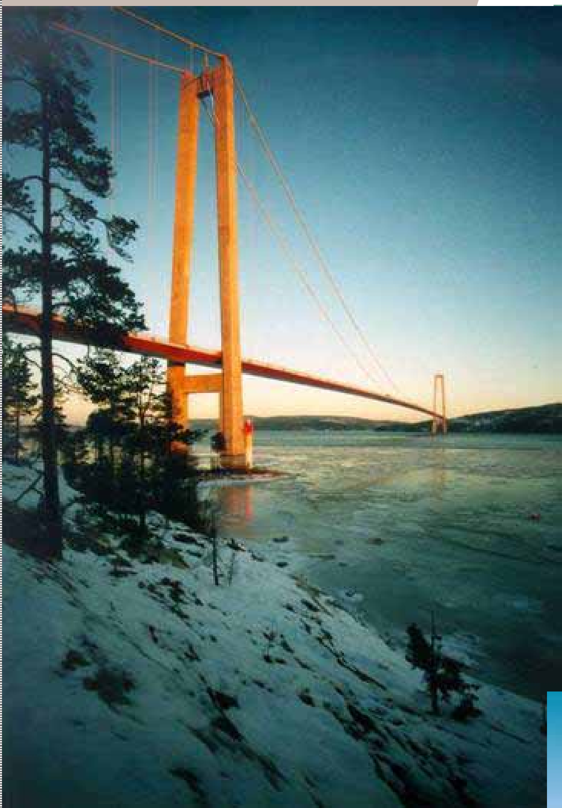
Structural Health Monitoring Systems



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Structural Health Monitoring Systems

First Edition

COWI - Futurtec

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1 Introduction

Structural Monitoring is basically an activity where actual data related to civil structures is observed / measured and registered. This has been performed through all times by responsible designers, contractors and owners with almost identical objectives - to check that the structures behave as intended. Historically the activity has required specialists, has been time consuming and hence costly and as a result hereof only a limited number of performance indicators - typically geometry - have been measured aperiodically and supplemented by regular visual observations.

This situation has been dramatically changed by the enormous development within information technology in the last two decades. High performance sensors, precision signal conditioning units, broad band analogue-to-digital converters, optical or wireless networks, global positioning systems etc. have all paved the way for a far more accurate, fast and cost efficient acquisition of data. Very sophisticated and powerful software for structural analysis has become available and increases the beneficial use of the large amounts of data that can be acquired. Finally, significant developments have been made regarding deterioration mechanisms and environmental loads on civil structures. These developments open the way for a wide range of applications related to efficient operation and maintenance of structures.

Structural monitoring has thus emerged as a distinct technical discipline as the new technologies have been introduced in the field of civil engineering. Numerous and rather sophisticated systems have been established. The development of many of these systems seems to have been driven more by the technological possibilities than by well defined objectives for application areas of design verification, trouble shooting, user safety and maintenance planning formulated by the “traditional key players”: the designers, contractors, operators and owners. Most likely this is due to the complexity of the new methodologies and systems and the vendors dedicated efforts to market new products, but scientific curiosity and enthusiasm may also have played a role. As a consequence of weakly defined objectives it seems as if the owners have not achieved the optimal benefit from the – often rather significant – investment in the structural monitoring systems and their occasionally extensive operation.

It is the experience of the authors that an early and thorough discussion with the future stakeholder(s) in the structural monitoring programme paves the way for an efficient and direct path to design, procurement, installation and operation of an adequate and cost effective monitoring system.

It is the intention with this text to give a presentation of

- The general objectives of structural monitoring, defining the framework for the planning of monitoring systems.

- A possible framework within which the stakeholders objectives can be defined in order to pursue the discussions with the same common understanding.

- A range of issues of strategic importance for systems layout and economy in order to clarify crucial matters as early as possible in the process.

- A general introduction to critical points of main options for structural monitoring systems for the stakeholders information and consideration

- A representative selection of existing structural monitoring systems exemplifying some of the general principles touched upon in the preceding sections

- A guide for the main issues to consider in procuring a structural monitoring system

With the hope that future plans and designs of structural monitoring systems will be straightforward and that cost efficient systems are developed that are fully compliant with the stakeholders' clear objectives.

Part I: BRIDGE MONITORING REQUIREMENTS

2 General Considerations

The stakeholders in civil engineering projects may have a common interest in gaining benefits from a structural monitoring system, and the objectives may be coincident, partly coincident or completely different from each other. Furthermore the required information to be established via a structural monitoring system will depend upon the level of the decision making that the information shall support and this in turn will have to be reflected in the structuring of the databases containing the acquired data and the control of monitored events.

Also economical considerations must be taken into account. The investment in the construction and operation of the structural monitoring system shall be possible to justify. The value of design verification, user safety, trouble shooting capability and maintenance optimisation can be very difficult to quantify. However it is possible to do some cost benefit analysis regarding the operation costs of a SHMS compared to assessed maintenance budgets. Structural monitoring systems designed on principals as outlined in the following will mostly ensure overall economical systems.

2.1 Stakeholders

The stakeholders are here defined as the parties that may benefit from the information established through a structural monitoring system.

Seven groups of stakeholders 'around' civil engineering structures may in many cases be identified - as illustrated in figure 1:

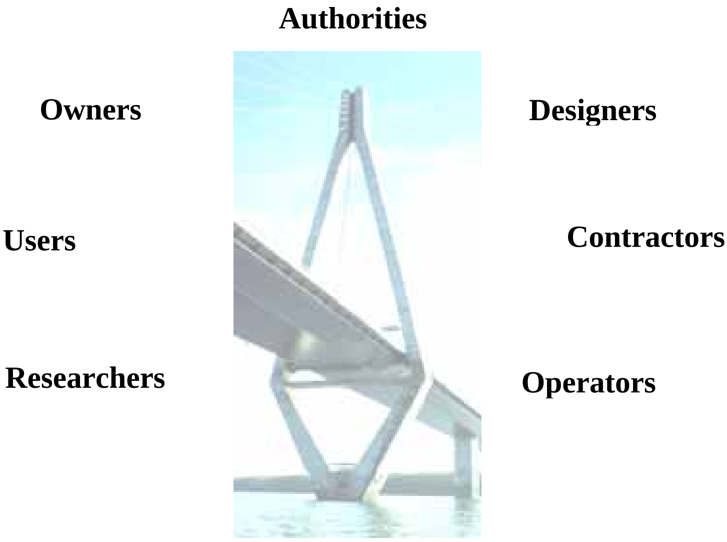


Figure 1: Stakeholder groups 'around' civil engineering projects

Examples of the objectives these individual groups of stakeholders may have in structural monitoring systems are illustrated in Table 1.

Table 1: Stakeholder groups and likely objectives associated with structural monitoring

STAKEHOLDER	Objective(s)
Authorities	- Required functionality of the structures shall be documented
Owners	- Reliability of the structures must satisfy codes and standards - Acceptable service life of structures must be ascertained - Life Cycle Cost optimization
Users	- Availability of services provided by the structures must be high - Must be able to use the structures safely
Researchers	- Full scale verification of structural modelling theories
Designers	- Verification and documentation of the final design
Contractors	- Verification of structural response and geometry
Operators	- High availability - Cost efficient operation and maintenance - Identification of causes for unacceptable behaviour (e.g. vibrations) or excessive wear

Table 1 show that authorities and concession holders will in general have the same interests as the owner. However they will also have the responsibility to ensure that the owner is meeting requirements of laws, codes and user safety.

The owner will primarily be interested in having a bridge as specified and constructed within the time schedule. Further it must be able to operate with high availability and sufficient safety for all activities during construction and service lifetime and within budget.

The users are primarily interested in high accessibility, visual comfort and safe use of the structure. If any events, e.g. high winds, accidents, maintenance works are preventing this, the users shall receive fast and easily understandable information about the problems and its duration. Furthermore toll charges should be as low as possible.

Researchers and Universities often have a role in the design process of ground-breaking structures. Usual the main interest will be in the design verification of new methods and the understanding of structural problems during the operation of the bridge.

The key interest of the designer is to collect environmental and seismic information of the site prior to the construction and to verify their design assumptions and values during and after the construction.

The contractor’s interest focuses on the efficiency of the process and safety of the site. It is important to ensure that construction is carried out as specified.

The operator’s main interest is to ensure that no irreversible errors have been made in the construction process, that safety of the users is ensured at all times and that operating costs can be reduced and maintenance streamlined. For lifetime costs it is important to use in particular front-line knowledge of integrating the data measured by a Structural Health Monitoring System (SHMS) into an overall Bridge Management and Maintenance System (BMS). For the maximum benefit of an SHMS it is essential to develop a BMS into which the SHMS will be integrated. Only this will ensure maximum optimisation of the bridge maintenance program and the reduction of maintenance costs.

Key issues are to clarify concerns of the stakeholders and identify their objectives, associated with the structural monitoring activities being planned.

2.2 Management Levels

When it has been decided to apply structural monitoring in order to document fulfilment of a stakeholders objective, the implementation of monitoring activities and the assessment of results will be carried out on typically three organisational levels as illustrated in Figure 2.

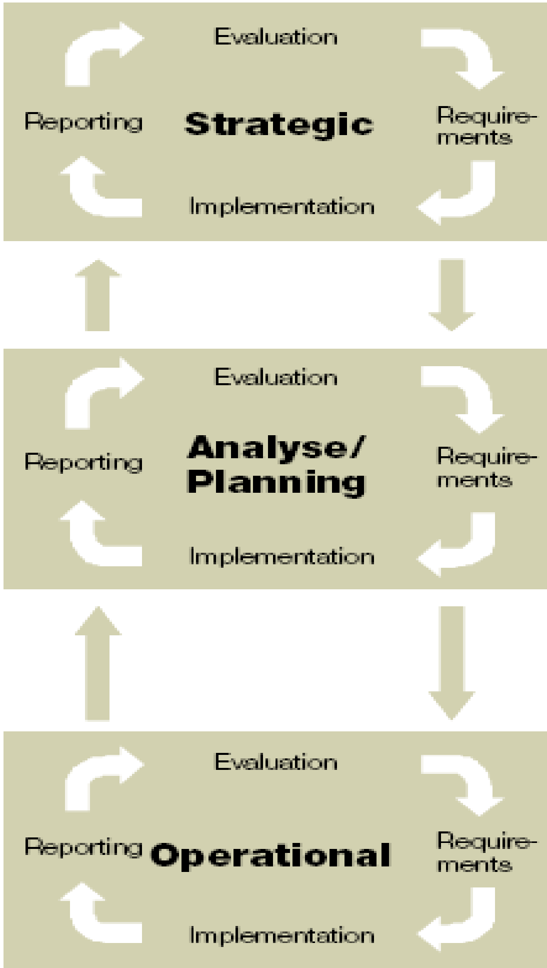


Figure 2: Generic model for the organisational levels taking care of structural monitoring activities.

On each level the activities are typically carried out in a cyclic manner where

- goals are defined and *requirements* for the deliverables from monitoring activities are defined
- the necessary activities are initiated to *implement* the systems and routines necessary to meet the goals
- data are acquired, analysed and *reported*
- the results are *evaluated* and existing goals are adjusted and/or new goals established

The model is explained in detail in the following sections

2.2.1 Strategic Level

On the strategic level the overall values of parameters that must be attained are defined in order that the objectives can be met.

Some parameters may be simple to derive, e.g. availability in percentage of time, while others may require rather extensive analyses and aggregation of larger amounts of data, e.g. in order to verify that the responses to wind loads are in accordance with the design assumptions.

Information of interest for this management level is hence typically aggregated data and the information is not needed in real-time.

However the strategic management level may require that strategic information is updated on a regular basis and systematically stored in a database with access at any time

2.2.2 Tactical Level

On the tactical level the monitoring activities are planned and the results are analysed. Statistical information is generated. The tactical level has also the responsibility for data management, such that data are acquired, analysed and stored in a systematic and readily accessible manner. The information acquired and generated may be used for example in the planning and execution of inspection and maintenance activities.

2.2.3 Operational and Control Level

On the operational level the monitoring system is supervised, data are acquired and stored in databases for use on the tactical level.

Operators will typically monitor the Structural Monitoring Systems (SMS) in 24 hour shifts on larger bridges, while on smaller bridges the operation of the SMS will be automatic.

The operators will carry out the control and immediate actions requested by the warnings and alarms of the SHMS. These can be events such as dangerous wind speeds/gusts, traffic accidents, fire, ship impact, earthquake, etc. requiring warnings to the users or closure of the bridge brought about by the information arriving through the traffic information systems.

2.3 Organisation of Structural Monitoring Data

The basis of structural monitoring is the acquired data from sensors installed on the structure. In order to support the above described organisational levels it is convenient to organise the data in similar levels.

On the operational level there will be one or several individual data acquisition systems storing the raw data in preset formats or databases. From these raw data, statistical information and sample time series selected based on the bypass of preset trigger levels will be passed on to the analysing and planning (tactical) level. Only the results of the management and control performed at the analysing and planning level will be reported at the strategic level. Alarms affecting the immediate safety of the bridge will always be reported instantaneous to all affected managers in the bridge organisation [1].

Figure 3 shows a graphical view of how to organise structural monitoring data.

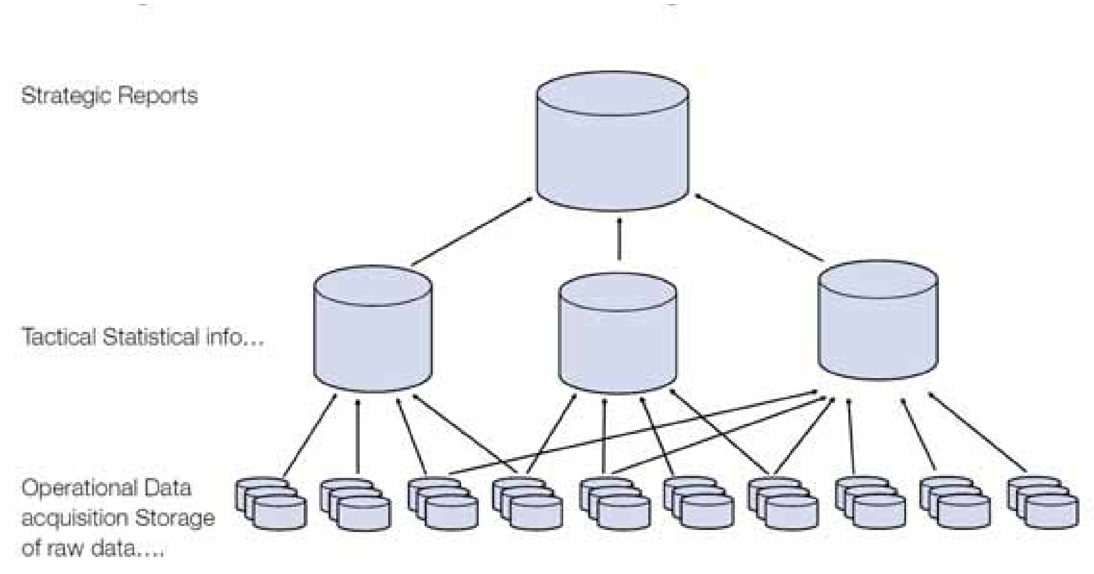


Figure 3: Organisation of structural monitoring data

2.4 Implementation Phases

In general, from a monitoring point of view, the life of a bridge can be described as pre-construction tests, construction, commissioning and operation. It is important in the planning of structural monitoring systems to keep it clear, for which phase the monitoring activities are carried out for. Examples are given in the following table.

Table 2: Monitoring objectives at different bridge life phases for different types of organisational levels.

Phase / Level	Pre-construction test	Construction	Commissioning	Operation
Strategic	Fatigue resistance	Geometry control	Tuned mass damper efficiency	Sufficient durability
Tactical	Field test planning	Planning of geometry checks	Testing programme and success criteria	Planning of deterioration surveillance
Operational	Field testing	GPS measurements	Instrumentation & testing	Corrosion cells and inspection

The SHMS designer shall carefully take the implications of the above table into account in collaboration with the stakeholders to use the system.

2.5 Main Structural Monitoring topics

The overall aims for structural monitoring systems depending on the users and the deliverables they demand has, through the large design and installation experience by COWI and Futurtec, been analysed to include one or several of the following main objectives;

- To ensure safe structures
- To obtain rational and economic maintenance planning
- To attain safe and economic operation
- To identify causes for unacceptable responses

For each main objective it makes sense to define and monitor several application areas and parameters.

The table below gives some examples of how the main objectives can be related to the stakeholders and the phases the system shall monitor from design to operation.

Table 3: Monitoring main objectives related to the stakeholders and the phases from design to operation.

Stakeholder \ Phase	Pre-construction test	Construction	Commissioning	Operation
Authorities		Safety provisions	Safety provisions	Safety provisions
Owners			Design Verification	Safety provisions Maintenance
Designers	Design Verification	Trouble Shooting Design Verification	Trouble Shooting Design Verification	Trouble Shooting
Researchers		Design Verification	Design Verification	Design Verification
Contractors		Trouble Shooting Design Verification	Trouble Shooting	
Users				Safety provisions
Operators				Safety provisions Trouble Shooting Maintenance

The table shows that the operation phase is the most demanding and a large shift in objectives of monitoring occurs from the commissioning phase to the operation phase. This is often reflected by having one SMS in the construction phase replaced by another SMS in the operation phase, each optimised for their specific phase.

In the following each main objective will be broken down into its governing application areas in order to give a comprehensive view of objectives and possible deliveries of Structural Monitoring Systems

2.5.1 Verification and certification

Structural monitoring systems can acquire data on loads and structural responses over long measurement periods to verify stochastic load parameters and structural response versus calculated response. Such data may be used by the constructor to certify the correctness of the structure or to verify deficiencies to the owner. Short time monitoring may include forced loading on a structure or monitoring unexpected loadings (e.g. wind induced vibrations). Such monitoring can be quantified as follows.

Stochastic response

Characteristics of seismic, wind or traffic load parameters and associated structural responses may be measured to verify predictions made by numerical models used in a design phase.

Internal loads

Short time measurement campaigns can be repeated over time to map changes in force distribution in cable stays, foundation piles, etc.

Cross sectional strain distribution can be monitored over long time periods to measure changes in stress distribution.

Fatigue response

Fatigue loads for welded joints, decks and beams are measured with advanced strain gauge or accelerometer systems. Rainflow cycle counting on sampled data is performed in real time by a data logger. Time series, statistical values and time correlated fatigue analysis will be based on Miner sums.

Figure 4: Fatigue monitoring of critical welds by the SHMS on the Øresund Bridge, Denmark - Sweden.

Deterministic response

Temperature movements obtained by hydraulic buffers/dampers and temperature dependent load distribution for orthotropic deck and expansion joints may be monitored by temperature sensors, tiltmeters and GPS systems.

Global static response

Static response for foundations, creep and shrinkage, strain distribution in main cables etc may be monitored by various special sensors. Measurements can be used to calculate parameters such as efficient mean temperature/strain and differential temperature/strain over large distances.

Figure 5: Calibration of FE model by applying a controlled force to a bridge structure.

2.5.2 Maintenance Planning

Monitoring of structures can provide quantification of degradation rates and wear which are essential to a regular updating of information on structural states. This in turn can be used in rational planning of inspection, maintenance activities and calibration of life time models.

Degradation of materials

Corrosion sensors can provide information on the migration of chloride in concrete structures. Service life models can be used to predict when chloride levels become critical and the best time for the establishment of preventive protection can thus be determined even before visible deterioration occurs and the demand for costly repairs arises.

Figure 6: Corrosion cell placed on reinforcement bars before casting concrete.

Wear

Accumulated movements of mechanical installations such as bearings, hydraulic buffers/dampers, expansion joints, etc, may be measured by sensors such as strain gauges, pressure sensors, displacement sensors or accelerometers. The Miners number is used to describe the fatigue level of a measured structure and is determined using the rain flow counting method.

2.5.3 Safety Provisions

Structural integrity of critical elements may be crucial to the operational safety of structural systems. Continuous surveillance of such elements can provide information or alarms to intervene before severe consequences emerge.

Road operation

Road sections may be monitored by metrological sensors (anemometers, wind wanes, rain gauges, etc) for assessment of need and design of side wind bridge obstacles, measures to avoid falling ice from high places on bridges and measures to warn high and light vehicles for dengue's wind conditions.

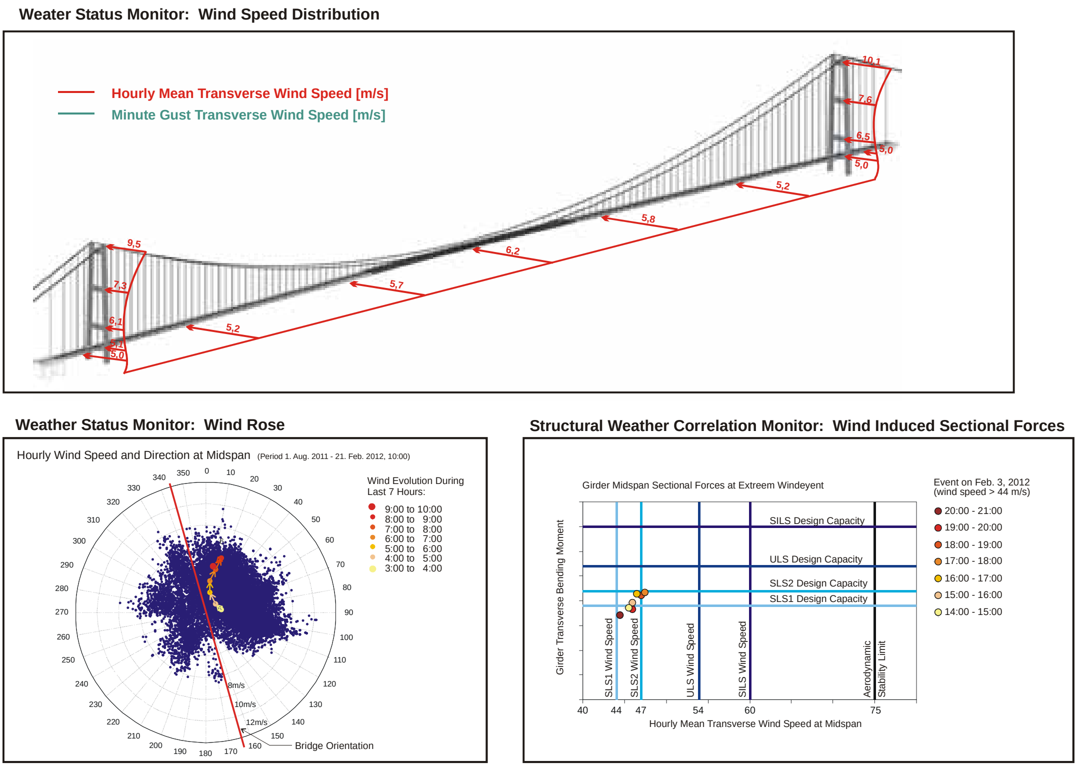


Figure 7: Example of weather monitor designed for the Messina Bridge for user and structural safety monitoring

Disasters

Earthquake and tectonic activity monitoring may also be included in order to give provisions for assessing the structural response.

Other potential disaster situations to monitor are the man-made events of road and rail accidents, ship or aeroplane collision or acts of terrorists. The monitoring system must withstand disaster conditions and partial system collapse yet still provide easy to interpret and reliable information for the operators.

2.5.4 Trouble shooting

Periodic and insufficiently understood responses of structures and associated load parameters (often wind) can be documented through automated measuring campaigns - often of extended duration.

Vibration source identification
The source of vibrations causing problems or structural deterioration can be identified by monitoring.

The measurements can be used to evaluate if acceptance criteria are fulfilled and to identify measures to avoid or dampen the vibrations

Wind induced vibrations
The magnitude of vibrations induced by wind can be difficult to predict during design and occasionally mitigation measures are needed due to unacceptable oscillations. Before implementation it will be necessary to document the extent of the problem and the structure must be monitored for a sufficiently long period of time with special low frequency accelerometers or strain gauges and metrological sensors in combination with Digital Video Camera (DVC) solutions in order to provide data for analysis. Measurements can be used in combination with advanced wind simulation software such as the COWI DVM Flow, bridge modelling software (e.g. IBDAS or TDV) and wind tunnel test results in order to determine the environmental physics behind the wind phenomenon.

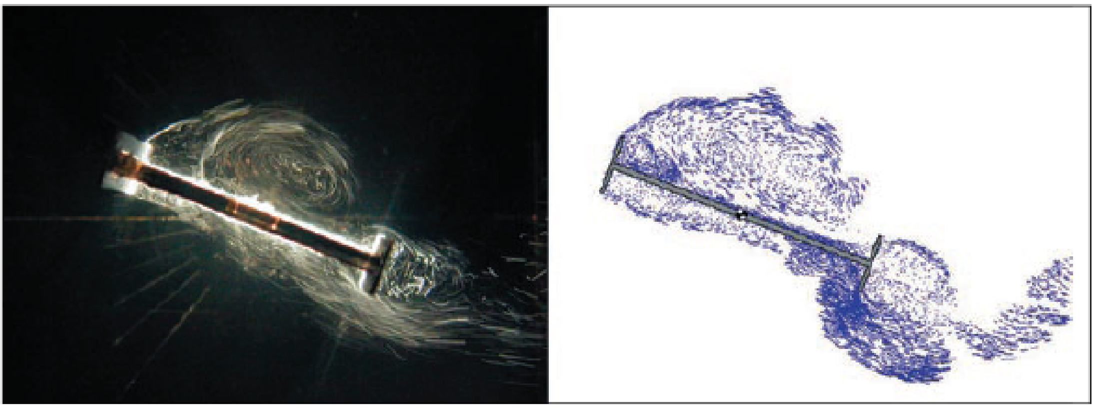


Figure 8: Wind tunnel test carried out to validate DVM Flow simulations.

2.6 Use of Structural Monitoring Systems

Based on the above discussed application areas of monitoring for the purpose of verification, safety, trouble shooting and maintenance modern Structural Health Monitoring Systems shall give operational support for the;

- Bridge operation and control
- Bridge maintenance and management

When planning the SHMS it is important to realise that these two modes of system operation in most cases will require different staff and will be operated in different ways and at different levels.

While the operation and control on most large infrastructures will be in real time 24 hours a day and require surveillance at all times, the maintenance and management will be a tool for the maintenance staff and the bridge management for the planning of inspections, maintenance budgets, forecasts, etc, and will have a time frame from hours up to decades.

Common to both types of operation is the need for event control. An Event shall be every signalling of anomaly, breakdown, accident, unforeseen incident, intrusion, sabotage that generates an alarm, as well as all planned activities that influence the structure's safety, traffic or durability.

The events' management shall first of all provide an estimation of the specific event's impact on the structure: more specifically, the impact on the admissible level of service will be assessed. Based on this evaluation, a management priority shall be assigned to each event.

2.6.1 Operation and Control

For the operation and control every event shall be monitored by the system in its whole duration through the properties of the SHMS.

Information collection related to the event's evolution will be carried out by the event managing module and will be acquired by SHMS, the maintenance sites, the accidents, as well as through coordination with the managers of the interconnected roadways/highways, and/or might be written in by the operator of the event managing or SHMS modules. All information collected on events, included localization, date and time, and on their evolution shall be recorded.

The system will visualize in real time all information related to the events, in the most appropriate way to obtain an immediate and efficient representation (maps, tables, videos), and will grant the research, visualization and necessary elaboration related to user-specified periods or events.

The management of particularly serious events, such as earthquakes, calamities, human actions, etc., shall provide the information concerning the evaluation of consequences and the planning of intervention, evacuation, coordination, allocation of appropriate resources, as well as the evaluation of intervention times.

2.6.2 Maintenance and Management

For the maintenance and management a bridge rating system shall be established to be included in the systematic approach for the inspection and maintenance concept in the proposal maintenance manual for the bridge. This system shall be the core of the Structural Health Evaluation System (SHES) [2].

The bridge rating system shall provide a rational basis for prioritisation of inspections and maintenance on primary and secondary structural components. The categories, primary and secondary structural components, are related to the load capacity analysis model. Secondary components may be out of function without collapse of the entire structure.

The rating system can be based on the results from the principal inspection and the structural health monitoring system (SHMS). Through use of these two in combination the additional inspection and maintenance work can be initiated in a risk based proactive manner. A work order system applying to the result of the bridge rating may also have to be defined as an independent module of the SHES.

The rating system shall be designed to ensure that the needed actions to be taken in order to keep structures safe and in good shape will be taken in time. Such actions include structural repair and strengthening as well as protection against environmental actions.

2.7 Common Design Mistakes

There is the possibility of going wrong in several areas when executing a Structural Health Monitoring project. Some of the mistakes lead to low performance to cost ratio and some actual safety issues. The following is a, in no way exhaustive, list of some typical pitfalls:

- Copying the monitoring scope and execution strategy from similar bridges without taking into account the differences in external factors.

- Substituting knowledge and experience with money.

- Making non-sustainable selections for the resources and technology.

- Underestimating the importance of professional services in configuration, commissioning, operation and maintenance.

3 Verification

The acquisition of data on loads and structural responses for a bridge structure can be used to verify stochastic load parameters and structural responses in comparison with calculated response from the design stage.

These data can be used by the constructor to certify the correctness of the structure or to verify deficiencies to the owner. The designer and researchers can benefit from the data in order to verify the structural response for limit breaking designs or the response to extreme environmental loads.

In general, verification monitoring can be divided into three groups as follows:

3.1 Design Verification - A priori

During the design process for large bridge structures the need for validating modelling procedures for simulating load and responses for wind, seismic, etc can show up.

The verification measurements are usually either carried out by making tests with mock-ups before construction or by measuring critical parameters on structures similar to the design under consideration.

As shown in the examples chapter an example of a priori design verification was the Humber Bridge instrumentation project sponsored by Stretto di Messina Spa (SdM) for verifying flutter ascensions for the box girder design making the Humber Bridge SHMS one of the first examples of a full scale a priori design verification system.

Another example is the monitoring of wind response on different types of vehicles at the work site during the construction phase for the Great Belt East Bridge in order to define wind speeds giving restrictions to the use of the bridge.

3.2 Design Verification - A posteriori

A posteriori design verification is the classic use of structural monitoring. Hereby the assumptions for stochastic load parameters and structural responses in comparison with calculated response can be verified.

Decades ago the modern use of structural monitoring was driven by the researchers need to verify limit breaking designs. It is still often seen that universities or researchers are responsible for the design of SHMS on a modern bridge to support their need for data to support research.

When designing SHMS today it shall be considered that the design verification supporting capabilities of the system most often only will be of interest during the first year of system operation. As time goes by for the service life of the structure the need for design verification data decreases. Having this in mind in the sensor system design can be an advantage, as specially embedded sensors are used for design verification. Once the limited life time for the embedded sensors supporting design verification has been used they can simply be left out without replacement as they have served their purpose.

3.3 Construction Verification

Monitoring during the construction phase of a bridge will provide for the detection of meteorological, seismic-tectonic, geometrical, structural data and/or other data considered as being useful to build the "history" of the construction work. Also a construction structural monitoring system can be the tool of choice for the designer and contractor in order to monitor construction phases and so provide information for:

- Environmental impact
- Geometry control
- Distribution of cable forces
- Load effects in temporary stages (e.g. tower construction)

When designing the construction structural monitoring system consideration should be given to use of same sensors that will be used for the final monitoring system as soon as they have been installed during the construction phase.

Use of the Structural Health Monitoring in verifying or certifying the state of structure at the point of project transfer from constructor to owner is also becoming a common practice. This transfer happens at the end of a warranty period or in the case of a BOT-contract at the end of the concession period. On one hand the constructor uses the solution to certify the quality of their design, materials, processes and workmanship prior to the transfer. On the other hand the monitoring results will unambiguously verify whether the structural loadings have been within the design limits and if the environmental, seismic, traffic loading and other external factors reflect the initial estimates. The above is of course true only if the solution has been used and has been reliable since construction start.

4 Inspection & Maintenance Planning

In order to get the full benefits of a structural monitoring system at any scale that will achieve the goal of support for increased safety and maintenance cost savings, application areas of the monitoring system such as those shown above must be planned and designed based on a very clear strategy from the beginning to reflect that the SHMS will have to support both operation and maintenance of the bridge.

A design approach ensuring the above will be achieved and can, especially for large scale monitoring systems, be based on the combination of two methods in order to provide the design basis for a SHMS.

First a Life Cycle Cost (LCC) analyse for the bridge to be monitored may preferably be carried out followed by the planning of a Bridge Rating System to provide a rational basis for prioritisation of monitoring/inspections and maintenance on primary and secondary structural components whereby, the monitoring need may be mapped.

These types of analysis can typically be widely re-used for specific bridge types such as cable stayed-, suspension- or arch bridges. In the following the concept of these analysing and planning tools are described more in detail.

4.1 Life Cycle Cost (LCC)

Typically the LCC will be carried out for a period of 30 years of operations covering the total cost of operation and maintenance of the bridge.

The operation and maintenance is typically defined as follows,

Operation covers: Surveying, cleaning, road and rail patrol, routine inspections, monitoring and administration.

Maintenance covers the following major elements: Main cables, hanger cables, cable clamps, roadway surfacing, railway track systems, external surfaces of the bridge girders and cross beams, upper surface of the railway bridge girder, external surfaces of towers, crash barriers and wind screens, roadway expansion joints, railway expansion joints, buffers at towers and terminal structure and the electrical system. Based on experience, maintenance of these elements covers 90% of all maintenance costs for a suspension bridge.

The level of operation and maintenance costs and thereby the extent of a SHMS can be reduced by paying attention to a combination of the following considerations:

- That the Owner provides a high level of attention to operation and maintenance considerations in the project requirements.

- That the bridge design will be based on many years of experience in design and maintenance of major bridges. This experience shall be fully applied and will ensure that intentions of operation and maintenance are incorporated in the bridge design.

4.2 Maintenance Management System

A maintenance and management system (MMS) can be planned to be included in the systematic approach described in the inspection and maintenance concept in the MMS for the bridge. The scale can be from very simple to complex, depending on the type and size of the bridge [2].

The MMS includes a rating system based on inspection and monitoring by the SMS. This can be provided from a rational basis for prioritisation of monitoring and maintenance on primary and secondary structural components. The categories, primary and secondary components, are related to the load capacity analysis model. Secondary components may be out of function without collapse of the entire structure.

The rating system shall be based on the results from the principal inspection and the structural monitoring system. By using these two in combination the additional inspections and maintenance work can be initiated in a proactive manner.

The rating system shall preferably be designed to ensure that the needed actions will be taken in time in order to keep structures safe. Such actions include structural repair and strengthening as well as protection against environmental actions.

Rating of components for management and maintenance may be influenced by many factors, most politically determined. However, normally three main factors are considered:

- Structural safety (sufficient load capacity)
- Durability (ensuring overall optimal maintenance for the entire life time)
- Safety for road users (risk as well as comfort)

The following figure shows how the SHMS may act as an integrated part of the management system similar to the inspections. This means that the management may benefit from the SMS in the long term planning of preventive maintenance and in the day to day corrective maintenance. Both superficial and maintenance inspections are routine inspections that create no information to be included in a rating process. It shall be emphasized that one should not rely fully on the data and results from a SHMS but on a combination of monitoring and inspections done by experts.

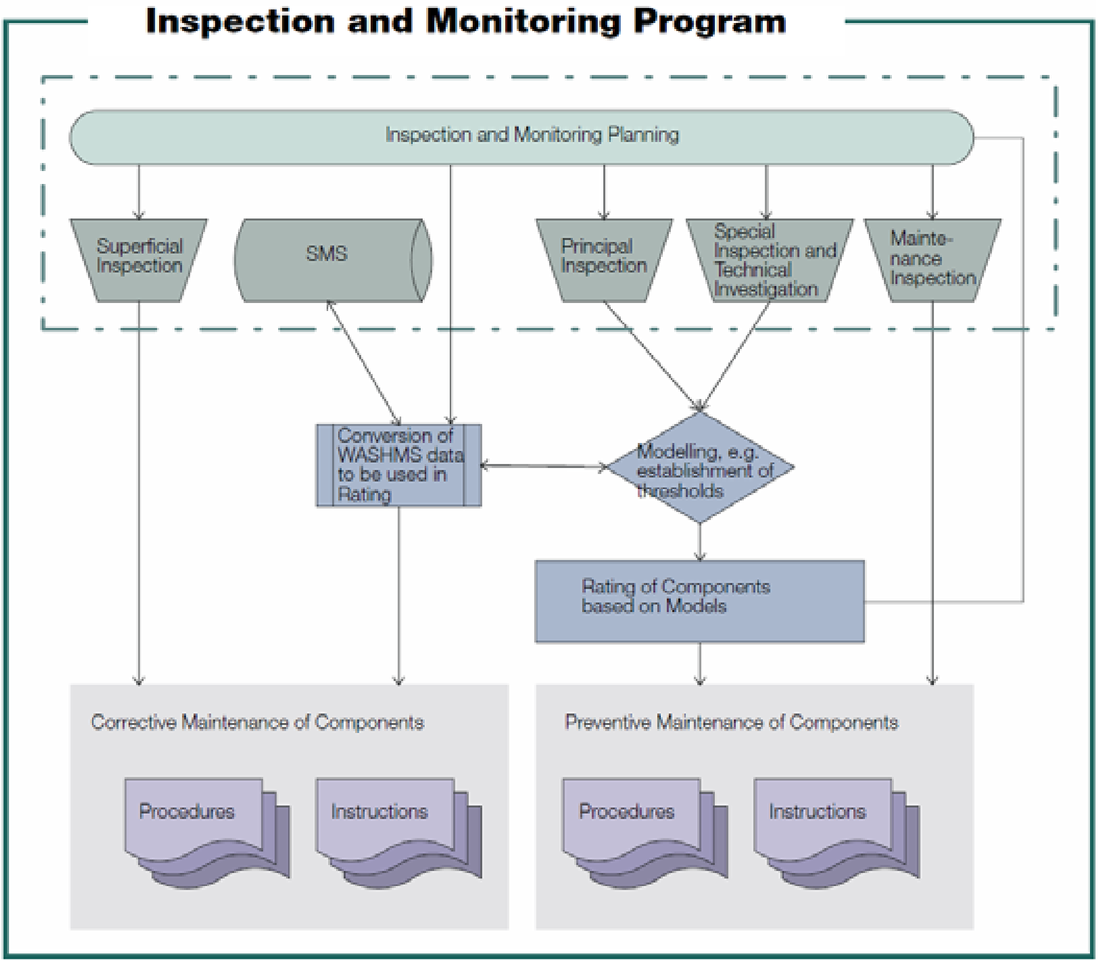


Figure 9: Bridge inspection program based on results from visual inspection and a structural monitoring system.

The Principal inspection creates the quantitative values to be included as the condition rating of the structural components. The evaluations done during a Principal inspection can be supplemented and supported by a monitoring programme. This monitoring may be done by an SHMS but also monitoring done during special inspections may create the supplementary measurements to create the basis for evaluation of the condition of the structural elements. It is important to be aware that the measuring methods in the SHMS and the related result evaluation shall be adjusted frequently as experience with the system grows.

4.3 Structural Health Evaluation System

A Structural Health Evaluation System (SHES) can be based on a general bridge rating system to enable the bridge operator to carry out the operation of the bridge and maintenance of the bridge structure and installation in a safe and structured manner.

The SHES will receive information on structural events from the event Manager, a program that sorts out all alarms and warnings from the monitoring system. This can either be events measured by the SHMS or events logged manually in the event database, based on visual inspections. By the properties of the event the SHES will automatically update the bridge inventory according to the outlined principals for bridge rating described in section 7.3.1.

The rating of the monitored structural component will be saved in the bridge inventory. The bridge inventory can be provided with a graphical front end, showing the operator the current maintenance state of the bridge at all times. When an alarm colour shows on the display as shown below, the operator can zoom in to se the structural component.

Also the graphical front end will be the planning tool for the maintenance planning system in order to evaluate what work orders for maintenance inspections shall be issued and to coordinate work orders planned at nearby locations on the bridge to be carried out at the same time.

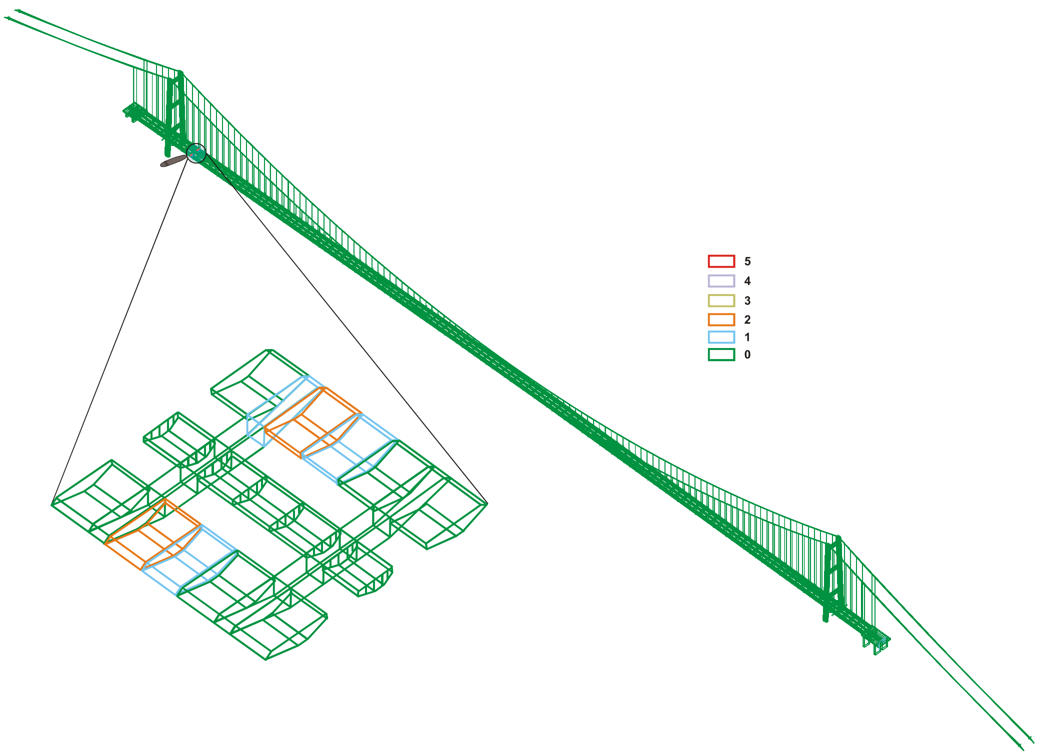


Figure 10: Graphical front end of bridge rating database

The system shall preferable operate together with a Traffic Management System (TMS) to be used to find out when maintenance works affecting the traffic flow can be carried out and what the consequence for the traffic demand will be.

5 Safety Provisions

Structural integrity of critical elements may be crucial to the operational safety of structural systems. Continuous surveillance of such elements can provide information or alarms to intervene before severe consequences emerge. In case of events affecting the user safety, the users must either be warned by proper information channels or be prevented from using the structure

5.1 User safety

The users will typical be warned about events affecting safety by the use of variable road signs and possibly by traffic radio announcements. For most types of events the users will still, depending on the risk, be able to use the structure, but will be warned. The following list shows some of the most common user safety events to consider what the planned SHMS has to handle

- Side wind
- Traffic accidents
- Vehicle stop
- Expansion joint openings
- Icing on road or on the structural elements. Potential falling of ice onto bridge users or third parties.
- Aquaplaning
- Ship impact

How to handle some of these user safeties related events are described in more detail in the following.

5.2 Third Party Safety

Third party safety is often underestimated when planning SHMS for a structure, as the structure itself and the users will be more directly in focus. However the safety aspects of common issues as follows must be considered

- Air warning light operation
- Ship warning light operation

- Moveable bridges - opening for shipping traffic
- Ice falling from the structure

5.3 Environmental Impact Surveillance

The demands for the protection of the environment surrounding structures from neighbours, NGO's and authorities have been increasing during the last decade. In urban areas restrictions may exists for traffic noise and air pollution which in turn calls for the measuring of impact in order to be able to assess if any damping / reusing measures shall be applied to the structure.

Also in nature reserves or similar areas, warning systems for severe oil or other liquid pollutant spillage may be required.

6 Trouble Shooting

Unforeseen structural problems due to the structures exposure to the environment are often seen. Such periodic and insufficiently understood responses of structures and associated load parameters (often wind) can be documented through the capabilities of an installed SHMS.

Most often a measuring strategy for trouble shooting will be based on measuring the structural response at a few structural components known often to give problems with wind, traffic etc. Then, if a problem shows, the extent can be measured by a portable data acquisition system in order understand and document the problem better than only to relay on visual observations and then to start a temporary monitoring system

In the following some considerations on common trouble shooting procedures are given.

6.1 Vibrations

Wind induced vibrations for structural components such as cables, railings, crash barriers, girders, etc are quit common for large bridges.

Such vibration incidents, especially for cables, are difficult to control and almost impossible to eliminate completely. However it is important, that the magnitude of vibrations is minimized to such an extent that the structural integrity is maintained, and failure due to e.g. fatigue will not occur. Also the visual discomfort of large cable or girder vibration can lead to traffic braking up and give rise to traffic accidents.

Sudden rupture of a cable is a safety risk and replacements of cables are costly and will cause disturbance to the traffic. Large cable and girder vibrations should consequently be avoided.

In order to find the cause of the vibrations, reducing the vibrations to an acceptable level by installation of vibration mitigation measures (dampers) and subsequent evaluation of the efficiency of the dampers, the SHMS must provide information about vibrations, wind velocities at- and temperatures of the monitored structural component.

6.2 Damage Identification

Vibrations, temperature variations and settlements can typically lead to damages such as fatigue, cracks and deformations.

The detection of damage can be carried out means of simple to very advanced methods as follows:

- By regular visual observations of the structure.

- By the direct incidents as large vibrations monitored by the SHMS or by observations leading to a concern or assumption of damage initiating a visual inspection.

- By advanced computer analysis of the data collected by the SHMS finding patterns in statistical and time data indicating damage at a structural section or component on the structure.

The advanced methods will typically be based on a 3-D finite element model for the structural components or sections of interest in order to have a better correlation with the measured results and to minimize the efforts of data conversion. The instrument locations and/or components will be referred to in the model for future correlation with measurement results. Here, vehicular load trials and ambient vibration measurements can be used to calibrate the static and dynamic characteristics of the modelled object. The calibrated model can then be continuously updated to form an important part of the structural health evaluation process for damage detection.

Through the process of validation with measured data, the criteria for monitoring of loads and responses can be calibrated or updated, which in turn improves the efficiency of the structural health monitoring and evaluation processes.

The model can then provide the basis for the establishment of predictive models for responses based on the methods of finite element-based system identification, statistical pattern recognition and neural network for damage diagnosis and prognosis [12].

6.3 Post-Accident Evaluations

After disasters such as major earthquakes, hurricanes, ship impacts, etc affecting the global structural integrity or more local accidents such as fire or traffic impact to structural components, the need for a check of the structural integrity arises.

Such checks will always be based on in-situ investigations carried out by structural engineers. However an SHMS can provide very important information regarding the dynamic impact on the structure as the accident happened and may help observing if any force redistribution or settlements' are indicating non visual damage.

7 Event Control

Structural Health Monitoring Systems shall give operational support for the;

- Bridge operation and control
- Bridge maintenance and management

Structural Health Monitoring Systems collect vast amounts of data; however the important data will in the long term only be a very small fraction of all data collected over time. In order to ensure that all important data to analyse will be acquired, event control and management is required.

The approaches for the acquisition, storage and compression of the data will be discussed in later chapters. Regardless of the amount of data, criteria for the selection of the few data adding adding new information to the application areas of design verification, user safety, maintenance planning and trouble shooting must be developed for each individual SHMS depending on the structure to monitor.

Subsequently an SHMS shall consider, as mentioned in chapter 2, an event as every signalling of anomaly, breakdown, accident, unforeseen insident, intrusion, or sabotage that generates an alarm, as well as all planned activities that influence the Bridge safety, traffic or durability. This includes both unforeseen events and expected or planned events.

Every event shall be monitored by the system for its' whole duration through the properties of the SHMS.

The event control system shall visualize in real time all information related to the events and the most appropriate way to obtain an immediate and efficient representation (maps, tables, videos), and will grant the research, visualization and necessary elaboration related to user-specified periods or events depending on the extent of the SHMS.

The SHMS operators shall for larger systems see a constant real time updated list presenting all events, the priority assigned to each event and what staff and systems will be responsible for following up on the events. It shall also be possible to track the status of an event until it has been registered as solved.

The management of particularly serious events, such as earthquakes, calamities, human actions, etc., will provide the information concerning the evaluation of consequences and the planning of intervention, evacuation, coordination, allowing securing the bridge in the best possible way

7.1 Operation & Control Events

Typical events effecting the operation of the bridge and requiring control by the intervention of the operational staff of the SHMS are situations concerning the user safety such as strong winds, traffic accidents, fire or natural disasters.

In the following some examples on event control are given.

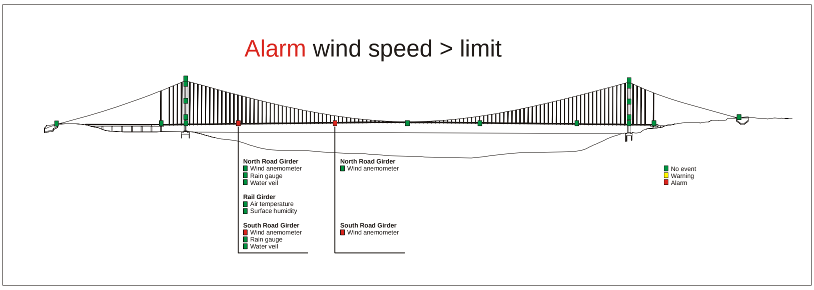
7.1.1 Weather Alarm

Whenever the wind speed experienced by vehicles on the structure is measured to be above the acceptable limits for different classes of vehicles an alarm will be flashed to the SHMS operator on the control room wall screen and the TMS manager’s screen.

As shown in Figure 11 the electronic traffic signs controlled by the bridge operator shall warn the users according to the alarm. Maintenance personal on the bridge will be updated and the weather forecast system will be initiated in order to predict the time until the user restrictions may be lifted.

Weather Alarm

Operational Status Monitor: Meterological Monitoring



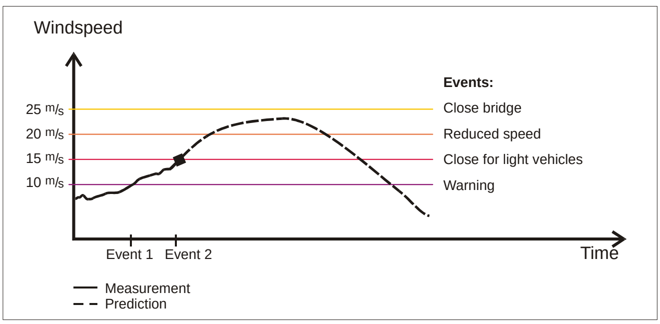
Event Management Initiates Automatically

Traffic information

Alarm personel

Weather forecast

Simulation and prediction monitor: Weather simulation



Update: - Bridge servicibility level update based on predictions
- Information to relevant autorities and regional traffic information
- SMS service to frequent bridge users

Figure 11: Wind speed warning to bridge users.

The TMS manager will be able to follow the development of the alarm condition on the simulation and prediction monitor. This information may also be relayed to users by mobile telephone SMS service for frequent bridge users and on the bridge web portal.

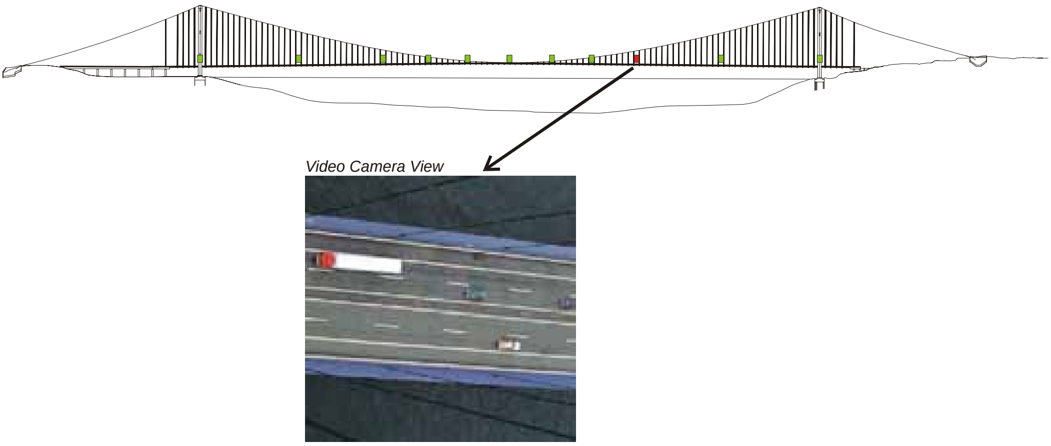
7.1.2 Accidental Actions

The SHMS shall take the reporting of accidental actions into account for event management. All accident scenarios described in the design shall be managed by an accident module of the SHMS event manager.

Accident Alarm

Traffic Status Monitor: Video Camera Monitoring

Alarm: Stopped Car Detected



Traffic Control Operator:

Emergency Identification and Traffic Alarm System Standard Input:

	Emergency Identification	Location	Severity
	Unautorized Stop		
	Cue		
X	**Accident**	1,000 km	3
	Fire		

Traffic Alarm System Automatically Initiates:

- Alarm to Emergency Service
  - Fire Brigade
  - Ambulance
  - Police
- Traffic Information (VMS)
- Alert Nearby Personel
- Information to Relevant Autorities, Regional Traffic Information, SMS Service to Frequent Users
- Short and Medium Term Bridge Serviceability Update

Figure 12: Accident alarm.

In the case of accidents, the event manger will, based on input from the TMS, give the SHMS operator the actions to carry out as soon as the operator, based on the video flow and data values he will receive, has classified the accident type for the system.

Figure 12 shows an example of a fire detected in a vehicle.

7.2 Maintenance Events

Common events affecting the maintenance of the bridge and requiring inspection by the maintenance staff are situations concerning the monitoring of developing fatigue, discontinuities in temperature expansion, vibrations, settlements, etc.

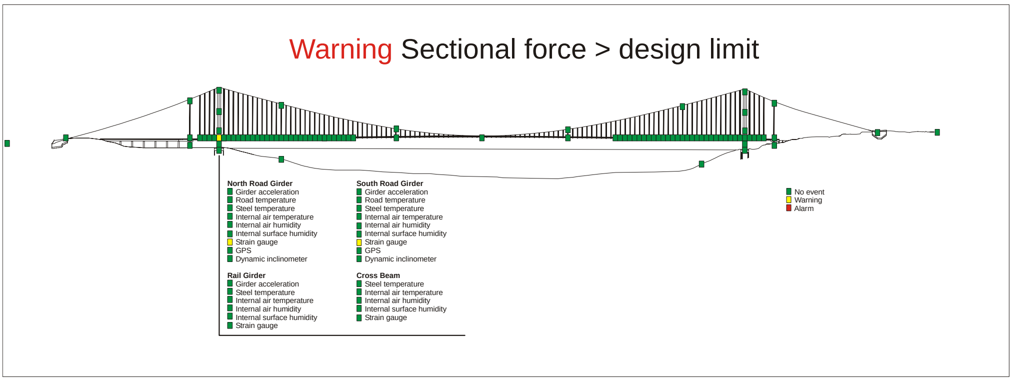
In the following some examples on maintenance events are given.

7.3 Structural Event

The SHMS monitors the structural state of the bridge. When a pre-set threshold value is trespassed the SCADA system will generate an event warning or alarm based on the severity. The event will be passed on to the event manager and be classified as a structural event. From here the event will automatically be passed on to the bridge rating module. Here the structural component monitored and all similar structural components will be given a rating based on preset weighing functions taking the importance of the structural component and the distance to other similar components into account.

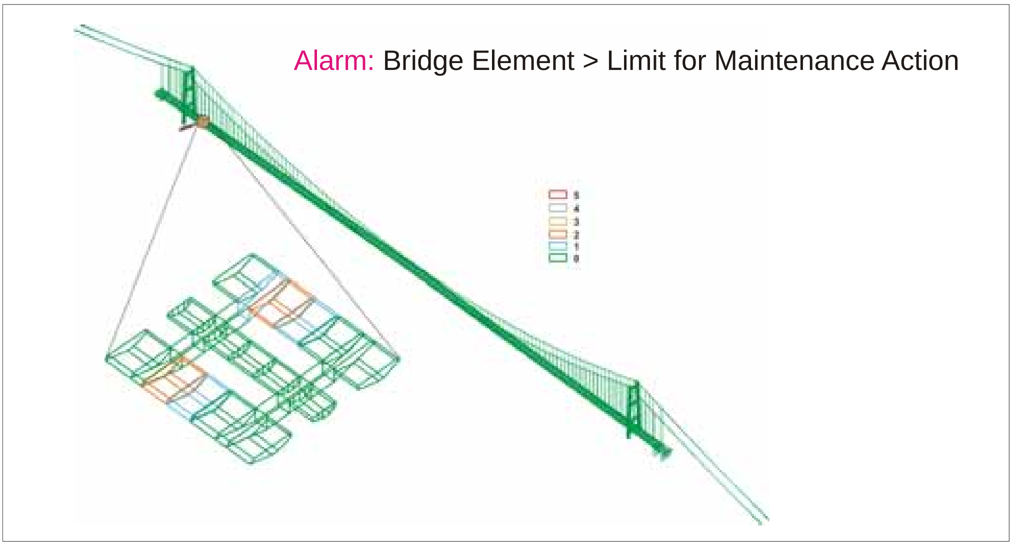
The result of the rating is stored in the inventory. The maintenance planning operator will have a graphical interface to the inventory, as shown in the following figure. Here he can at any time see the current state of all structural components and their actual rating. The graphical interface can be used to allow the Maintenance Planning operator to take immediate decisions concerning the operation of the bridge if an alarming condition is shown. Similarly by the works maintenance planning manager for the optimisation of maintenance works and coordination of different maintenance tasks to be carried out at the same locations at the same time on the bridge.

Operational Status Monitor: Structural Monitoring



↓ Automatical update of Bridge Rating

Bridge Rating Monitor: Structural Health Overview



↓ Automatical Alarm Message

Maintenance Management

Work Order

Works maintenance planning system

- Change of maintenance plan
- New inspection tasks

Structural simulation

- Caculation effect of warning
- New monitored tests

Figure 13: Example of structural alarm/warning and subsequent work flow.

7.3.1 Evaluation of structural response

The evaluation of structural response will be based upon real time structural events collected by the SCADA. Structural events may be passed on from the event manager to a Bridge Rating Module.

The rating system will provide a rational basis for prioritisation of inspections and maintenance on primary and secondary structural components. The categories, primary and secondary components, will be related to a load capacity analysis model. Secondary components may be out of function without collapse of the entire structure.

The rating system will be based on the results from the principal inspection and the structural health monitoring system (SHMS). By using these two in combinations the additional inspections and maintenance work can be initiated in a proactive manner managed by the maintenance planning system.

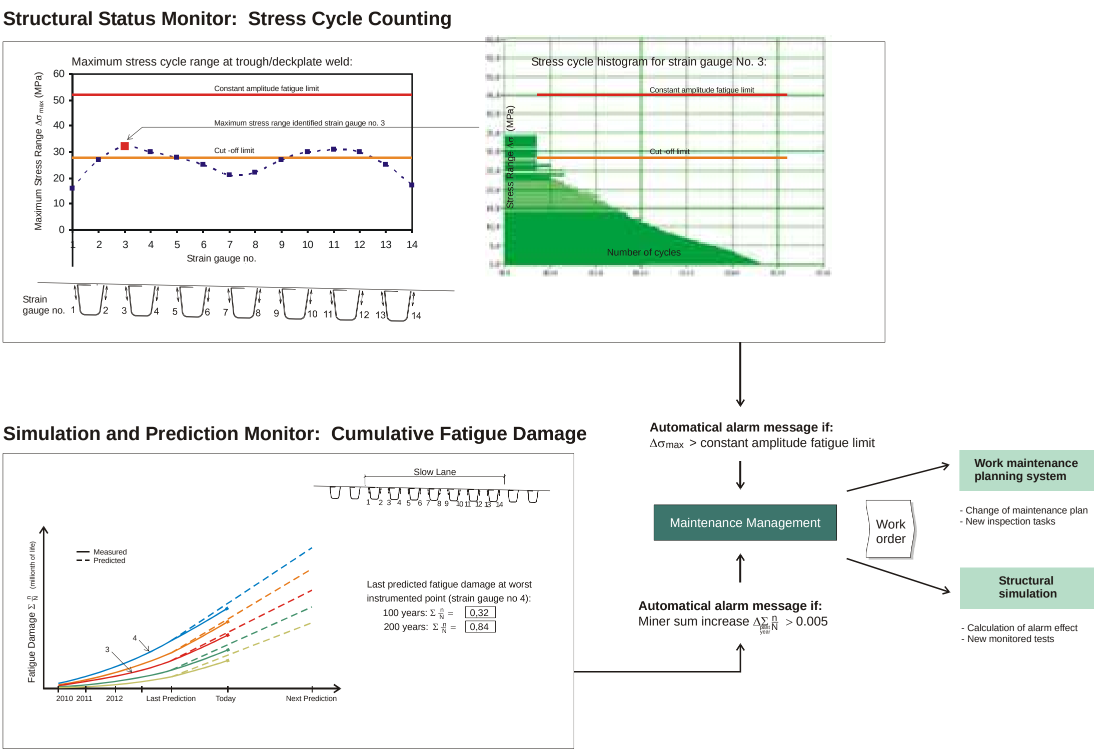


Figure 14: Monitoring stress cycles and fatigue.

As shown in the above figure, the evaluation of structural response could be a fatigue problem. Once the SHMS has reported the threshold value for fatigue based on real time rain flow counting has been passed, the event will be interpreted by the event manager and the bridge inventory will be updated with an automatically set rating for the monitored cross section. Once reported to the works maintenance planning system a work order for visual inspection will be initiated. The system will help the manager to plan the inspection to take place together with other inspections at the same location and will insure the inspector is equipped with the correct tools, work plans and certificates to undertake the work. The visual findings will be reported back into the inventory and maintenance planning system and, based on the result, either further analyses involving the structural simulation system may be initiated or the SCADA operator may be instructed to adjust the threshold values for the monitoring system,

7.3.2 Service life models

Service life models for the structural components of the bridge will be derived from information from the bridge rating module stored in the bridge inventory, trends derived from analyzing data in the SCADA database and simulation information from the structural and traffic simulation systems.

This means that the system will be able to handle structural elements and combine information on condition and materials and relate these data to components. Additional specified algorithms will be added on the material level.

The following example shows how the probability of corrosion will develop over time, based on two different models taking monitored data into account

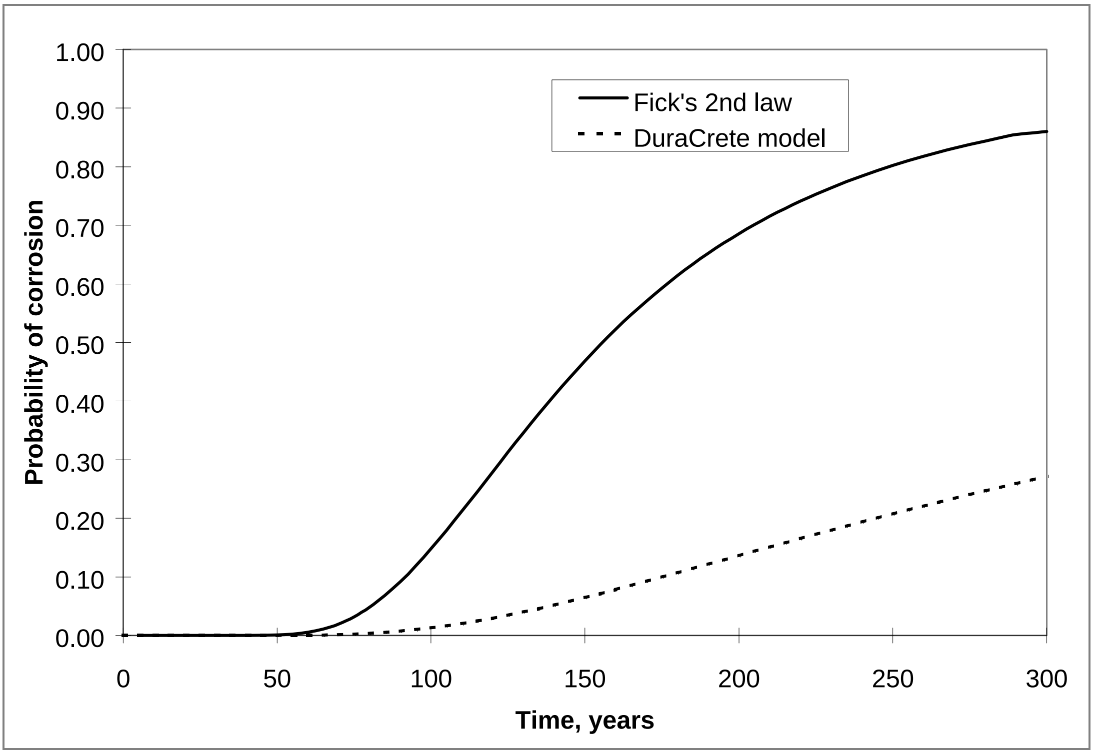


Figure 15: Probability of server corrosion damage as a function of time

7.4 Structural Health Evaluation Systems

In order to support the maintenance staff and maintenance planning of a bridge with a SHMS, a post processing system for health evaluation can be considered. The SHES shall be an integrated part of the Bridge Maintenance Management System (BMS) for the bridge.

On large scale systems there will typically be a control and operation centre acting as the central module for the coordination, control and management of each sub system of a SHMS and controlling the interface to other monitoring applications.

In the following an example for the organising of an SHES comprised of the following applications

- Event Manager
- Bridge Rating Calculation Unit
- Maintenance Planning System

7.4.1 Event Manager

The Event manager will be an application to sort out structural events from the recordings of the SHMS

The system will consider as an Event every signalling of anomaly, breakdown, accident, unforeseen event, intrusion, sabotage that generates an alarm, as well as all planned activities that influence the Work's safety, traffic or durability.

The event management will first of all provide an estimate of the specific event's impact on the work: more specifically, the impact on the admissible level of service will be assessed. Based on this evaluation, a management priority will be assigned to each event.

The management of particularly serious events, such as earthquakes, calamities, human actions, etc., will provide the information concerning the evaluation of consequences and the planning of intervention, evacuation, coordination, allocation of appropriate resources, as well as the evaluation of intervention times.

7.4.2 Bridge Rating Calculation Unit

A rating system may be established to included the systematic approach described by the inspection and maintenance concept in the proposal maintenance manual for the Bridge.

The rating system will provide a rational basis for prioritisation of inspections and maintenance on primary and secondary structural components. The categories, primary and secondary components, are related to the load capacity analysis model. Secondary components may be out of function without collapse of the entire structure.

The rating system is based on the results from the principal inspection of the BMS and the SHMS. By use of these in combination the additional inspections and maintenance work may be initiated in a proactive manner.

The rating system shall be designed to ensure that the actions that need to be taken in order to keep structures safe will be taken in time. Such actions include structural repair and strengthening as well as protection against environmental actions.

Rating of components for management and maintenance may be influenced by many factors. However, normally three main factors are considered:

- Structural safety (sufficient load capacity)
- Durability (ensure overall optimal maintenance for the entire life time)
- Safety for road and rail users (risk as well as comfort)

A point ranking concept will be general which means that the method may be used on both structural components and installations (mechanical and electrical).

For maintenance management of structural components it is necessary to consider the risk imposed by the possible failure modes of the individual component.

The point ranking method, which calculates the final priority-ranking point for the component, *PR,* is in this context based upon the load capacity points P_{cap}, but also such factors as the condition points, P_{con}, and other influencing factors, such as for instance road user points, P_{road}, shall be taken into consideration. Thus *PR* can in general be expressed as a function:

$$PR = f(W_{cap}, P_{cap}, W_{con}, P_{con}, W_{road}, P_{road}, \ldots)$$

W expresses the weightings of the factors for the individual component. For instance will W_{cap} express the weight (the importance) of the load capacity for the considered component being maintained.

The range of the Condition Mark will normally be from 0 to 5 and can be interpreted as follows:

Rating 0:	As new component
Rating 1:	Registration of no significant defects
Rating 2:	Recognizable defects but of minor, non-urgent nature
Rating 3:	To be included for attention/repair in preventive maintenance programme
Rating 4:	Severely damage and requires urgent remedial work.
Rating 5:	Alarm

For the structural components automatically rated by the data from the SCADA the main component will receive the full rating, while structural components similar to the monitored component will receive a rating based on a weighing function taking the distance from the primarily monitored component into account [2].

7.4.3 Inspection Program

The priority ranking is based on a system of inspections and monitoring. Inspections such as maintenance, principal and special inspections create together with different monitoring the data to be included in a priority ranking process.

The Principal Inspection creates the quantitative values to be included as the condition rating of the structural components. The evaluations done during a Principal Inspection will be supplemented and supported by the monitoring programme. This monitoring will be done by the SHMS, but also monitoring done during special inspections can create the supplementary measurements to create the basis for evaluation of condition of the structural elements. It is important to be aware that the measuring methods the SHMS and the related result evaluation can be adjusted frequently as experience with the system grows.

An important part of the inspection and monitoring programme is the execution of special inspections and technical investigations when necessary. These inspections and investigations are initiated due to e.g. unexpected SHMS measurements, extended damage or indication of the beginning of failure of the components. Most of the data evaluation and modelling is expected to be done on the basis of special inspections. The work flow is showed in Figure 16, an example from the design of the Messina Bridge.

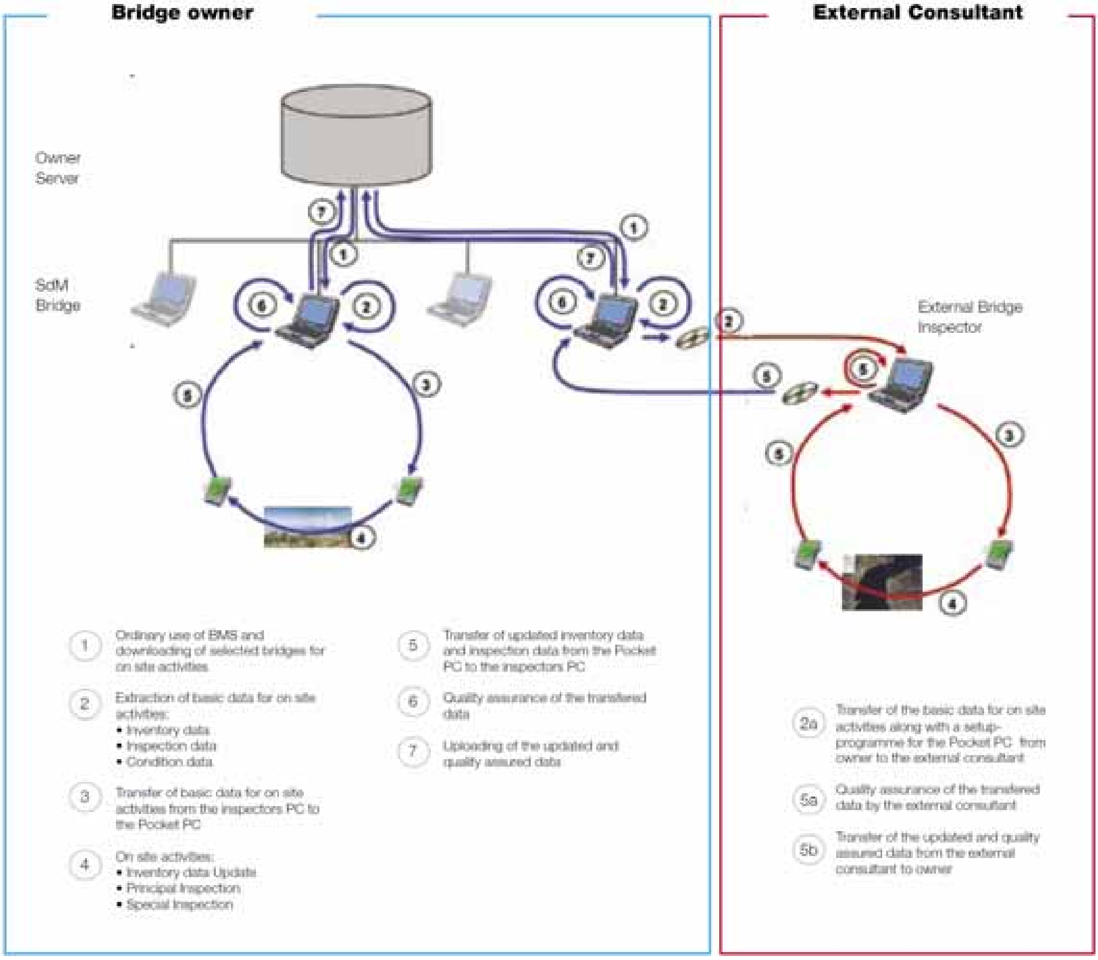


Figure 16: Maintenance workflow based on events recorded by SHMS and inspections.

Part II: BRIDGE MONITORING APPLICATION EXAMPLES

8 Examples of Systems on Existing Bridges

Since the 1970's Structural Monitoring Systems based on automatic data acquisition has slowly been developed from relatively small systems logging only semi static parameters to today's distributed data acquisition systems with a high degree of build-in structural evaluation and decision support.

In Figure 17 the extent/size of monitoring systems are plotted for cable stayed bridges (blue dots) and suspension Bridges (green dots) as a function of completion time and main span length. The figure indicates that the extent of monitoring activities is increasing with the size of the main span - and as span lengths are ever increasing the size of the monitoring systems is also increasing.

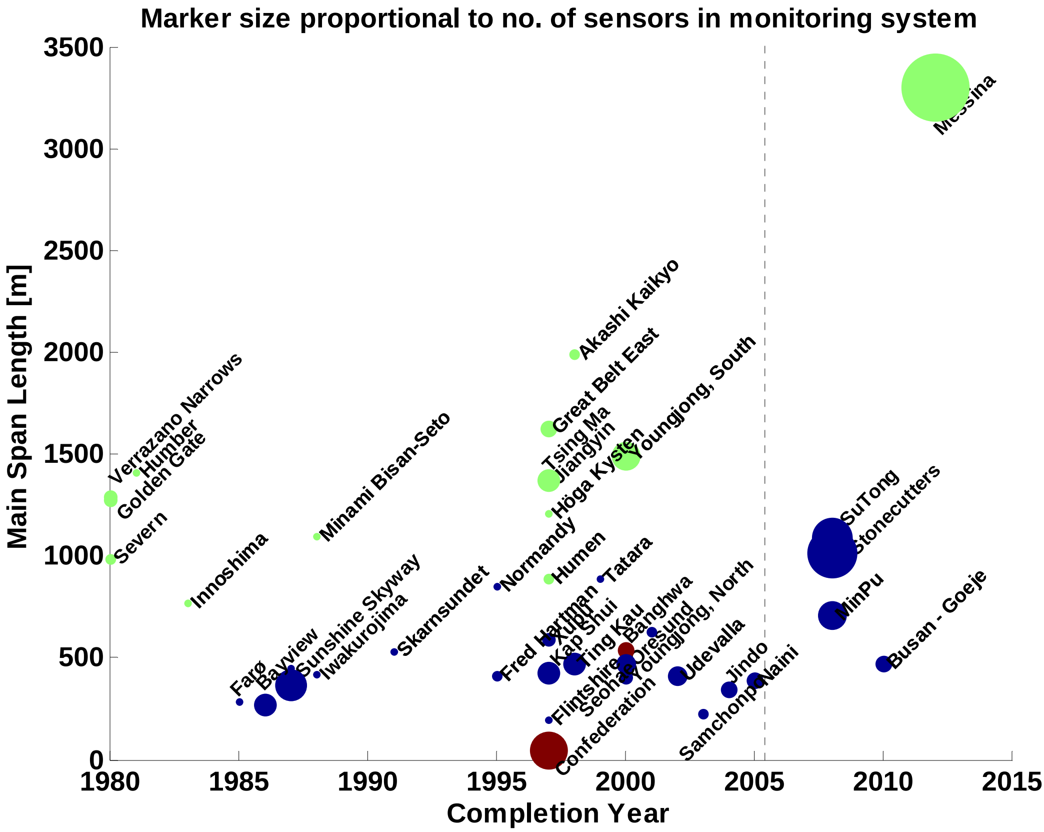


Figure 17: *Size of applied monitoring systems plotted against construction completion year and main span length for suspension bridges (green dots) cable stayed bridges (blue dots) girder bridges (brown dots).*

In the following some typical systems will be described to show the development over time, and the application to various bridge types in many countries around the world.

8.1 Humber Bridge, UK - 1981

The Humber Bridge opened in 1981 is a suspension bridge which from 1984 to 1998 held the world record for largest span, at 1410 m.

Figure 18: Humber Bridge, United Kingdom

8.1.1 Quick Facts

- Name and Location: Humber Bridge – Kingston-upon-Hull, England, United Kingdom.
- Owner: The Humber Bridge Board.
- Structure category: Suspension bridge gravity-anchored, inclined hangers, asymmetric
- Spans: main span 1410 m, total length 2220 m, span lengths 280 m - 1410 m - 530 m
- Structural system: Reinforced concrete towers and steelbox girder.
- Start of SHMS: 1985 - 1992
- Number of sensors installed: 58 sensors
- Instrumentation design by: Bristol University & Stretto di Messina Spa.

8.1.2 Description of the structure

The Humber Bridge is a suspension bridge. The 1410 m main span is one of the longest in the world, and the bridge has a total length of 2,220 metres. The main span is suspended between towers that rise 152 metres above their supporting piers. It carries a four-lane highway and pedestrian walkways. The bridge comprises reinforced concrete towers, aerial-spun centenary cables and a continuously-welded, closed – box road deck supported by inclined hanger cables. Its design lifespan is 120 years.

8.1.3 Purpose of the instrumentation

In the 1980s research was being conducted to establish the performance of long span suspension bridges subject to dynamic loads. Humber was subsequently used for validating the modelling procedures for simulating wind-induced response of the performance of a proposed 3300m span for the Stretto di Messina (Messina Straits) suspension bridge [3]. To this end, an instrumentation project was sponsored by Stretto di Messina Spa (SdM) making the Humber Bridge SHMS one of the first examples of a full-scale a priori design verification system. Figure 19 is a schematic of the elaborate instrumentation package installed on the bridge, employing over 32km of instrument cabling [5].

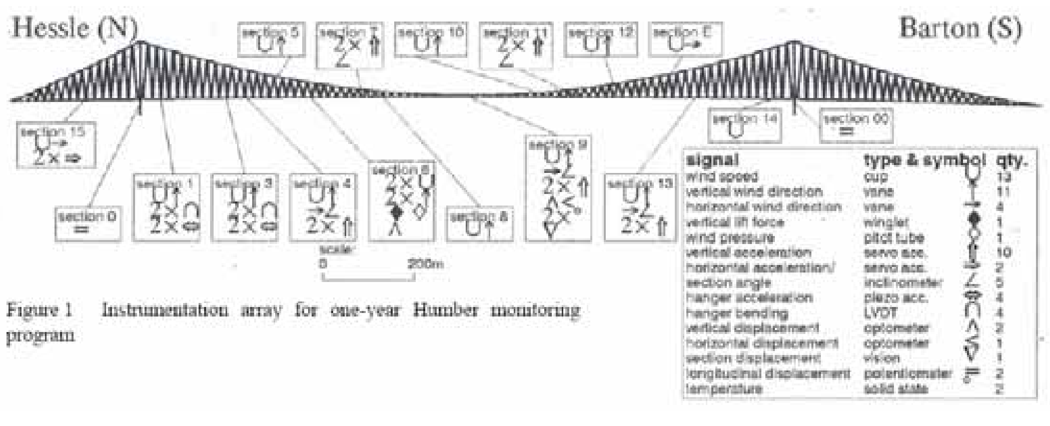


Figure 19: Temporary SHMS installed at the Humber Bridge, UK.

8.1.4 Examples of outcomes

Safe (high) flutter speeds achieved through design of the deck girder shape depends on good understanding of the wind-structure interaction. Even with reasonably accurate modelling of the structure there is still great uncertainty in the loading mechanisms. In the Humber monitoring exercise, wind, displacement and acceleration signals were recorded for a range of wind conditions, allowing for system identification of the aero-elastic components of the stiffness and damping, for comparison with values estimated from wind tunnel studies. More importantly, predictions of response based on knowledge of the structure, wind conditions and structural and aerodynamic system were validated, allowing for the same modelling procedures to be used to predict the response of the Messina Bridge based on local climate, structural design of the bridge and aerodynamic parameters determined from wind-tunnel test.

8.1.5 Benefits of using SHMS technologies in the project

The monitoring exercise provided data to establish relationships between loading effects and responses.

Inspection and maintenance programs for Humber follow UK guidelines: Each structural component is checked every two years, with principal inspections every six years and special inspections. Numerical simulations showed that observation of global response e.g. deck accelerations is highly unlikely to indicate structural damage or deterioration to the major components of the superstructure. The components that do need occasional attention or even replacement are hangers (suspenders) and bearings, for which a range of short term assessment procedures can be applied and this could be an ideal application for low cost autonomous wireless vibration sensors.

Subsequently the SdM / Bristol University system was removed and all the cabling stripped around 1992, and the owner only did ad-hoc measurements since then [3].

8.2 Farø Bridges, Denmark - 1985

With a total length of 3322 m, this bridge complex is one of the longest in Europe. It consists of two bridges, a northern bridge from Zealand to the small island of Farø and a southern bridge from Farø to Falster.

8.2.1 Quick Facts

- Name and Location: Farø Bridges – Farø, Denmark
- Owner: Danish Road Authority (Vej Direktoratet)
- Structure category: Main bridge, Cable stayed bridge, one centre cable plane
- Spans: main span 290 m, total length 3322 m, span lengths 120 m - 290 m - 120 m
- Structural system: Reinforced concrete towers and steel box girder.
- Start of SHMS: 1985
- Number of sensors installed: 32 sensors

- Instrumentation design by: COWI.

8.2.2 Description of the structure

The northern bridge has twenty 80 m spans and a total length of 1596 m. The southern bridge has a total length of 1726 m which includes a cable stayed bridge with a navigation span of 290 m, side spans of 120 m and 80 m spans for the approaches.

8.2.3 Purpose of the instrumentation

The installed monitoring system if one of the first based on small data acquisition computers based on open platform PC’s. The sensors comprise anemometers, wind vanes, temperature sensors, corrosion cells and strain gauges on the orthotropic steel deck.

The PC's working by MS-DOS and special programmed software are connected to a display wall at the bridge maintenance staff office near the Bridge and has a modem connection to a similar display wall at the Danish Road Authority in Copenhagen, approximately 120 km from the bridge.

The monitoring system was mainly focused on design verification at an operational level and the system was more pushed by technology than based on analysis as described in Chapter 2.

8.2.4 Examples of outcomes

Due to an unconventional construction method between the steel deck and the bulkheads for the orthotropic deck, full scale tests were carried out to verify design calculation for fatigue.

By applying static and dynamic loads by means of a heavy loaded truck trailer the load response was measured by strain gauges from the SHMS. The test verified that the loads below the wheels were reduced by 30%, but increased more than 50% in the adjacent troughs, compared to static tests.

8.2.5 Benefits of using SHMS technologies in the project

Besides helping in the process of design verification, the benefits of this SHMS have been small. Today only wind measurements are used for giving side wind warnings to the users and temperature for slippery road condition warnings in winter time.

The monitoring of the orthotropic deck has never been used for rain flow counting. The calculation power of the data acquisition equipment was insufficient to carry out this task in real time, but it could have been done for selected periods off-line.

Only the corrosion monitoring has been used proactively in the maintenance planning for the bridge during its operation.

Figure 20: The Farø - Falster Bridge, Denmark

8.3 Sunshine Skyway Bridge, USA - 1986

At May 9, 1980 the freighter Summit Venture rammed into the old Sunshine Skyway Bridge and knocked out a 400 m length of the bridge across the mouth of Tampa Bay. Thirty five people plunged 30 m to their deaths.

The accident, one of the worst bridge disasters in U.S. history, raised consciousness about protecting bridges from ship impacts. Supports for the new Sunshine Skyway, which opened in 1987, have a design that is supposed to keep such a tragedy from happening again.

This massive bridge was equipped with a bridge protection system, designed by Parsons Brinkerhoff. This protection system was developed to withstand an impact from an 87,000-ton tanker travelling at 10 knots.

8.3.1 Quick Facts

- Name and Location: Sunshine Skyway Bridge, Tampa Bay, St. Petersburg, Florida, USA
- Owner: Florida Dept. of Transportation (FDOT)
- Structure category: Main bridge, Cable stayed bridge, one centre cable plane
- Spans: main span 380 m, total length 7000 m, span lengths 170 m - 380 m - 170 m
- Structural system: Reinforced concrete towers and concrete girder.
- Start of SHM: 1987
- Number of sensors installed: 534 sensors
- Instrumentation design by: CTL Group, Leica and General Positioning LLC.

8.3.2 Description of the structure

The Sunshine Skyway Bridge is a twin-pylon cable-stayed bridge with a main span of 380 m and two side spans of 170 m. The bridge deck cross-section consists of precast post-tensioned concrete box segments. There is one plane of cables at each pylon with a semi-harp arrangement. Built using the balanced cantilever method, the bridge has an overall length of 7000 m.

8.3.3 Purpose of Instrumentation

The objective of the structural monitoring program was to monitor construction-related loading, measure time-dependent inelastic structural response, and verify design assumptions. The system designer CTL performed material property tests for mix design and seven instrumented segments during casting [6].

CTL developed a program to instrument seventeen box girder sections and both pier towers during construction to measure temperature and strain. The sensor array consisted of a total of 228 strain gages and 306 temperature sensors. An automatic data acquisition system was installed during construction.

In 2003 the system was upgraded with GPS receivers by FDOT and Leica, having General Positioning LLC to analyse the data

Figure 21: Sunshine Skyway Bridge, Florida, USA.

8.3.4 Examples of outcomes

The structural deflections related to temperature and wind loads have been analysed in order to map these relations. The measured deflections by GPS acquired from the pylon tops and the bridge centre was compared to a FE beam model and metrological observations from a nearby airport (no weather station is working on the bridge).

With the GPS, metrological data and numerical model results it was possible to find relatively straightforward explanations for the complex motions seen in the GPS measurements.

Most aspects of the diurnal motions ultimately were caused by the towers bending slightly because of temperature differentials. The sunward sides of the towers are significantly warmer than the shaded sides, and these results in the towers bending away from the sun as it moves across the sky. The longitudinal motion is limited by heat diffusing through the tower, which reduces the temperature differential between the sunward and shaded sides, and by the cable-stays. In fact, the longitudinal motion of the north tower is effectively eliminated by countering forces transmitted through the cables [7].

8.3.5 Benefits of using SHMS technologies in the project

The SHMS has apparently only been used for design verification.

8.4 Skarnsundet Bridge, Norway - 1990

The Skarnsundet Bridge is a cable stayed bridge across a strait in the inner part of the Trondheimsfjord, Norway, where it substituted a ferry service when inaugurated in 1991.

8.4.1 Quick Facts

- Name and Location: Skarnsundet Bridge, Tronheimsfjord, Norway
- Owner: Norwegian Public Road Administration
- Structure category: Main bridge, Cable stayed bridge, one centre cable plane
- Spans: main span 530 m, total length 1010 m
- Structural system: Reinforced concrete towers and concrete girder.
- Start of SHM: 1991 - 1993
- Number of sensors installed: +50 sensors
- Instrumentation design by: NGI & Noptel OY.

8.4.2 Description of the structure

The total length of the bridge is 1010 m with a main span of 530 m. The deck is formed as a closed triangular concrete box section. The Skarnsundet Bridge presently holds the world record span for cable stayed bridges with concrete deck. The three cable-stayed spans are supported by a total of 208 cables. The bridge cross-section is a concrete box girder of triangular shape, 13 m wide and 2.15 m high. The two towers are A-shaped concrete frames of height 152 m above sea level.

8.4.3 Purpose of the instrumentation

The monitoring program was designed to monitor critical construction operations, as well as to acquire data needed for design verification studies and long-term performance assessment. Subsequent to completion of the bridge the monitoring program was extended to include performance measurements during the first two winter storm seasons.

The data acquisition system is a distributed system developed by NGI for structural monitoring applications. The hardware consists of remote intelligent nodes that communicate via an RS-232 serial line to a local PC. The data acquisition system at the bridge site is connected via a telephone modem to NGI’s offices in Oslo, 600 km away, where the operation of the system is monitored and controlled [11].

Figure 22: Skarnsundet Bridge, Norway.

8.4.4 Examples of outcomes

The laser optical systems were used during the first part of the monitoring program for direct measurement of static and dynamic displacements of the tower. Subsequent to completion of the bridge the monitoring program was extended to include performance measurements during the first two winter storm seasons.

8.4.5 Benefits of using SHM technologies in the project

The monitoring program lasted two years and the instrumentation functioned well. The laser devices were used mainly in the first phase of the monitoring program and both were reported to have functioned satisfactory. The devices were dismantled and moved to another project at an early stage in the monitoring program. Enough practical experience was obtained, however, to confirm that they are well suited for direct measurements of displacements on bridge structures.

8.5 Confederation Bridge, Canada - 1995

The Confederation Bridge, which opened for traffic in 1997, is 12.9 km long and is one of the longest reinforced concrete bridges built over water in the world. The bridge crosses Northumberland Strait, connecting the Canadian provinces of Prince Edward Island (PEI) and New Brunswick. Heavy storms with winds in excess of 30 m/s and the presence of ice in the strait for four months each winter, along with other harsh environmental conditions at the bridge site posed many challenges for the design and construction of the bridge.

Figure 23: Confederation Bridge – New Brunswick, Canada.

8.5.1 Quick Facts:

- Name and Location: Confederation Bridge – PEI / New Brunswick, Canada
- Owner: Governments of New Brunswick and Prince Edward Island
- Structure category: Long span girder
- Spans: 45 spans, 43 spans are 250 m long and 2 spans 165 m long
- Structural system: pre-cast concrete segments assembled using post-tensioned tendons
- Start of SHM: June, 1997
- Number of sensors installed: 113 sensors
- Instrumentation design by: Public Works and Government Services, Canada

8.5.2 Description of the Structure

The Confederation Bridge consists of two approach bridges at its ends and a main bridge between them. The approach bridge at the Prince Edward Island end has 7 piers and a length of 555 m. The New Brunswick end has 14 piers and a length of 1275 m. The main bridge has 43 spans that are 250 m each, and two end spans that are 165 m each. The piers of the main bridge range from 38 m to 62 m high. Both the approach bridges and the main bridge were built of precast concrete segments which were assembled using post-tensioned tendons.

8.5.3 Purpose of the instrumentation

The purpose of the instrumentation of Confederation Bridge is to gather data on a continuous basis that will tell engineers about the long-term properties of the materials in response to the harsh environmental conditions at the bridge site. Analysis of the data shall make reliable and timely diagnoses on the conditions of the bridge structure possible. Thermocouples are used to compensate for temperature effects. Surface mounted strain gauges are used to measure the strains in different locations and directions, tilt meters and accelerometers are used to measure displacement [10].

8.5.4 Examples of outcomes

The instrumentation for Confederation Bridge is installed over three spans of the main bridge, between piers P30 and P33. A network of 76 accelerometers is used to monitor and measure dynamic effects due to traffic, wind, ice and seismic loads. Thermocouples at six sections have been in use since completion of the bridge to continuously monitor thermal effects. The corrosion monitoring system consists of 29 corrosion probes that were wrapped around the reinforcement to be monitored and then embedded in the concrete.

The health assessment procedure consists of two stages, overall (or global) and a detailed structural health assessment. The overall assessment is based on the results of the measured vibrations as recorded by the dynamic instrumentation. The detailed assessment is based on the measurements of all effects.

The overall structural health assessment is based on the natural frequencies of the vibrations of the bridge. Since the bridge is designed to behave purely elastically under expected traffic loads, wind, and ice forces, the natural frequencies of vibrations of the bridge, determined from recorded vibrations due to such loads, must be almost constant with time.

8.5.5 Benefits of using SHM technologies in the project

Using SHM technologies in the Confederation Bridge project provides information about the health of the bridge due to dynamic loads, ice forces, short- and long-term deformations, thermal effects, and corrosion. The two-stage method for health assessment looks at both the overall and a detailed structural health assessment based on the natural frequencies of the vibrations of the bridge.

8.6 Tsing-Ma Bridge, Hong Kong - 1997

Tsing Ma Bridge of Hong Kong is the world's sixth largest suspension bridge. It has two decks and carries both road and rail traffic. The upper deck carries a dual three-lane carriageway and there are two tracks of railway and a two-lane emergency roadway in the lower deck for maintenance and the diversion of traffic during high winds. It has a main span of 1377 metres and a height of 206 metres. The span is currently the largest of all bridges in the world carrying rail traffic.

8.6.1 Quick Facts

- Name and Location: Tsing Ma Bridge, Hong Kong, China
- Owner: Highways Department, Hong Kong
- Structure category: Suspension bridge with girder carrying road traffic on top of girder and rail traffic inside the girder.
- Spans: main span 1377 m, total length 2032 m, span lengths 280 m - 1410 m - 530 m
- Structural system: Reinforced concrete towers and closed steelbox girder.
- Start of SHM: 1997
- Number of sensors installed: 350 sensors, 900 for the common monitoring system WASHMS for the three bridges Tsing Ma, Ting Kau and Kap Shui Mun.
- Instrumentation design by: Fugro.

8.6.2 Description of the structure

The 41m wide bridge deck carries six lanes of automobile traffic, three lanes in each direction. The lower level contains two rail tracks. There are also two sheltered carriageways on the lower deck for maintenance access and as backup for traffic when particularly severe typhoons strike Hong Kong. Though car traffic would need to be closed in that case, trains could still get through in either direction. Along with the Ting Kau Bridge and Kap Shui Mun Bridge, it is closely monitored by the Wind and Structural Health Monitoring System (WASHMS).

8.6.3 Purpose of the instrumentation

The Wind and Structural Health Monitoring System (WASHMS) is a sophisticated bridge monitoring system, costing US$1.3 million, used by the Hong Kong Highways Department to ensure road user comfort and safety of the Tsing Ma, Ting Kau, and Kap Shui Mun bridges that run between Hong Kong and the Hong Kong Airport.

In order to oversee the integrity, durability and reliability of the bridges, WASHMS has four different levels of operation: sensory systems, data acquisition systems, local centralised computer systems and global central computer system.

The sensory system consists of approximately 900 sensors and their relevant interfacing units. With more than 350 sensors on the Tsing Ma Bridge, 350 on Ting Kau and 200 on Kap Shui Mun, the structural behaviour of the bridges is measured 24 hours a day, seven days a week.

The sensors include accelerometers, strain gauges, displacement transducers, level sensing stations, anemometers, temperature sensors and dynamic weight-in-motion sensors and GPS. They measure everything from tarmac temperature and strains in structural members to wind speed and the deflection and rotation of the cables and any movement of the bridge decks and towers.

These sensors are the early warning system for the bridges, providing the essential information that help the Highways Department to accurately monitor the general health conditions of the bridges.

The computing powerhouse for these systems is in the administrative building used by the Highways Department in Tsing Yi. The local central computer system provides data collection control, post-processing, transmission and storage. The global system is used for data acquisition and analysis, assessing the physical conditions and structural functions of the bridges and for integration and manipulation of the data acquisition, analysis and assessing processes [12].

The Tsing Ma Control Area (TCMA) WASHMS is properly the most advanced and well equipped brisdge structural monitoring system in operation so fare (year 2006).

8.6.4 Examples of outcomes

In the WASHMS the monitoring parameters can be categorized into three groups, namely: the loading sources (or input parameters) which include wind, temperature, traffic (highway and railway) and seismic loadings, the system characteristics (or system parameters) which include static influence coefficients and global dynamic characteristics, and the bridge responses (or output parameters) which include geometric configuration (or displacements of the bridge), cable forces, stress/strain distribution and fatigue stress estimation.

8.6.5 Benefits of using SHMS technologies in the project

Using SHMH technologies on the Ting Kau Bridge provides following benefits:

- The ability to collect information of real loading effects and bridge responses, which are valuable in evaluating design parameters and assumptions
- The ability to provide data useful in validating and updating damage-oriented structural modelling and in identifying damage-sensitive features
- The opportunity to provide data in verifying the feasibility and reliability of damage detection methods
- The ability to help in maintenance and rehabilitation planning, and to predict the deterioration when combined with the analytical model

8.7 Seo Hae Bridge, Korea - 2000

The Seo Hae Bridge, which opened to traffic in November 2000, is located approximately 65 km south of Seoul and is one of the longest bridges in Korea. The bridge crossing Asan Bay is 7.31 km long and consists of a cable-stayed bridge and two different types of PSC box girder bridges.

8.7.1 Quick Facts

- Name and Location: Seo Hae Bridge, Asan Bay, South Korea
- Owner: Korean Highway Corporation
- Structure category: Main bridge, Cable stayed bridge, double cable plane
- Spans: main span 480 m, total length 7400 m, main span lengths 200 m - 480 m - 200 m
- Structural system: Reinforced concrete towers and composite steel concrete girder.
- Start of SHM: 2000
- Number of sensors installed: 120 sensors
- Instrumentation design by: Highway and Transportation Technology Institute, Korea.
- Bridge Management System by: Daewoo Engineering and COWI

8.7.2 Description of Structure

The cable-stayed bridge, which is 990 m long, consists of three cable-stayed spans of 200 m + 470 m + 200 m and two 60 m approach spans of simply-supported composite girders. Because the side spans are less than half of the main span, the end spans are hinged to the end of the cable-stayed side spans to eliminate uplift at the intermediate piers.

The deck cross section consists of two longitudinal steel girders spaced 34m apart, steel floor beams between these edge girders at 4.1 m interval and pre cast concrete panels in between. The two pylons are H-shaped concrete structures, 187 m high. The three cable-stayed spans are supported by a total of 144 cables, ranging in length from 54 ~ 247 m.

8.7.3 Purpose of the instrumentation

The SHMS consists of five subsystems, i.e., the sensory system, the data acquisition system, the data processing and storage system, the LAN-based networking system, and the display and control system. More than 120 sensors are installed on the superstructure, the pylons, and the stay cables. The data continuously collected from the sensors is transferred to the maintenance office, about 3 km from the bridge, through a fibre optic local area network [0].

The normal logging procedure is to continuously sample dynamic sensors at 100 Hz and static sensors at every 10 minutes. At the end of each 10 minute sampling period, the statistical data such as maximum, mean, minimum are determined for each sensor and stored in the database.

The objectives of the SHMS are:

- To monitor the structural response and evaluate the performance of the bridge
- To provide information required for operating the computerized Bridge Management System (BMS)
- To provide useful information to the bridge engineers.

Figure 24: Seo Hae Bridge, Asan Bay, South Korea.

8.7.4 Examples of outcomes

Two-dimensional and three-dimensional finite element models have been developed to evaluate the structural response and acquire dynamic characteristics. The SHMS have been used to rule out the differences between the real structure and the identification model. Since modelling errors affect the resulting identified parameters, the implementation of the identification model was needed. After the static and dynamic load tests, the identification model was calibrated with the test results. This refined finite model was used to evaluate the bridge's behaviour for design verification purpose.

The longitudinal movements of the bridge are accommodated by two large expansion joints located at the end of the 60 m end spans away from the cable-stayed spans. Longitudinal movements measured at the edge of the 60 m approach spans has been from April 2001 to December 2004. The data is in the form of hourly mean value. Although the movements show repeated sine curves with yearly temperature variations, intermittent spikes and irregular patterns have been identified. Close inspection showed that these normalized errors were caused by the bearing of a support beam not working properly in winter time.

8.7.5 Benefits of using SHM technologies in the project

The SHMS has helped to show the long-term behaviour of the structure is mainly being affected by temperature variations. Together with a calibrated global FE model to evaluate the temperature effects for the longitudinal movements of the superstructure it was found that there was a good linear relationship with positive slopes between the superstructure's thermal expansions and the temperatures.

From the polynomial regression analysis of the longitudinal displacements at the top of the pylons, it is shown that the long-term behaviours of the pylons show a tendency to incline toward the main span. It has been judged that the trend was caused by the effect of creep.

Also the SHMS has already provided important information to the optimization of the Maintenance Management System for the bridge

8.8 Neva Bridge, Russia - 2004

The Neva bridges are part of a new highway in St. Petersburg; Russia, crossing the Neva River inside the city. Two bridges will be built next to each other. By 2004 the first has been finished and the second is under construction

8.8.1 Quick Facts

- Name and Location: Neva Bridge, St. Petersburg, Russia
- Owner: Russian Federation
- Structure category: Main bridge, Cable stayed steel bridge, double cable plane
- Spans: main span 382 m, total length 730 m, span lengths 174 m - 383 m - 174 m
- Structural system: Steel deck and steel pylons.
- Start of SHM: 2003
- Number of sensors installed: 56 sensors
- Instrumentation design by: Design Institute Gibrostroymost / Futurtec OY

8.8.2 Description of the structure:

The twin pylon structure has a cable-stayed span with a main span of 382m and two back spans each of 174m long. The deck is supported by a total of 112 stay cables in 56 pairs - 28 pairs on each pylon. Both the deck and the pylons are made of steel. During construction, the deck segments are fabricated by bolting together several elements to create a 24.9m-wide, 2.4m-deep and 12m-long double box girder segment that weighs 120t. There are two pylons which are also built of segments of varying sizes and geometries, also bolted together to construct the pylon to a full height of 124m.

8.8.3 Purpose of the instrumentation:

As a part of the design of the cable stayed bridge over the river Neva in St. Petersburg, Russia a careful study was made on life-cycle monitoring needs for the facility. This was performed by the design institute Gibrostroymost. The study consisted of a careful risk assessment of each construction stage extending to the service life of the facility. Key items in defining the configuration have been to keep it as simple as possible to ensure reliability and avoid data overload. Another main item of the system itself has been the user friendly graphical interface, easy maintenance and expansion capabilities [1].

8.8.4 Examples of outcomes

Results from the construction period monitoring have shown the instant and long term value of the SHMS. An example from the construction phase is the plots on pylon displacements and twisting during stay cable pretension. Especially important has been the cellular communication link which has enabled access to the data anytime and anywhere. Reliability and redundancy of the SHMS through the construction monitoring period has been high due to the 'keep it simple' system design strategy.

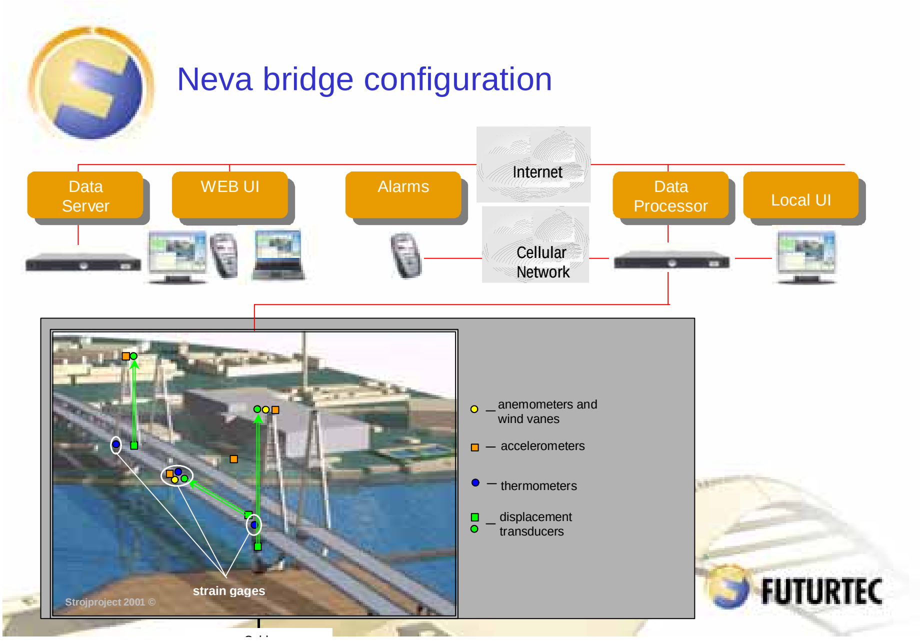


Figure 25 Neva bridge configuration during construction.

8.8.5 Benefits of using SHM technologies in the project

The SHMS has been an integrated part of the project from the beginning of construction into the operation phase. Through easy to use mobile communication interface and redundant design the system could provide assistance for the design engineers for geometric control during the construction phase and to provide design verification information. Now the SHMS is in a transition phase to support the bridge safety and the maintenance of the bridge during operation.

8.9 Ermanninsuo Railway Embankment, Finland - 2005

The Train speeds and axle loads are being increased on many railways in Europe and India. The existing infrastructure should bear ever larger loads and traffic volumes. Old bridges and railways will cause increasing concern in the future. The designers, owners, maintainers and users of bridges and railways are more and more interested in the condition, endurance and safety of bridges and railways. There are special problems, if the railway section lies in a soft soil area. The above-mentioned factors bring about the need for real-time monitoring of problem sites.

One such area, Ermanninsuo is located near Humppila, Finland, where the Turku-Toijala railway section is located. At the location, the railway has been built on boggy land. When the railway section was straightened about ten years ago, about 400-metre concrete slab on piles was constructed to support the railway.

The railway section has heavy traffic. The speed limit under normal conditions is 170 km/h.

Figure 26: Ermanninsuo construction site, Finland.

8.9.1 Quick Facts

- Name and Location: Ermanninsuo, Humppila, Finland
- Owner: Finnish Rail (VR)
- Structure category: Railway embankment, prestressed reinforced concrete
- Spans: Not applicable
- Structural system: Reinforced concrete piles and prestressed beams.

- Start of SHM: 2004
- Number of sensors installed: 28 sensors
- Instrumentation design by: Futurtec OY

8.9.2 Description of the structure

The problem in this railway section is that the railway embankment/foundation has collapsed. In spring 2004, the collapsed section was estimated to be 40 metres in length while the track at the worst has shifted 40 cm downward.

The collapsed railway section was repaired in 2004. The repair work schedule was prepared by VR-Track Ltd. The collapsed section was reconstructed/reinforced with a new type of design and construction process using precast concrete slabs and supporting beams parallel to the track. These rests on reinforced concrete piles, erected on both sides of the track. In addition, it was planned that tongued and grooved steel profiles should be used on both sides of the reconstructed section.

8.9.3 Purpose of the instrumentation

Futurtec Ltd was contracted to design and provide a structural monitoring solution to analyze the stability of the new design and ensure safety by means of real-time alarming facility from the remote site.

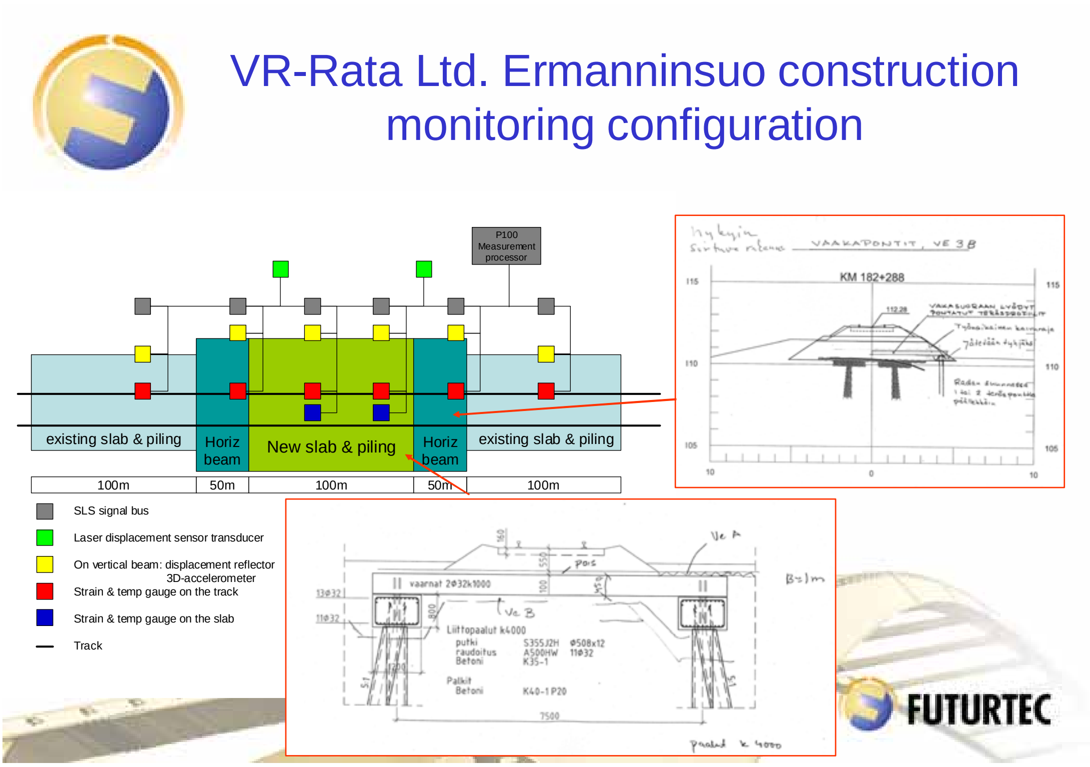


Figure 27: Ermanninsuo initial monitoring configuration, Finland.

8.9.4 Examples of outcomes

As expected the dynamic loading response of the new type of construction process and structural design could not be completely modelled. One of the key findings has been the unforeseen level of the impulse created by the first axle of the locomotive interacting with the three dimensional, discontinuous design.

8.9.5 Benefits of using SHM technologies in the project

Both the design and the construction process have been modified during the project. Information from the SHMS solution and analyses provided have played a key role to identify change requirements early and assist in redesign to create the improved solution.

8.10 Naini Bridge, India - 2005

The 4 lane highway bridge crosses the Yamuna River near the intersection to the Ganges River and links the cities Naini and Allahabad in the state of Uttar Pradesh.

8.10.1 Quick Facts

- Name and Location: Naini Bridge, Allahabad, UP, India
- Owner: National Highway Agency of India (NHAI)
- Structure category: Main bridge, Cable stayed bridge, double cable plane
- Spans: main span 260 m, total length 1510 m, main span lengths 185 m - 260 m - 185 m
- Structural system: Reinforced concrete towers and concrete girder.
- Start of SHM: 2005
- Number of sensors installed: 534 sensors
- Instrumentation design by: COWI / Devcon Infrastructures Private Ltd.

8.10.2 Description of the structure

The bridge comprises a 630 m cable stayed section with a 260 m long main span, a 515 m long approach bridge with spans of 60 m, and a 365 m long viaduct with spans of 25 m. All foundations are deep open wells except for the viaduct, where 1.2 m diameter burred piles are used. The concrete pylons are 90 m high with slender solid rectangular legs above the deck, and robust hexagonal shaped legs below the deck.

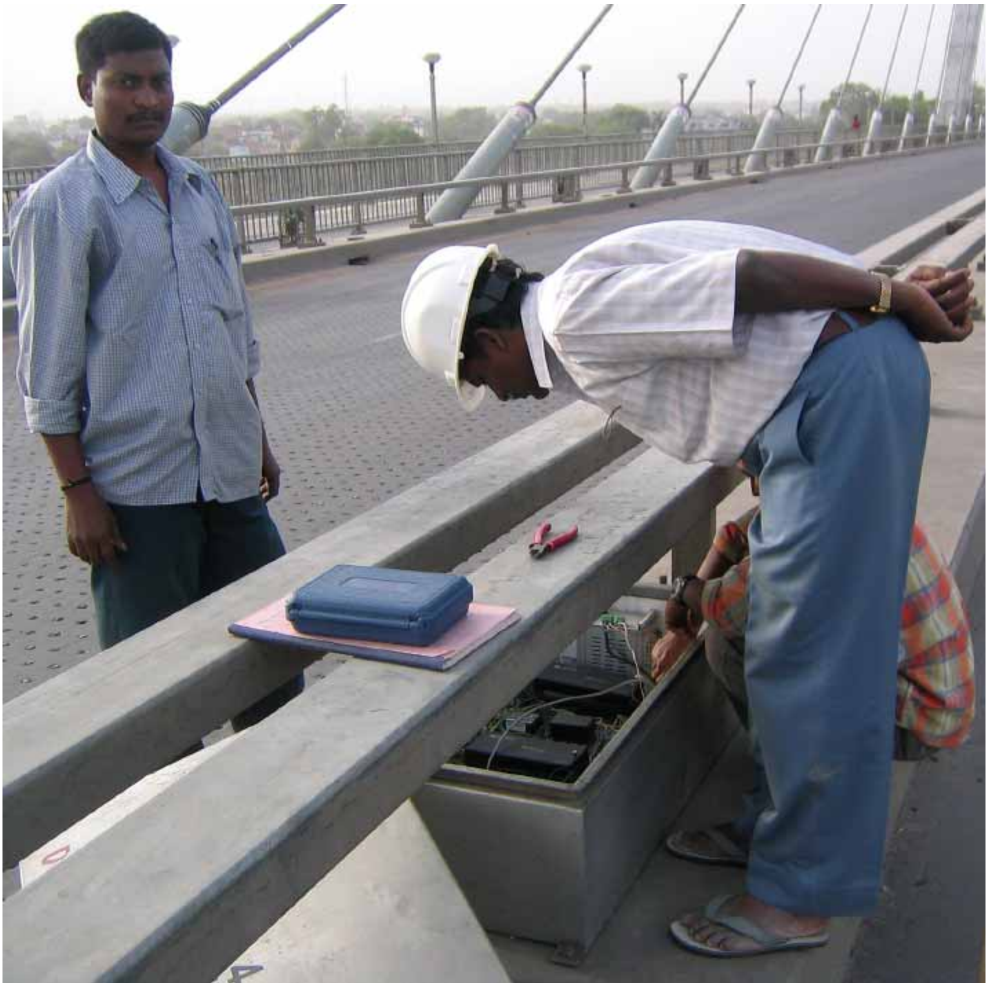


Figure 28: Supervision of SHMS at Naini Bridge, India.

8.10.3 Purpose of Instrumentation:

Naini Bridge is an example of a fully integrated structural monitoring system based on a low cost installation approach and without the capability of automatically providing the basis for structural health evaluation.

The system has been designed according to the principals described in chapters 2 - 6, e.g. having the purpose of monitoring carefully selected points of the bridge in order to provide the basis for design verification, user safety, maintenance planning and trouble shooting. However the direct support for user safety is low as the system dos not give real time alarms to the bridge users.

All evaluation is based on engineers analysing the statistical information recorded by the system and time histories in the case where some pre set limits have been passed.

8.10.4 Examples of outcomes

By 2005 the system has been running for one year. Until now some design verification analysis has been carried out for the temperature movements of the bridge by comparing temperatures, deflections at expansion joints and the movement of pylon tops measured by differential GPS.

As the Naini bridge is one of the first bridges to have installed a new generation of GPS combined with advanced post processing software, absolute deflections in 3D has been measured with mm accuracy. This makes the analysis particular interesting.

The analyses are now waiting to be compared with results of the FE model used in the design phase. As the appointment of a maintenance contractor for the bridge has been delayed through 2005, the SHMS has been in a passive mode collecting data without anybody yet using the data

8.10.5 Benefits of using SHM technologies in the project

The SHMS was already used in the construction phase for geometrical monitoring and measurement of cable forces as the balanced cantilever was moved forward during the girder construction.

8.11 Stonecutters Bridge, Hong Kong - 2008

The Stonecutters Bridge is a cable-stayed bridge with a main span of 1,018 m under construction and planned to open in 2009. The main span is supported from two single central towers both placed on land providing a clear entrance to the container port with a vertical clearance of minimum 73.5 m.

8.11.1 Quick Facts

- Name and Location: Stonecutters Bridge, Hong Kong S.A.R., P.R. China
- Owner: Highways Department
- Main Consultant - Ove Arup & Partners Hong Kong Limited
- Structure category: Main Bridge, Cable stayed bridge, double cable plane, and two girders.
- Spans: main span 1018 m.
- Structural system: Composite steel - reinforced concrete towers and steel box girders inter connected with cross girders. Back span as concrete girder
- Planned start of SHM: 2009
- Number of planned sensors: 1420 sensors
- System Concept and Functions initiated by: Bridges & Structures Division of Highways Department, the Government of HKSAR.
- Instrumentation design by: COWI (as sub-consultant to Arup).
- System Operation by: Bridges & Structures Division of Highways Department, the Government of HKSAR.

8.11.2 Description of the structure

The 53.5 m wide bridge deck consists of twin box girders connected by cross girders. The stay cables connect to the outside edges of the deck only. The deck is in steel in the main span and 50 m into the first back span while the rest of the back spans are in concrete.

Figure 29: Stonecutters Bridge, Hong Kong, P.R. China. ©Arup.

8.11.3 Purpose of the instrumentation

The Stonecutters Bridge Structural Health Monitoring System is an example of a distributed monitoring system with the provisions for all the aspects of health evaluation based on automatically processing of data.

In designing the structural health monitoring systems for Stonecutters Bridge, COWI and Highways Department took full account of the valuable experience gained in operating the Wind and Structural Health Monitoring System (WASHMS) for Tsing Ma Bridge, Kap Shui Mun Bridge, Ting Kau Bridge and the cable-stayed bridge (Hong Kong Side) in Hong Kong - Shenzhen Western Corridor. In order to obtain a whole life health record of Stonecutters Bridge, a construction stage structural health monitoring system will be implemented in addition to a more conventional operation stage structural health monitoring system. This will allow a comprehensive track record of the structural health condition of the bridge obtained starting from its construction stage for future identification and quantification of the root causes of any structural problems during its operation stage [13].

The scope of monitoring includes:

- Environments and status.
  - Wind monitoring.
  - Temperature monitoring.
  - Seismic monitoring.
  - Corrosion status monitoring.

- Traffic loads.
  - Highway traffic monitoring.

- Bridge characteristics.
  - Static influence coefficients monitoring.
  - Global dynamic characteristics monitoring.

- Bridge responses.
  - Cable forces monitoring.
  - Geometric configuration monitoring.
  - Strain/Stress distribution monitoring.
  - Fatigue stress monitoring.

- Articulation monitoring.

The scope of monitoring for the structural health monitoring system operating under the stage-by-stage erection of steel deck segments includes:

- Bridge - towers.
  - Tower deflection profiles.
  - Tower - base forces.
  - Variation of dynamic characteristics.

- Bridge - deck system.
  - Deck deflection profiles.
  - Deck force at selected locations of towers and piers.
  - Variation of dynamic characteristics.

- Stay cable system.
  - Stay cables at each deck segment erection.

8.11.4 Planned outcomes of the SHMS

The objective of the structural health monitoring system for in-service condition is to monitor the loading and structural parameters set by the bridge rating system (which will be updated continuously through correlation analysis and features extraction of measured and analyzed data and information) so that the bridge performance under current and future loading can be evaluated, and such evaluated results should be able to facilitate the planning and scheduling of the bridge inspection and maintenance activities, and be able to determine not only the cause of structural damage, but also the extend of remedial works required, once the structural damage is identified.

The objectives of the structural health monitoring system for stage-by-stage deck segment erection are:

- To monitor the geometry and stress in steel deck segments, stay cables, towers and piers during the erection of steel deck segments in main span
- To identify defect♦ occurred in erection stage and to quantify their effects on bridge performance under in-service condition.

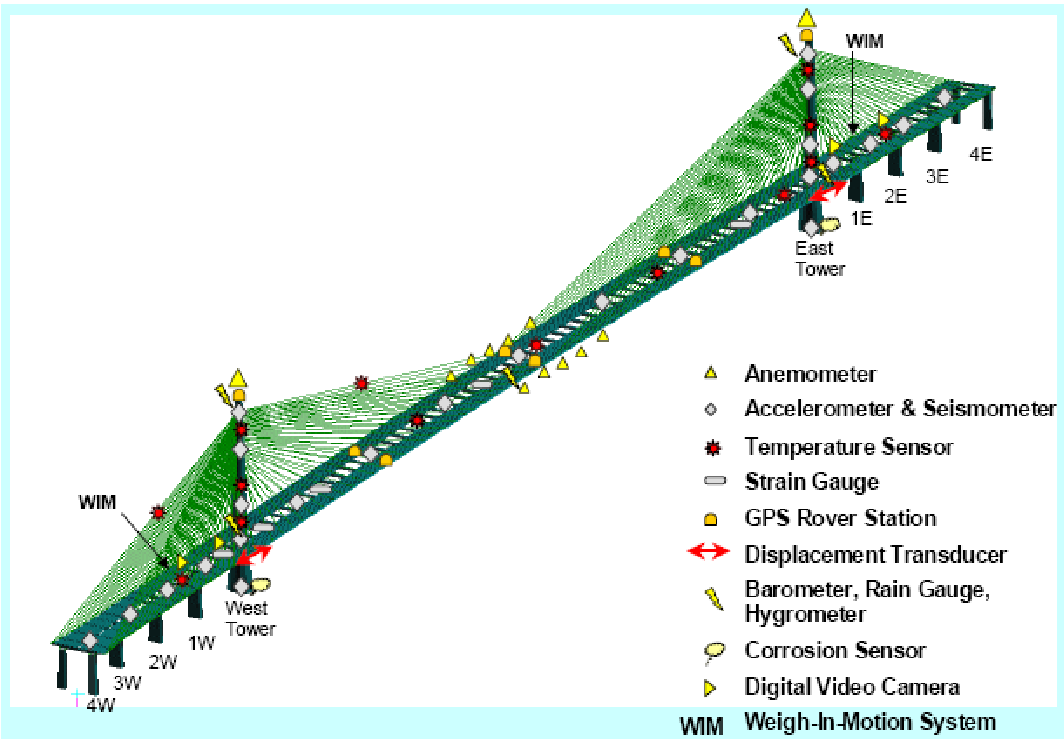


Figure 30: Wind and Structural Health Monitoring System (WASHMS) at Stonecutters Bridge.

♦ defects refers to those as-built unmatched geometric profiles, but within the allowed construction tolerance

The operation of SHMS is divided into two processes, i.e. the structural health monitoring process (SHMP) and the structural health evaluation process (SHEP). The SHMP, which is basically an on-line process, is designated primarily for real-time monitoring of bridge performance and operating status of all sensors and data acquisition units; whereas the SHEP, which is basically an off-line process, is designated primarily for the execution of correlation analysis and structural health evaluation.

The SHMP is the routine process for continuous monitoring of bridge performance through comparisons of the measured results such as environments, traffic loads, bridge characteristics and bridge responses to those design values. In the routine SHMP, as shown in Figure 31, the signals received from the bridge are first detected for anomalous signals. If anomalous signals are detected, fault report will be issued to the System Maintenance Team for follow-up maintenance action. If no anomalous signal is detected, the data processing and analysis will carry out to compare the measured data with the designed performance criteria. If the criteria are exceeded, structural health evaluation process (SHEP) will be executed, otherwise the routine procedures of updating, display and storage of analyzed data will be executed.

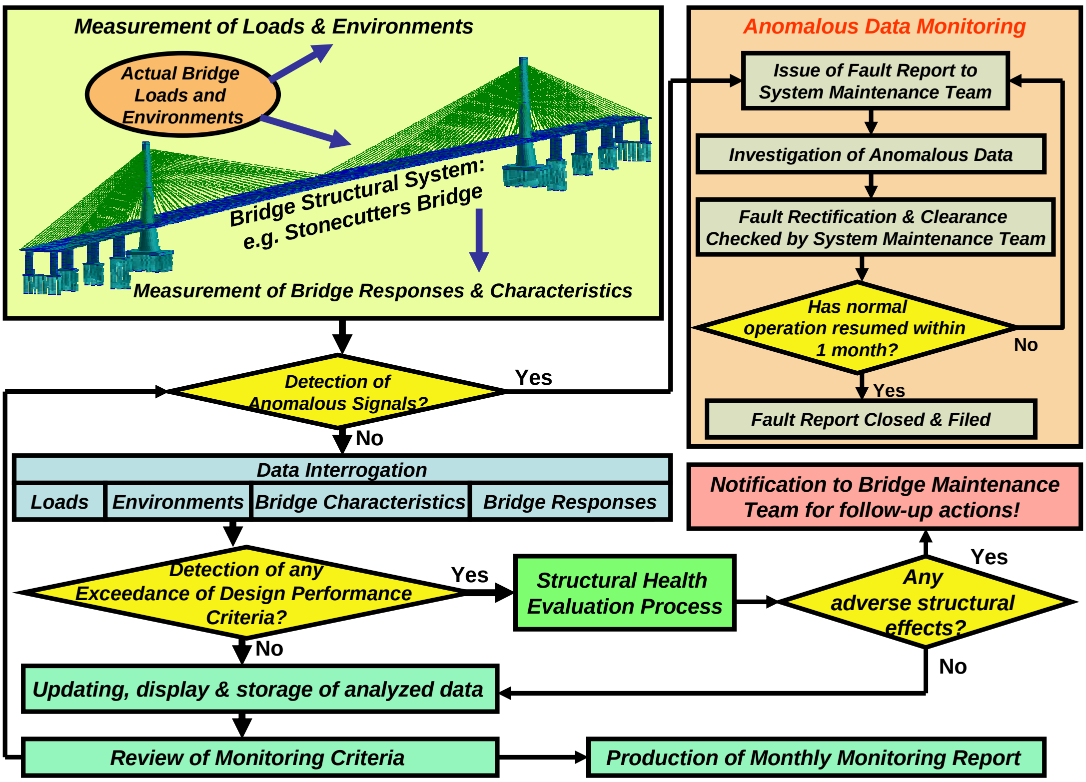


Figure 31: Flow diagram of structural health monitoring process (SHMP) at the Stonecutters Bridge.

The SHEP is to identify whether such exceedance has any adverse effect on bridge performance, if so the bridge maintenance team will be notified for follow-up detailed bridge inspection action, otherwise routine updating, display and storage will be executed. Comparison of the current measured data with previous measured data and pre-configured performance criteria are the usual procedures in SHMP to monitor the current structural health conditions of the bridge. For long-term structural health monitoring, the output of SHMP is periodically updated, basing on historical bridge performance records, in accordance with its intended functions under inevitable aging and degradation effects.

The SHEP is in fact the process of structural health diagnosis and prognosis on bridge performance. The former evaluates the bridge performance under any identified structural defects and/or under any occurred extreme events such as historical strong typhoons and earthquakes, or major vehicular and vessel collisions. The latter attempts to:

- Forecast future bridge performance basing on current measured bridge states of loads, structural characteristics and responses.
- Estimate the future bridge loads to be acting on the bridge.
- Predict the remaining useful life of the bridge basing on the results of above bullets.

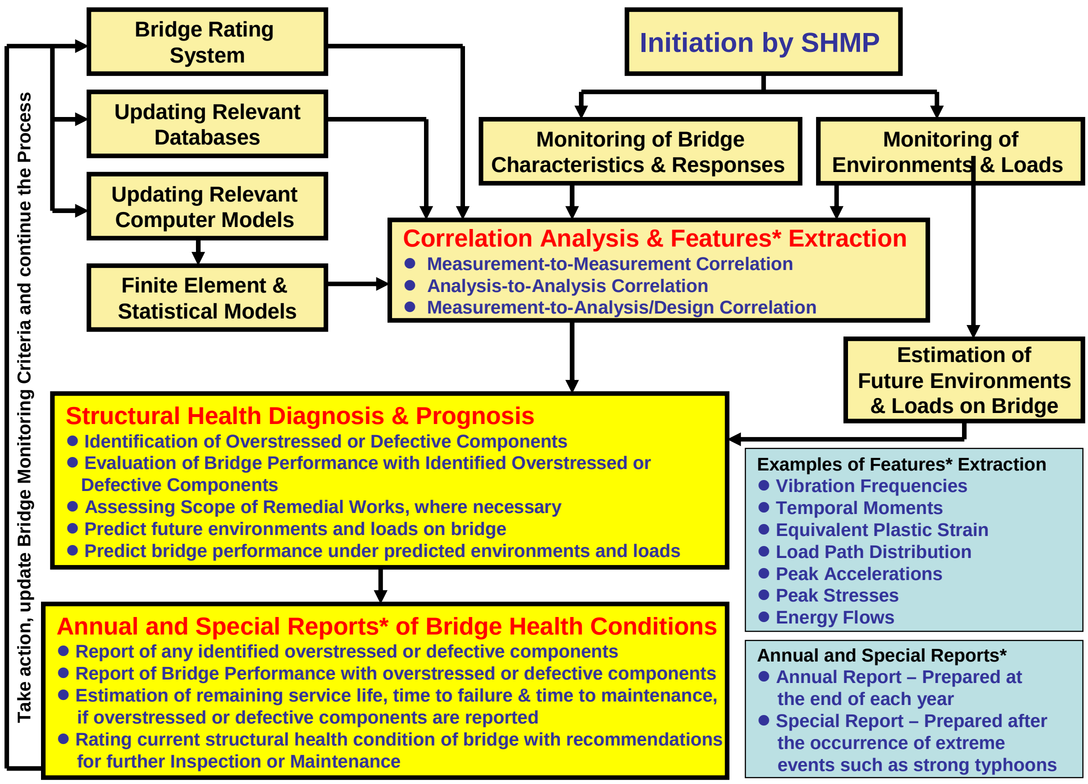


Figure 32: Flow diagram of structural health evaluation process (SHEP).

Figure 32 illustrates the flow diagram of SHEP. In the figure, it shows that SHEP is initiated by SHMP for the execution of different types of correlation analyses and subsequently structural health diagnosis and prognosis are then executed.

8.12 Messina Bridge, Italy - 2012?

The planned Messina Strait Bridge will connect the coasts of Sicilia and Calabria in southern Italy. It is planned to carry a four lane highway with emergency lanes and a dual railway line. The bridge is a suspension bridge with a world record breaking 3300 m main span. The design life of the bridge is 200 years.

8.12.1 Quick Facts

- Name and Location: Messina Bridge, Strait of Messina, Italy
- Owner: Stretio de Messina, Spa
- Structure category: Main bridge, suspension bridge, double main cables and three girders, two for road and one for rail traffic.
- Spans: main span 3300 m, total length 3666 m, span lengths 333 m - 3300 m - 333 m
- Structural system: Steel towers and steel girders.
- Planned start of SHMS: 2008
- Number of sensors planned to be installed: 2400 sensors
- Instrumentation tender design by: COWI A/S for Impregilo Spa.

8.12.2 Description of the structure

The suspended deck is arranged with the cross girders spaced at 30 m as the main elements whereas the two roadway girders and the central railway girder are taken as secondary elements spanning between the cross girders. Thereby the Messina Strait Bridge will be the first bridge in the World to adopt the triple box concept for the deck, 68 m wide. The main cables consist of twin cables spaced 1.75 m - i.e. a total of four cables are required for the bridge. The sag to span ratio of the cables is fixed as 1:11.

The towers are frame structures with slightly inclined legs (inclination of approx. 2°) and three connecting cross beams. They are constructed in steel. The tower top level is at 382.6 m.

Figure 33: Messina Bridge, Italy.

8.12.3 Purpose of the instrumentation:

The purpose of the structural monitoring and the data acquisition is to supply information on all relevant events related to operation and status of the bridge structure to the operator and assist him to take the necessary corrective actions, either through manual commands or automatic responses, if allowed in advance by the operator.

The monitoring and control activity is necessary:

- To check the physical-environment, structural and traffic conditions of the Bridge.
- To identify, verify and notify anomalous events and situations, such as trespassing of attention and/or criticality thresholds in the monitored area.
- To constitute the infrastructure's history, through data collection and elaboration.
- To constitute the data base necessary for the infrastructure's management and maintenance.
- To visualize the status of the systems on displays in the control room.
- To assist the operator in his management of the bridge and the traffic on the bridge.

The creation of an historical file of collected data will consent the development of maintenance and management strategies, as well as the planning of short, medium and long term interventions.

The Messina Bridge Structural Health Monitoring System has been designed strictly according to the considerations discussed in chapter 2 - 6.

The Structural Health Monitoring System will provide reliable data for condition of all relevant structures of the Bridge. The measurements will be carried out during both construction and operation period of the Bridge.

The SHMS will consist of three independent sub-monitoring systems, namely the

- Meteorological Monitoring System
- Seismic Monitoring System
- Structural Monitoring System (including geotechnical monitoring)

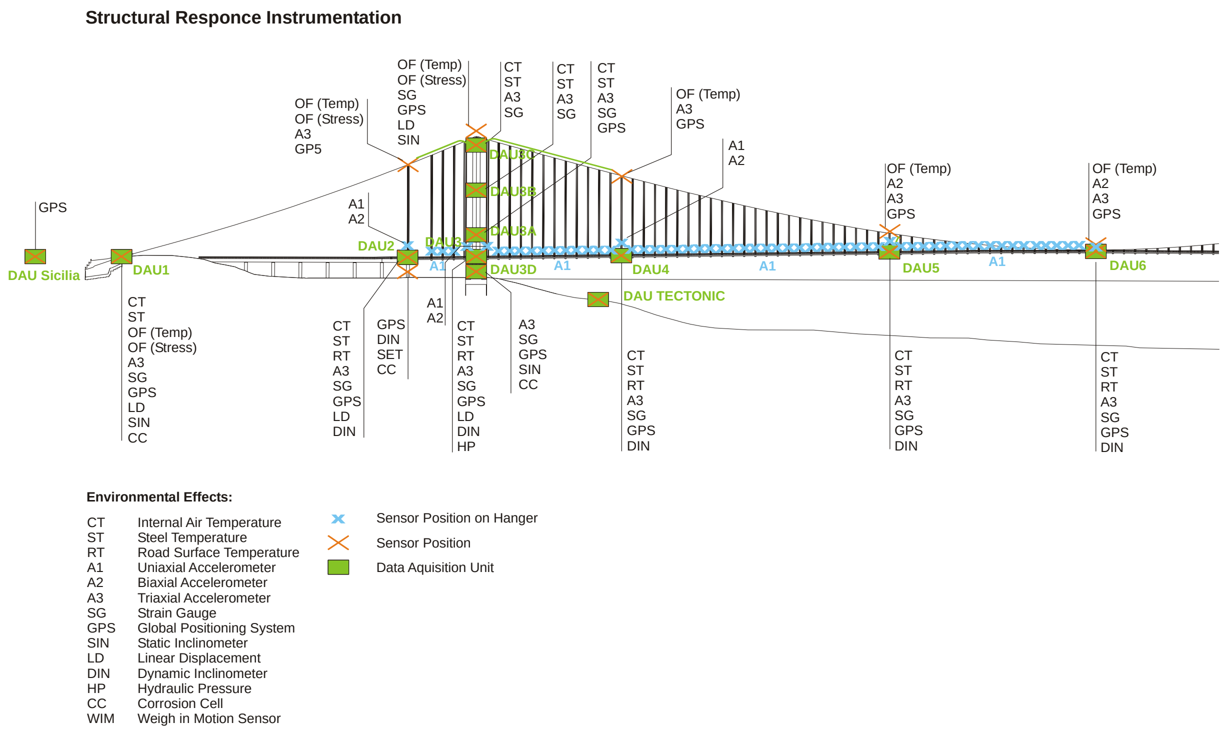


Figure 34: Sensor design for the SHMS of half the Messina Bridge. The other half will be similar.

The SHMS will be a separate monitoring system which acquires data and controls automatically in real time carrying out the measurements, temporary data storage, data calculation and data exchange with the SCADA system. Several separate monitoring systems besides the SHMS will work on the bridge. All the monitoring systems will share a common IT infrastructure and be integrated into one SCADA interfacing to a Management, Administration and Computer Simulation system (MACS). The SCADA and the MACS will together act as a Management & Control System for the bridge. The system will as far as possible be designed to use standard applications and only rely on special programming for the interface between the SCADA and the MACS.

All available information (measurements, estimations, meteorological-climatic, seismic-tectonic and traffic ones, alarm signalling, etc.) will be used by the SCADA & MACS both for evaluating the actual state of the Bridge, and for assessing the expected state within the short (ca 10 min), medium (1 or 2 hours) and long term (one or more days), time span.

Based on these evaluations and estimations, the maximum actual, medium and long-term admissible level of service for the Bridge will be evaluated.

8.12.4 Examples of planned outcomes

Temperature

The visualization of the predicted steel temperature monitoring results is illustrated in Figure 35 by an example of the control room displays or monitoring reports showing the temperature gradient at user selected cross sections of the tower and girder.

Structural Status Monitor: Structural Temperatur Gradient

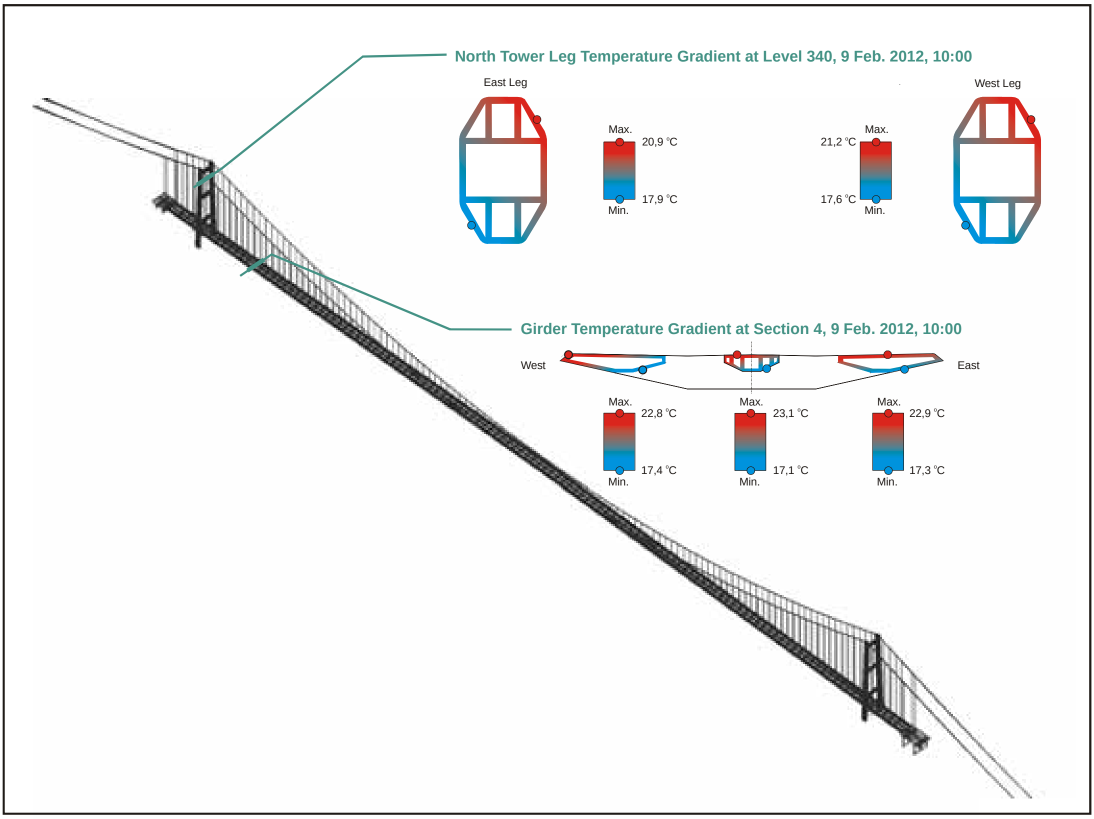


Figure 35: Visualization of the steel temperature monitoring results: Structural temperature gradient

Furthermore, the planned visualisation of the structural temperature results are illustrated in Figure 36 by an example of the control room displays or monitoring reports showing the temperature history for a user selected time period.

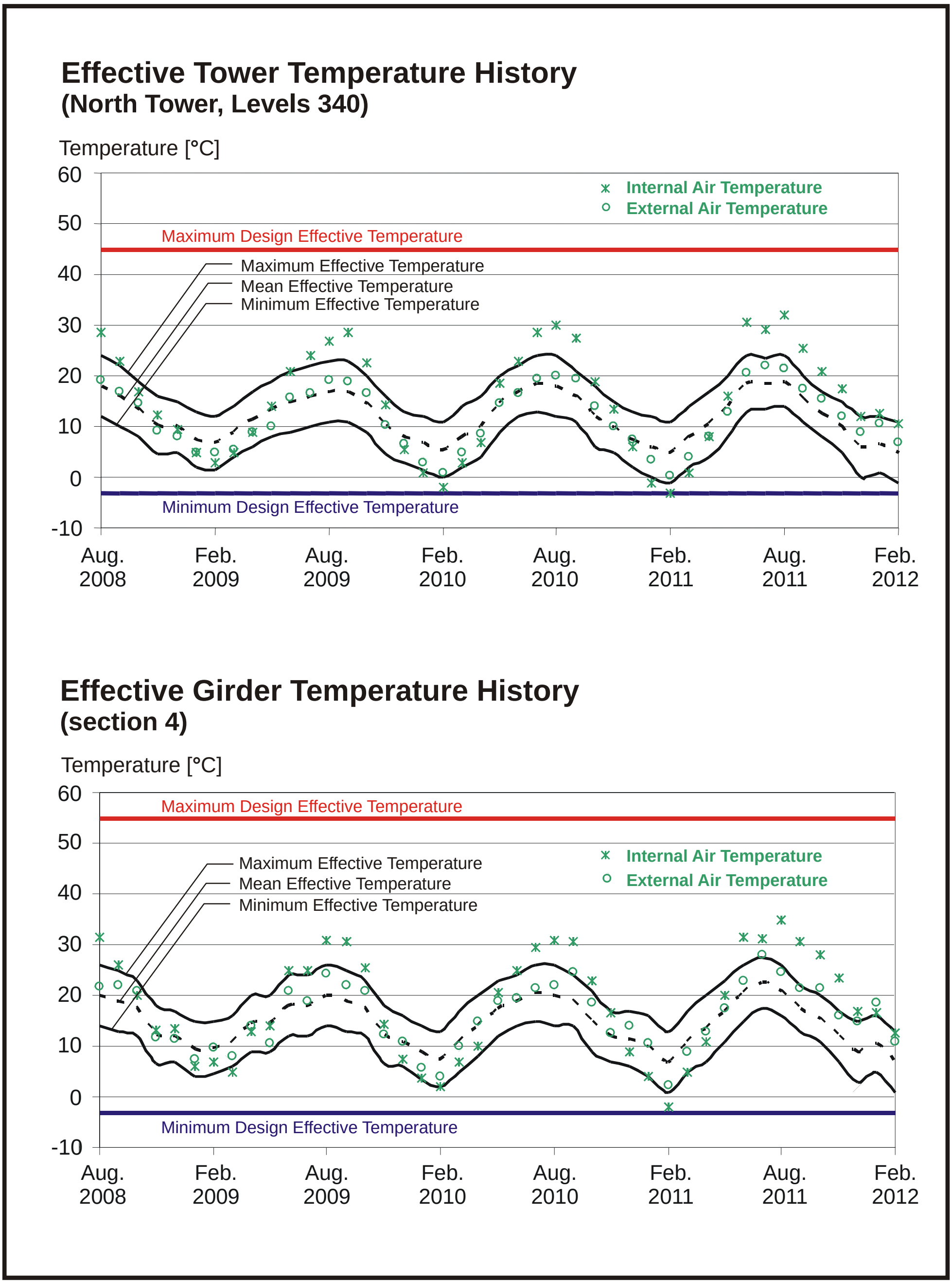


Figure 36 Structural temperature results: temperature history

Strain gauges

The planned visualization of the strain gauge monitoring results for fatigue damage assessment is illustrated in Figure 37 by examples of the control room displays or monitoring reports showing the maximum stress range identification and a stress cycle histogram.

Structural Status Monitor: Stress Cycle Counting

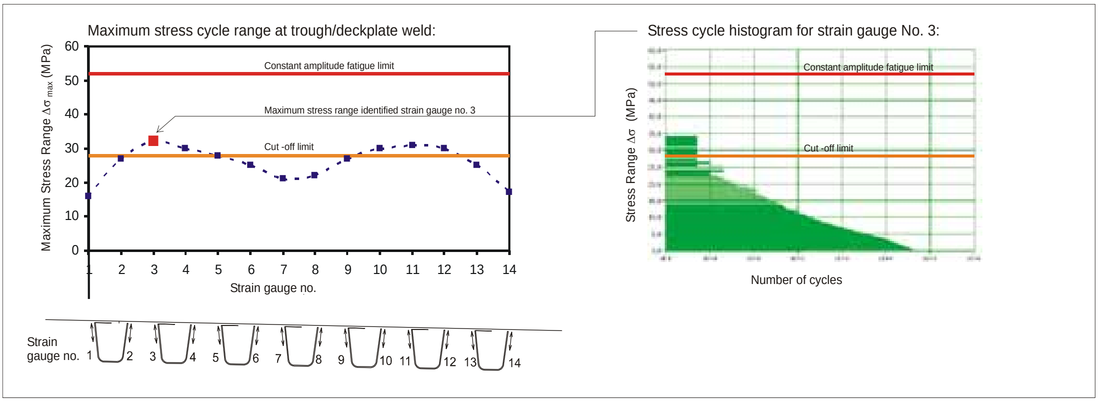


Figure 37 Visualization of the strain gauge monitoring results for fatigue damage assessment: maximum stress range identification and stress cycle histogram

Furthermore, the predicted visualisation of the simulation and prediction results are illustrated in Figure 38 by an example of the control room displays or monitoring reports showing the fatigue damage evolution predicted based on traffic prognosis.

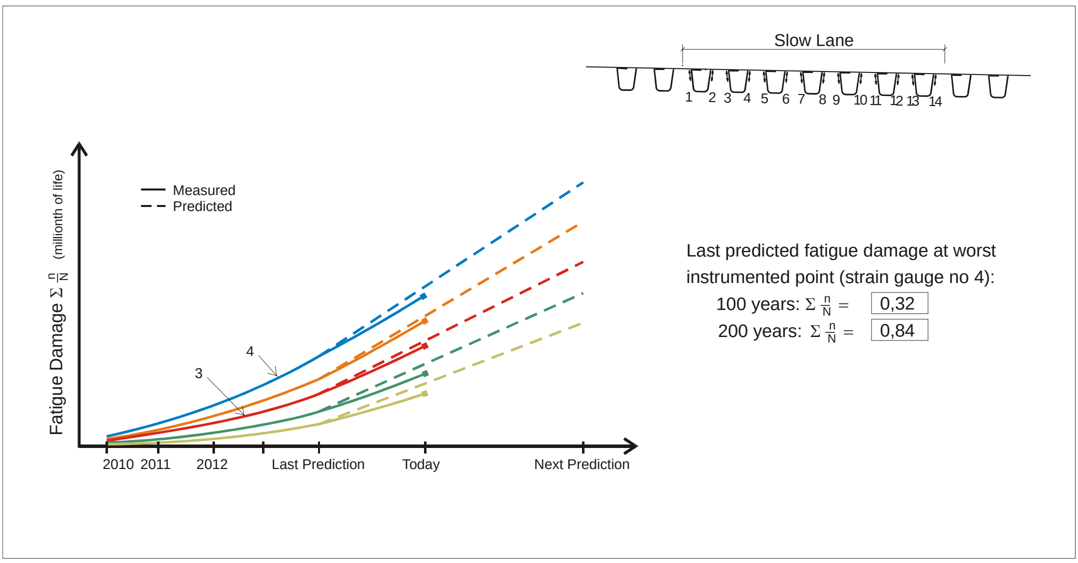


Figure 38 Visualization of the simulation and prediction results: fatigue exposure evolution predicted based on traffic prognosis

All strain gauges will be provided with temperature compensation over the range of temperature and humidity defined.

Global satellite positioning system

The GPS will be designed to be capable of real-time cinematic 3-dimensional spatial position updating of the instrumented locations and transmission of real-time data to the SCADA room for on-screen presentation of real-time dynamic measurement by visual animation display.

The planned visualization of the global bridge geometry is illustrated in Figure 39 by an example of a continuously updated control room display showing the quasi-static motion of the global bridge structure, based on data measured by GPS and inclinometers.

Structural Status Monitor: Global Structural Geometry

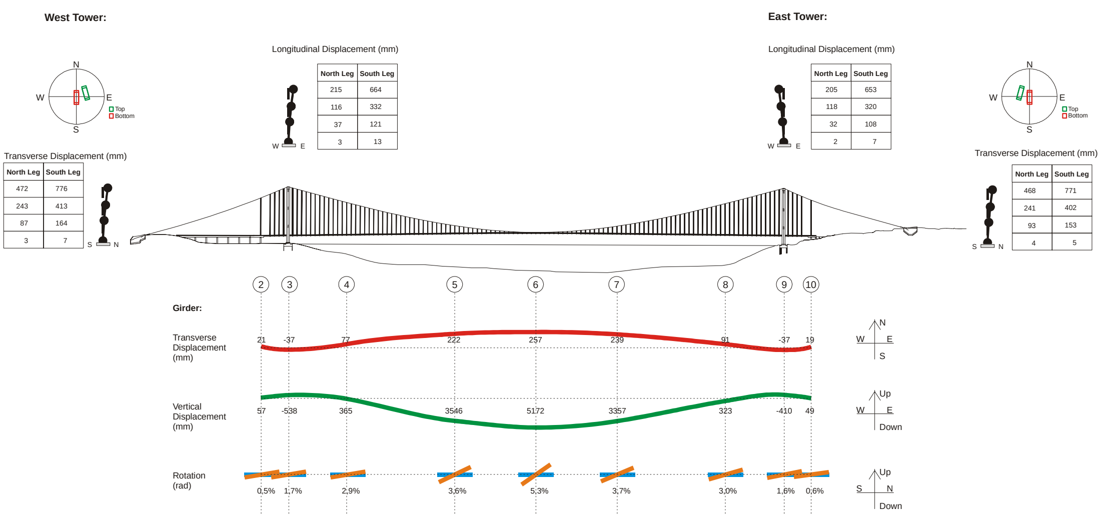


Figure 39 Visualization of the global bridge geometry: quasi-static motion of the global bridge structure

Part III: MODERN BRIDGE MONITORING DESIGN

9 Approaches for Data Collection & Control

The approaches for the acquisition, storage and compression of data is one of the most important issues to clarify once the economics and functional requirements for a SHMS have been established. Regardless of the amount of data, criteria for the selection of the few data adding value to the application areas of design verification, user safety, maintenance planning and trouble shooting must be developed for each individual SHMS

9.1 Data Collection

9.1.1 Establishing Data Bases

Several approaches for establishing the data bases exist. Basically the data collection can be divided into two approaches, either by inspections or measurements. The chosen approach depends on the needed extent, deliveries and the allowed costs of the structural monitoring system.

Inspections

Traditionally inspections are carried out by an experienced bridge inspection engineer. Structures are visually inspected based on inspection manuals. Observed structural conditions will be reported in inspection forms on paper or PDA. The forms can be part of a Bridge Management System (BMS).

Part of the visual inspection can also be carried out by means of video surveillance.

Measurements

Measurements are carried out either by NDT or sensors. In the simple form the experienced bridge inspection engineer can examinate structures by simple tools or NDT instruments based on visual assessments. A more structured approach for this method is to monitor specific locations at each inspection by the use of a portable logger and temporary sensors.

Permanent sensors can also monitor important structures continuously in real time.

9.1.2 Data Acquisition, transmission and pre-processing

The data acquisition and transmission of structural monitoring data must be planned very well, as the strategy and layout for this greatly will affect the installation and maintenance costs of the system.

The main decision to take is to decide based on assessments whether continuous monitoring of selected structural components is necessary or not, in combination with the extent of sensors distributed across the bridge, can justify the installation of a data transmission network on the bridge.

For small scale monitoring systems it should be considered basing the monitoring around a portable data acquisition computer. The computer can be placed for monitoring different objects over pre-set periods or on an ad-hoc base. The data can either be collected at intervals at the portable computer or can be downloaded through an internet connection based on either wireless net or high speed mobile connection.

The need for continuous monitoring will almost always point to install a permanent data acquisition network on the bridge. Normally such a network will be a fibre optic double ring LAN to ensure redundancy, with connection switches distributed along the network alignment.

Small programmable automation controllers (PAC's) can be connected at the switches. PAC's combines PLC ruggedness with PC functionality under open, flexible software architectures. With these controllers, systems incorporating software capabilities such as advanced control, communication, data logging, and signal processing with a rugged controller performing logic, motion, process control, and vision can be used for the monitoring.

In this case data will automatically be transmitted to a central server and may be temporarily stored at the PAC, should the central server be unavailable for a short period

9.2 Data Storage

The data storage consideration will reflect the model for data organisation discussed in chapter 2. Depending on the extent and purpose of the monitoring system strategies for data storage can be as follows

- None.
- Ad hoc reports aperiodic / periodic.
- Statistical.
- All raw data.

For small monitoring systems only supporting the user safety of the bridge one can chose only to save alarms and warnings when exciding preset trigger values, but not storing any measured data.

Saving no data can also be the situation for monitoring systems based on ad hoc aperiodic / periodic reports, thereby reflecting the periods where the monitoring system is not in operation.

Ad hoc measurement are often more sensible to discard and only archive the resulting analysis, as the measurement points are often mobile and the measurement tools will differ from time to time.

On the other hand, it is logical to record raw measurement data from static measurement points that are connected through a network into long time storage, as it is hard to be certain what kind of information will be necessary or useful during the expected lifetime of 30 years or more.

Especially in ground breaking designed bridges, the structure might hold several surprising new effects that become evident only after several years of use. Collecting raw data (e.g. vibration and strain data) gives the designer and maintenance unit a possibility to later both prove the design and react to unexpected features, such as cable vibration or slow structural bending.

This leads to the idea that the measurement data should be collected as raw data. That means synchronised measurement moments and recordings unmodified by calibration, but with calibration setting recorded in the beginning of the data files for each saved cluster of data.

If the data is processed into FFT maps or histograms and the raw portion of it thrown away, there will always remain the risk that there will be later different analysis needs like rain flow bending counts.

9.3 Data Access

The data Access systematic is closely related to the chosen data storage strategy. This can be on the following basis.

- Ad hoc.
- Periodic.
- Continuous.

As the collected raw data are gigabytes or terabytes in size, accessing it is an interesting challenge. The access needs of users vary. The bridge designer wants a value that can be compared to his original design calculations, the constructor wants values that describe what is happening in the structure at the moment, the operators wants values that describe how the bridge is operating under load and the unit responsible for maintenance planning wants values that describe how the bridge changes in the long run.

All these data and visualisations have to be pulled from the same measurement-archive.

The maintenance staffs have a different approach to the data. Their needs are for all the data and in as raw a form as possible. It is easiest to just bring a copy of the current measurement archive to them on a USB/Firewire hard disk, from which they can take the data and decide on the best way to analyze them.

The key point about access to the data is that all access methods have to use open protocols and to be documented with ease of access in mind, just documenting the data access protocols is not sufficient.

9.4 Data Processing and Management

The SHMS will collect measurement data, status of affairs and fault information generated by the individual sub-systems and equipment. Detailed information on the fault will be available to operators based on the diagnostic facilities provided for individual equipment.

The SHMS shall also be designed to allow it to normally run unmanned and the operation be performed by non-technical staff.

The operator shall have the facility to request displays of all current values or status, initiate logs and reports on events, change engineering parameters or set points, add/delete/modify data reading statuses within each monitoring routine, change point description, status and alarm description and engineering unit description, add new data reading states to the system, obtain programme and database listings, initialize data analysis and request reports.

All equipment shall automatically perform a series of default hardware and software tests during the initial power-up and regularly during operation and all operating parameters shall be adjustable by the user depending on user security status and administration level.

The SHMS shall derive and synchronize the system standard time from a single reference clock signal (e.g. GPS or the atomic clock in Frankfurt by radio waves).

Figure 40 gives as an example on overview of the data processing from sensor to data storage, corresponding to the strain gauge instrumentation for fatigue monitoring of the orthotropic deck due to traffic load.

The example in the right side of the diagram shows how a fatigue measurement on the orthotropic deck will be carried out:

1. The analogue signals are measured by strain gauges and sent into the DAU where they are first converted to digital strain signals.
2. The DAU will check if the signals are free of noise and within the stress design limit range. If not, an event will be transmitted to the SCADA with high priority.
3. The DAU will pre-process the measured strain time histories into stress time histories.
4. The DAU will, on blocks of 10 minutes time series, calculate statistical values such as mean, max, min for stress. The values will be stored in the DPCS.
5. Real time rain flow counting will be carried out in the DAU. The histograms will be sent to the DPCS every 10 minutes.

6. In the DCPS the Miner sum will be calculated and remaining service life time found. Predictions on the development in service lifetime will be calculated based on results from the traffic prognosis system.

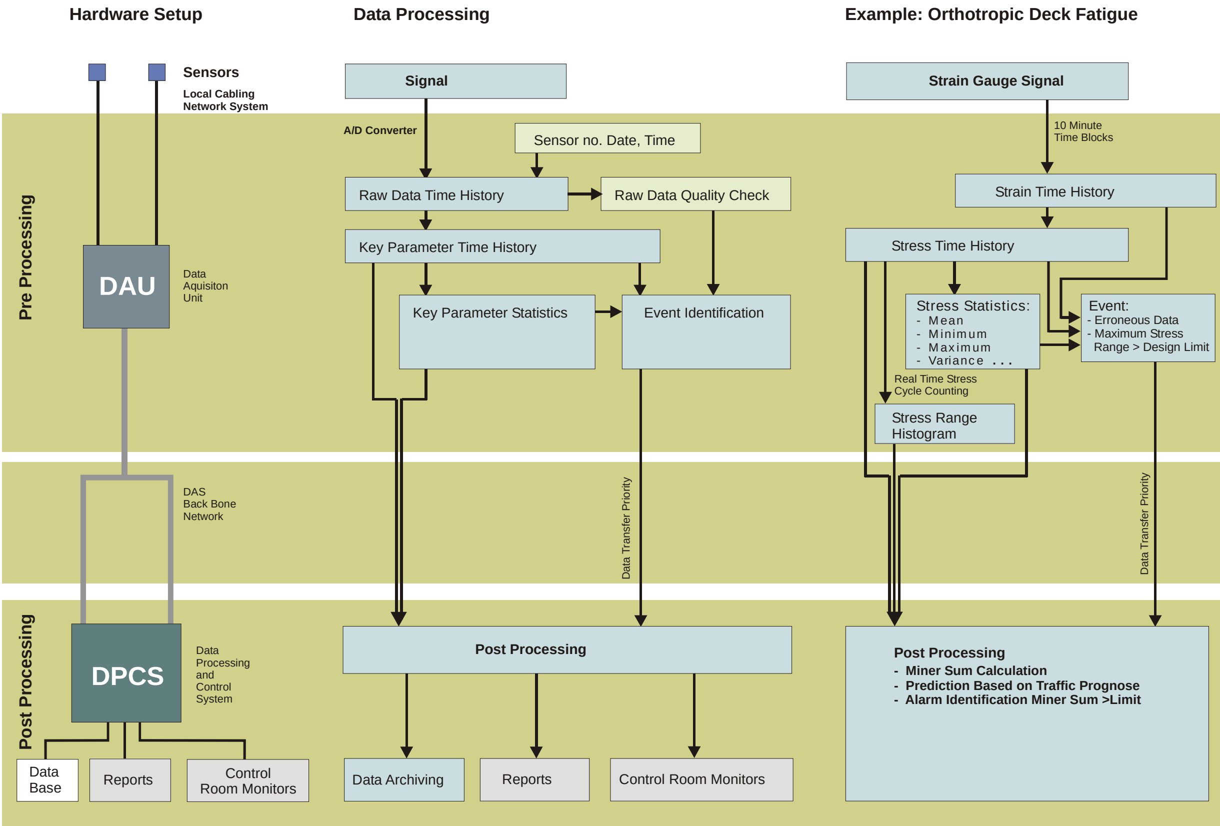


Figure 40: Data processing overview and example.

9.5 Supervisory Control (SCADA)

Monitoring during the bridge operational phase will require the use of systems for automatic detection of events.

All SHMS measurements, signals, detections performed, and the related information on location, date and time of detection, shall be recorded and made available by the system to some kind of SCADA (Supervisory Control and Data Acquisition). The SCADA is typically used for integration of information from several monitoring systems like traffic management and surveillance systems.

After the SHMS solutions have been configured and procured there follows the construction solution including component sourcing, -manufacture, application development and integration. Depending on project type and scope the system commissioning can happen as one continuous project but more often is phased with the structural development. Solution design for its lifetime support is the key to reliability and its life cycle value. Proper testing and documented QA processes are needed in all phases of the solution lifecycle to ensure reliability and accuracy.

Most of the currently installed systems are ‘custom engineered’ and based on high performance, modified laboratory type equipment with compromised operability, service life and upgradeability. Only within the last few years have the bridge SHMS solutions been available in ‘turnkey’ packages like Futurtec First Alert. These second generation solutions provide necessary reliability, ease of use, serviceability, upgradeability and most importantly lifetime vendor support.

10 SHMS Building Blocks

It is important to know the structure and elements (Building blocks) of a SHMS in order to be able to integrate the advantages an SHMS offers into a bridge design and to be able to design sustainable SHMS solution.

Regardless of the extent all SHMS can be designed based on a common template.

Technically the template for the developed SHMS will consists of the following major parts to organise the activities:

- Sensing modules placed on the structure. These modules consist of various types of sensors depending on the nature of the structure. This also includes a signal collection, conditioning and digitization unit.
- Portable and/or fixed data acquisition systems to execute pre-processing and local buffering for sensors distributed in a limited geographical area.
- Data communication system for the transfer of the collected data to a remote computer.
- Data Processing and Control System with database application. This collects stores and processes the sensor data in real time, in order to provide an evaluation of the condition of the structure.
- User Interface
- Maintenance tools
- Interfaces to external systems

Figure 41 gives a simplified illustration of the concept.

The SHMS shall generally be a separate monitoring system which works automatically and controls in real time the carrying out of the measurements, temporary data storage, data calculation and data exchange.

In the following sections are given the basis for the considerations and analyses about the above shown bullets about the organisation and technical set-up to run through prior to start of any design works.

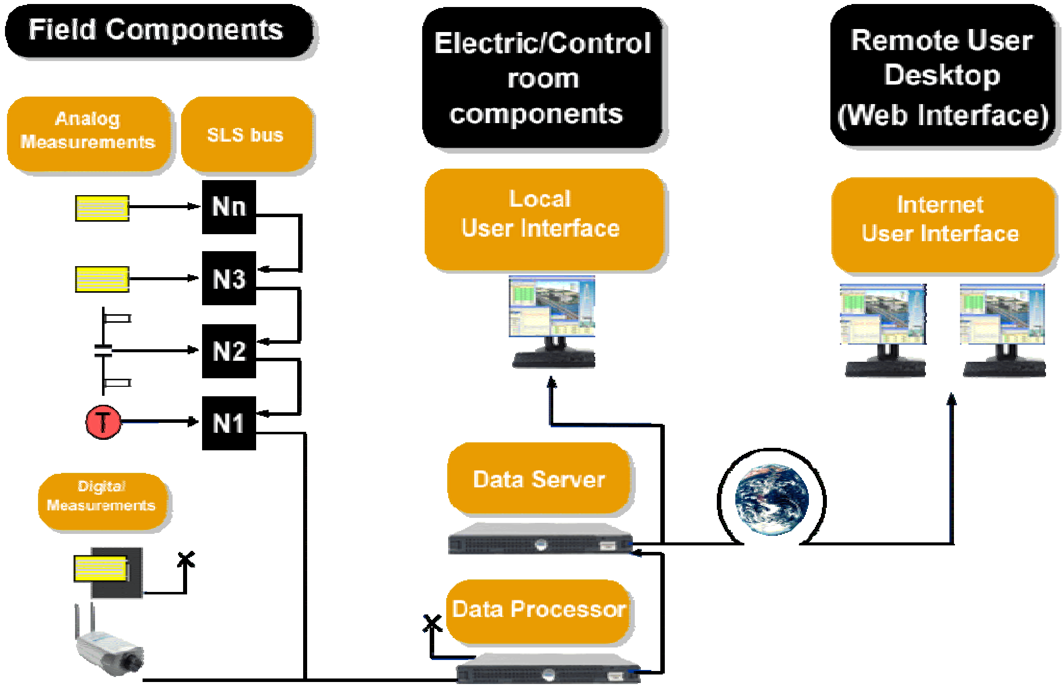


Figure 41: SHMS design concept.

10.1 Sensory System

The sensory System will include the sensors and their corresponding interfacing units for input signals gathered from various monitoring equipments and sensors such as anemometers, temperature sensors, dynamic weigh-in-motion sensors, corrosion cells, hygrometers, barometers, rainfall gauges, digital video cameras, weld able strain gauges, vibrating-wire strain gauges, displacement transducers, global positioning systems, fixed and removable accelerometers, etc.

10.2 Data Acquisition System

Only a decade ago A/D converters were still expensive and therefore typical monitoring system designs were based on either moving a portable logger around or by making star configurations with analogue cables connected to multiplexers at a central A/D converter at an acquisition unit. In this configuration problems with analogue noise and too slow sample rates for dynamic incidents often occurs.

Now that A/D converters have become relative inexpensive there is a tendency to use these converters as near the sensors as practical, forming socalled distributed data acquisition networks. The benefit is that digital data can either be stored locally at the A/D converter or sent through a LAN without any quality loss.

Modern measurement systems for bridges tend to grow rather large. This forces the designer to take into account not only the measurement that is done, but also the topology of the network that connects the different measurement points.

In a simple situation when all the parameters that need measuring are close to each other, it is possible to build a star network where each measurement point is connected to the measuring instrumentation by its own dedicated cable. This solution is intuitive and easy to implement, but it becomes complex to manage when the number of measurement points grows to over 30, or the distances are more than 80 meters.

For larger networks some form of serial topology is necessary. That means a structure where one cable runs through all the measurement points and they share this cable connection. This structure works painlessly up to structure sizes of 1000 m. After that it is easiest to split the network into several sub networks connected to a long fibre optic main cable. The fibre optical trunk can also be structured as a logical loop which means that the fibre can be broken from any one spot and still all the measurement points are accessible, ensuring a high level of redundancy.

Fibre optic cables are an easy way to control several common problems with long networks. It won't generate electronic problems like short-circuits or energy surges from a nearby lightning strike or voltage changes from an accident with an electric welder. The downside is that the costs of connecting to fibre cables are still rather high. It is better to connect the measurement points that are close to each other in a sub network that is based on copper wiring and then let the data signal jump to the fibre in an easy to control and well screened position.

A good rule of thumb for sub network sizing is to build them from somewhere between 5 to 60 measurement points. If you have less than 5 points it is advisable to try to make a long wire to the closest other sub network. On the other hand when the number of points crosses 60 it is a good idea to break the network into two sub networks to simplify maintenance.

The design of the main fibre and the small sub networks ensures high redundancy and makes is easy to isolate problem areas for maintenance. When the number of measurement points goes beyond 4000 the maintainability and ability to isolate problem areas becomes a major factor. The larger the system the more important it is to keep things simple and easy to control.

The normal mix of measurements often has fast and slow measurements close to each other. For example accelerometers, strain gages, wind vanes and temperature sensors. These would normally be measured with speeds of 100 Hz, 10 Hz, 1 Hz and every 10 minutes respectively. It is important to be able to collect the data from, for example strain gages and accelerometers in synchronisation with each other, so that it is possible for example to cross-correlate the wind and structural vibrations and note what kind of stresses it places on the structure. It is easy to build a system, where the measurement sub segments are not synchronized with each other leading to serious problems at the analysis end. This is a problem that is easy to correct in the design phase of the bridge and costly to repair after installation.

10.2.1 Portable Data Acquisition Systems

A portable data acquisition system is composed of portable data loggers, the functions of which can be as follows:

- Trouble shooting unforeseen problems related to structural dynamics by use of high gain accelerometers and video displacement sensors.

- Corrosion monitoring data logger unit for data logging of corrosion cells.

10.3 Data Communication

SHMS' intelligent distributed substations in the field shall communicate with the SHMS central computer in the control room via a common data communication network, which optimally shall be provided for all computerised systems on the bridge. It means that the data transmission protocol shall be adapted to the standard protocol dictated by the common network.

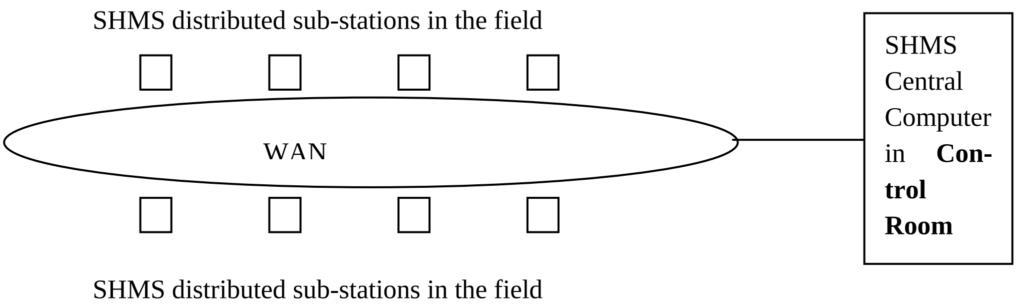


Figure 42: Data communication via WAN.

The data acquisition and transmission system comprises the following three sub-systems:

These Data Acquisition Units (DAU or Processor) shall be installed in the bridge-deck and bridge-towers and will be used for the collection and pre-processing of signals from the sensory system.

- The local cabling network system refers to the cabling network (shielded instrumentation cables) connecting sensory system and DAU's and is used for the transmission of signals received from sensory system to related DAU's.

- The global cabling network system refers to the fibre optic cabling networks installed in the bridge-deck and tower-shaft that are used for the transmission of digitized data from DAU's, GPS reference stations, Weigh in Motion systems and digital video equipment to the SCADA Room.

10.4 Data Processing and Control System

The master screen can be either a desktop display with the ability to transfer between different functions quickly and easily, or a large display wall which can preferably be divided into three large screens, build up of standard display modules, with the following functions:

- Provide overall control of the DAUs through the Data Acquisition System (DAS) backbone network regarding data acquisition and processing, data transmission and filing control, data archiving and backup, and all display and operational control.

- Post-processing and analysis of the collected data from the DAS.

- Generation of instant monitoring reports regarding the monitoring of loading sources and bridge responses.

The man-machine-interface which will be established for the SCADA will be used for display of general interest's views from the SHMS monitored systems. The SHMS operator stations will though still allow for local display of structural events related to the maintenance of the bridge, as well as it will allow for remote control of threshold values for each SHMS sensor system.

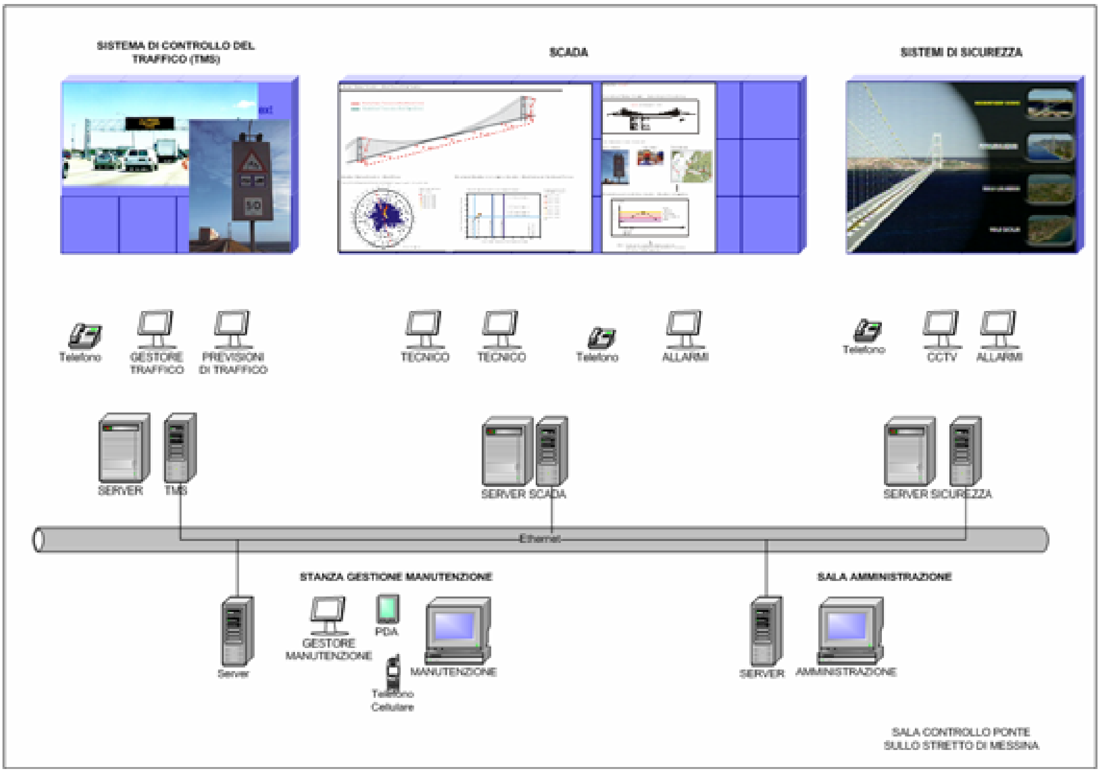


Figure 43: Example on control room design (SCADA).

For a large SHMS the system will visualize in real time all collected information, in the most suitable way for an immediate and efficient representation (graphs, tables, videos), and will allow the research, visualization and elaboration related to user specified periods.

The above shown examples and more screens will all be possible to show on the master screens in the bridge control room for the SCADA.

The large display wall can preferable be divided into three large screens, built up of standard display modules, with the following functions:

- Screen 1: Traffic events monitoring
- Screen 2: Technical systems status and events monitoring
- Screen 3: Safety systems status monitoring (Surveillance)

The screen system will be freely addressable and the functions may be changed by the operators e.g. in case of failure in a part of the display wall.

10.5 User Interface

The conventional bridge monitoring solutions have been forced to use local, workstation based user interfaces due to the limitations originating from the lack of proper hardware and software integration. The trend in all applications is towards use of a universal and standard based web interface. The clear advantages of such an approach are:

- Number of simultaneous users/viewers is limited by server and bandwidth capacity only.
- Bridge personnel can easily relay questions to an off-site expert, making it easier for a single expert to advise on several bridges simultaneously.
- Viewing and usage of information may be performed without time, space or hardware limitations.
- User interfaces may vary depending on need. The same data may be visualized on a monitoring computer or on a cell phone.
- Data analysis is separated from its consumption thus enabling usage of optimized platforms for each need.
- Backward and forward compatibility is a non-issue compared to major issue on workstation based user interfaces.
- Usage of a modern XML-format in data transmission ensures compatibility of archiving, analyses and display tools for decades to come.
- Standard formats also simplify future upgrades and monitoring needs to be integrated.
- Usage of robust hardware and standards based software and interfaces enable the system to become sufficiently reliable for critical alarming functions. Usage of web interface and standard development tools allows flexible delivery of alarms to the operator with email, SMS, screen messages, etc.

The user interface has to be optimised to the different phases of the bridge lifetime as discussed in earlier chapters. During the construction phase the operators stay motivated by the dynamic nature of the construction process. The measurement system has to be nimble and almost insanely error resistant and the user interface might change often to accommodate the ever changing temporary measurement needs of the construction.

On its second role the bridge measurement system is used by the bridge operator and maintenance staff. Over the years the role of the UI (User Interface) changes. The UI has to be extremely simple as the users are often not as skilled or motivated as people were during construction. Even very small user interface problems when repeated day after day year after year get to be intolerable. The interface must offer only the absolutely necessary numbers and try hard not to overwhelm the user with unnecessary data. Changes to the monitoring system or the UI will be few and will have to be carefully considered to minimize the need for personnel retraining.

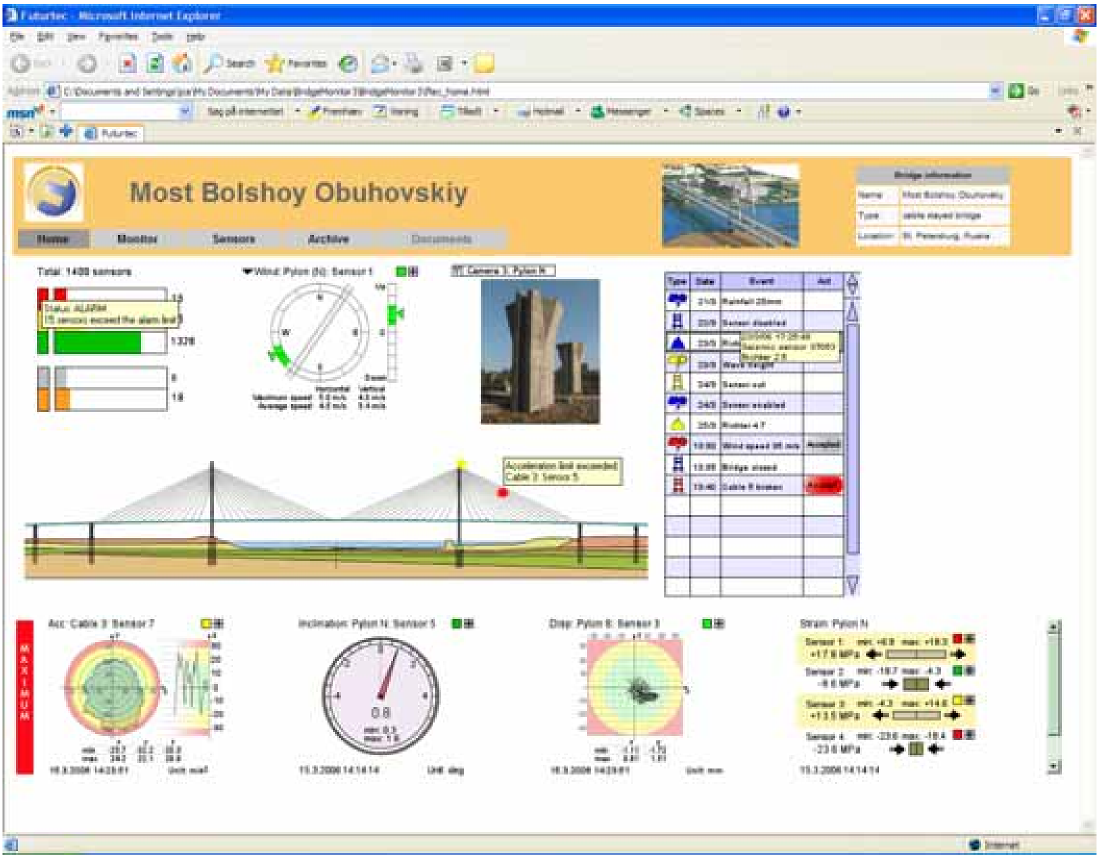


Figure 44 Optimized internet user interface at the Neva Bridge

The third role of the monitoring system and its UI is when something unexpected and sudden happens (e.g. traffic accidents, fire, ship impact, etc). In this situation the user is extremely stressed and things are happening faster than he can keep up with them. Further the user interface must give only the most critical information, it must not limit the users options, but it must do all it can to minimize the conceptual load on the user.

Conclusion is that in any situation the bridge management system must work so that it enables operators to understand and trust the information provided by the system and rapidly act on it regardless of tools, time and space.

10.6 Maintenance tools

A Portable Inspection and Maintenance System (PIMS), which is composed of mobile PC-based notebook computers, can be used for the inspection and maintenance of bridge cabling network and sensory system.

10.7 SHMS Interfaces

The SCADA system can be interconnected with a common management and control system software, which will be used for an overall management of tasks and events related to operation and maintenance of the bridge, as well as information exchange between the bridge operator and operators for connected highways, railway operator and the authorities.

Data communication to the Maintenance Management System can be provided through the SCADA interface and/or database server and not directly. This facility will allow for a more coordinated database function for the total system.

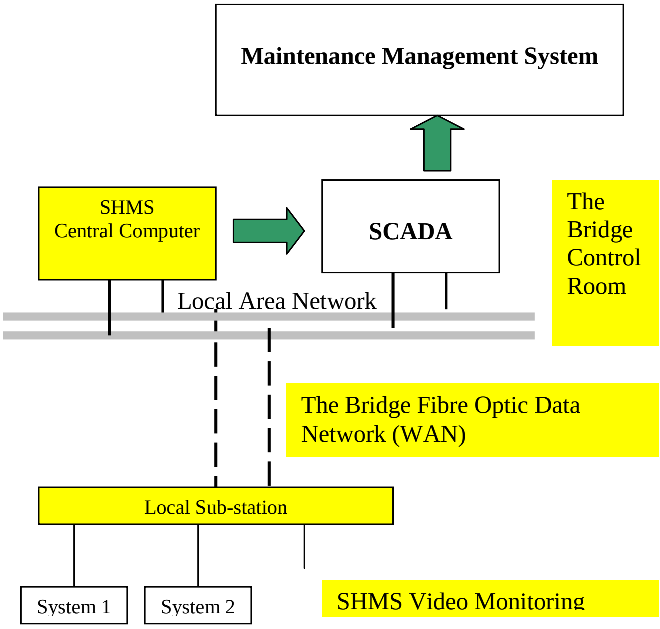


Figure 45: Configuration of the Structural Health Monitoring System.

11 Application based System Designs

Having the previous discussions about organisation of the SHMS management, data organisation, data collection and the general template for SHMS in mind the SHMS can be designed.

Typically three different types of structural monitoring systems should be considered

- Construction Monitoring Systems.
- Structural Evaluation Monitoring Systems.
- Structural Health Monitoring Systems.

This is because the monitoring objectives for the construction and operation phase most often vary significantly from each other and to reflect that the resulting structural health evaluation quite different system designs may or may not be integrated .

However the considerations regarding monitoring parameters, data acquisition systems, user interface and management and control systems will be common for all three types of monitoring systems.

11.1 Construction Monitoring Systems

Monitoring during the construction phase of a bridge will provide for the detection of meteorological, seismic-tectonic, geometrical, structural data and/or other data considered as being useful to build the "history" of the bridge.

All measurements and detections can be performed with adequate periodicity, can include information related to location, date and time of the detection, and can be recorded and made available by the master module of a management & control system during the construction phase.

During the construction phase the following areas can be managed and give information feedback to the bridge Designer and Contractor.

- Safety of construction sites against sabotages and fraud, inspection of transported goods and products/intermediate materials by means of scanners (gamma-rays) and control of accesses to the construction sites through the surveillances and security system

- The monitoring of environmental impact during the construction phase will be carried out by monitoring system for ambient environmental parameters

- The Structural Health Monitoring System (SHMS) for the operation phase will be installed during the construction of the bridge as soon as the parts to be monitored have been constructed. All sensors will start to monitor from day one after installation during the construction phase connected to the

- GIS management system will be one of the main interfaces for construction monitoring

11.2 Structural Evaluation Monitoring Systems

For new and larger than experienced constructions certain specific parameters are typically monitored during construction and the structural warranty period in order to evaluate and validate the design assumptions. Such solutions do not need to be operational on a 24/7 basis, nor does the information need to be available without delay. The structural evaluation systems are typically tailor made to the application based on high performance but low reliability components and require a lot of manual intervention and data analysis.

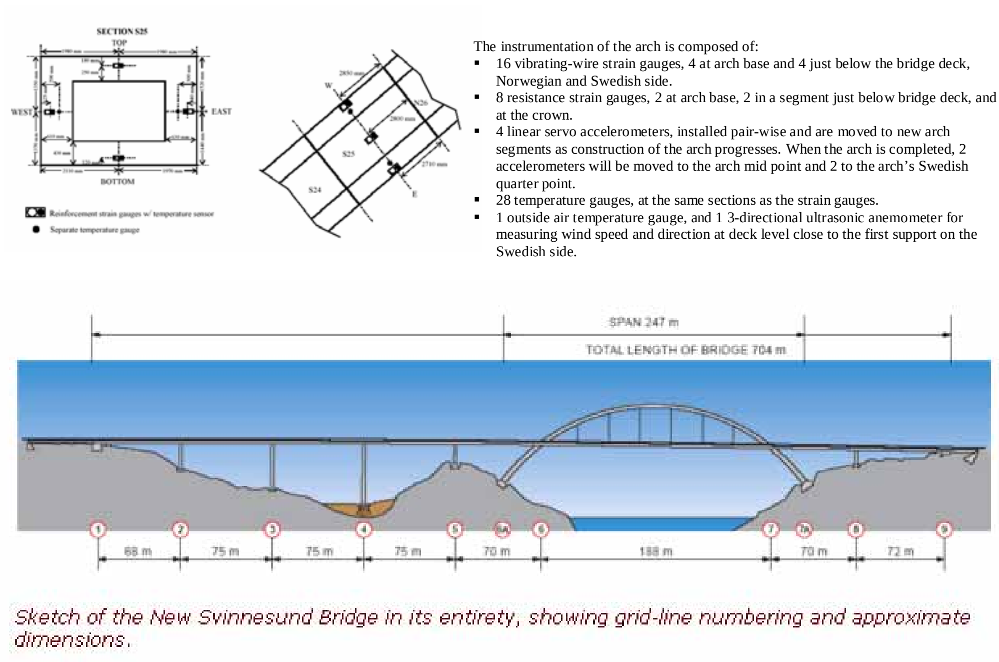


Figure 46 Sensor configuration for a small construction monitoring solution in Sweden.

11.3 Structural Health Monitoring Systems

The Structural Health Monitoring System is based on a comprehensive monitoring strategy as part of the bridge design or rehabilitation definition documentation as discussed in the chapters above. The task of the SHMS is to monitor the in-situ behaviour of a structure accurately and efficiently, to assess its performance under various service loads, to detect damage or deterioration, and to determine the health or condition of the structure. The SHMS system should be able to provide, on demand, reliable information pertaining to the safety and integrity of a structure. The information can then be incorporated into bridge maintenance and management strategies, and improved design guidelines. The damage-detection capabilities of the SHMS can be graduated as to how accurately the damage detection shall be carried out. This can be from very simple analysis of mode shapes from time histories to very advanced in-situ calibration of accurate FE models and the use of neural networks for damage detection.

These activities are usually carried out a Structural Health Evaluation System (SHES) presented earlier.

11.4 Monitoring Parameters

If the monitoring parameters are not planned very carefully based on the applications the SHMS will support, the structure type, the loads subjected to the structure and the acceptance level for structural responses the number of sensors in a SHMS can easily grow very large. Especially the use of strain gauges and temperature sensors used for the design verification of many structural components of the bridge can make the number of necessary sensors change from hundreds to thousands.

For each planned sensor it must be closely considered if the information provided by the sensor is needed to know or nice to know. Basically nice to know information should be avoided in order to keep the system economical and to avoid the risk of drowning important data in a vast amount of less important data.

Also the redundancy issue should be considered: high redundancy will create a need for duplicating the same types of sensors, whilst the extent of sensor types shall be kept low.

The following table is a summary of monitoring parameters to consider based on load effects, response types, bridge type and importance of knowing the information the sensors can provide.

			Class 1	Class 2	Class 3	Class 4
ENVIRONMENTAL EFFECTS*						
Air temperature			SL	SL	SL	SL
Air and surface humidity				L	SL	SL
Precipitation					SL	SL
Pavement water veil					SL	SL
Ice formation					SL	SL
Athmospheric pressure						SL
Solar radiation						SL
LOAD EFFECTS*						
Wind	Tower top & girder level		L	L	SL	SL
Traffic	Load and traffic count			SL	SL	SL
Structural temperature	Girder, tower and cables				L	SL
Seismic/tectonic activity	Seismic activity and tsunami				SL	SL
	Correlation at midspan					L
STRUCTURAL RESPONCE						
Corrosion	Concrete reinforcement	splash zone	SL	SL	SL	SL
Joint relative displacement			SL	SL	SL	SL
Special element responce				L	SL	SL
Stress/Strain	Fatigue	orthotropic deck		L	L	SL
		cable anchorage			L	L
Dynamic motion	Global bridge behaviour				L	L
	Cables				L	L
Concrete creep	In situ concrete				SL	SL
Stress/Strain	Global bridge sectional forces					L
Global structural positioning						L
GEOTECHNICAL RESPONCE						
Ground settlement and inclination				SL	SL	SL
Ground pressure					L	L
Interstitial pressure					L	L
Special element responce					SL	SL

* eventually supplied by external weather station / traffic control center / Seismic-tectonic measurement station

Bridge size		class	
S	Short span	1	Important for all bridges
L	Long span	2	Necessary for minimum maintenai
		3	Necessary for an optimal health m
		4	Nice to know, may be monitored if

Figure 47: Ranking of monitoring parameters.

12 System Procurement

Smaller and more portable system construction lead times are typically calculated in weeks or months and most of their components are available off the shelf. Mid to large size system engineering and construction can take from six months to several years including several complete sub deliveries. All hardware components need to go through component level testing prior to integration. Application development has to be executed under a verified quality system. All application modules have to undergo component level testing prior to application testing and porting to the actual SHMS hardware. Integration and load testing are performed prior the final Factory Acceptance Test (FAT) that is a requirement for shipping authorization. FAT is typically overseen by a client representative and takes 1-5 days to complete.

12.1 Commissioning

On-site installation quality defines the lifetime reliability of the solution and thus the need to follow as strict a quality process as for the system construction. It is typical that tasks requiring lower competence like cable and support structure installations are performed by local subcontractors. Sensor and processor installations, component connections and testing are always the responsibility of the SHMS supplier’s specialist personnel.

Very important parts of the commissioning are the operator and maintenance training. Also invaluable are intuitive user interface and applications. Written user instructions in local language are required but more important are clear and fast on-line search and help functions.

On the large and long term projects lasting several years it is very demanding to ensure integrity of the system software due to additions and changes to the initial scope during the project. Also the possibility to integrate technology becoming affordable or otherwise necessary during the projects is a requirement. Both of these have to be part of the initial operating system and application design.

12.2 Lifetime Support

Component availability is typically guaranteed for 5-8 years for the SHMS. Operating system, user interface and application support availability in the future will be highly variable, depending on the supplier and can pose a serious risk to the upgradeability if an improper choice is made.

As the lifetime expectation for the solutions in question is over a decade and potentially several decades, the safest choice is to require the system to be based on an open source operating system like Linux, user interface to be built into a standard web browser and internal communications utilizing xml. Ensuring support for the application itself can only be achieved by requiring a third party software escrow arrangement as even the largest vendors cannot provide guarantees' for the required competence availability after several years. These selections give the best guarantee available for 'future proofing' the investment.

12.3 System Efficiency and Redundancy

The system has to provide full and detailed information storage under disaster conditions to enable fast recovery and post disaster off-line analyses. The most critical usage pattern for the monitoring system is during disaster recovery. This dictates the requirements for user interface simplicity and intuitiveness

13 Commercial solutions

For structural health monitoring needs there are two commercially available types of solutions to choose from.

- Permanently installed, tailored ‘turn key’ solutions.

- Pre-packaged portable solutions.

The above can be exploited separately or in the case of large structures as a combination.

13.1 Tailored Turn Key Monitoring Solution

Futurtec First Alert is used as an example of a modern SHMS solution. The system collects data from a multitude of environmental, structural and usage measurements, makes complex neural analyses of them, without delay makes control actions and provides information for decision support in accurately and easy to interpret format.

Futurtec First Alert consists of four main parts that are:

- The measurement solution with several different types of sensors ranging from the tiniest strain gauges to WIM-scales weighing several tons.

- SLS signal transmission bus to ensure that signal quality as well as installation and transmission costs are optimised using a mixture of wired and wireless technologies where best suited,

- Data Processing for the complex Neural and other analyses in the Data Server providing the consolidated and easy to interpret Local and

- Internet User Interface.

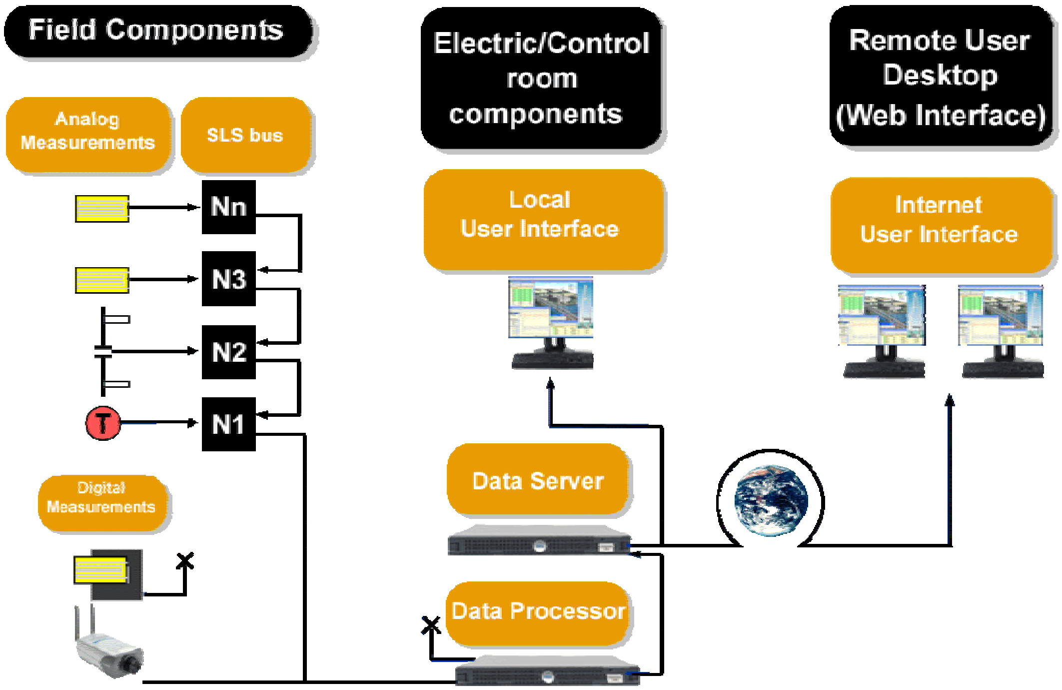


Figure 48: Turn Key SHM solution.

13.1.1 Sensor System

Futurtec first Alert M100-measurements support following sensor types to collect the necessary data for the analyses:

- Wind speed/direction/gust characteristics
- Temperature: Ambient/structural
- Visibility
- Wave height, water level, ice level
- Icing
- Corrosion build-up/penetration
- Material breakage
- Strain/Stress peak/accumulation
- Acceleration, displacement and position
- Image view and analysis
- Weight in Motion systems
- Speed radar
- Photo cells

The optimal configuration is selected for each application based on the process described earlier.

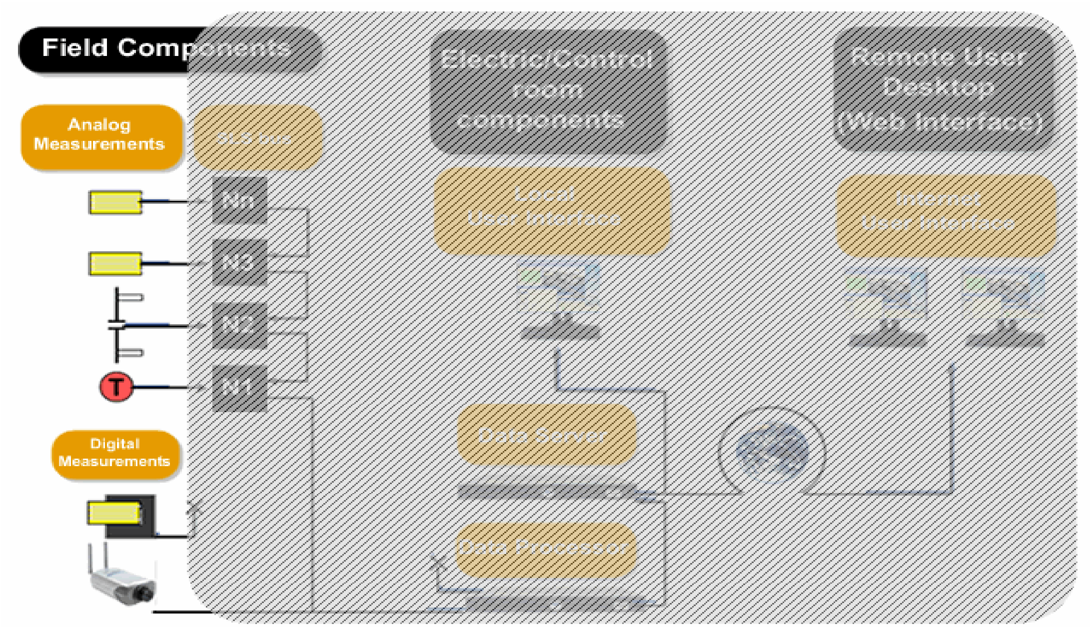


Figure 49: Sensor System.

13.1.2 Data Acquisition System

Both analogue and digital sensors are used in the Futurtec First Alert system. Analogue signals are transformed to digital as close to the transducer as possible to limit the noise to a minimum. The signal is then transported to the measurement processor in a combination of wired and wireless network called the SLS-bus.

The key benefits of the SLS-bus are:

- Ultimate reliability achieved by years of experience from field use of the components.
- High accuracy through 24-bit architecture.

Installation cost savings enabled by the intelligent serial communications design combined with the usage of the state of the art wireless technologies.

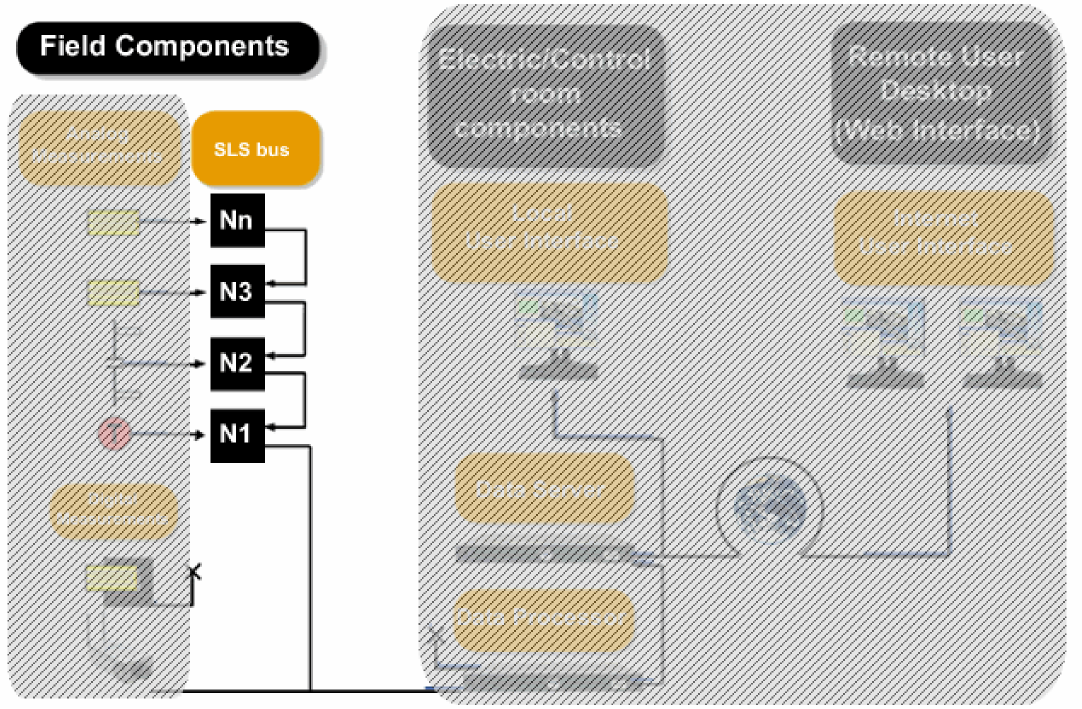


Figure 50: Data acquisition system.

13.1.3 Data Processor and Data Server

The Futurtec P100 Data processor receives measurement data from one or several measurement networks (SLS-based or other). The design has been made with extreme ruggedness in mind. The P100 has no moving parts and it has a wide operational temperature range. The P100 can operate as a stand-alone data processing and collecting unit or as a processing group. The P100 forwards data to an S100 server unit. In critical applications the P100 provides alarm and control outputs directly bypassing potential security bottlenecks. The ultimate stand-alone version of P100 is the battery powered solution.

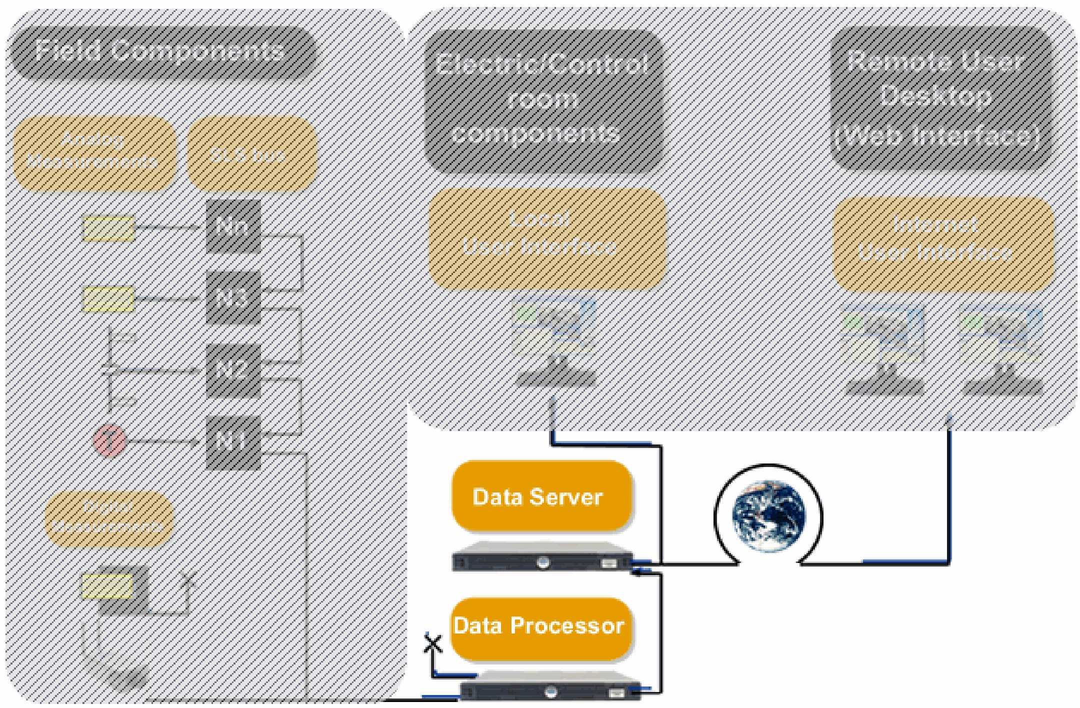


Figure 51: Data Processor and Data Server.

The Futurtec S100 Data Server receives measurement data from one or several P100 Data processors. The S100 resides between the Internet connection and the measurement system. The S100 Server collects and visualizes the data from the P100 units. it works as a single login point for maintenance. Server side software and more complex data visualization software will reside inside S100 and export their analysis as web-pages or animations.

The S100 houses large hard disks and records the measurements and does old data rotation and if necessary forwarding data to specified addresses.

13.1.4 Key benefits of the Data Processor and Data Server

Ruggedness (P100) and versatility (S100) designed to reside in the optimum parts of the system architecture.

The Processor-Server-architecture ensures 24/7 alarm and control operation even in the harshest of environmental, electrical and data transmission conditions.

Futurtec data processor and Data Server use the rugged, reliable, industry standard Linux Operating system.

13.1.5 Internet User Interface UI100i

After the signal acquisition, signal transmission, data analyses and –consolidation, Futurtec First Alert provides the operator easy to interpret / easy to use information for manual decision making or controlling directly the use or access to the asset monitored.

13.1.6 Key benefits of the Internet user interface

All key information for rapid decision-making, even for large assets are visible in easy to understand and interpret format on one single page.

The UI100i provides fast access to detailed analysis of all important areas of the monitored asset. All information is provided both in easy to use graphical format as well as in numerical format straightforward to export for further use in other systems.

Varying use of server bandwidth and priority settings is supported to ensure uninterrupted utilization of the key users at all times and all conditions.

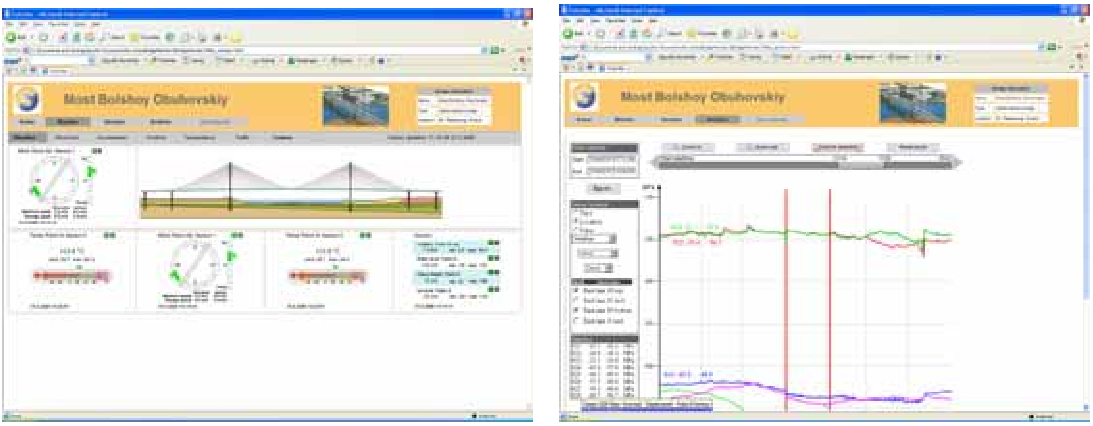


Figure 52: Customer-specific turnkey SHMS user interface.

13.2 Pre-packaged Portable Monitoring Solution

The portable solution can be employed in two ways.

- An independent solution that is typically serving several locations and operated either by the bridge operator or by an analysis partner like COWI, or
- As part of a large installation used to analyze or troubleshoot targets identified by the fixed system or in visual inspection.

The portable monitoring solution need not provide ultimate reliability neither upgradeability nor serviceability as the task duration seldom exceeds some weeks in length. On the other hand price/performance ratio must be very high and connectivity to the analyzing system flexible and straightforward. Capability to synchronize the measurements at millisecond level with the other systems is a must. At minimum the portable package has included sensor technology for:

- powerful acceleration analyses,
- several types of strain measurements,
- DGPS Displacement measurement rover station. (if the portable system is independent then the DGPS base station is required to be included as well)
- high performance video imaging capable of not only general recording but for example also stay cable or hanger large scale vibration mode, amplitude and frequency analyses.
- connectivity to any external analogue signal

The Futurtec portable solution packages the above in a rugged container together with the necessary local processing equipment, installation materials and cables.

Figure 53: Portable SHMS.

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15 Glossary

A/D	Analogue to Digital
ADC	Analogue to Digital Converter
BMS	Bridge maintenance and Management System
BOT	Build, Operate and Transfer
DAU	Data Acquisition Unit
DAS	Data Acquisition System
DPCS	Data Processing and Control System, Data Server
DGPS	Differential Global Positioning System (see also GPS)
FFT	Fast Fourier Transformation
FAT	Factory Acceptance Test (see also SAT)
FE	Finite Element
FEM	Finite Element Method
GCNS	Global Cabling Network System, fibre (see also LCNS)
GPS	Global Positioning System (see also DGPS)
LCC	Life Cycle Cost
LAN	Local Area Network (see also WAN)
LCNS	Local Cabling Network System, copper (see also GCNS)
MACS	Management Administration and Computer simulation system
MMS	Maintenance management systems (see also BMS)
NDT	Non-Destructive Testing
PAC	Programmable Automatic Controller (see also PLC)
PIMS	Portable Inspection and Maintenance system
PLC	Programmable Logic Controller (see also PAC)
SAT	Site Acceptance Test (See also FAT)
SCADA	Supervisory Control And Data Acquisition
SHES	Structural Health Evaluation System
SHMS	Structural Health Monitoring System
SLS	Safe Load System
SLS-Bus	High performance digital measurement information transfer bus
SMS	Structural Monitoring System

TMS	Traffic Management System
UI	user Interface
WAN	Wide Area Network (see also LAN)
WASHMS	Wind And Structural Health Monitoring System (see SHMS) WiM
	Weight in Motion (moving vehicle weighing method)
XML	eXtensible Markup Language

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