains obtained experimentally and numerically, for the crossings of Viliato train, was found that there are no significant variations between the results obtained, also allowing conclude that the dynamic effect is unrepresentative for the loadings and speeds analyzed. Figure 8 presents a comparison between the maximum strain obtained from different sensors and from the computer model, when the Viliato crossed the bridge at a speed of 5 km/h and 25 km/h.

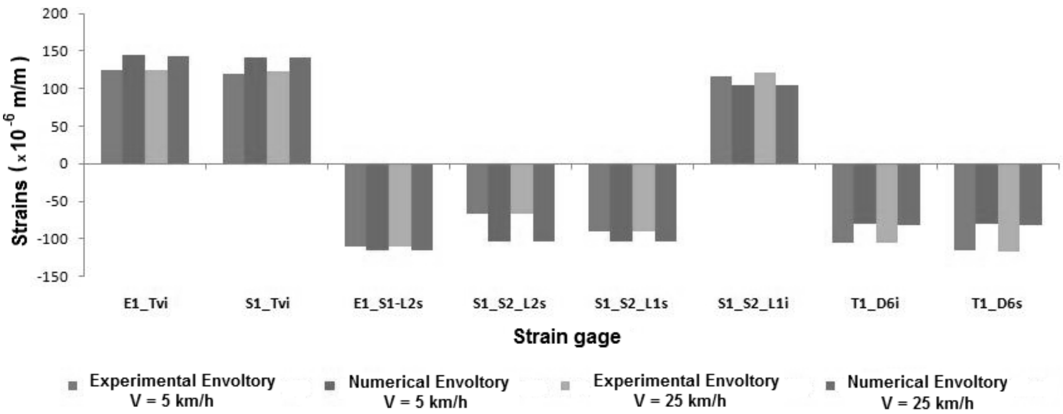


Figure 8. Numerical and experimental displacements for the Viliato train (v = 5 km / h and v = 25 km / h).

The maximum displacements obtained experimentally and by computer model, at the points where the displacement transducers were installed, are presented in Table 1. The wheel loads obtained experimentally when the Viliato train crossed the bridge at 5 km/h are presented in Figure 9. A scheme of the Viliato train is illustrated in Figure 10.

Table 1. Maximum displacements obtained in the passes of the Viliato train.

Sensor	Maximum Displacements (mm)					
	Experimental Displacement V=5km/h	Numerical Displacement V=5km/h	Experimental Displacement V=25km/h	Numerical Displacement V=25km/h	Experimental Displacement V=35km/h	Numerical Displacement V=35km/h
TD1	8,9	9,09	7,8	9,11	7,9	9,04
TD2	4,0	4,28	4,1	4,28	3,9	4,26
TD3	4,6	4,28	4,7	4,28	4,8	4,26

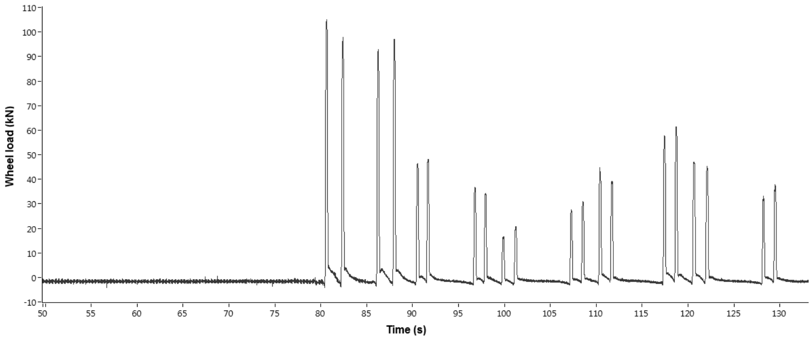


Figure 9. Wheel loads measured during passage of the Viliato train at a speed of 5km/h. The first load obtained (t ≈ 80 s) refers to the first axle of the locomotive.

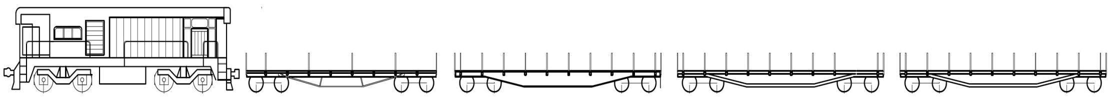


Figure 10. Scheme of the Viliato train.

3.2 Dynamic analysis

At 24th September 2009, immediately after the passage of a full ore freight train, was performed the measurement of accelerations at the bridge. The main results and their treatment are presented in Figure 11.

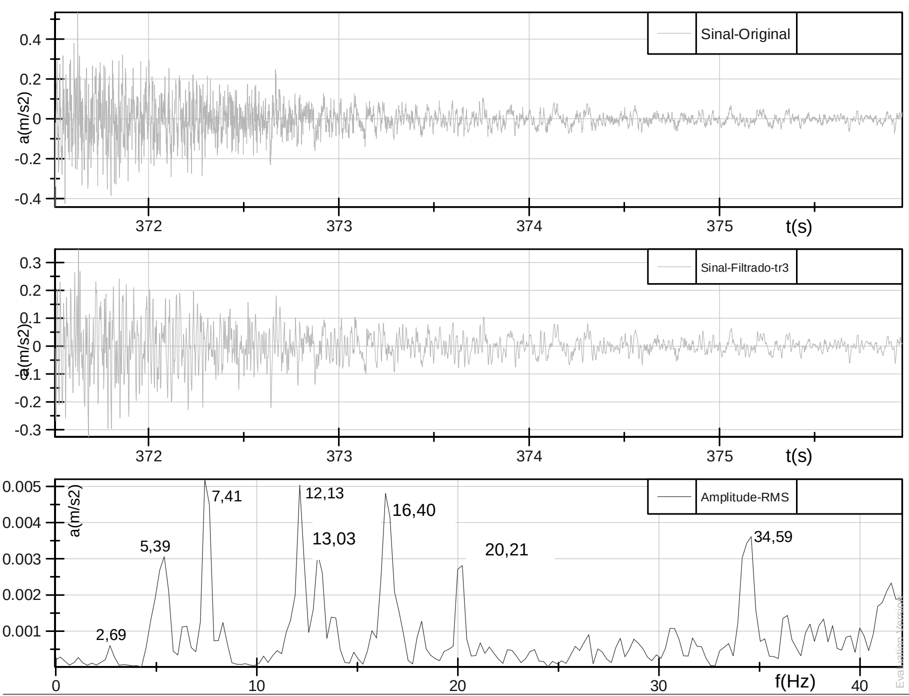


Figure 11. Free vibration response obtained in a transverse floor beam of the bridge.

It is known that the free vibration of the structure immediately after train crossing will contain useful information about natural frequencies and the associated excited modes of vibration of the structure. These frequencies can be identified through the analysis of peaks that are present in the RMS spectrum of acceleration and information about vibration modes can be obtained by simultaneous analyses of the behavior of different accelerometers signals in the time domain. These analyses were done and the main results are summarized in Figure 11 and Table 2. However, since the spectral results of Figure 11 refers to the situation immediately after the train crossing, the influence of the mass of the train in the natural frequencies of the bridge was not considered in the analysis. Also, in the numerical modeling analysis the train mass was not considered so that both results can be compared themselves. The obtained solution is summarized in Table 2. At the top of figure 11 the original signal is presented, while the intermediate chart provides the filtered signal after application of a Butterworth filter with 4 poles and bandpass (0.1 Hz to 150 Hz). The intermediate chart shows the spectrum RMS of the filtered signal. Frequencies of the main components (peaks) are indicated on the spectrum. The achievement of the numerical natural frequencies for the modes of vibration of the Suaçuí River Bridge was performed considering the collaboration of the railway over the bridge and its surroundings (rail, sleeper and ballast).

Table 2. Comparison of natural frequencies (f_n) obtained by the computational model and analysis based on experimental results presented in Figure 11.

Computational Model		Experimental Results		
Modes of Vibration	f_n (Hz)	Order	Frequency Obtained (Hz)	Possibly excited mode (based on the numerical result)
1	2,458	1	2,69	1
2	3,527	2	5,39	3
3	5,207	3	7,41	4
4	7,669	4	12,13	9
5	9,086	5	13,03	10
6	9,238			
7	10,851			
8	11,445			
9	12,312			
10	13,205			

4 CONCLUSIONS

This work presented a case of structural monitoring in a Warren truss railway bridge, with measurements of strains, displacements, accelerations and wheel loads. In all cases examined, the strains in the structure were relatively small. The displacements observed in various situations presented low values, indicating significant stiffness of the structure. The numerical model represented satisfactorily the response of the bridge for strains and displacements in structural elements, although a comparison of numerical and experimental results suggest a model more flexible than the structure. Important parameters of the dynamic behavior were determined from the analysis with the accelerometers measurements. Spectral analysis of dynamic signals provided information about structural behavior characteristics that were compared with results of the numerical model, being checked convergence between numerical solution and experimental results.

5 REFERENCES

Marecos, VMS. 2008. Bridge safety control in real time. *M. Sc. Dissertation.* National Laboratory for Civil Engineering (LNEC). Lisbon.

Bittencourt TN et al. 2009. Monitoring of the Suaçuí River Bridge. Technical report. São Paulo. 111 p.

Thakkar, SK; Ghosh, G; Singh, Y. 2006. Structural damage identification and health monitoring and damage identification of Bridges. *Advances in Bridge Engineering,* March 24-25: 11-30.