Adjustment of the Rion-Antirion Cable-Stayed Bridge: An Innovative Multidisciplinary Response to a Construction Challenge

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Key words: cable-stayed bridge, computer aided construction, stay adjustment, deck geometry, total station, instrumentation, laser pendulum, non-contact inductive sensors, DMP method

SUMMARY

The objective of the adjustment procedures used for the construction of the Rion-Antirion cable-stayed bridge is to build a structure that strictly complies with the design definition, even if on-site conditions sensibly differ from model assumptions. A particular attention has been paid to make their use as easy as possible and to reduce to a strict minimum their impact on work schedule.

An original instrumentation has been set up, in order to provide the adjustment software with the relevant input data. Non geodetic sensors, with some of them innovative, have been required, when more conventional solutions are no more applicable.

With the chosen solution, it has been possible to build 560 m long cantilevers with a profile accuracy of ±15 mm, with typical adjustment operations lasting less than half an hour, including survey measurement and data processing.

RESUME

Le but des procédures de réglage mises en œuvre sur le pont à haubans de Rion-Antirion est de réaliser une structure tout à fait conforme à la définition donnée par les études, même si le chargement de l’ouvrage en cours de construction diffère sensiblement des hypothèses prises en compte dans le modèle de calcul. Une attention toute particulière a été portée sur la facilité de leur mise en œuvre et le fait de réduire leur impact sur les travaux au strict minimum.

Une instrumentation originale a été développée pour pouvoir fournir au logiciel de réglage les données requises. Des capteurs spécifiques, innovants pour certains d’entre eux, se sont révélés nécessaires, là où les solutions plus traditionnelles n’étaient pas adaptées.

La solution choisie a permis de réaliser des fléaux de 560 m de long avec des imperfections de construction de ±15 mm. Les opérations courantes de réglage ne dépassant pas la demi-heure, mesures et calculs compris.

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1. INTRODUCTION

With the Olympic Flame of the XVIII Olympiad (Athens 2004) crossing the newly completed Rion-Antirion Bridge, a one hundred year old great dream becomes reality for good. Thanks to its 2252 m continuous deck fully suspended to stays, the two shores of the Corinth Gulf strait are now connected by a permanent link, which will play a significant role in the development of the area.

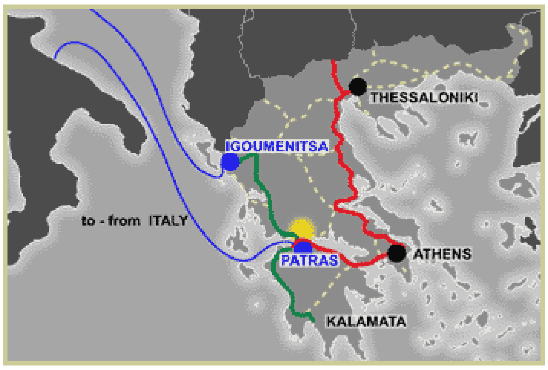

Figure 1: Bridge location

Figure 2: General view

Designed to withstand the strongest winds (250 km/h) and the severest earthquakes (Richter magnitude 7), this bridge out of ordinary also represents a reference at its opening day, as it is the longest multispanned cable-stayed bridge in the world. In addition to the extreme service conditions, the project had to face serious construction difficulties due to the water depth of up to 65 meters and to poor seabed soil properties. The adopted solution consisted in using piers made of floating concrete structures that were towed and laid to their final position, after the ground had been reinforced by a dense mesh of steel tubes (fig. 3).

From a structural standpoint, the bridge comprises 4 pylons that support the weight and loads of the deck transferred by two symmetrical rows of stays, the corresponding span distribution being: 286-560-560-560-286 m.

The deck is made of 12 m long composite steel and concrete segments and precast on land. Once a pylon is completed, the deck construction can proceed. Segments are transported from shore to position by a Taklift floating crane and erected by using the cantilever technique, the new segment being assembled to the deck by splices.

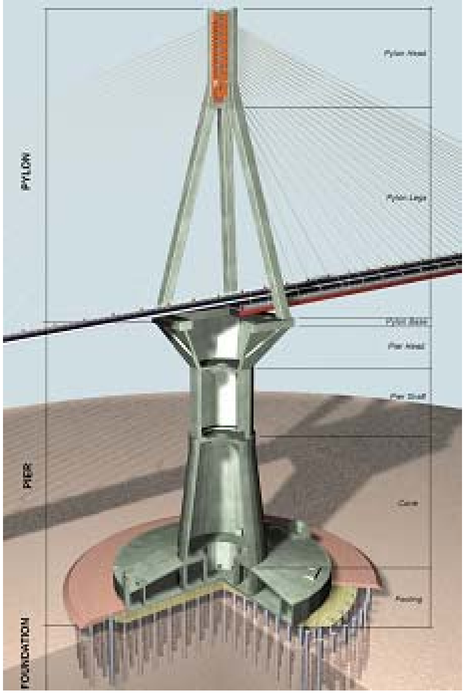

Figure 3: Pier and pylon

Figure 4: Taklift floating crane

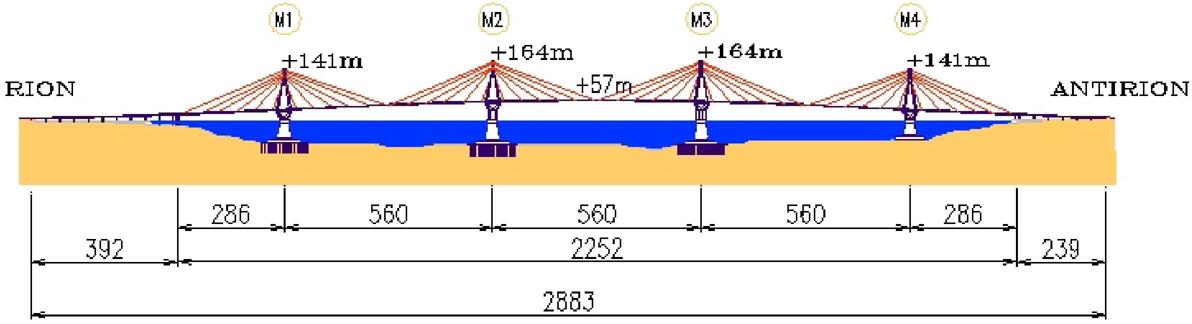

Figure 5: Bridge elevation

Figure 6: Deck cross-section

Figure 7: Cantilever construction

It is necessary to precisely set the new segment relatively to the section of deck already built and to maintain their position unchanged during the bolt tightening operation. For this purpose, a specific equipment called Quick Connection Device has been designed on the basis of a safe static scheme: the weight of the segment is balanced by a vertical reaction applied to a temporary bearing fixed at the deck end, whereas moment equilibrium is obtained by two horizontal forces exerted by an hydraulic jack device that provides translation and rotation adjustment capabilities.

Figure 8: Segment lifting

Figure 9: Quick Connection Device

Segments are alternatively erected at each end of the cantilever. Once a segment is assembled, a new pair of stays is installed and tensioned.

During its construction, the deck is subjected to vertical deflections, which increase with the cantilever length, up to reach an amplitude of about 1.50 m when assembling the last segments or stressing the last stays. The horizontal displacements of the pylon anchorages are limited to amplitudes of about 100 mm, due to the stiffening effect of the 4 legs. In addition, the structure is very sensitive to the effect of unspecified site loads and to thermal variations; for instance, at completed cantilever, a variation of 10° C of the stay temperature produces a vertical displacement of 100 mm.

In spite of these large deformations, with some of them difficult to control, the bridge must be adjusted with precision, in order to obtain a final deck profile and a force distribution in the structure, which strictly comply with the design definition.

The purpose of this paper is to present the approaches that have been adopted for the adjustment of the Rion-Antirion Bridge, with a particular stress on:

- the specific problems to be solved in the framework of this project,
- innovative instrumentation solutions that have been set up to meet the particular constraints,
- results obtained,
- and finally, experienced collaborative teamwork, which involved experts and engineers from various disciplines or functions, and which appears today to be a key factor for the success of such a task.

2. PROBLEMS TO BE SOLVED

In all cable-stayed bridge projects, adjustment procedures represent a major topic, which requires a rigorous preparation and a careful attention, in order to achieve satisfactory results, both from quality and productivity standpoints.

For the Rion-Antirion Bridge, the situation was in fact more critical than usual, due to several factors.

- A tight delivery schedule combined with numerous days of windy weather, during which construction was stopped, imposed a rigorous management of available working time. In particular, adjustments tasks should impact as little as possible construction operations.
- Stays must be adjusted very precisely when being installed, as no re-tension operation is planned after span closure.
- Due to harsh environment conditions span connection must be achieved as quickly as possible, once the closure operation has started.
- 560 meters long spans represent a significant extrapolation from dimensions generally adopted for cable-stayed bridges made up of a composite steel and concrete deck.
- Stay adjustment uses, as input data, the actual displacement values of the deck and pylon anchorages. As pylon are out of reach of geodetic instruments, an alternative instrumentation solution must be developed to accurately measure pylon deflection.

3. PRINCIPLE OF ADJUSTMENT PROCEDURES

3.1 General

Before examining in detail the specific solutions adopted for the Rion-Antirion Bridge, it is worthwhile to present the general problem of cable-stayed bridge adjustment, as well as the principles of a modern computer aided construction approach, which has been already used successfully for previous projects and which has been retained as a starting point for developing the Rion-Antirion Bridge's adjustment methods.

3.2 Conventional Approaches of the Adjustment Problem

With conventional approaches, the results provided by the stage-by-stage structural analysis are most often directly used to perform the related on-site adjustment operations. For instance, a stay being placed is tensioned so that its force at the end of the stressing process is equal to the theoretical value given by the model. In a similar way, a new segment being positioned is adjusted at an altitude that corresponds to the cantilever end theoretical deflection value for this stage.

Although still of common use, these practices suffer numerous drawbacks. For each adjustment operation, the actual loading of the structure must strictly coincide with its theoretical counterpart (site loads, temperature distribution, …). Then, two alternatives are possible:

- either, adjustment operations are carried out in respecting carefully the loading scheme adopted at the design time,
- or, the design computational model is updated with the most recent loading survey and temperature measurement, in order to get adjustment instructions. appropriate values.

Neither of these solutions is in fact satisfactory:

- in the first case, specific precautions that impose stringent constraints to the work schedule are necessary: the adjustment of a stay or of a newly erected segment must be performed early in the morning, when temperature distribution in the structure is uniform, whereas no unspecified site load must be present on the deck during the adjustment operation.

- in practice, the latter solution appears to be poorly reliable, as important discrepancies are generally observed among the measured temperature values. In addition, collecting the measurements and running the computations require a significant time during which the thermal state of the structure may evolve.

As far as stay adjustment is concerned, unstressed cable length is sometimes used as an adjustment criterion on site. However, due to its extreme sensitivity to construction tolerances, the method appears to be inaccurate.

Finally, using some of the calculation results as adjustment parameters prevents from reliably checking if the actual structure under construction behaves as predicted by the computational model.

From these observations, it clearly appears that the conventional approaches used for cable-stayed bridge adjustment must be re-visited in depth, in order to develop methods, which are at once reliable, robust, accurate and easy to use on site.

3.3 Proposed Approach

3.3.1 Origin

In the early 90's, FORMULE INFORMATIQUE engaged a R&D work in this direction and set up an original computer aided construction solution, which has been applied in 1993 for the first time and with success to the Iroise Bridge adjustment in France. This approach, which has been continuously improved, has been adopted for the construction of 3 other major projects in Europe: Second Severn Crossing in Bristol (UK), Vasco da Gama Bridge in Lisbon (Portugal), and Third Millenium Bridge in Gdansk (Poland), and now for the Rion-Antirion Bridge.

3.3.2 Aimed objectives

- Organize rigorously the so-called geometry control operations performed on site during construction and precisely define the role of each of them.

- Adopt a set of adjustment procedures that are independent of theoretical loadings taken into account in the design computational model for each stage.

- Allow for a high level of adjustment accuracy, without having to comply with unusual construction tolerance constraints.

- Reduce to a strict minimum the interference with schedule and construction process.

- Provide the adjustment team with suitable tools that allow adjustment operations to be performed in best conditions

- Automatically keep track of adjustment instructions specified to the construction team, as well as of measurements from which they have been derived

3.3.3 Structuring construction control operations

The survey procedures used during the construction of a cable-stayed bridge can be organized into two main groups: adjustment procedures and verification procedures.

a) Adjustment procedures
Adjustment procedures are tightly connected to on-site construction operations. Their purpose is to specify to the production team precise quantitative instructions, in order to build a structure that complies with design definition.

These procedures essentially concern two distinct items that must be clearly separated:
- the geometrical shape adjustment to impose to the deck (and possibly to the pylon) during their construction
- the adjustment of each stay being installed

b) Verification procedures
Verification procedures are more a subject of interest for the design engineers rather than for the site engineers, as these procedures are meant to check if the structure actually behaves, as erection proceeds, in accordance with the predictions of the computational model.

In practice, verification operations are carried out by surveying the actual deck and pylon deflections, the site load positions, the temperature in the structure - and possibly by measuring the stay forces - at stages for which the loading case of the structure is clearly defined (uniform temperature, no moving loads on the deck, …). Then, a comparison can be performed between these surveyed values and the results provided by a simulation run for the same case of loading.

In case of discrepancy between observed and theoretical structure behaviors, a careful analysis is carried out to investigate the origin of the problem and to determine the most appropriate solution to adopt.

c) Organization of the construction control operations
The organization of these adjustment and verification procedures, which correspond to the so-called geometry control operations, can be represented by the following sketch.

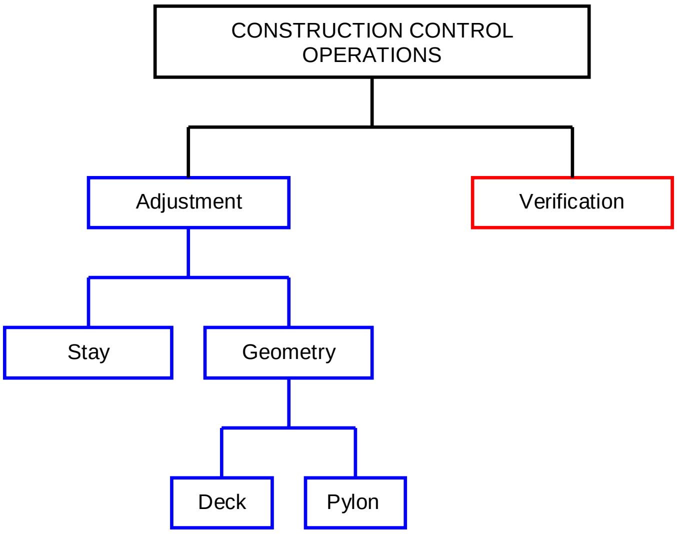

Figure 10: General organization of construction control operations

3.3.4 Basic ideas of the adjustment approach

The proposed adjustment approach is based on two fundamental principles:
- Adopt as adjustment parameters input data of computational model rather than its results.
- Use only adjustment parameters that are not sensitive to variations due to construction tolerances

Satisfying the first principle presents several advantages:
- Input data characterizes the adjustment intrinsically, in that their values do not depend on the loads applied to the structure during construction
- The adjustment parameters are not affected by uncertainties related to the material physical properties taken into account in the structural behaviour simulation (concrete E modulus, shrinkage and creep laws, …)
- Using the same input data for construction simulation and for on-site adjustment -without having to rely on any result from the calculations in adjustment operations -enables to perform a rigorous comparison between observed and predicted behaviours of the bridge under construction in the verification procedures framework.

3.3.5 Stay adjustment

The adjustment target is characterized by a reference state from which structure displacements are measured and for which stay tensions T_{ref} are perfectly known. The choice of the reference state is rather conventional, but in practice it coincides with the theoretical state of the bridge, either at opening day or at infinite time.

The principle of the stay adjustment procedure is based on a differential method: knowing at a given construction stage the actual values of stay tension T_{actual}, stay temperature $\theta_{actual}°$, and anchorage displacements u_D and u_P, it is possible to deduce the elongation Δl to apply to the stay, in order to reach the adjustment target.

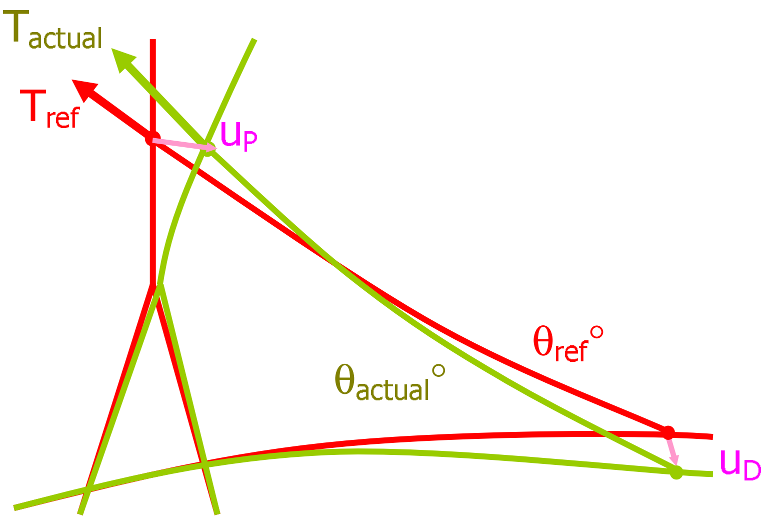

Figure 11: Stay adjustment principle

3.3.6 Deck geometry adjustment

The adjustment of deck geometry lies on the pilot line notion. The pilot line is defined as the profile that the deck would display, if it was built without any construction errors at all. In practice, the pilot line is characterized by a set of benchmarks laid on actual concrete surface. Each benchmark has a vertical offset η from the pilot line, which represents the construction error.

The pilot line plays an essential role in adjustment procedures, as it allows to get free from construction tolerance effects. For instance, vertical deck deflection w at a benchmark location can be evaluated, at any stage, from benchmark altitude by the simple formula:

$$w = z_B - \eta - z_D$$

with z_B being the measured benchmark altitude and z_D the theoretical project line altitude as represented in drawings.

When a new segment is erected, it is positioned relatively to the deck end, using the section of the pilot line located on the last deck segment.

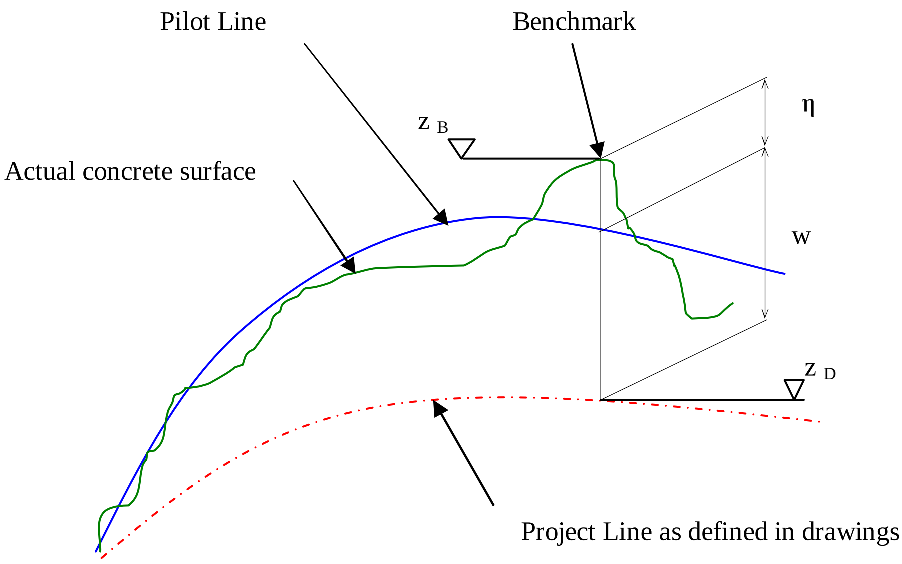

Figure 12: Evaluation of η and w values from pilot line

Once the new segment is assembled, the deck pilot line is extrapolated by using a specific geometrical construction, which involves a least square fitting and a deformation correction.

4. REQUIRED MEASUREMENTS

4.1 Adjustment Operations Performed on Site

In practice, three different types of adjustment operations are performed, named:

- ERECT : positioning of a new segment relatively to last cantilever segment
- CANT : prolonging the pilot line on the new assembled segment
- STAY : stay adjustment

4.2 Required Site Data

- ERECT
  - Angle between new segment and last cantilever segment
- CANT
  - Benchmark relative altitudes on new segment and on an adjustment block consisting of the last two cantilever segments,
  - Survey of actual site loads and stay tensions on new segment and adjustment block, for deformation correction.

- STAY
  - Stay tension at anchorage
  - Deck and pylon anchorage displacement values
  - Stay and structure temperatures

4.3 From Measurements to Anchorage Displacements

Displacements of pylon anchorages are obtained by interpolation of displacement values measured at 5 specific levels by devices that are described in the next section.

Deck anchorages displacements are deduced from surrounding benchmarks displacements, which in turn result from absolute altitudes measurement (see fig. 12).

4.4 Frames Used for Deck Construction

Three frames are used for distinct purposes during deck construction.

As already mentioned, deck pylon line is extrapolated by performing coordinate measurements in a *local frame* attached to the adjustment block made of the two previous cantilever segments.

As the cantilever suspended to a pylon is built independently from the other cantilevers, it has been chosen to assign a frame to each pier. It acts as the *absolute pier frame* for the related pylon and cantilever. This solution minimizes distances involved during measurements and makes stay adjustment and structure verification procedures independent of any foundation movement.

Finally, it is essential to ensure consistency between *absolute pier frames*, especially in case of tectonic movement or foundation settlement. For this purpose, a *bridge global frame* is used, in which pier point positions are monitored in conjunction with shore reference points by using several methods: static GPS for planimetry, trigonometric leveling, geometric leveling.

To each frame corresponds a different level of accuracy: some tenths of millimeters for altitude in *local frame*, one or two millimeters for *absolute pier frame*, five millimeters for *bridge global frame*.

Regularly performed surveys of *absolute pier frames* about the *bridge global frame*, allows to detect and evaluate any potential movements, and then to adopt, relevant adjustment corrections. In fact, no significant displacement has been observed during deck construction and no correction has been required.

5. ADOPTED SOLUTIONS FOR MEASUREMENT INSTRUMENTATION

5.1 Instrumentation for ERECT Operation

In order to allow for a quick and safe new segment positioning, it has been chosen not to use geodetic instruments, but instead to develop a laser based adjustment device. A laser source and a diaphragm plumb with the last cantilever segment end benchmarks, materialize a line attached to this segment. The aimed angle is obtained when the laser spot on the target fixed on the new segment reaches the pre-determined position.

Figure 13: Laser device for ERECT operation

5.2 Instrumentation for CANT Operation

The benchmark altitude values required by CANT operation are measured in a local frame located at deck end by using a high accuracy total station in non-compensated mode. In order to validate measurements and improve their precisions (some 1/10 millimeters), several survey series are automatically performed.

5.3 Instrumentation for STAY Operation

a) Deck displacement

Figure 14: Motorized total station with reflectors

Figure 15: Linear wire sensor

Benchmark altitude values are measured about a global frame with the same total station as for CANT operation, but with a smaller precision requirement of 2 to 3 mm. Redundant measurements are as well performed.
Deck longitudinal displacement at pylon axis is measured using a linear wire sensor connected to deck and pier.

b) Pylon head displacements

Figure 16: Laser device for measuring pylon base horizontal displacements

Because of the vertical unprotected distance of about 100 m between pier top and pylon head base, it was chosen to materialize the vertical direction by a laser ray, in order to avoid any undesirable interference with wind. The displacements of the pylon head base are tracked by a specific laser pendulum supplied by DYNAOPT GEODESIE INDUSTRIELLE, which consists of:

- a laser transmitter passing through an automatic optical plummet
- an optoelectronic receiver

The measurement accuracy of the impact point is less than 1 mm over a range of ±70 mm in both directions.

Then pylon head displacements are measured at 4 specific levels regularly distributed, by using two invar wire pendulums. Relative table positions in XY directions are determined by automatic non-contact inductive position sensors, specially developed in the Rion-Antirion bridge project framework. These innovative devices designed by J.O.E., manufactured and installed by DYNAOPT GEODESIE INDUSTRIELLE offer a measurement accuracy of less than 1 mm over a range of ±60 mm.

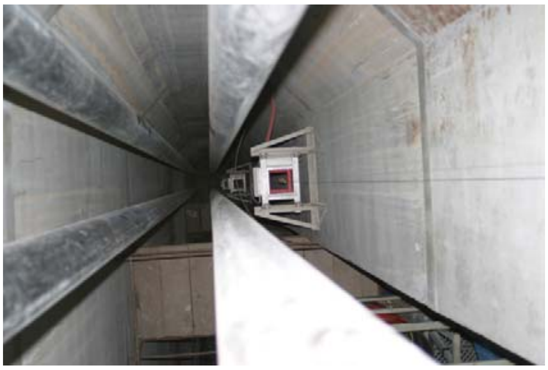

Figure 17: Wire pendulum in pylon head

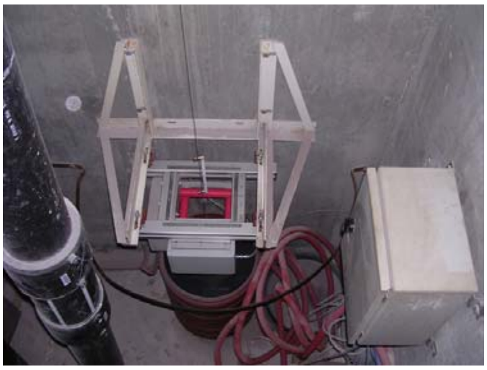

Figure 18: Inductive position sensor

c) Temperature values

Temperature in stays is estimated by using a mock-up made of a duct and strands section and placed on deck, which simulates the thermal state in stays. Temperature sensors are installed in the four pylon legs and in the pylon head, as well as in the concrete slab and on the main beams of the deck.

Figure 19: Stay mock-up

Figure 20: Data acquisition analysis

5.4 Data Acquisition

A software, specifically developed for this purpose, collects the values at regular time intervals over a specified period and analyzes them from a statistical standpoint (mean values, standard deviation, evolution trend).

5.5 Instrumentation Design Philosophy

All the specifically developed measurement devices have been developed in order to allow for performing simultaneously a manual and an automatic data reading. This precaution is required not only to cope with possible equipment breakdown, but also to easily verify if a measurement is reliable.

6. RUNNING ON SITE ADJUSTMENT OPERATIONS

Survey and stay tension measurements are pre-processed and checked by the adjustment team assigned to the considered pylon. Then, the corresponding files, as well as those provided by the data acquisition unit, are transferred by radio link to the on shore adjustment engineers.

Once the adjustment software relevant module has been run, the practical adjustment instruction to be applied is transmitted to the construction team, whereas the history report generated is sent to the Quality Department.

For stay adjustment, time necessary to perform measurements, analyze data, and run computer program is less than one half hour. This is a breakthrough compared to other projects considering the amount of data to be collected and the final results quality.

7. OBTAINED RESULTS

The adopted adjustment method, associated with the use of fully suitable measurement approaches – which, for some of them, have required innovative developments – have made it possible to reach very satisfactory results, both from the standpoints of schedule respect and of construction quality.

As a matter of fact, the erection of a more than 2 km long deck took less than one year, in spite of adverse weather conditions, which have frequently stopped site activities.

Figure 21: As-built construction error η along cantilever

The deck has been built with construction tolerances of about ±15 mm, whereas the theoretical deck profile deflection at cantilever completion was coinciding with the computational model predictions with a precision of ±15 mm (with an exception at cantilever ends where this value reaches ±30 mm).

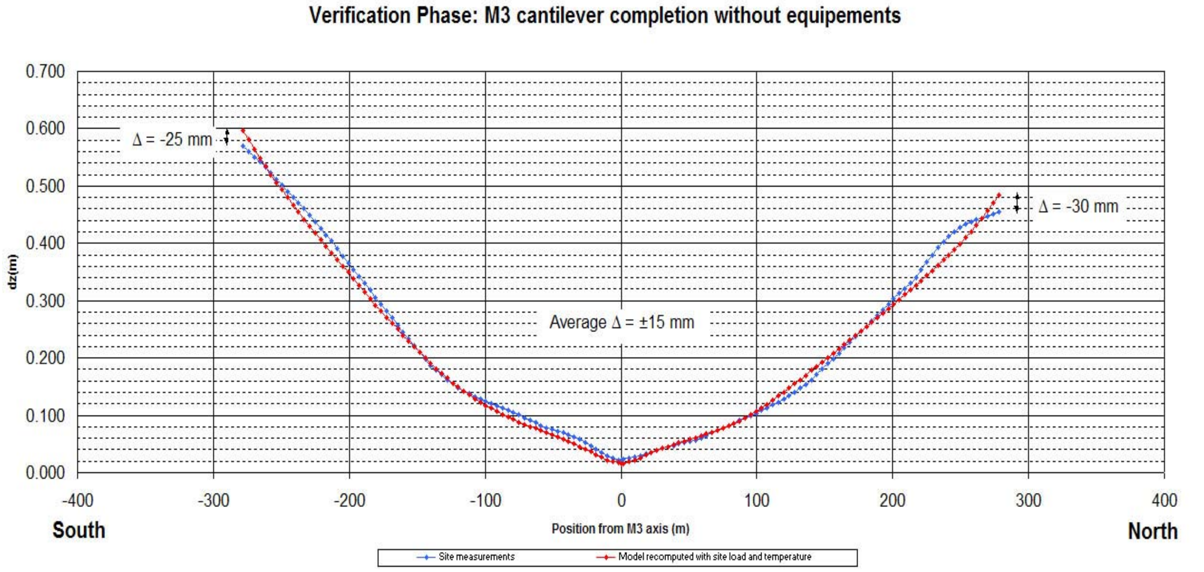

Figure 22: Comparison measured cantilever deflection vs. model predictions

8. CONCLUSION

The technical challenge of completing the Rion-Antirion project within the planned schedule has been won, as the bridge opens about 3 months ahead the initially announced date.

Such a success is, among others, the result of a meticulous preparation work carried out by a multidisciplinary team, which involves experts and engineers from various disciplines and functions (design, production, method, survey, computer aided construction, instrumentation, electronics, software).

Designing and tuning the adjustment solution presented in this paper passes through a continuous improvement process that supposes a tight collaboration between all the parties. Each engineer must keep an open-minded attitude to understand constraints from other disciplines and to be ready to devise innovative solutions when more conventional ones are no more applicable.

Finally, stress must be put on the role of the so-called DMP method, which has served as a guidance, all along the preparation work. According to this method, whose acronym stands for Design-Method-Production, each item that is imagined or modified must be analyzed by considering the interactions between these three points of view.

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