Full-scale monitoring of wind and suspension bridge response

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Abstract. Monitoring of real structures is important for many reasons. For structures susceptible to environmental actions, full-scale observations can provide valuable information about the environmental conditions at the site, as well as the characteristics of the excitation acting on the structure. The recorded data, if properly analyzed, can be used to validate and/or update experiments and models used in the design of new structures, such as the load description and modelling of the structural response. Various aspects of full-scale monitoring are discussed in the paper and the full-scale wind engineering laboratory at the Lysefjord suspension bridge introduced. The natural excitation of the bridge comes from wind and traffic. The surrounding terrain is complex and its effect on the wind flow can only be fully studied on site, in full-scale. The monitoring program and associated data analysis are described. These include various studies of the relevant turbulence characteristics, identification of dynamic properties and estimation of wind- and traffic-induced response parameters. The overall monitoring activity also included a novel application of the remote optical sensing in bridge engineering, which is found to have an important potential to complement traditional “single-point” wind observations by sonic anemometers.

1. Introduction

During the last 4 years, an extensive monitoring program has been ongoing on the Lysefjord Bridge in Norway \[1, 2, 3, 4, 5\]. The aim is, among other things, to develop measurement methods and to increase understanding of the behavior of suspension bridges across deep, and often wide, Norwegian fjords. The project has been cofounded by the University of Stavanger, the Norwegian Center for Offshore Wind Energy (NORCOWE) and the Norwegian Public Road Administration (NPRA) as the main contributor. The project is considered as a part of the multifaceted ongoing preparatory research for the ferry-free Coastal Highway Route E39 project \[6, 7\].

This paper discusses the role of monitoring loading processes and structural response in modern society. The monitoring program at the Lysefjord suspension bridge is introduced and described in terms of instrumentation, data acquisition, data management and communication systems, data analysis and related research on wind load modelling and structural response analysis.
2. The importance of monitoring

Modern society relies on civil infrastructure for all of its functions. It includes buildings, bridges, tunnels, factories, power plants, offshore installations, heritage structures, port facilities and geotechnical structures, such as dams and foundations.

In-operation structural monitoring is important in assessing the reliability and safety of established infrastructure. The following list introduces a number of cases where structural monitoring may be required [8]:

- Modifications of an existing structure,
- monitoring of structures affected by external works,
- monitoring during demolition,
- structures subject to long-term movement or degradation of materials,
- feedback loop to improve a future design based on experience,
- fatigue assessment,
- novel systems and/or methods of construction,
- assessment of structural integrity after a major event such as an earthquake or storm,
- growth in maintenance needs,
- changes in design philosophy such as the move towards performance-based design.

Bridge monitoring programs have historically been implemented for the purpose of understanding and eventually calibrating models of the load-structure-response chain. Their monitoring, therefore, generally falls into the category of a feedback loop to improve future design, based on experience, or in some cases to verify novel systems of construction. The deployment of sophisticated wind and structural health monitoring (WASHM) systems on cable-suspended bridges has significantly increased since the end of the 90s, in particular in East Asia [8, 9, 10, 11]. In Europe, WASHM systems have been notably deployed in Great Britain [12, 13] and more recently in Norway [1, 14].

Despite great progress in understanding bluff-body aeroelasticity, there continue to be surprises in long-span bridge aerodynamics [15], and the strategic importance and capital investment justify the expense of the most elaborate monitoring systems applied to civil infrastructure [16].

Long-span bridge monitoring systems also provide ideal opportunities to implement and study structural health monitoring (SHM) techniques. In the last decade, permanent bridge monitoring programs implemented in major bridge projects have often evolved into structural health monitoring systems [17]. This allows studies concerning the performance of the bridges themselves, as well as of SHM methodologies.

A direct motivation for monitoring is also found within bridge management programs, bridge upgrading or new bridge projects, where in all cases some form of validation of models and methods is required [18].

Finite-element modelling procedures applied to the Lysefjord Bridge were for instance validated by comparing ambient vibration survey data and finite-element simulations. The same procedures were then applied in a similar mode for simulating the performance of proposed ultra-long multi-span bridges planned for crossings over wide and deep Norwegian fjords [19].

3. Key aspects of monitoring

Structural monitoring has a wide definition and is implemented in different ways for varying motives, as previously mentioned. However, all approaches have the following common components:

(1) sensors,
(2) wired or wireless connections,
(3) data acquisition,
(4) data storage,
(5) data transmission,
(6) database management,
(7) data mining for feature extraction,
(8) load/effect model development from the study of data.

In case of structural health monitoring, additional steps would involve learning from past experience (heuristics), and decision-making based on identified features in combination with identified models.

4. The full-scale wind engineering lab at the Lysefjord suspension bridge
The bridge over the Lysefjord connects the municipality of Forsand, in Rogaland, with the surrounding communities through highway 13 (see Figure 1). The bridge was built in the period of 1995 to 1997 at a cost of about 150 million Norwegian kroner. The bridge is 649 m long in total, but the main span is 446 m long. The deck is a closed steel section, 2.7 m in height and 12.3 m wide. The two concrete towers carrying the bridge deck are 102 m high. The bridge deck stands roughly 55 m above the sea level, allowing ferries and other sailing vessels safe passage under the bridge on their way in and out of the Lysefjord. The bridge deck is oriented from north-west to south-east in a mountainous environment, and is entrenched between two steep hills with slopes ranging from $30^\circ$ to $45^\circ$ and a maximum altitude of 350 m to the North and 600 m to the South. The bridge is exposed to winds that may descent from mountains nearby or follow the fjord over a longer path. The West side of the bridge is exposed to a more open and levelled area. Preparations for the monitoring of the bridge began in 2011, but the first instruments were installed in November 2013. Since then, the monitoring system has been expanded and improved several times, last in June 2017.

The main considerations and steps taken in preparing and implementing the monitoring setup, were, and generally are, the following:

- **Planning and Preparation (2011-2013, 2014, 2015, 2017):**
  - Planning the relevant instrumentation based on what is desired, required and possible.
  - Financing.
  - Selecting suitable equipment depending on availability, robustness, applicability, price.
  - Ordering equipment and accessories, such as cables and connectors.
  - Selecting the final location of each sensor depending on scientific objectives and practicalities.
  - Designing and constructing brackets and fasteners for the instruments.
  - Installation, subject to availability of technicians, lifts, traffic control and other services.

- **Monitoring (15.11.2013 onward):**
  - Monitoring strategy, for example continuous monitoring vs. triggered monitoring.
  - Data capacity on local hard disks.
  - Data transfer.
  - Data server service at the University.
  - Maintenance, replacement and improvements.

- **Data analysis (2014 onward):**
  - Strategy.
  - Parameters.
  - Methods.

Figure 2 gives an overview of the instrumentation currently installed on the bridge and the location of individual sensors.
Figure 1. The Lysefjord Bridge and surroundings

Figure 2. Overview of the current instrumentation of the Lysefjord Bridge.

4.1. Anemometers and weather station
Currently, the instrumentation on the bridge is composed of eight sonic anemometers (3D WindMaster Pro from Gill Instrument Ltd), which can be used with a sampling frequency up to 32 Hz. The anemometers are either mounted directly on brackets that are fixed to the hangers, or placed on the top of a 2.5 m long vertical steel pole placed above the main cables and fixed to the safety railings for the main cables. The sonic anemometers measure the wind along three perpendicular axes, i.e. the along-, across- and vertical wind components, respectively. On the west side of the deck, there is also a weather station on hanger H-10, which measures wind direction, wind speed, temperature, humidity, atmospheric pressure and precipitation at a sampling frequency up to 4 Hz. The anemometers are all located approx. 6 m above the deck,
except at the hanger 8 (H-08) location, where there are two anemometers located at 6 m and 10 m above the deck, respectively. As the distance between each hanger is 12 m, the distance between the anemometers ranges from 24 m to 168 m.

4.2. Accelerometers and GPS sensor

Inside the bridge deck, four pairs of tri-axial accelerometers have been installed. They are located in four sections, near hangers 9, 18, 24, and 30. Their placement is determined so that both symmetric and asymmetric modes can be captured efficiently. Each of the four sections has two sensors, one on either side of the bridge deck, to monitor the bridge torsional response around its longitudinal axis (y), in addition to the translational responses. The lateral distance between two accelerometers constituting a pair is ca. 7.15 m and the maximal sampling frequency of each accelerometer is 200 Hz.

In addition, there are two accelerometers at the top of the northwest tower, one in each of the two box-shaped columns.

The accelerometers used are triaxial MEMs (microelectromechanical systems) silicon accelerometers from Canterbury Seismic Instruments Ltd. Figure 4 shows an accelerometer within the bridge deck.

In addition, the displacement of the bridge deck is monitored using a Real-Time Kinematic-Global Positioning System (RTK-GPS). More precisely, as the rover is located on top of the main cable, it is the displacement of the main cable in the middle of the bridge span, app. 3 m above the bridge girder that is being observed (see Figure 5b).

The Global Positioning System (GPS) or Global Navigation Satellite System (GNSS) technique has provided new possibilities for continuous monitoring of deflections of structural systems through direct measurements [20, 21, 22]. A differential GPS, which depends on accurate measurement of transit times for radio waves from satellite to receiver, promises direct and absolute measurement of deflection. A base station GPS antenna and logger is set up on a stable (fixed) reference location as close as possible to the monitored structure, with line of sight to at least five orbiting GPS satellites. A rover antenna and logger are installed on the structure,
with the same satellite visibility. The locations of rover and base station are obtained in the appropriate geodetic coordinates, but each will have a measure of inaccuracy depending on factors affecting radio transmission times between the satellites and receivers. If the base station and the receiver are close, the error factors should affect the two signals in almost the same way. The RTK-GPS base-rover combination improves the accuracy of measurements by recording the relative displacement between a “fixed” base station on the northwest side (Figure 2, green dot) and a “moving” rover station located on the main cable at mid-span (Figure 2, blue dot). Naturally, the accuracy varies depending on the quality of the instruments used. In the present case, a set of Trimble BD930 GNSS receivers are coupled to Trimble AV33 GNSS antennas. These sensors can handle data sampling at a frequency of 20 Hz, with an accuracy of ±8 mm +1 ppm for the horizontal displacements and ±15 mm +1 ppm for the vertical displacements. The GPS technique is ideal for tracking the performances of long-span suspension bridges due to their low natural frequency and large amplitude displacements.
4.3. Data acquisition, communication and management

The sensors all produce digital signals and are connected to five data acquisition units using Cat5 cables. The DAQ units are three CUSP-3 units, one CUSP-M4 unit and one CUSP-M8 unit from Canterbury Seismic Instruments Ltd. The current system can serve 21 three-channel sensors, i.e. 63 channels in total. Each data acquisition unit is connected to a GPS receiver that provides an accurate timestamp to the data.

The data acquisition units are then connected to a local area network (LAN) that provides communication to the external world through a 3G modem. The local Ethernet network extends from the NW tower to Hanger 24, a distance of ca. 350 m, split up by 4 switches.

The data from each of the five data acquisition stations is then resampled by a separate data acquisition unit (CUSP-M32) which provides a common communications backbone that outputs a single, synchronized, time-aligned data-set for every 10 minutes. The sampling frequency is 50 Hz for all data, which is then reduced to 20 Hz during post-processing by decimation. The data-set is stored locally and simultaneously transferred through a 3G router via the mobile network to a server located at the University of Stavanger. It should be noted that the data sampling is continuous, so the amount of data already stored is enormous. The 3G router and the mobile network enables data transfer and data acquisition control from anywhere in the world.

5. Recorded data and analysis

The studies based on the recorded data, have focused on improving the understanding and modelling of wind loads and wind-induced response of long-span bridges, to facilitate an economic and safe bridge design.

The analysis based on the data recorded at the bridge have evolved around the following subtopics:

- Mapping and interpreting wind conditions and turbulence characteristics using data from Sonic anemometers and long-range lidars [3, 4, 23]. The objective being to improve the understanding of the parameters used in wind to load modelling.
- Monitoring of wake effects using short-range lidars [24].
- Evaluation of the bridge buffeting response based directly on the acceleration data and numerical load-response models [1, 25]. With the purpose of testing and improving available load-response models.
- Evaluation of traffic-induced response and methods to distinguish between traffic-induced response and wind-induced response [26]. For many applications, it is of key importance to be able to isolate the traffic-induced response when evaluating the statistical measure of the wind response.
- System identification of the response is an integral part of all response studies as well as for physical modelling of structures. Natural frequencies and damping ratios have been evaluated and studied for instance with regard to environmental variables such as mean wind velocity [1], temperature [5] or sample duration [27]. Several system identification (SI) methods have been tested and compared in the process.
- Displacement response from GNSS measurements has been systematically compared to displacements evaluated from acceleration data [2].

An important part of that objective comes through measurements and modelling of turbulence and the associated wind-induced bridge vibrations. Figure 6 shows two examples of common wind conditions at the Lysefjord Bridge. In general, the wind direction is strongly affected by the surrounding landscape and the wind direction largely follows the orientation of the fjord, as can be seen by comparison with Figure 1. There is also a pronounced higher turbulence
Figure 6. Wind rose of mean wind velocity (top) and turbulence intensity (bottom) recorded in 2015 on the Lysefjord Bridge [23, p. 60-61].

The turbulence intensity ($I_u = \sigma_u/U$) in the flow when the wind comes from the north. It can be explained by the proximity of high mountains that cause significant disturbance of the flow and thereby variability in the velocity, which is reflected by the normalized standard deviation of velocity i.e. the turbulence intensity.

As Figure 6 indicates, the prevailing wind direction is almost never perpendicular to the bridge deck. As a result, the conditions generally modelled in wind tunnels, where the aerodynamic properties of the bridge are primarily explored for wind perpendicular to the bridge deck, rarely or never occur. At the same time, cross-sectional properties are usually always tested with a much smaller turbulence intensity than the measurements portray. This reality is partly what makes full-scale measurements important. That is, to assess the reliability of design and modelling approaches and the validity of the simplifications generally made in simulations of the behavior of real structures, whether they are experimental or numerical.

Figure 7 shows an example of data from the acceleration measurements in the form of the standard deviation of acceleration plotted as a function of the mean wind velocity component normal to the deck, for NNE wind directions and SSW wind directions, respectively. The measured acceleration data are obtained using a sampling frequency of 20 Hz. The computed acceleration of the bridge is obtained using a frequency domain approach, where the turbulence model from the handbook N400 [28] used for bridge design in Norway is applied, with a terrain category (cat.) from 2 to 4. The response shown is the lateral displacement, the vertical displacement and the torsional displacement of the deck, shown across the bridge ($x$-factor), motion up and down ($z$-factor) and winding longitudinal axis ($\theta$-factor). As can be seen, the dynamic response of the bridge deck is considerably larger for wind from NNE than wind from SSW, which is mainly associated with higher wind turbulence for wind from NNE. It is also seen that traditional buffeting models tend to underestimate the movements of the bridge when the turbulence intensity is high, i.e. for the wind from NNE.

Figure 8 shows an example of the standard deviation of vertical and horizontal displacement at the center of the deck, on one hand, from accelerometer data and on the other hand, from the GNSS measurements. As can be seen, the comparison is quite good, especially for the lateral displacement, which provides both confirmation of the method used to calculate post-acceleration, as well as the potential of GNSS technology to measure the displacements of structures of this type. However, Figure 8 also shows that the GNSS measurement overestimates the vertical motion compared to the acceleration measurement. Since the accuracy of GNSS measurement technology is generally in the range of several millimeters to centimeters, the movement of the
structure must be several centimeters in order for the technology to provide reliable results. The resolution in the vertical direction is also at only half of that for horizontal motion, which probably explains to some extent why the GNSS measurement gives a slightly higher vertical displacement than the accelerometers.

6. Additional monitoring campaigns at the Lysefjord Bridge
In addition to recording the wind velocity and the bridge response using the permanently installed monitoring system, separate monitoring campaigns have been undertaken to test relatively new measurement techniques based on optical remote sensing. The instruments used were the so-called lidar. Lidar is the acronym for Light Detection And Ranging. It is a remote sensing technology based on the emission of a laser beam and the analysis of the backscattered light by gas and particles in the atmosphere. A lidar is, therefore, made of three main components: a laser, a telescope, and the detection system. These devices are either designed to measure over long distances of several km (long-range lidar) or short distances from 10 m to 200 m (short-range lidar). The Lysefjord Bridge has been used as a test site for temporary experiments using both of the above-described lidar types [3, 4, 24].

A long-range lidar (WindCube 100S by Leosphere) was acquired through NORCOWE and installed approx. 1.8 km from the bridge. Its scanning head was oriented towards the bridge. It was used to observe the wind flow conditions around the bridge, across the entire bridge span, following several different scanning scenarios. The range gate of 25 m and the recording interval

![Graphs showing measured and computed lateral, vertical, and torsional acceleration response of the Lysefjord Bridge.](image)

**Figure 7.** Measured and computed lateral (top panel), vertical (middle panel) and torsional acceleration (bottom panel) response of the Lysefjord Bridge. The data set considered comprises every 10-min bridge acceleration and wind records obtained in 2015.
of at least 1 s, enabled characterization of large, low frequency gusts [4].

A short campaign was also undertaken using two synchronized short-range lidars (see Figure 9) to measure two components of the wind velocity along horizontal and vertical lines about 40 m southwest of the deck [3, 24]. The short-range WindScanners are owned and operated by the Technical University of Denmark (see http://www.windscanner.dk/). Figure 10 shows schematically the setup of the instruments, which were located 90 m apart sending out and detecting beams of light that cross at a certain distance away from the bridge. Where the rays cross, two wind speed components can be identified, one in \( x \)-direction and the other in \( y \)-direction. An example of the measurements obtained can be seen in Figure 11, which shows, among other things, the wind velocity as a function of height. As the figure shows, the bridge deck, which is located about 55 m above sea level, has a significant effect on the flow, i.e. the figure visualizes the wake that forms behind the deck as the flow passes the bridge.

The experience gathered through these two lidar campaigns from an existing bridge has been

Figure 8. Standard deviation of the GNSS and accelerometric vertical (left) and lateral (right) displacement using a full day of continuous bridge vibration records on 2015-10-07 and a frequency range from 0.1 Hz to 1 Hz. The solid line represents the case of a perfect correlation.

Figure 9. Short-range lidar on the bridge (photo by DTU).
Figure 10. Schematic of the short-range lidar (R2D1 and R2D2) on the bridge.

Figure 11. 150 seconds of the along-beam velocity component recorded by one short-range lidar in the wake of the bridge deck, on 23-05-2014 from 05:30, (left) and corresponding 10-min mean wind profile 40 m downwind of the bridge.
applied to develop a novel experiment in Bjørnafjord south of Bergen, where one of the major fjord crossings along the E39 Coastal Highway is being planned. In 2016, three long-range lidars were used to monitor the turbulence conditions in the middle of the 5 km wide fjord, in order to link this information to the turbulence characteristics observed by the anemometers on the shore [29].

7. Final remarks
In this paper, various aspects of full-scale monitoring have been discussed and the full-scale wind engineering laboratory established on the Lysefjord Bridge has been introduced.

Wind and traffic-induced vibrations of a suspension bridge in a complex terrain have been studied in full scale. The focus has been on modal parameter characterization, a central step for proper evaluation of the buffeting response. Environmental effects have been observed, such as the daily and seasonal fluctuations of the natural frequencies. As the monitoring is continuously ongoing it may be possible, with sufficient amount of data, to evaluate probability distributions for the key excitation-, system- and response parameters. These could then subsequently be used to develop performance indicators or criterias for structural health management purposes.

Wind measurement techniques based on optical remote sensing (lidars) have been seen to complement single point wind data from sonic anemometers. Full-scale monitoring of flow around a suspension bridge using a system of small lidars shows promising potential for studies of wind-structure interaction. However, data quality of optical remote sensing instruments is strongly influenced by the day to day environmental conditions, especially for long-range lidars. The data quality will also depend on the type of wind statistic pursued, and the complexity of the scanning pattern.

Monitoring of excitation, created by environmental forces and the related response of real structures is important for many reasons. New information is gathered about the nature and characteristics of the excitation forces that the building is exposed to, as well as the properties and behavior of the structure itself. Both aspects, excitation and response, can be used to validate and/or update experiments and models used in the design of new structures, such as the load description and modelling of the structural response.

Information gathered through monitoring generates increased safety in construction, giving both designers and owners added confidence in the design information and methods applied. In addition, long-term observations of structural behavior can be used for health monitoring and facility management. In fact, structural monitoring should be, and is becoming, an integral part of civil infrastructure management.

It is also important to be able to test and validate the capabilities of new measurement and monitoring technologies through comparison with data from established sensors and monitoring techniques, such as those provided by the full-scale wind engineering lab at the Lysefjord Bridge.

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