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Comparison of strains at the superstructure of a bridge: mathematical model vs field test with a fiber optic system

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ABSTRACT: Integration of tasks such as instrumentation, monitoring, calibration of mathematical models and experimental testing leads increasingly to develop intelligent structures with systems that allow quickly identification of misbehavior and practical details that will help organize maintenance and repair works, as well as prevent damage or catastrophic failures. Because bridge safety is an important issue in road management, structural health monitoring (SHM) has become a very useful tool for the management of these structures. This paper describes an implemented monitoring system in the Chiapas Bridge developed to study its structural behavior. Also, a series of load setups and results of these tests are described and compared with results obtained from a simplified mathematical model. Study of strains induced by temperature changes and strain records obtained on site due to passing trucks is described as well.

1 INTRODUCTION

Experimental load tests, using instrumentation, have been widely used to assess performance and structural capacity of bridges, as well as to evaluate the condition of damaged bridges, determine the efficiency of repairs and more accurately evaluate the capacity of a bridge to distribute live loads [Hirachan, J. (2006)]. Field inspection and periodic evaluation are needed for early detection of damage and to determine the safety and reliability in a consistent and up-to-date approach [I-Wen Wu et al. (2007)].

Regarding instrumentation, because of advances in the developing of fiber optic sensors, they have been widely used in different fields of civil engineering and it is well known their potential and use in bridge health monitoring.

One of the main objectives of this work is to verify the effectiveness of optical fiber sensors, which may also be used in practical conditions for the registration of deformations during load testing. Another of the main objectives of this work is to develop a mathematical model of the Chiapas Bridge reproducing properly its responses due to the passage of vehicles. With a calibrated model, based on the experimental field tests, it will be possible in the future to predict causes affecting the performance of the bridge with a better approximation than with a model based only on design codes, since in many occasions the latter tend to underestimate the structural response [Andersson et al (2006)].

Also, in this paper, it is shown how a system of continuous monitoring, using optical fiber sensors, can provide quantitative information about the response of a bridge under live loads and environmental changes, and a rapid prediction of the integrity of the structure. The results will be the seed of an initial database of the structure, in good condition, for the assessment and management of the future status of the bridge.

2 THE STRUCTURE AND ITS INSTRUMENTATION

The bridge is located in the State of Chiapas, it is part of the highway between Las Choapas, Raudales Malpaso and Ocozocoautla de Espinoza; it crosses the Netzahualcoyotl dam and is located at kilometer 961+731. The bridge has a total length of 1,208 m with eight spans (see figure 1): one of 124 m, five of 168 m, one of 152 m and one of 92 m. The width of its carriageway is 10m and provides enough room for 2 traffic lanes. Its maximum height is about 80 m from the bottom of the reservoir. This article only deals with the superstructure which consists of 102 orthotropic dowels (segments) of structural steel A-50. These were built using an incremental launching process [Gómez et al. (2004)].

The bridge was set into operation since 2003, but it was not until 2008 that was instrumented with optical fiber sensors placed along the structure [Gómez et al (2009)]. In spite of this kind of receivers and transmitters being more expensive, humidity of the region and extreme changes in temperature provided the reasons to select optical fiber sensors. These are low weight, small size and resistant; they operate uniformly from -55°C to +125°C without degradation of their characteristics; and they are water and corrosion resistant with an adequate protection [Micron Optics Inc. (2005)].

It is well known that different fiber optic sensors can be combined in the same fiber. For our study two types of sensors were used in the bridge: strain and temperature. They were placed in specific segments at certain distances and were located so that they could facilitate identification and measurements of variables. To organize monitoring, two arrays of sensors were designed for different segments of the bridge (see figure 1). In some arrays (type A), only four strain sensors were placed, and in other arrays (type B), in addition of these four sensors, two more temperature sensors were installed. Sensors were placed on the bottom plate as well as on the top plate inside the superstructure. A total of 82 sensors were installed along the bridge: 64 are used to monitor strains and 18 to monitor temperature. All of them were distributed in 16 segments and a specific recording channel was assigned to each segment. Furthermore, in spans 4 and 8, cross sections located at ¾ y ¼ of the span length were also instrumented. Electric power is supplied by means of a photovoltaic system.

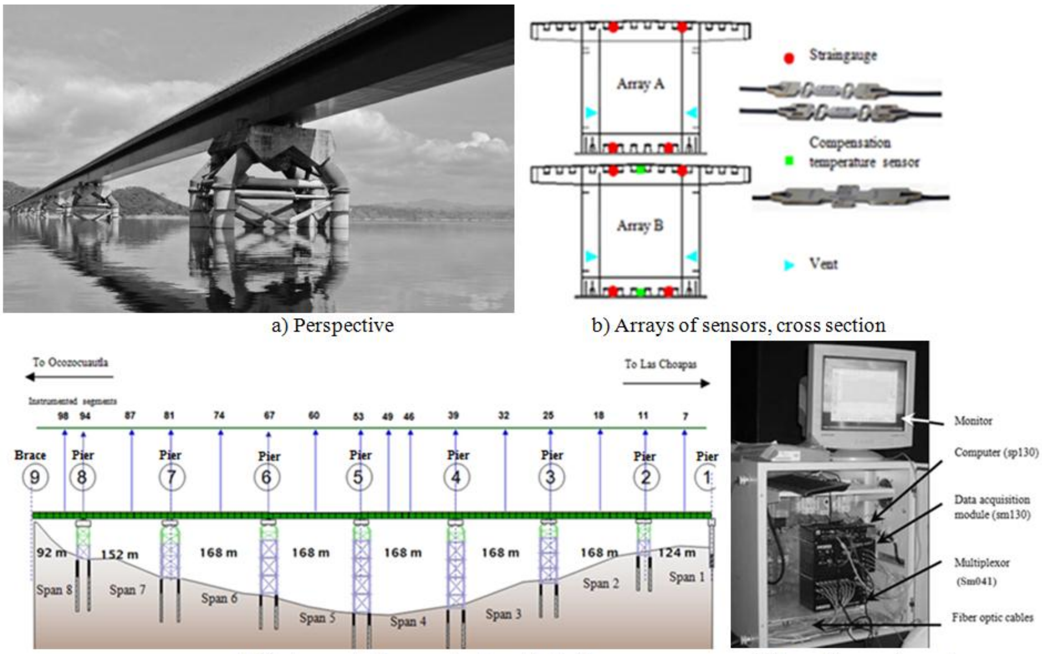
3 MONITORING OF STRAINS IN THE SUPERSTRUCTURE

Only strains due to temperature changes and truck loads are discussed herein. To determine the effects of temperature increments on the bridge, time history records were recorded and transformed to strains. And to determine the effects of passing loads on the bridge, tests were conducted using relatively heavy trucks. In addition, a mathematical model was developed to reproduce the effects due to these loads. These two type of records obtained during the monitoring and their results are presented in the following paragraphs, as well as comparison of analytical data with results of field tests..

The monitoring system included special software [Micron Optics Inc. (2009)] that was used for processing the information recorded during the total length of the experimental program.

3.1 Monitoring of strain increments due to temperature

To assess the effects of temperature gradients, it was necessary to revise cycles of increments throughout the day, for several days, and observe how strains vary in the different segments along the bridge. Temperature records for structural analysis obtained in the bridge were recorded at a frequency of 0.067 Hz, i.e. every 15 s. Because temperature varies gradually during the day, shorter intervals were not considered because records would be very large and difficult to process. Besides, it would demand more electric power.



a) Perspective   b) Arrays of sensors, cross section

b) Instrumented segments along the bridge   c) Recording equipment

Figure 1. Instrumentation with fiber optic sensors

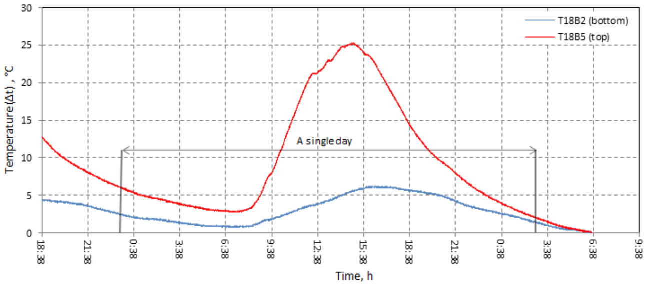
In this paper we only present two temperature records (see figure 2). The first one was labelled EsC31 and contains data registered along a day and a half; the second one, E15sC44, contains data corresponding to four and a half days of continuous monitoring. Figure 2 shows these temperature plots recorded in a segment at the center of a 168 m span; T18B2 denotes the sensor located at the bottom plate and T18B5 is related to the sensor on the top plate.

At certain hours of the day, it was observed a large change in temperature and therefore in the deformation. Record E15sC44 test was the most illustrative of the fluctuating temperature on the third day of monitoring. The most part of the increase in temperature practically occurs between 9:00 AM and 3:00 PM, from the lowest value recorded to the highest during the day. Regarding the correspondent increment in µm/m, this exceeds 270 µm/m. From 11:05 AM to 11:16 AM, a variation of 1°C produced up to 15 µm/m.

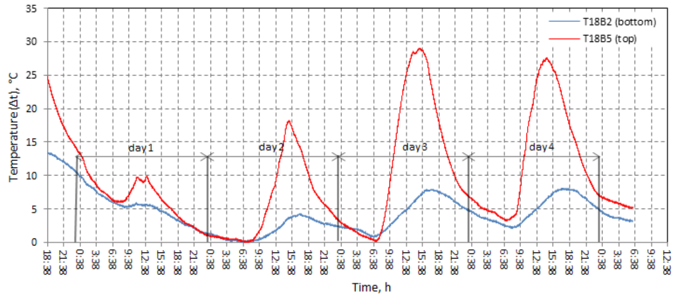
3.2 Monitoring of strain increments due to vehicles (field tests)

Load tests were aimed to follow-up and obtain records of strain increments produced on the superstructure due to permit trucks [SCT (2008)], passing on the bridge. Once obtained, these increments were compared with those calculated using a simple analytical model with the purpose of reviewing and improving maintenance and task inspections of the bridge. This, of course, depends on the accuracy of the calibration of the analytical model.

Vehicle load (dynamic) tests in the Chiapas Bridge took place in June 2010 using 2 permit trucks: a T3-S2 with a gross weight of 158.2 kN, and a T3-S3 with a gross weight of 291.3kN (Table 1).



2a. Test EsC31, temperature increments at segment 18, span of 168 m



2b. Test E15sC44, temperature increments at segment 18, span of 168 m

Figure 2. Temperature strain increments at the central cross section of a 168 m span

Table 1- Characteristics of trucks used in the tests

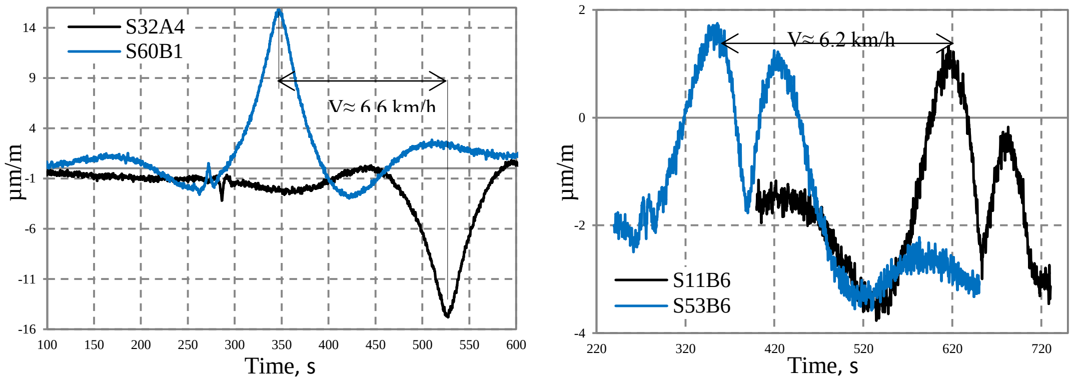
Truck	Axis	Weight per axle (kN)	Distance between axles (m)
T3-S2	1	45.20	0
	2	35.70	4.6
	3	30.60	1.5
	4	24.22	10.56
	5	22.55	1.3
T3-S3	1	39.42	0
	2	64.82	4.4
	3	68.06	1.35
	4	55.31	7.1
	5	32.36	1.2
	6	31.38	1.2

Only results of four out of a total of twelve tests will be presented herein. They are:
1) Test 1.- Truck T3-S2 running on one lane, direction Ocozocoautla-Malpaso, average speed 6.5 km/h; 2) Test 3.- Trucks T3-S2 and T3-S3 running in parallel, one on each lane, direction Ocozocoautla-Malpaso, average speed 54.6 km/h; 3) Test 5.- Trucks T3-S2 and T3-S3 running in opposite directions (round trip), average speed 59.7 and 57.3 km/h, respectively; and 4) Test 11.- Trucks T3-S3 and T3-S2 running in parallel, direction Tuxtla – Malpaso, average speed 53.9 km/h.

To avoid interference in the monitoring of strain/deformation records, due to other vehicles, traffic was interrupted during the testing, before and after the permit trucks crossed the bridge. Data were recorded with a sampling maximum frequency of 125 Hz. Thereby, obtained records showed sufficient resolution despite the velocity of trucks, which was relatively high. This fact allowed a reduction in the time of interrupting the traffic in each lane.

Regarding the nomenclature used in the following figures, S represents a strain-gauge sensor. Literals A and B are used to identify an specific array of sensors (see figure 1). For an A array 4 strain gauges were installed and for a B array 4 strain gauges and 2 temperature sensors were used. Finally, the position of each sensor is identified as follows: for array A: 1 = bottom left, 2 = bottom right, 3 = top left , 4 = top right; for array B: 1 = bottom left, 2 = bottom center, 3 = bottom right, 4 = top left, 5 = top center and 6= top right.

Analysis of stress increments produced during the tests was performed with the filtered data using the MATLAB program [MathWorks, Inc, (2008)]. Figure 3 presents deformations increments caused by the passage of the T3-S2 truck in two different spans of 168 m : sensors S32A4 and S60B1. It is shown that in both cases the value of the maximum increment is almost the same (15 µm/m) but in opposite directions, one in tension and the other in compression. Also, in Figure 3 it is shown the increment of deformation in two sensors located at piers 2 and 5, respectively, both for test 1. Due to the time it takes for the truck to pass an instrumented segment to another one, an out of phase detail is observed in this figure. Knowing that the distance from sensor S32A4 to S60B1 is 336 m, and from S11B6 (segment 11) to S53B6 (segment 60) is 504 m, it is possible to estimate an average speed of the truck, 6.4 km/h.

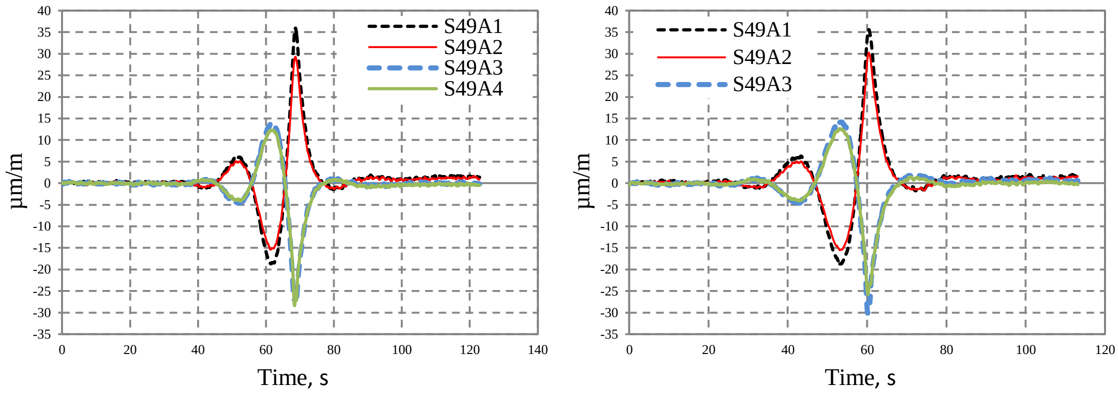


3a. Sensors S32A4 and S60B1

3b. Sensors S11B6 and S53B6

Figure 3. Time histories of strains, test 1

Figure 4 shows evidence of experimental results recorded at the four sensors in segment 49 during tests 3 and 11, which have similar conditions in terms of speed and direction. In this comparison, for all segments, it was observed that passing the truck on either lane does not represent any influence, because strains are very similar, and the effect is similar to a point load passing on the bridge, as well.



4a Test 3, at ¾ of a 168 m span

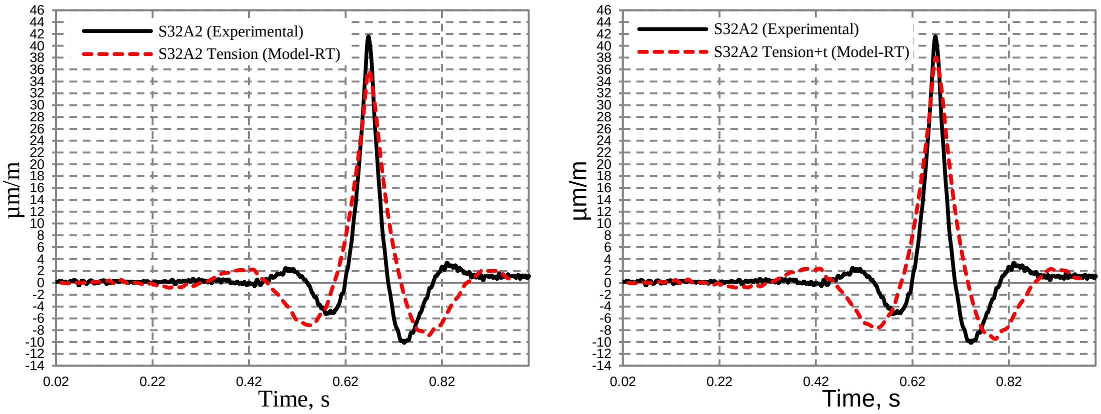
4b Test 11, at ¾ of a 168 m span

Figure 4 – Comparison of strain increments, experimental tests 3 and 11

4 ANALYTICAL MODEL

An analytical model was developed using SAP2000 software [SAP2000 (2009)] and using beam elements, which formed a continuous girder of 8 different cross sections. Analyses were prepared to reproduce the results of field tests in the time domain, defining vehicles and their speeds during each test. Hooke´s law was used to compare experimental and analytical micro-deformations and stresses.

Thermal effects were considered in the analyses; minor differences were observed. Figure 5a and 5b show a comparison between experimental and numerical results without and with thermal effects, respectively. It was observed that temperature changes are lower in the zone of supports that in the central areas of each span:



5a Test 3, at ¾ of a 168 m span, without thermal effects

5b Test 11, at ¾ of a 168 m span, whit thermal effects

Figure 5 – Comparison of strain increments, experimental vs model, test 3

Step by step analyses were used to simulate experimental tests. These analyses in turn were divided into two types depending on the assignment of loads: load static multi-step (EMP) and time response (RT). Linear analyses were performed considering only axle loads and their transverse distribution.

For the type of static load multi-step analysis (EMP), it was assumed that the speed of vehicles have no effect on the results, except for the knowledge in change of position between one and another load to pass over the bridge; for time response analyses (RT), dynamic effects are important and different results can be expected depending on the speed of vehicles.

For the whole bridge and for some tests, information was recorded along the total duration. Figure 6 shows a series of graphs of test 5 corresponding to various stages of the passage of trucks over the bridge: approaching or moving forward each other in different lanes in the same span; crossing and departing or going away in the same span. Again, experimental deformations are compared to strains obtained with the mathematical model, although only results from a sensor in compression are shown and the comparison with the step by step analysis of the time response (RT). At the top part of the figure there are also illustrations of the simulations produced with the mathematical model. Differences about 5µm/m between analytical and experimental tests are shown along the whole length of recording. In most cases the results of RT analysis are greater than the experimental ones.

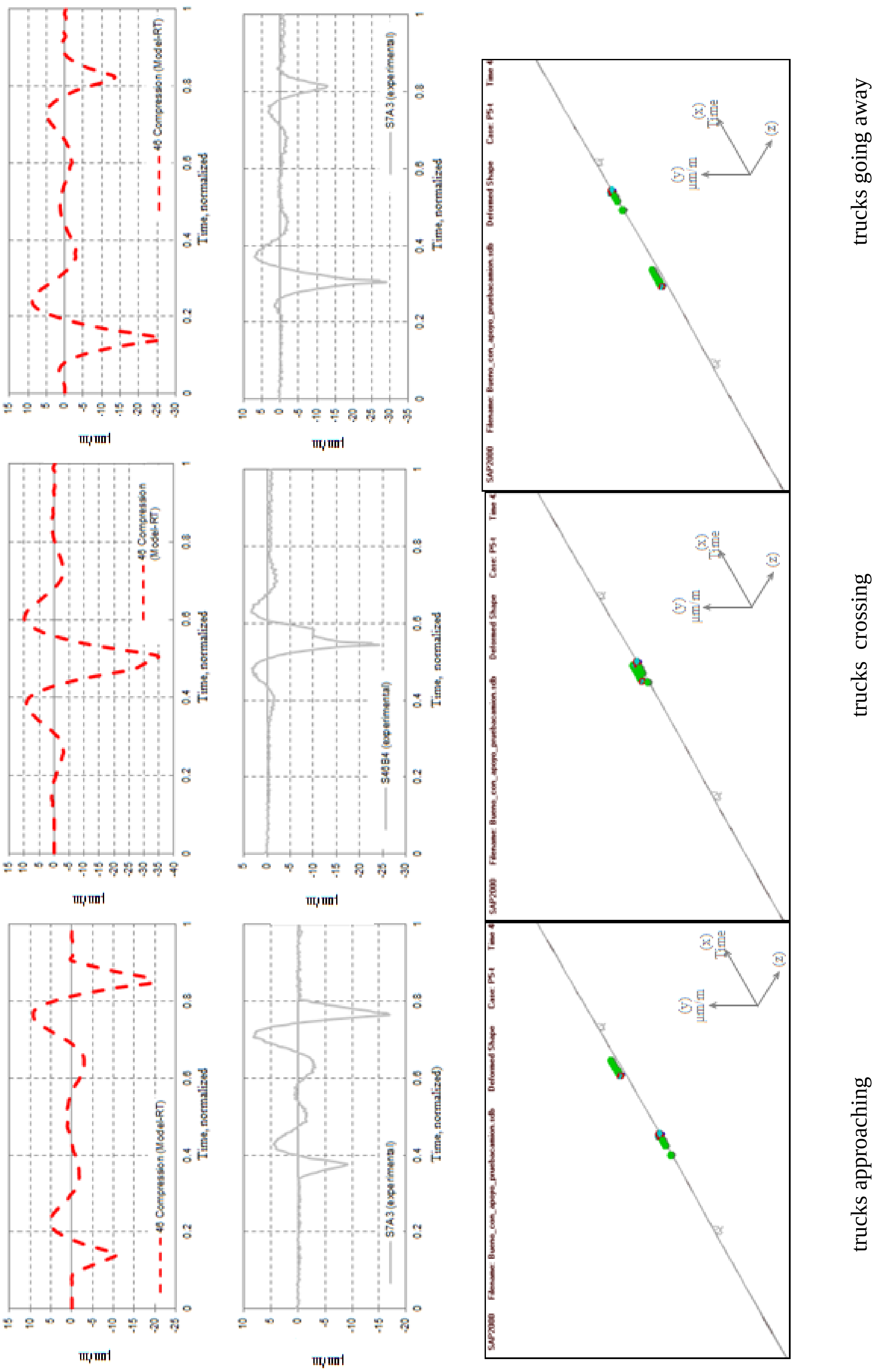


Figure 6 – Different stages of trucks running on the bridge, analytical (top) and experimental (center) responses

5 CONCLUSIONS

The analytical model reproduces, in an acceptable manner, experimental responses recorded during testing. The maximum difference of deformation between the model and the experimental results of the tests, without thermal effects was about 17%, and when thermal effects were considered this differences can be reduced from 15% until 13%.

In a monitoring a long term it was noted that thermal effects produce more significant quantities of µm/m compared to those produced by live loads or vehicles used in the field tests, with a maximum difference of 85%.

The largest increments in µm/m produced by truck loads were found in tests 3 and 11, specifically in segments 60 and 74, which suggest the existence of areas of concentration of stresses. Slightly better results are obtained with the multi-step by step analysis (RT) than with the time response analysis (EMP).

Although the instrumentation of the bridge with strain and temperature sensors sheds much valuable information that helps to understand aspects of the behavior of the bridge, is advisable to reinforce the monitoring of the structure with the implementation of other instruments, including a certain level of redundancy to have a better control of the recorded parameters.

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