Overview of 40 Bridge Structural Health Monitoring Projects

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ABSTRACT:

In the last 15 years, fiber optic sensing has become a useful and increasingly widely used tool for structural health monitoring of bridges and other civil structures. We have been fortunate to participate to their development and introduction to real field applications. This paper is an overview of 40 bridge monitoring projects carried out over the last 15 years in 13 different countries. 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. Finally, as an example of a Structural Health Monitoring project, we will briefly present the Monitoring system of the new I35W St. Anthony Falls Bridge in Minneapolis.

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 limited 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. 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. The distribution by continent is shown in Figure 2.

The main part of the bridge population is in Europe, reflecting the location of SMARTEC in Switzerland. The prominence of Europe mainly comes from the first years of activity and new projects are more evenly distributed among continents. Furthermore, applications in Asia and the Americas tend to be carried out by our partners, so several projects were not included in the survey because of the lack of details.

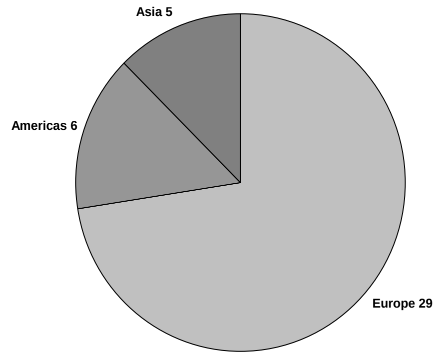

Figure 2: Bridge population by continent

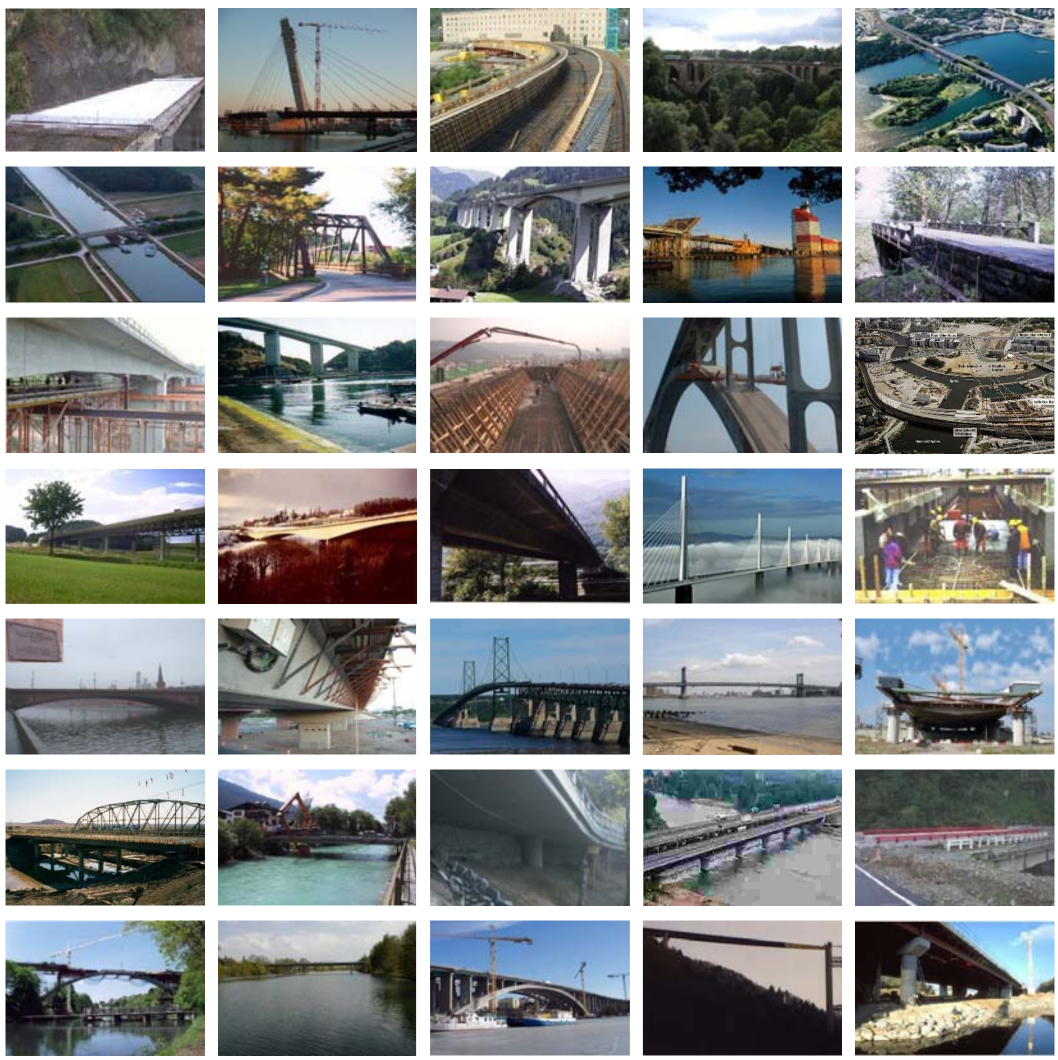

Figure 1 Photo Gallery of 35 of the 40 bridges considered in this overview, shows the great variety of bridge types that can benefit form monitoring.

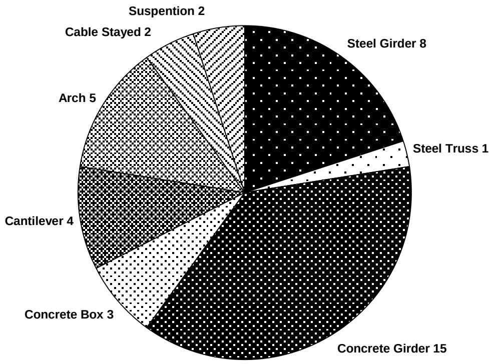

Figure 3: Bridge population by structural type

BRIDGE TYPE – Figure 1 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.

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

- 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.

MONITORING

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.

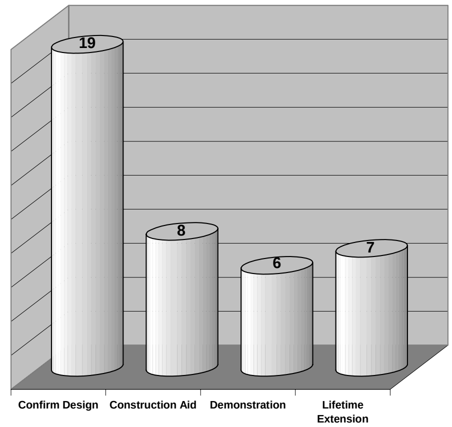

Figure 3: Purpose of monitoring

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 (see Figure 4).

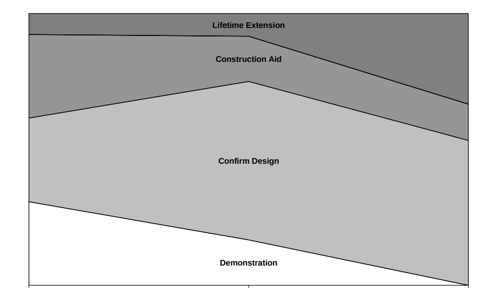

Figure 4: Time evolution of the reasons for monitoring

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.

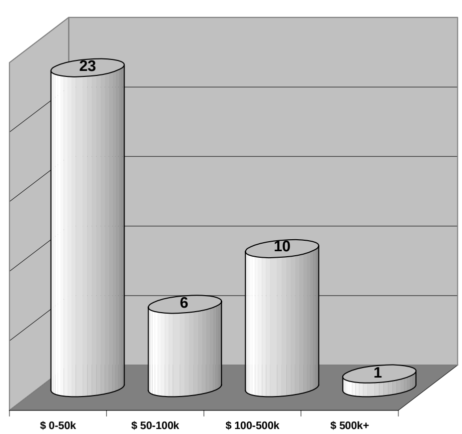

Figure 5: Monitoring system budget

BUDGET - Figure 5 shows the distribution of cost for the installed monitoring systems. This includes the cost of the hardware and the installation, but not the cost of data analysis and system maintenance. 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.

RESULTS

It is obviously difficult to draw general conclusions about the results obtained by such diverse monitoring projects. We will however try to summaries the main findings in the next paragraphs.

SURVIVAL RATE: INSTALLATION - In the case of embedding in concrete, the typical survival rate of SMARTEC sensors is between 90% and 100%. There were however projects with significantly lower survival due to mishandling or installation errors. In the case of surface installation, damaged sensors can be replaced or repaired. In the case of embedded sensors, one has to foresee a certain level of redundancy to account for possible losses or foresee replacements by surface installation or reservation tubing.

SURVIVAL RATE: LONG-TERM - Once installed, SMARTEC fiber optic sensors typically age very well. We have observed a failure rate of approximately 1-2 % per year. Higher fatalities were observed in very aggressive environments or were the protection of exposed parts was insufficient.

In the case of permanent monitoring systems, the weakest link is usually the measurement system and the associated PC controller. Fortunately, these elements are easily serviced.

MAIN FINDINGS - Here are some examples of the main findings that could be gained in the cited projects:

- Observe the apparition of transversal cracks a few days after concreting.
- Measure the apparition of the cracks and the associated redistribution of the deformations in a quantitative way.
- Observe deformations during load test and compared to the ones predicted by finite elements programs and security standards
- Curvature variations of the bridge under thermal loading
- Measurements in fresh concrete allowed the prediction of cracking long before the cracks became visible and the optimization of the concrete mix for successive pours.
- Confirmed the excellent adherence between the old and new concrete.
- Follow the long-term shrinkage of concrete and the seasonal deformations due to temperature changes.
- Verify the amount of pre-stressing effectively given to the slab.
- During the push phase it was possible to observe the deformations induced in the caisson as its support conditions changed, for example when passing on a support.
- The sensors embedded in concrete were used to determine the amount of shrinkage and pre-stressing that was transferred from the concrete slab to the steel caisson.
- Verify the structural response of the beams wrapped with FRP.
- Continuous monitoring of prefabricated beams before transportation on-site, during transportation and during the pouring of the deck.
- Measure the local deformations of concrete and reconstruct the radial displacements during scaffolding removal and during the freestanding period of the arch.
- Daily temperature influence on the arch is particularly large and should be taken into account when performing point-measurements like triangulation.
- Monitoring the behavior of old columns during under traffic before and after repair.
- Deformation of the bridge during the construction phases and for the whole life cycle.
- Temperature monitoring and correlation with the measured strains.
- Pre-stress load transfer identification after deck completion, dead load deformation monitoring.
- Detection of fatigue crack onset in steel girders.
- Verify that no damage is induced in a bridge which is laterally moved form the construction location to the final location.
- Measure the dynamic amplification factors.
- Measure modal frequencies and mode shapes.
- Verify that the piers are not having excessive relative movements due to foundation instability.
- Verify that no damage is induced to a bridge due to nearby construction.
- Preserve bridge of historical value.
- Verify effect of thermal changes in the deformation of stays and main cables.
- Verify the distribution of live loads among individual wires in a cable bundle.

For additional details, please refer to the papers cited in the references and covering individual projects.

APPLICATION EXAMPLE: I35W BRIGE

This application example is a good example of a truly integrated structural health monitoring system, combining different sensing technologies to achieve the desired level of monitoring.

Figure 6: New I35W Bridge in Minneapolis

The collapse of the old I35W Bridge in Minneapolis in 2007 shook the confidence of the public in the safety of the infrastructure that we use every day. As a result, the construction of the replacement bridge (see Figure 6) must rebuild this confidence, by demonstrating that a high level of safety can not only be attained during construction, but also maintained throughout the projected 100-year life-span of the bridge.

One of the central factors contributing to this is the design and installation of a comprehensive structural health monitoring system, which incorporates many different types of sensors measuring parameters related to the bridge performance and ageing behavior. This system continuously gathers data and allows, through appropriate analysis, to obtain actionable data on the bridge performance and health evolution. The data provided is be used for operational functions, as well as for the management of ongoing bridge maintenance, complementing and targeting the information gathered with routine inspections.

The monitoring system was designed and implemented through a close cooperation between the designer, the owner, the instrumentation supplier and University of Minnesota.

The main objectives of the system are to support the construction process, record the structural behavior of the bridge, and contribute to the intelligent transportation system as well as to the bridge security.

The design of the system was an integral part of the overall bridge design process allowing the SHM system to both receive and provide useful information about the bridge performance, behavior and expected lifetime evolution.

Monitoring instruments on the new St Anthony Falls Bridge measure dynamic and static parameter points to enable close behavioral monitoring during the bridge's life span. Hence, this bridge can be considered to be one of the first 'smart' bridges of this scale to be built in the United States.

Figure 7: Sensing components

The system includes a range of sensors which are capable of measuring various parameters to enable the behavior of the bridge to be monitored. Strain gauges measure local static strain, local curvature and concrete creep and shrinkage; thermistors measure temperature, temperature gradient and thermal strain, while linear potentiometers measure joint movements. At the mid-spans, accelerometers are incorporated to measure traffic-induced vibrations and modal frequencies (Eigen frequencies). SensCore corrosion sensors are installed to measure the concrete resistivity and corrosion current.

Meanwhile there are long-gauge SOFO fiber optic sensors which measure a wide range of parameters, such as average strains, strain distribution along the main span, average curvature, deformed shape, dynamic strains, dynamic deformed shape, vertical mode shapes and dynamic damping – they also detect crack formation. Some of the installed sensors are shown in Figure 7.

The sensors are located throughout the two bridges, the northbound and southbound lanes, and are in all spans. However, a denser instrumentation is installed in the southbound main span over the Mississippi river, as depicted in Figure 8. This span will therefore serve as sample to observe behaviors that are considered as similar in the other girders and spans.

Figure 8: Sensor locations

This project is 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 using a single database and user interface.

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 my 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.

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