Health Monitoring of timber bridges

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Summary

Timber bridges require often more frequent maintenance intervals than concrete and steel bridges. Continuous measurements can provide opportunities for better tools to put the maintenance activities at the right time. New technology provides better opportunities for continuous measurement and which provides more information and increased opportunities to influence the maintenance costs. This paper reports initial steps to find reliable and cost-effective measurement systems for health monitoring timber bridges. A timber bridge for pedestrians will to be built over the Skellefte River. The construction of this advanced bridge provides a unique opportunity to test, develop and evaluate methods for wooden structures. For verifying the structural design it is planned to use three different systems, triaxial accelerometers, fiber optic system and GPS-system. Comparisons between these systems will be done due to, accuracy, complexity, costs and reliability for long time use.

Keywords: Timber bridge, cable-stayed bridge, health monitoring, moisture measurement, fiber optic sensors, GPS, MEMS

1. Introduction

A timber bridge for pedestrians (a cable-stayed bridge, span about 130 m) is in the starting position to be built over the Skellefte River. The construction of this advanced timber bridge provides a unique opportunity to test, develop and evaluate methods for wooden structures. The timber bridge can be planned in a unique way to contribute to wood research on specific areas such as: crack propagation in large cross sections, failures and vibrations, resistance, measurement methodologies, information transmission and analysis tools.

The project is in its start up phase and the final decision to build the wooden bridge and also the decision to implement a research project was taken in April 2010. This means that the structural design of the timber bridge and the decisions of sensors and measurement systems are to be performed simultaneously. The assembly of the bridge is planned to start in early September and the entire bridge is expected to be completed in December 2010. Dynamic analysis has been performed and during June to August continues the detailed design of the bridge. Final decisions on what measurements to be carried out in will be based on the requirements and available resources.

1.1 Health Monitoring of timber bridges

The use of wood in timber bridges has many benefits including the fact that wood is a renewable and sustainable resource. Large wooden structures have increased in number over the past 20 years. The amount of timber bridges in Sweden has grown from a dozen old bridges in 1990 to approximately 600-800 bridges. Wood is a natural engineering material that is prone to deterioration caused by decay fungi, insect attack and temperature. Therefore, it is important to conduct frequent inspections of timber bridges with modern inspection equipment. Normally today in Sweden a visual inspection of bridges and smaller tests are made with an interval of 6 years. These inspections have a number of weaknesses when only visible damages are detectable. For concrete and steel bridges there are ongoing research projects to state assessments and focusing mostly on the bearing capacity [1]. For wood and wooden bridges, the correlation is strong between durability of the material and the bearing capacity. Deformations in a timber structure are often a good indicator of the structural condition.

Wooden bridges require often more frequent maintenance intervals than concrete and steel bridges. Long time measurements, can provide opportunities for better tools to put the maintenance activities at the right time. New technology provides better opportunities for continuous measurement and this provides more information and increased opportunities to influence the maintenance costs.

Health Monitoring Technology (methods of measurement and analysis device) would be a great help in determining the resistance especially if the measurements are made over a long time. This can be done by continuous measuring instruments, placed in the production factory or at the buildingsite. With the help of analysis tools, the maintenance personnel can follow the beam/bridge over a long period of time and devices may indicate that something is wrong.

1.2 The research project, vision and objectives

The vision for this project is, by continuous measurement of timber bridges evaluate the function over long term and thereby give better knowledge to improve the maintenance and reduce the cost of maintenance work.

The objective of this project is also to provide better knowledge about using advanced timber bridge inspection techniques and equipments. The possibility to test and compare various technical means will be implemented in the new bridge built over the Skellefte River.

The aims of this study are:

(1) Verify design by measuring and monitoring static, quasi-static and dynamic response in short- and long term.

(2) Evaluate reliable and cost-effective systems for health monitoring of timber bridges.

(3) Comparison between accelerometer-measured signals (conventional and fiber optic) and Global Positioning System, GPS.

(4) Measuring the influence of wind, traffic and climate variability.

The project's priority areas are measuring systems, analysis tools and evaluation methods, visualization and maintenance.

Measuring System
Each new bridge requires specially designed measuring systems depending on structural design and weather protection system. Expensive systems with a lot of sensors give good understanding about the bridge current status and can be used for bridges with big budgets. For smaller bridges it is a challenge to find effective systems that are affordable for the owner of the bridge.

Analysis tools and evaluation methods
Data from measurements requires verification in order to achieve the right information for users. Analysis of output from the measurements can be numerical analysis, image analysis, visualization, etc. The analysis tool should include advanced methods for control of individual components but also the whole construction.

Maintenance / Action
Weather protection is important for timber bridges. The quality of the weather protection, as covering boards or pavements has impact on the structural bearing capacity. Decision tools that provide support for the maintenance work or support for maintenance schedules is a good help for keeping the weather protection in good quality.

2. The Construction of the bridge, the municipality´s needs and investigation

The area where the bridge will be erected is a part of the city Skellefteå where new wooden construction is used as example of future constructions. Three six-story wooden buildings have been built on the north side of the river and there is a need for a new connection to the south side of the river. The geotechnical survey of the area showed that the soil at the river bank could not cope with heavy loads. There was therefore a clear advantage in choosing wooden constructions because of the small dead weights. If the buildings had been heavier it probably not been able to build so close to the river bank. The new pedestrian and cycle bridge location is shown in the sketch below.

Figure 1 New timber bridge of Skellefte river,
Illustration: Skellefteå municipality

Large construction projects, with modern wood technology, were also seen as an excellent portal for the promotion of the expertise available within the region.

Long cable-stayed bridges of timber are sensitive to wind loads because of their small dead-loads. Dynamic behaviour of this type of bridges is therefore an important part of the structural design. The damping was for this bridge assumed to 0.6 % and it is a normal value used at designing this type of bridges. Other measurements show much higher damping, but also the change of damping during time is of interest [2],[3],[4].

2. The timber bridge

This cable-stayed footbridge crosses the Skellefteå River nearby the city center and has a span of 130 meter. The pylons are built up of four square glulam sections (900x900 mm^2) and are homogenous. The heights of the pylons are 23 meter and they are made of untreated European whitewood. The distance between the pylons across the bridge is 8,7 meter. The pylons are connected to main beams by four parallel cables with diameters 45 and 63 mm. The pylons are anchored to anchor blocks by two parallel cables with a diameter of 80 mm.

The distance between the main beams is 4.8 m which gives a clear distance between the beams of 4.40 meter. The main beams are made of glulam, 645x 1100 mm^2. The span consists of a horizontal truss that carries the deck and wind forces acting on the structure. The bridge deck is made of 45 mm open plank deck on longitudinal beams.

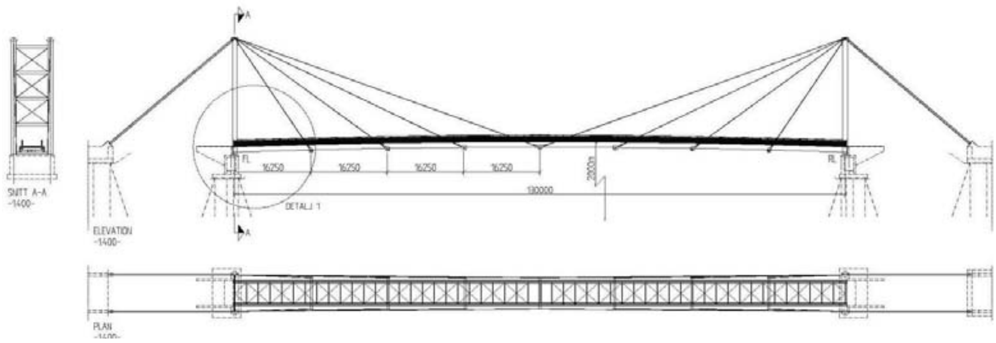

Figure 2 Elevation of the bridge,
Illustration: Martinsons Träbroar AB

The bridge is designed for a uniformly distributed load of 4 kN/m^2 or alternatively two axle loads, 20 and 40 kN of a maintenance vehicle. The design maximum deflection is l/400 of the span.

Aerodynamic analyses made by COWI show that:

- The steady state wind load coefficients of the girder cross section are in reasonable agreement with figures known from other bridges of similar design.
- The flutter analysis yielded critical wind speed of approximately 35-37 m/s depending on the mass condition for the girder cross section in the in-service condition for horizontal and the flutter will be dominated by torsion. The required minimum wind speed at deck level for aerodynamic instability is reported to be 28,6 m/s. The galloping wind speed is estimated to be 51 m/s and higher than the flutter wind speed, but is not expected to become a problem.
- The lock-in wind speed was high, above 39 m/s. The lock-in wind speed for torsion oscillations was lower and depending on the moment of inertia, 15,4-27,6 m/s. This may lead to vortex induced torsion oscillations with moderate peak deflection in order of 0.2º and depending on the actual installation mass. Vortex induced oscillation of the girder is not considered to become a problem even as the lock-in wind speed is close to the design wind speed.
- Vertical and horizontal buffeting responses to turbulence at the design wind speed of 22 m/s are small, 10-100 mm.

3. Health monitoring system

One of the objectives of these measurements is investigating and try to find out a system that can be used as a simple and cost-effective measurement tool even for smaller wooden bridges. This, together with analysis tools can give the owner of the bridge a better basis for maintenance work.

There are various deformations monitoring systems, both for long-term deformations as for instantaneous deflections. There are usually two kinds of deformations for a suspension timber bridges, long-term movements caused by stress relaxation, local deformations due to change in moisture (also creep) and foundation settlement, and short-term dynamic movements induced by wind, traffic, temperature etc. To detect deformations normally conventional, triaxial accelerometers give information about movements in the short term. As an alternative we plan to have two other systems for long-term deformations, fiber optic solution and GPS-solution.

There are two main reasons for these measurements, verifying the structural design and verifying the bridge long-term behaviour. Verifying the structural design we plan to use three different systems, triaxial accelerometers, fiber optic system and GPS-system. Comparisons between these systems will be done due to;

- accuracy,
- complexity,
- costs,
- reliability for long time use.

Accelerometers
Accelerometers have been used extensively for bridge dynamic monitoring and are well known, triaxial accelerometers could measure three orthogonal accelerations simultaneously. Conventional accelerometers have a seismic mass that deforms a piezocrystal when put in acceleration. The change in capacitance will be read out as a change in acceleration.

Load cells
Load cells will be spot welded on the main cables to measure the strain. Load cells uses strain gauges to convert strain in to an electric signal, as the strain gauge in the load cell is elongated the resistance will change. The change in resistance is used to calculate the strain.

MEMS
Micro-electro-mechanical sensors or MEMS are sensors with sizes in the micrometer to millimeter range. MEMS consist of a microprocessor and microsensor on a silica substrate. MEMS sensors have in recent years found lot of applications in consumer electronics as mobile phones, videogame remotes, etc. which has made them an attractive option to conventional sensors because of their low prices. MEMS sensors have started to gain attention for structural health monitoring uses, where MEMS accelerometers perhaps are of most interest. MEMS accelerometers consist of a cantilever made of silica with a piezocrystal at the supporting end of the beam. When the structure that is monitored vibrates the cantilever will vibrate with it, causing changes in the capacitance of the piezocrystal. The changes in capacitance are used to derive the acceleration [5].

Moisture sensors
Wood constructions for outdoor use it is important to monitor the moisture content. The moisture content will vary during the year depending on the season and climate. If the moisture content exceeds 20% for an extended period there is a large risk for rot, which will decay the wood and considerably decrease the strength of the construction. The timber bridge will be equipped with wireless moisture sensors throughout the construction.

Weather station
The bridge will be equipped with weather stations to monitor wind speed and wind directions as well as temperature and relative humidity. To monitor the microclimate surrounding the bridge weather stations will be placed under the bridge span and on top of one of the pylon towers.

GPS
Cable-supported bridges carry big loads across big distances and by the bridge designs they are dynamic structures affected due to the loads imposed by wind, traffic and climate-change. High performance GPS/GNSS receivers' and supplemented with software and advanced processing algorithms can be ideal tools for health monitoring. GPS gives us the opportunity to verify even the movement of the abutments [6], [7].

Fiber optic sensors
The light propagating in an optic fiber will change in intensity, phase, time of flight or wavelength when it is exposed to a change in strain, temperature, pressure, etc. which makes them appropriate for sensing applications. Fiber optic sensors have many advantages over traditional sensors; they are robust with expected lifetime of >50 years [8], easily formable, immune to electric and electromagnetic interference, small, low noise and acts both as sensor and as signal transmission system. Below is a short presentation of different types of fiber optic sensors.

> *Bragg gratings sensors*
> Bragg grating sensors are one of the most used types of fiber optic sensors. The sensor measures strain, displacement and temperature. A Bragg grating sensor consists of short segments of gratings engraved with UV-light. The grating reflects a certain wavelength of light. A change of wavelength corresponds to a change in strain or temperature. If the gratings reflect different wavelengths it is possible to put several sensors on the same optical fiber, called multiplexing of the fiber. Since changes in both temperature and strain can occur at the same time it is important to use a reference fiber for temperature measurements to compensate the strain measurements [9], [10], [11].
>
> *Fabry-Perot sensors*
> A Fabry-Perot sensor consists of a capillary tube with a cleaved optical fiber, which has a small air gap in between. The two surfaces of the cleaved fiber will act as a partially reflecting mirror and a completely reflecting mirror. The two parts of the fiber is attached on each end of a sensor housing and a change in distance of the gap is equivalent to the average strain change. When the air gap changes the phase of the light reflected from the sensor changes accordingly [9], [11].
>
> *Brillouin scattering sensors*
> Brillouin scattering measures strain and temperature along the sensor length, which can be up to 50 km long. Brillouin scattering emerges when a light wave is reflected from an induced sound wave in the optical fiber. As the sound wave propagates through the optic fiber the frequency of the light wave will change due to the Doppler effect. The velocity of the sound wave can be determined by the size of the change in frequency of the reflected light. The velocity of the sound wave depends on both temperature and strain. By measuring light pulses from different parts along the optical fiber the frequency shift and intensity can be separated, and temperature and strain can be measured independently [12].
>
> *Raman scattering sensors*
> Raman scattering can be used to measure temperature along the whole sensor, with lengths up to 30 km. Raman scattering appears when light is propagating in the fiber, and the light and silica in the fiber interact. The interaction will cause two frequency-shifted components, Raman Stokes and Raman anti-Stokes. The relative intensity between the two components is dependent on the local temperature in the fiber. With a pulsating light source the relative intensity can be plotted against the time of flight for the pulsated light and local temperature along the fiber can be decided [10].

SOFO sensors

SOFO is a French acronym for *surveillance d'ouvrages par fibres optiques* or in English monitoring of infrastructure with fiber optics. The SOFO sensor can be used to measure displacement and strain. A SOFO sensor consists of a housing containing two optical fibers, a measuring fiber and a reference fiber. The measuring fiber is attached in both ends of the housing and pre-tensioned whereas the reference fiber is attached in one end. The sensor housing is mounted on the structure. A change in strain in the structure will cause a strain in the measure fiber while the reference fiber remains unaffected. The phase change of the light between the two fibers is used to determine the strain [10].

Micro bending sensors

Micro bending sensors uses intensity losses in the fiber to measure displacement and strain. Micro bending sensors are made of twisted optical fibers, or an optical fiber twisted with a metallic wire. As the sensor elongates the fibers will bend around each other and parts of the light in the fiber will escape since the reflection in the fiber never reaches 100 %. The magnitude of the intensity loss is directly related to how much the fibers are being bent. The strain or displacement is calculated of intensity and amplitude losses in the returning light [9], [10].

4. Methods and equipment

4.1 Sensors

It is planned to install a monitoring system to measure the behaviour of the bridge due to normal loads. The system will consist both of fiber sensors, GPS and conventional sensors which will be connected to one monitoring station and one single database. Table 1 show examples of structural phenomena, monitoring strategies, suitable sensors and location. The quality of the result depends on the characteristic of the used sensors and sensor systems. The budget of the project can influence the quantity and quality of the sensor system. Parameters that influence the final selection of the sensors are sample rate, resolution, temperature influence, costs, etc.

Table 1 Example of structural phenomena, strategies, sensors

	Phenomenon	Monitoring Strategies	Sensors/equipment	Symbol
1	Displacement, deck	Long-term	GPS	◆
2	Vibrations	Long-term	Accelerometers Optical sensors	●
3	Moisture	Long-term	Temperature and moisture sensors	
4	Displacements foundation	Long-term	GPS	◆
5	Displacement pylon	Long-term	GPS	◆
6	Vibrations pylon	Long-term	GPS	◆
7	Climate change	Long-term	Weather station	▲
8	Tension, cables	Long-term	Load cells	◉
9	Strain, bridge deck	Long-term	Optical sensors	●

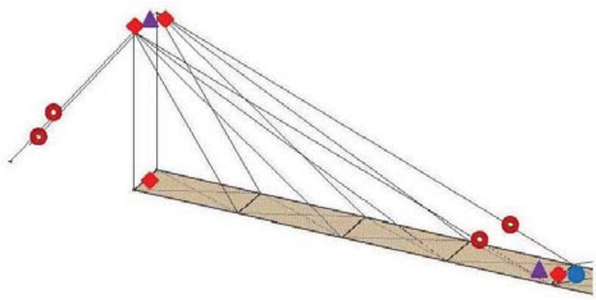

Figure 3 Location of the sensors, symbols see table 1
Illustration: Anders Gustafsson

4.2 Acquisition system and communication

Sampling rate
The resonance frequency for this type of timber bridge are usually below 5 Hz, but to achieve a good signal to noise ratio over sampling is recommended. Previous work shows that a sampling rate of 200 Hz is suitable for measuring vibrations [13]. For moisture measurements of wood a sampling frequency of one measurement per hour is sufficient to achieve useful data. Sampling rate of the weather station should be between 12-30 times per hour. To obtain useful data every sensor system must be synchronized. To achieve time synchronization the processing unit for the different processors must timestamp every measurement.

Database
Monitoring of the bridge will be conducted for several years, which will result in large amounts of data. Data will be used to analyse long time behaviour and validation of the construction phase. Data acquired from the bridge will also be used for design of future timber bridges and timber structures. Since data will be accumulated over several years the massive amount of data must be stored. To get a perspicacious view over data the amount must be less dense. Using threshold values interesting parameters can be saved, while data containing normal values can be excluded from the database.

4.3 Analyse of the results

Using real time monitoring it is possible to evaluate stress variations, vibrations and deformations in graphs. It is in our interest is also to have actual measurement results for further FE-models. By using continuous monitoring or periodic long-term monitoring changes of the structure can be a help for predicting future performance.

5. Discussion and Conclusions

In this paper, the first part of this project is presented, and the initial ideas on identifying suitable measurement techniques due to a vision of finding a reliable and cost-effective system for health monitoring timber bridges. The result has so far been satisfying regarding existing systems that can be used, but there is still a long way to go for finding cost-effective systems for all sorts of bridges.

The investigation concerning suitable measurement systems have so far showed;

- There are quit many different systems including analysing tools. Many of them are advanced systems but for a relatively high costs. The cost may be acceptable for big projects and for the bridge over the Skellefte River the cost for the system is about 2-4% of the construction costs for the bridge.
- Combination of different systems can be complicated regarding to communication, synchronization of the systems etc.
- It is a need for verifying the design for this type of bridges and the value for damping is to be controlled over time. Values for damping varies much in different standards and therefore require more verified data.

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