Components of structural monitoring process and selection of monitoring system

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ABSTRACT: Structural monitoring is a process aiming at providing accurate and in-time information concerning structural condition and performance. It consists of permanent continuous, periodical or periodically continuous recording of representative parameters, over short- or long-terms. The information obtained from monitoring is generally used to plan and design maintenance activities, increase the safety, verify hypothesis, reduce uncertainty and to widen the knowledge concerning monitored structure. In spite of its importance the culture on structural monitoring is not yet widespread. It is often considered as an accessory activity, which doesn't require detailed planning. The facts are rather the opposite. Monitoring process is very complex process full of delicate phases and only a proper and detailed planning of each of its steps can lead to its successful and maximal performance. Main steps of the structural monitoring process are selection of monitoring strategy, installation and maintenance of monitoring equipment and data management. Each of these steps is also complex itself, e.g. monitoring strategy consists of definition of monitoring aim, selection of representative parameters to be monitored, selection of monitoring system, definition of sensor network design and schedule of monitoring etc. The totality of devices used to perform monitoring is conventionally called monitoring system. The main components of the monitoring systems are the sensors, the reading unit and the managing software, while accessory components are extension cables, connection boxes etc. The selection of the monitoring system depends on monitoring requirements and effectiveness of the system in answering on these requirements. These requirements have to include not only monitoring performances of the system, but also ease of integration in each step of monitoring process, i.e. ease of installation, maintenance and data management. In this paper structural monitoring process is defined and described in details, its interaction with selection of monitoring system is examined and illustrated in case of the SOFO monitoring system on real on-site applications.

1 INTRODUCTION

Civil structures are omnipresent in every society, regardless of culture, religion, geographical location and economical development. It is difficult to imagine a society without buildings, roads, rails, bridges, tunnels, dams and power plants. Structures affect human, social, ecological, economical, cultural and aesthetic aspects of societies and associated activities contribute considerably to the gross internal product. Therefore good design, quality construction as well as durable and safe usage of civil structures are goals of structural engineering.

The most safe and durable structures are usually structures that are well managed. Measurement and monitoring often have essential roles in management activities. The data resulting from the monitoring program is used to optimise the operation, maintenance, repair and replacing of the structure based on reliable and objective data. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information.

In this paper, first an introduction to the monitoring process and concept of structural monitoring of concrete structures is presented. It includes notion of structural monitoring, presentation of principal components of the monitoring systems and monitoring assessment. In the second part of paper, particularities related to selection of monitoring system are presented and illustrated by examples performed on-site using the monitoring system called SOFO.

2 INTRODUCTION TO STRUCTURAL MONITORING PROCESS

Structural monitoring is a process aiming at providing accurate and in-time information concerning structural condition and performance. It consists of permanent continuous, periodical or periodically continuous recording of representative parameters, over short- or long-terms.

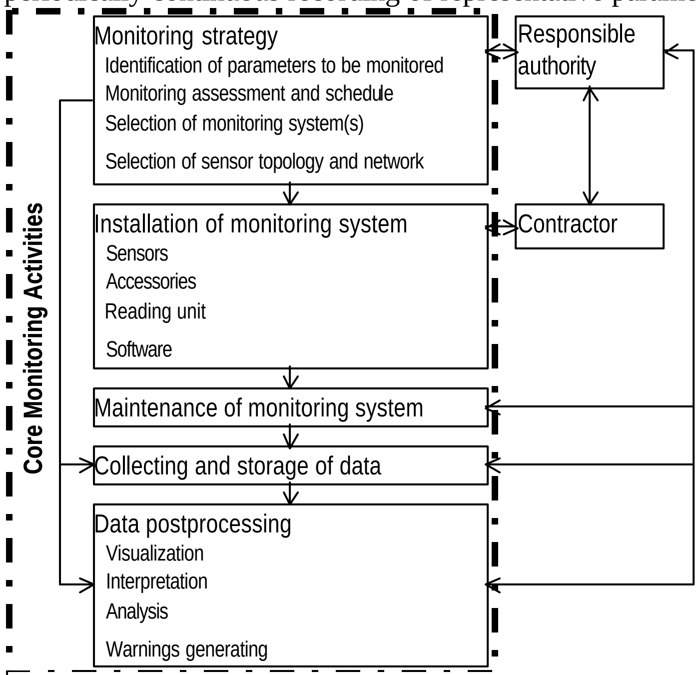

Figure 1. The five core activities involved in monitoring process and their interactions.

In spite of its importance and complexity, the structural monitoring process was often considered as an accessory activity, not necessary to be planned in details. This approach can lead to improper selection, installation and exploitation of monitoring resources. In order to avoid misuse of the monitoring process it is necessary to consider all activities involved in monitoring, their mutual interaction, as well as their interaction with environment. The five core activities involved in monitoring process and their interactions are presented in Figure 1.

The company devoted to monitoring (monitoring company) is responsible to develop the monitoring strategy in collaboration with the responsible authority (owner of structure, legal authority etc.). The same company is responsible for delivery of the monitoring system. The responsible authority interacts with monitoring company and provides for input monitoring parameters. The same authority is later responsible for maintenance, collection and exploitation of data (directly or by subcontracting to monitoring company). The installation of monitoring system is usually performed by contractor with support of the monitoring company and responsible authority. The core monitoring activities are presented in more details and compared with the performance of the SOFO system in the next sections.

3 INTRODUCTION TO SOFO SYSTEM

The monitoring system SOFO (French acronym for Surveillance d'Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers) is used in presented example. It is based on low-coherence interferometry in optical fiber sensors (Inaudi 1997). It consists of long-gage sensors, a reading unit and data acquisition and analysis software.

Typical sensor gage-length ranges from 250 mm to 10 m. The resolution (minimal detectable change of optical signal translated in measured deformation) reaches 2 µm independently of the gage length and accuracy of measurement is 0.2% of the measured value (linear correlation between the optical signal and the deformation). The dynamic range of the sensors is 0.5% in compression and 1.0% in elongation, and single measurement typically takes 6 to 10 seconds.

The SOFO system was developed in early 1990's and since 1995 it has been commercialized and applied to the monitoring of a wide range of civil structures, such as geotechnical structures, bridges, dams, residential and industrial buildings, just to name a few (SMARTEC 2003). The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 5 years, making it ideal for both short- and long-term monitoring.

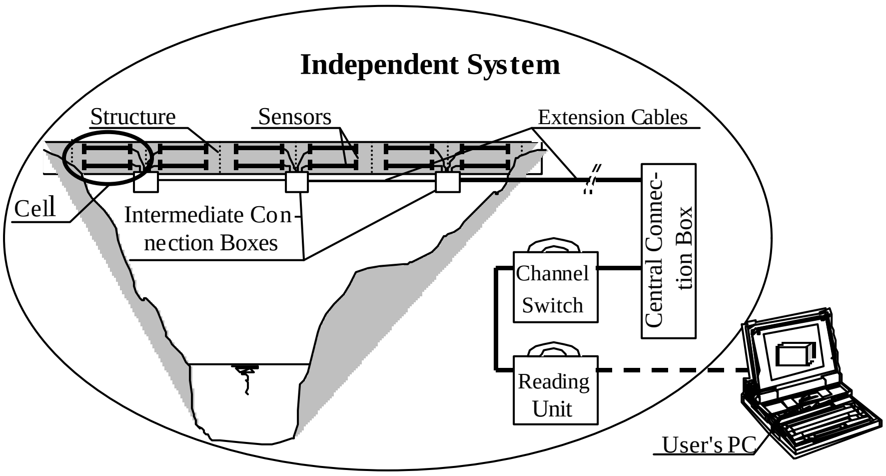

Figure 2. Typical application and components of the SOFO monitoring system, with network consisting of cells equipped with parallel topology

Being designed for direct embedding in concrete, the sensors allow easy installation; require no calibration and feature high survival rate (better than 95% for concrete embedding). The long gage-length makes them more reliable and accurate than traditional strain sensors, averaging the strain over long bases and not being influenced by local defects in material (e.g. cracks and air pockets). More information on the SOFO system and its applications can be found in the references (SMARTEC 1997). The components of the system are presented in Figure 2.

4 SELECTION OF MONITORING STRATEGY

4.1 *Monitoring parameters, monitoring assessment and schedule*

Monitoring (or auscultation) of structures involves recording of time dependent parameters during certain periods. To start a monitoring project, it is important to define the goal of the monitoring i.e. to identify the parameters to be monitored, monitoring assessment and schedule. Monitored parameters can be physical, mechanical, chemical or other, and are usually present in each point of the structure. These parameters have to be properly selected in a way that they reflect the structural behavior. Each structure has its own particularities and consequently its own selection of parameters for monitoring.

There are different approaches to assess the structure and we can classify them in three basic categories: static monitoring, dynamic monitoring, and system identification and modal analysis, and these categories can be combined. Each category is characterized by advantages and challenges and which one (or ones) will be used depends mainly on the structural behavior and the goals of the monitoring.

Each category can be performed during short and long periods, permanently (continuously) or periodically. The schedule and pace of monitoring depends on how fast the monitored parameters change in time. For some applications, periodical monitoring gives satisfactory results, but information that is not registered between two inspections is lost forever. Only continuous monitoring during the whole lifespan of the structure can register its history, help to understand its real behavior and fully exploit the monitoring.

4.2 *Monitoring systems and structural monitoring*

The totality of means used for monitoring is called monitoring system. The main components of a monitoring system are sensors, carriers of information, reading unit, interfaces and data managing subsystems (managing software).

The aim of the sensor is to detect the magnitude of the monitored parameter and to transform it to transportable information (e.g. optical of electrical information). The carrier leads the information from the sensor to the reading unit, which decodes the information and retrieves the magnitude of the monitored parameter. The measurement is visualized and presented to the operator by a user interface. Finally, the data managing subsystem is necessary to control and manage the data obtained from monitoring. The components of a monitoring system can be separated or differently combined (e.g. sensor and carrier can make one device). An example of a monitoring system and its components, in case of the SOFO system, is presented in Figure 2.

Generally, the sensors can be discrete or distributed. Discrete sensors can have short or long gage. Discrete sensors detect the observed parameter only at the location where it is installed, while the distributed sensor detects the observed parameter in several locations of the structure. SOFO, Bragg-grating and Brillouin scattering based sensors are examples of discrete long-gage, discrete short-gage and distributed sensors.

Selection of type of sensor depends on level on which the structure is to be monitored – global structural, local structural or local material. Monitoring at structural level (global or local) can only be performed using a sensor that is not influenced by local material defects or discontinuities such as cracks, inclusions, joints etc. Therefore, if the construction material is a subject of defects or discontinuities (e.g. concrete), then the appropriate sensor is to be selected. Since the short-gage sensors are subject local influences the only good choice are long-gage and distributed sensors. SOFO sensors are provided with the long gage length and are therefore suitable for structural monitoring.

4.3 *Selection of sensor topology and sensor network for structural monitoring*

Several parameters are often required to be monitored, such as average strains and curvatures in beams, slabs and shells, average shear strain, deformed shape and displacement, crack occurring and quantification as well as indirect damage detection. The use of separate monitoring systems and separate sensors for each of mentioned parameters would be costly and complex from the point of view of installation and data assessment. This is why it is reasonable to use only limited number of monitoring systems and types of sensors.

In order to extract maximum data from the system it is necessary to place the sensors the representative positions on the structure. The long-gage sensor has advantage of combining in different topologies, depending on geometry and type of structure to be monitored, allowing monitoring and determination of several important structural parameters with the same network of sensors (Glisic, Inaudi, Vurpillot, Nan 2003).

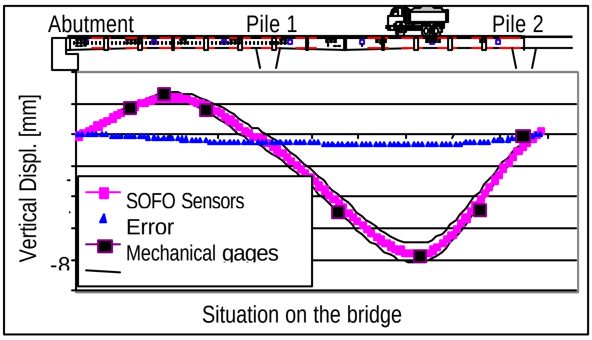

Figure 3. Monitoring during the load test using parallel topology and SOFO SPADS software

To perform a monitoring at a structural level it is necessary to cover the structure, or a part of it with sensors. For this purpose the structure is firstly divided into cells (see Figure 2). Each cell contains a combination of sensors appropriate to monitor parameters describing the cell's behavior. Knowing the behavior of each cell, it is possible to retrieve the behavior of the entire structure. The combination of sensors installed in a single cell is called sensor topology. Totality of sensors is called sensor network. Sensor network can contain cells with different topologies. The most used are the simple topology, the parallel topology and the crossed topology (Inaudi, Glisic 2002). Example of results obtained using parallel topology and software SOFO SPADS (see Section 8) is presented in Figure 3.

5 INSTALLATION OF MONITORING SYSTEM

The installation of the monitoring system is particularly delicate phase. Therefore it must be planned in details considering seriously on-site conditions and notably the structural component assembling activities, sequences and schedules. Main principles and issues met during the installation are briefly cited in this subsection.

The components of the monitoring system can be embedded into the fresh concrete or installed on the structure surface using fastenings, clamps or gluing. The installation takes time, and if it is to be performed during the construction of the structure, it may delay the works. Components of monitoring system that are to be installed by embedding can only be safely installed during a short period between the rebars completion and pouring of concrete. Hence, the schedule of installation of the monitoring system has to be carefully planed taking into account the schedule of works, time necessary for the system installation, but in the same time it has to be flexible in order to adapt to work schedule changes that are frequent in building sites.

Figure 4. SOFO sensor network (white plastic cables) installed on pile rebars before pouring

When installed, the monitoring system has to be protected, notably if monitoring is performed during the construction of the structure. The protection has to prevent accidental damage during the construction but also to ensure the longevity of the system. Thus, all external influences, periodical or permanent, have to be taken into account when designing the protection for the monitoring system.

The SOFO system is designed for fast, easy and simple installation. The construction works were practically never delayed due to installation. The sensors and accessory components can be installed on surface of the structure but also can be embedded in the concrete. The SOFO sensor network installed onto the rebars of pile before the pouring of concrete is shown in Figure 4.

6 MAINTENANCE OF MONITORING SYSTEM

After the monitoring system is installed, it is necessary to maintain it. Different monitoring systems have different maintenance requirements. In case of SOFO system, the only necessary maintenance works are the periodical cleaning of connectors (once a year to once every three years) and revision and change of safety battery in the reading unit (depends on hours in use, number of charging and discharging, temperature, etc., typically every two to five years).

7 COLLECTING AND STORAGE OF DATA

The monitoring data can be collected manually or automatically, on-site or remotely, with or without human intervention, periodically or continuously. These options can be combined in different way, e.g. for example during the test of the bridge it is necessary to perform measurements automatically, on-site, with human intervention and periodically (after each load step). For long-term in use monitoring the maximal performance is automatic, remote (from the office), continuous collecting of data without human intervention.

Data can be stored in form of reports, tables, diagrams etc. on different types of supports such as electronic files (on hard disc, CD, etc.) or hard versions (printed on paper). The manner of storage of data has to ensure that data will not be lost and that a prompt access to any selected data is possible (e.g. one can be interested to access only data from one group of sensors and during a selected period of monitoring).

The softwares that manage the collecting and storage of data are to be a part of the monitoring system. Otherwise, the data management can be difficult, demanding and expensive.

The SOFO system fully supports automatic, remote and independent data collecting, and storage in single relational database, allowing easy and simple further export and postprocessing.

8 DATA POSTPORCESSING

Data postprocessing consists of interpretation, visualization, analysis and optionally generation of warnings (alarms). Collected data is in fact huge amount of numbers (dates and magnitudes of monitoring parameters), and has to be transformed to useful information concerning the structural behavior. This transformation depends on monitoring strategy and algorithms that are used to interpret and analyze the data. It can be performed manually, semi-automatically or automatically.

Manual data postprocessing understands manual export and analysis of data. It is practical in cases where the amount of data is limited. Semi-automatic postprocessing consists of manual export of data and automatic analysis using the softwares. It is applicable in cases where the data analysis is to performed only periodically. Automatic postprocessing is the most convenient, since it can be performed rapidly and independent of data amount or frequency of analysis. Finally, based on information obtained from data analysis, the warnings can be generated in order to guaranty safety of the structure's service.

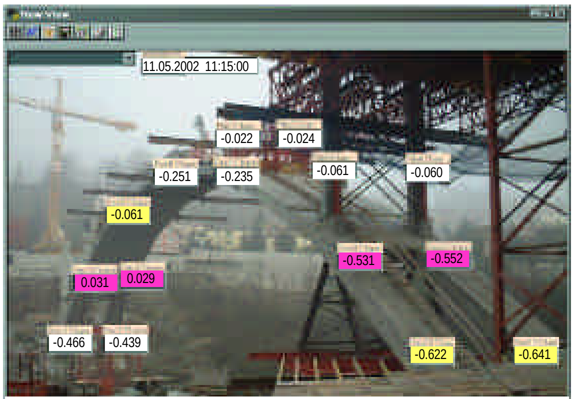

Figure 5. Visualization and generated warnings using SOFO View software

The data postprocessing has to be planned along with selection of monitoring strategy and appropriate algorithms and tools compatible with the choosen monitoring system have to be selected.

The SOFO system allows user friendly and quasy real-time data postprocessing. Software packages such as SOFOPro, SOFO View and SOFO SPADS allows personalization of data interfaces, visualization in forms of tables, diagrams and figures, automatic calculus of complex parameters such as curvatures, thermal stains, etc., calculus of deformed shapes and displacements, and generation of prewarnings and warnings. Personalized type of visualization (in form of figure) with prewarning and warning indicators (yellow and red color) generated by SOFO View software is presented in Figure 5. Deformed shape of a bridge obtained using the SOFO SPADS software is presented in Figure 3.

9 CONCLUSIONS

The complexity of structural monitoring process is presented in this paper. The five core activities were identified (monitoring strategy, installation, maintenance, data collecting and storage and data postprocessing) and discussed in detail. The comparison of monitoring requirements with the specifications of the SOFO system, used in monitoring of wide types of structures, has been done in parallel, and the SOFO performances are highlighted.

10 ACKNOWLEDGEMENTS

The authors are indebted to Dr. Samuel Vurpillot, Dr. Pascal Kronenberg and personnel of IMAC-EPFL for collaboration, technical support and interest in new technologies.

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