COWI - Futurtec

Structural Health Monitoring Systems

First Edition

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Foreword

The present book about Structural Health Monitoring Systems has been written as result of talks between employees of COWI A/S and Futurtec OY. It was agreed that a general presentation of Structural Health Monitoring Systems and benefits towards using such technologies were missing in form of a general book towards this issue. Dr. Jacob Egede Andersen from COWI and Anttoni Vesterinen, Futurtec OY, now Agentis OY made a draft and later the book was finalised with Mario Fustinoni, CEO Futurtec OY replacing Anttoni Vesterinen.

The manuscribt was developed by common effort between COWI A/S and Futuretec OY, however the final book were printed in a seperate version for each company with different cover.

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1 Introduction

Structural monitoring is basically an activity where actual data related to civil structures are observed / measured and registered. This service 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 this activity has required specialists, has been time consuming and hence costly and as a result hereof only a limited number of structural performance indicators - typically geometry - have been measured at intervals and were usually supplemented by regularly timed 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 and others 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 the civil structures. These developments open the way for a wide range of applications related to safe and efficient operation and maintenance of the structures.

Structural monitoring has thus emerged as a distinct high-tech technical discipline since the new technologies have been introduced and are more commonly in use 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 somewhat weakly defined objectives it seems that the owners have not achieved the optimal cost/benefit ratio from the – often rather significant – investment in the structural monitoring systems.

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 through a cost/benefit assessment. The value of design verification, user safety, trouble shooting capability and maintenance optimisation can be very difficult to quantify. However in terms of a minimal assessment, it is possible to do some cost benefit analysis regarding the investment and operation costs of a SHMS compared to assessed maintenance budgets. Structural monitoring systems designed on principals as outlined in the following sections of this book 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 participating to some extents in the civil engineering structures may in many cases be identified - as illustrated in figure 1:

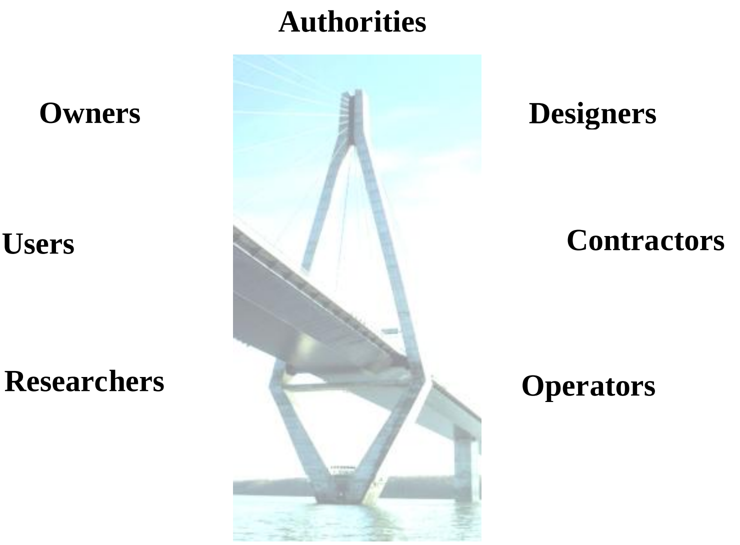

Figure 1: Typical stakeholder groups in civil engineering projects

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 safety and functionality of the structures shall be documented
Owners	- Reliability of the structures must satisfy codes and standards - Acceptable service lifetime 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 inte rests 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 a nd service lifetime and keep it within budget.

The users are primarily interested in high accessibility, visual comfort and safe use of the stru c-ture. If any events, e.g. high winds, accidents, maint enance 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 struc-tures. Usually the main interest will be in the design verification of new design methods and materials as well as the understanding of structural problems du ring the operation of the bridge.

The key interest of the designer is to collect environmental and seismic i nformation 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 i m-portant to ensure that construction is carried out as spec ified.

The operator's main interest is to ensure that no irreversible errors have been made in the design and construction process, that safety of the users is ensured at all times and that operating costs can be reduced and maintenan ce streamlined. For the verification of the residual lifetime of the structure and the LCC it is important to use in particular front -line knowledge of int egrating the data measured by a SHMS into an overall Bridge Management and Maintenance System (BMS). For the maximum ben efit 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 maint e-nance program and the reduction of maint enance costs.

Key issues are to clarify conce rns of the stakeholders and identify and assess their objectives, associated with the structural mon itoring activities to be planned.

2.2 Management Levels

When it has been decided to apply structural monitoring in order to document fulfilment of a stakeholders objectives, the implementation of monitoring activities and the assessment of r e-sults will be carried out on typically three organis ational levels as illustrated in Figure 2.

Figure 2: Generic model for the organisational levels taking care of structural mon i-toring 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 de-fined.
- the necessary activities are initiated to *implement* the systems and routines necessary to meet the goals.
- data are acquired, synchronised, reported, archived and analysed.
- 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 (archive database), 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 easy and timely 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, synchronised, 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 SHMS in real time on 24 hour shifts on larger bridges, while on smaller bridges the operation of the SMS will be automatic or can be remotely controlled.

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 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 instantaneously to all affected managers in the bridge organisation [1].

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

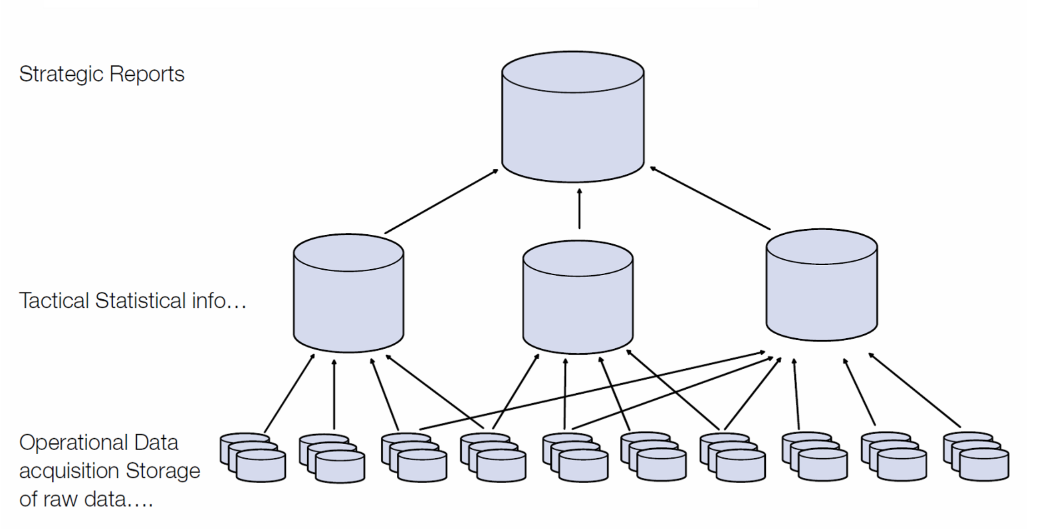

Figure 3: Organisation of structural monitoring data

2.4 Implementation Phases

In general, from a monitoring point of view, the life of a bridge can be described as pre-construction tests (wind tunnel etc.), 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 for easy and efficient use of 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 SHMS in the construction phase replaced/completed by another SHMS in the operation phase, each optimised for their specific task.

In the following sections 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 a SHMS.

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 on site to verify predictions made by numerical models used in a design phase.

Internal loads

In addition to the permanent measurements, short time, intensive measurement campaigns can be repeated over time using mobile sensors, 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. A dedicated data logger performs Rainflow cycle counting on sampled data in real time. Time series, statistical values and time correlated fatigue analysis will be based on Miner sums.

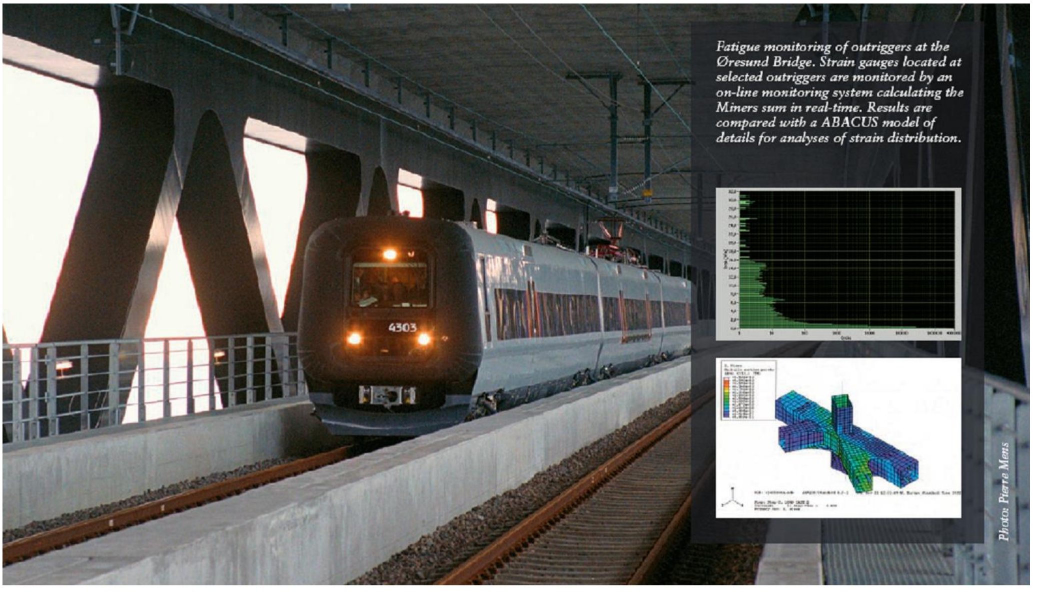

Figure 4: Fatigue monitoring of critical welds by the SHMS on the Øresund Bridge, Denmark - Sweden.

Deterministic response

Movement in hydraulic buffers, dampers, expansion joints dependent from temperature and load distribution in orthotropic decks can be monitored by temperature - and displacement sensors, tilt meters 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 and calculation of the residual lifetime. 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