Tailor Made Concrete Structures – Walraven & Stoelhorst (eds)

Load capacity assessment of "Antonio Dovali Jaime" bridge using static and dynamic tests

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ABSTRACT: The "Antonio Dovali Jaime" Bridge is an important cable stayed bridge, located in the southeast of Mexico. The bridge has a total length of 1170 m and the main span is 288 m. It was open to traffic in 1984, and was the first cable-stayed bridge in Mexico. In order to asses the current state of the bridge an extensive program of non destructive tests was carried out; the field tests included measurements of stresses, a complete geometric survey of deformed configurations due to vehicle loads, and different series of ambient vibration measurements. The main results of the tests were: load-deformation relationships and dynamic properties (modal shapes, damping and frequencies) of first vibration modes. The results were employed to validate and improve a 3D finite element model of the bridge. The results obtained from FEM calculations were used to asses the actual state of the bridge.

1 INTRODUCTION

The "Antonio Dovali Jaime" Bridge is a major concrete cable stayed bridge in Mexico (Figure 1). The bridge was inaugurated on 1984, and is subjected to particularly aggressive geographic and environmental conditions: earthquakes, high winds, heavy rainfall, marine and oil refinery environments.

Like any cable stayed bridge, this is a very flexible structure and consequently eventually prone to vibrations. The understanding of its real dynamic behaviour is therefore important because it represents the way the structure is operating (Figure 2). After 23 years of service, it was important to evaluate the structural behavior of the bridge. Static and dynamic tests were proposed to fulfill two objectives: to assess its real structural behavior, and to create and refine a numerical model of the full bridge. The numerical results of FEM calculations of the bridge subjected to design loads, and the results of a detailed inspection allow to asses its service capacity.

This paper summarizes the results obtained from different series of measurements and numerical calculations.

Figure 1. View of the Antonio Dovalí Jaime bridge.

2 DESCRIPTION OF THE BRIDGE

The Antonio Dovalí Jaime Bridge (also known as Coatzacoalcos II) is located near the cities of Minatitlan and Coatzacoalcos on the southeast of Mexico. It crosses the Coatzacoalcos River and was opened to

Figure 2. Example of traffic conditions on the A. Dovali bridge used as ambient excitation.

traffic on June 7th, 1984. It was one of the largest cable stayed bridges in the world when built. The bridge is a key link in the freeway that bypasses Coatzacoalcos and connects to the southwest part of Mexico (Yucatan peninsula).

The total length of the bridge is 1170.00 m, but the main cable stayed part is 698.15 m long. The central span is 288 m long (Walther 1998). The main towers are 147.12 m high, and the top of the pylon is 61.29 m above the bridge deck. All the piers and towers are reinforced concrete and have a rectangular hollow box cross section. The cable-stayed superstructure has 18.10 m wide and consists of a 3.3 m deep prestressed concrete box. The deck is supported by one central plane of stays. There are 17 ⊘ 15 stay cables (33 to 61 strands) per pylon spread in two fans. For each pylon the stay are continuous and positioned in the pylon on a deviation saddle.

The main bridge and the access viaducts were constructed by cantilever method from piers (Fig. 3).

Figure 3. View of the Antonio Dovalí Jaime bridge during construction.

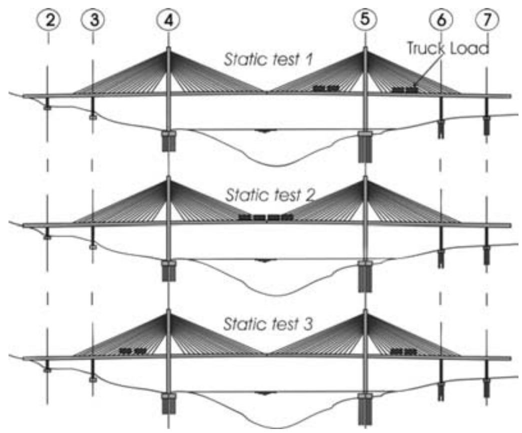

Figure 4. Load configurations for static tests.

3 STATIC TESTS

A group of static tests was performed. The tests considers the measurement of static response of the bridge (deflections) under known loads placed on different points over the bridge.

3.1 *Description of tests*

In order to evaluate the response of different parts of the cable-stayed bridge under live loads, three different types of static tests were defined (Fig. 4). For each load case vertical deflections were measured in 18 points of the bridge (Fig. 5). The vehicles used for the tests were 8 three-axle trucks each one weighting 30 tons (Fig. 6). The horizontal deformations on the top of the pylons were also measured.

The static tests were realized early on the morning, mainly to avoid thermal effects, and to minimize the perturbation associate with the total closure of the bridge during static tests.

Deflections at the defined points were first measured with only the dead load condition; successively, the position of each point was again measured during the application of each configuration load. The difference in the elevation of each selected point between its dead-load position and its loaded position represent the load condition displacement. Also a final measurement of the deflections of the bridge was made after the static tests were concluded.

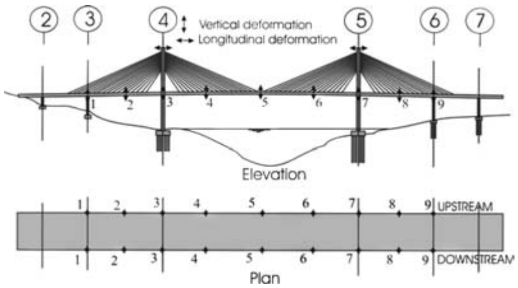

Figure 5. Location of deflection measurement points.

Figure 6. Trucks over the bridge during Static Test No. 2.

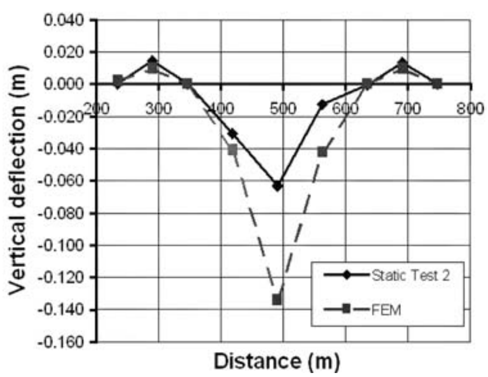

Figure 7. Vertical deflection of the main bridge during ST2.

3.2 *Results*

As expected, for each load case, the maximum vertical deflection of the deck was observed in the neighborhood of the position were the test vehicles were placed. The maximum vertical deflection register was 13.5 cm, and correspond to the central part of the main span during Static Test 2 (Fig. 7). One important result was the fact that the bridge returned to his original position after static test campaign. Hence, residual deformations were not observed.

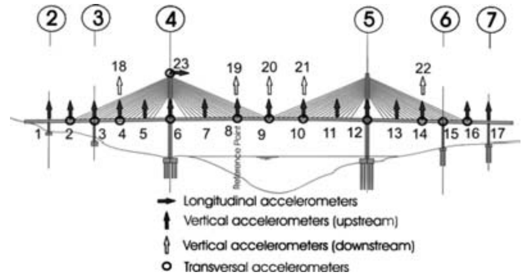

Figure 8. Sensor locations for dynamic tests.

4 DYNAMIC TESTS

Although the first dynamic tests were formalized by the aircraft construction industry to appreciate phenomena leading to failures under repeated loads, the realization of dynamic tests on bridges is more recent. Various reasons justify the realization of dynamic tests on bridges: to enrich knowledge of structural dynamic behaviour, to check modeling choices, to evaluate structural integrity, or to monitor structural condition. The improvement of computing capacities led to the development of powerful algorithms for the determination of the mechanical characteristics. Information can then help to reduce uncertainty associated with the structural strength, and thus to allow a more relevant structural reliability assessment. One of the primary objectives of dynamic testing is the determination – or identification – of the modal characteristics of the structure.

4.1 *Type of tests and instrumentation plan*

A campaign of ambient vibration test was conducted. This source of excitation is particularly important because its helps to appreciate the structural behaviour in operating conditions.

The measurements during dynamic tests were made using accelerometers (model PCB seismic ICP 393B31 with a 10 V/g sensitivity).

The number, the localization of the sensors and the sampling frequency, was chosen from the results of a preliminary campaign test, and the results of a preliminary FEM model of the bridge. For large structures such the Antonio Dovalí Bridge, is no always possible to map the whole structure with transducers; in this case, the acquisition was performed in several setups keeping 2 channels as reference points. Figure 8 presents the general instrumentation plan. Figure 9 shows a transducer mounted on the bridge and the data acquisition system used.

During the tests the data were acquired with a sampling frequency of 256 Hz using windows of 15 minutes period for each series. Figure 10 provides an example of data recorded at the reference points.

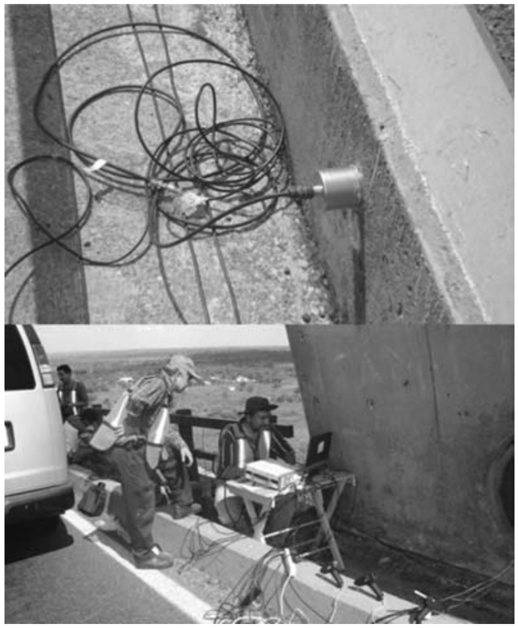

Figure 9. Acceleration transducer installed and data acquisition system.

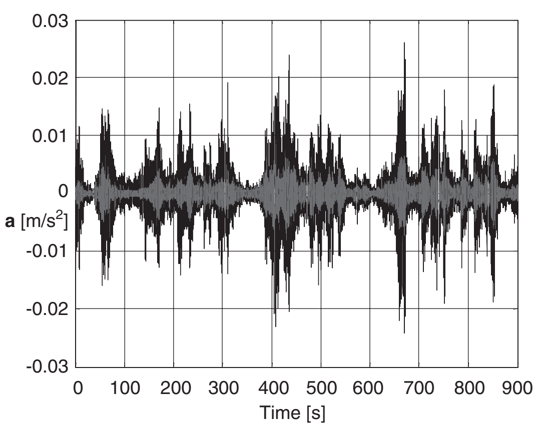

Figure 10. Example of recorded accelerations (black: vertical, grey: transversal).

Figure 11 provides the spectrum of this recorded data. These results show a glimpse of the lowest frequencies vibration modes of the bridge (comprised between 0.4 and 3.5 Hz).

4.2 *Modal identification*

The experimental modal identification was carried out using the random decrement technique coupled with the Ibrahim Time Domain method (Cremona 2004).

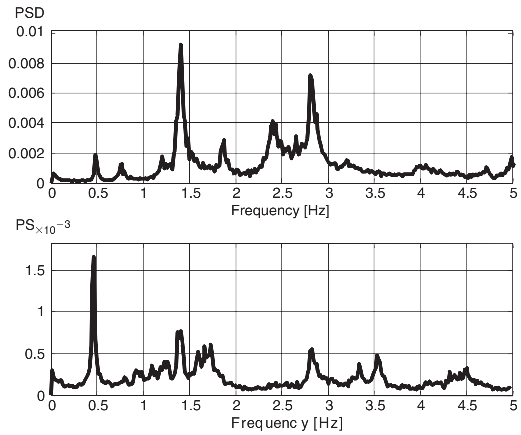

Figure 11. Example of spectrum of measurement point on main span (vertical & transversal).

Table 1. Identified modal parameters of the first 5 modes.

Mode	Period [sec]	Damping ratio [%]
1	2.151	0.20
2	2.041	0.40
3	1.311	0.32
4	1.261	0.77
5	1.088	0.63

The identified mode shapes of the bridge are shown in figure 13.

The principle of the random decrement technique is to consider functions known as random decrement functions issued from averages of measurement segments under triggering conditions. These functions are damped functions, which makes it possible to apply traditional identification algorithms such as the Ibrahim Time Domain technique. The processing of measured data by these techniques was made using LCPC-Sys_Ident toolbox.

Twelve modes were identified. Table 1 summarizes the identified modal parameters for first modes of the bridge.

5 FEM MODELLING AND CORRELATION WITH TESTS RESULTS

The experimental program was used to complement a 3D finite element model of the full bridge.

The model was elaborated based on the original construction drawings, and the results of a detailed inspection and geometrical survey of the bridge realized in 2006.

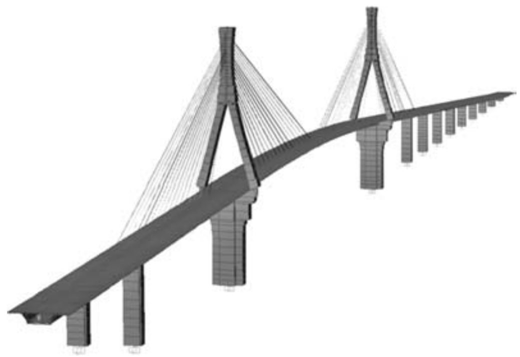

Figure 12. View of the 3D finite element model of the bridge.

The model was made using the program SAP2000. A total of 833 nodes and 902 elements (cable and beam) were employed in the FEM model (Fig. 12).

The mechanic characteristics of the constitutive materials of the bridge (weight, Young's modulus, etc.) were based on available technical data and typical "design" assumptions.

5.1 *Model validation*

The theoretical response of the bridge due to the static load arrays were calculated using the FEM model. These results were compared with those obtained by the tests. A relatively good agreement between the model and static test results (similar deformed shapes) was found. However the deformations measured on the bridge during static load tests were less important that those numerically calculated (Fig. 7). This tendency was the same one for all the static load cases.

The FEM model was also used to calculate the modal shapes and natural periods of the lowest modes of vibration of the bridge. The results are summarized on Figure 13. The results show also a reasonably good agreement between numerical and test measurements: comparable modal shapes and vibration periods of same order. Nevertheless, the FEM model underestimates the periods of all vibration modes. The results shows the same tendency found in the static case: numerical model was more flexible than the real bridge. Despite the fact that the numerical model was detailed as much as possible, the stiffness appeared to be underestimated consistently throughout the bridge.

5.2 *Model updating*

A parametric study was made changing some model assumptions like Young's modulus and density of materials. However, normal variations in those parameters were not sufficient to explain the differences

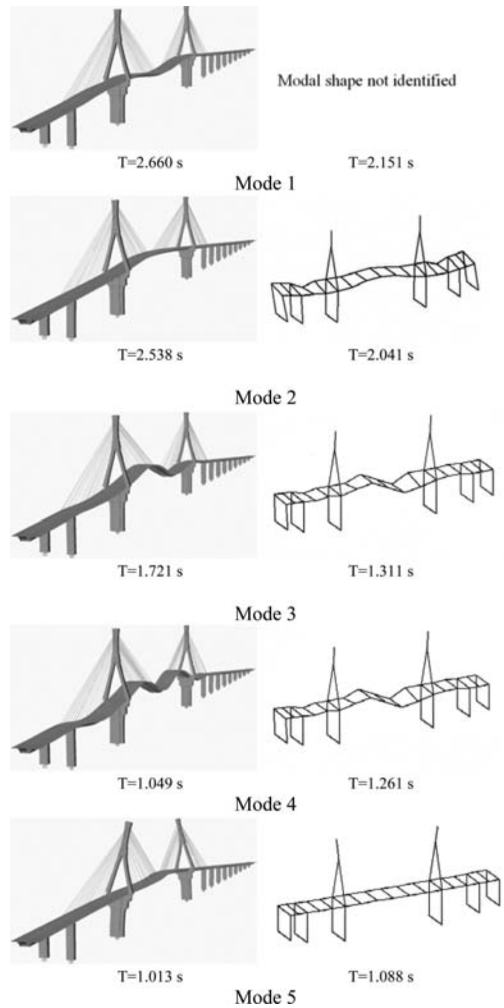

Figure 13. Calculated and identified modal shapes for first five modes.

obtained between FEM model and tests results. These unexpected differences prompted the authors to do an additional search of information about the characteristics of the bridge. It was found that the stay cables are protected against corrosion by a 5.6 mm thick steel tube injected with cement grout (Fig. 14). This solution is not usual in cable stayed bridges were polyethylene ducts are normally used to protect stay against corrosion. It was also found that the bridge designers organized the erection stages of the main bridge in order to guarantee a permanent compression on the injected grout of each stay (AFPC 1986).

This fact modifies the structural behaviour of the stay: the steel duct and the injected grout played a part in resisting the stresses due to live and dynamic loads.

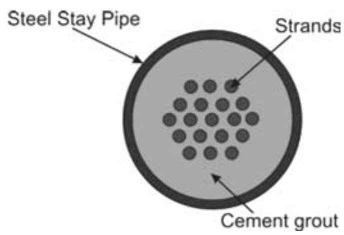

Figure 14. Detail of stay protection.

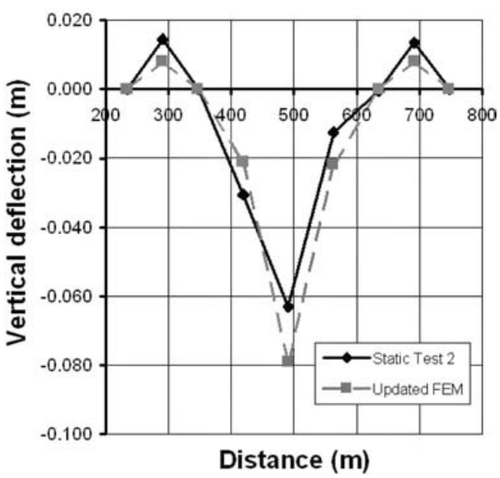

Figure 15. Vertical deflection of the bridge during ST2.

Table 2. Comparison of periods of the first five measured and calculated modes of the bridge (Updated Model).

Mode	Measured [s]	Calculated [s]
1	2.151	2.353
2	2.041	2.017
3	1.311	1.353
4	1.261	0.960
5	1.088	0.908

Consequently, the stiffness of the stays is bigger than assumed.

Therefore, the additional stiffness of the stay was calculated taking into account the pipe area and the equivalent "steel" area of grout. This assumption increases the stay stiffness by 100 % approximately. This improved considerably the correlation between FEM model and experimental results, for both static and dynamic tests (see Figure 15 and Table 2).

With the above results the numerical model was considered validated and acceptable to study the response of the bridge to environmental and operation loads.

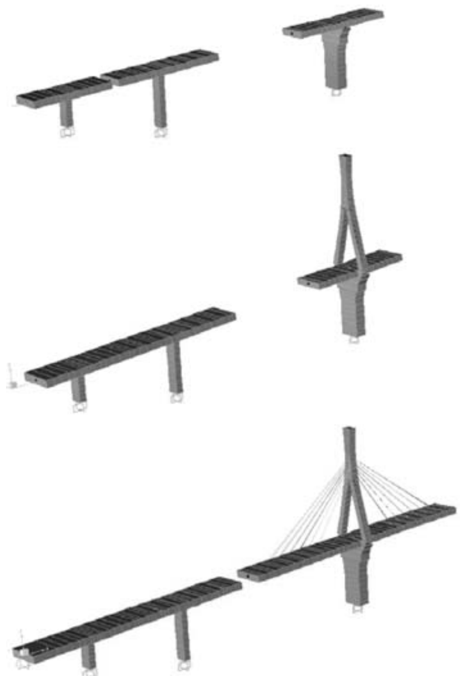

Figure 16. Examples of construction stages considered.

6 LOAD CAPACITY ASSESSMENT

The response of the bridge to the different "design" loads (earthquake, wind, live load) was calculated with the updated FEM model. The results of these calculations were used to verify the ultimate load and service capacity of the different structural elements of the bridge.

The "dead load" condition was calculated taking into account the construction stages followed when the bridge was build (Fig. 16): cantilever construction, installation of prestress cables, installation of stay cables, etc. The creep and shrinkage of concrete was also considered in "dead load" numerical calculations.

The verification of the resistance and service capacity of the bridge was made following the specifications of AASHTO-2002 code and Mexican bridge design specifications. Figure 17 shows an example of the type of verifications made.

Some relevant results were:

- Flexion moments on the deck of main bridge due to live load were reduced by 10% thanks to the increase of stays stiffness due to steel stay pipe and injected grout.

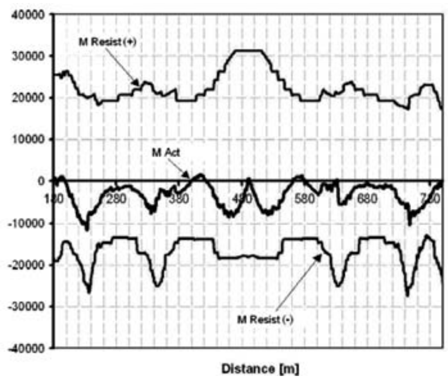

Figure 17. Verification of flexion resistance of the deck of the main bridge.

- The seismic forces on the bridge calculated with the updated model are 15% bigger than those calculated with the non-updated model.
- The state of the bridge and his load capacity are satisfactory.

7 CONCLUSIONS

A rational methodology for structural assessment of an important cable-stayed bridge was presented. The methodology is based on the use of static and dynamic tests, modal identification and finite element model validation and updating.

The test-based calibration model offers an excellent correlation with all the experimental results. It can be concluded that the updated model give an accurate representation of the actual bridge. The results provided from the updated FEM model were used to evaluate the structural safety under environmental and service loads.

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