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Integrated Structural Health Monitoring Systems for High-Rise Buildings

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ABSTRACT: High-rise buildings are complex structures. They are made of multiple elements and components that are stressed and interact with one another when exposed to internal and 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 and precise 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.

When designing a Structural Health Monitoring system, one should always focus on the specific requirements of the structure under exam. This paper presents a 7-step systematic approach to the design and implementation of an optimized SHM system for a specific structure. When selecting the best sensors for the specific risks associated with a given structure, it is often necessary to combine different measurement technologies.

This paper presents a generalized architecture for SHM monitoring system combining multiple sensing technologies and several application examples to real buildings, including high-rise buildings, towers and arenas.

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 (Glisic, B. and Inaudi, D. , 2007), 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 to cheaper, safer and more durable structures with increased reliability, performance and safety.

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 (Del Grosso, A. and Inaudi, D. ,2004).

1.1 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 of follow a trend. These monitoring systems, although perfectly working from a 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 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.

2.1 Step 1: Identify structures needing monitoring

This step might seem trivial, but is indeed a very important 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.

2.2 Step 2: Risk 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 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 and uncertainties are corrosion, loss of pre-stressing, creep, subsidence of foundations, earthquake strike, unauthorized overloads, impact, inaccuracy of Finite Elements Models, poor building material quality and poor execution.

The severity and probability of each risk will be classified using the usual risk analysis procedure to produce a ranking of risks. At this point, some risks 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.

2.3 Step 3: Responses to degradations

For each of the retained risks, 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 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.

2.4 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. 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.

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.

2.5 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 user manual and a calibration report.

2.6 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.

2.7 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 building 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.

2.8 Summary

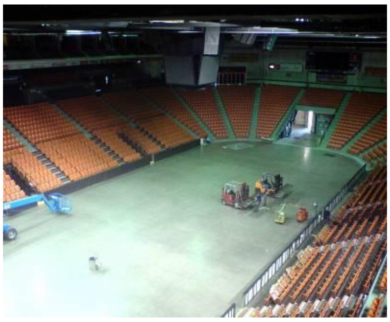
Designing and implementing a structural health monitoring system for a building is a process that is not much different from designing and building the structure itself. It requires experienced professionals and a combination of multidisciplinary skills.

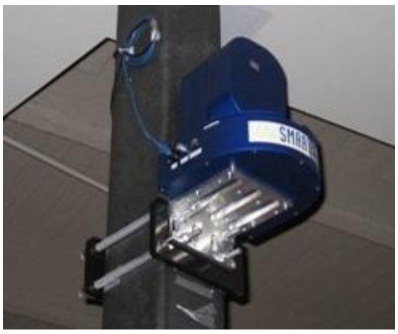
Unfortunately, this process is not yet formalized in the same way as for example the construction process, where codes, laws and regulations reduce the uncertainty and improve the interaction between the different actors involved in the process.

Recommendations and drafts codes for the implementation of SHM system are however starting to appear; certainly an important step towards a mature SHM industry.

3 APPLICATION EXMAPLES

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. In the next paragraphs, we will apply the 7-step design methodology to three application examples: a sports arena, a tall building and the world’s highest skyscraper.

<table>
<tr><th colspan="3">Step 1: Identify structure</th></tr>
<tr><td>
</td><td></td><td></td></tr>
<tr><td>Halifax Metro Center, Canada</td><td>Nikken Sekkei Tower, Japan</td><td>Burj Khalifa, Dubai</td></tr>
</table>

Step 2: Risk / Uncertainty / Opportunity analysis		
R1: Snow loads R2: Concert loads U1: Compliance to codes U2: Deflections under loads O1: Residual capacity	R1: Damage due to earthquake U1: Correspondence with FEM calculations U2: Correspondence with modal predictions U3: Performance of tuned-mass damper	R1: Foundation capacity R2: Wind loads U1: Correspondence with FEM calculations U2: Correspondence with modal predictions
Step 3: Responses (associated with Risks / Uncertainties / Opportunities)		
R1: Strain / Deflections R2: Strain / Deflections U1: Need for strengthening? U2: Deflections O1: Reduced strain levels and deflections	R1: Strain redistribution, cracks U1: Difference in predicted and real strain U2: Difference in predicted and real vibrations U3: Strain amplitude variations	R1: Strain / friction R2: Tilt and vibrations U1: Difference in predicted and real strain
Step 4: Design SHM system and select appropriate sensors (selected sensors)		
MuST Long-gauge strain sensors Temperature sensors Robovec Laser distance meter (for deflection measurements	SOFO Long-gauge sensors Temperature sensors	SOFO Long-gauge sensors (foundations) ActiMon tilt sensors ActiMon accelerometers
Step 5: Installation		
 Robovec Laser distance meter	 SOFO sensor embedding in steel columns	 SOFO installation in piles

Step 6: Data Acquisition and Management		
 MuST data acquisition unit	 SOFO reading unit	 Actimon tilt and acceleration sensor
Step 7: Data Assessment		
Recorded loads and deflections during snow fall and concerts were lower than calculated. No strengthening deemed needed to comply with new codes. (Manetti, L. et al. 2008)	No major event detected so far. Deformation under static load, shrinkage and creep are in line with predictions. (Glisic, B. et al. 2003)	Measurements in test piles helped optimizing the foundation design. Deflections under wind loads are in line with predictions.

4 CONCLUSTIONS

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 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.

5 REFERENCES

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