Short-term monitoring of a cable-stayed timber footbridge

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Summary

Älvsbacka cable-stayed timber bridge was built in 2010, over Skellefteå River in Sweden. Sensors were integrated at strategic locations of the bridge during the construction process. This paper explores the bridges' synchronized structural health monitoring system that consists of GNNS, force transducers, a weather station and wireless accelerometers. The initial results from short-term monitoring are reported and correlation between deformation of the bridge and effect of temperature changes is emphasized. It is planned to perform long-term monitoring for complete understanding of structural behaviour of the bridge.

Keywords: structural health monitoring, GPS/GNSS, cable-stayed bridge, timber bridge, short-term monitoring, climate effect

1. Introduction

Älvsbacka cable-stayed timber bridge was built in summer 2010, over Skellefteå River in Sweden. This timber footbridge connects the two neighbouring areas of Anderstorp and Älvsbacka. The bridge was constructed as part of the "Sense Smart City" European Union project under which Luleå University of Technology and Skellefteå Municipality are cooperating. The overall aim of this project was to reduce the cost of maintenance work of timber bridges by implementing a continuous measurement system on the structure over the long term. Furthermore, the feedback from monitoring result ensures that the design of the next generation of timber bridges will be safer and more durable.

Currently Älvsbacka cable-stayed timber bridge is the longest cable-stayed timber bridge in Scandinavia, with a span of 130 meters. This unique timber bridge provides exclusive opportunities for researchers to investigate and understand the behaviour of long-span timber structures.

The sensors for monitoring of the bridge were integrated during construction. This procedure provided an efficient solution for collecting data from strategic locations of the timber bridge. Non-destructive evaluation has been implemented at the bridge since March 2011 and the information that is collected from the sensors is being saved for current and future analyses.

In this paper the monitoring system of Älvsbacka bridge is presented and the initial results from short-term monitoring are reported. The main scope of this paper is to explore and investigate the correlations between changes of climate and bridge movements/deformations.

2. The timber bridge specifications

This cable-stayed footbridge was constructed in summer 2010 and has a span of about 130 meters. The bridge deck is held by 48mm and 64mm diameter steel cables which are connected to four wooden pylons and each pylon is anchored to concrete anchor blocks by two parallel steel cables with a diameter of 80 mm. The height of the pylons is 23 m and they have an identical cross-section of 900x900 mm^2 and are manufactured from untreated European white wood.

The main beams are manufactured from glulam with a cross-section of 645x1100 mm^2 and the distance between the main beams is 4.8 m. The bridge deck consists of a 45 mm open plank deck on longitudinal beams and cross beams which carry the deck. The camber of the bridge deck is 1m.

Fig. 1 Cable-stayed Timber Bridge of Skellefteå River

The bridge was designed for a uniformly distributed load of 4 kN/m^2 or alternatively 40 and 20 kN of a maintenance vehicle (e.g. forklift or sky lift). According to Eurocode 5, the bridge is designed for a the maximum deflection of L/400 where L is the total span of the bridge [1], [2].

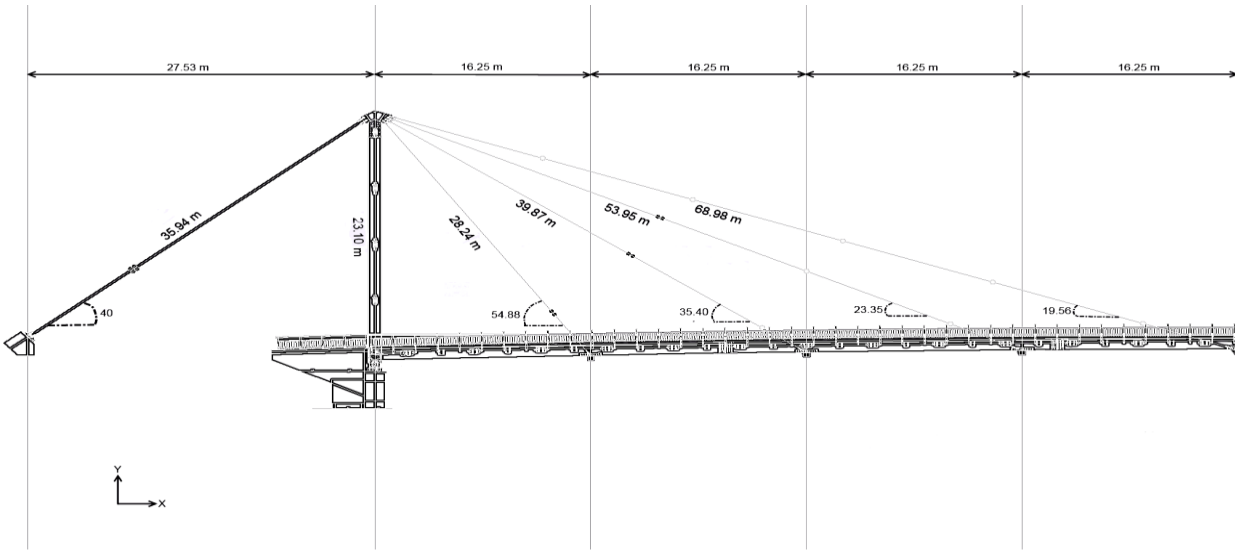

Fig. 2 Elevation of symmetrical half of the bridge

3. Structural Health Monitoring (SHM)

Monitoring technologies are now well-established and they have been used in many complex infrastructures all around the world. Nevertheless, deployments are still mostly limited to very large-scale or severely deteriorated structures or are implemented for research activities [3]. This means that SHM is still a high-cost option for operators. On the other hand, the data that are provided by the SHM systems give crucial information about the structural integrity, characteristic behaviours, fatigue behaviours, etc. of structures that are observed in short and long-term. Maintenance planning and action is mostly performed by using the live-data or post-processed data from the infrastructures. Thereby, the cost of maintenance may be optimized and necessary reinforcements and modifications can be done before they reach a risky level.

A good overview of the state of the art of monitoring technologies and the implementations and practical applications of SHM systems is given in the literature [4], [5]. However, most of today’s implementations of SHM are performed on concrete infrastructures. In the literature, there are few applications of SHM on wooden structures. Nevertheless, owing to their increasing of complexity and scale, these timber structures demand advanced monitoring techniques.

3.1 Monitoring system of Älvsbacka timber bridge

The SHM system for Älvsbacka timber bridge was designed for both long-term and short-term monitoring. The monitoring system consists of advanced monitoring sensors to observe and understand the long-span bridge’s behaviour. The sensors were mounted only on the southern half of the bridge due to its symmetrical geometry. Therefore, resolution of the data is increased and a more detailed view of the behaviour of that part of the bridge is obtained. Table 1 shows the monitoring system details and specifications.

Table 1 Monitoring system details and specifications

Sensors/Equipment	Quantity	Specification/ Brand	Phenomenon	Sampling Interval	Resolution	Accuracy
GNSS	3	Leica GMX 901/AS10	Displacements	1 s.	0.2 mm rms	±20 mm
Force Transducer	5	HBM	Cable tensions	1 s.	0.01 kN	±0.10%
Weather Station	1	Vaisala WXT 520	Climate changes	2 s. – 5 s.	0.1	*
Wireless Accelerometer	18	Mulle v6.2	Vibrations	0.02 s.	3.9 mg/LSB	±1%
Data Logger	1	Delphin Top Message	Data acquisition for cable tensions	1 s.	21 bit	-
Computer	2	Amb. Ctrl. Atom 1,66 Ghz	General data acquisition	-	-	-

* ±0.3 m/s wind speed, ±3° wind direction, ±3°C temperature, ±3 %RH relative humidity

In this project, the aim is to create a synchronized monitoring system with different types of sensor. Therefore, the correlations between data from the sensors are performed easily without introducing any time shift.

3.2 Sensors and deployment

To optimize the health monitoring costs it was assumed that the bridge behaves homogeneously, and that the structural characteristics can be mirrored or identification of the system can be obtained from one half of the span of the bridge. Sensor locations and the main unit are illustrated in Figure 3.

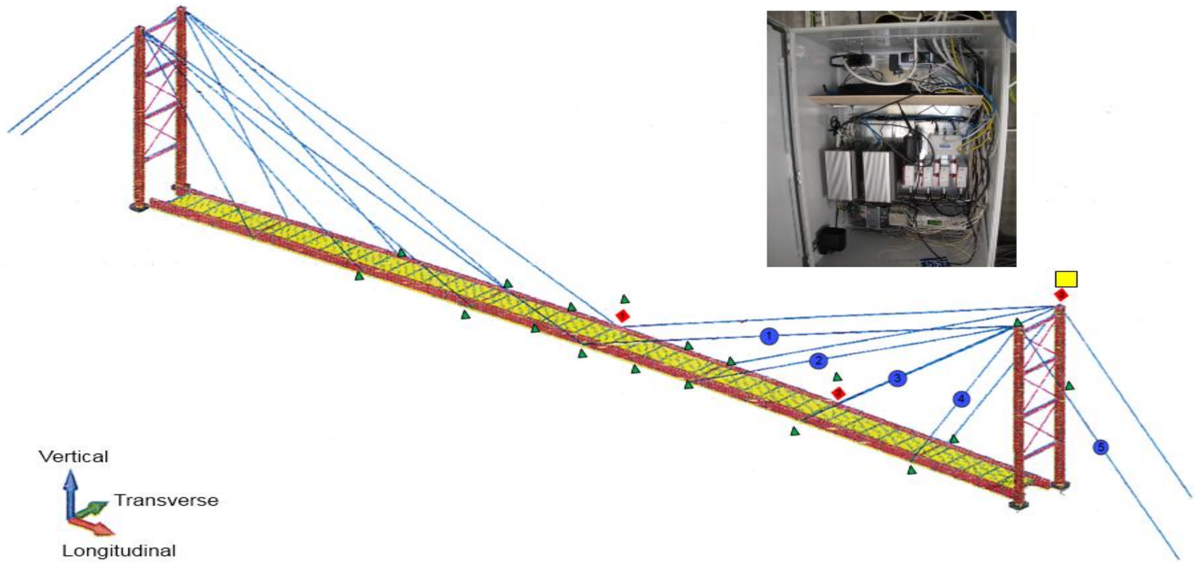

Fig. 3 Sensor locations of Älvsbacka Timber Bridge and backend unit. Red diamonds are GNSS antennas, green triangles are wireless accelerometers, blue circles are force transducers and yellow square is weather station.

3.2.1 Global Navigation Satellite System (GNSS)

Three Leica GMX 901 GNSS receivers and AS10 type antennas were mounted on the bridge. One is on the mid-span, one is on the quarter-span and the last one is on the south-east pylon. The antenna mounted on the south-east pylon is used as a reference antenna for the antennas (rover antennas) mounted on the eastern side of the deck. Rover antennas provide relative 3D coordinate changes based on the reference antenna. The sampling interval of all the GNSS receivers is 1 s and they are connected to a backend unit. The navigation information is being recorded in NMEA (National Marine Electronics Association) GGQ files [6].

3.2.2 Force Transducers

Five custom-made strain gauge based force transducers were integrated in the stay cable on the western side of the bridge. These force transducers use Wheatstone bridge resistance elements that provide better signal control in harsh environmental conditions, and are connected to a Delphin Top Message data logger with a sampling interval of 1 s. The data logger is then connected to one computer to store the tension data.

3.2.3 Weather Station

Climate conditions around the bridge area are measured by a Vaisala WXT520 type weather station [7]. The weather station was mounted at the top of the south-east pylon. Four different climate parameters are being measured by the weather station, namely temperature, humidity, average wind speed, and average wind direction. The sampling frequency of the weather station is between 0.3 Hz and 0.5 Hz.

3.2.4 Wireless Accelerometers

On the bridge 18 wireless micro-electro-mechanical system (MEMS) accelerometers have been used to identify the bridge’s dynamic characteristics. The locations of these accelerometers are illustrated in Fig. 3. The accelerometers’ boards are designed to use battery power; however, due to harsh climate conditions, wired electricity is in fact used to supply the power to the accelerometers. The results from the accelerometers are out of the scope of this paper, the emphasis of which is on the short-term deformation of the bridge and climate changes.

3.3 Backend unit and synchronization

The backend unit consists of data acquisition systems, receivers, a data logger, power supply and heating unit. All these systems are in a protective box located under the southern part of the bridge. The heating unit governs the inside temperature of the protection box,as can be seen in Fig. 3, and protects the sensitive equipment against harsh winter conditions. Two of the three data acquisition systems (Amb. Ctrl. Atom 1,66 Ghz) are connected to the weather station, force transducers and GNSS receivers output. The third one is connected to the wireless accelerometers to collect vibration data.

Different types of sensor have been deployed to create a comprehensive SHM system for Älvsbacka timber bridge. Since the sensors are different, in order to shorten the post-processing time and perform better correlation between sensor responses, time synchronization plays a significant role. Synchronization between the different sensors are established by using one data acquisition unit as a Network Time Protocol (NTP) server. This unit is connected to the GNSS receivers which receive the time stamps from the satellite, and this time stamp then constitutes the basis for the other sensors' time stamps. Thereby the data interval of all the sensors' output is equal. Synchronization provides is highly convenient during the post-processing of data when instant correlation between measurements is needed.

Remote access to data acquisition systems has been established by an internet connection to of the construction area. This feature makes, inspection of the sensors' health easier because there is now no need to phsically go to the constructional area. Another advantage of remote access is the ability to observe the bridge's structural condition from a distance provided the user/owner has an internet connection.

4. Short-term monitoring results

In this section, short-term monitoring results of Älvsbacka timber bridge are presented. The emphasis is on correlation between climate condition changes and the bridge's total deformation.

4.1 GNSS measurements

Älvsbacka timber bridge has been observed using three GNSS system since March 2012. The results provide a verification of the structural design in the short-term. Generally, deformations in a timber structure are a good indicator of its structural condition. The short-term measurements provide the bridge's daily or instant total deformation pattern, which is mostly influenced by temperature changes.

GNSS measurement data are saved in NMEA (National Marine Electronics Association) GGQ files with the file extension of "*rtl*". Each file consists of 3D navigation data, coordinates quality, the number of satellites the antenna sees, time stamps, etc. The length of each measurement file is 25 hours, which consists of 90,000 lines of navigation data. These files are then post-processed using MATLAB commercial software.

It is assumed that, if the antenna mounted on the top of the south-east pylon is accepted as a reference antenna, due to the robustness of the foundation of the bridge's pylons, deformation measurements in vertical direction will less error than in the longitudinal and horizontal directions.

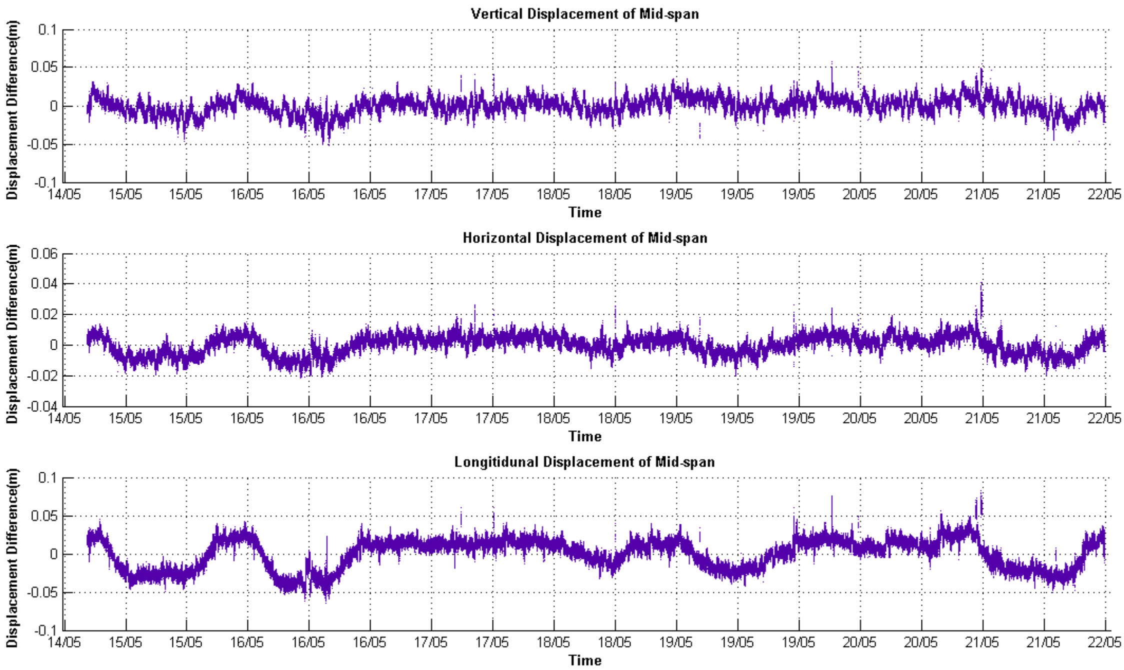

Fig. 4 Vertical, horizontal, and longitudinal relative movements of the mid-span of the bridge.

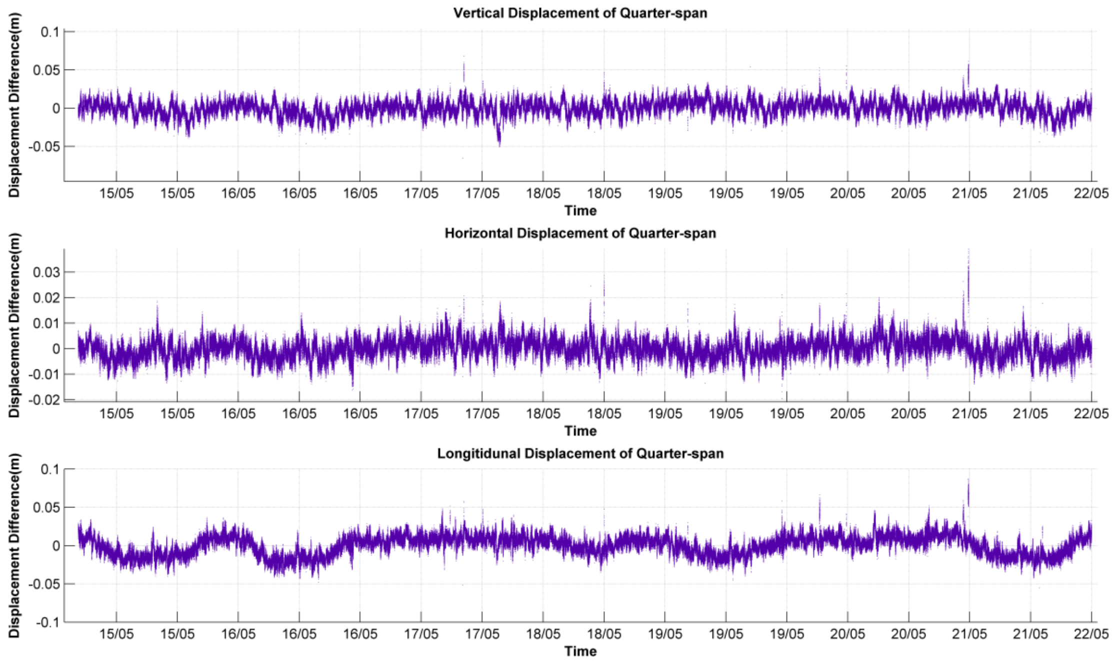

Fig. 5 Vertical, horizontal, and longitudinal relative movements of the quarter-span of the bridge

The GNSS measurements show the relative movements of the mid-span and the quarter-span of the bridge based on the reference antenna position. The great interest is in the relative vertical movements of the mid-span and the quarter-span of the bridge, which can be seen in Figure 4 and Figure 5. The magnitudes of the vertical and longitudinal relative movement were in the interval of ±0.05 m during the monitoring period. However, rapid fluctuations were observed in the vertical movements, while the longitudinal movements had slower fluctuations. Furthermore, Figure 4 and Figure 5 show that there were not abnormalities observed that could amplify the deformation of the bridge during the monitoring period. The horizontal movements of the mid-span and the quarter-span of the bridge were in the interval of ±0.02 m.

4.2 Weather station measurements

The weather station mounted on the top of the south-east pylon has records temperature, average wind speed, average wind direction and relative humidity.

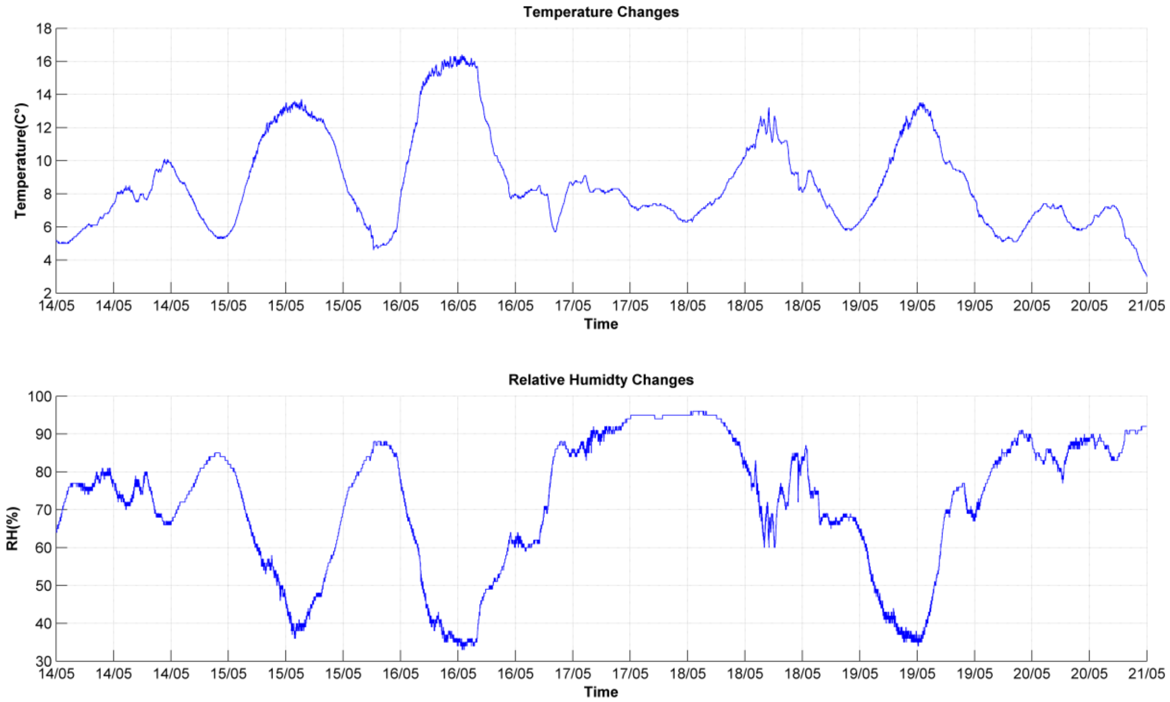

Fig. 6 Temperature and humidity changes during monitoring time

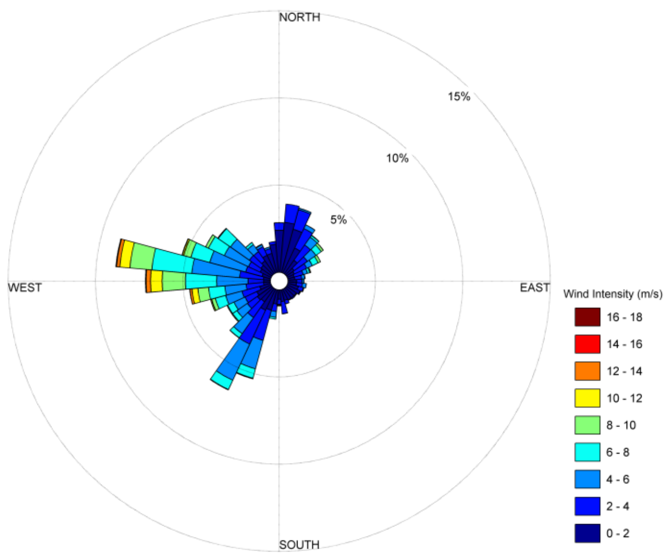

Fig. 7 Wind rose plot that shows wind direction and wind speed

Figure 6 and Figure 7 show the weather conditions measured by the Vaisala WXT 520 weather station during the monitoring period. The temperature range between 16° C and 3° C. Relative humidity varies between 95% and 35%. It should be noted that temperature and humidity measurements illustrate the air conditions around the bridge area, which can in fact differ from the temperature and humidity of the wooden structural elements themselves.

Figure 7 illustrates the wind speed and the wind directions. Wind intensity reached around 16-18 m/s and the wind direction was mostly from the western side of the *bridge*. Wind direction and wind speed measurements can be correlated with the bridge's horizontal movements.

4.3 Cable tension measurements

Custom-made force transducers recorded the stay-cable tensions during the monitoring period. Since these pre-tensioned cables are manufactured from steel and have a high thermal expansion coefficient, they have a dominant influence on the vertical movements of the bridge. In [8], it is reported that a 20° C temperature changes can cause a 1.5 mm axial deformation of a 15 m wooden pole. This means that the thermal expansion of the pylons has a negligible effect on the vertical movements of the bridge.

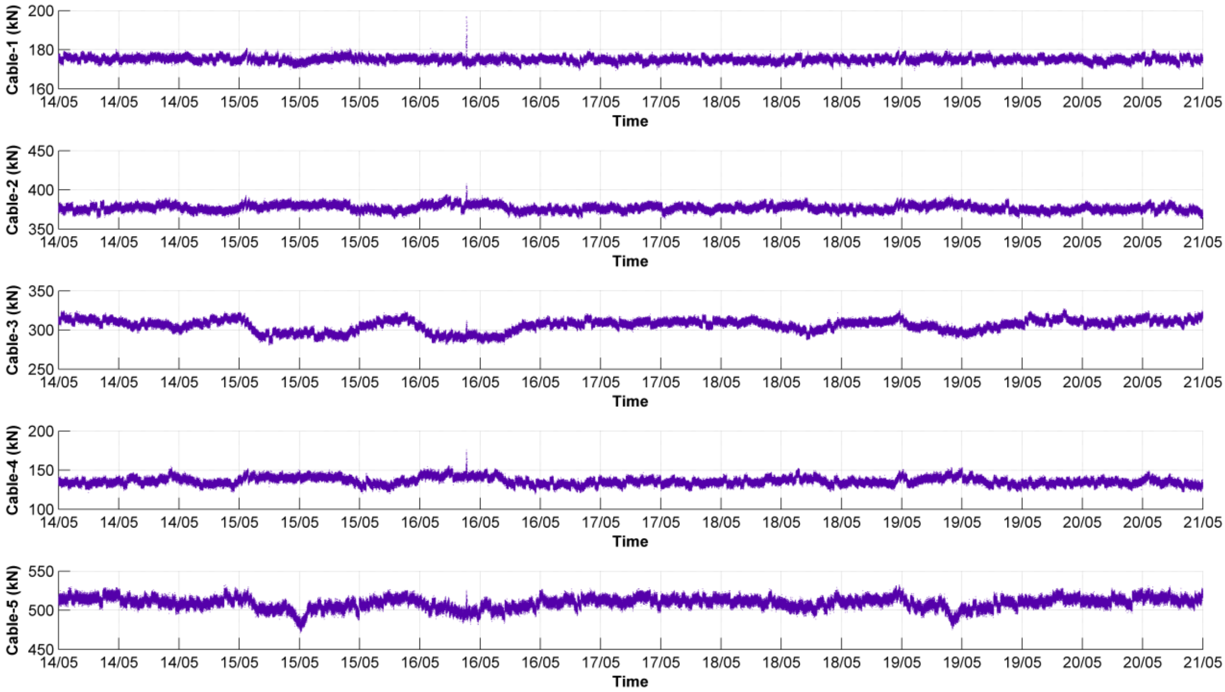

Fig. 8 Tension changes of pre-tensioned stay-cable during monitoring period

Figure 8 shows the change of tensions in the steel stay-cables. Thec cable numbers have the same numebering as illustrated in Figure 3. During the short-term monitoring period not any abnormal changes were observed in the stay-cables except for one instantaneous fluctuation which was observed on May 16 2012, which can be attributed to the restoring forces of the bearings being suddenly released. For the design conditions, these sudden releases are within the limits of the standards. However, these sudden reactions might cause secondary problems, such as restraints in the expansion joints [5].

4.4 Correlations

By using a synchronized monitoring system with different sensors, it is possible to perform short-term and instantaneous correlations between sensors that provide information about the response of the structure to changes in climate. If any abnormal changes occur during the monitoring time, these correlations deliver information on the reason for the abnormalitiesi indicating weather they are due to climate conditions or not. Furthermore, by monitoring the bridge in the short and long time, the structural design verification can be done. In this section, the one-day correlations between temperature changes and bridge vertical movements, and also between wind speed and bridge horizontal movements are presented. However, long-term monitoring provides a more holistic approach to the effect of climate on bridge movements.

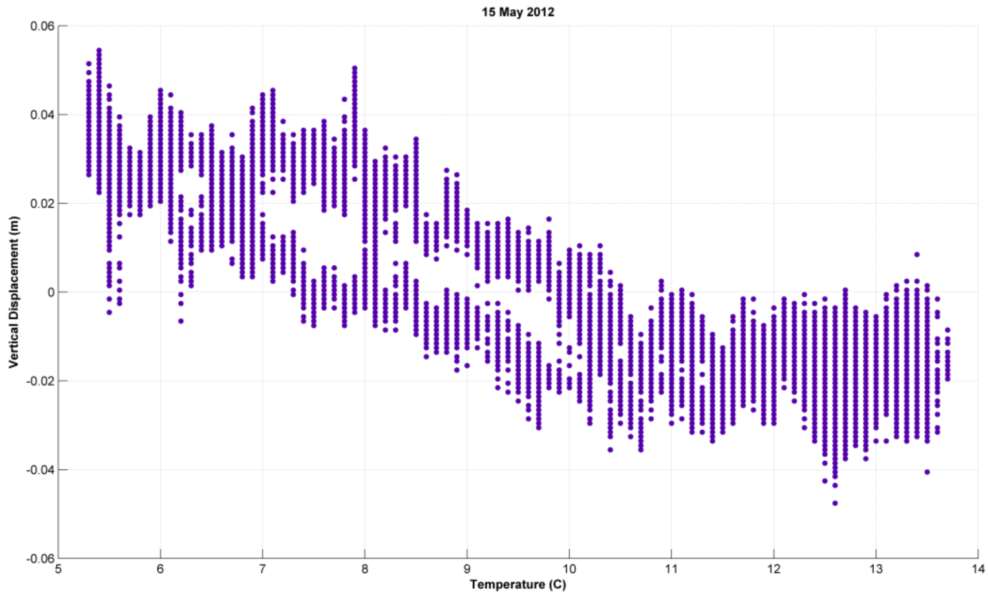

Fig. 9 Temperature changes influence on relative vertical movement of the mid-span bridge in a day.

Temperature changes have a clear effect on the stay-cables, as can be seen in Figure 9. Increase of temperature causes expansion of the steel cables so the mid-span of the bridge has negative displacement and vice versa. However, to investigate the permanent deformation of the bridge it is necessary to analyse long-term monitoring results. From Figure 9, it can be seen that about 5° C temperature change causes 0.05 m deformation of the mid-span of the bridge.

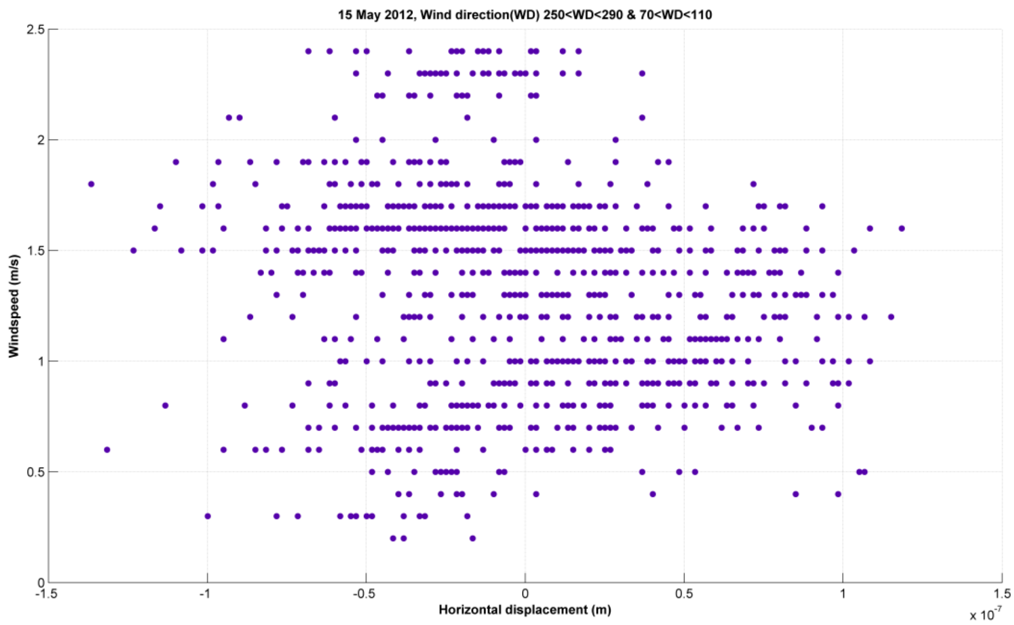

Fig. 10 Horizontal movements that is triggered by horizontal wind speed.

The weather station records the wind direction in terms of degrees, such that 0° is North, 90° is East, 180° is South and 270° degree is West. To investigate the horizontal wind speed effect on the horizontal movements of the bridge, wind directions between 250°-290° and 70°-110° were filtered out assuming that the filtered angles reflect the horizontal wind speed. Figure 10 shows the influence of the filtered wind speed on the horizontal movements of the bridge. Nevertheless, on 15 May, while the wind speed reached more than 10 m/s, the maximum horizontal wind speed reached only 2.5 m/s. The horizontal wind speed has a negligible effect on the horizontal movements of the bridge. Furthermore, the horizontal wind speed can only create a risk of torsional oscillations when it exceeds 15.4 m/s, and also the actual mass moment of inertia of the bridge should be a certain value to trigger torsional oscillations. In order to investigate torsional oscillations induced by horizontal wind speed, it is necessary to perform long-term monitoring and investigate those days on which is the horizontal wind speed exceeds 15.4 m/s.

5. Conclusions

This paper presents the experimental short-term monitoring results of Älvsbacka cable-stayed timber footbridge. A monitoring system that consists of different types of sensors is introduced and the synchronization between the sensors is explained.

Analysis done by MATLAB commercial software shows that temperature changes have the dominant effect on the bridge's movement due to the steel cable's thermal expansion. However, to obtain the permenant vertical deformation of the bridge span, it is necessary to monitor the bridge over a longer period. Furthermore, based on the Eurocode standard, the design deflection criteria of L/400 is verified in the short-term monitoring period.

Horizontal wind force has a negligible effect on the bridge's horizontal movements. However, the wind speed measurements were recorded at the top of the south-east pylon which has a height of 23 m. Therefore, to increase the measurement accuracy of the effect of wind force, it is necessary to measure the wind from both the east and west sides of the bridge.

The short-term monitoring results show that no abnormalities occurred during the monitoring period. Furthermore, the measurement results are a good indicator of the bridge's structural condition.

Älvsbacka timber bridge is still being monitored to understand its behaviour and the effects of the climate in the long-term. Investigation of the bridge's movements in very cold climate conditions will provide the valuable information on the structural integrity of the bridge that can be feed-back for the next generation of timber bridges. It is planned to present the long-term monitoring results in future studies.

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