Multivariate Screening of the Weather Effect on Timber Bridge Movements

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Monitoring displacements and weather impact of complex structures, such as a large cable-stayed footbridge, generates a large amount of data. To extract, visualize, and classify health-monitoring data for better comprehension, multivariate statistical analysis is a powerful tool. This paper describes screening to evaluate if principal component analysis is useful for health monitoring data. Principal component analysis (PCA) and projections to latent structures by means of partial least squares (PLS) modeling were used to achieve a better understanding of the complex interaction between bridge dynamics and weather effects. The results show that PCA gives a good overview of the collected data, and PLS modeling shows that winds from east and west best explain bridge movements.

Keywords: Timber bridge; PCA; PLS; Multivariate statistics

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INTRODUCTION

In the last two decades, the use of wood as a construction material has become quite common throughout Europe, in particular for the design of pedestrian bridges. In Sweden, approximately 1000 modern timber bridges for traffic and pedestrians have been built in the last 25 years (Pousette *et al.* 2004). The development of modern adhesives and engineered wood, *e.g.*, glue-laminated timber, make timber a good construction material for bridges. Currently, timber footbridges can be designed with spans longer than 100 m (Caetano and Cunha 2013). Moreover, the timber bridge has advantageous properties such as abundance, easy shaping, good strength to weight ratio, renewability, sustainability, and an aesthetically pleasing appearance.

Because wood is a biodegradable material, the behaviour of timber structures is sensitive to environmental conditions, such as relative humidity (RH), temperature, and wind (Piazza *et al.* 2005). Therefore, timber structures require continuous maintenance to preserve their strength and architectural appearance. To determine the timber's structural response to different environmental conditions, the best approach would be to rely on a continuous structural monitoring system (Wenzel 2009).

In 2011 a cable-stayed timber footbridge, Älvsbacka Bridge, was erected in Skellefteå, Sweden. The Älvsbacka Bridge consists of approximately 200 tons of timber and 70 tons of steel (Jacobsson *et al.* 2013). The bridge is located in the northern part of Sweden, where temperatures can range from below -30 °C to over 30 °C during the year. The bridge is equipped with a health monitoring system (Björngrim *et al.* 2011; Saracoglu and Bergstrand 2015), which consists of several different sensors that measure displacement, weather effects, moisture content, *etc*. New sensor technology provides continuous measurements suitable for health monitoring of timber bridges (Tannert *et al.*

2011). These new sensors provide more information than visual inspection and could reduce the maintenance cost and provide a better basis for planning maintenance activities and evaluating the remaining service life. Monitoring of timber bridges can also assist in the development of the next generation of timber bridges (Saracoglu and Bergstrand 2015).

The complexity of the bridge regarding materials with different thermal properties together with the comprehensive data from the health monitoring system make it interesting to investigate how the bridge responds to external parameters, such as temperature and wind. When dealing with large data-sets of measurements, data that contain many variables and observations, multivariate statistics by principle component analysis (PCA) is a suitable tool to extract and visualize data (Eriksson *et al.* 2006). In this paper, a multivariate approach was used to group and model weather phenomena affecting the Älvsbacka Bridge to better understand large timber constructions.

The objective of this paper was to use a multivariate statistics tool to analyze the huge database of health monitoring timber bridge movements and responses to temperature and wind.

EXPERIMENTAL

Älvsbacka Bridge

In August 2011 the Älvsbacka Bridge was erected in Skellefteå (64°45'N 20°57'E). The Älvsbacka Bridge connects the Älvsbacka district on the north side with the Anderstorp district on the south side of the Skellefteå River. The bridge is used primarily for pedestrian and bicycle traffic and is designed to carry a snow removal vehicle (a distributed load of approximately 4 kN/m^2). The cable-stayed bridge spans 130 m and is in total 182 m long, with the bridge deck measuring four meters wide and 24-m-high pylons. The pylons secure the 20 cables suspending the bridge deck. The cable diameter varies between 45 and 80 mm. The superstructure consists of two glulam beams with a cross section of 0.65 by 1.10 m. The pylons have a cross section of 0.9 by 0.9 m. The glulam is made of untreated Norway spruce (*Picea abies*) with a defunct Swedish grade L40 (comparable to European grade GL30C). The superstructure is covered with painted spruce and matching tongue and groove board cladding of panels (22 x 145 mm). Such panels are used for UV protection as well as prevention from moisture ingress in the wood. Between the cladding and glulam beam, there is a 25-mm air gap for ventilation. Cross-bracing and other metal details are made of steel hot-dipped in zinc. The bridge has an open decking with 45-mm-thick pine boards. The bridge has a technical lifetime of 80 years. The Skellefteå municipality is the owner of the bridge.

Monitoring System

Figure 1 displays the south half of the bridge with the monitoring sensors. Blue circles show the GNSS receivers and the green circle shows the weather station.

Global navigation satellite systems (GNSS)

The bridge is equipped with three Leica GMX 901 receivers (Leica Geosystems, Sweden) (Fig. 2 (a)). The receiver acquires its longitudinal, latitudinal, and altitudinal position from American Global Positioning System (GPS) and the Russian equivalent Global Navigation Satellite System (GLONASS). Two sensors are mounted on the east side of the bridge on the mid- and quarter-span; the third sensor is mounted on top of the southeast pylon. The sensor mounted on top of the pylon is used as a reference antenna. The sensors measure the vertical, longitudinal, and transverse position at sampling intervals of 1 Hz.

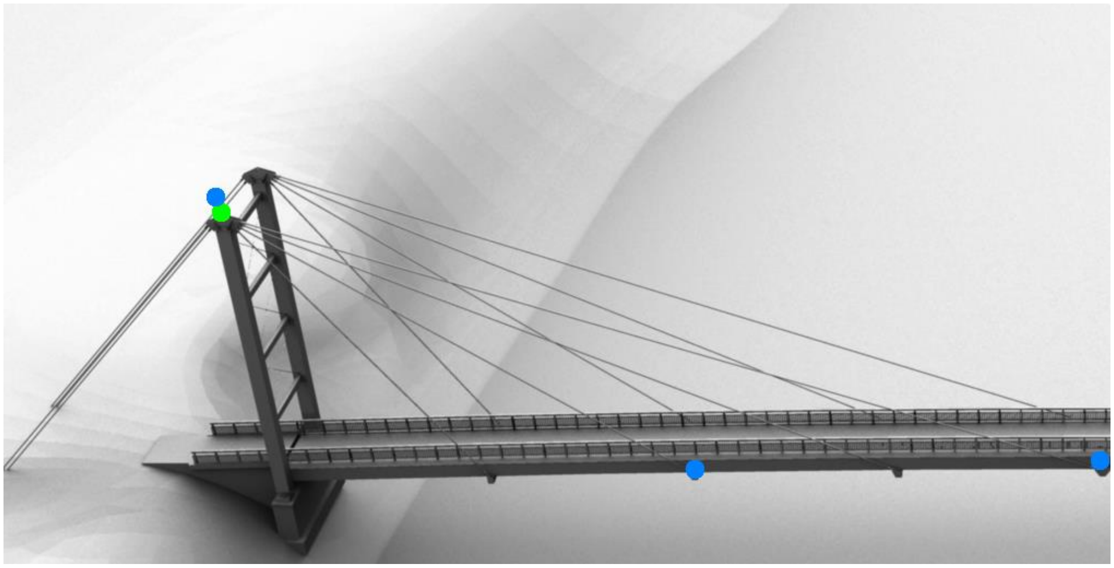

Fig. 1. Model showing the south half of the bridge with monitoring sensors

Weather station

The weather station mounted on the southeast pylon is a Vaisala Weather Transmitter WXT520 (Vaisala, Finland) (Fig. 2b). The weather station measures wind velocity, wind direction, relative humidity (RH), and temperature. The accuracy of wind velocity is ±3% at 10 m/s. The accuracy for wind direction is ±3°. To ensure correct measurements during the winter, the weather station can be heated to keep the sensor free from snow and ice. The weather station takes a measurement every two to five seconds.

(a) (b)

Fig. 2. (a) Leica GMX 901 receiver and (b) the Vaisala Weather Transmitter WXT520

Data collection and analysis

The data used for this study were collected from January 17th, 2013 to May 18th, 2013. These days were chosen because of the clear differences in temperature. The temperature on January 17th was approximately -22 °C during the measured period, and on May 18th, the temperature reached +22 °C.

The weather station collects approximately 7,000 data points per day, and the GNSS collects approximately 86,400 points per day. To compare these data, data from the weather station have to be interpolated, so that a certain time corresponds with a certain movement given from the GNSS. Weather data consist of wind velocity in m/s. Wind direction is given in degrees, where north is 0°, east is 90°, south is 180° and west is 270°. Relative humidity is presented in percent and temperature in degrees Celsius. In the model, north is defined as the interval from 316° to 45°, east as 46° to 135°, and so forth. The GNSS data is displayed as the offset from a normal position, in meters.

The PCA analysis was computed with Simca 13 software (Umetrics, Sweden). The X-variables for the PCA model were RH, temp, wind velocity, and latitudinal, longitudinal, and transverse displacements of the mid-span and quarter-span of the bridge.

For the PLS analysis, the six displacement parameters were set as Y-variables to evaluate how weather parameters affect the bridges movements. For the PLS model, the dummy variable wind direction was introduced and used together with RH, temp, wind velocity, and the product of wind direction and wind velocity as X-variables. The wind direction, which is a dummy variable, was denoted as north (N), east (E), south (S), or west (W) and is given the value 1 for a correct wind direction and 0 for an incorrect wind direction. Wind direction was also multiplied with the wind velocity to assess the magnitude of the wind. To give all the variables the same weight in the model, all variables were mean-centered. Mean centering calculates the average for each variable, and then subtracts it from the data.

When a PCA or PLS model is evaluated, R^2 and Q^2 values are important parameters. The R^2 value is the goodness of fit, a measure of how much the variation of the data can be explained by the model. For PCA, the R^2 of the X variables was used; for PLS, the R^2 of Y data was used for evaluation. The Q^2 value indicates how good the model is at predicting new observations. By leaving out a small part of the observations when the model is created, then using the model in an attempt to predict the left-out data, and finally comparing the predicted values with actual observations, the model can be cross-validated. Comprehensive explanation of PCA and PLS can be found in Eriksson *et al.* 2006.

RESULTS AND DISCUSSION

PCA Results

The result of the PCA analysis is shown in Table 1; the R^2 value of the model is 0.873, with a Q^2 value of 0.491. The PCA score plot is shown in Figs. 3 to 5, and the loading plot is given in Fig. 6.

The PCA analysis shows that mid-span movements in all three directions together with longitudinal movements at the quarter-span are strongly correlated with temperature, RH, and wind speed. Transverse and vertical movements are not as strongly correlated. The PCA was conducted to find groupings in the data. The score plot was colored by wind direction to find groupings. Three groups were found, colored by winds from east, south, and west.

Table 1. PCA model

Type	*A**	*N**	R^2 (cum.)	Q^2 (cum.)	Model
PCA-X	4	115645	0.873	0.491	PCA-All
*A is the number of components, *N the number of observations.					

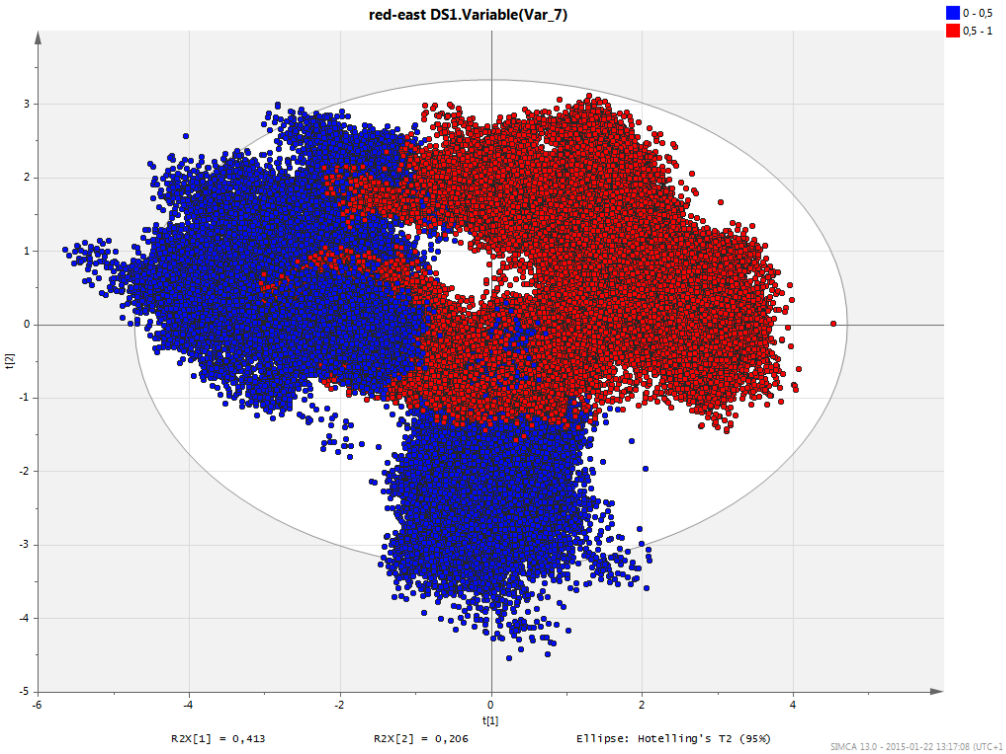

Fig. 3. PCA score plot with red denoting winds from east

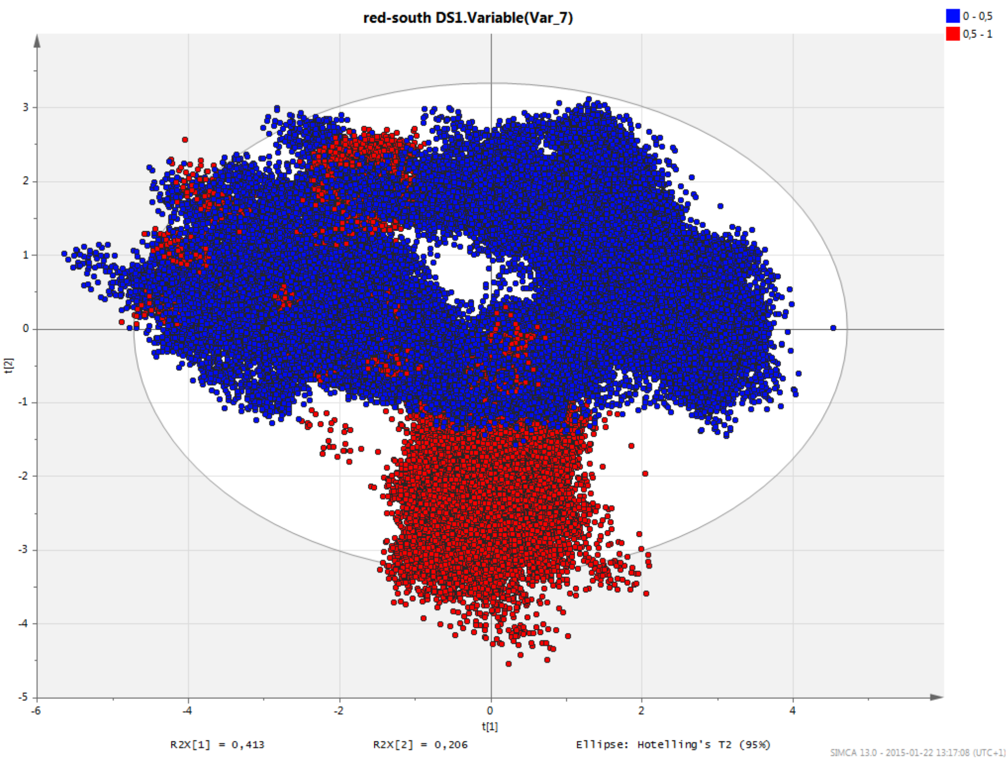

Fig. 4. PCA score plot with red denoting winds from south

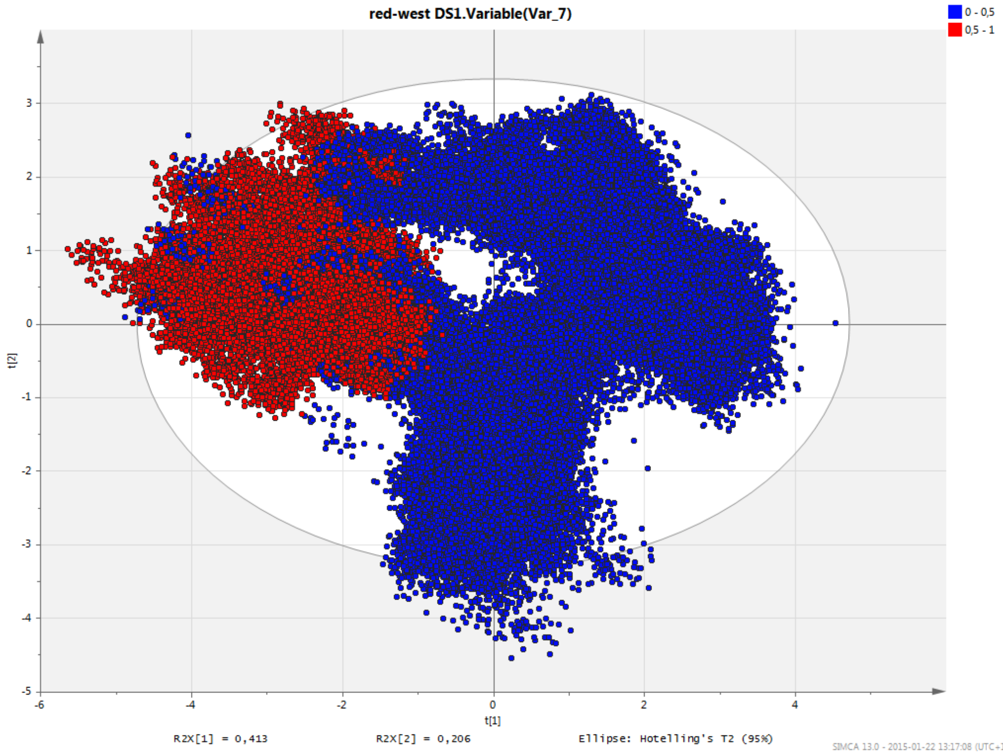

Fig. 5. PCA score plot with red denoting winds from west

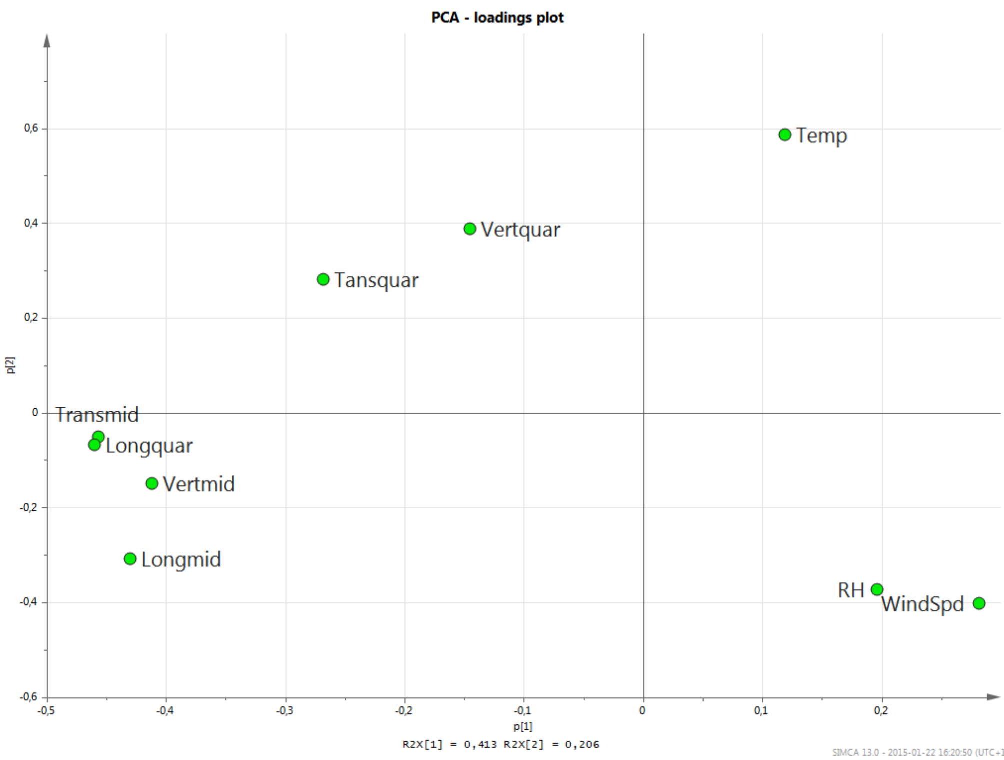

Fig. 6. PCA loading plot

PLS Results

The PCA models were used to model the transverse, vertical, and longitudinal movements on the deck. For each of the three directions, a model containing the whole data set, the subset of west wind groupings, the subset of south wind groupings, and the subset of east wind groupings were created.

Twelve models were created (Table 2). The models based on the whole data set best explained the modeling of the movements in all three directions of the bridge deck (Figs. 7 to 9). The transverse model had an R^2 and Q^2 of 0.662. The variables that had the biggest impact on the model, which were the winds from east and west together with wind velocity. The longitudinal model had an R^2 and Q^2 of 0.737.

Table 2. PLS model

Type	A*	N*	R^2 (cum.)	Q^2 (cum.)	Model
PLS	2	115645	0.662	0.662	Transverse All
PLS	3	32125	0.436	0.436	Transverse West
PLS	4	38169	0.536	0.536	Transverse South
PLS	2	68687	0.36	0.36	Transverse East
PLS	3	115645	0.737	0.737	Longitudinal All
PLS	5	32125	0.533	0.533	Longitudinal West
PLS	4	38169	0.406	0.392	Longitudinal South
PLS	3	68687	0.631	0.631	Longitudinal East
PLS	3	115645	0.525	0.525	Vertical All
PLS	5	32125	0.383	0.383	Vertical West
PLS	4	38169	0.206	0.203	Vertical South
PLS	3	68687	0.354	0.354	Vertical East
*A is the number of components, *N the number of observations.					

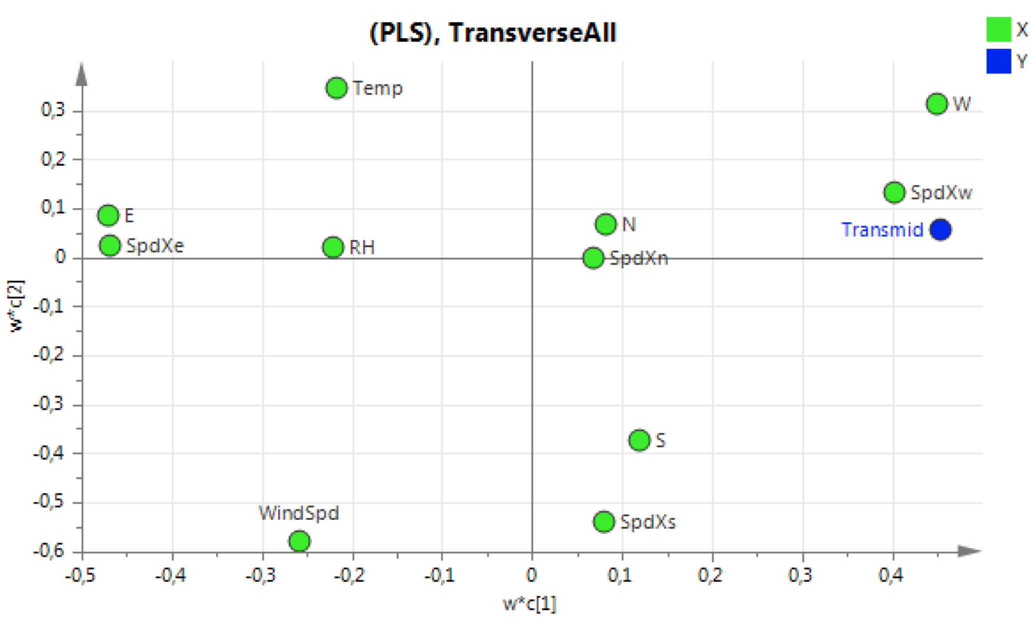

Fig. 7. PLS loading scatter plot for transverse movements

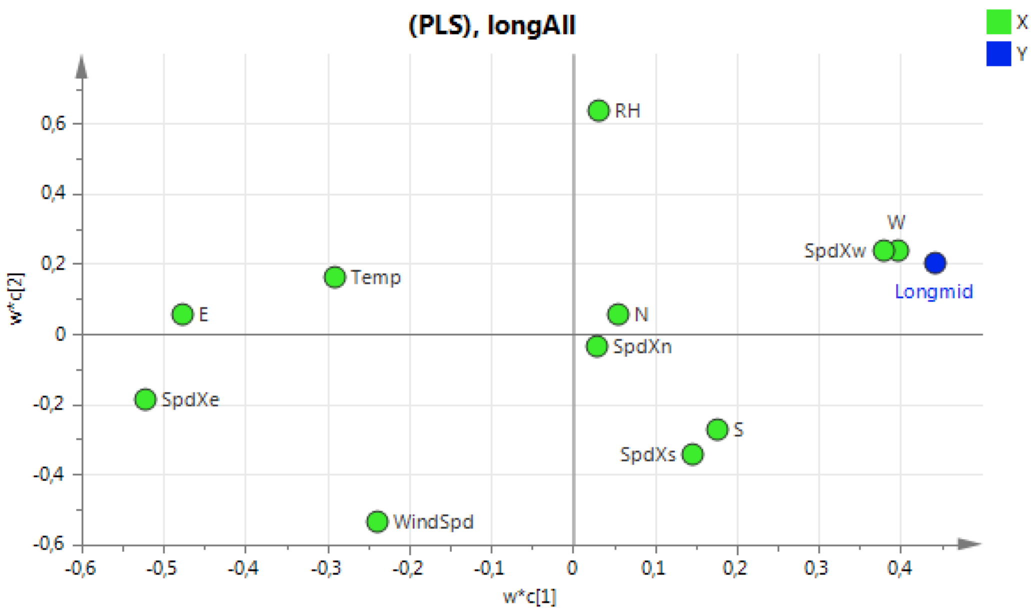

Fig. 8. PLS loading scatter plot for longitudinal movements

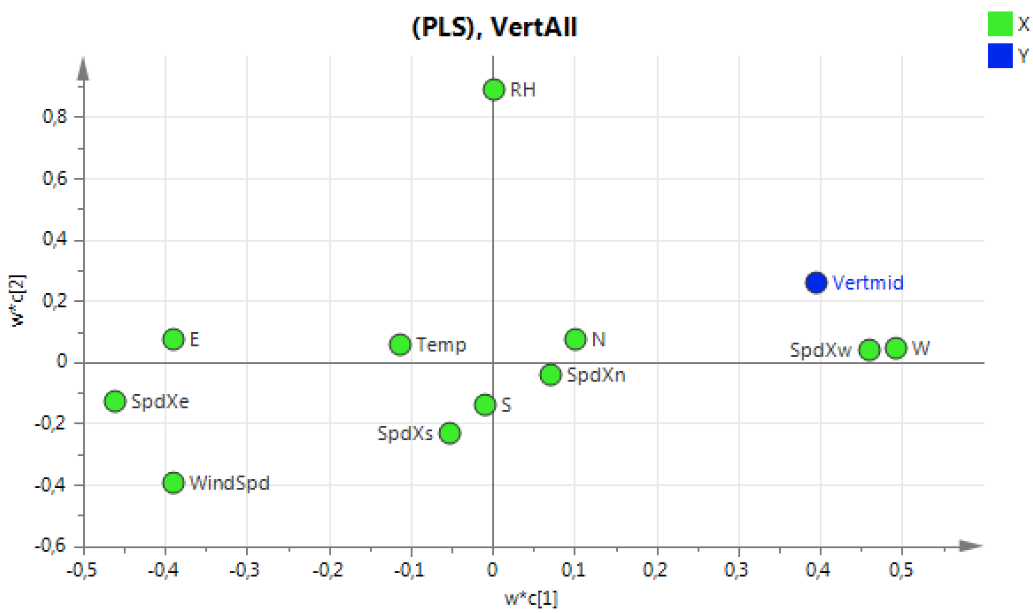

Fig. 9. PLS loading scatter plot for vertical movements

The most influential parameters were the winds from east and west multiplied with the wind velocity. The temperature also had an impact in predicting the longitudinal displacements. The vertical model had the weakest impact R^2 and Q^2 of 0.525. The wind direction multiplied with the velocity from west and east was the biggest factor; RH was also influential for the model.

When the observed *vs*. predicted values were plotted, it was evident that there were two mechanisms affecting the longitudinal movements. These two different directions found originated from the temperature differences in the data set. Hence two models based on a subset with the data from January 17th and May 18th was evaluated. Longitudinal movements with data from January 17th had an R^2 and Q^2 of 0.469, with temperature being the strongest variable. Longitudinal movements based on the data from May 18th had an R^2 and Q^2 of 0.894. Temperature, wind velocity, and RH all contributed to explaining the model.

CONCLUSIONS

1. The Älvsbacka Bridge was built in the north and south direction. The winds from east and west were the most influential on the bridge deck movements as expected. The reported dominant wind direction at the bridge site is from the south.
2. The PCA gave a good overview over the data set and found a distinct grouping in the data set. The PLS models were over-fitted due to the large amount of measurement data, but still gave insight for the dynamics of the bridge.
3. The vertical movement gave the model with the lowest goodness of fit. This could be due to the vertical movements having a stronger correlation with temperature and the thermal expansion of the supporting cables. The thermal expansion-contraction of the steel cables was not accounted for here, but they will affect the bridge deck movements, especially in the vertical direction.
4. The RH showed correlation to the bridge deck movement. Because a change in the RH directly affects the MC of the wood and thus the mass of the structure, it can account for small changes in the damping of the bridge.
5. Longitudinal movement could be due to pylon movements, or abutment and ground displacements. By modeling the longitudinal movements from the May data and January data independently, the variables affecting the model changed.
6. Multivariate data analysis is a powerful tool to evaluate bridge characteristics and can handle large amounts of sensor input, in order to create better health monitoring tools.

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