Long-term static Structural Health Monitoring

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ABSTRACT

In the last 15 years, Structural Health Monitoring has become a useful and increasingly widely used tool for the construction, management and lifetime extension of bridges and other civil structures. A lot of attention has been devoted to dynamic monitoring of structures in the aim of performing system identification and damage detections. The monitoring of static parameters such as strains, deformations, tilts and displacements is another useful and complementary tool to asses the long term performance and to identify changes in behavior that are often difficult to spot with dynamic monitoring.

This paper is based on the experience gathered in monitoring more than 40 bridge monitoring projects carried out over the last 15 years using advanced sensing systems including fiber optics, GPS and corrosion sensing. In particular we concentrate on the analysis of the different types of bridges that were monitored, their situation (new construction, existing structure, refurbishment…) and the main purpose of the installed monitoring system. Two main categories emerge form this analysis: new bridges with innovative aspects or particular relevance and existing bridges with known deficiencies.

A methodology to design an integrated monitoring system capable of monitoring the whole structure with a limited number of sensors, of the right type and placed at the right locations will be introduced.

Finally, an application example of Structural Health Monitoring system design and implementations for the I35W will be briefly presented.

INTRODUCTION

The life of each structure is far from being monotonous and predictable. Much like our own existence, its evolution depends on many uncertain events, both internal and external. Some uncertainties arise right during construction, creating structural behaviors that are not predictable by design and simulations. Once in use, each structure is subjected to evolving patterns of loads and other actions. Often the intensity and type of solicitation are very different form the ones taken into account during its design and in many cases they are mostly unknown in both nature and magnitude. The sum of these uncertainties created during design, construction and use poses a great challenge to the engineers and institutions in charge of structural safety, maintenance and operation. Defining service levels and prioritizing maintenance budgets relying only on models and superficial observation can lead to dangerous mistakes and inefficient use of resources. Regular inspection can certainly reduce the level of uncertainty, but still presents important limitations being confined to the observation of the structure's surface during short times spaced by long periods of inactivity. Structural Health Monitoring aims to provide more reliable data on the real conditions of a structure observe its evolution and detect the appearance of new degradations.

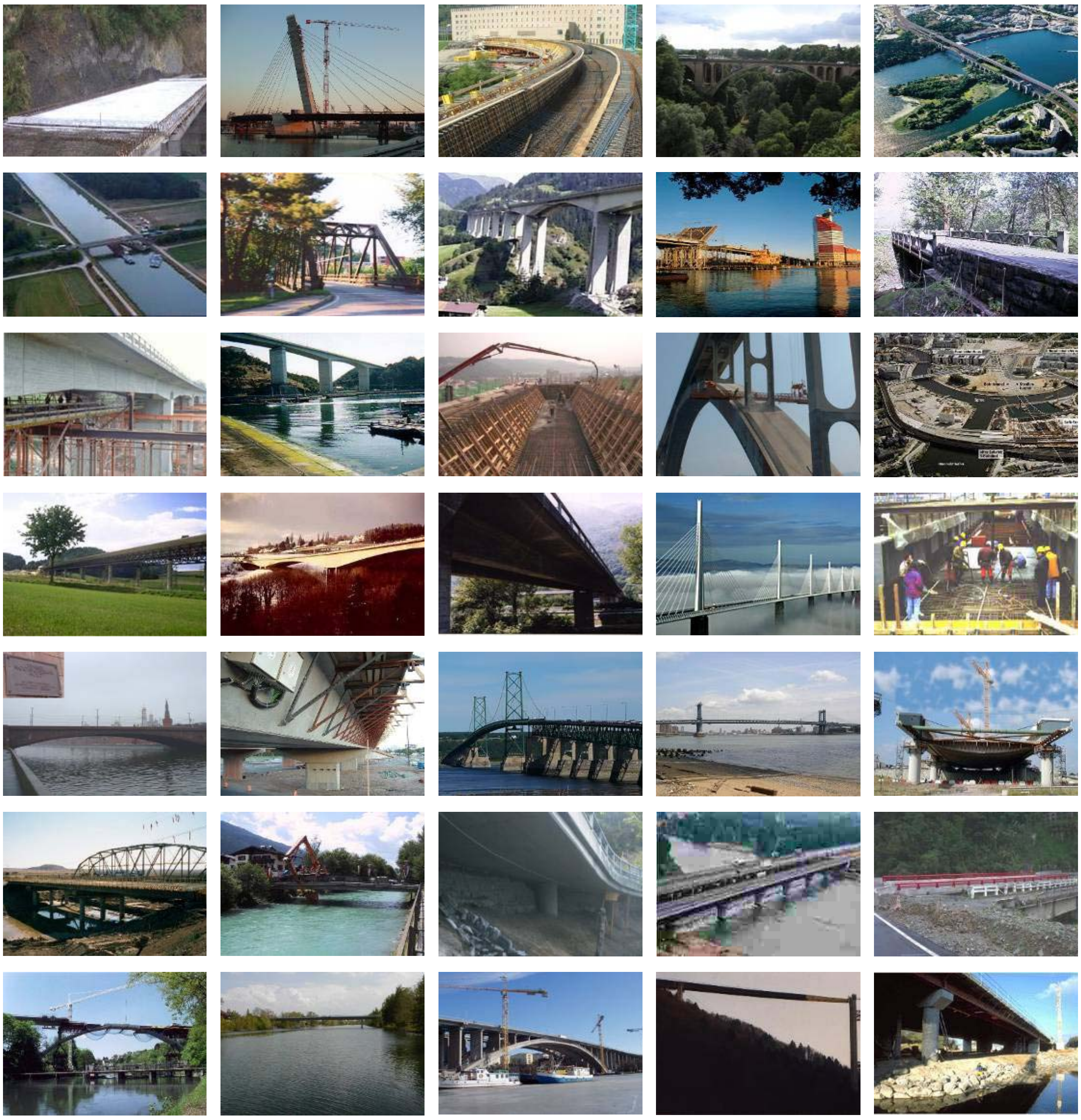

Figure 1 Photo Gallery of 35 of the 40 bridges considered in this overview, shows the great variety of bridge types that can benefit form monitoring.

By installing a number of sensors, measuring parameters relevant to the structural conditions and other important environmental parameters, it is possible to obtain a picture of the structure's state and evolution. Monitoring is a new safety and management tool that ideally complements traditional methods like visual inspection and modeling. This paper resumes the reasons and results of monitoring 40 bridges worldwide in the last 12 years. In that time period, our company and partners has instrumented other bridges (as well as hundreds of other structures), but we limited our overview to those bridges were reliable data was available on the purpose of monitoring and the obtained results. Figure 1 shows a collage of pictures of the bridges considered in this survey.

BRIDGE TYPES

Let's first consider the distribution of monitored bridges, most of them depicted in Figure 1, both geographically and by type.

LOCATION - The 40 bridges considered here are located in the following countries: Austria, Belgium, Canada, Croatia, France, Germany, Italy, Japan, Luxembourg, Russia, Sweden, Switzerland, Taiwan and the USA. Several other projects were not included in the survey because of the lack of details.

BRIDGE TYPE – Figure 2 illustrates the diversity of brides that were monitored. There is a prominence of concrete girder bridges, which the also the most common types of bridges in the global population. It is however interesting to notice that signature bridges, including suspension and cable-stayed bridges represent only a small percentage, while more ordinary bridges constitute the vast majority of the population. This reflects the fact that monitoring can be applied with success to any type of bridge.

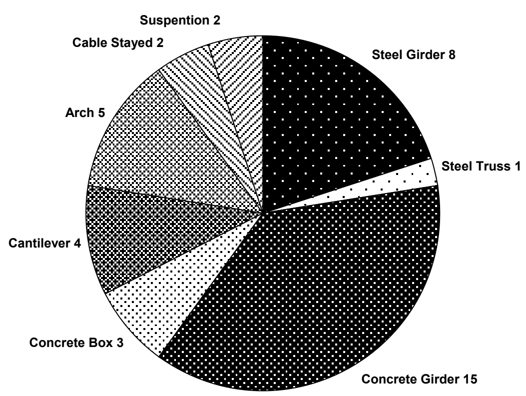

Figure 2: Bridge population by type

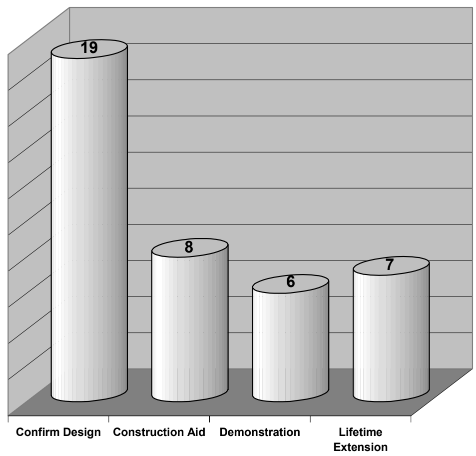

Figure 3: Purpose of monitoring

LIFETIME PHASE - Monitoring can be applied in different phases of a bridge life. The 40 bridges considered here reflect this diversity:

- New Bridges (installation during construction): 18
- Existing Bridges (installation on an existing bridge): 13
- Bridges under Refurbishment (installation during works): 9

There is therefore an even distribution between new and existing bridges.

PURPOSE OF MONITORING - The reasons for monitoring a bridge can be different. The most common are to obtain quantitative date about the structural behavior in order to confirm design assumptions, to provide real-time feed-back during construction and to perform a controlled lifetime extension of a bridge with known problems. Some projects are also considered as demonstration projects, driven more by the interest in new technologies than by a specific monitoring purpose. As shown in Figure 3, in the majority of projects, the main purpose of monitoring was to confirm design assumptions. This is especially true for new bridges, but also applies to many existing bridges, where monitoring helps to evaluate the real current condition of the bridge and allows the engineers to take informed decisions about their future and to plan maintenance or repair actions. In the case of bridges classified as "lifetime extension" the monitoring system is used to increase the safety of the structure and provide early warning of an acceleration of the known degradations that are being monitored.

It is interesting to see how this subdivision has evolved in time. If in the early years (1995-1998) demonstration projects and applications concerning only the construction phase accounted for a majority of the applications, in more recent times the main reasons for monitoring has become the confirmation of design hypotheses and the controlled lifetime extension of existing structures. It is important to notice that projects aiming to a confirmation of the design assumptions concern all phases of the bridge's lifetime. For new bridges, one can confirm the sound design of the structure; in the case of existing bridges, a monitoring program is usually targeted at fine-tuning the model to the real conditions of the structure. In this case, monitoring is used to reduce the uncertainties introduced during the constructions and the successive degradations.

CUSTOMER - A monitoring project can be initiated and financially supported by different institutions. In the case of the bridges in this study the paying customers were subdivided as follows:

- Bridge Owner: 23
- University (through research founds): 13
- Engineering company: 4

This demonstrates that structural health monitoring is still considered a research topic by many owners. It is however encouraging to see that the majority of projects originate from owners and engineers.

INSTALLATION - The same distinction applied to the installation of the monitoring system itself:

- Owner: 1
- University 15
- Instrumentation Company24

Only in one case the system has been installed by a team working directly for the structure's owner. In all other cases the system was installed by a professional instrumentation company, in some cases SMARTEC itself, or a university.

BUDGET – Budget figures include the cost of the hardware and the installation, but not the cost of data analysis and system maintenance.

- 0 – 50 k$: 23
- 50 - 100 k$: 6
- 100 – 500 k$: 10
- 500+ k$: 1

Many projects fall in the range below 50'000$. These are typically short-term projects or projects with a reduced number of sensors. The category 100-500 k$ typically includes those projects that aim to permanent and autonomous monitoring with remote access. Among the ones considered here, only one bridge instrumentation project exceeded 500'000$.

INSTALLED SENSORS - The number of sensors installed for each project is the following:

- 1-10: 19
- 11-25: 8
- 26-50: 5
- 51-100: 5
- 100+ : 3

Small projects (20 sensors or less) dominate again in this case.

SENSOR LOCATION - The sensors can be installed on different parts of the bridge. In the considered projects the most instrumented elements were the following (in some cases multiple elements are monitored):

- Deck: 9
- Load-carrying elements (beams, arch, cables): 31
- Piers: 4
- Foundations: 2

The main concern is therefore, as expected, with the elements that transfer loads.

FREUENCY - Finally, a monitoring project can span different lengths in time and occur with varying frequencies:

- Short-Term (less than 12 months): 17
- Long-Term (more than 12 months, but non continuous): 12
- Permanent (continuous monitoring): 11

Short-term monitoring dominates (especially in the early years). In those cases, once the original question is answered, the monitoring system is abandoned. This is typically the case of projects that concern the construction phase in particular.

DESIGNING AND IMPLEMENTING AN SHM SYSTEM

Designing and implementing an effective Structural Health Monitoring System is a process that must be carried out following a logical sequence of analysis steps and decisions. Too often SHM system have been installed without a real analysis of the owner needs, often based on the desire to implement a new technology of follow a trend. These monitoring system, although perfectly working from a technical point of view, often provide data that is difficult to analyze or which cannot be used by the owner to support management decisions. The 7-step procedure that is detailed in the next paragraphs has proven over the years to deliver integrated structural health monitoring systems that respond to the needs of all parties involved in the design, construction and operation of structures of all kinds.

Step 1: Identify structures needing monitoring

This step might seem trivial, but is indeed a very im-portant first step. Before considering a structural health monitoring system, it is important to consider if a specific structure will really benefit from it. The following list includes some of the situations where and SHM system is believed to be beneficial:

- New structures including innovative aspects in the design, construction procedure, or materials used.
- New structures with unusual associated risks or uncertainties, including geological conditions, seismic risk, meteorological risk, aggressive environment, vulnerability during construction, quality of materials and workmanship.
- Structures that are critical at a network level, since their failure or deficiency would have a serious impact on the rest of the network and the users.
- New or existing structure which is representative of a larger population of identical or very similar structures. In this case most information obtained from a subset of structures can be extrapolated to the whole population.
- Existing structures with known deficiencies or very low rating resulting form visual inspections.
- Candidates for replacement or major refurbishment works. In this case SHM is used to assess the real need for such action and to better design and execute the repair.

The result of this step is a list of structures that need an SHM system.

Step 2: Risk / Uncertainty / Opportunity analysis

The SHM system designer, the design engineers or the engineers in charge of the structural assessment and the owner, must jointly identify the risks, uncertainties and opportunities associated with the specific structure and their probability. The risk analysis will lead to a list of possible events and degradations that can possibly affect the structure. Example of risks are corrosion, loss of pre-stressing, creep, subsidence of foundations, earthquake strike, unauthorized overloads, impact, poor building material quality and poor execution. The uncertainty list includes all unanswered questions about the structural conditions and performance. Examples of uncertainties include the performance of the construction materials (e.g. the E modulus of concrete or the thermal expansion coefficient of a composite), the magnitude of loads or the correspondence between the calculated and the real strain levels.

The Opportunity list includes all parameters and performance indicators that might be better than expected or assumed. Examples include reserve load bearing capacity, better properties of structural materials, presence of synergetic effects, additional stiffness and reduced deflections.

The impact and probability of each risk and opportunity will be classified using the usual risk analysis procedure to produce a ranking of risks. At this point, some risks and opportunities will be retained and others will be dropped because of a low impact or probability. The result of this step is a list of risks that must be addressed by the SHM system.

Step 3: Responses

For each of the retained risk, uncertainty and opportunity, we now need to associate one or several responses that can be observed directly or indirectly. For example corrosion will produce a chemical change, but also a section loss. Subsidence will produce a settlement or a change of pore pressure. The inaccuracy of the Finite Element Model will produce a difference in the response between the structure and the model.

At this stage, it is also useful to roughly quantify the expected responses. For example is a tilt is expected as the result of an uneven settlement, one should estimate if the tilt is in the order of milliradians or several degrees. This is very important to select the sensors with appropriate specifications. At this stage it is also possible to determine which responses are easily and efficiently observed by a periodic visual inspection and which others require instrumentation. The physical locations where these responses are expected or will appear at their maximum extend also need to be established. The output of this step is a list of responses that need to be detected and measured, their estimated amplitudes and their location.

Step 4: Design SHM system and select appropriate sensors

This is typically the first step that is approached by inexperienced SHM system proponents or by those offering a specific sensing technology and trying to find applications for it. In our approach it is however only the forth step and it becomes a much easier one. The goal is now to select the sensors that have the appropriate specifications to sense the expected responses and are appropriate for installation in the specific environmental conditions and under the technical constraints found in the structure (Glisic and Inaudi 2003). At this stage one should also consider the required lifetime of the SHM system and the available budget. It is often beneficial to include sensors based on different technologies, to increase the system redundancy and complementarily. On the other hand, having too many data acquisition systems will increase the system cost and complexity, so a good balance is required.

It is of fundamental importance that a monitoring system is designed as an integrated system, with all data flowing to a single database and presented through a single user interface. The integration between the different sensing technologies that can be simultaneously installed on the structure, e.g. fibre optic sensors, vibrating wire sensors, tilt meters, weather stations and corrosion sensors, can be achieved at several levels. Different sensors can be connected to the same datalogger; otherwise several dataloggers can report to a single data management system, typically a PC, which can de installed either on site or at a remote location. The data management system must interface to all types of dataloggers and translate the incoming data into a single format that is forwarded to the online database system as shown in figure 1.

Although many vendors of sensors and data acquisition systems provide their own software for data management and presentation, these tend to be closed system that can only handle data from their specific sensors. Since a monitoring project often requires the integration of several technologies, it is important to provide the end-user with a single integrated interface that does not require him to learn and interact with several different user interfaces. The design of the system also needs to take into account the constraints associated with its installation and the construction schedule in the case of a new structure. The result of this step is a design document, including a list of sensors, installation and cable plans, installation procedure and schedule as well as a budget.

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These indications should be considered as a stating point for designing an integrated bridge health monitoring system. It is however necessary to perform a specific risk analysis for each single bridge or at least for each family of similar bridges. For example a concrete bridge in the Alps will see an increased risk of corrosion from the use of de-icing salt compared to an identical bridge in the Arizona desert. The ideal monitoring system will therefore be different for these two bridges.

Step 5: Installation and Calibration

Installation of all systems must adhere to the supplier's specifications. Parts of the installation work can be carried out by the general contractor, with appropriate instruction and supervision. The system calibration and testing must be carried out by the SHM contractor and can sometimes be divided in different phases, if the sensors are not all installed at the same time. This step can be concluded by a Site Acceptance Test (SAT). If needed, the thresholds for automatic warning generation must be defined at this step by the responsible engineer and the owner. The result of this step is an as-built plan of the SHM system, a system manual and a calibration report.

Step 6: Data Acquisition and Management

This is the operational part of the process. The data is acquired and stored in a database, with appropriate backup and access authorizations. Documentation of all interventions on the structure and on the system is also important in this phase. The result of this step is a database of measurements and a log of events.

Step 7: Data Assessment

This is often the most difficult step, but having followed the above procedure it becomes much easier. By analyzing the responses of the structure, the engineer will be able to identify if any of the foreseen risks and degradations have materialized. At this step the owner will also establish procedures to respond to the detection of any degradation. For example, the detection of a given degradation could simply be listed in a yearly report, while another might require the immediate closure of a bridge for further inspection. The analysis of the data might prompt for further investigation, including inspection, testing or installation of additional sensors. The output of this step is a series of alerts, warnings and periodic reports.

Summary

Designing and implementing a structural health monitoring system for a bridge is a process that is not much different from designing and building the bridge itself. It requires experienced professionals and a combination of multidisciplinary skills. Unfortunately, this process is not yet formalized in the same way as for example the construction process, where codes, laws and regulations reduce the uncertainty and improve the interaction between the different actors involved in the process. Recommendations and drafts codes for the implementation of SHM system are however starting to appear; certainly an important step towards a mature SHM industry.

BRIDGE SHM EXAMPLE: I35-W BRIDGE, MINNEAPOLIS

To put the previous methodology in practice, we will now consider how it can be applied to design integrated structural health monitoring systems for a bridge. In the next paragraphs, we will apply the 7-step design methodology to this example.

Step 1: Identify structure

The new I35W Bridge (Inaudi D. et al 2009) is composed of two twin bridges with spans of approximately 100m, 154m, 74m and 45m, with a width of 57 m. It is composed to two pre-stressed concrete box girders in each traffic direction, supported on for concrete columns at the end oaf each span. Figure 4 shows the almost completed bridge.

Figure 4: The I35W Bridge nearing completion

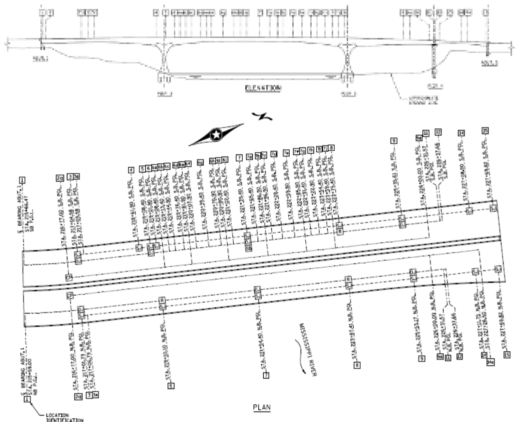


Figure 5: Location of installed instruments

The main reasons for designing and installing a SHM system is to support the construction processes, record of structural behaviour for future references and guarantee the Bridge security, restoring the public confidence in using the bridge.

Step 2: Risk / Uncertainty / Opportunity analysis

The following potential risks (R), uncertainties (U) and opportunities (O) were identified:

- R1: loss of pre-stress
- R2: non-working bearings and expansion joints
- R3: cracking of concrete
- R4: settlement of piers
- R5: chlorine penetration
- U1: Correspondence between Finite Element Model and real strains / stresses
- U2 Correspondence between calculated vibration modes an real behaviour
- O1: Accelerating construction sequence

Step 3: Responses

The following responses were associated with each of the abovementioned phenomena:

- R1: global deformation, change of curvature
- R2: reduced movement of expansion joints
- R3: curvature, crack opening
- R4: redistribution of loads, global deformation
- R5: rebar corrosion
- U1: Difference in predicted and real strain
- U2: Difference in predicted and real vibrations
- O1: Maturity of concrete, reduced creep

Step 4: Design SHM system and select appropriate sensors

Based on the previous list, an adapted SHM system was designed. Sensors are located throughout the two bridges, the northbound and southbound lanes, and are in all spans. However, a denser instrumentation array is installed in the southbound main span over the Mississippi river, as depicted in Figure 5. The list of the different sensor types, their measurements and purpose according to the identified responses are listed in Table 1. In this project, fiber optic has been selected as a complementary solution to vibrating wire strain gauges (Glisic and Inaudi 2007). This project is also one of the first to combine very diverse technologies, including vibrating wire sensors, fiber optic sensors, corrosion sensors and concrete humidity sensors into a seamless system, with a single database and user interface.

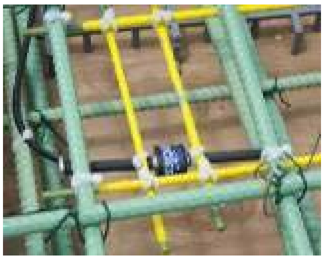
Step 5: Installation

Some of the installed sensors and data acquisition systems installed in the bridge are shown in Figure 6.

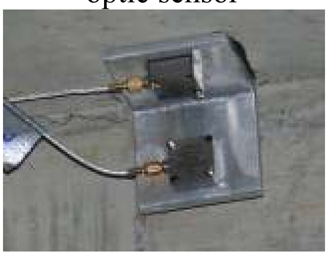
Table 1. Sensor types, purpose and addressed risk or uncertainty

Sensor Type	**Measurement**	**Purpose**
Vibrating-wire strain gauges	Local static strain	Concrete shrinkage and creep (R1,O1) Correspondence with FEM (U1)
	Local curvature	Loss of pre-stress, creep (R1)
Thermistors	Temperature	Concrete T during curing (O1) T induced deformations (U1,O1)
	Temperature gradient	Temperature induced strain (R2, U1)
Linear Potentiometers	Joint and bearings movements	Stuck joints and bearings (R2) Anomalous global movements (R2,U1)
Accelerometers	Traffic induced vibrations	Excessive vibrations (U2) Dynamic amplification (U2)
	Modal Frequencies	Correspondence with analysis (U2)
	Dynamic damping	Stuck joints and bearings (R2) Anomalous global behavior (U1)
Corrosion Sensors	Concrete resistivity	Water exchange in concrete deck (R5)
	Corrosion current	Corrosion of concrete deck rebars (R5)
Long-gauge fiber optic sensors	Average strains	Detection of Cracks (R3) Correspondence with analysis (U1)
	Strain distribution	Temperature induced deformations correspondence with analysis (U1)
	Average Curvature Deformed Shape	Loss of pre-stress, creep (R1) Correspondence with analysis, settlements (R4)
	Dynamic Strains, dynamic deformations, mode shapes	Anomalous global behavior (U2)
Topography	Deformed shape, global deformations	Loss of pre-stress, creep (R1), settlements (R4)


Long-gauge SOFO fiber optic sensor


Vibrating Wire Strain Gauge


Concrete humidity and corrosion sensors


Accelerometer


SOFO Fiber Optic Sensor Datalogger


Vibrating wire and temperature sensors datalogger

Figure 6: Overview of sensors and data acquisition systems installed in the I35W Bridge

Step 6: Data Acquisition and Management

All data from the conventional and the fibre optic sensors is collected by the respective data acquisition units and saved in a single relational database that can be remotely accessed by authorized users for data analysis.

Step 7: Data Assessment

The SHM monitoring system is currently gathering data from the sensors, complementing the manual readings that were taken during construction. Additional data was acquired during a load test performed in September 2008 All data is managed and analyzed by the university of Minneapolis.

CONCLUSIONS

This overview on the monitoring of 40 bridges with optical fiber sensors shows how diverse and multi-faced this domain can be. The projects include everything form a simple short-term test with a couple of sensors to verify a design hypotheses to a large-scale instrumentation project with hundreds of sensors to extend the lifetime of a bridge with known problems.

After an initial phase where many projects were driven by the curiosity of both universities and owners towards a new technology, we have now moved to applications where the customer wants to address a specific question or increase safety in the case of known deficiencies or degradations. Those projects show that a well planned and executed monitoring projects can provide actionable information to the owner and the bridge engineer.

As for any engineering problem, obtaining reliable data is always the first and fundamental step towards finding a solution. Monitoring structures is our way to get quantitative data about bridges and help us in taking informed decisions about their health and destiny. This paper has presented the advantages and challenges related to the implementation of an integrated structural health monitoring system, guiding the reader in the process of analyzing the risks, uncertainties and opportunities associated with the construction and operation of a specific bridge and the design of a matching monitoring system and data analysis strategy.

REFERENCES

Glisic and Inaudi 2007, Fibre Optic Methods for Structural Health Monitoring, , John Wiley & Sons, Ltd.

Glisic and Inaudi 2003, Strain, deformation and crack monitoring in bended structural members using long-gauge fiber optic sensors, , Test 2003, 13-15 May 2003, Nurenberg, Germany, paper A3.4 on conference CD.

Inaudi et al (2009), Structural Health Monitor-ing System for the new I-35W St Anthony Falls Bridge, 4th International Conference on Structural Health Monitoring on Intelligent Infrastructure (SHMII-4) 22-24 July 2009, Zurich, Switzerland.