LYRA: an autonomous bridge stays and hangers monitoring solution

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Abstract
Cable-stayed bridges are widespread and usually require periodic tension measurements to verify their structural integrity and avoid failures such as those that occurred in Genova (2018) or Toulouse (2019). This procedure is often complex, time consuming, requires trained staff, and is prone to uncertainties due to the environmental conditions and to the sparsity of the measurements. The Walloon region, for instance, is capable of carrying out tension identifications at best once a year. In this paper, we introduce LYRA, an autonomous cable tension measurement solution comprising wireless accelerometers attached to each instrumented stay; an autonomous solar powered central station which is responsible for the computation of the tension, the management of the wireless nodes, and for the data upload; and a cloud solution to visualize the data and send alarms if the measured tensions are outside predefined bounds. The capabilities of the system are demonstrated on the Lanaye bridge, whose 30 stays are being monitored since October 2021.

1 Introduction

Cable-stayed bridges are widespread all over the world. If left unattended, they might be prone to failures as observed recently in Genova (2018) and Toulouse (2019), for instance.

Measuring the tension in bridge cables is one way of verifying their structural integrity, because the rupture of strands in a cable would lead to a redistribution of the loads in the bridge's stays or hangers [1, 2, 3, 4].

In Wallonia (Belgium), the monitoring is carried out by the "Service Public de Wallonie" (SPW). This procedure, detected a 20% tension reduction in the Lanaye bridge between 2001 and 2020 (see 1-b, orange curve), and led the authorities to replace the stay before critical damage occurred [1]. It was later determined that the failure was due to cracking and corrosion in the cable (see 1-c), which is a worldwide subject of concern even though the steel strands and rods are installed and protected with great care [4, 5, 6].

The current procedures usually rely on sparse on-site measurements (at best once a year in Wallonia) and on the taut string theory [4], which is only valid for cables with negligible bending stiffness and anchor effects. To address these limitations, V2i, the University of Liège, and the SPW developed LYRA, an autonomous monitoring system with wireless sensors capable of operating remotely and of continuously measuring the tension of cables irrespective of their bending stiffness and anchor conditions. It is therefore applicable to long stay cables as much as to short hangers in bowstring bridges. The solution has been monitoring the tension of the 30 stays of the Lanaye bridge (located at the border between Belgium and the Netherlands) since October 2021.

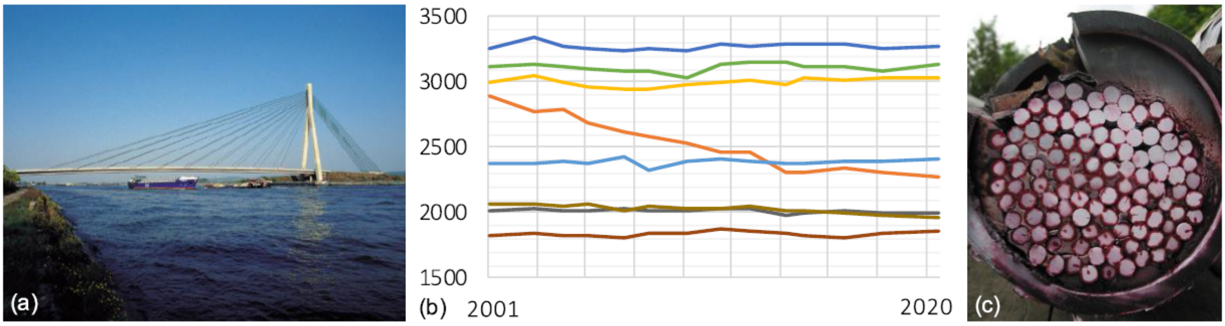

Figure 1: Photograph of the Lanaye bridge (left), Tension variation with time in relevant stays (middle), photograph of cross section of a damaged stay (right).

2 Monitoring solution

LYRA comprises three main components which interact with each other to provide a full monitoring solution (see Figure 2). Wireless accelerometers are attached to each instrumented stay and dispatch their measurements to a central station. The central station computes the tension in the cable from the acceleration measurements, saves the data in an internal database and finally dispatches the key processing indicators (KPIs) to a cloud server. Finally the cloud server can be used to visualise the data and to send alarms when the KPIs reach user defined thresholds.

Figure 2: Overview of the LYRA monitoring solution showing a wireless sensor mounted on a cable (left), the central station with its solar panel (middle) and the web application (right).

2.1 Central station

The central station has three main functions. First, it controls the acquisition system. Several strategies are implemented to minimize the risk of collision or loss of packages. For instance, the station activates the sensors one after the other according to a specified schedule. A quality index is associated to the time series depending on their signal-to-noise ratio and the stability of the wireless connection. It allows to determine confidence levels for the subsequent identification of tensions or to directly discard some measurements. The sensors are also able to keep a part of the signal on their internal memory for a few seconds to transmit it correctly even though the connection with the station is intermittent.

Second, the station processes the acceleration measurements received from the wireless sensors and computes the tension in the cables.

Third, the station acts as a relay by uploading and organizing raw data received from the acceleration and the temperature sensors but also the tension estimates and information about the remaining capacity of the batteries, both on an online server and on its own on-site database.

In addition, some parameters are embedded inside the memory of the station and can be modified either by direct access, either via the cloud. Typically, it encompasses the length and mass of the cables that are necessary for the axial force identification. Apart from that, the sampling frequency, the duration of acceleration measurements, their timing and the SSI parameters (see section 2.4.1) are defined there as well.

The central station can either be powered by the network or using a solar panel, for remote applications. As both sources of power are usually intermittent, an internal battery powers the station during the losses and a controller makes sure the battery does not fully discharge.

2.2 Wireless nodes

The acceleration measurements are performed using wireless sensors, which have many advantages. First, it does not require pulling wires along the whole bridge to link the sensors with the central station. Second, it allows the sensors to be easily placed far enough from the bridge deck to prevent vandalism issues. Third, it avoids adding mechanical weak points to the network, such as wires which are in addition complicated to repair or to replace.

The sensors are powered by special D-size batteries with low self discharge and high robustness to temperature variations. These batteries are sufficient to record five-minute long signals, four times a day, for ten years, at least. The sensor and battery assemblies have then been placed inside IP66 rated, waterproof and UV-resistant casings whose internal structure has been 3D printed according to our needs. They also contain a temperature sensor with an accuracy of 0.25°C, an antenna and the electronics necessary to communicate with a central station.

Finally, the casings are clamped to the stays by means of U-shaped metallic elements which can by adjusted to fit the diameter of the instrumented cable. In order to ensure that the natural frequencies of the cables are well distinct from those of this acquisition system, it has been tested on a shaker. It has been shown that the sensor resonates at very high frequencies, that are hardly ever excited when dealing with ambient vibrations.

2.3 Cloud solution

Last but not least, a web application dedicated to the monitoring of axial forces in the stays and the hangers of cable supported bridges has been developed. It allows to visualize the variation of the tension in each cable by means of tables or graphs and it sends automatic warnings if an issue is detected on the central station (e.g. a power loss) or if the tension in an instrumented cable is outside specified limits.

2.4 Identification procedure

The identification method is made of two steps. The natural frequencies of the stay are first computed from the temporal acceleration measurements. Then, the tension in the cable is computed using a mathematical model and the identified natural frequencies.

2.4.1 Frequencies identification

The natural frequencies of each instrumented cable are computed from the acceleration measurements using the "crystal clear" version of the Stochastic Subspace Identification (SSI) and a stabilization diagram [7, 8]. The obtained frequencies and their orders are then fed to the mathematical model of the cable in order to compute the tension. Figures 3 and 4 display the Harchies bridge (Belgium), which is a bowstring bridge with short hangers, and an example of identification, respectively. The top and middle sub-figures show the measured response and corresponding PSD and stabilization diagrams, respectively. The bottom sub-figure depicts the corresponding $F(N)/N$ curve, obtained by computing the ratio between the natural frequency and the mode number for the first 5 natural frequencies. This figure illustrates the necessity to model the bending stiffness of the cable as the taut string theory would predict $F(N)/N =$ constant [3].

Figure 3: Photograph of the Harchies bowstring bridge, from the "Structurae" database [9].

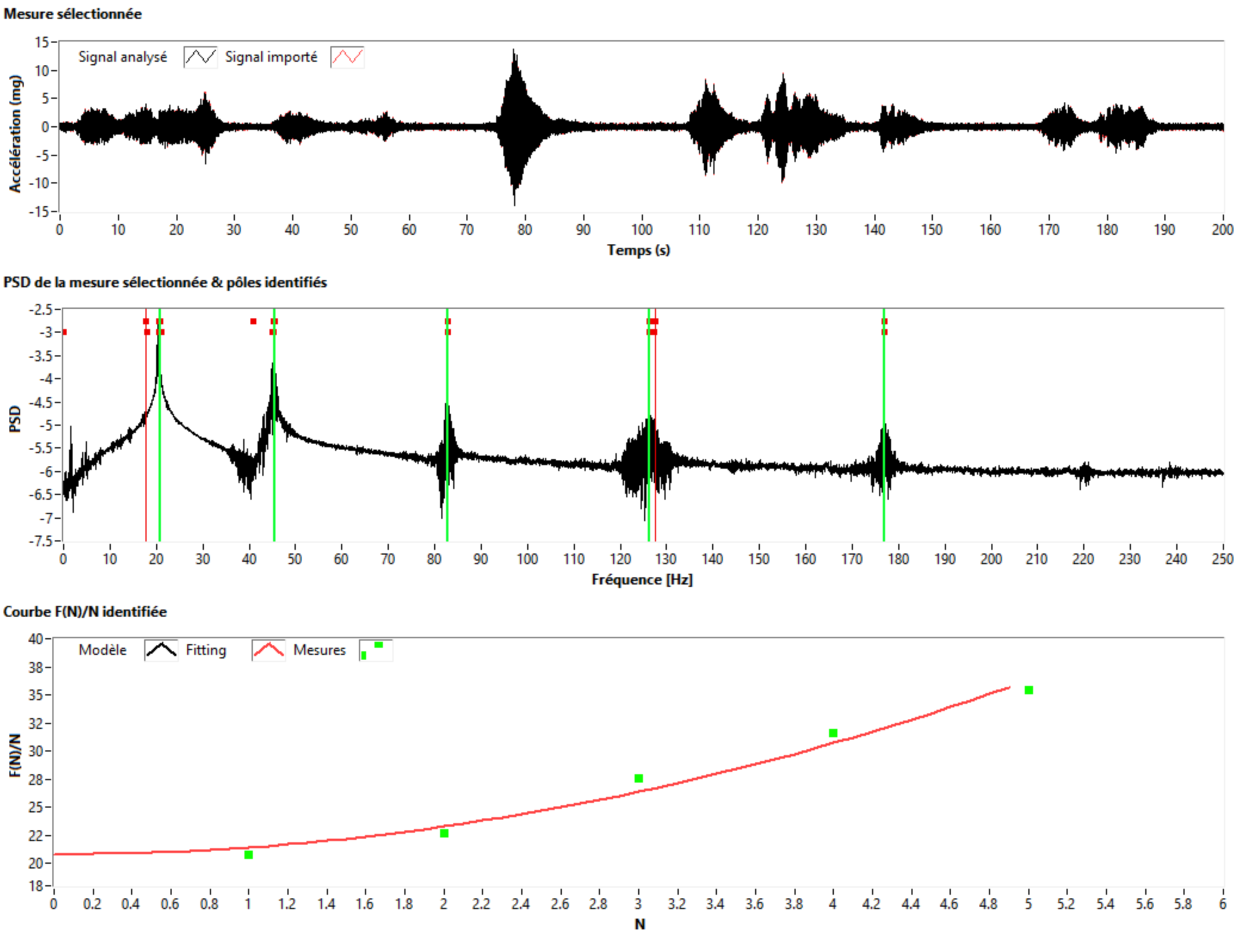

Figure 4: Identification of the natural frequencies of a stay in the Harchies bridge showing the response of the cable (top), the stabilization diagram and PSD of the response (middle) and the resulting natural frequencies distribution (bottom).

2.4.2 Tension identification

The parametric model of a cable with length l, mass per unit length μ, cross section stiffness EI and tension H attached in each end by supports of dimensionless rotational stiffnesses ρ_i and translational stiffnesses ρ_i^* is illustrated in Figure 5. Solving the equations of motion of this cable provides a relationship between f_n, the natural frequencies identified from the acceleration measurements, and the tension.

If the bending stiffness of the cable is equal to 0, the supports boundary conditions have no effect, the cable

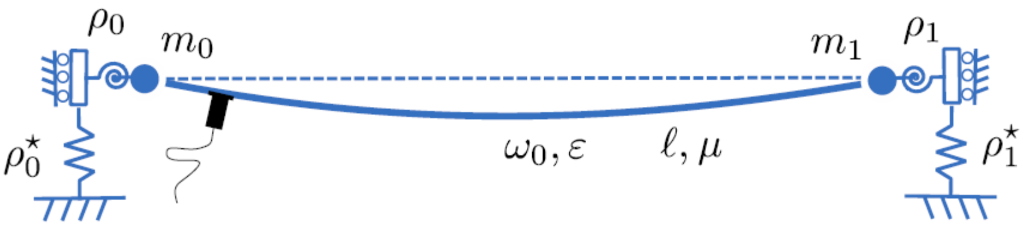

Figure 5: Structural model of a cable with flexible supports and a non-zero bending stiffness. See [10] for a thorough description of the parameters

behaves as a taut string [4] and the tension, H, is directly related to the natural frequencies of the cable f_n through

$$f_n = n \times \frac{1}{2}\sqrt{\frac{H}{\mu l^2}} \tag{1}$$

This formulation was used by the SPW and by many control organisms in the past to identify the tension in bridges.

If the bending stiffness is small, it is possible to use a perturbation method to derive an asymptotic solution of the equations of motion, which also directly links the tension in the cable to its natural frequencies

$$f_n = \frac{\omega_0}{2}(n + 2np\varepsilon + n\left(\frac{\pi^2 n^2}{2} + 4p^2\right)\varepsilon^2) + ord(\varepsilon^3) \tag{2}$$

where

$$\omega_0 = \sqrt{\frac{H}{\mu l^2}}$$

is the non-dimensional tension,

$$\varepsilon = \sqrt{\frac{EI}{Hl^2}}$$

is the (assumed small) non-dimensional bending stiffness of the cable, whose value determines the validity of the asymptotic solution. And finally, p, is a non-dimensional parameter that takes the anchors stiffness in translation and rotation into account and has values $p = 0$ if the cable is hinged-hinged and $p = 1$ if the cable is clamped-clamped (see [10]). Note that if the bending stiffness is equal to 0, Equation (2) is equivalent to the equation of the taut string.

If the bending stiffness is not small, a semi-analytic solution is used an inverse problem is solved to obtain the tension from the natural frequencies with an optimization algorithm (differential evolution). Additional details about the asymptotic solution, the semi-analytic solution and the optimization algorithm are available in Foti et al. [10].

The identification strategy implemented in the LYRA, illustrated in Figure 6, uses both the asymptotic and the semi-analytic methods depending on the measurement results:

1. Asymptotic solutions are computed from the measured natural frequencies assuming the cable is hinged-hinged or clamped-clamped. If the results of the computations are close and if the output ε is small, the computation is over: it is not necessary to refine the estimation of the tension.

2. If ε is too high or if the two asymptotic models provide different outputs, the model is not valid and the semi-analytic model is used, assuming $p = 0.5$ (intermediate value between fully clamped and fully hinged). If $\varepsilon < 10\%$ the computation is over.

3. If $\varepsilon > 10\%$ it might be possible to also identify p. The semi-analytic model is used several times with a variable anchor stiffness parameter p. If the results are close, the results of the model with variable p

are used. Otherwise the results obtained from step 2 are used.

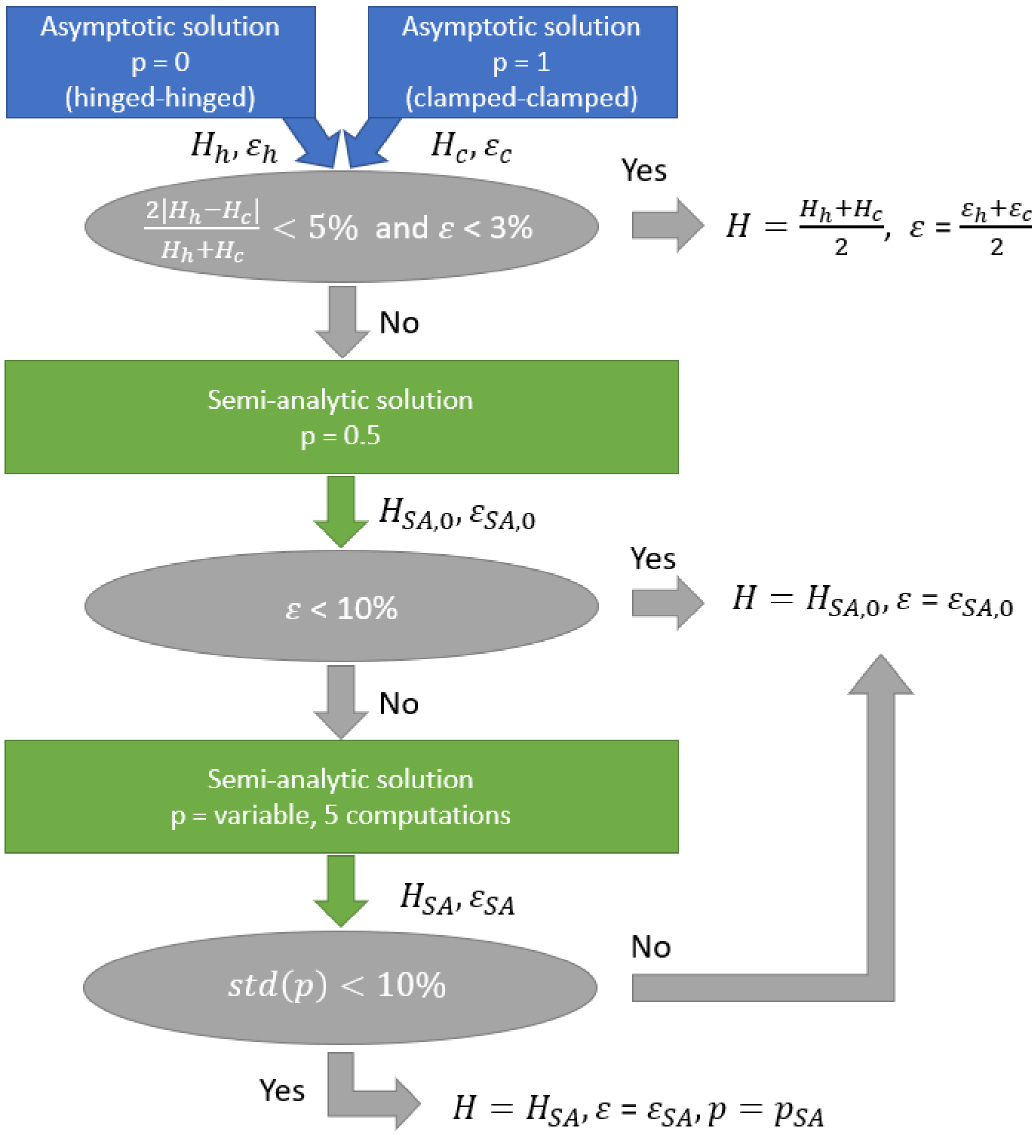

Figure 6: Identification strategy implemented in the LYRA

3 Measurement results on the Lanaye Bridge

The 30 stays of Lanaye bridge have been instrumented since October 2021. Figure 7 shows photographs of the bridge with the wireless sensors, the central station and the solar panel.

The time variation of the tension in stays LG6 and LG14 (sixth and fourteenth cables on the Liège side of the bridge) are depicted in Figures 8 and 9, respectively. The results show that the method is very robust and the 2σ-values (bounds within which 95% of the measurements are found) are 4.0% and 2.6% of the nominal values for cables LG6 and LG14, respectively. Nevertheless, several outliers are observed, which illustrates further the necessity to monitor bridges for a long period of time rather than performing spot measurements. No significant tension variation has been observed since the installation of the system.

Figure 10 displays the tension profile in all the stays on the Maastricht (black) and Liège (red) sides of the bridge. All the stays have a similar tension and no issue has been detected in the considered time frame. Stays 1 to 10 are located on the West end of the pylon whereas stays 11 to 15 are on the East end, which explains the sudden tension variation.

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Figure 7: Photographs of the LYRA system attached to the Lanaye bridge showing the central station (right), the solar panel (center) and the wireless nodes attached to cables LG11 to LG15 and MA11 to MA15 (right)

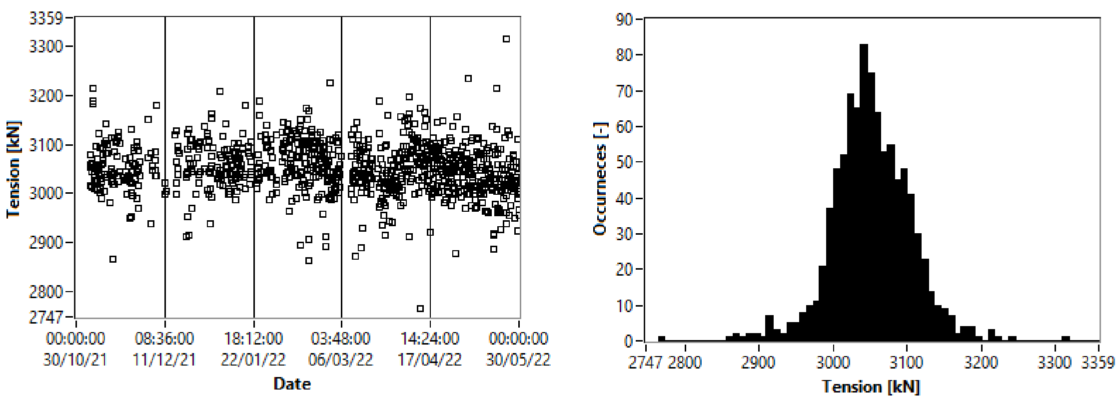

Figure 8: Time variation of the tension of stay LG6 (left) and corresponding histogram (right).

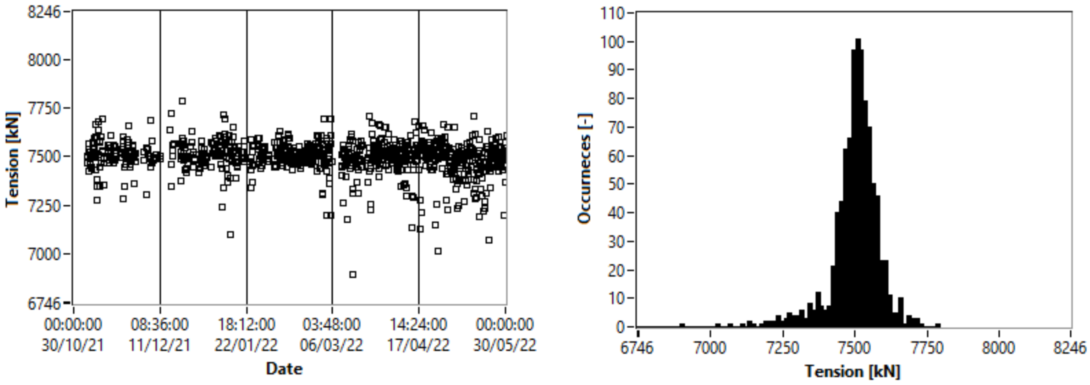

Figure 9: Time variation of the tension of stay LG14 (left) and corresponding histogram (right).

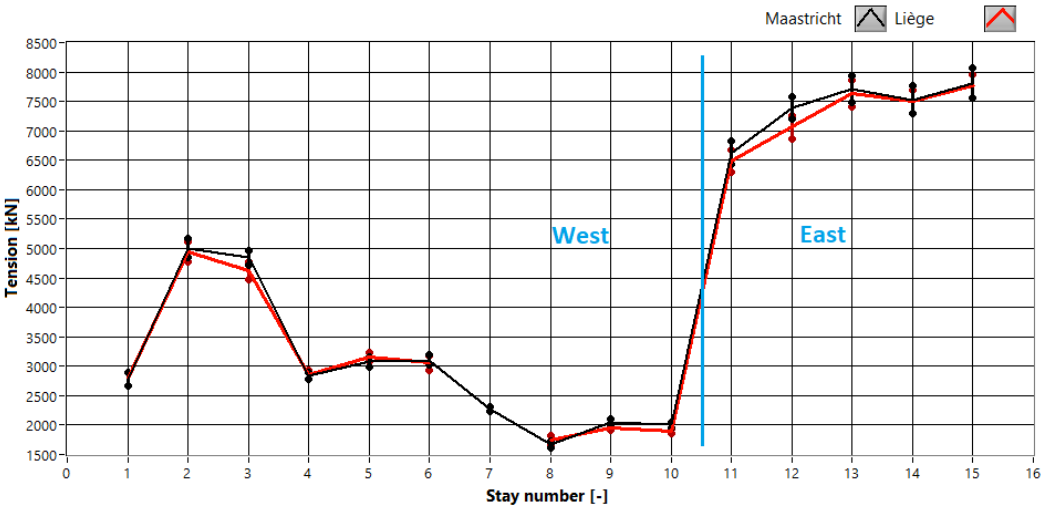

Figure 10: Tension distribution in the Lanaye bridge. The errorbars indicate the 2σ-values.

4 Conclusions

This paper briefly described and demonstrated the capabilities of the LYRA, a novel integrated solution for bridge hangers and stays monitoring. The LYRA is easy to install thanks to wireless sensors network, can operate remotely thanks to batteries, solar panels & 4G communication systems and uses state of the art tension identification algorithms that provide accurate results irrespective of the cables' bending stiffness and anchor conditions.

Acknowledgements

This research project has been funded by the Walloon Public Service Department (SPW) and the work of Margaux GEUZAINE is supported by a FRIA Grant received from the Belgian Fund for Scientific Research (F.R.S.-FRNS).

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