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REPORT

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Construction and Geometric Control of the Baluarte Cable-Stayed Bridge, Mexico

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Summary

The Baluarte is the most remarkable bridge on the new Durango-Mazatlán highway, and was opened to traffic in October 2013. The bridge is cable-stayed with a total length of 1124 m, the main span is 520 m long. It is the highest cable-stayed bridge in the world, with a maximum drop of 402.5 m from the deck level to the bottom of the Baluarte river. The access viaducts have a concrete deck, and were built by the symmetrical cantilever method. The highest pile of the viaduct is 147.5 m high. The main deck is made of composite material (steel/concrete), and was erected by the cantilever method. The bridge's site is very complex from the topographical and geotechnical points of view. It crosses the steepest part of the Sierra Madre Oriental in the north of Mexico. This region is also prone to high-speed winds caused by hurricanes. This paper presents the main characteristics of the bridge, the technical challenges and main stages of its construction. The erection methods and geometric control of its deck are also presented. And lastly, a comparison between the results of analytical models of staged construction, and the actual measurements of the bridge's deflections, is made.

Keywords: Piers, pylon, composite deck, cable-stay, prestressed concrete, geometric control.

1. Introduction

This paper includes several topics. Firstly, it provides a general idea of the location of the Baluarte Bridge; secondly, it presents the main characteristics of the bridge. Then, the stages of the construction process, for both the concrete and mixed segments, are shown. Thereupon, a brief description of the geometric control theory is given; this was the basis to carry out proper monitoring. Finally, all the results of this work are presented. These results are divided into: displacements, stresses, as well as the final profile.

2. The Baluarte Bridge

2.1 Location

The Baluarte Bridge is located on the Durango-Mazatlan highway, in the limits of the states of Sinaloa and Durango in the north of Mexico. This bridge crosses a deep canyon named "*El Espinazo del Diablo*" ("The Devil's Backbone"), due to its dangerous highlands. Its location is shown in figure 1. The typical topography of the bridge site is shown on Figure 2.

2.2 General Description

The Baluarte bridge is a unique structure, 1124 m long. It is a cable stayed structure and has 11 spans with lengths comprised between 40 and 70 m. The main span is 520 m length. The general configuration of the bridge is shown on Figure 3.

Fig. 1: Location of the Durango-Sinaloa highway Mexico

Fig. 2: Topography of the bridge site

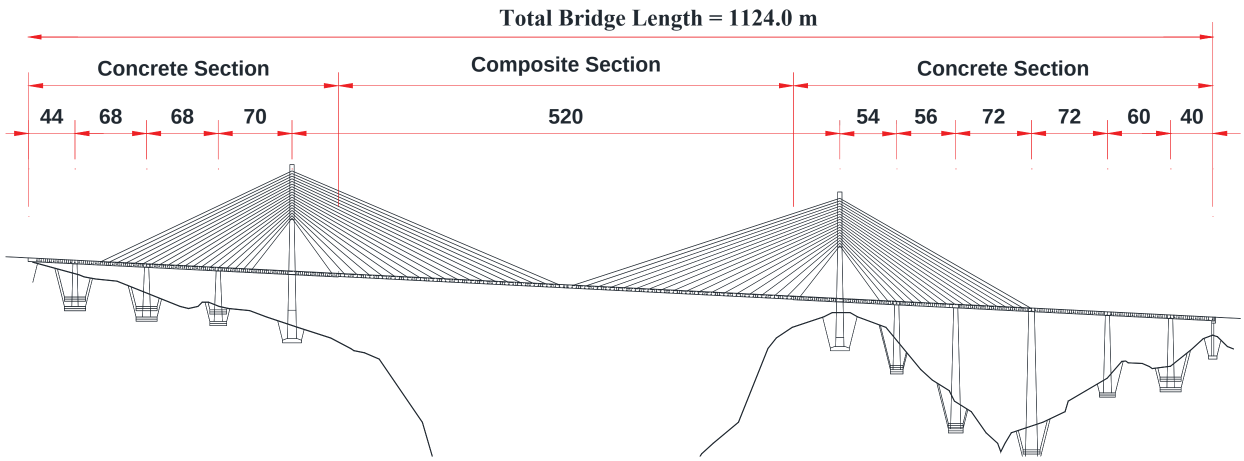

Fig. 3: General arrangement of Baluarte Bridge

2.3 Foundation and substructure

The foundation and substructure are composed by reinforced concrete elements. Piers and pylons have different shapes and dimensions due to the complex of the site topography. The summary of the configuration of these elements is presented in Figure 4.

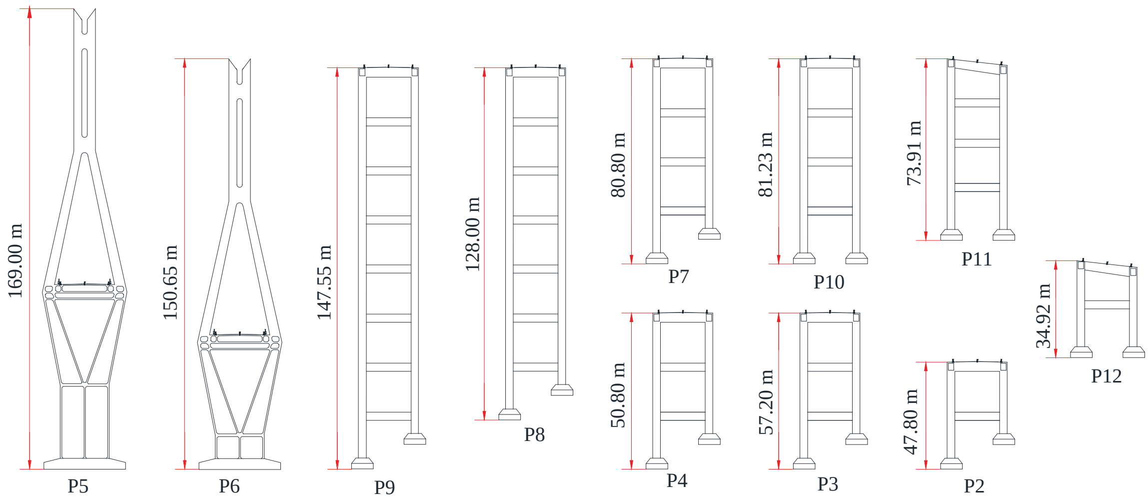

Fig. 4: Shape of the bridge main piers and pylons

The cross section of all piers is box shaped, and varies in depth. The height of the piers is also variable, ranging from 35 m (pile 12) to over 145 m (pile 9).

The pylons are diamond shaped and are also in reinforced concrete. The height of the pylons are 169.0 m and 150.7 m for the pylons 5 and 6, respectively. Figure 5 show a view of the different stages of the construction of the piles and pylons. The geometric control of the piers only consists in building them vertically. It was a relatively easy task, as long as the pier does not present a significant inclination; otherwise, the deformation due to this inclination has to be considered. This condition also applies for pylons.

Fig. 5: Piers and Pylons during construction

2.4 Bridge deck

The bridge has a concrete deck 22.06 m width in the access spans, and a composite steel/concrete 19.76 m width deck in the central part of the main span (Figures 3, 6 and 7).

Concrete deck

The deck of the access viaducts is formed by two box-type sections, joined by steel beams that support a concrete slab (Figure 6). These boxes are postensed and built by cantilever method.

Composite deck

The composite deck is formed by two steel "I" girders, connected by transverse steel beams, with a 4 m separation between them, having on top of them a 23 cm thick concrete slab (Figure 7).

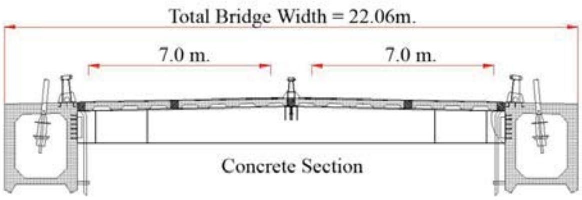

Fig.6: Transverse section of the concrete segments in access viaduct

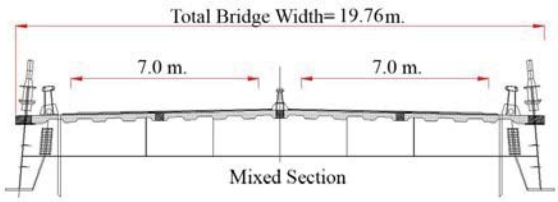

Fig.7: Transverse section of the steel segments in main span

Stays

The stays which number 76 per half plane, are composed of galvanized polyethylene coated 0.6" strands housed within a polyethylene external duct. The number of strands per stay varies from 20 to 43.

3. Stages of construction

The main stages of construction were: 1) Construction site access, 2) Excavation of foundations, 3) Construction of foundations, piles and pylons, 4) Construction of concrete segments (access viaducts), 5) Construction of the steel segments, concrete slabs, and cable installation in the main span, 6) Placement of superimposed dead loads. To better serve the purpose of this paper, we will focus on the construction of the pylons, concrete segments, steel segments, concrete slabs and installation of the cable-stays.

3.1 Construction of the concrete access viaduct

3.1.1 Piers and Pylons

The construction process of the piers and pylons is almost the same up to the level of the deck. The construction of piers and pylons was made by mobile formwork. The most complex part of the procedure was the construction of the pylons, because they have inclined members above and below the level of the superstructure; however, it was solved through struts and ties, with arms both closed and open. The main aim of the geometric control of the pylons was to maintain the verticality of them until the end of the construction, as it progressed in cantilever. Hence, the forces in the cable-stays were higher landside to ensure the vertically of the pylons after the non-linear behaviour.

3.1.2 Concrete deck

The concrete segments were built using double-cantilever mobile carriages, which were advancing to the next and previous pier, on both sides; using the following procedure on both ends in symmetrical manner: 1) Installation of a mobile carriage. 2) Preparation of the reinforced steel. 3) Placement of the pre-stressed ducts. 4) Casting of the concrete segments. 5) Tension of the pre-stressed steel. 6) Movement of the mobile carriage. Every 3 or 4 segments, the concrete slab was cast in sections of 12 metres. The slab was supported by steel beams that join the two concrete "boxes". These elements were installed after moving the mobile carriage in order to have a more stable cantilever. This procedure was repeated until the cantilevers of the piers and pylons were joined. Figures 8 to 10 show the stages of the construction in the cantilever of the concrete segments. In this part of the bridge, the geometric control was made by camber, this means, there was a target profile. It is important to note that once the construction of the concrete viaduct was finished, the continuity external prestress cables were installed. These were designed to withstand the service loads.

Fig.8: Steel reinforcement for concrete segments

Fig. 9: Construction of the double-cantilever

Fig. 10: Closing of typical viaduct span

3.2 Assembly procedure of the steel deck and installation of the cable-stays of main span

The typical steps were as described below:

1) Placing the device in position; the Launcher had to be attached to the deck. See figure 11; 2) Moving segments below the device, near the cantilever. Sometimes, the steel segment was assembled below the Launcher; 3) Critical condition in the launch: this is when the segment is taken by the device for its installation. See figures 12 and 13; 4) Installing the complete steel segment in the final place; 5) Moving elements of the next steel segment under the pylons; generally, the steel segment was assembled in this place; 6) Placing reinforcement steel for the slab. Usually, while the steel reinforcement is being put together, the wires are installed simultaneously; 7) First tension of stays to 30% of final tension; this permits recovering deflections due to self-weight and it allows to support the weight of the slab; 8) Casting Slab; this step is intended to increase the force in the cable-stays 9) Second tension to stays to 80% of final tension; this step was conceived to check the target profile. If the profile was near the target, the force applied in the cable-stays would be the minimum; if not, the force applied could be increased in order to achieve the target profile; 10) Third and final tension. From the previous step the applied force is defined; 11) The target profile is checked, and then the cycle is repeated until the end.

3.3 Other important Aspect (Wind)

The bridge site is prone to high speed winds coming from hurricanes (peak velocities up to 180 km/hr). During the design phase of the bridge wind tunnel tests were made for service and construction stages. As a result of these tests, the deck section of the main span of the bridge was reprofiled by means of cornices and baffles. During the construction of the main span a meteorological survey was established in order to predict high wind speeds on the bridge site.

4. Geometric Control

Geometric control of a bridge becomes very important depending on the course and flexibility of the deck, as it not only involves reaching a desired geometry, therefore, it is necessary to evaluate each of the stages during the construction profile. Cable-stayed bridges can be built using different erection techniques; the control of the desired geometry appears to be extremely easy when the simplest erection methods are used, only adapted to medium spans. For large bridges the control of desired geometry becomes quickly a major problem as the flexibility of the deck increases with the length of the cantilever in construction.

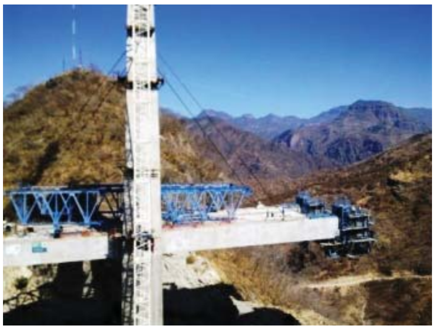

Fig.11: View of pylon 6. Ready for starting the construction of composite segments

Fig. 12: View from above of the critical condition for installing

Fig. 13: Bottom view of the rotation of the dowel for connecting

4.1 Methodology used for geometric control

A precise structural analysis in construction situations is necessary to make a serious control of the erection geometry. However, a designer’s main aim is to obtain a good final distribution of permanent forces in the bridge. The analysis thus, clearly proceeds backwards: the designer first selects the final situation, and from it, the construction situations are evaluated.[1] The clear goal is to determine the cable tensions to have both a convenient distribution of forces in the bridge under permanent and erection loads, and the required geometry.

4.1.1 Backwards analysis

Once the final situation of the bridge has been selected, the construction analysis can be developed. Normally, the erection situations are computed backwards from the final one, as if the bridge were dismantled in the same way it was designed to be built, but backwards. Such a backwards analysis provided a first estimation of tension that had to be given to the different cables at the time of their installation: in a given cable, this initial tension results from the final one, selected as we explained before, and from all the tension variations, which result from the different dismantling operations, from the final situation, back to the step when this cable is to be tensioned.

4.2 Numerical modelling and challenges during the project

A numerical model of the entire bridge was developed to take into account the stages of construction described before. The non-linear behaviour of constitutive materials of the bridge was also considered (creep and shrinkage of concrete, relaxation of stays and prestress) in numerical analyses. The loads were the most unpredictable factors, considering loads, self-weight, and construction equipment. Even though, there was detailed engineering, there was a difference between the theoretical and actual weights. However, this was no obstacle to control the target profile. It was possible to define the weight of the steel segments by weighing each of the segments by launch device. Thermal effects are important in all bridges, especially for the geometrical control of bridges built by the cantilever method. The Baluarte Bridge was measured in the morning, and in the afternoon, obtaining significantly different results, despite being at similar temperatures.

The Baluarte Bridge has an array of cables named semi-harp, which allows an excellent stress control, all along the concrete and steel segments. One of the goals of a good geometric control is to reduce differential creep deformations, through a good selection of cable tensions and construction steps. The construction program, was also defined to minimize the cantilever construction time of the main span, in order to reduce the risk of important vibrations due to high speed winds (this region of Mexico is prone to hurricanes). The figure 14 shows the most critical stages of construction of the main span.

Analytic *vs* real bridge behaviour

As explained before, the theoretical model of the bridge was calibrated during all the bridge construction. This calibration implies the adjustment of different basic analytical assumptions, like weight of materials, and construction equipments, mechanical properties of constitutive materials (Young modulus, creep and shrinkage coefficients of concrete, etc).

Fig. 14: Images of construction of the main span

4.2.1 Comparison of forces in the cable-stays

Calibration of analytical models was not easy, as it was necessary to carry out many measurements, of both profiles, and tension forces. The graphs of figure 15 present the stress levels on the stays from the actual forces under different load conditions. The load conditions are: 1) After the construction; 2) On service. Redistribution of forces along the bridge was satisfactory. It was possible to maintain a nearly constant percentage of allowable ultimate force (FPU). The average percentage of FPU for dead load + superimposed load is 40% FPU, whereas for conditions of service (live load) is near to 45%FPU [2].

4.2.2 Comparison of theoretical, and field measured vertical pylons

The control of the piles was complex, because during the construction of the pylon, the deck was in the process of construction too; however, adequate levels of verticality could be maintained. Figure 16 shows the actual vs. theoretical profiles of pylons. The pylon 6 shows a better performance, this was because of the calibrations were first made in the pylon 5 (it was the first pylon constructed). It is important to note that, besides calculating the forces in the cables and verifying the profiles of the deck and the pylons, it was necessary to control the stress levels on both elements.

4.2.3 Comparison of theoretical and field measured profiles

During each of the construction stages, the profiles on the deck, and the forces in the cables were measured. The results were satisfactory, and throughout the construction, the target profile was reached. These conditions are shown in Figure 17, along the bridge. There is a minor variation in elevation in some places; however, these differences are within the tolerance.

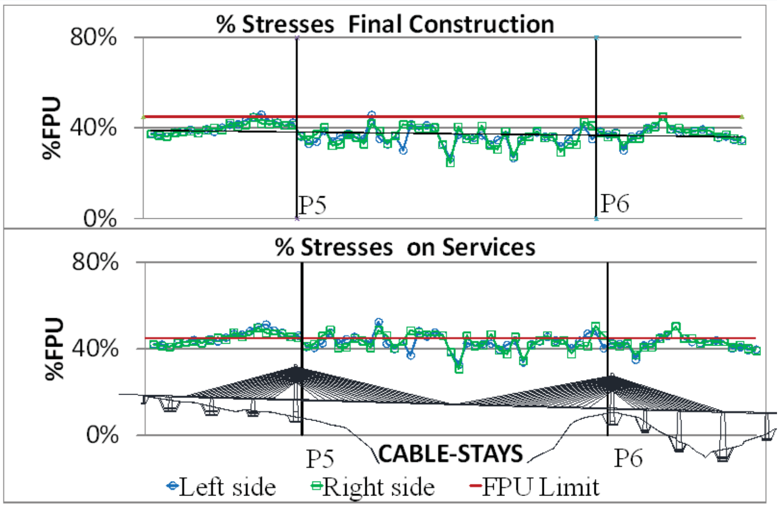

Fig. 15: Percentage of stress in every cable-stay in different stage

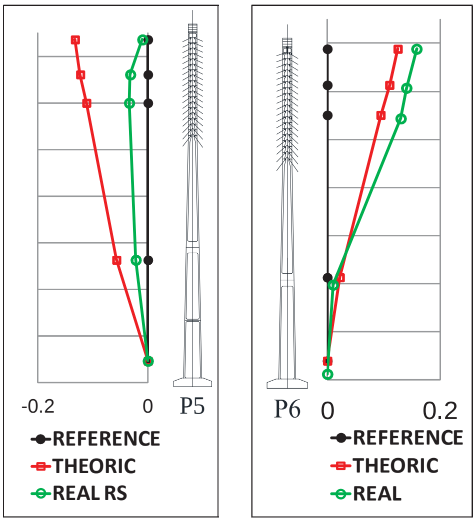

Fig. 16: Typical form for the verticality of both pylons

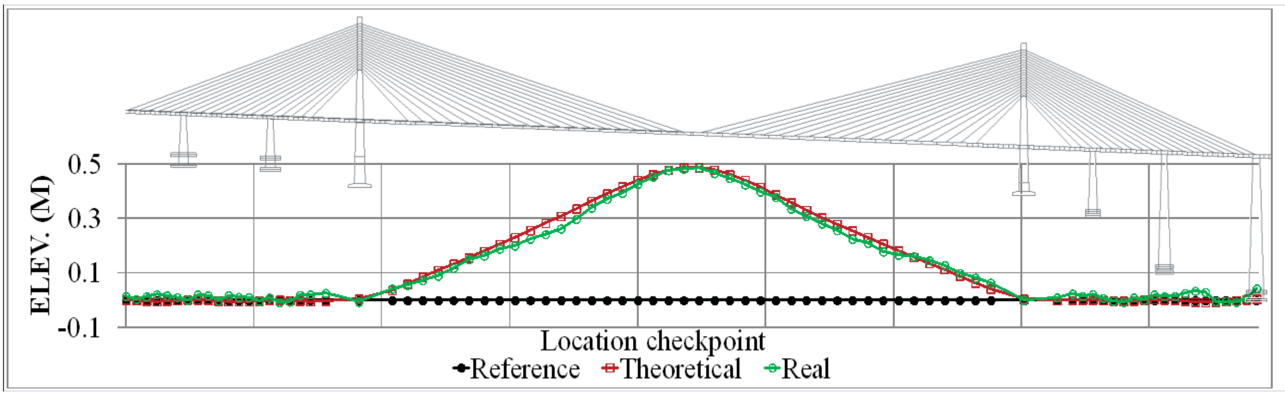

Fig. 17: Comparison of real values of deck vertical deformations against theoretical ones at closure.

4.3 Closing of the central span

It was a great challenge to reach the cantilever in mid-span. When this happened, the problem was how to close the span. It was necessary to carry through the following steps: 1) Checking the elevation on both work faces (See figure 18); 2) Tension cables to match the elevation on both sides; 3) Measuring and cutting central beam (See figure 19); 4) Fixing the closing device to install the central beam (See figure 20); 5) Connecting the central beam by weld; 6) Removing the closing device; 7) Placing slab formwork; 8) Casting concrete slab; 9) Removal of mounting devices; 10) Placing superimposed loads. Once the bridge was closed, tests were made to verify the behaviour of the bridge, and these were acceptable. An important event was the placement of the asphalt carpet, which had a known weight, and allowed us to evaluate the performance of the calibrated numerical model. Figure 21 shows the profile of the deck at the end of the construction.

Fig. 18: Checking the target profile, before closing the main span

Fig. 19: Measuring of the last steel segment

Fig. 20: Installation of a closing device to control thermal deformations

4.4 Structural check of the bridge to real permanent loads and mobile design loads.

We have described the geometric control, as to the displacement control on the deck and the pylons. However, as to the structural review, it was important to know the level of demand in the mechanical elements. Figure 22 shows the summary of stresses on the deck under dead load plus live load combination, as well as the limits and tolerances permitted by the main international regulations, such as AASHTO [3], [4].

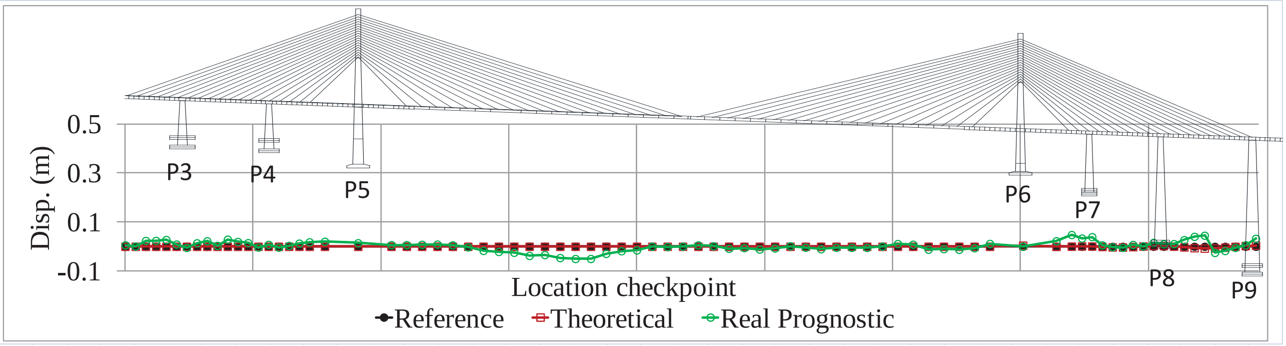

Fig. 21: Theoretical profile for checking the geometrical control, after superimposed load

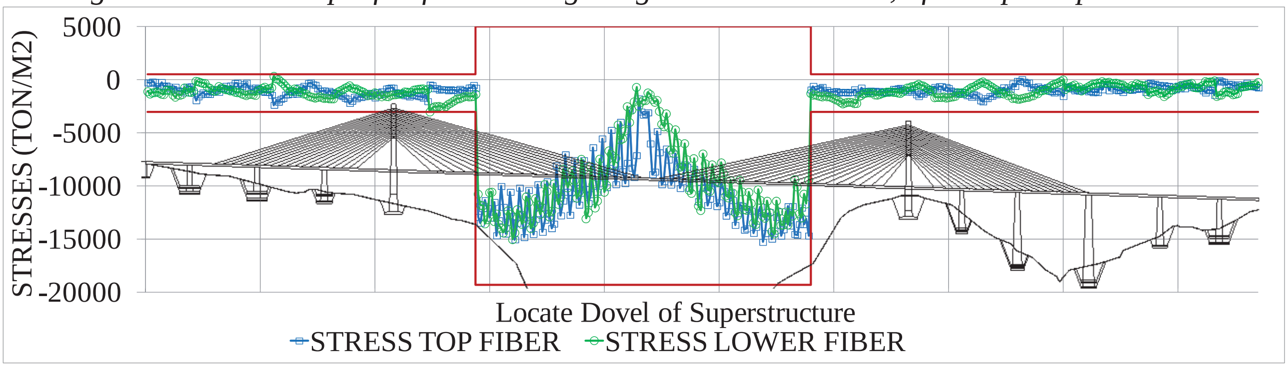

Fig. 22: Stresses along the entire bridge in service. Dead load + superimposed load + live load

5. Conclusions

The Baluarte Bridge faced great challenges during its construction. Calibrating the mathematical model proved to be one of the toughest; however, when you have the necessary tools and data, the task becomes less difficult. In addition, unpredictable factors play a very important role in such a large project, so it was necessary to define the levels of acceptance of the models. To summarise, it can be said that the geometric control of the bridge was carried out satisfactorily. These are its main features: a) Good behaviour regarding deformations and forces in the cables, b) Levels of stress of the principal components were acceptable, and levels of stress during the construction and in service were within international standards limits; c) Deformations were within the tolerance;. e) The excellent communication between the design and construction teams was the key to make this project a success.

6. References

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