Integrated Structural Health Monitoring Systems for Buildings

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Abstract

When designing a Structural Health Monitoring system, one should always focus on the specific requirements of the structure under exam. The first step in the design process consists in identifying the probable degradation mechanism and the associated risks, in cooperation with the structure's owner and designer. Next, the expected responses to these degradations are established and an appropriate Structural Health Monitoring Systems is designed to detect such conditions. Only at this stage, the appropriate sensors are selected. Once the sensors are installed and verified, data collection can start. If these logical steps are followed and the monitoring data is correctly acquired and managed, data analysis and interpretation will be greatly simplified. On the other hand, if one designs an SHM system starting from a specific sensor system, it often ends up with a large quantity of data, but no plans on how to analyze it.

When selecting the best sensors for the specific risks associated with a given structure, it is often necessary to combine different measurement technologies. As an example, a high-rise building could require fiber optic sensors for strain monitoring, a corrosion monitoring system for the concrete pylon, vibrating wire pressure cells for measuring the pile loads in the foundations and a laser distance meter to observe the global deformations. To insure that the data from these systems is correctly fused and correlations between the measurements can be found, an integrated data acquisition and management system is required. Our experience has shown that the use of relational database structures can greatly simplify the handling of this large and heterogeneous data-flow. With an appropriate data structure, the measurement data and other related information on the monitoring network, the structure and its environment can be organized in a single repository that will follow the structure's life in the years.

Keywords: Structural Health Monitoring, monitoring strategies, instrumentation, damage detection

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1. Integrated Structural Health Monitoring systems for buildings

High-rise buildings and arena/stadium are complex structures. They are made of multiple elements and components that are stressed and interact with one another when exposed to external actions. Buildings vary widely in size, geometry, structural system, construction material, and foundation characteristics. These attributes influence how a building performs when overcharged or when under stress of natural events.

Structural Health Monitoring allows rapid assessment of a building's state of health and such approach is becoming recognized as a proper mean to increase the safety and optimize operational and maintenance activities of complex buildings. The data resulting from the monitoring program are used to improve the operation, the maintenance, the repair and the replacement of the structure based on reliable and objective data. Detection of ongoing damages can be used to discriminate deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

The malfunctioning of residential, high-rise buildings and arena/stadiums can often have serious consequences. The most severe are failures involving human victims. Even when there is no loss of life, populations suffer if the structure is partially or completely out of service. The economic impact of structural deficiency is reflected by costs of reconstruction as well as losses in the other branches of the economy.

Learning how a building performs in real conditions will help to design better structures for the future. This can lead

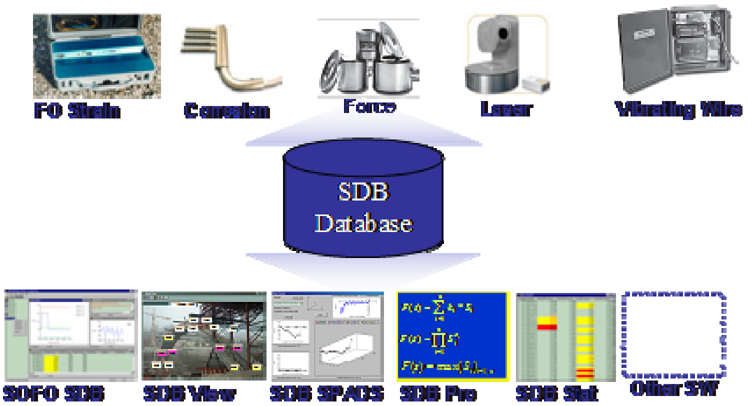

Fig. 1: Integration of sensing technologies into a single database / user interface

to cheaper, safer and more durable structures with increased reliability, performance and safety.

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 subject to evolving patterns of loads and other actions. Often the intensity and type of solicitation are very different from 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 building 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 and up-to-date information on the real conditions of a structure, observe its evolution and detect the appearance of new degradations. By permanently installing a number of sensors, continuously measuring parameters relevant to the structural conditions and other important environmental parameters, it is possible to obtain a real-time picture of the structure's state and evolution [1].

Instrumental Monitoring is a new safety and management tool that ideally complements traditional methods like visual inspection and modeling. Monitoring even allows a better planning of the inspection and maintenance activities, shifting from scheduled interventions to on-demand inspection and maintenance [2].

1.1. Monitoring strategies

Each monitoring project presents its peculiarities and although it is possible to standardize most elements of a monitoring system, each application is unique in the way they are combined.

It is however possible to classify the monitoring components according to several categories [3,4],

- Scale: Local scale, Member scale, Global scale, Network scale.
- Parameter: Mechanical, Physical, Chemical, Environmental, Actions.
- Periodicity: Periodic, Semi-continuous, Continuous.
- Response: Static or Dynamic.
- Data collection: None, Manual, Off-line, On-line, Real-time.

All these types of monitoring can be mixed and combined according to the specific need of the bridge under exam. This freedom requires a rigorous design approach to select the appropriate approach.

1.2. System integration

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. fiber optic sensors [5, 1], vibrating wire sensors, tilt meters, weather stations and corrosion sensors can be achieved at several levels. Different sensors can be connected to the same data logger; otherwise several data loggers can report to a single data management system, typically a PC, which can be installed either on site or at a remote location. The data management system must interface to all types of data loggers and translate the incoming data into a single format that is forwarded to the 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 a 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.

1.3. Benefits of SHM

The benefits of having a Structural Health Monitoring system installed on a building or any significant structure are many and depend on the specific application. Here are the more common ones:

- Monitoring reduces uncertainty
- Monitoring discovers hidden structural reserves
- Monitoring discovers deficiencies in time and increases safety
- Monitoring insures long-term quality
- Monitoring allows structural management
- Monitoring increases knowledge.

2. 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 systems have been installed without a real analysis of the owner needs, often based on the desire to implement a new technology or follow a trend. These monitoring systems, although perfectly working from a

Figure 2: Building under monitoring

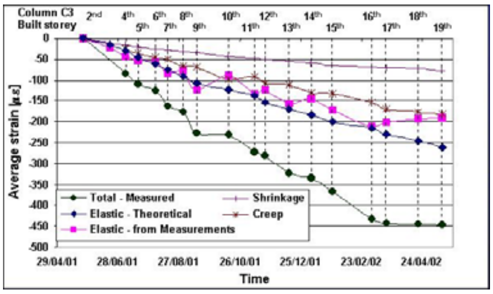

Figure 3: Recorded deformation after each stage of construction and separation of contributing components

Table 2. typical expected responses and the candidate types of sensors to measure risks

Risk / uncertainty	Response / consequence	Candidate sensors
Correspondence between Finite Element Model and real behavior	Strain distribution and magnitude different from model	Local strain sensors, including strain gauges, vibrating wire gauges and fiber optic sensors
Dynamic strain due to traffic, wind, earthquake, explosion,…	Large strains, fatigue, cracks	Local strain sensors, including strain gauges, vibrating wire gauges and fiber optic sensors, with dynamic data acquisition systems. Distributed fiber optic crack sensors. Crack-meters
Creep, relaxation of pre-stress	Global deformations, bending	Long-gauge fiber optic strain sensors, settlement gauges, laser distance meters, topography
Correspondence between calculated and real vibration modes	Mode shapes and frequencies different from model	Accelerometers, long-gauge fiber optic strain sensors
Cracking of concrete or steel	Crack opening	Crack-meters: potentiometers, vibrating wire or fiber optics
Temperature changes and temperature gradients in load bearing elements	Strain redistribution, cracking	Temperature sensors: electrical, fiber optics point sensors or distributed sensors
Differential settlement between foundations	Global movements, tilting, strain redistribution	Laser distance meters, topography, settlement gauges, tilt-meters
Change in water table or pore water pressure around foundations	Change in pore water pressure	Piezometers: vibrating wire or fiber optics
Change in the concrete chemical environment: carbonation, alkali-silica reaction, chlorine penetration	Corrosion of rebars	Concrete corrosion and humidity sensors
Environmental conditions	Actions on building	Weather station, wind speed

technical point of view, often provide data that is difficult to analyze or cannot be used by the owner to support management decisions.

The 7-step procedure that is detailed in [6] and summarized next, 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
- Step 2: Risk analysis
- Step 3: Responses to degradations
- Step 4: Design SHM system and select appropriate sensors
- Step 5: Installation and Calibration
- Step 6: Data Acquisition and Management
- Step 7: Data Assessment.

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.

2. Buildings SHM

To put the previous methodology in practice, we will now consider how it can be applied to design integrated Structural Health Monitoring systems for buildings.

Table 1 discusses the typical expected responses and the candidate types of sensors to measure risks that are typically found on buildings and can be used as a starting point for a specific analysis pertaining to a given building.

3. Application example: High-Rise Buildings in Singapore

Singapore is a cosmopolitan city-state often described as a gateway to Asia with a city landscape of tall buildings. The Housing and Development Board (HDB), as Singapore's public housing authority, has an impressive record of providing a high standard of public housing for Singaporeans through a comprehensive building program. As part of quality assurance of new HDB tall buildings, it was decided to perform long-term structural monitoring of a large number of new buildings.

Currently more than 200 buildings, such as the one in Figure 2, have been instrumented and are regularly monitored [7]. This monitoring project is considered as a pioneering project with two aims: to develop a global monitoring strategy for column-supported structures such as buildings, and to collect data related to the behavior of this buildings providing rich information concerning their behavior and health conditions. The monitoring is performed during the whole lifespan of the building, from construction to the use. Thus, for the first time the sensors are used in a large scale life cycle monitoring of high-rise buildings.

The aims of monitoring are (1) increase of knowledge concerning the real structural behavior, (2) verify the construction process, (3) increase of safety during the service, (4) enhance maintenance activities and (5) evaluation of structural condition after risky events such as earthquake, strong wind or terrorist attack. The monitoring is performed at (1) local, column level and (2) global, structural level.

The ground columns have been selected for monitoring, being the most critical elements in the building. A total of ten long-gauge fiber optic sensors were installed by embedding in each construction block.


Figure 4: Metro Center

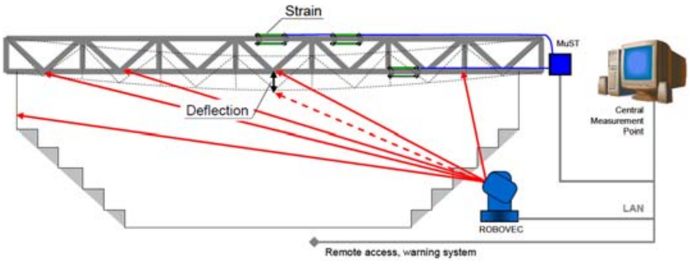

Figure 5: Setup with strain and deflection sensors

The monitoring program has yielded actionable results from the insights gained from enlarged knowledge concerning the real column behavior during construction, including detection of columns with abnormal behavior. The detailed analysis of column behavior is performed semi-automatically using the SDB Pro software and notably Concrete Analyzer macro-sensor. It was possible to separate different parts of measured total strain such as elastic strain, creep and shrinkage as shown in Figure 3. The monitoring strategy has shown high performance in spite limitations imposed by design criteria and the limited number of equipped columns.

4. Application example: Halifax Metro Center, Canada

Halifax Metro Centre (Figure 4) has become a first class multi-entertainment, sports facility and exhibition centre connected to the World Trade and Convention Centre, in a strategic downtown location at the centre of metro business activity. It is the largest arena in Halifax and is host to a range of entertainment and sporting events in the city. The main aim of the project is to measure and monitor in the real-time the strain and deflection of the roof's structure caused by extraordinary events such as heavy snowfalls or punctual events happening inside the arena (e.g. concerts) and requiring heavy equipment to be hanged on the roof's trusses. Since the arena's construction in the late 1970s, the design loads have increased substantially and there is an ever increasing use of suspended equipment for lights and sound for special events, increasing the loads. The owners therefore decided to conduct a structural investigation of the roof structure and provide means to effectively monitor the actual snow loads and manage the entertainment loads suspended from the roof. Based on the research, a complete Structural Health Monitoring System combining MuST fiber-optics strain sensors and a ROBOVEC robotic laser distance meter unit was installed and provides real time information on the status of the roof structure (Figure 5). Both Reading Unit for the fiber optic sensors and Laser instrument are connected to the existing LAN and a dedicated PC manages the sensors, the data acquisitions and the measurements. The strain data of the fiber optic sensors are automatically compensated using the corresponding temperature sensors, while the laser angle and distance measurements are automatically transformed in a deflection value. Warning and alarms are dynamically generated and notified when predefined strain thresholds in the beams or deflection thresholds of the trusses are measured.

5. Application example: Royal Villa Monza, Italy

The Royal Villa in Monza, close to Milan, Northern Italy, was built in 1777 – 1779 by architect Piermarini for Maria-Therese of Austria. It was modified by the Italian King Umberto I. After the king was killed in 1900, the villa was not used by the Royal family any more, and it was practically abandoned during last decades of the XX century. Cracks and degradation of wooden structures are the main issues found in this building prior to restoration. Italian government and authorities of Milan and Monza decided to renew the villa and to transform it into a museum. Due to complex static system and uncertainties related to structural behavior it was decided to monitor the villa before, during and after the work [8]. Monitoring data was practically used to “govern” renewal works. Both conventional and optical fiber sensors were used. The view to Royal villa is shown in Figure 5. Optical fiber sensors were mainly used as extensometers installed between the walls, orthogonal to the corridor axes, but shorter sensors were also used for crack monitoring. The sensors installed between the walls are shown in Figure 6.

The data interpretation and analysis has been statistically carried out, due to the complexity of the structure and uncertainty related to its static system and structural behavior. The monitoring systems installed in the Royal Villa of Monza have allowed the monitoring-based rehabilitation process.

6. Conclusions

Structural Health Monitoring is not a new technology or trend. Since ancient times, engineers, architects and artisans have been keen on observing the behaviour of built structures to discover any sign of degradation and to extend their knowledge and improve the design of future structures. Higher buildings and larger domes were constructed and sometimes failed during construction or after a short time. Those failures and their analysis have led to new insight and improved design of future structures. 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 our buildings 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 associated with the construction and operation of a specific building and the design of a matching monitoring system and data analysis strategy.

Figure 6. Royal Villa in Monza

Figure 7. Sensor installation

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