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# Monitoring and control of the longest suspension bridge in Brazil during its complex rehabilitation process

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ABSTRACT: The iconic and centenary Hercílio Luz Bridge in Florianopolis was the first road link to be erected between the island of Santa Catarina and the mainland. It has been closed to traffic for safety reasons for more than 20 years, after a crack was found on one bar of the suspension system. A major restoration project is ongoing, with a planned opening to traffic by the end of 2019. This demanding work includes the restoration and reinforcement of the foundations, metallic superstructure, bearing supports, eye-bars, and suspension cables as well as the reconstruction of the road deck and construction of new foot and cycle decks.

One of the most important parts of the project is the replacement of the entire suspension system, which involves the critical task of load transfer from the suspension cables to the temporary support structure. The combination of monitoring and control is essential in such cases, where the age and design uncertainties increase the chances of unpredictable behavior. To support such a task, a complex system with several sensors was implemented for real-time measurement of strain, temperature, inclination, wind, and flow during the actuation of the elevating hydraulic jacks. Different sensor technologies were combined, including numerous Fiber Bragg Grating sensors (FBG).

This article presents the details of the contracted monitoring system, including the hardware and software used to implement it. It will also show the challenging installation of almost 300 FBG sensors, performed in a record time of little over a month, which was a determining factor for the choice of technologies. Data on the load transfer tasks to dismount the suspension elements will be exposed and compared with theoretical predictions.

## 1 INTRODUCTION

Designed in 1922 and put into service four years later in 1926, Hercílio Luz Bridge (Figure 1), became the first road bridge connecting the island of Florianópolis, part of Santa Catarina state, Brazil, to the mainland, Steinman (1928). Being in a maritime location, the bridge has been subjected to intense corrosive aggressions and the natural wear of decades. It has also faced changes to the load and number of vehicles that overcame the design standards of its time. Other bridges have inevitably suffered damage or even collapse due to complex factors such as the environmental load variation, natural disaster and material degradation, Ko et al (2005).

Figure 1. Hercílio Luz Bridge with some facts and figures.

Planned and executed maintenance works were insufficient to ensure the bridge's safety and, after 64 years of operation, the bridge was closed to traffic after a crack was found on one bar of the suspension system. In 1991, the bridge was completely closed and the structure relieved of the 400 tons of permanent loading from the asphalt flooring of the central span, Barth et al (2014).

Visual inspections and non-destructive tests indicated the need for replacement of the main structural elements of this bridge, Carvalho et al (2017). In a project that may take almost three years, Teixeira Duarte has been contracted to completely restore the Hercílio Luz Bridge. This involves replacing the main tower supports, strengthening and restoring the foundations, restoring the metal structure, and replacing the eye-bars, pins, and hanger cables. In addition to a renovated road deck, the renewed bridge will have one foot and one cycle deck.

## 2 REHABILITATION PLAN AND PROGRESS

The iconic and historic importance of the bridge to the people of Santa Catarina increases the demands of a project where the structure's geometry and construction method details need to be kept unchanged. This constant care can be gauged, among others, by the more than 200 000 rivets attached during the rehabilitation works so far.

Figure 2. Attachment of rivets.

For the suspension system replacement, main cables built from 360 eye-bars are linked by pins and 28 supporting hanger cables. A load transfer of the total midspan was required from the suspension elements to the temporary support structure erected below the central span.

Such a critical task, especially when performed on an old and damaged structure, required careful control and monitoring. For this project, Teixeira Duarte decided to opt for HBM technology, including sensors and data acquisition systems of different technologies.

Figure 3. Replacement of the midspan deck (left), of a saddle on the top of the main tower (middle), and of a main tower supporting bearings (right).

## 3 EXPECTED STRUCTURAL BEHAVIOR

The load transfer procedure consisted of the transference of the total load, supported by the eye-bars, to the provisory structure in four phases. The methodology defined by the rehabilitation design company, RMG Engenharia (Carvalho, 2017), was further detailed by Teixeira Duarte's consultant, Dott. Ing Massimo Marini. Each step of the load transfer represented a stress release of the suspension system and a load increase in the temporary structures.

Phase 1: Elevation of the main span in a pre-defined non-linear shape by 500 mm at the center and no elevation at extremities; Phase 2: Removal of the 28 hanger cables following a pre-defined sequence; Phase 3: Final stress release of the eye-bars that form the catenary in the main and side spans. These operations consisted of the sag reduction of the main span catenaries by about 1000 mm, with simultaneous elevations of the eye-bars, by small steps between the north and side to prevent exaggerated torsion of the main towers; Phase 4: Reduction of the force of eye-bars that form the upper chord of the center of the main span by inverting the shape of the truss lowering the central part.

The eye-bars in the central part of the truss are simultaneously part of the suspension system and upper chord of the truss. This is a design topology that represents savings in the total weight of the bridge, which validated its construction in the 20's. However, this design technique creates some difficulties in rehabilitation studies when the numerical model must compose the interaction between the suspension system and rigidity truss. In addition, due to the uncertainty of the starting stress distribution, other construction parameters, possible rehabilitation works, and damage evolution in some sections due to loading and extreme corrosion, it was impossible to predict with 100% certainty the stress condition at the beginning of the load transfer. The obtained predictions represented a possible theoretical solution, compatible with all the data available: historical studies, topographical survey, weight calculation based on existing elements, and force measurement on existing hanger and main cables. Despite being uncommon in other engineering works, there was an established 20% margin for the admissible force-displacement analysis during the load transfer for this project.

All operations of the load transfer were performed during the night to minimize the temperature influence on the structure. During the day, the stress fluctuation with the temperature variation and solar light incidence would make any stress analysis impossible as the steel structure was revealed to be very sensitive.

The mounting sequence is not addressed on paper; however, a reverse methodology is implemented.

## 4 MONITORING AND CONTROL OF THE LOAD TRANSFER

### *4.1 Actuating system*

The elevation of the truss was made possible using 58 hydraulic jacks of 50 and 100 tons, operating in synchronism by three power units controlled on a single master console. The operation was controlled by displacement; therefore, 18 displacement sensors were installed with the jack groups. As the total displacement required exceeded the jack strokes, several intermediate steps were performed and the bridge was supported in metallic supports design to integrate the jacks, as shown in Figure 4.

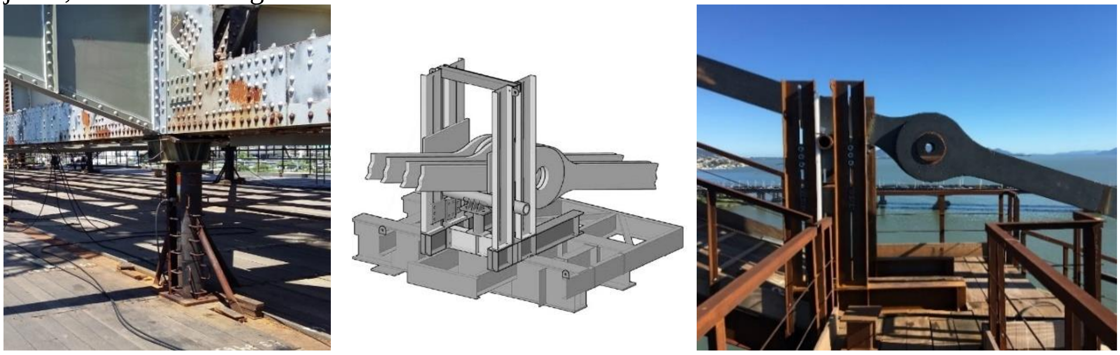

Figure 4. Elevating system of the main truss and temporary supports (left) and mechanism to support and elevate the catenary in the main span (center and right).

The system to elevate the catenary consists of 14 supplementary jacks of 50 tons and two power units. Like the elevation of the truss, intermediate steps were needed to accomplish the total sag reduction required to null the stress in the eye-bars. An on-demand structure was designed to allow the elevation of the eye-bars, with several intermediate stops for the adjustment of the jacks. This system is depicted in Figure 4.

### *4.2 Topographical survey*

A topographical monitoring system was designed to follow the displacement of critical points of the bridge and the temporary support structure. In total, 62 prism reflectors GPR112 and 10 retro reflective targets were installed. The GPR112 allowed the total station LEICA TS30 to collect their position during the night events. These measurements were taken periodically, twice a week, and at every step of the load transfer. The results obtained were then analyzed and compared with data collected by the hydraulic system and theoretical values.

### *4.3 Monitoring system*

The complete monitoring system included several sensors and data acquisition devices of different technologies, all collected under the same software and synchronized.

For strain and temperature measurements, the chosen technology was optical, namely Fiber Bragg Grating (FBG). In total, 284 sensors were used to measure loads at 64 critical locations.

FBG sensors were selected for their faster installation and because of the long distances that could be attained between the sensors and the acquisition system, which allowed the concentration of the devices in a control room. Their resistance to moisture or corrosion was also taken into consideration due to the project duration, Casas et al (2003).

An additional 26 conventional technology sensors were used for other measurements.

Overall, 20 inclination sensors were placed on the temporary structure and the main tower of the bridge: four on each corner of the temporary structure's foundation platform and two on each side of the main towers. Wind, environmental temperature, and tide loads were also controlled as this is a bridge at a location that forms a narrow passage between the island and mainland. Wind gusts are common and often reach high speeds of up to 110 km/h, compromising the work progress.

### 4.3.1 Installation

Installation efficiency was an essential aspect for the project. Rehabilitation had already started, and the load transfer scheduled when the monitoring project was approved by the client. Nevertheless, the installation had to be concluded before the start of the load transfer. To ease and speed up the work onsite, HBM supplied the optical sensors already grouped and connected in series in accordance with the sensor's final position. This alone reduced onsite tasks by 11 splice connections.

Two installation methods for the sensors were selected depending on the element of installation. Bonded sensors, with faster installation times but long-term dependence on adhesives, were chosen for installation on elements to be replaced. Spot weldable sensors that require special equipment for installing were chosen for new or kept elements.

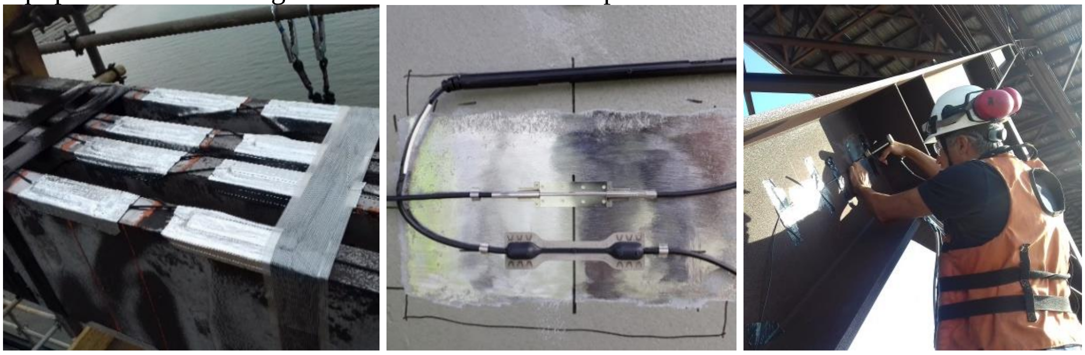

Figure 5. FS62 Composite Strain Sensor and FS63 Composite Temperature Sensor (left), FS62 Weldable Strain Sensor and FS63 Weldable Temperature Sensor (middle) and spot-welding process (right).

Between arrays and to the control room, where optical data acquisition systems were positioned, cabled connections were laid via splices, also performed onsite. Multi-fiber cables were deployed along the bridge; on each relevant position, one fiber would be pulled out and connected to the sensor (Figure 6). However, this was not the only function of these cables. The same infrastructure was used as a communication link between the electrical PMX data acquisition systems distributed through the bridge.

Figure 6. Multi-fiber cable splice protection box (left and center) and PMX device (right).

The six PMX systems needed were deployed along the structure at the needed locations: on the four provisory structures and on the main towers. Being in the open, equipment like this had to be protected inside proper cabinets (Figure 6).

### 4.3.2 Data acquisition

All equipment was connected in the control room. All measuring devices were connected through optical Ethernet switches: the PMX from the optical cable and the optical interrogators directly. As mentioned before, six PMX units were used to acquire the 26 electrical signals. For the almost 300 FBG sensors, three BraggMETER interrogators with eight optical channels each were used.

All devices were synchronized via catman software and measurement was recorded and processed.

For the overall system, two PCs were used, one dedicated to live and continuous data acquisition and the other to post-processing of previously saved data. The powerful software permits easy data configuration, visualization, storage, and processing, allowing the creation of scripts that automatically create periodic reports and alarms for workers onsite and responsible engineers local or remotely.

Figure 7. Control room with fully operational monitoring and control system and rack with three Industrial BraggMETER interrogators (left). Example of one of the panels with real-time data visualization over the bridge scheme: Real-time indicators of wind speed and temperature, sensor sections positions, and color status.

### 4.3.3 Software configuration and developed scripts

Catman software is a powerful tool prepared for easy data acquisition, configuration, and saving. Apart from its useful features, catman allows the creation of scripts in VBA, which can be extremely useful on complex projects such as this one.

The total setup was prepared, with standard configuration and via scripts, in order to support data management and visualization. All raw data is computed into, for example, strain, temperature, and inclination in the intuitive catman configuration interface. With the prepared scripts, the mathematical computations from measurands to relevant data (strain to load, for example) are simplified, as a user interface is created.

The amount of sensor data and visualization panels make control difficult without the creation of automatic alarming. Visual indication on the monitors as well as alarm messages sent via HBM Push were programed. With push notifications, a defined group of users can receive email or SMS messages instantly upon an alarm event.

Scripts were also prepared for post-processing. Acquired and saved data was “cleaned” from eventual outlier measurements and automatic reports were created in Word and Excel.

## 5 LOAD TRANSFER DATA

The load transfer operation to dismantle the suspension system started in October 2017 and was fully completed by December 2017 with the removal of the last eye-bar.

During the load transfer operations, two engineers, one from RMG Engenharia and one from Teixeira Duarte, carried out a real-time analysis of the force evolution of the elements monitored, comparing the results with the theoretical predictions.

At the end of each operation, a report was elaborated through software with data available from all the sensors. This report was important for the entire team involved in the process, who performed a detailed analysis of the force evolution and compared it with other data available, such as the force-displacement results from the hydraulic elevation system, the topographical survey, and the theoretical model.

Figure 8 presents the graphs included in the report with the force, temperature, and wind evolution for all the bars monitored. The data depicted in both graphs was measured during one operation of Phase 3, while elevating the catenaries in the main span. This analysis was made in post-processing to allow easier control of the data selection without compromising the ongoing measurements.

The overlap of force evolution for elements with similar and comparable results was a major advantage during the analysis. The software used for analysis allowed imprinting of all the force evolutions in the same graph, which made the comparison of results and correlation between different elements during the same operation easier.

For example, Figure 8 depicts the force evolution on the elements of the bridge. The operation was subdivided into two steps, the first on the north side and the second on the south. Both events were registered on the same graph and the force variation could be easily observed, first with the drop on the red and blue curves at 1:25 am and second by a second drop of the green and cyan lines at 3:10 am.

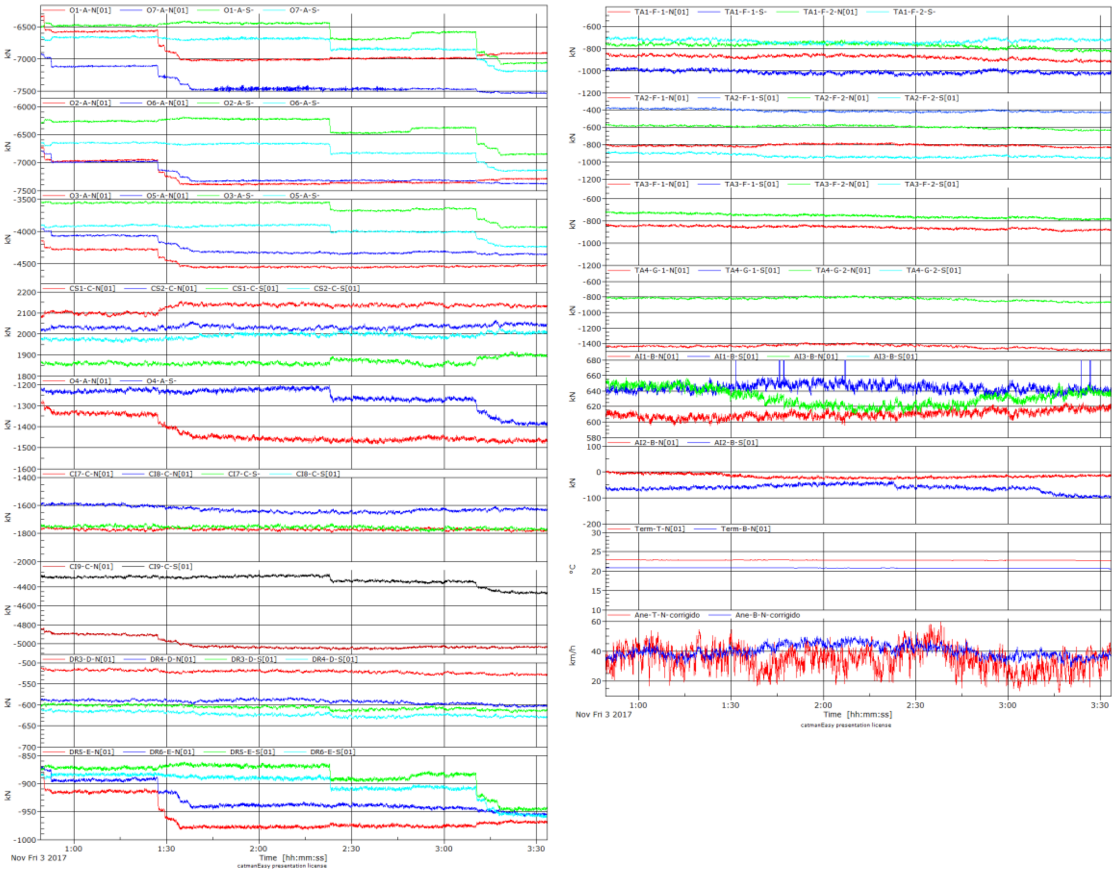

Figure 8. Force measurement of the sensors installed in the main truss (left) and in the supporting auxiliary structure (right) during operation Phase 3- 80%.

For this event, no major changes were observed in the understructure as no additional weight was added to the temporary supports as shown in Figure 8. This graph also presents the temperature and wind evolution because this support structure has the critical element that withstands these aggressive climacteric conditions.

The climacteric sensors were also implemented for real-time verification before the start of operations. Due to safety reasons, the work could start only with wind speed lower than 40 km/h and a good forecast.

The inclinometers installed were observed in real time to verify whether any unexpected movements may have occurred during the load transfers. A set of alarm values were defined for the maximum admissible deflection considering extreme conditions (wind, temperature, and load). The operation occurred within the admissible values and no alarm was fired for the understructure in the process. The inclinometers installed in the main towers were prepared to detect its rotation during the load transfers as predicted by the numerical model. Furthermore, the movement of the main towers was in accordance with the theoretical model.

Besides the analysis during each operation, for some critical sections, a cumulative analysis was studied in order to understand the force evolution throughout time. Figure 9 shows the force evolution of point O6-A-N measured from Phase 1 to 3 in comparison with the theoretical values.

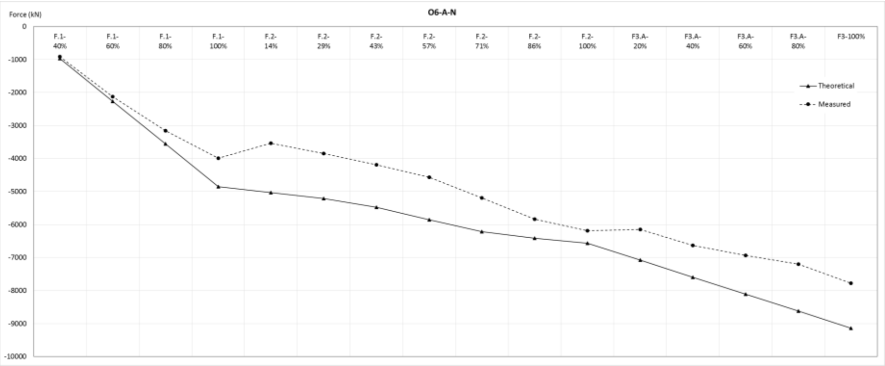

Figure 9. Force measurements at point O6-A-N from Phase 1 to 3.

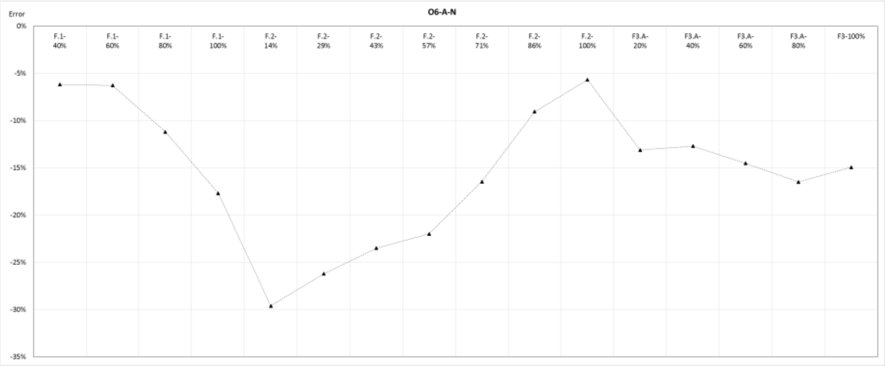

Figure 10. Error evaluation at point O6-A-N from Phase 1 to 3.

This point corresponds to the eye-bar in the main span that belongs to the catenary. By the end of Phase 3, only some residual force remained in the bars and they could be safely removed.

Each load transfer operation is illustrated horizontally. The force evolution was constructed using the values measured before and after each operation. The stress relieved at each operation was then compared to the theoretical model.

Figure 10 represents the deviation between the measured data and the theoretical prediction from Phase 1 to 3 for point O6-A-N. The values observed are within the admissible error initially defined for this project. Nevertheless, some adjustments of the load transfer procedure were made to ensure safety conditions on removal of the first bars. This reinforces the importance of the monitoring system installed to control the complex operation and working mechanism.

## 6 MAINTENANCE

The system was design to withstand aggressive site conditions, with the selection of an appropriate shielded optical fiber cable and supplementary protection with polymeric tubes in critical regions. However, the ongoing works with part replacement, blasting, and painting of the structure demanded a close and continued maintenance of the whole system.

Several times, the optical fiber was partially cut and removed for preservation during the rehabilitation of some sections and reinstalled after the works were complete and good conditions for the perseverance of the system ensured. The splice technique was always used in the repair works to ensure better quality of signal transition.

One person was trained during the installation phase to perform maintenance of the entire system in operation. There were necessary daily verifications onsite to prevent failure of the system due to the ongoing reconstruction works close to the monitoring system. Online support from the HBM team was ensured upon request for software configurations and overall system verifications. When the rehabilitations works were finished, the maintenance demand was highly reduced as the system installed was very well-protected against climacteric aggressive conditions.

## 7 CONCLUSION

The complex ongoing rehabilitation work of Hercílio Luz Bridge is an interesting case study on the “smart” maintenance of our structural legacy, where tasks and progress generate data used for control. The load transfer was a success, which was only possible in a controlled and safe environment due to the extensive measurement systems installed.

Monitoring and comparison between data and expected behavior can be a powerful tool to understand the correctness of the model and support in rehabilitation processes. All data, when compared to the model, were revealed to be within the admissible error defined initially for this project. Moreover, the use of several technologies combined and synchronized in a single interface with one powerful software allows the optimization of the overall monitoring system, taking advantage of each.

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