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Sammendrag
Mange av bruene i Norge ble bygget på 1960-, 1970- og 1980-tallet, da kunnskapen om betongens bestandighet var begrenset. Dette har resultert i mange bruer som trenger rehabilitering. For å estimere gjenværende levetid og planlegge kostnadseffektivt vedlikehold, er det viktig å ha en god oversikt over konstruksjonens tilstand. Dagens bruforvaltning er hovedsakelig basert på inspeksjoner, som er kostbare og tidkrevende. Kontinuerlig overvåking med sensorer kan forbedre vurderinger og beslutningsprosesser. Rapporten gir en oversikt over prosjekter med sensorteknologi brukt til bruovervåking, og beskriver beste praksis og suksesskriterier.

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Title
Sensor Technology for continuous monitoring of bridges

Subtitle
Evaluation of successful projects and best practices for sensor technology in monitoring

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Sensor technology, monitoring, bridges, maintenance, service life

Summary
Many of Norways bridges were built in the 1960s, 1970s, and 1980s, when knowledge about concrete durability was limited. This has resulted in many bridges now needing rehabilitation. To estimate remaining lifespan and plan cost-effective maintenance, it is important to have a good overview of the structure's condition. Today's bridge management is mainly based on inspections, which are costly and time-consuming. Continuous monitoring with sensors can improve assessments and decision-making processes. The report provides an overview of projects using sensor technology for bridge monitoring and describes best practices and success criteria.

Pages 86

Rapport

Sensorteknologi for kontinuerlig overvåking av bruer

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SAMMENDRAG

Many of the bridges in Norway were built during the 1960s, 1970s and 1980s. The knowledge about reinforcement corrosion and durability of concrete was limited during this period. The requirements regarding both concrete cover and quality were very liberal compared to today's requirements. This has resulted in many bridges that now need both minor and major repair.

To estimate the remaining service life and to be able to plan cost-effective maintenance, it is important to have a good overview of the condition of the structures and the damage propagation. Today, bridge management is mainly based on results from inspections, including field observations, sampling and laboratory investigations. However, inspections are costly, time-consuming, and carried out at specific time intervals only. Additionally, they rely on subjective assessments, making it challenging to accurately assess the structural condition and to determine which structures require repair or should be replaced by new ones.

The Norwegian Public Roads Administration is considering whether continuous monitoring with sensors on the bridges, in addition to inspections, can improve the quality of assessments and simplify the decision-making process. By combining objective sensor data with traditional inspections, there might be a potential to identify and implement better and more effective measures to extend service-life of bridges.

The report provides a comprehensive overview of projects where sensor technology was and/or is used successfully in bridge monitoring, providing data used as support when making decisions regarding bridge management. The purpose of the report is to better understand the use of such technology by describing best practice and success criteria, so that the use of sensor technology can be recommended in cases where it is appropriate and will provide added value for the bridge owner and manager.

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2. BACKGROUND

Many of the bridges in Norway were built during the 1960s, 1970s and 1980s. The knowledge about reinforcement corrosion and durability of concrete was limited during this period. The requirements regarding both concrete cover and quality was very liberal compared to today's requirements. This has resulted in many bridges that now need both minor and major repair.

To estimate the remaining service life and to be able to plan cost-effective maintenance, it is important to have a good overview of the condition of the structures and the damage propagation. Today, bridge management is mainly based on results from inspections, including field observations, sampling and laboratory investigations. However, inspections are costly, time-consuming, and carried out at specific time intervals only. Additionally, they rely on subjective assessments, making it challenging to accurately assess the structural condition and to determine which ones that require repair or should be replaced by new ones.

The Norwegian Public Roads Administration is considering if continuous monitoring with sensors on bridges, in addition to inspections, can improve the quality of assessments and simplify the decision-making process. By combining objective sensor data with traditional inspections, there might be a potential to identify and implement better and more effective measures to extend service-life of bridges.

Structural Health Monitoring (SHM) has emerged as a key technology in the management of bridges, allowing for continuous assessment of structural integrity and behaviour through sensor-based systems. By providing real-time data and insights, SHM has proven to be a valuable tool for optimizing maintenance, extending service life, and ensuring the safety of infrastructure.

This report presents a comprehensive overview of successful projects where sensor technology has been employed as decision support in bridge management. The SHM systems have provided valuable information to the bridge owner regarding the structure's condition, leading to informed decisions about maintenance, rehabilitation, or operational strategies (Figure 1).

The purpose of the projects is described together with information on which sensors that were used, data acquisition and processing, and the use of the data in making decisions regarding bridge management. An overview of a state-of-the-art sensor and data platform architecture is also provided. The purpose is to better understand the use of such technology by identifying best practice and success criteria, so that the use of sensor technology can be recommended in cases where it is appropriate and will provide added value for the bridge owner and manager.

The Norwegian Public Roads Administration might need to strengthen expertise and procedures to make use of sensor data, in bridge management, i.e. to be able to transform data into information and to make use of the information in bridge management.

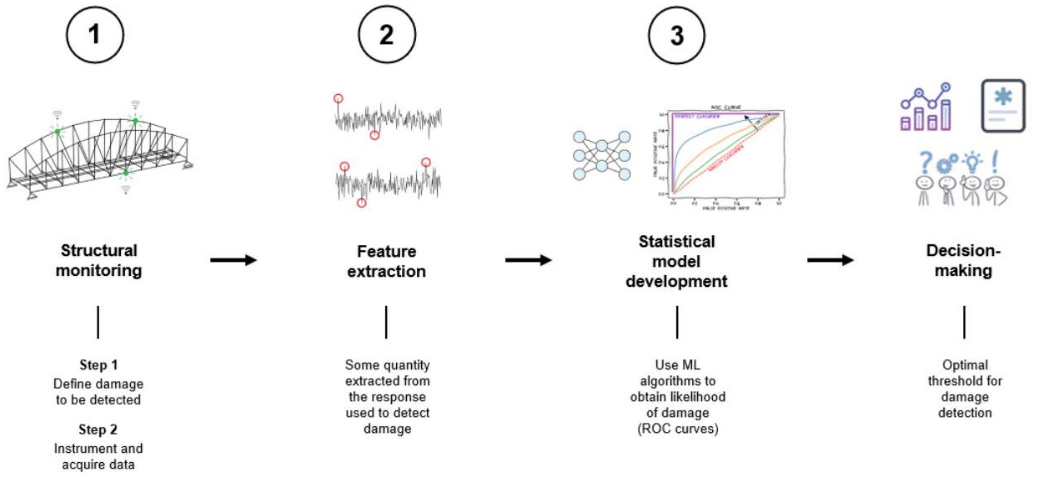


Figure 1: SHM implementation process (Courtesy of Bjørn Thomas Svendsen, NTNU/Ramboll).

3. BRIDGE INSPECTIONS

Procedures and details describing bridge inspections are given in publication N-V441 Bruinspeksjon from the Norwegian Public Road Administration. The following three types of inspections are defined:

Generell inspeksjon – general inspection

Enkelinspeksjon – single inspection

Hovedinspeksjon – main inspection

Spesialinspeksjon – special inspection

The main purpose of the bridge inspection is to assess the load capacity of the bridge, traffic safety, durability and the visual appearance of the bridge. The inspections are part of bridge management. The main tasks are shown in Figure 2.

The results of the inspections are reported and documented in the bridge management system BRUTUS in accordance with instructions given in N-V441.

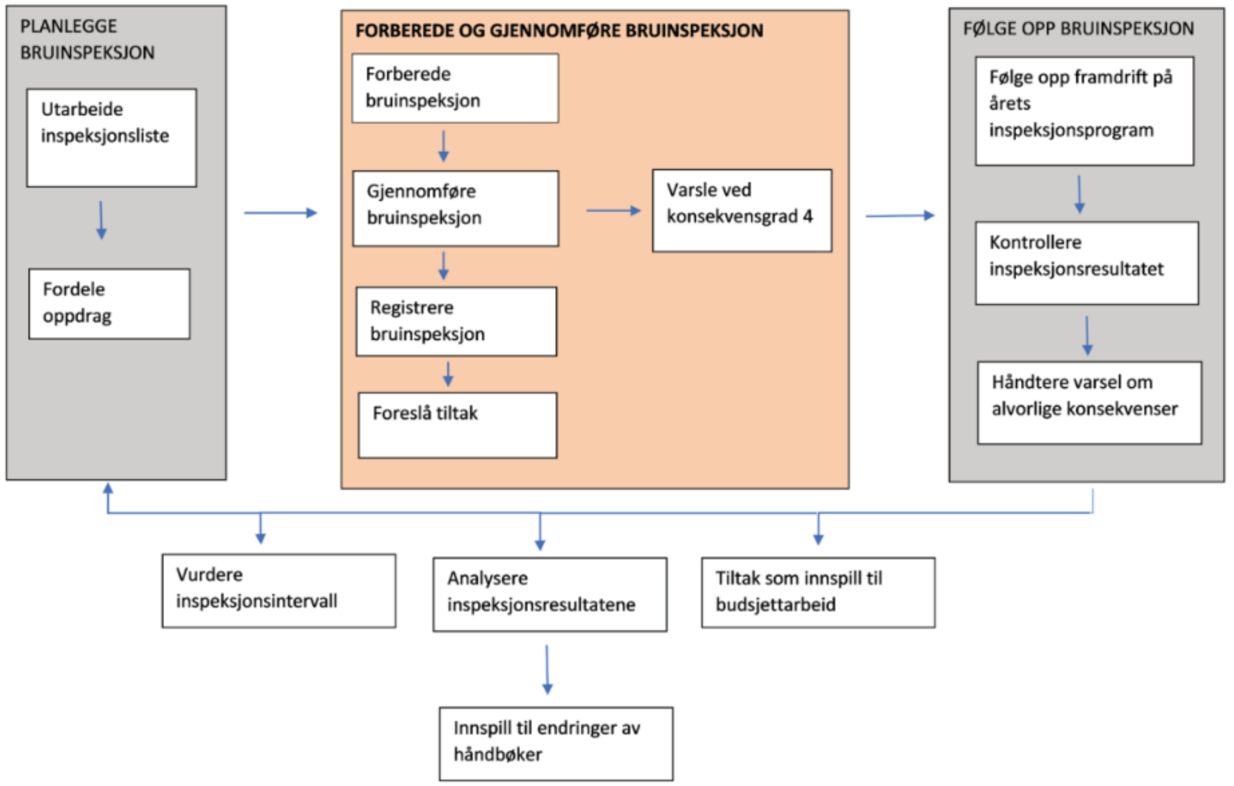


Figure 2: Summary of the bridge inspection process. From N-V441.

The purpose of **General inspection** is to monitor the functionality of the road network and is carried out on a regular basis by the operating contractor.

Single inspection is done to register damage and/or other factors that can influence the bridge's capacity, traffic security, maintenance or appearance within a short time period. The inspection is a visual inspection only.

All bridge components are inspected closely during a **Main inspection**.

Special inspection is done after incidents that might result in damage to bridge components or when there is need for accurate knowledge of the state of the bridge or specific bridge components.

Main inspection and **Special inspection** will often include measurements and collecting samples to assess the state of materials – remaining thickness of coating/paint/corrosion protection; chloride content of concrete; etc.

4. CASE SELECTION

In this chapter, we describe the methodology followed to shortlist and finalize the cases to be examined and studied in this report.

The outcomes of SHM applications can be classified into several categories as follows:

1. Detection of damages
2. Detection of unexpected bridge behavior
3. Detection of vibration issues
4. Prediction of remaining fatigue life
5. Monitoring before and after the retrofit or rehabilitation
6. Artificially damaged bridges for testing capability of SHM methods
7. Continues monitoring of bridges under extreme events

Each category demonstrates how SHM data have differently supported decision-making in bridge management. In this report, these categories present real-world examples of bridges in Europe where SHM has played a significant role in detecting damage, identifying anomalies, resolving issues, and improving overall bridge performance. The detailed description of categories is as follows:

Category 1: Detection of damages

In this category, damage is defined as any change in the bridge system that causes it to deviate from its normal operating condition. This can include structural issues that affect the overall behavior or performance of the bridge, potentially compromising its integrity and leading to large-scale failures or even collapse if left unaddressed. It may also refer to localized issues affecting specific components or areas of the bridge, without necessarily compromising the bridge's overall structural integrity. Examples of bridges in this category may experience changes such as crack formation, the rupture of a structural member, or changes in boundary conditions. SHM systems play a key role in detecting these anomalies, which can either trigger automated alerts or be identified through manual data analysis. Once damage is confirmed, informed decisions can be made regarding necessary maintenance or rehabilitation actions.

Examples of bridges in this category:

- Hammersmith Flyover (UK)
- Stavå Bridge (Norway)
- Vanersborg Bridge (Sweden)
- Hell Bridge (Norway)
- Musmeci Bridge (Italy)
- Ferriby Road Bridge (UK)

Category 2: Detection of unexpected bridge behavior

While not indicating direct damage, this category focuses on instances where SHM data reveals unexpected bridge behavior. Such discrepancies occur when the forces or loads on certain bridge members differ significantly from initial design assumptions. Identifying these issues early through SHM data can lead to proactive decisions, such as retrofitting to improve performance or extending the bridge's service life.

Examples of bridges in this category:

- The First Bosphorous Bridge (Turkiye)
- Cleddau Bridge (UK)
- Hardanger Bridge (Norway)

Category 3: Detection of vibration issues

Excessive vibrations, often caused by phenomena like vortex-induced vibrations, resonance, or cable vibrations, pose challenges for flexible bridges, such as cable-supported or slender footbridges. SHM systems help detect these issues and facilitate their analysis to understand the root causes. Once identified, appropriate remedial actions can be implemented, ensuring the safe operation of the bridge.

Examples of bridges in this category:

- Øresund Bridge (Denmark)
- Second Severn Crossing (UK)
- Alamillo Bridge (Spain)
- Stange Bridge (Norway)
- Tamar Suspension Bridge (UK)
- Hålogaland Suspension Bridge (UK)

Category 4: Prediction of remaining fatigue life

With increasing traffic loads and density, many bridges face a reduced fatigue life. SHM systems offer a direct method for measuring strain (and indirectly stress), providing more accurate estimates of remaining fatigue life. These data-driven insights help bridge owners make informed decisions about inspection intervals, rehabilitation, or necessary interventions to prolong the structure's lifespan.

Examples of bridges in this category:

- Vanersborg Bridge (Sweden)
- Hell Bridge (Norway)
- Kabalskraal Bridge (South Africa)

Category 5: Monitoring before and after the retrofit or rehabilitation

SHM systems play a crucial role in assessing the effectiveness of retrofitting, rehabilitation, or maintenance activities. By monitoring the bridge's behavior before and after interventions, SHM data allows for a clear comparison of the performance of the introduced changes. Based on the insights gained, decisions are made regarding the success of the intervention and the need for further modifications.

Examples of bridges in this category:

- Hammersmith Flyover (UK)
- The First Bosphorous Bridge
- Cleddau Bridge (UK)
- Øresund Bridge (Sweden)
- Marlo Bridge (Norway)
- Tamar Suspension Bridge (UK)

Category 6: Artificially damaged bridges for testing capability of SHM methods

In this category, intentionally damaged, decommissioned bridges serve as testbeds for validating SHM systems and damage detection algorithms. These controlled experiments provide essential feedback on the performance and accuracy of SHM technology in detecting structural issues.

Examples of Bridges in this Category:

- Z24 Bridge (Switzerland)
- Hell Bridge (Norway)

Category 7: Continuous monitoring of bridges under extreme events

Certain bridges are monitored continuously throughout their operational life, with SHM systems providing crucial data during extreme events, such as storms or earthquakes. In these cases, SHM data helps to confirm whether significant structural changes have occurred, allowing authorities to respond accordingly. This real-time monitoring reduces the need for extensive visual inspections and helps maintain the bridge's safety.

Examples of bridges in this category:

- The Second Bosphorous Bridge (Turkiye)
- Brussels-Schuman Station Bridge (Belgium)

Criteria-based selection of bridges:

When selecting bridges from the candidates, we prioritized the following criteria:

1. **Successful SHM Implementations**: We focused on examples that provide precise and effective measurements for detecting structural issues and anomalies. Based on the

findings from these monitoring efforts, the data directly informs the decision-making process. Consequently, the report details successful projects where sensor technology has been used as a decision support tool in bridge management.

2. **Coverage of different structural types**: We aimed to include a variety of bridge types to ensure comprehensive coverage of SHM implementations:
    a. Cable-stayed bridges
    b. Suspension bridges
    c. Concrete arch bridges
    d. Steel-box girder bridges
    e. Steel-truss bridges
    f. Pre- and post-stressed concrete bridges
3. **Variety of sensor types**: We included examples that showcase the application of different sensor types in SHM systems, such as acoustic emission (AE) sensors, accelerometers, inclinometers, strain gauges, temperature sensors, displacement transducers, and fiber-optic strain sensors.
4. **Scoring criteria:** The chosen bridges were evaluated and scored using a grading system based on four key factors: Motivation, Relevance of Detected Problem, Benefit (Added Value) of SHM, and Resource Availability (See Table 1).
5. **Coverage of categories:** We aimed to include at least one example from each of the seven defined SHM categories. For brevity and greater diversity, when a specific structural type was already represented in a category, a different bridge type was prioritized, even if it had a slightly lower score. This approach ensured a broader representation of bridges, highlighting their versatility and the adaptability of SHM systems.

As a result of the criteria-based selection process, 10 bridges were chosen from a pool of 20 candidates, as detailed in Table 1. These selected bridges exemplify successful implementations of SHM systems, providing valuable insights into their role in detecting structural issues and supporting effective decision-making in bridge management. A comprehensive overview of these 10 SHM projects is presented in Section 5.

Table 1: The selected bridges.

NAME	LOCATION	TYPE	AGE	CATEGORY	GRADE				
					Motivation	Relevance of detected issue	Added value of SHM	Resource availability	Score
Hammersmith Flyover	UK	Post-tensioned RC bridge	64	1 & 5	80	100	100	100	97
Stavå Bridge	Norway	Concrete arch bridge	80	1	80	100	100	100	97
Vänersborg Bridge	Sweden	Steel-truss bridge	108	1 & 4	70	100	80	100	92.5
Hell Bridge	Norway	Steel-truss bridge	110	1 & 4 & 6	70	100	80	100	92.5
Musmeci Bridge	Italy	Concrete arch bridge	43	1	70	90	80	50	71.5
First Bosphorus Bridge	Türkiye	Suspension bridge	51	2 & 5	100	100	100	80	93
Cleddau Bridge	Wales	Steel box-girder bridge	49	2 & 5	100	100	100	80	93
Øresund Bridge	Sweden	Cable-stayed bridge	25	3 & 5	70	90	90	70	80
Z24 Bridge	Switzerland	Pre-stressed RC bridge	61	6	70	90	60	100	86
Second Bosphorus Bridge	Türkiye	Suspension bridge	36	7	100	0	100	50	47.5

5. CASES

In this section, we will provide a comprehensive overview of the 10 selected SHM projects, as summarized in Table 1. For each project, we will present detailed information about the bridge, the purpose and duration of the SHM project, and the reasons for initiating the monitoring campaign. We will describe how the instrumentation was implemented, including how data was collected and processed. Additionally, we will explain the follow-up activities after the monitoring setup and how the decision-making process was managed throughout the project.

The section will also include an outcome assessment that highlights the results of successful SHM applications. Furthermore, the recommendations and improvements suggested by the bridge management teams and the engineers responsible for these SHM applications will be provided. It is important to note that the outcome assessment, as well as the recommendations and improvements, are based on the information provided by the references for each case. Our own comments and suggestions will be provided separately in the discussion section and the SHM system architecture section at the end of the report.

5.1. THE HAMMERSMITH FLYOVER, LONDON, THE UK

5.1.1. Overview of the bridge and the monitoring project

About: Constructed in the early 1960s (see Figure 3)

Importance: A critical part of the A4 trunk road, a major transport route leading into London from the west.

Structural features:

- 622-meter-long structure with 16 spans
- Post-tensioned concrete deck supported by the roller bearings at RC piers
- Longitudinal movement restrained at the abutments

Purpose and duration of the project:

- The primary goal of the project is to conduct condition monitoring of the bridge to identify potential structural issues.
- The SHM system has been in operation since September 2009.

Figure 3: The Hammersmith Flyover [1].

5.1.2. Reasons for monitoring

- **Corrosion issues:** Recent intrusive inspections have revealed that the severity of corrosion is far greater than initially anticipated. This can pose a significant threat to the structural condition and live load capacity of the flyover [2].

- **Roller bearing performance:** "A second concern was the performance of the roller bearings and whether deterioration was resulting in a restraint against expansion" [2], as shown in Figure 4. Corrosion in these bearings may cause them to restrict movement of the deck, leading to additional bending moments in the piers and deck. This could result in the opening of segment joints and increased stress on the prestressing tendons [2].

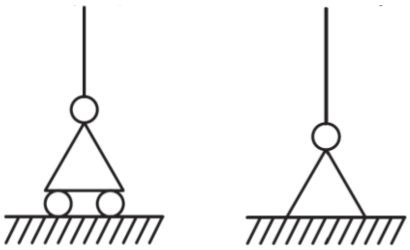


Figure 4: (a) Symbolic representation of fixity of bridge roller bearing as designed (b) possible actual operational fixity in the deteriorated state.

5.1.3. Instrumentation and data acquisition

Two SHM systems were deployed on the Hammersmith Flyover: a Research System, installed by Cambridge University in September 2009, and a Commercial System, installed in July 2010, as shown in Figure 5.

Types of sensors:

- **Research System sensors:** Inclinometers, strain gauges, and displacement transducers.
- **Commercial System sensors:** Approximately 300 acoustic emission (AE) sensors, Inclinometers, strain gauges (installed on the interior of the piers), robotic survey total stations, temperature sensors and displacement transducers.

Measurements:

- **Research System:** Measured strain, inclination, and longitudinal displacements of piers and retaining walls.
- **Commercial System:** Focused on detecting wire breaks in the prestressing tendons using AE sensors, pier interior strain, temperature, and displacements.

Data collection and storage:

- Data from all sensors were transmitted to a data logger housed in a cabinet at the flyover's eastern abutment. The collected data was sent via an internet-connected 3G modem to a database server. The data were not made publicly available and the details on storage and management are unknown.

Data Processing and Analysis:

- The acoustic signature of each potential wire break detected by the commercial system was analyzed by Physical Acoustics Ltd. using a proprietary method. This method is designed to differentiate between actual wire breaks and other similar-sounding events. It is claimed by the company that "The results provided to the client included the time of each confirmed wire break and its location, accurate to within 500 mm" [2]. The details of the detection method or data handling are not available since it was performed by a commercial partner.

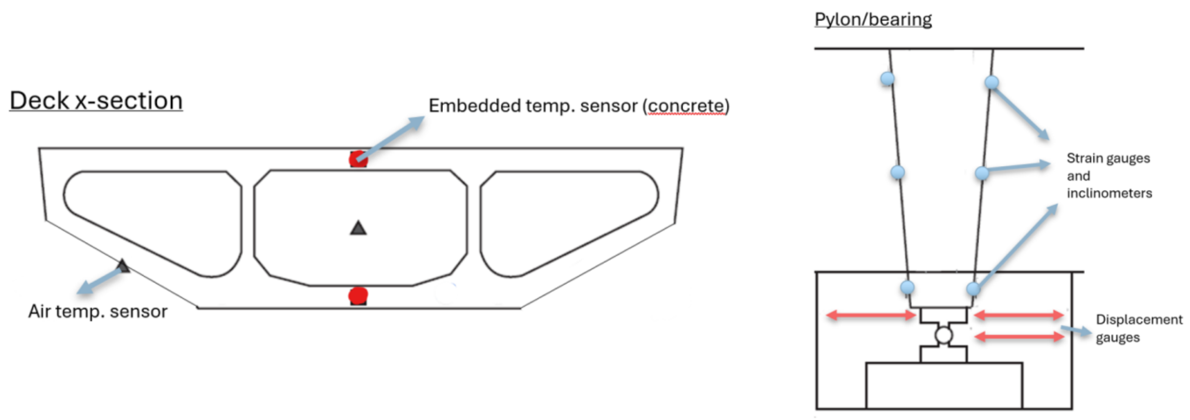


Figure 5: Representative locations of the sensors [2].

5.1.4. Project follow-up and decision-making

- The follow-up of the project is assumed to be based on analysis of the collected data by both the commercial and research parties. No information on an alert system is found, therefore we assume that an alert system was not used in the project.

- Inspection of the data collected by the Acoustic Emission (AE) monitoring system revealed wire breaks in the post-tensioning tendons (Figure 6) and helped identifying deteriorating strands. It is also mentioned that the data were used to develop a deterioration model that predicts the remaining lifespan of the bridge before it loses its reserve capacity [3]. Since the data handling and model development were done by a private company, the details of these are not available.

- The engineers analyzed the continuous SHM data collected from the displacement and temperature gauges and identified that the pier bearings were not functioning as intended restricting the movement of the deck relative to the piers. The displacement data revealed that two pier bearings were partially restrained, likely due to corrosion, which limited the bridge's thermal movements. This finding was later confirmed through visual inspection.

Decision-making:

- As a result of the SHM findings (Acoustic Emission), the critical spans of the flyover were propped in 2011, and the structure was fully closed to traffic on December 23, 2011, to facilitate more detailed investigations to determine with greater accuracy and resolution the condition of the post-tensioning system. Following a reassessment of the condition factors, the bridge was partially reopened with one lane in each direction, restricted to light vehicles (up to 7.5 tonnes), while emergency strengthening works were carried out. The emergency strengthening works involved installing an external post-tensioning system over five critical piers to restore compression and regain full load-carrying capacity. By May 30, 2012, all lanes were reopened to traffic, just in time for the London 2012 Games. In parallel, a second project was launched to complete the strengthening of the remaining sections of the flyover.

- The second phase of work, which started in October 2013 and finished in November 2015, involved the installation of a new post-tensioning system throughout the structure, as well as the replacement of bearings and expansion joints. It is also stated that the SHM was employed to ensure the structure's safety during these works and to track the effects of construction activities, such as tendon stressing and jacking of the structure during the bearing replacement process.

(a) (b)

Figure 6: (a) Failed wire strands and (b) acoustic emission sensor [3]. (Courtesy: Peter Jones / James Brownjohn [3])

5.1.5. Outcome assessment

Summary of the tangible outcomes:

- The SHM system helped detect wire breaks and monitor bearing performance, which informed the emergency propping of critical spans in 2011. After the temporary measures, the bridge was reopened with restricted access to only light vehicles.

- The system provided data-driven insights that helped guide decisions for emergency strengthening. The emergency work included installing an external post-tensioning system, which restored compression and load-carrying capacity to critical areas. All lanes were reopened to traffic on May 30, 2012.

- The second phase of repairs (2013-2015) included the full installation of a new post-tensioning system and bearing replacements. After the completion of the works, a reduced monitoring system remained in place to monitor bearing movements and detect any further opening of critical segment joints, providing continued assurance of the structure's safety.

- The strengthening work led to reduced maintenance demands [2] owing to newer technology. Further, the continued monitoring of the bearings would help the inspection and maintenance routines post-strengthening since it was shown that the effects of corrosion on them can be detected through data.

Comments on the added value of monitoring:

- Without instrumentation, the engineers would have had to rely on visual inspections.

    1. Without the monitoring data, it would not be possible to detect wire breaks in the deck and assess the loss of bearing capacity.

    2. While visual inspection might have revealed surface-level problems such as corrosion in bearings, the implications of the corrosion-induced restraint could not have been known in such an extent. The monitoring data has helped better and more informed visual inspections.

    3. The lack of awareness of the wire breakages could also reduce the bridge's overall lifetime and might have led to sudden loss of capacity with catastrophic consequences.

Cost-benefit considerations:

- The total cost of monitoring is not given and is not easy to obtain. However, the monitoring system detected wire breaks in the post-tensioning strands, which is a kind of damage that is both difficult to detect in visual inspections and also have significant consequences on the bearing capacity and remaining service life of the structure. Considering the importance of the bridge, it is deemed that for this particular case the benefits of monitoring outweighed the costs.

- A statement from the contractor on the strengthening works also claims significant improvements on the service life and its environmental impact. Phase 2 of the strengthening works, carried out by the contractor, was completed in 2015 and achieved a notable environmental benefit by saving 75,000 tons of carbon emissions. The project team states that "the project successfully extended the operational lifespan of the

Hammersmith Flyover by 70 years, with no requirement for major maintenance work during this period" [4]. This extension will significantly reduce long-term operational costs. Additionally, the strengthening has enhanced the flyover's capacity to manage modern traffic loads.

5.1.6. Recommendations and improvements

Useful take-aways:

- The increasing rate of suspected wire breaks, indicated by the acoustic emission data, guided investigators to specific areas that required further visual inspection. It appears that this sensor technology can be effective in detecting such specific damage and aid in inspection routines.
- Measuring displacements on bridges is in general a challenging task and not commonly preferred, but turned out very useful here, in a case where the movement was restrained due to degradation of the bearings.
- An important factor that had led to success in the case of the Hammersmith was the insight into the potential damages that were expected on the bridge and tailoring the monitoring efforts for these. Such an approach is more cost effective and result-oriented, especially for bridges reaching their end of life.

Challenges with monitoring:

- Strain measurements from the deck were insufficient for detecting small strain changes due to wire breaks, primarily because of noise from live traffic loads. Acoustic Emission system plays important role in identifying these breaks where traditional strain measurements fall short.
- Information on the potential weaknesses of the acoustic emission sensors was not found in the available sources on the Flyover. Although it appears as an effective tool for damage detection of post-tensioning strands, potential challenges with practical implementation are yet to be revealed.
- This project required extensive data analysis carried out by different parties. Analysis of such data requires expert engineering competence and knowledge on sensor technology. As understood from the reports, reaching data-driven conclusions on the structural deficiencies were not trivial.
- The data collected by SHM systems requires extensive post-processing and interpretation by structural engineers. Installing an SHM system alone does not automatically generate useful insights. Instead, raw data must be carefully filtered and analyzed to extract meaningful information. Engineers need to strategically decide which parameters to measure, where to place sensors, and how to convert the data into actionable insights. They must also ensure that the monitored effects are significant enough to be detected reliably, minimizing interference from noise caused by other factors.

5.2. STAVÅ BRIDGE, TRØNDELAG, NORWAY

5.2.1. Overview of the bridge and the monitoring project

About: Constructed in 1942 (See Figure 7)

Importance: Over many years the Stavå bridge served as an important connecting segment of the national-spanning highway E6. Importance is deemed very high [5].

Structural features:

- 103.4 m reinforced concrete bridge with a main span of 54 m.
- Longitudinal movement restrained at one of the abutments

Purpose and duration of the project:

The NPRA/SVV gave in 2019 SAP the task of equipping the Stavå bridge with sensors suitable for testing out SHM on full scale [6]. Two different systems were used at different times. The initial and simple system (system 1) was extended to a much more comprehensive (system 2) in 2019 after an extreme event that caused damage.

- The primary goal of the project is to conduct condition-monitoring of the bridge to identify potential structural damage and to explore SHM as a complementary tool to manual bridge inspections.
- The SHM system was operational from 2019 until the bridge was closed following an alarm in 2021.

Three main objectives of the monitoring efforts were identified [6]:

1. Damage detection /condition monitoring
2. The global behavior of the most prominent eigenmodes
3. Crack hot-spot identification
4. Redundancy of sensors and for backup and control

Figure 7: Left panel shows trailers on their way southbound on Stavå bridge. The right panel shows photo during construction of the interim bridge just east of the original Stavå concrete bridge. [Both photos by Kjetil Sandvik Sletten/Statens vegvesen].

5.2.2. Reasons for monitoring

- It was known that the bridge suffered from aging, and major cracks were detected in inspections (2016). An event in 2018 caused further cracks.

- The main reason for monitoring was to investigate the use of SHM as a complementary source of information to follow the bridge's structural status, in addition to the yearly inspections and the main inspections every 5th year.

5.2.3. Instrumentation and data acquisition

The core of the system was one centralized system acting as a gateway [6]. This central gateway was to communicate with distributed sensor groups over local Wi-Fi. The gateway was also equipped with a camera for capturing still images of passing traffic. The sensors and the local Wi-Fi-communications were powered by battery (High performance Li-$SOCl_2$) that required periodic replacement. Sensor installation was completed over the course of one week in December 2019 and the entire monitoring phase was planned to run for three years.

Due to the R&D nature of the project, the bridge was heavily equipped with sensors (Figure 8). Three-axis accelerometers were to observe the global behavior of the bridge, and four crack-width sensors (displacement gauges) were installed to monitor the detailed dynamics of existing cracks in the main beams. Four additional displacement gauges were mounted on the north and south side of the bridge deck to monitor the movement in relation to the abutments.

Types of sensors:

- 20 three-axis accelerometers sampling at 64 Hz
- 8 displacement gauges (position sensors) measuring at 128 Hz
- 1 temperature sensor sampling every 10 min
- Camera at position of gateway – photos every 2 seconds

Measurements:

- **20 three-axis accelerometers sampling at 64 Hz** – acceleration and vibration from abrupt changes during vehicle passages, as well as long-term development of static angles derived from the accelerometers.
- **8 displacement gauges (position sensors)** – crack width, movements of the abutments.
- **1 temperature sensor** – ambient temperature at site
- **Camera** at position of gateway – photos every 2 seconds
- **Ambient temperature** from MET Norway
- **Traffic load** from SVV

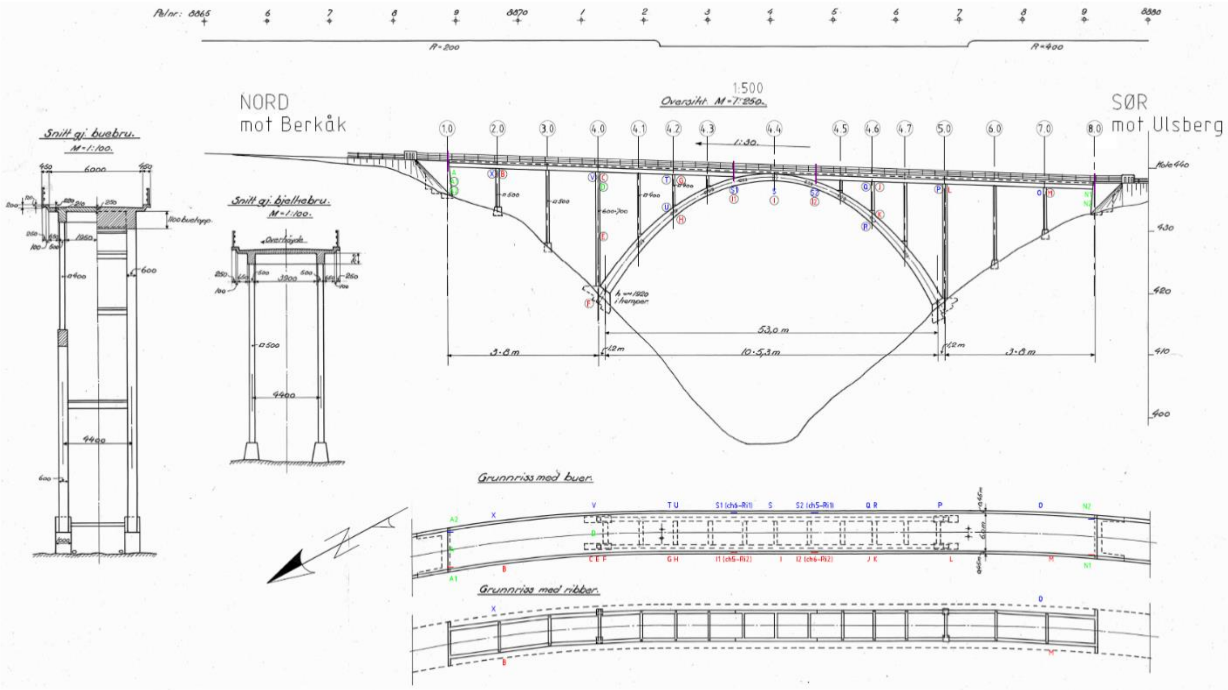


Figure 8: Overview of sensor setup after the 2019 upgrade (system 2). (drawing courtesy of Statens vegvesen)

Data collection and storage:

The sensors digitized the signals locally and data were sent over Wi-Fi to the central PC in the gateway (running Balena OS). This continuously received raw data and packed this into chunks that were pushed via the internet connection to the SAP cloud. For the R&D-phase it was planned that the data was to be stored on Amazon Web Services, AWS S3 [6].

Data processing and analysis:

The collected data were processed with the aim of creating a digital twin of the bridge for a better understanding of the structural response. The framework was hosted by the proprietary SAP-product "Predictive Engineering Insights", PEI. The framework rests heavily on deriving user-specific Key Performance Indicators, KPI's, describing the response of the structure.

The monitoring system comprised a total of 72 channels from the 20 accelerometers and an additional 8 channels from the displacement gauges. Using these measurements, secondary derived parameters, such as frequency content (via Fast Fourier Transform, FFT), were generated to analyze the bridge's overall energy and eigenfrequency response.

Apart from the raw data and the physically based derived quantities, two types of KPI's were addressed: Energy Response Indicator (ERI), representative of the apparent impulse energy, and Energy Characteristic Indicator (ECI), which corresponds to a normalized measure of frequency. The former is a measure of the energy content of the signal, where the latter is a measure of the frequency content. Both are calculated from the high frequency accelerometer signal (64Hz) that was low-pass filtered to 1 Hz resolution, as well as lower resolutions on minute / hourly / daily / weekly scales. For long time stability the apparent angle of the horizonal plan of the bridge was calculated over 5-minute intervals.

5.2.4. Project follow-up and decision-making

Project follow-up and damage detection:

The first anomaly was detected on November 3rd, 2018, where a series of vehicle crossings resulted in high amplitude signals in the acceleration data (in the order of 0.5g). It was confirmed later that the severe response was due to the NATO Trident Juncture exercise that took place at the time, where heavy military vehicles with equipment crossed the bridge. An emergency inspection was issued and 3 major cracks at the bridge girders were found. This was in addition to an existing crack that was noted in a regular inspection. Later, the metrics ERI and ECI were examined before and after the event as shown in Figure 9. Metrics of ECI and ERI in week 43 and 44. There was a dramatic change in the behavior [7] Figure 9. A change in behavior is apparent before and after the damaging event.

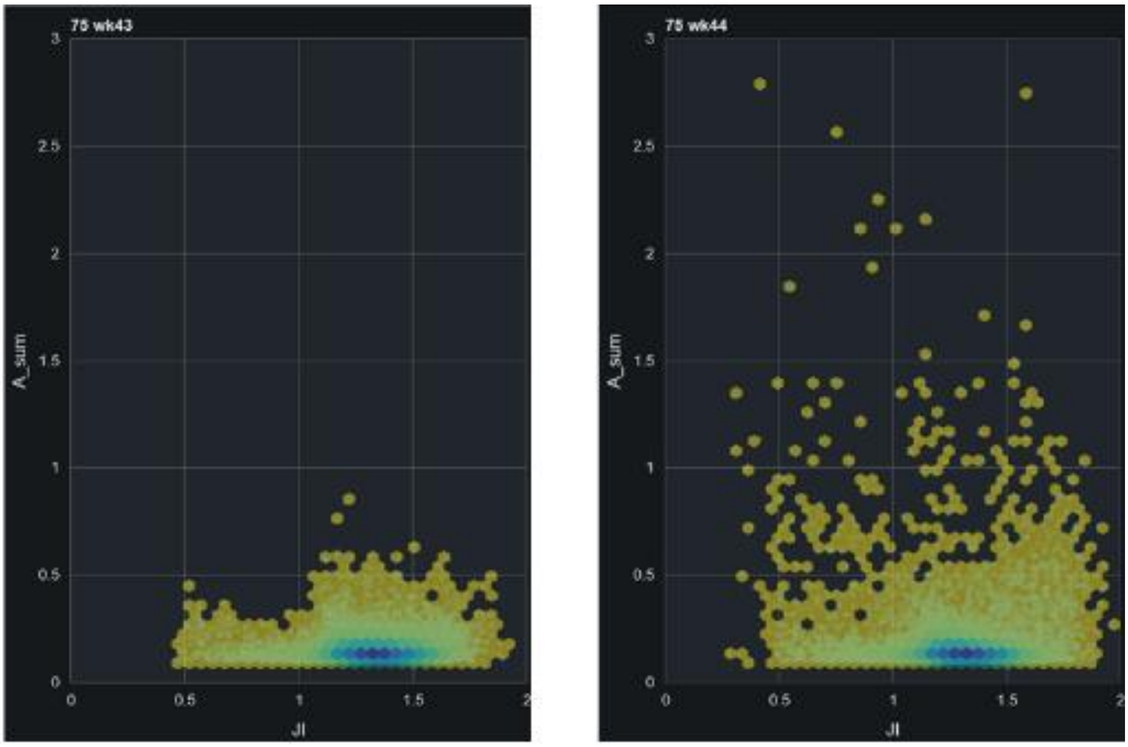


Figure 9. Metrics of ECI and ERI in week 43 and 44. There was a dramatic change in the behavior [7]. (courtesy of Arnulf Hagen)

The event of November 2018 caused concern on the safety of the bridge but also has shown that the damage could be identified using the SHM data. This led to a research project where a lot more comprehensive monitoring system has been implemented on the Stavå Bridge (as described above as system 2). Thresholds were set on the metric in a similar way as before (based on ERI metric). It is reported that the thresholds are exceeded every now and then due to heavy traffic or extreme weather. However, in April 2021, the alarms started to ring almost every hour (instead of about every 24 hours, as it did before). This indicated another novelty in the bridge. Visual inspections later found that the concrete below the bearing of the south abutment was lost (Figure 10). Such damage causes severe modification of the boundary conditions and causes peaks in the nearby acceleration signals due to the introduced flexibility.

Figure 10. Damaged support (left) and repaired support (right). [7]. (courtesy of Kjetil Sandvik Sletten/Statens vegvesen)

Decision-making:

The monitoring revealed important findings regarding the bridge, from both the accelerometer data as well as from the displacement gauges. At all instances of alarms, NPRA/SVV chose to partly/completely close off the bridge and reduce the maximal traffic loads or other actions reducing the probability for dangerous consequences from traffic passing the bridge. However, the decision-making process was not systematic and left mostly to subjective decisions. The data and the metrics helped guide decisions, but it seems that it was often hard to interpret the data and derive useful information.

When the alarms went off in the April incident, NPRA acted quickly. A responsible person traveled to the bridge and made a quick inspection. However, the damage shown in Figure 10 could only be found 3 days later. Analysis of the data helped locate the damage. After the damage was found, the traffic was restricted on the bridge (only one lane left open) until a temporary replacement bridge was built. The faulty bridge abutment was quickly repaired by a shorter steel-bridge segment, before the whole Stavå bridge was replaced in March 2022 with the longest temporary bridge in Norway spanning over in total 140 m, and a 90 m free span over the ravine. Now the intermittent solution awaits a permanent bridge as a part of the new E6.

The project was essentially a research project and was an early attempt to include SHM in bridge management. It is therefore natural that both the damage detection and decision-making processes were not very systematic. However, it is clear that the SHM system was essential in both detection of damage and in the decision-making process.

5.2.5. Outcome assessment

Summary of the tangible outcomes:

- The case of Stavå Bridge is unique. In two separate instances, significant damage was found on the bridge based on SHM data. Warnings were issued in both cases.
- This is also a rare case where vibration data were used to detect damage. This was achievable partly due to the severity of the damage and partly due to the successful implementation of the SHM.
- The relatively early decisions based on SHM data prevented further propagation of the damage.

Comments on the added value of monitoring:

- Without instrumentation, the engineers would have had to rely on visual inspections to detect the damage, which could have been too late given the severity of the issue. The existing damage might have propagated into much more significant structural failures, potentially leading to catastrophic consequences. It should be noted that after the SHM

system detected an anomaly in April, it took several days to confirm it with visual inspections, despite the severity of the damage.
- The detection of the strong response in April 2021-event eventually informed the decision for building of the new (intermittent) Stavå bridge and the upcoming replacement.

Cost-benefit considerations:

- The cost-benefit of the installation is not explicitly addressed, however, considering the severity of damage and the importance of the bridge and the potential life and economic loss, it is evident that the benefits outweigh the costs.
- There are, however, very positive cost-benefits in all the knowledge that was built under this monitoring effort [6].

5.2.6. Recommendations and improvements

Useful take-aways:

- The SHM implementation mostly based on accelerometers was able to detect damage based on changes in the metrics derived from acceleration signals.
- The metrics were useful in detecting changes; however, it was a challenge to identify thresholds for damage, and even more of a challenge to interpret the warning when a threshold was exceeded.

Challenges with monitoring [6]**:**

- The mounting of the sensors was, according to NPRA/SVV, a rather cumbersome affair even if it only took a week. A complicated scaffolding needed to be built and moved for each of the axes of the bridge where sensors were to be mounted [6].
- The project team used KPIs of their own devising, which were successful in identifying changes. However, the KPIs were difficult to interpret by a bridge engineer and for further decision making.
- One challenge was that the hardware was procured by NPRA from one company, the installation was executed by another company in accordance with installation descriptions iterated between NPRA/SAP and sensor provider. Regarding system integration there are vast fauna of different sensors and electronics products in use at NRPA/SVV. In order to streamline this there is a need for standardization, both from the scientific point of view but more importantly in terms of spare parts, dual use and overhaul of sensor systems.
- Some accelerometers needed changing batteries, and this proved not be an easy affair during wintertime. Since there are basically no sidewalks on the bridge and walking out to clear out packed snow from the snowbanks, turned out to be not only exhausting, but also very dangerous. This problem was even more pronounced for the displacement gauges which consumed battery charge rapidly and needed battery changes every 3-4 months. Relying on sensors with changeable batteries can be practical in short term projects as it eliminates cabling. However, it is obviously not optimal for long-term projects.

Recommendations:

- The project team claims that less than 1% of the data was worth storing at high resolution for future use. This 1% originates from investigating the data from the Stavå bridge with development over time, as well as specific vehicle passages.
- Some problems pointed out here (e.g. battery) would be solved by a wired sensor system. Today there are a few daisy-chain systems (with only one cable running through several

sensors), which are good enough to fulfil sensor fidelity, bandwidth and continuous power to the sensors and the network.

- If a wired system is chosen the placement of cable needs to be properly shielded and secured from mechanical damage, e.g. snowplows or damage from vibrational motions. The same holds true for the sensor nodes which needs at least a IP67 casing [6], if not even IP68. The choice of plastic boxes for instrument protection is standard today, but improvements in both choice of mounting location and robustness can be improved. The displacement sensors on the abutments may need a higher degree of IP-protection, as water and debris from the bridge joints came down onto the sensor node and made the node corrode and not work as intended. There are other non-mechanical devices offering techniques for measuring displacements that could be further investigated.
- For the R&D project phase only, a few sensors were set up to be part of the alerting scheme. In retrospective, SAP concludes that all sensors should be considered allowed to alert.
- From the perspective of the bridge owner, the responsibility for temporary loss of sensors should be included in the procurement together with the installation and the total cost including data storage over time should have been addressed early on.

5.3. VANERSBORG BRIDGE, VANERSBORG, SWEDEN

5.3.1. Overview of the bridge and the monitoring project

About: Constructed from 1914 to 1916 (see Figure 11).

Importance: A single-leaf bascule bridge carrying railway traffic over a canal.

Structural features:

- Riveted steel truss railway bridge (bascule design for allowing boat passage)
- The structural steel is classified as St37, with a yield stress of 240 MPa and an elastic modulus of 210 GPa

Purpose and duration of the project:

- Condition monitoring and damage detection of the aging bridge.
- Instrumented in 2021 to register the load effect and possible changes in structural behavior.

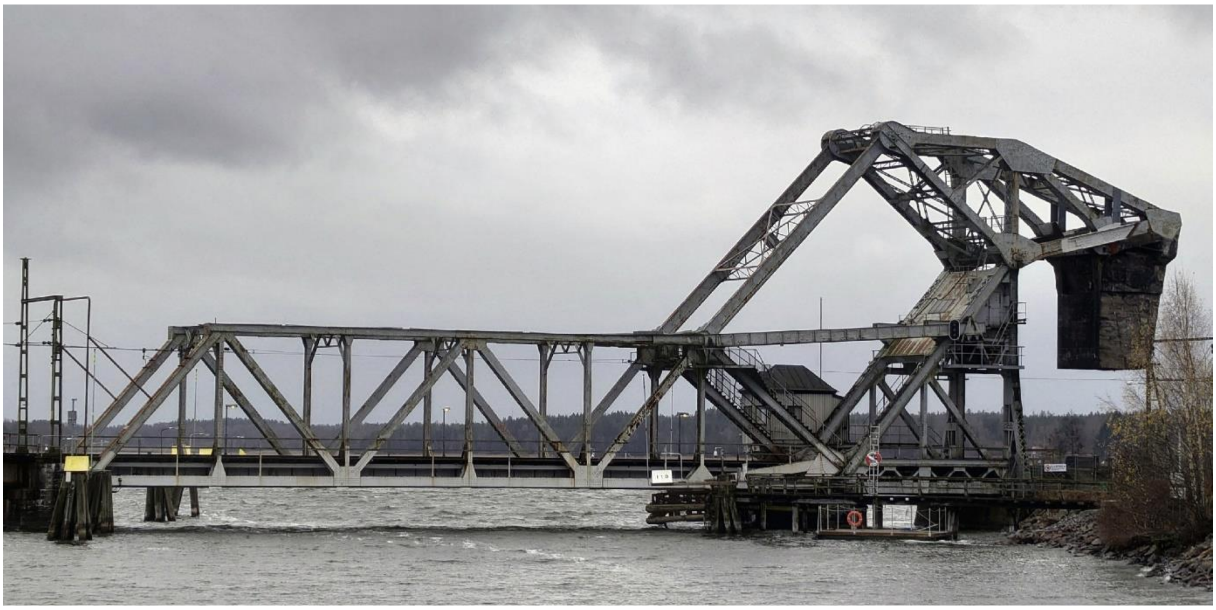


Figure 11: Vänersborg Bridge [8].

5.3.2. Reasons for monitoring

- **Deterioration:** Due to old age of the bridge, it was affected by severe corrosion, and cracks were found in the inspections.

- **Upcoming rehabilitation:** A large-scale reparation of the bridge was anticipated. It was decided to monitor the condition as the bridge was deemed vulnerable prior to rehabilitation.

5.3.3. Instrumentation and data acquisition

A monitoring system consisting of 5 accelerometers, 16 strain gauges, 1 inclinometer and 3 weather measurement sensors were installed on the bridge (Figure 12).

Types of sensors:

- 5 single-axis accelerometers
- 16 strain gauges
- 1 inclinometer

- Weather measurements

Measurements:

- **Accelerometers (PCB type 393A03):** 4 of the accelerometers measured vertical acceleration (A1, A2, A3 and A5). A4 measured horizontally when the bridge is closed. Note that the axes change with opening.
- **Strain gauges (HBM weldable 350 ohms, LS31HT-6/350VE):** measured axial strain at the outer edges of cross-sectional members.
- **Weather station:** measured wind direction, speed and air temperature
- **Inclinometer (Vigor Technology SST141):** measured the inclination of the girder in the open position.

Data collection and storage:

- A data acquisition system from HBM of type CX22B-W (assumed commercially available) is used to collect data locally at the site.
- The data were sampled at 200 Hz. Low pass filtered at 50 Hz. Weather data at 4 Hz.
- The data are sent to a cloud-based service (provided by IoTBridge AB, a company established by the researchers who monitored the bridge). This is a service that includes some processing. The service also includes storage in the cloud.

Data Processing and Analysis:

- Data processing is done in the cloud. (parsing, filtering, cleaning, storage in a database)
- Built on Open Geospatial Consortium (OGC) SensorThings [8].
- Anomaly is detected using machine learning algorithms.
- An alarm is issued in case of anomaly
- Fatigue calculation using strain gauges [8].
- Feature extraction and damage detection:
    - *Preproccesing:* The data are divided into "*events*" that are time series that are analyzed independently. Examples of these are train passings (for different train types), rest sequences or bridge openings.
    - *Feature extraction:* consists of extracting features of these time series (frequencies, cross-correlations, autoregressive model parameters, etc.)
    - *Detection of change*: Features of the same type of "events" are compared to one another. (based on Mahalanobis distance [8], takes into account multiple measurement points)

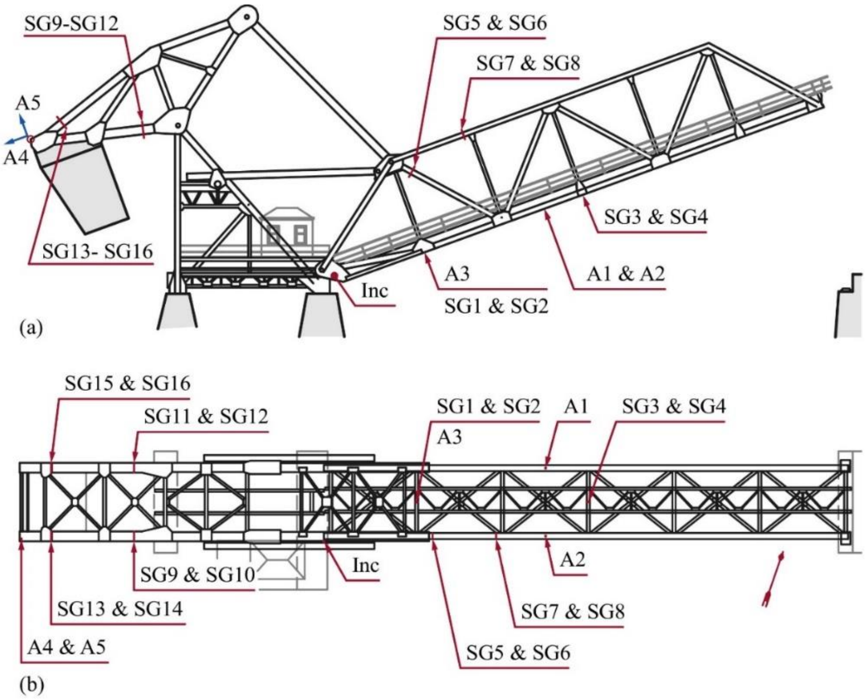


Figure 12: Overview of the measurement system: sensor placement [8].

5.3.4. Project follow-up and decision making

- A monitoring and analysis dashboard is implemented. This is thought to assist inspectors and bridge managers. The dashboard includes information about the monitoring system and the bridge itself, such as:
  - The health of sensors (if the sensor is working)
  - Number of train passages
  - Number of bridge openings
  - Timing of events
  - Analytical information for maintenance planning (fatigue damage is mentioned, possibly other information)
  - Detected changes
  - Environmental variability is mentioned (very pronounced). This requires at least a year of monitoring to capture all seasonality.

Damage and decision-making:

- The system gave an alarm indicating a change in measurement features.
- Details of decision-making are unclear following the alarm. But it is understood that the data were examined and the need for inspection was confirmed.
- An inspection is carried out following the alarm, and the visual inspection revealed a cracked member. From the available pictures, it appears that this damage could have easily been missed even if a regular inspection was carried out.
- As a final decision, the cracked member was strengthened, and the bridge was scheduled for replacement. Although this decision-making procedure could be done without a monitoring system solely based on the damage-revealing inspection, it is likely that a more informed decision is made considering the substantial data of strain/stress and remaining fatigue life of the bridge by the monitoring system.

Figure 13: Detected damage [8]. The damage is a fatigue crack that has occurred at the bottom flange (and part of the web) of the angle profile shown in the picture.

5.3.5. Outcome assessment

Summary of the tangible outcomes:

- The system detected actual damage on an operating bridge. This is a very rare event in the world of SHM.
- The damage is confirmed by visual inspection following the alarm. The inspection is more likely to be successful when informed by monitoring data.
- The finding has led to a decision for strengthening and finally replacement of the bridge.

Comments on the added value of monitoring:

- Without instrumentation, the engineers would have had to rely on visual inspections to detect damage and approximate load models for calculation of fatigue damage for maintenance. Further, the inspections would be done in a prescheduled manner.
    1. Without the monitoring data, in the best scenario, the crack would be detected in a regular visual inspection. By the time an inspection is made, it is likely that the crack grows or leads to more damage, even closure of the bridge.

    2. Monitoring data allowed also a more informed decision after damage is detected, as it aids in more accurate estimates of the fatigue damage.

Cost-benefit considerations:

- The monitoring system used at Vanersborg Bridge is rather minimalistic and therefore not very costly, in comparison with other expenses relating to condition assessment of such a bridge.
- In retrospect, and considering the detected damage, it is our assessment that the benefits of monitoring outweigh the costs in this specific case.

5.3.6. Recommendations and improvements

Useful take-aways:

- A simple system was enough to successfully detect damage that led to important decision making.
- Strain gauges were very useful for detection, where accelerometers could also detect damage with the correct detection approach.
- The fatigue damage estimation using strain data predicted a service life of about 100 years, which corresponds to the time the damage was detected.

Challenges with monitoring:

Several challenges are acknowledged by the authors:

- Sensor failures were experienced. The system was found robust to such failures in terms of false alarms.
- It is difficult to interpret the anomaly when a change is detected by the system or machine learning algorithms. It is therefore also difficult to base decisions on such warnings. The authors mention possible use of finite element models and additional sensors (such as cameras) for understanding the nature of the warnings better. Whether this would be useful or not is an open question.
- Discriminating environmental changes from the structural is crucial as such changes are typically higher in magnitude compared to changes in features due to small damages.

5.4. HELL BRIDGE, STJØRDAL, NORWAY

5.4.1. Overview of the bridge and the monitoring project

About: Constructed in 1902 (closed and replaced in 2016), located in Stjørdal, Norway. A span of the bridge was moved to an open laboratory and now serves as the "Hell Test Arena" used by NTNU for research on SHM and damage detection [10].

Importance: Railway bridge (connection to Værnes)

Structural features:

- Riveted steel truss bridge
- Railway bridge

Purpose and duration of the project:

- The bridge was planned to be replaced. Condition monitoring and damage detection on the old bridge for research purposes.
- Instrumented in 2016 for testing a measurement system for SHM research. After the discovery of a damage by the SHM system, the project evolved into a larger scale research project on damage detection using a span of the decommissioned bridge.

Figure 14: Hell (Stjørdalselva) Bridge [9].

5.4.2. Reasons for monitoring

- **Research on monitoring:** The project was a minor research project for health monitoring with focus on reducing modeling uncertainty in fatigue life estimation.

- **Upcoming replacement:** It appears that the motivation was not condition monitoring. But the aged bridge still is a good case study.

- **Hell Test Arena:** A span from the decommissioned bridge is now used as a research arena for projects on structural health monitoring and damage detection [10] [11] [9].

5.4.3. Instrumentation and data acquisition

A monitoring system consisting of 20 triaxial accelerometers (Figure 15), 93 strain gauges, and temperature sensors were installed on the bridge.

Types of sensors:

- 20 triaxial accelerometers
- 93 strain gauges
- Temperature sensors

Measurements:

- **Accelerometers:** were distributed along the main truss as shown in Figure 15.
- **Strain gauges:** measured axial strain/stress at steel members and connections.
- **Temperature:** was recorded on the steel to compensate for sensor drift.

Data collection and storage:

- Data logging was managed through the internet.
- Data were recorded locally and transferred to the servers at NTNU for central storage.
- Monitoring was done continuously but not everything is stored.

Data Processing and Analysis:

- Data processing was done manually by the researchers.
- No alert system or damage detection algorithm were used.

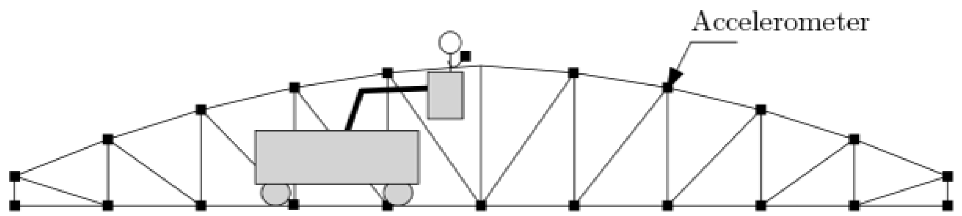


Figure 15: Schematic illustration of the placement of accelerometer sensors [12].(courtesy of Gunnstein T. Frøseth)

5.4.4. Project follow-up and decision making

- The project was closely monitored through data analysis by the researchers, with a primary focus on modeling uncertainty for estimating the remaining fatigue life, combined with axle load measurements.

Damage detection and decision-making:

- Initial data analysis revealed significant variations in stress levels among structurally similar members.
- Although stress levels were high, raising concerns about the structure's fatigue life, they did not pose an immediate risk to structural integrity.
- An emergency inspection was conducted, aided by monitoring data that quickly pinpointed the damage location (Figure 16).
- The inspection uncovered a crack at the connection between a cross-beam and a longitudinal beam, which had not been identified in previous inspections.
- The damage caused a doubling of stresses in the stringer (Figure 17). Such an increase in stress causes a disproportionate decrease in the fatigue life.
- Given that the bridge was already scheduled for replacement and no additional cracks were found, the bridge owner decided to proceed with the replacement as initially planned.

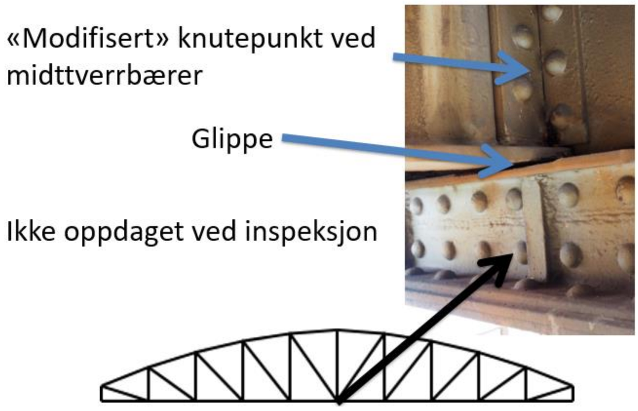


Figure 16: Detailed view of the damage [12]. (courtesy of Gunnstein T. Frøseth)

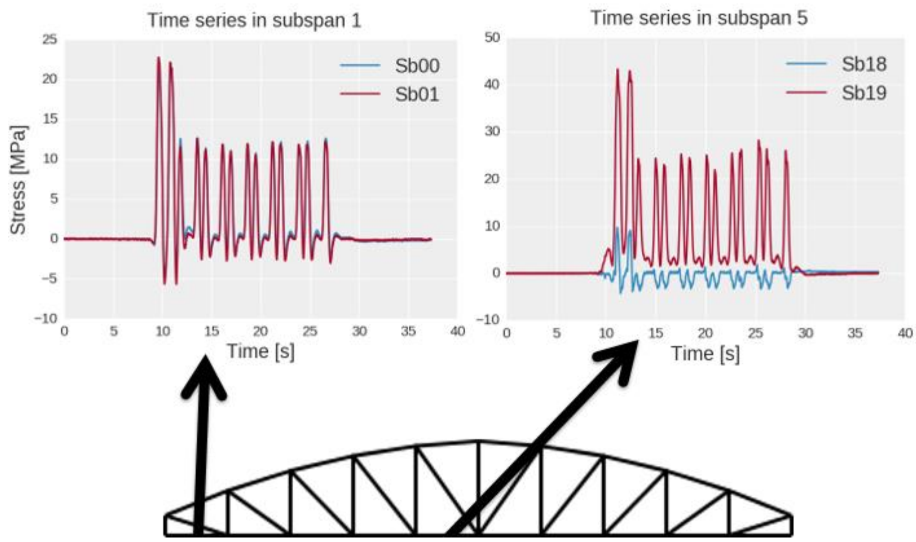


Figure 17: Stresses derived at different sub-spans of the bridge. Undamaged members have equal stress distribution on the stringers at each side of the bridge section (left). In the damaged sub-span, the damaged stringer does not carry load, where the stringer on the opposite side has increased stresses [12]. (courtesy of Gunnstein T. Frøseth)

5.4.5. Outcome assessment

Summary of the tangible outcomes:

- The system detected actual damage on an operating bridge, albeit not automatically. The nature of the discrepancy suggests that this kind of a damage would be detected by a state-of-the-art system with an alert.
- The damage was confirmed by visual inspection following the detection. The inspection revealed damage that was not discovered in regular inspections, showing the value of monitoring. The monitoring data also helped locate the damage.
- The finding has forced a decision. The decision was to carry on with the upcoming replacement as planned.

Comments on the added value of monitoring:

- The damage was not detected by regular inspections, meaning that the asset owner was not aware of the reduction in fatigue life. Although the outcome would probably not be different owing to the circumstances of the specific case, there was potential for propagation of damage.
    1. Monitoring data revealed a discrepancy that was not obtained through traditional inspection and informed the asset owner about a potentially hazardous situation.
    2. Monitoring data allowed also a more informed decision after damage is detected.

5.4.6. Recommendations and improvements

Useful take-aways:

- The monitoring system helped to successfully detect damage and informed decision making.
- Strain gauges were very effective in detecting the damage in this application.
- SHM system provided information that was overlooked in traditional inspection. Together with visual inspection, it provided better grounds for decision making.
- Fewer sensors could be used to detect the damage.

5.5. MUSMECI BRIDGE, POTENZA, ITALY

5.5.1. Overview of the bridge and the monitoring project

About: Constructed from 1971 to 1976, located in Potenza, Italy (see Figure 18)

Importance: It connects Potenza city center to Sicignano motorway, unique architecture, declared "monument of cultural interest" by the Italian government.

Structural features:

- Reinforced concrete bridge
- Bridge is composed of one membrane that is arch shaped
- Cast in-situ

Purpose and duration of the project:

- Condition monitoring
- Testing the prototype sensors
- Monitoring system implemented for 1 year

Figure 18: Musmeci Bridge [13].

5.5.2. Reasons for monitoring

- **Deterioration:** Some signs of aging were reported. Corrosion, exposure of reinforcement.

5.5.3. Instrumentation and data acquisition

Two identical optical fibers were installed along the arch over a length of 13 m (Figure 19. The cables are parallel to each other and differ only in their adhesive properties. This was done for research purposes (identifying potential differences caused by the used adhesive).

Types of sensors:

- Brillouin Fiber optic sensors (portable prototype)

Measurements:

- **Brillouin fiber optic sensors:** measure strain and/or temperature along an optic fiber by transmitting a pulsed laser light along the cable. The spatial resolution depends on the duration of the optical pulse signal. In this application, it was set to 1 m, meaning that an average strain over 1 m is obtained. It is also reported that a single measurement takes about 1 minute, meaning dynamic effects cannot be captured.

Figure 19: Instrumentation of optic fibers [14].

Data collection and storage:

- Data were collected by a dedicated data acquisition system at the site.
- A simple laptop was used to control the logging.

Data Processing and Analysis:

- A software (details not clear, it is likely provided by the supplier) was installed at the laptop. Signal processing was done by the software in a fully automatic manner.

5.5.4. Project follow-up and decision-making

- Signals were inspected visually. Compressive strain along the fiber over a length of 13 m was obtained with 1 m resolution.

Damage and decision-making:

- Analysis of sensor signals revealed an increase in the compressive strain at the position z ≈ 10.5 m of the fiber (shown in Figure 20).
- The measured strains were due to temperature changes.
- A crack was found at the location of the increased strain.
- We do not know if this led to a decision.

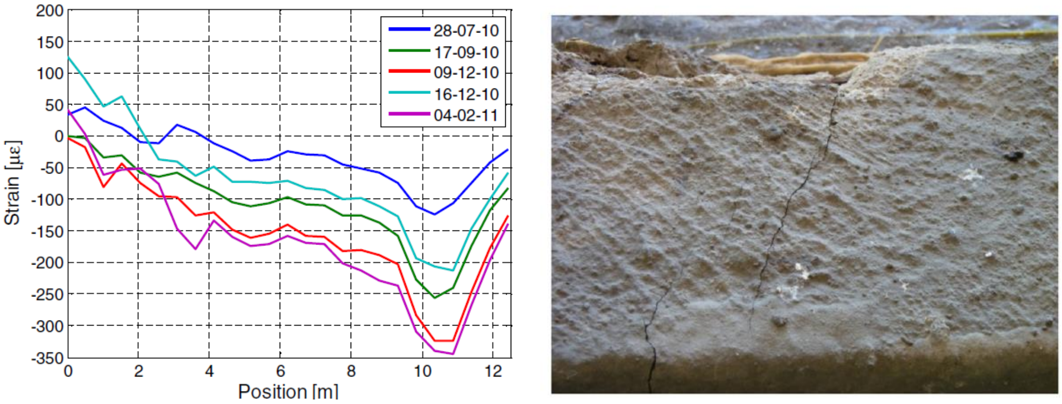


Figure 20: Detected damage [14]. The damage is successfully localized by the help of monitoring. Although a rather small crack, the discrepancy is apparent in the data (left), despite the low resolution (close to 0.5 m).

5.5.5. Outcome assessment

Summary of the tangible outcomes:

- The system detected existing damage on an operating bridge. The crack was already there when the sensors were installed. Although the system is not able to measure dynamic deformation caused by traffic, temperature-induced strains showed a discrepancy.
- The damage is confirmed visually. The sensors also managed to locate the damage with good accuracy.

5.5.6. Recommendations and improvements

Useful take-aways:

- The sensors proved very effective in detecting damage despite the simple setup.
- Continuous strain data is very useful, it is interpretable by any engineer and provides location of the discrepancy.
- Even though dynamic effects are missing from the data, and the crack already existing, the system was able to detect damage.

Challenges with monitoring:

Although no specific challenges were mentioned, some potential challenges can be pointed out:

- The spatial and temporal resolution of the data were rather low compared to other sensor technology. This could be a potential limitation in some cases.
- Dynamic effects are not captured.
- The sensors require continuous bond with the structure along the line of measurement. This might be difficult to obtain in certain situations.

5.6. THE FIRST BOSPHORUS BRIDGE, ISTANBUL, TURKIYE

5.6.1. Overview of the bridge and the monitoring project

About: Constructed in 1973 (see Figure 21)

Importance: The first suspension bridge to span the Bosphorus, connecting the European and Asian coasts

Structural features:

- 1074-meter-long steel suspension bridge with eight lanes
- Originally, it was designed to be suspended by inclined hangers (Figure 21a) [15].

Purpose and duration of the project:

- Quickly reporting a bridge's operational condition immediately following extreme events.
- Monitoring the bridge's structural condition by tracking parameters such as fatigue, deformation, and stress variation.
- Verifying the bridge's geometry and performance in response to future extreme events. The extreme events considered in the Structural Health Monitoring (SHM) system design include:
    - ➢ (1) severe earthquakes, (2) strong winds and typhoons, (3) extreme traffic conditions, such as heavy truck loading, (4) human-induced loading, such as marathons, and (5) extreme thermal loading.
- The SHM system has been in operation since September 2008.

(a)

(b)

Figure 21: The bridge (a) with inclined hanger [16] (b) with vertical hanger after the hanger replacement operation (the original image is resized) [17].

5.6.2. Reasons for monitoring

The primary reason for monitoring is to identify critical structural responses and determine whether they exceed predefined threshold values for each bridge component. When a threshold is exceeded, the system generates an alert as demonstrated in Figure 22, gathers and processes the relevant data, and produces a preliminary report for the bridge authority. The system tracks anomalies and triggers alerts, helping to manage the bridge’s operation.

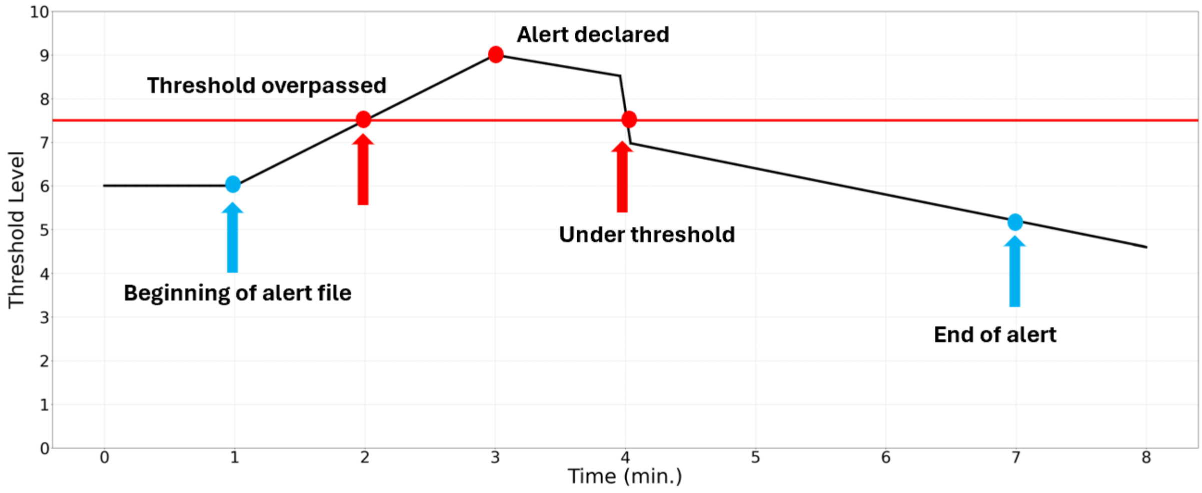


Figure 22: An illustrative example generated to represent the data recorded before and after an alert on a channel. For the original figure, see [18].

5.6.3. Instrumentation and data acquisition

The first Structural Health Monitoring (SHM) system for the bridge was implemented in 1993. To ensure continuous operation and improved monitoring, the authorities at the General Directorate of Highways (KGM) decided to enhance the existing SHM system in 2008. The current SHM system shown in Figure 23 uses a total of 168 sensors, using 258 channels as summarized in Table 2, are strategically positioned at key locations on the bridge, considering its overall structural characteristics [15]. The bridge has the same sensor configuration on both sides of the elevation. Therefore, the locations of the sensors are demonstrated schematically in Figure 23 only for the European side.

Types of sensors:

- Accelerometers, tiltmeters, force transducers, strain gauges, laser displacement sensors, global positioning system (GPS) units, thermocouples, and weather stations

Measurements:

- Accelerations, inclinations indicating changes in the angle of structural elements, forces in the cables, strain (deformation), displacements, the precise position of points on the bridge in three dimensions via GPS, temperature changes in structural components, and environmental data such as temperature, humidity, wind speed etc.

Data collection and storage:

- The data acquisition system includes site supervisor software, backup computers, and hardware. The data from each sensor is acquired and stored on the backup computer. The site supervisor, located in KGM's monitoring facility, gathers live data from a backup computer on the bridge.

Data processing and analysis:

- Data retrieved from the backup computer is processed, displayed, and analyzed through SHM software. This includes signal filtering, resampling, and generating automatic reports to monitor bridge performance and detect threshold exceedances during dynamic events.

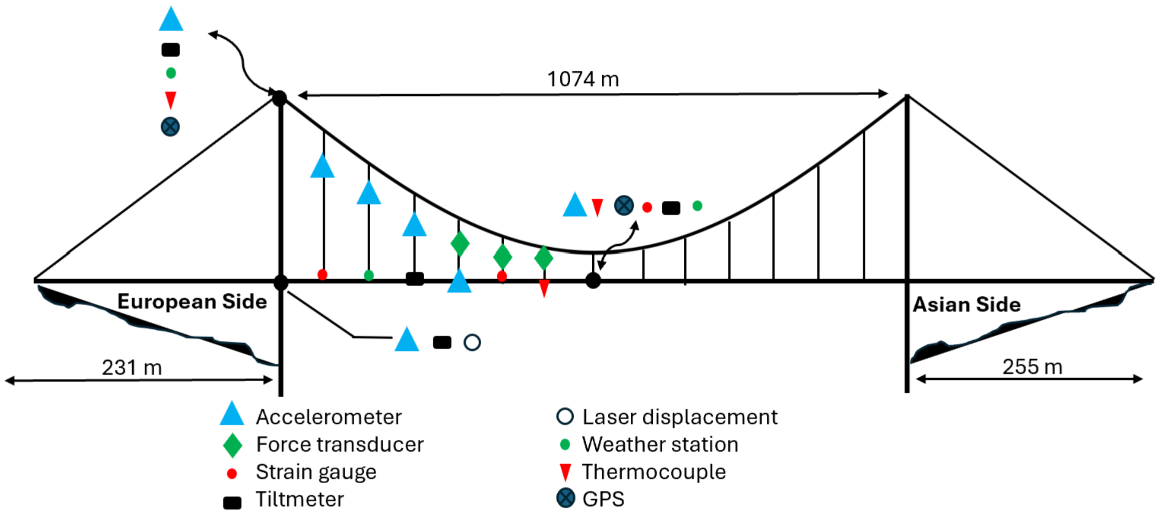


Figure 23: An illustrative example generated to represent sensor arrangement of the SHM system of the First Bosphorus Bridge characteristics. For the original figure, see [15].

Table 2: Types, features, and quantity of the sensors of SHM system of the First Bosphorus Bridge [15].

Sensor type	**Quantity**	**Features**
Accelerometer	19	Measurement range: ±2.00 g, Sensitivity (mV/g):2000, -3 dB cut off frequency: 300 Hz.
Force transducer	12	Measurement range: ±1.50 mm, Repeatability / Linearity: 0.30 × 10^{-3} mm/m, Operating temperature: -10 to +80° C.
Strain gauge	70	Resistance tolerance (%): ±0.30, Operating temperature: -70 to 200° C for static, -200 to +200° C for dynamic.
Tiltmeter	15	Measurement range: ±14.50, Resolution: 1 Arc second, -3 dB cut off frequency: 5 Hz.
Laser displacement	8	Measurement range (mm): 200- 2000, Resolution: 1-3 mm, max-Measuring frequency: 10 Hz, Operating temperature: -20 to 70° C.
Weather station	6	Range of wind speed: 0-130 mph, Threshold sensitivity: 2.40 mph, Operating temperature: -50 to +50° C.
J type thermocouple	33	Error limits (%): ±10° C
GPS	5	Precision (rms): 0.2 mm, Humidity: up to 95%, Sampling rate: 1 Hz, Operating temperature: -40 to +65° C.
TOTAL	168	

5.6.4. Project follow-up and decision making

The First Bosphorus Bridge endured a storm that occurred on 18th April 2012. This was the first extreme event experienced and studied by several researchers [19, 20, 21]. They examined and compared the results with those obtained from normal weather conditions.

- The results revealed that the bridge was excited in the transverse direction, and the period of the 1st effective mode of the bridge and corresponding amplitude in the transverse direction is noticeably affected as its first fundamental vibration frequency decreased during the storm.
- It was also observed that one hanger in each pair was bearing more tensile force than its counterpart.

Decision-making:

- Based on the data gathered after this extreme wind event, authorities decided to replace the inclined hangers with vertical ones in 2015 due to their insufficient force capacity.
- After the hanger replacement, the SHM system showed that the new hanger configuration effectively reduced normal tensile forces along the deck [22].

5.6.5. Outcome assessment

KGM has implemented advanced applications on bridges to define performance criteria, drawing on lessons learned from past extreme events. Recently, KGM established a state-of-the-art SHM center for all long-span bridges in Turkey, integrating these systems with an early warning system for seismic and other dynamic events.

Summary of the tangible outcomes:

- The implementation of the SHM system on the First Bosphorus Bridge proved critical in optimizing both decision-making and long-term maintenance strategies taken after the storm event.

- On 17th September 2010, during the Intercontinental Istanbul Marathon, the SHM system detected visible vibrations caused by foot loading, yet the bridge remained structurally safe. Although there was momentary concern among the runners, authorities quickly informed the media based on real-time SHM data, which was later validated through field observations.

Comments on the added value of monitoring:

- Without instrumentation, the engineers would have had to rely on visual inspections.
    1. Without the monitoring data, it would not have been possible to detect a reduction in the natural frequency of the bridge during the storm, which could indicate structural damage. Additionally, it would have been difficult to identify that one cable was exposed to significantly higher tensile forces compared to its counterpart, which could have dramatically reduced the fatigue life of this structural element.

    2. Promptly informing the public that the bridge remained structurally safe after the Istanbul marathon event demonstrated how the SHM system enabled rapid analysis without disrupting traffic. This highlighted its critical role in ensuring both the functionality and safety of the bridge in a densely populated region like Istanbul.

Cost-benefit considerations:

- While the total cost of monitoring is difficult to determine, the SHM system was instrumental in the decision-making process for replacing the hangers, changing their configuration from inclined to vertical. Thanks to the SHM system, this radical adjustment

in structural configuration was timely, preventing potential long-term structural deficits that could have incurred substantial costs to maintain integrity.
- Following extreme events, monitoring the structural condition immediately and without traffic interruptions contributes significantly to cost-benefit considerations.

5.6.6. Recommendation and improvements

Useful take-aways:

- The SHM systems enable timely and informed decision-making, especially in response to extreme events, optimizing long-term maintenance strategies.
- Continuous monitoring helps identify structural issues, such as shifts in natural frequency and cable tension, that visual inspections alone might miss, supporting proactive maintenance.
- Cost-saving benefits include facilitating timely structural adjustments, such as hanger configuration changes, which prevent more costly, long-term repairs.
- Real-time monitoring data provides critical reassurance to the public, as demonstrated during the Istanbul Marathon, ensuring safety without disrupting traffic.

Challenges with monitoring:

- No specific challenges related to SHM monitoring of the bridge were mentioned in the referenced resources.

5.7. THE CLEDDAU BRIDGE, PEMBROKESHIRE, WALES

5.7.1. Overview of the bridge and the monitoring project

About: Constructed in 1975 (see Figure 24).

Importance: It connects Pembroke Dock at the north end and Neyland at the south, crossing the estuary of the River Cleddau.

Structural features:

- An 820-meter steel box girder road bridge with 7 spans.
- The single-carriageway bridge is elevated 37 meters above the maximum high tide water level.

Purpose and duration of the project:

- After nearly forty years in operation, the bearings were nearing the end of their service life. Monitoring the bridge was aimed at detecting any adverse behavior in the bearings.
- The SHM system was initiated in October 2011.

Figure 24: The Cleddau bridge [3]. (Courtesy: James Brownjohn & Pembrokeshire County Council)

5.7.2. Reasons for monitoring

- **Corrosion issues:** The bearings were susceptible to corrosion due to water accumulation during wet and cold seasons. Inspections revealed corrosion on both a bearing and its bearing plate [23].

- **Roller bearing performance:** The primary concern was whether deterioration in the roller bearings was causing a restraint against expansion. Corrosion in these bearings could lead to locking and exposure to excessive forces [23].

5.7.3. Instrumentation and data acquisition

The monitoring system consists of various sensors designed to measure both temperature and displacement, as demonstrated in Figure 25.

Types of sensors:

- Twelve one-wire digital temperature sensors inside the box girder, three of them placed on each face of the girder.
- Two linear potentiometers in the center of both the inner and outer faces of each bearing, one string-pull potentiometer 500 mm from the outer end of each bearing.

Measurements:

- Recording temperatures every minute, structural displacements, longitudinal movements at both ends of each roller bearing, measuring the gap between the suspended span and the northern section of the bridge. Bearing and gap displacements are collected at one-second intervals.

Data collection and storage:

- There is no information provided on how the data is collected and stored in the referenced resources.

Data processing and analysis:

- The engineers manually post-processed the data, focusing on time histories of temperature measurements. This analysis revealed that diurnal variations in ambient conditions can create complex temperature distributions across the bridge. Specifically, transverse temperature gradients lead to plan bending, which induces twisting at the bearings. The twist magnitude was calculated by measuring the difference between displacement readings at the inner and outer ends of the bearings [23].
- When examining bearing lock, the displacement data showed that movements occur incrementally, with friction playing a significant role. Bearings were observed to briefly lock and then release, particularly during rapid temperature fluctuations [23], as shown in Figure 26.

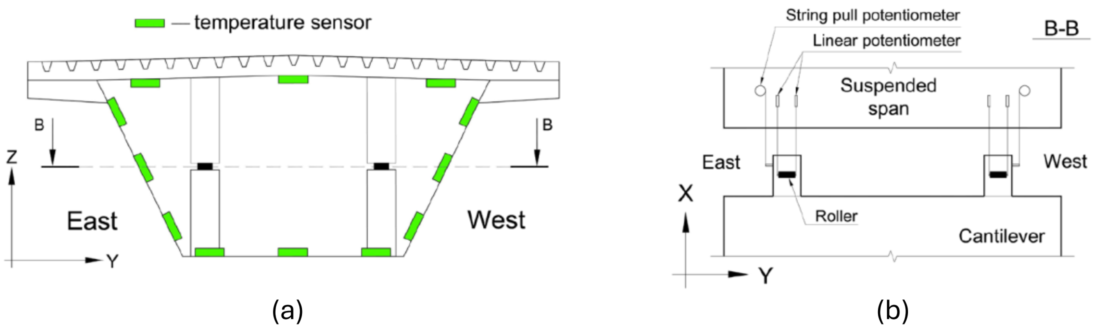


Figure 25: The location of (a) one-wire digital temperature sensors (b) displacement sensors [3]. (Courtesy: James Brownjohn)

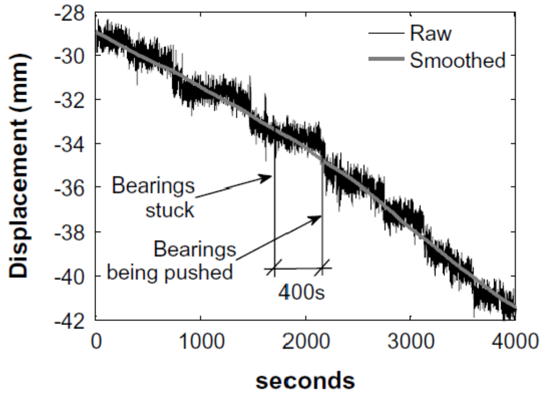


Figure 26: Measurements over a one-hour period showing bearing locking and release [3]. (Courtesy: James Brownjohn)

5.7.4. Project follow-up and decision-making

The SHM system revealed significant issues with the bearings of the bridge. The system provided valuable insights into the bearing movements under both operational and environmental loadings, particularly the impact of thermal effects on the bearing's performance.

- It revealed that thermal gradients, especially across the box girder, induced planar bending and caused the bearings to lock and experience excessive forces. These forces accelerated wear, corrosion, and eventual damage to the roller bearings. This included visible wear on pinions and racks, previously observed during visual inspections.

The observed temperature distributions significantly differed from those recommended in design codes (BS EN 1991-5: 2003) [3].

Decision-making:

- As a result of the SHM findings, a decision was made to replace the bearings in May 2024.

5.7.5. Outcome assessment

Summary of the tangible outcomes:

- The SHM system played a key role in guiding the decision to replace the roller bearings on the Cleddau Bridge.
- The SHM system continued to monitor the bridge, ensuring the newly installed bearings could accommodate the range of movements observed during the monitoring phase [23].

Comments on the added value of monitoring:

- Without the SHM instrumentation, engineers would have been limited to visual inspections, making it impossible to detect bearing locking and to quantify the movement range that the new bearings must accommodate under rapid temperature fluctuations.

Cost-benefit considerations:

- While the total cost of monitoring is not specified and challenging to determine, the monitoring system revealed critical issues with the bearings, enabling proactive maintenance and preventing potentially costly failures or emergency repairs. This early intervention likely resulted in substantial long-term cost savings by extending the lifespan of bridge components and reducing unplanned downtime.

5.7.6. Recommendations and improvements

- Transverse temperature distributions across box girders play a significant role in determining bearing movements.
- The SHM data revealed that the temperature gradients specified in the Eurocodes did not accurately reflect the actual thermal effects experienced by the Cleddau Bridge. This finding suggests that future designs for similar structures should incorporate more detailed temperature gradient modeling beyond the standard provisions in current codes [23].

5.8. THE ØRESUND BRIDGE, MALMØ, SWEDEN

5.8.1. Overview of the bridge and the monitoring project

About: Constructed in 1999 (see Figure 27)

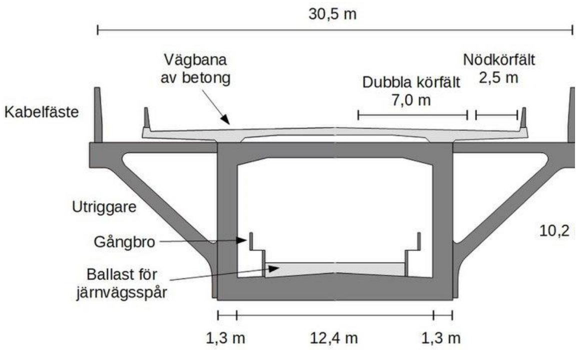
Importance: Sweden and Denmark are linked by the Øresund fixed connection, which includes an 8 km bridge and a 4 km tunnel, connected by a 4 km artificial island.

Structural features:

- 491 -meter-long cable-stayed bridge with the two H-shaped towers
- Supported by ten pairs of cables on each side.
- A distinctive two-level design with a four-lane highway on the top level and a two-track railway on the lower level.

Purpose and duration of the project:

- The primary goal of the project is to address the bridge owner's concerns about the oscillations of the stay cables under high wind conditions, as well as the deformation of the bridge caused by passing trains or heavy trucks.
- The SHM system has been in place since 2000; however, due to malfunctions in the old system, it was recently replaced with a new SHM system.



(a) (b)

Figure 27: (a) Cable-stayed part of the Øresund Bridge (the original image is resized) [24]. (b) Cross section of the cable-stayed bridge spans [25].

5.8.2. Reasons for monitoring

The primary reason for monitoring was to detect critical structural responses, particularly those induced by wind- and ice-related galloping.

5.8.3. Instrumentation and data acquisition

Øresund Bridge monitoring system used 85 dynamic channels with a variety of sensors to collect both dynamic and static data.

Types of sensors:

- 22 triaxial accelerometers, strain gauges, temperature sensors, and weather stations.

Measurements:

- Cable vibrations (acceleration),
- strain to measure torsion caused by wind and traffic,
- wind speed, direction, humidity, and temperature.

Data collection and storage:

- Data acquisition was managed by the CR-4 central recorder, which handled both dynamic and static channels. The system recorded dynamic data at a sample rate of 100 Hz from accelerometers and strain gauges, while static data, including long-term temperature and weather information, was used for analysis.

Data processing and analysis:

- The CR-4 system allowed remote data retrieval and processing through a combination of SEISLOG software for data acquisition, CENTRAL for remote control, and CMS for managing static data and alarms if any of the monitored parameters was out of its allowed range [26].

5.8.4. Project follow-up and decision making

- Vibration monitoring, along with weather data, confirmed that the cables were experiencing vibration due to ice and wind-induced galloping.

Decision-making:

- The combined vibration and strain monitoring of the cable-supporting outriggers provided crucial information, leading to the decision to retrofit the outriggers, as the measurements revealed that cable vibrations had significantly shortened their fatigue lifespan [27, 28].

5.8.5. Outcome assessment

Summary of the tangible outcomes:

- The retrofitting decision was a direct result of the insights gained from the continuous monitoring system, which allowed for timely interventions to maintain the structural integrity of the bridge. It highlights the practical value of the monitoring system in extending the bridge's operational lifespan [27, 28].

Comments on the added value of monitoring:

- The continuous monitoring also highlighted how Operational Modal Analysis of the dynamic data provides valuable insights into the bridge's condition. By measuring and analyzing cable vibrations, the system effectively monitors cable tension, while the vibrations of the deck and tower provide key information for assessing the health of these structural components [26].

Cost-benefit considerations:

- Although specific monitoring costs are not detailed, the SHM system effectively identified and addressed critical fatigue issues in the outriggers. By enabling timely retrofitting and extending component lifespans, we could say that the system generated clear maintenance cost savings by preventing costly future failures.

5.8.6. Recommendations and improvements

In addition to the information provided [27, 28], here we summarize useful insights and challenges regarding the current SHM application at the Øresund Bridge, based on input from Davor Peric, Facility Data Coordinator at the Øresund Bridge.

Useful take-aways:

- Mr. Peric highlighted that the primary benefit of monitoring is identifying trends early, enabling timely interventions to minimize consequential damage. For instance, in the stay cable system, monitoring helps detect when a damper is losing effectiveness, allowing for its replacement before complete failure. Without SHM, damper failure would only be identified during physical inspections or when the stay cable starts oscillating. Early replacement is usually a minor intervention, while failure can lead to increased wear on the stay cable, shortening its lifespan and complicating repairs.
- They also work on several inventories with threshold values. They aim to create a system where exceedances in the threshold values automatically will generate work orders for the maintenance provider. For example, motion sensors on bridge bearings are utilized to analyze movements over a year. Combined with physical inspection data, this will help assess wear and estimate the lifespan of components like wear parts.

Challenges with monitoring:

- Mr. Peric mentioned the transition from the old monitoring system to the current Mageba monitoring system and the challenges associated with environmental factors such as weather and wind. For instance, laser sensors have produced inaccurate data due to condensation. Proper sensor placement is critical, as snow, ice, and strong winds can impact monitoring reliability. Ensuring the monitoring system withstands extreme weather is essential since such conditions are when structural components are most likely to reach critical limits.

5.9. THE Z24 BRIDGE, CANTON BERN, SWITZERLAND

5.9.1. Overview of the bridge and the monitoring project

About: Constructed in 1963 (see Figure 28)

Importance: A highway overpass for the A1, connecting Bern and Zurich.

Structural features:

- 60-meter-long pre-stressed concrete bridge with 3 spans

Purpose and duration of the project:

- Before its planned demolition, the Z24 Bridge was extensively studied as a test case for Structural Health Monitoring (SHM) research, becoming one of the most analyzed bridges in SHM history.
- The SHM system was in operation from November 11, 1997, to September 10, 1998.

Figure 28: The Z24 bridge [29].

5.9.2. Reasons for monitoring

- The primary purpose of monitoring is to assess the effectiveness of Structural Health Monitoring methods in detecting, locating, and quantifying damage. This campaign seeks to deepen our understanding of how environmental factors influence system responses.
- Within the SIMCES project, a series of progressive damage tests were conducted. These included pier settlement, concrete spalling, simulated landslides, cutting of concrete hinges, anchor head failures, and tendon ruptures [30].

5.9.3. Instrumentation and data acquisition

The monitoring system utilizes a total of 49 sensors to gather both environmental and vibration data. The locations of the accelerometers and temperature sensors are shown in Figure 29.

Types of sensors:

- The system includes 16 accelerometers, 6 soil temperature sensors, 24 bridge temperature sensors (distributed across 3 sections), and 1 air temperature sensor.

Measurements:

- The monitoring system records various parameters, including accelerations, air temperature, humidity, rainfall, wind speed, wind direction, bridge expansion, soil temperatures at boundary locations, and concrete temperatures within the bridge structure [31].

Data collection and storage:

- The Environmental Monitoring System (EMS) collects data on an hourly basis, measuring environmental parameters both before and after vibration measurements.
- Acceleration time histories are recorded in 8 segments, each lasting a total of 11 minutes, with a sampling frequency of 100 Hz. Time signals were recorded hourly over a span of nine months. The total data collected (6 GB) was stored on 10 CD-ROMs and required further processing.

Data processing and analysis:

- Researchers worldwide post-processed the data and applied a variety of analytical methods. These analyses utilized both data-driven approaches [31] and modal-related parameters [32], establishing a strong foundation for future SHM applications in civil engineering.

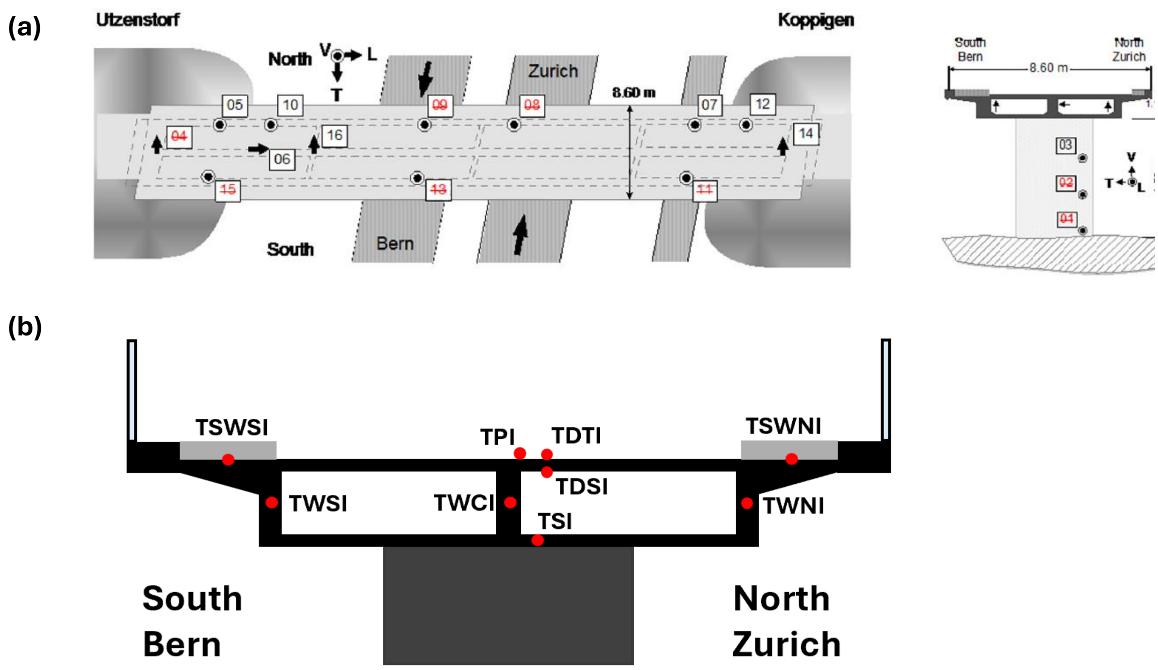


Figure 29: (a) The position and direction of the accelerometers [29] (b) an illustrative example generated to represent the position of temperature sensors. For the original figure, see [33].

5.9.4. Project follow-up and decision-making

The Z24 Bridge became a landmark in SHM research due to the comprehensive dataset collected during the project, which contributed significantly to the advancement of SHM technologies and methodologies. The research focused on several key areas, contributing to better decision-making in maintaining and managing civil structures:

- Long-term SHM: The project involved continuous monitoring of the bridge over an extended period to detect structural changes or potential damage. This included monitoring environmental factors such as temperature, humidity, and varying external loads, which affect the long-term health and stability of the structure.
- Validation of SHM techniques: The Z24 Bridge served as a testbed for validating a variety of SHM methods. Techniques such as vibration-based monitoring, sensor technology, and advanced damage detection algorithms were tested under real-world conditions to assess their practical application in civil engineering structures.

Decision-making:

- Since this monitoring campaign was designed as a test case for Structural Health Monitoring research prior to the demolition of the structure, no decisions were made based on the findings.

5.9.5. Outcome assessment

Summary of the tangible outcomes:

- The SHM methods performed well in detecting artificially induced damage, including progressive degradation like pier settlement.
- The bridge's dynamic behavior was well documented during both normal operational conditions and the artificial damage scenarios, making the system reliable for long-term monitoring and damage detection under varying conditions.
- Various machine learning models, including deep learning techniques, achieved over 90% accuracy in classifying different damage states during the PDT. These results confirm that SHM can be highly effective for real-time structural health assessment in bridges [34].

Cost-benefit considerations:

- The reviewed studies focused on evaluating the effectiveness of Structural Health Monitoring (SHM) methods in detecting, locating, and quantifying damage. However, they do not provide information on the cost-benefit analyses of SHM applications

5.9.6. Recommendation and improvements

Useful take-aways:

- The Z24 bridge case study suggests that future SHM systems can benefit from more advanced data-driven methods, such as edge computing, to reduce latency and improve real-time monitoring efficiency. This approach could also make SHM systems more scalable and deployable across different infrastructures without relying on cloud computing [34].

Challenges with monitoring:

- The system faced challenges in filtering out environmental noise, particularly the influence of temperature on modal parameters and pointed out the importance of using advanced black-box models and statistical methods like Gaussian Mixture Models (GMM) to improve the accuracy of damage detection under varying environmental conditions [32].
- The success of the monitoring system was also influenced by the placement of sensors. For future projects, it was recommended to carefully consider sensor locations to capture the most critical data points, avoiding placement in nodal points of mode shapes, where minimal vibrations are detected [31].

5.10. THE SECOND BOSPHOROUS BRIDGE, ISTANBUL, TURKEY

5.10.1. Overview of the bridge and the monitoring project

About: Constructed in 1988 (see Figure 30)

Importance: It connects the European and Asian coasts. It is worth noting that this bridge endures significant heavy traffic loads, as it is the only route on the TEM (Trans-European Motorway) permitted for trucks and other heavy vehicles [35].

Structural features:

- 1090-meter-long steel suspension bridge with eight lanes.

Purpose and duration of the project:

- Rapidly reporting the bridge's operational condition immediately after extreme events.
- Monitoring the bridge's structural condition by tracking parameters such as fatigue, deformation, and stress variation.
- Verifying the bridge's geometry and performance in response to future extreme events.
- The SHM system has been in operation since September 2001.

Figure 30: The Second Bosphorus bridge [36].

5.10.2. Reasons for monitoring

Similar to the First Bosphorus Bridge, the primary reason for monitoring is to identify critical structural responses and assess whether they exceed predefined thresholds for each bridge component. By tracking anomalies and triggering alerts, the system assists in managing the bridge's operation effectively.

5.10.3. Instrumentation and data acquisition

The SHM system, shown in Figure 31, consists of 12 accelerometers, four displacement meters, two seismometers, two GPS, one weather station, and one thermometer [35]. A total of 21 sensors is detailed in

Table 3.

Types of sensors:

- Accelerometers, seismometers, displacement meter, global positioning system (GPS) units.

Measurements:

- Accelerations, recording the motion of the ground during an earthquake, the precise position of points on the bridge in three dimensions via GPS, temperature changes in structural components, and environmental data such as temperature, wind speed etc.

Data collection and storage:

- The procedure of data collection and storage is similar to the First Bosphorus Bridge as mentioned earlier.

Data processing and analysis:

- The procedure of data processing and analysis is similar to the First Bosphorus Bridge as mentioned earlier.

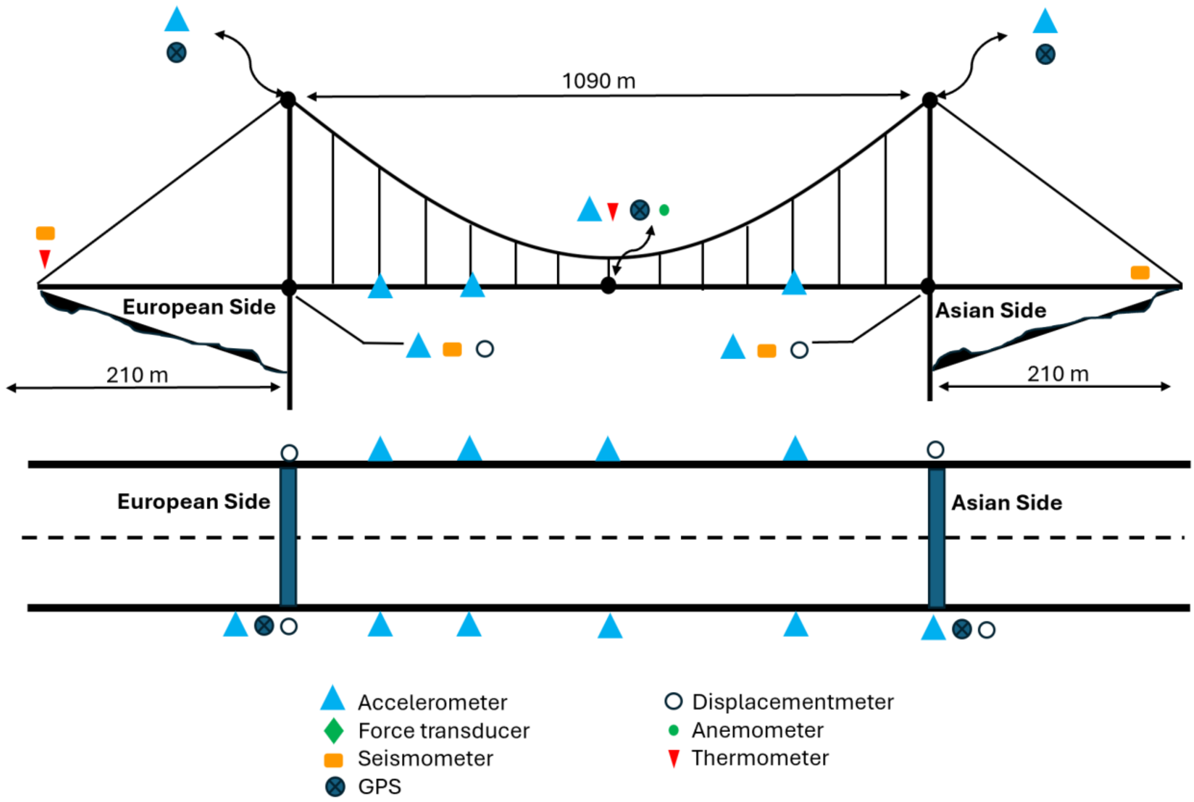


Figure 31: An illustrative example generated to represent sensor arrangement of the SHM system of the Second Bosphorus Bridge characteristics. For the original figure, see [35].

Table 3: Types, features, and quantity of the sensors of SHM system of the Second Bosphorus Bridge [35].

Sensor type	**Quantity**	**Features**
Accelerometer	12	Measurement range: ±0.59 g, Frequency range: 0-50 Hz, Filter: 50 Hz Butterworth
Displacementmeter	4	Located at expansion joints, Capacity: 50 cm, Resolution: 0.01 cm
Seismometer	2	Natural frequency: 0.5-1.0 Hz, Component: Lateral, vertical water proof
Data acquisition	1	Two parallel PC system, A/D converter, 200 kHz sampling rate, 1-128 channels, 12-24 bit resolution
GPS	2	Position update: Up to 10/sec, Position latency: 30 ms
TOTAL	21	

5.10.4. Project follow-up and decision making

The system has not detected any damage, reinforcing the safety of the structures.

- During the 2013 truckers' protest, the SHM system confirmed that the Second Bosphorus Bridge maintained its structural integrity and operational performance, despite being subjected to unusually heavy truck loads.
- Following the Silivri earthquake on September 26, 2019 (Mw 5.8), the SHM provided critical data that allowed authorities to continuously monitor the structural health of the bridge. This enabled rapid decision-making without the need for physical inspections or closing the bridge, reducing both costs and public inconvenience. The system also reassured the public and authorities that the bridge was safe to use.

Decision-making:

No decision-making actions have been documented in the referenced sources.

5.10.5. Outcome assessment

It is understood that authorities could monitor future events in real-time to assess the structural health of bridges for facilitating prompt decision-making.

Summary of the tangible outcomes:

- The SHM system has consistently confirmed the structural safety of the bridge, with no damage detected to date, supporting confidence in ongoing operations.

Cost-benefit considerations:

- The references did not provide specific information on the SHM system's effectiveness in reducing maintenance and inspection costs.

5.10.6. Recommendations and improvements

Useful take-aways:

- Real-time monitoring data provides critical reassurance to the public, as demonstrated during the 2013 truckers' protest and the Silivri earthquake.

Challenges with monitoring:

- It is recommended to continue advancing the SHM system by optimizing sensor deployment and improving signal-to-noise ratios to enhance the accuracy of detecting critical parameters. Plans are underway to install additional sensors, including those for monitoring cable elements, expansion joints, and anchor points, which will expand the system's monitoring capabilities and provide more comprehensive data on the bridge's condition.

6. DISCUSSION

6.1. Scope

In the previous sections, we have carefully selected and examined some outstanding cases from the SHM literature, where a novelty or a deviation from the design assumptions was detected at the bridge, which led to a decision by the bridge manager. It was noticed immediately that despite the vast scientific literature on SHM, very few such cases could be identified on real-life and operational bridges. This could partly be attributed to the fact that not all such cases were published and made available for the public.

A total of 10 bridges have been examined which included a good selection of different bridge types (1 concrete arch bridge, 2 steel railway bridges including a bascule bridge, 3 prestressed concrete bridges, 3 long-span suspension bridges and 1 steel box-girder bridge). In five of these cases, a damage (in some cases minor, e.g. Musmeci, in some cases rather severe, e.g. Stavå) was discovered using monitoring data. In three cases, a deviation from the design assumptions were identified based on monitoring data with consequences on the service life of the structure. Using the selected case studies as basis, we will now systematically discuss the milestones that have led to success. Specifically, the following questions are attempted to be answered:

- Which sensors (or a combination of sensors) were instrumental in success?
- What was the effect of data handling procedures?
- How to set up criteria for damage detection?
- How was the interplay between traditional visual inspections and SHM in condition assessment?
- What was the effect of monitoring in decision making?

It should be noted that the discussions here are based primarily on the studied cases, although reference is made when needed to other projects from the literature. Care should therefore be taken in generalizing these findings.

6.2. Monitoring strategy (extent, sensor technology and placement)

It is seen that the monitoring systems used in the examined cases differ somewhat in used sensor types, density of the sensor network, and placement of the sensors. However, there are also some commonalities among the projects, especially for the same bridge and damage types. In the following, a discussion of monitoring strategy is given, reflecting on the 10 projects examined. The issues of sensor type, bridge type and nature of damage are addressed.

Temperature and environmental sensors

Almost all the examined projects included temperature measurements in their monitoring setup. Although it is difficult to argue that temperature measurements were essential in success of each of the case studies, the importance of measuring the environmental effects were highlighted by most of the authors (Vanersborg [8], Herøysund [37]). All types of bridges, whether concrete or steel, long or short span, are affected by variations in temperature. Changes in temperature induce variability in the data, which needs to be accounted for if thresholds will be established based on “normal” behaviour. This was addressed also in the example of the Z24 Bridge [31]. In the case of Claddeau Bridge, however, temperature induced loading was the main driver of the identified problem, making it even more important to measure temperature. It should be noted that placement of temperature sensors is not a trivial task, as temperature will vary along the structure, and from one side of the structure to another, depending on thermal properties of the materials and solar radiation, meaning that a single-point weather station might not be the optimal solution.

Similarly, depending on the bridge type and location, other types of sensors that monitor the environment could be necessary. Wind is an important factor in long-span bridges and cable-systems, which has implications on both the dynamic characteristics and response. Wave elevation could be important for example for floating bridges, where tidal levels are meaningful in the case of ferry dock bridges or sea-crossing bridges. Icing or snow accumulation could be of interest in the case of arctic conditions. The examples can certainly be extended but the take home message here is that the environmental variability in the data should be reduced for better practice in SHM. To that end, machine learning tools or more traditional statistical analysis could be used.

Accelerometers

Accelerometers are one of the most used sensors in bridge monitoring and essential if a vibration-based monitoring strategy is adopted. In the cases considered here, most projects included accelerometers in their systems, with the exceptions of Hammersmith, Cleddau and Musmeci Bridges. The sensors are commonly used to extract the dynamic (modal) properties of the structure to track changes in the system characteristics. This was illustrated on the Z24 bridge, albeit not in operational conditions [38]. Other metrics or features can also be extracted based on response characteristics (i.e. response to traffic loads) as done in the example of the Stavå Bridge. In the case of Stavå Bridge, both extracted features and signals themselves were used to detect anomalies. Accelerometers are easily accessible, relatively easy to install and quite robust. The threshold for implementing a monitoring system composed of accelerometers is not high, which could partly explain its popularity. One of the important challenges with accelerometers is the interpretability of the data and anomalies. Processing and interpretation of the acceleration data require expert knowledge on structural dynamics, meaning that it is not accessible to every bridge engineer. Even with expertise, the interpretation of anomalies is still difficult. If a detection strategy based on tracking of the vibration characteristics is adopted, it is likely that local damages in minor members that has little influence on the main vibration modes will be overlooked. Moreover, localization of a damage is also challenging in such an approach. If instead, thresholds will be used directly on the signals, the outcome will be very sensitive on the location of the sensors and other effects (sensor fault, external impact). In the case of Vanersborg, the authors have used metrics fed by multiple sensors to overcome this challenge. However, such thresholds would be useful in detecting potentially dangerous dynamic phenomena, such as vortex-induced vibration (as in the case of the Øresund) or rain-wind induced vibrations. For more advanced monitoring strategies using computational models of the structures as “digital twins”, accelerometers could be used to calibrate the models based on modal analysis.

Strain gauges

Strain gauges are also commonly used in many of the cases considered here and were essential for successful detection of novelties, for instance in the case of the Vanersborg and Hell Bridges. Traditional strain gauges are simple and cheap and can accommodate very high sampling frequencies. A big advantage of having strain gauge measurements is that it gives an indirect measure of stress in the member, i.e. the ultimate load effect that every engineer is familiar with. Therefore, if an anomaly is detected, such as in the case of the Hell or Vanersborg Bridges, the extent and the approximate location of the damage could be more or less understood from the data. Further, the implications of the damage on the rest of the structure (due to redistribution of forces) could be seen. Measuring stresses directly could also provide a very accurate basis for fatigue life calculations. In other words, since a direct engineering metric is provided, the data can be used easily in decision making. For example, the fatigue calculations of the Vanersborg Bridge using measured (derived from strain) stresses revealed that the bridge has reached its fatigue life and led to decision on closure. A disadvantage with the sensors could be that they measure over a rather small distance, i.e. locally, meaning that some effects that are more pronounced in the global behaviour could be missed and one typically needs a dense sensor network.

Displacement sensors (inclinometers, tiltmeters, displacement gauges)

Measuring displacement is more tedious compared to single-point measurements as it requires a reference point where the gauge measures the relative movement. It is therefore not practical to do such measurements on many locations on the bridge. Remote methods also exist such as laser or photogrammetry, however they are sensitive to environmental obstructions in a long-term setting. Here, in the cases of Hammersmith and Cleddau Bridges in the UK, displacements were measured at the bearings of the bridges and led to replacement/repair of the bearings. Similar instrumentation was included in the updated system for the Stavå Bridge and a recent system implemented in the Øresund Bridge. Such measurements are useful for both verification (if the bearing has the displacement capacity and behaviour as it was assumed in design) and for novelty detection (if there's deterioration or damage in the bearing, affecting its movement). As in the case of measuring strain, displacement in the same way gives a more easily interpretable measure and can be used in decision making, as was done in Cleddau. A downside could be that such sensors are less environment-proof and may require more maintenance.

Fiber-optic cable sensors (continuous strain, temperature)

These sensors, as presented in the case of the Musmeci Bridge, can measure strain or temperature along a fiber-optic cable that is bonded to a structure. Therefore, in the case of damage along a member that causes displacement (e.g. sagging in a beam), this is visible in the data. Moreover, the data directly shows a performance metric that is easily interpretable by any engineer. The Musmeci case shows also that even though the damage was already there, it could still be identified due to opening and closing of the cracks due to temperature effects. It should be noted that opening and closing would not be detected under more rapid loading such as traffic, as the sensors cannot measure dynamic strains. The sensor cables can also be arranged in a mesh for measuring 2D strain. It appears that this technology could be effective in condition monitoring of cantilever bridges (long-term deflections), retaining walls, concrete members subject to cracking (e.g. due to alkali-silica reaction)

Acoustic emission sensors

These sensors were used only in the case of Hammersmith Flyover among the studies we considered here. To the best of our knowledge, they are not commonly employed in bridge condition monitoring. However, the sensors were essential in detecting wire breaks in the prestressing tendons of the Hammersmith. The accuracy or robustness of the sensors are not known to us, however, detection of a wire break in a tendon is crucial information for condition assessment, that is not easily obtained by visual inspection. Another advantage is that such instrumentation can be applied to an aging bridge without knowledge on previous behaviour and provides the location and the extent of damage, which could lead to effective decision making. Disadvantages are: 1) the sensor is very focused on one specific type of damage and requires a relatively dense network. 2) only effective in the case of rather severe damage (break). 3) A rare technology that is not easily accessible (only a few suppliers in the world), the downsides are largely unknown due to rare use.

6.3. Data collection, storage, processing and feature extraction, integration into bridge management practice

Even though information on how the data was handled is scarce for most of the projects studied here, some good practices can still be identified. All the projects used different data acquisition systems. The sensors and data acquisition system in most cases can be acquired together from the supplier. It is important to be aware of the compatibility of all the desired sensors, synchronization and data acquisition needs. It is desirable to integrate the data from all sensors in a single platform with time-synchronization. In terms of data handling, the most organized and transparent study was of Vanersborg, where the data were collected locally and transferred to cloud. An interface was available at the cloud solution for inspection of data, some metrics were provided on the health and performance of the monitoring system (if for instance a sensor is down) and of the structure. The user was able to see separate events and inspect data. Finally, the data were published and made available to the public. This is considered an example of good practice. Such online and cloud-based tools are usually offered by the suppliers of monitoring solutions, but the user should be aware of the sensor compatibility (for instance, if it is extensible with new sensors) and additional costs due to cloud storage.

Vanersborg and Stavå also present good cases on feature extraction. It is not possible to rigorously assess the performance of different features here, however, a lesson from Stavå is that the features should also be connected to interpretable quantities and should be understood by practicing engineers to be used in decision-making. Otherwise, although some novelty is detected, the following decision-making processes become more difficult. Both cases also highlight the importance of learning “normal” behavior and extracting environmental variability in order to detect anomalies in the features.

Almost all bridges are integrated to a bridge management system (managed typically by the infrastructure owner), where some metadata on the bridge, visual inspections, changes and maintenance are logged. From the examined cases, we have not come across a case where the bridge monitoring system was integrated with such a management tool.

6.4. Novelty (damage) or discrepancy detection (metrics, thresholds and alerts)

In most of the cases examined here, a damage, i.e. a change in the structure (appears at some point during the lifetime of the structure) or an unusual behaviour that deviates from the design assumptions (existing from the first day, but may or may not manifest itself under normal operating conditions, e.g. excessive vibrations due to wind that depends on loading) were found using the monitoring data. When such a change happens in the structure, it is desirable to detect it at once using the monitoring system, so that a timely decision can be made. Today, most suppliers of monitoring solutions provide also a software for some simple data handling, which includes also functionality for detecting anomalies. However, in most cases, this is also not a trivial task and should be adjusted based on the particular needs and characteristics of the project and also the sensor network.

In cases where a specific engineering quantity is measured, such as the displacement in a bearing, normal strain in a member, vibrations of cable, it is possible to select threshold values based on engineering judgement, as the acceptable ranges for these quantities are known based on design assumptions considering limit states of the structure (e.g. ultimate capacity, fatigue life) or based on normal operating conditions. Therefore, an alarm can be issued when such threshold values are exceeded. Such thresholds could be used for instance in the cases of Øresund, Hell, Bosphorus Bridges, Cleddau and Hammersmith Bridges. However, for all the mentioned cases, it was challenging to identify the *cause of the change* without visual inspection or rigorous modelling, implying that decision making will likely not happen immediately after detection. It is also important that possible sensor failures and environmental effects could be distinguished from actual structural changes.

When a more holistic approach is taken, where many sensors were used and mostly global quantities are measured, such as in the cases of most suspension bridges and Vanersborg, Z24 and Stavå cases examined here, having thresholds on the individual sensor signals is not the best practice. The reason is that a minor damage does not manifest itself clearly in the signals of the sensors and commonly drowned in the variability and noise. In these cases, signal processing is required to extract useful features to track, and employing multiple sensors is essential to increase the robustness. Such features can be the vibration modes of the structure (frequencies, mode shapes, etc.) as shown in Hardanger Bridge [39] or features based on temporal statistics of the response signals (Stavå, Hell [11]) Having thresholds on such metrics is very difficult based on engineering judgement alone, as they are dependent on the characteristics of structure, environmental conditions and the loading and not directly connected to the limit states of the structure. Further, a threshold exceedance implies that there is something wrong with the bridge and an emergency inspection should perhaps be issued. This means that thresholds should be set sufficiently high to avoid excessive and unnecessary visits to the bridge. It is therefore necessary to have algorithms that "learn" the statistics of the metrics to identify events that fall out of normal operating conditions. The interpretability of an alert is still typically low as demonstrated in the case of Stavå.

6.5. Added value of SHM in bridge inspections

The cases we have examined show that having continuous monitoring on a bridge cannot replace the need for inspections (visual or more detailed) when decisions will have to be made on maintenance, repair or replacement. However, it is seen that a detection by the monitoring system is often followed by a visual inspection to confirm the issue and take decisions. Therefore, monitoring data and inspections go hand in hand. Just as monitoring data could be used to schedule inspections and concentrate the effort to the parts of the structure (as it was done for example in Hell, Hammersmith, Musmeci Bridges), inspection data could be used to identify problematic aspects of the structure and therefore aid in tailoring the monitoring effort, as discussed in the previous sections (e.g. selection of sensor types and locations, thresholds and metrics, etc.). Further, the data from monitoring provides valuable insight into the decision-making process, as was shown in the cases of Vanersborg or Hell Bridges, where the fatigue life of the members were calculated based on measured stresses, which guided the decisions.

A systematic attempt to incorporate monitoring data into the inspection procedures (or vice versa) was not seen in the projects examined. To elaborate on how the monitoring data and bridge inspections can be used in tandem, it is deemed necessary here to take a look at the bridge inspection practice in Norway.

A drawback is perhaps that the monitoring is done by a party with a certain specialty and the inspections are carried out by a different party. It is therefore important that the parties communicate the essential information to each other in an understandable and standardized way. For instance, events and warnings recorded by the monitoring system should be integrated into the same tool used by the inspectors (using accessible language and metrics), so that the inspectors are aware of possible problems. In the same way, if the inspections reveal a problem that does not require immediate action (e.g. a minor crack, some corrosion) the monitoring effort could be initiated or concentrated for tracking this problem. The main interaction, however, as observed in the examined cases, will be issuing inspections based on alerts from the monitoring system. Depending on the structure, it is possible that the inspection intervals are adjusted based on monitoring or the inspections are replaced partially or completely by automatized systems (e.g. using drones, computer vision and photogrammetry). However, we have not seen an example of this in the projects evaluated for this report. Discussions regarding such applications are therefore considered out of the scope of this report and the reader is referred to the scientific literature.

Finally, the monitoring system can also serve as a quick inspection after or during extreme events (storms, floods, etc.), where the conditions are perhaps not ideally suited for inspection and the resources are scarce. For the bridges instrumented with a dense and rich sensor network, where some processed performance metrics (both on the sensors and the structure) can be reached easily, it is certainly valuable to see if there's something out of balance in the data. Although an SHM system brings added value in such cases, care should still be taken as there is an asymmetry in how knowledge is gained: meaning that if a novelty is found in the data, this will most likely indicate an actual damage in the structure. However, if nothing of statistical significance was found in the data, this is hardly an assurance on structural safety.

6.6. Decision making in the aftermath (maintenance, rehabilitation, closure, replacement)

It is seen that after some novelty is discovered in the data, whether through automatic issuing of alerts or crunching through the dataset manually, the problem must be confirmed via inspection. After damage or a discrepancy is found, the bridge manager is left with the task of deciding on taking actions to ensure safe operation of the bridge. Depending on the extent of the damage, early maintenance or a more comprehensive rehabilitation can be carried out. The bridge might be closed to ensure safety and perhaps might be replaced if the damage is more extensive. The Hammersmith Bridge case serves as an excellent example of how early detection of severe damage, such as wire breaks and bearing malfunctions, through SHM enabled the bridge owners to take timely interventions. These included emergency propping and lane closures before the London Olympics, followed by strengthening measures such as the installation of a post-tensioning system after the Olympics. The task of such a decision making is not so different compared to cases without SHM system, where an assessment of the bridge's condition and bearing capacity, as well as its remaining useful lifetime should be evaluated. Although the traditional procedures can certainly be applied, in the case of monitoring data, additional information can be used to improve the quality of the assessment. For example, the measured quantities can be used directly in the assessment (stresses in the cases of Vanersborg and Hell, ruptured tendons or restricted bearings in the case of Hammersmith) or be used to update the models that are used in the evaluation process (Z24, Øresund, Hammersmith, Bosphorus). In many cases, information was obtained that is beyond the capabilities of traditional inspections and proved valuable in the decision-making process.

Further, if more sophisticated methods are adopted in the decision-making process, such as risk or resilience assessment [40], predictive maintenance [41] or digital twinning, monitoring data is indispensable.

6.7. Costs, benefits and the value of SHM

A rigorous cost-benefit analysis of the projects described here is out of our reach, as information on the costs, available budgets and quantification of benefits are not available to us. However, the added value of SHM can be seen very clearly in most cases. For instance, in the case of Hammersmith Bridge, the project team reports that "the project successfully extended the operational lifespan of the Hammersmith Flyover by 70 years, with no requirement for major maintenance work during this period [4]." A such extension in lifespan is in line with the goals of reduced carbon emissions and sustainable infrastructure. Similarly, in the cases of the First and Second Bosphorus Bridges, SHM systems monitored the structural condition following extreme events (the Istanbul Marathon, the Silivri Earthquake, the truckers' protest) without causing traffic disruptions. In all the examples discussed, early structural interventions based on SHM data are prompted by the detection of anomalies. The potential for substantial long-term cost savings is clear, which is achieved by extending the lifespan of bridge components, reducing unplanned downtime, and avoiding costly future failures and maintenance efforts. Our assessment is that in all the cases described here, the benefits outweigh the costs. This is not so surprising as only the cases where a novelty of significance was found by the help of SHM were considered here. It is more difficult to argue that SHM was useful if the bridge was completely healthy, for instance for the first 10-20 years of the operation, where hardly any damage or deterioration is expected. In that period, it is not unexpected that the costs of operating and maintaining an SHM system outweigh its benefits. The example of over 25 years of monitoring of the Tsing Ma Bridge in Hong Kong [42] showed virtually no changes in the structural parameters. However, much valuable information was gained, some of which was published. Considering the building and operating costs of a suspension bridge, the cost of a monitoring system is of minor importance, but it might be the opposite for a midsize, more common bridge.

The value of SHM becomes more pronounced for aging bridges, as the probability of having damage is higher. However, starting to monitor very late in the lifetime of the structure could result in missing critical trends in deterioration. To address such considerations, the field of Value of Information (VoI) analysis has emerged, quantifying the monetary value of information that is gained through SHM [43]. It seems possible that the bridge owner can decide whether to have a monitoring system using such quantitative assessment. In any case, it is important that the value of gained information is appreciated even when no significant damage is detected. Further, having quantitative data on early stages of the structure would provide valuable insights into long-term deterioration effects, enabling better planning of maintenance and inspection routines.

6.8. Recommendations

- Selection of the monitoring system, including the number and type of sensors, their placement and data collection and preliminary processing is decisive for successful implementation of SHM and early detection of damage.
- The most important factors to be considered are the type and age of the bridge. Known issues with the specific bridge (using classical data, e.g. inspections) and commonly encountered issues in similar bridges (around the same age) should be used to identify the potential issues to tailor the SHM system for specific damage types (e.g. measuring displacement on a bearing that is affected by corrosion).
- The total cost including the operating costs of the bridge and its importance (is it a lifeline infrastructure? Is it critical in case of disaster management and emergency situations?) should be taken into account. For a landmark suspension bridge the cost of monitoring can be a fraction of the cost of the bridge, where continuous monitoring composed of many different sensors from the first opening is feasible.
- For smaller and lower profile bridges, the resources might be limited for extensive monitoring. Also, for a new bridge, where no significant damage is expected in the first half of its service life, the monitoring costs could be overwhelming. In such cases, it is recommended that short-term monitoring is applied using rapid-deployable systems for obtaining a reference. Vibration-based systems with evenly distributed accelerometers are the most appropriate choice for this application. In cases where it is expected damage or potential issues are pointed out, long-term monitoring that target specific issues can be deployed.
- Setting up of thresholds and alerts that would trigger warnings and eventually emergency inspections seems to be inherently challenging. Inevitably, too strong a criterion would result in too many inspection visits and too weak a criterion might overlook important events. This is not an exact science, but practice improves with experience. We recommend that the metrics used are related to physical quantities that are interpretable by most of the involved parties.
- In long-term continuous monitoring, the environmental variability of the data should be extracted to better detect changes in the structure. A statistical analysis based on at least 1 year of data should be employed to achieve this.

7. SHM SYSTEM ARCHITECTURE

As seen in the bridge examples, there are many ways to approach bridge monitoring. The bridges range in characteristics when it comes to the year they were built, when monitoring was started, what data was collected, how it was stored and how it was accessed.

The following section describes high level decisions that need to be made when choosing the architecture for sensors, connectivity, storage and access. An underlying assumption is that there are multiple data stakeholders in such monitoring systems, such as:

- Bridge monitoring and maintenance personnel who are interested in receiving alerts when sensor data indicates that specific threshold limits have been exceeded.
- Research scientists who will utilize the data ad-hoc to evaluate natural or planned experiments.
- Data scientists and data analysts who will build reports and experiment with algorithms based on system events.
- Consumers of reports from insights systems such as a data visualization interface from a central data platform.

And there are likely even more individuals involved. Furthermore, the requirements for such a monitoring system would likely not only be determined by the data consumers. There will be security, cost, compliance and environmental considerations that might affect architecture selection.

7.1. Sensor technology

As described in previous sections, the selection of sensor types relates to the monitoring use case at hand. However, there are many aspects to setting up the sensor architecture for a bridge.

Firstly, any sensor will need power supply. There are sensors on the market that are battery provided, but feedback from field workers indicate that this is sub-optimal due to the inconvenience of changing the batteries at regular intervals. In many cases wired power is preferred whereas solar energy perhaps could be considered as a secondary source of energy. There are also Internet of Things (IoT) products on the market with hyper-optimized energy capacity where the vendors claim to have many years of battery duration. These products would need field testing to verify that the vendor’s claims are valid in Nordic conditions.

Secondly, a sensor would need connectivity towards some sort of hub, often referred to as a data logger. For many sensors it is possible to have cellular setup directly on the device with individual 4G or 5G IoT-subscriptions embedded in the device. This eliminates the need for any intermediate devices such as microcontrollers (MCs) or single-board computers (SBCs) as a hub towards the cloud or an on-premises server. Even if choosing a less costly Narrowband IoT subscription for each device this approach still is costly and not very scalable across many sensor nodes. Therefore, using wired connectivity from a cluster of sensors to an intermediate data transmission and processing device could be an option. The alternative options are Wi-Fi, Bluetooth or other wireless technologies such as Zigbee and LoRaWAN.

Thirdly, when a direct cloud connection via device level IoT (cellular) subscriptions is not preferred there would be a need for one or more intermediate devices working with data transmission. For small scale projects this could be MCs such as Arduino or SBCs such as

Raspberry Pi or edge computing devices. SBCs, although more expensive than MCs, are considered better at handling multiple sensors compared to MCs. There are vendors providing various sorts of robust data loggers that are built for industrial use.

7.2. Connectivity and communication

From the centralized hub(s) that receive data from the sensor nodes, there needs to be a connection to the cloud or an on-premises server. Microcontrollers will typically not have built-in 5G and not necessarily ethernet capabilities but could have Wi-Fi compatibility. Single-Board Computers will in many cases have both ethernet and Wi-Fi compatibility and might be extended to having 4G and 5G capabilities with addons. If, from a security perspective, a cellular connection setup is acceptable and preferred, it is wise to have extra storage capacity on the device. This should then enable message queuing on the device so that once a disconnected device comes back online, it will forward the captured data from the offline session. Also, keep in mind that the 2G-networks in Northern Europe are about to be sanitized and therefore devices should not rely on 2G (or for that matter 3G) for primary or back-up connectivity.

The basic idea is that the data processing device which receives signals from a cluster of sensors will act as a data transmitter on the preferred connectivity. Hence, the need for single 4G or 5G subscriptions on the sensor devices is removed. The preferred communication protocol for IoT is MQTT. MQTT (Message Queuing Telemetry Transport) is a lightweight, publish-subscribe network protocol designed for machine-to-machine (M2M) communication.

It is particularly well-suited for connections with remote locations where network bandwidth is limited. MQTT operates over Transmission Control Protocol/Internet Protocol (TCP/IP). This is a set of communication protocols used to interconnect network devices over the internet. It is known for its efficiency, reliability, and minimal resource consumption. MQTT’s minimal packet size and low overhead make it ideal for devices with limited processing power and memory, such as microcontrollers and single-board computers. Furthermore, the MQTT architecture allows for the configuration of what data is to be transmitted, at what frequencies, whether all data changes are to be published or whether threshold-based publishing of data is to be established. Additionally, devices could be connected directly to a cloud IoT Hub via MQTT or a MQTT Broker can be used to transfer data from multiple devices.

7.3. Cloud architecture

Based on the number of data stakeholders mentioned at the beginning of this chapter, there could be a need for a scalable architecture. Whether or not to move the data into the cloud is a decision to be made. This is often conducted to be able to scale storage and compute power seamlessly instead of having to handle the infrastructure. The cloud decision might be made based on an assessment of budget, scope, scalability needs, security requirements and the availability of tools. Whether one is building a stand-alone system for a single bridge or a system across multiple bridges would perhaps be one of the drivers for choosing the cloud for scalability.

This section describes a high-level architecture of how the data might be processed and transformed once it has reached the cloud (Figure 32). Assuming the SHM system will not be a Software-as-a-Service (SaaS) product which is managed by a third party, then various cloud components from the preferred cloud vendor would be required to build this in your own cloud tenant.

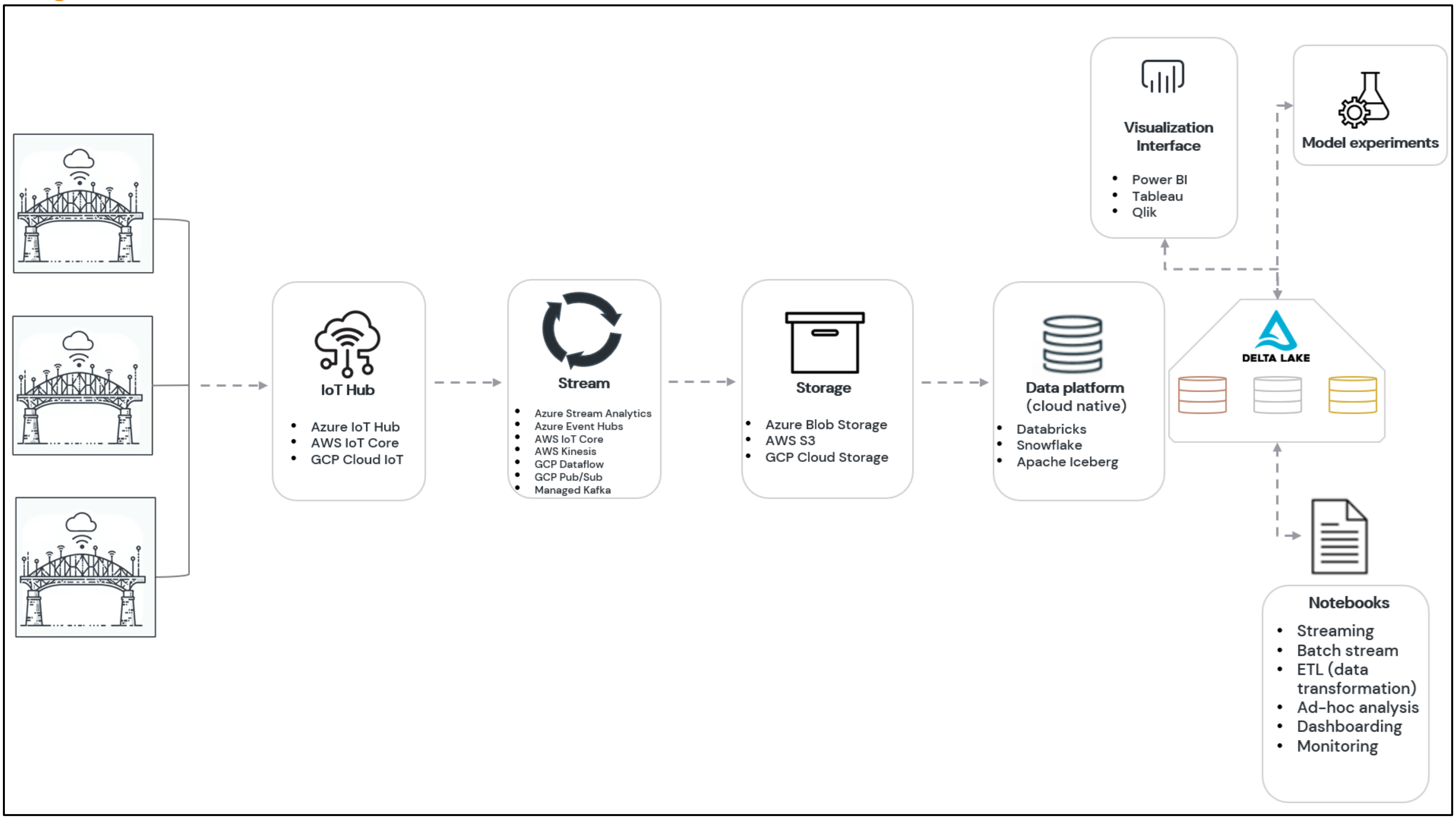


Figure 32: High-level cloud architecture with components from Amazon Web Services (AWS), Google Cloud Platform (GCP) and Azure.

Firstly, an IoT Hub that manages device master data would be the landing site for raw data. In Amazon Web Services (AWS), the service is named IoT Core whereas in Microsoft Azure it is called Azure IoT Hub, and in Google Cloud Platform it is named Cloud IoT Core. The main requirement is that this Hub should support modern communication protocols such as MQTT and would be set up to route messages to other cloud components. This is where devices would be registered, and policies are set up to define what actions devices could perform in the hub. As the data is received in an IoT Hub, a processing component is needed to forward the data into a data platform or directly to storage in a storage account. There are various products available across the cloud vendors and there are managed streaming services available such as Kafka that could handle this operation.

Secondly, it is possible to stream the data into a centralized data platform once the stream component has been set up as a job in e.g. Azure Stream Analytics. Modern data platforms such as Databricks or Snowflake come with close to real-time streaming features and support so-called batch streaming. Batch streaming is a non-continuous stream of data which could be configured to be triggered at certain time intervals or manually. Put simply, this means that it is possible to fetch data from the source periodically rather than having a system that fetches the data 24/7.

By doing batch streaming of the data, it is possible to reduce processing costs significantly. A continuous data stream into a data platform does imply costs of one or more virtual machines with a significant size of memory. If alarms, reports, dashboards and data extraction from the data platform need to have as minimal latency as possible (close to real time updates), then a streaming approach is preferable.

One drawback with batch streaming is that the data will have latency prior to being stored permanently in the data platform. Therefore, it is important to determine which bridge use cases that have real-time data requirements, and which use cases where latency optimization is less important. It is possible to use streaming for certain bridges and batch streaming for other bridges, and it is possible to convert an existing continuous stream to batch streaming.

On the other hand, if the SHM alarming logic is embedded in the data logger locally then it is natural that real time monitoring happens outside of the centralized data platform with a separate system that is consuming sensor data based on pre-defined alarm thresholds (in MQTT). This could be a system that uses an on-premises time series database or similar. The data platform could then, rather than acting as a monitoring system, instead act as a data collection, machine learning experimentation and visualization platform where data stakeholders might explore the data without impacting a production system.

The modern data platforms also support a modelling approach named "Data Lakehouse". This means that the Data Lakehouse architecture allows data teams to store semi or unstructured data in the same location as structured relational data. By doing this, it is possible to link relational data with raw IoT data, and allow research scientists, data engineers and data scientists to not just work with raw sensor data from a data lake. Traditionally, this has been an issue in the big data space as raw signal data alone often does not provide the necessary insights: "The data lake without the analytical infrastructure simply becomes a data swamp. And a data swamp does no one any good" [44].

Furthermore, in the lakehouse architecture one would not only receive raw sensor data prior to data transformation. Ideally, one would have an integration into BRUTUS (e.g. by doing nightly or twice daily data extraction) to update relevant dimensions and fact data tables on the data platform. A pre-requisite for this is that there are workflows with notebooks that orchestrate the jobs whereas the raw sensor data needs to be either processed in a stream or batch stream. Notebooks, as illustrated in Figure 32 have become a central tool in any data platform. These are developer environments within the data platform that allow data engineers to work with streaming and batch processing of data while also enabling researchers and data analysts to work directly with databases.

7.4. Potential data architecture

In either case, the data platform will most likely be the only place where sensor data, bridge facts and device metadata can be processed at scale with historical values available. A common solution for a data platform is to follow the Data Lakehouse architecture which was describe above. Most modern data platforms rely on a back-end system named Delta Lake for their overall tables and structures. Delta Lake stores the data in a highly processing and cost optimized file format named parquet. While parquet has become the golden standard for big data processing, it is a file format which is easy to interact with via Delta Lake using programming languages such as Python, Rust, SQL or R. It also makes table partitioning and optimization easy while enabling table version roll-back and automatic version history logging. Essentially this means that we can conduct time travel on a table to restore old versions.

Delta Lake, which is an open-source technology used by many of the platform vendors, is suited for large amounts of data combined with the need to refine data as a stage wise process. The three database symbols in Figure 33 illustrate how raw data is ingested. The raw data is often referred to as the bronze layer of the data architecture. Then as the data needs cleaning and preparation prior to analysis, there is a processing step in the middle – often referred to as the silver layer of the architecture. Finally, when the data is modelled into data products which are ready for analysis it ends up in the gold layer which is where aggregated information is available.

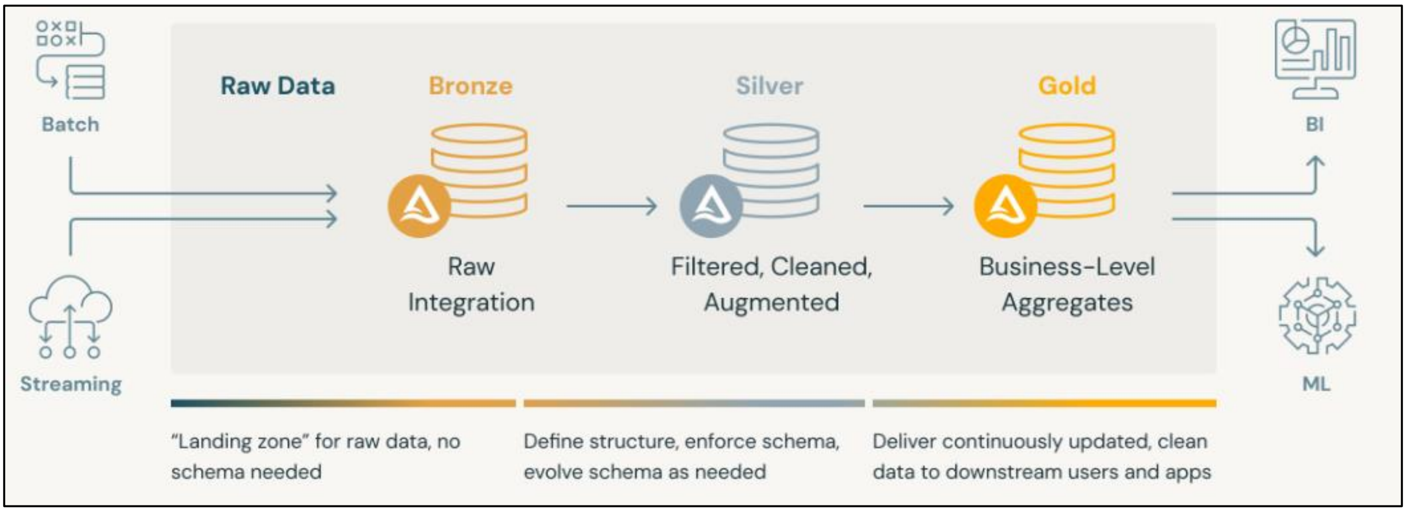


Figure 33: A traditional data flow using modern data engineering architecture [45].

7.5. Theoretical data model

In the following section, a theoretical data model is described. This way of modelling the data assumes that a data platform has been set up to fetch device observations from multiple bridges and the model could serve as an idea of how to model IoT data in the same environment as relational data. We also assume that data has landed in the bronze layer of the architecture in the form of raw data, and that we have done some cleaning of the data in the silver layer.

We can use a star schema modelling approach for this. In Figure 34 a star schema table structure is described on the right-hand side where an observation table is at the centre of the model. The observation table is linked with a bridge dimension table and a device dimension table, where metadata on the bridges and devices should be captured from the source systems (IoT Hub and the bridge registry system BRUTUS).

Primary keys (pk) from the dimension tables are linking the respective metadata tables with the observation fact table's foreign keys (fk). This way of modelling the data could be seen as an intermediate step prior to making aggregates, reports and dashboards that are calculated based on the three tables. Additionally, as the history of the tables and inspections are of interest these are suggested as two linked tables where the actual content of the tables would rely on the structure of the current databases today and the potential standardization across the registered bridges and inspections.

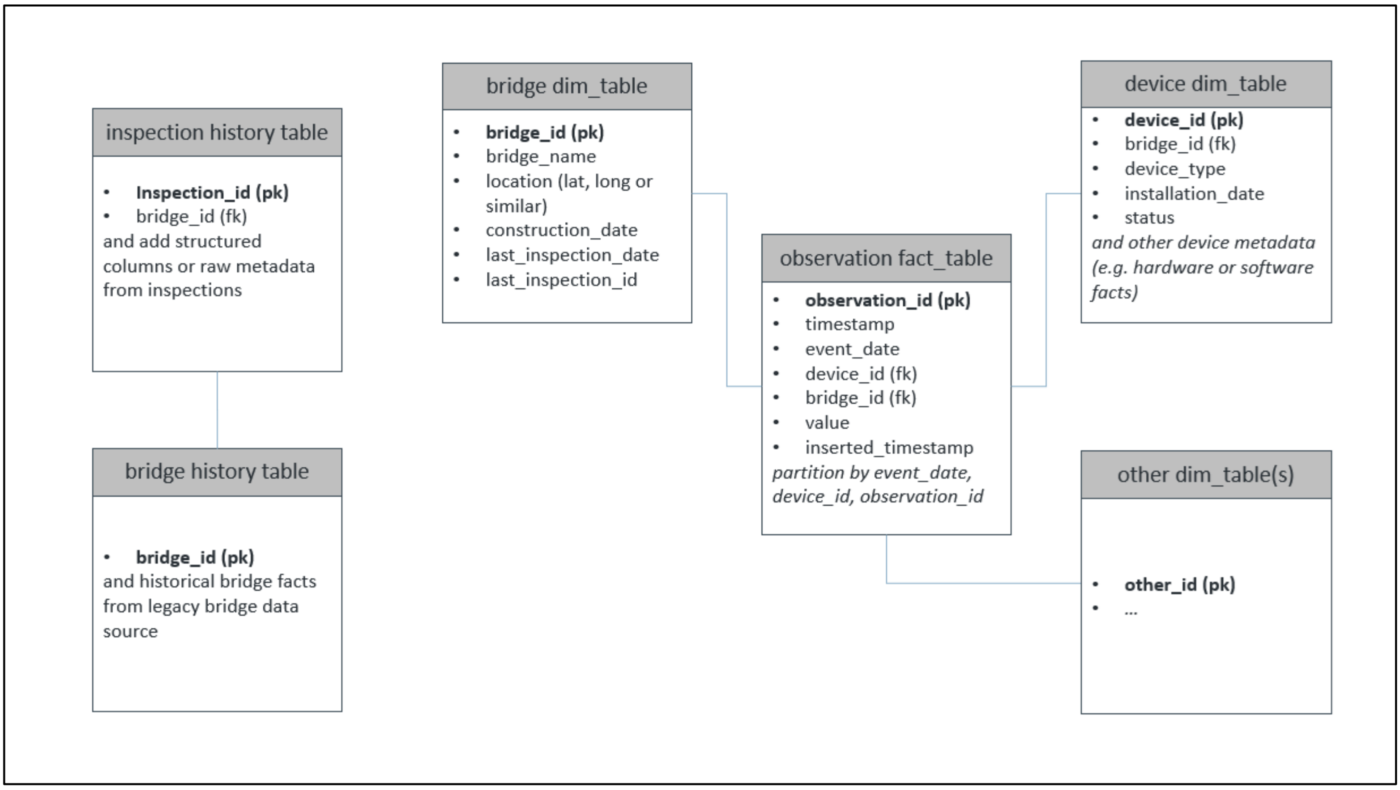


Figure 34: Potential data architecture for device observations facts and observations.

It is possible to expand this data model based on specific user requirements. For example, the device_type from device dimension table could instead be replaced with a device_type_id which references a device type table. This would make sense if there were a large amount of standardization of devices across all bridge projects.

A theoretical example of an observation from the observation fact table might be:

observation_id: 101 (unique identifier assumed *big integer* datatype)

timestamp: 2024-11-18T09:00:00Z (*timestamp* of observation at the device)
device_id: 501 (identifier of device, assumed to be defined as *big integer* datatype)

bridge_id: 23 (identifier of bridge, assumed to be defined as *integer* datatype)

value: 22.5 (assuming device measurement is temperature in Celsius – assumed to be *decimal* datatype)

inserted_timestamp: 2024-11-18T09:00:30Z (*timestamp* of insertion into data platform)

If each device only sends one measurement type, then this structure could work. The metadata on the device observation could be stored in the device dimension table. It could make sense to expand the table structure by having a measurement id or observation type id that would hold metadata on the sensor measurement. In the example above this would describe the sensor measurement details, and if implemented in the star schema it would be possible to join aggregates from the observation fact table on the measurement dimension table to enrich any selected observations with textual descriptions. This would also limit the amount of textual (string) values in the observation fact table, which is good for query performance and from a storage cost perspective.

With the proposed data model from Figure 34, the observations table would grow over time. It might be of interest to model the data in a different way, e.g. by having a separate observation table per bridge or to model each table per observation type. In either case, proper partitioning of the tables is crucial to enable efficient processing. With data partitioning, the table creator will specify a list of columns that are to be used for dividing the large dataset into smaller, more manageable pieces. Ultimately, the partitioning structure will affect the file structure in the file system that is managing the back-end system of the table.

7.6. Summary of technical considerations

The following section highlights technical considerations that are to be made while setting up a Structural Health Monitoring (SHM) project for multiple bridges. Several architectural decisions which need to be made to ensure the system's effectiveness and scalability are listed. These were also discussed in detail in the prior sections of the report:

Sensor Technology

Power Supply: Choose between battery-powered sensors, wired power, or alternative energy sources. Battery-powered sensors offer flexibility but require regular maintenance, while wired power provides a stable long-term solution.

Connectivity: Decide on the connectivity method for sensors. Options include direct cellular connections (4G/5G), wired connections to a data logger, or wireless technologies like Wi-Fi, Bluetooth, Zigbee, or LoRaWAN.

Data Transmission and Processing

Intermediate Devices: Determine whether to use Microcontrollers, Single-Board Computers or vendor specific data loggers for intermediate storage and data transmission. MCs are cost-effective but less capable of handling multiple sensors compared to SBCs, which offer more processing power and connectivity options.

Communication Protocols: Select the appropriate communication protocol, with MQTT often being a preferred choice for its efficiency and reliability in IoT applications. Decide whether to communicate over MQTT directly per device or to use a MQTT broker across many devices.

Cloud vs. On-Premises

Data Storage and Processing: Decide whether to store and process data in the cloud, on-premises or both. Cloud solutions offer scalability and ease of access, while on-premises solutions may provide better control over data security and compliance. A combination could be used whenever certain data points need to be processed for alarm flagging purposes and other data points are to be stored for future research and development purposes.

Cloud Services: If opting for the cloud, choose between services from the large cloud vendors (AWS, Azure, or GCP). There are other cloud vendors available, but these have not been assessed. Each vendor offers IoT hubs (e.g., AWS IoT Core, Azure IoT Hub, GCP Cloud IoT Core), storage options and data processing tools. There are cloud native data platform services that could be deployed in tenants of each vendor.

Data Architecture

Data Lakehouse: Consider implementing a Data Lakehouse architecture to manage both structured and unstructured data efficiently. This approach supports advanced analytics and integration with existing data systems. One alternative is to process the IoT data in a traditional data lake while storing the relational, structured data in a data warehouse. None of these data architectural designs needs to be deployed in the cloud.

Data Partitioning: For larger table structures, plan for proper data partitioning to optimize processing and storage. This is crucial for managing large datasets and ensuring query efficiency as the data volumes increase over time.

Latency Requirements

Real-Time vs. Batch Processing: Assess the need for real-time data processing versus batch processing. Real-time processing is essential for immediate alerts and monitoring, while batch processing can reduce costs and is suitable for less time-sensitive analyses. As discussed, it is possible to stream certain data points in real-time where alarms have been triggered (given by a pre-defined threshold) while conducting batch processing or batch streaming of the remaining data.

7.7. Summary of non-technical considerations

The following section highlights non-technical considerations that are likely to be assessed in a project where a scalable approach to Structural Health Monitoring (SHM) is considered. These aspects were not included in the previous sections but serve as guidance for a potential project:

Risk Management and Mitigation: Conduct a risk assessment to identify potential larger risks (e.g., sensor failure(s) on a bridge, data breaches in a hub or similar, signal jamming on a location etc.), their estimated likelihood, consequences and strategies for mitigating these risks.

Data Privacy and Security: Assess how data privacy and security will be managed, especially given the multiple stakeholders involved. This will be tightly linked to the technical selections made in the project.

Maintenance and Calibration: Discuss the maintenance schedules for sensors and assess the options for calibration to ensure data accuracy.

Cost Analysis: Given the technical scoping of the project, conduct a high-level cost analysis or budgeting considerations for the different components and technologies.

Regulatory Compliance: Evaluate the regulatory standards or compliance requirements that need to be adhered to for SHM systems.

8. CONCLUSION

In the preceding sections, we have systematically selected and examined ten prominent cases from the SHM literature, where a novelty was detected in the SHM data and led to a decision of the asset owner. A good variety of cases was sought in terms of structural and material types, purpose of SHM and detected novelties. The selected cases were then scrutinized with emphasis on their monitoring strategy, use of sensor technology, and treatment of data as basis for decision making. Many different bridge types and structural problems have been covered. The key outcomes from each examined case were summarized and then carefully discussed to deduce recommendations for best practice.

It is seen that monitoring data was essential not only for detecting novelties but also in the following decision-making processes (e.g. issuing inspections, repair or replacement) for the majority of the cases. The downside of relying on subjective bridge inspections is stressed relying on the example cases, where existing damage was overlooked in visual inspections, and later discovered by the help of SHM. Owing to the variety of the examined cases, the case-specific nature of selecting the right monitoring system is highlighted, including the aspects of sensor technology, system architecture, and data-processing. The milestones that led to success and the challenges faced were identified.

The scalability and possibilities regarding the SHM data architecture is presented. It is seen that the possible solutions range from rather simple and primitive setups with manual data collection to IoT-based solutions where information from all infrastructure is integrated. It is recommended that a more holistic approach is taken where many bridges and their metadata are integrated and centrally managed, rather than a project-by-project approach. A such extensible solution would have a high initial investment cost but would be more efficient later, when more of the bridge inventory is monitored.

In conclusion, the SHM field is mature enough to be systematically implemented into the bridge management practice. There are indeed challenges to be faced, and the practice is rather demanding in terms of experienced and skilled personnel, however, SHM system could provide objective data supporting decisions, resulting in added value when making decisions and informing inspections. Considering the current trends and demands of sustainable and resilient infrastructure, and the accessibility of the sensor technology, it appears that SHM is likely to be even more relevant in the future.

Although an SHM system brings added value in many cases, care should still be taken as there is an asymmetry in how knowledge is gained: meaning that if a novelty is found in the data, this will most likely indicate an actual damage in the structure. However, if nothing of statistical significance was found in the data, this is hardly an assurance on structural safety.

9. DEFINITIONS

4G or 5G IoT-subscriptions	High speed cellular connectivity offerings provided by mobile operators which use e-SIM or physical SIM cards to connect devices to the cellular network. Devices could be mobile phones (iPhone, Android) or machine-to-machine devices such as the ones used in IoT.
Arduino	An easy-to-use electronics platform designed for making interactive projects.
Centralized hub	A platform that acts as the main control point for managing and facilitating communication between various IoT devices and a cloud-based solution.
Communication protocol	A set of rules and conventions that allow two or more devices to exchange information.
Edge computing device	A gadget that can process data locally, near the source of data generation.
IoT	Internet of Things – any device connected to the internet. Devices that can be controlled remotely are often referred to as IoT devices.
LoRaWAN	Long Range Wide Area Network – communication protocol designed for low-power, long-range IoT applications.
Microcontroller (MC)	A compact integrated circuit designed to govern a specific operation in an embedded system.
MQTT	Message Queuing Telemetry Transport – a lightweight messaging protocol designed for small sensors and devices which is optimized for high-latency or unstable networks. The protocol is based on a publish/subscribe model to enable multiple consumers of data.
Narrowband IoT-subscriptions	An IoT specific cellular connectivity offering which is tailored for low-power, wide area IoT connectivity which enhanced battery lifetime and coverage reliability in IoT.
Raspberry Pi	A small, affordable single-board computer developed for use in the fields of simple and complex automation and robotics.
SaaS (Software as a Service)	A cloud-based software delivery model where applications are hosted by a service provider (supplier) and made available to customers over the internet.
Single-board computer (SBC)	A complete computer built on a single circuit board which includes a microprocessor, memory, input/output (I/O) ports, and other essential components required for a functional computer.
TCP/IP	Transmission Control Protocol/Internet Protocol - a set of communication protocols used to interconnect network devices on the internet.
Zigbee	A wireless communication protocol designed for low-power, low-data-rate applications, making it ideal for IoT and smart home devices.

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