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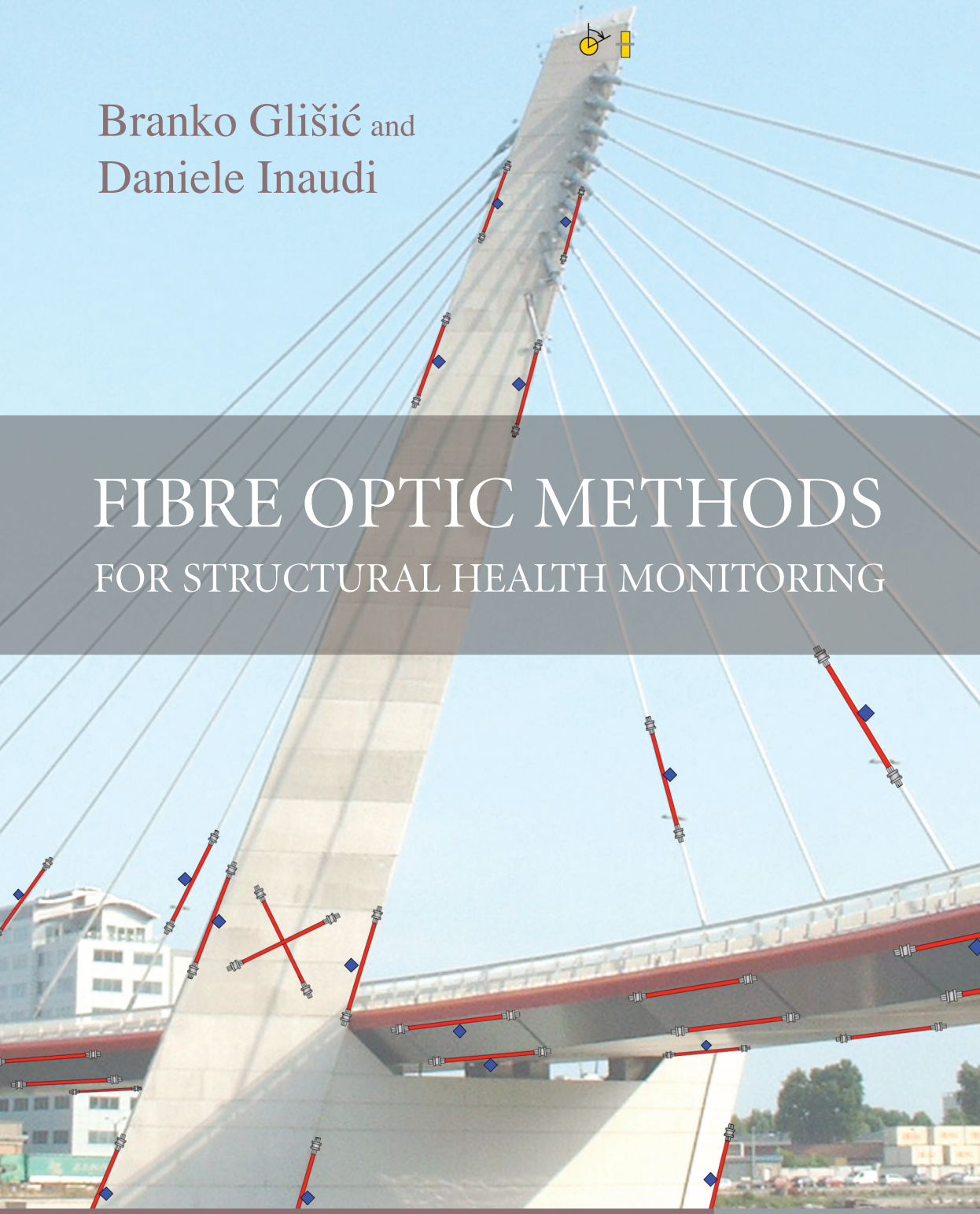
FIBRE OPTIC METHODS
FOR STRUCTURAL HEALTH MONITORING



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1

Introduction to Structural Health Monitoring

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1.1 Basic Notions, Needs and Benefits

1.1.1 Introduction

Civil and industrial 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, railways, 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 and durable and safe exploitation of structures are goals of structural engineering.

Malfunctioning of civil structures often has serious consequences. The most serious is an accident involving human victims. Even when there is no loss of life, populations suffer if infrastructure is partially or completely out of service. Collapse of certain structures, such as nuclear power plants or pipelines, may provoke serious ecological pollution. The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by costs of reconstruction, whereas the indirect impact involves losses in the other branches of the economy. Full collapse of historical monuments, such as old stone bridges and cathedrals, represents an irretrievable cultural loss for the society.

The safest and most durable structures are those that are well managed. Measurement and monitoring often have essential roles in management activities. The data resulting from a monitoring programme are used to optimize the operation, maintenance, repair and replacing of the structure based on reliable and objective data.

Structural health monitoring (SHM) is a process aimed at providing accurate and in-time information concerning structural condition and performance. It consists of permanent continuous, periodic 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 hypotheses, reduce uncertainty and to widen the knowledge concerning the structure being monitored. In spite of its importance, the culture on structural monitoring is not yet widespread. It is often considered as an accessory activity

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that does not require detailed planning. The facts are rather the opposite. The monitoring process is a 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.

1.1.2 Basic Notions

The SHM process consists of permanent, continuous, periodic or periodically continuous recording of parameters that, in the best manner, reflect the performance of the structure (Glišić and Inaudi, 2003a). Depending on the type of the structure, its condition and particular requirements related to a monitoring project, SHM can be performed in the short term (typically up to few days), mid term (few days to few weeks), long term (few months to few years) or during the whole lifespan of the structure.

The representative parameters selected to be monitored depend on several factors, such as the type and the purpose of a structure, expected loads, construction material, environmental conditions and expected degradation phenomena. In general, they can be mechanical, physical or chemical. The most frequently monitored parameters are presented in Table 1.1. This book focuses mainly on monitoring mechanical parameters and partially on physical parameters using optical-fibre sensors.

Table 1.1 The parameters most frequently monitored

Mechanical	Strain, deformation, displacement, cracks opening, stress, load
Physical	Temperature, humidity, pore pressure
Chemical	Chloride penetration, sulfate penetration, pH, carbonatation penetration, rebar oxidation, steel oxidation, timber decay

The monitoring can be performed at the local material level or at the structural level. Monitoring at the material level provides information related to the local material behaviour, but gives reduced information concerning the behaviour of the structure as a whole. Monitoring at the structural level provides better information related to the global structural behaviour and indirectly, through the changes in structural behaviour, also provides information related to material performance. The difference between the local material and global structural monitoring is presented in more detail in Section 3.2.3.

If the human body is considered as a structure, then an unhealthy condition is detected by the nervous system. Based on information that the brain receives (e.g. pain in some parts of the body), a patient realizes that he is ill and addresses a doctor in order to prevent further development of the illness. The doctor undertakes some examinations, establishes a diagnosis and proposes a cure. This process is presented in Figure 1.1.

The concept presented above can also be applied to structures. The main aim of monitoring is to detect unusual structural behaviours that indicate a malfunctioning of the structure, which is an unhealthy structural condition. Detection of an unhealthy condition calls for a detailed inspection of the structure, diagnosis and finally refurbishment or repair work. This process is compared with that presented for the human body in Figure 1.1.

In order to follow the schema presented in Figure 1.1, monitoring must allow the following actions:

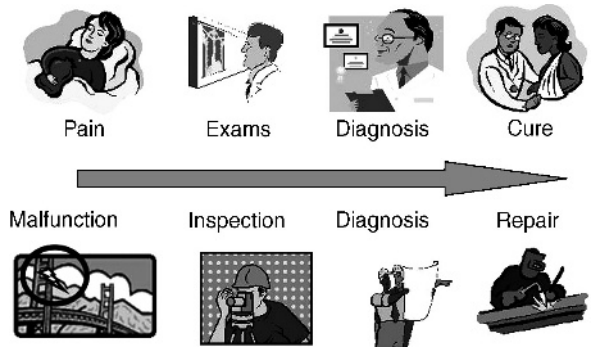


Figure 1.1 Monitoring as structure's feelings (courtesy of SMARTEC).

1. Detect the malfunction in the structure (e.g. crack occurrence, . . .)
2. Register the time of problem occurrence (e.g. 19 July 2004 at 14:30, . . .)
3. Indicate physical position of the problem (e.g. in the outer beam, 3 m from abutment, . . .)
4. Quantify the problem (e.g. open for 2 mm, . . .)
5. Execute actions (e.g. turn the red light on and stop the traffic!).

Monitoring is not supposed to make a diagnosis; to make a diagnosis and propose the cure it is necessary to carry out a detailed inspection and related analyses.

Detection of unusual structural behaviours based on monitoring results is performed in accord with predefined algorithms. These algorithms can be simple (e.g. comparison of measured parameters with ultimate values), advanced (e.g. comparison of measured parameters with designed values) or very sophisticated (e.g. using statistic analysis). The efficiency of monitoring depends on both the performance of the applied monitoring system and the algorithms employed. Simple and advanced algorithms are presented in a general manner in Chapter 3. The presentation of sophisticated algorithms exceeds the scope of this book.

1.1.3 Monitoring Needs and Benefits

In the first place, monitoring is naturally linked with safety. Unusual structural behaviours are detected in monitored structures at an early stage; therefore, the risk of sudden collapse is minimized and human lives, nature and goods are preserved.

Early detection of a structural malfunction allows for an in-time refurbishment intervention that involves limited maintenance costs (Radojicic *et al.*, 1999).

Well-maintained structures are more durable, and an increase in durability decreases the direct economic losses (repair, maintenance, reconstruction) and also helps to avoid losses for users that may suffer due to a structural malfunction (Frangopol *et al.*, 1998).

New materials, new construction technologies and new structural systems are increasingly being used, and it is necessary to increase knowledge about their on-site performance, to control the design, to verify performance, and to create and calibrate numerical models (Bernard, 2000). Monitoring certainly provides for answers to these requests.

Monitoring can discover hidden (unknown) structural reserves and, consequently, allows for better exploitation of traditional materials and better exploitation of existing structures. In this case, the same structure can accept a higher load; that is, more performance is obtained without construction costs.

Finally, monitoring helps prevent the social, economical, ecological and aesthetical impact that may occur in the case of structural deficiency.

1.1.4 Whole Lifespan Monitoring

Monitoring should not be limited to structures with recognized deficiencies. First, because when structural deficiency is recognized, the structure functions with limited performance and the economic losses are already generated. Second, the history of events that lead to structural deficiency is not registered and it may be difficult to make a diagnosis. Third, the information concerning the health state is important as a reference, notably for complex structures where direct comparison of structural behaviour with design and numerical models does not allow for certain detection of a malfunction. That is why whole lifespan monitoring, which includes all the important phases in the structure's life, is highly recommended (Glišić *et al.*, 2002a).

Construction is a very delicate phase in the life of a structure. In particular, for concrete structures, material properties change through ageing. It is important to know whether or not the required values are achieved and maintained. Defects (e.g. premature cracking) that arise during construction may have serious consequences for structural performance (Bernard, 2000). Monitoring data help engineers to understand the real behaviour of a structure, and this leads to better estimates of real performance and, if required, more appropriate remedial action. Installation of monitoring systems during the construction phase allows monitoring to be carried out during the whole life of the structure. Since most structures have to be inspected several times during service, the best way to decrease the costs of monitoring and inspection is to install the monitoring system from the beginning.

Some structures have to be tested before service for safety reasons. At this stage, the required performance levels have to be reached. Typical examples are bridges and stadiums: the load is positioned at critical places (following the influence lines) and the parameters of interest (such as deformation, strain, displacement, rotation of section and crack opening) are measured (Hassan, 1994). Tests are performed in order to understand the real behaviour of the structure and to compare it with theoretical estimates. Monitoring during this phase can be used to calibrate numerical models that describe the behaviour of structures.

The service phase is the most important period in the life of a structure. During this phase, construction materials are subjected to degradation by ageing. Concrete cracks and creeps, and steel oxidizes and may crack due to fatigue loading. The degradation of materials is caused by mechanical (loads higher than theoretically assumed) and physico-chemical factors (corrosion of steel, penetration of salts and chlorides in concrete, freezing of concrete, etc.). As a consequence of material degradation, the capacity, durability and safety of a structure decreases. Monitoring during service provides information on structural behaviour under predicted loads, and also registers the effects of unpredicted overloading. Data obtained by monitoring is useful for damage detection, evaluation of safety and determination of the residual capacity of structures. Early damage detection is particularly important because it leads to appropriate and timely interventions. If the damage is not detected, then it continues to propagate and the

structure no longer guarantees required performance levels. Late detection of damage results in either very elevated refurbishment costs (Frangopol *et al.*, 1998) or, in some cases, the structure has to be closed and dismantled. In seismic areas, the importance of monitoring is most critical.

Material degradation and/or damage are often the reasons for refurbishing existing structures. Also, new functional requirements for a structure (e.g. enlarging of bridges) lead to requirements for strengthening. For example, if strengthening elements are made of new concrete, then good interaction of the new concrete with the existing structure has to be assured: early age deformation of new concrete creates built-in stresses and bad cohesion causes delamination of the new concrete, thereby erasing the beneficial effects of the repair efforts. Since newly created structural elements that are observed separately represent new structures, the reasons for monitoring them are the same as for new structures. The determination of the success of refurbishment or strengthening is an additional justification (Inaudi *et al.*, 1999a).

When the structure no longer meets the required performance level and when the costs of reparation or strengthening are excessively high, then the ultimate lifespan of the structure is attained and the structure should be dismantled. Monitoring helps in dismantling structures safely and successfully.

1.2 The Structural Health Monitoring Process

1.2.1 Core Activities

The core activities of the structural monitoring process are: selection of monitoring strategy, installation of monitoring system, maintenance of monitoring system, data management and closing activities in the case of interruption of monitoring (Glišić and Inaudi, 2003a). Each of these activities can be split in to sub-activities, as presented in Table 1.2.

Each of the core activities is very important, but the most important is to create a good monitoring strategy. The monitoring strategy is influenced by each of the other core activities and sub-activities and consists of:

1. Establishing the monitoring aim
2. Identifying and selecting representative parameters to be monitored
3. Selecting appropriate monitoring systems
4. Designing the sensor network
5. Establishing the monitoring schedule
6. Planning data exploitation
7. Costing the monitoring.

To start a monitoring project, it is important to define the goal of the monitoring and to identify the parameters to be monitored. These parameters have to be properly selected in a way that reflects the structural behaviour. Each structure has its own particularities and, consequently, its own selection of parameters for monitoring.

There are different approaches to assessing the structure that influence the selection of parameters. We can classify them in three basic categories, namely static monitoring, dynamic monitoring, and system identification and modal analysis, and these categories can be combined. Each approach is characterized by advantages and challenges, and which one (or ones) will be used depends mainly on the structural behaviour and the goals of monitoring.

Table 1.2 Breakdown structure of the core monitoring activities

Monitoring strategy	Installation of monitoring system	Maintenance of monitoring system	Data management	Closing activities
• Monitoring aim	• Installation of sensors	• Providing for electrical supply	• Execution of measurements (reading of sensors)	• Interruption of monitoring
• Selection of monitored parameters	• Installation of accessories (connection boxes, extension cables, etc.)	• Providing for communication lines (wired or wireless)	• Storage of data (local or remote)	• Dismantling of monitoring system
• Selection of monitoring systems	• Installation of reading units	• Implementation of maintenance plans for different devices	• Providing for access to data	• Storage of monitoring components
• Design of sensor network	• Installation of software	• Repairs and replacements	• Visualization	
• Schedule of monitoring	• Interfacing with users		• Export of data	
• Data exploitation plan			• Interpretation	
• Costs			• Data analysis	
			• The use of data	

Each approach can be performed during short and long periods, permanently (continuously) or periodically. The schedule and pace of monitoring depend on how fast the monitored parameters change in time. For some applications, periodic 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 behaviour and fully exploit the monitoring benefits.

Monitoring consists of two aspects: measurement of the magnitude of the monitored parameter and recording the time and value of the measurement. In order to perform a measurement and to register it, one can use different types of apparatus. The set of all the devices destined to carry out a measurement and to register it is called a monitoring system. Nowadays, there is a large number of monitoring systems, based on different functioning principles. In general, however, they all have similar components: sensors, carriers of information, reading units, interfaces and data management subsystems (managing software). These components are presented in more detail in Chapter 2.

The Selection of a monitoring system depends on the monitoring specifications, such as the monitoring aim, selected parameters, accuracy, frequency of reading, compatibility with the environment (sensitivity to electromagnetic interference, temperature variations, humidity, ...), installation procedures for different components of the monitoring system, possibility of automatic functioning, remote connectivity, manner of data management and level at which the structure is to be monitored (i.e. global structural or local material).

For example, monitoring of new concrete structures subject to dynamic loads at the structural level can only be performed using sensors that are not influenced by local material defects or discontinuities (such as cracks, inclusions, etc.). Since short-gauge sensors are subject to local influences, a good choice is to use a monitoring system based on long-gauge or distributed sensors. In addition, the sensors are to be embeddable in the concrete, insensitive to environmental conditions and the reading unit must be able to perform both static and dynamic measurements with a certain frequency and a certain accuracy.

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 occurrence and quantification, as well as indirect damage detection. The use of separate monitoring systems and separate sensors for each parameter mentioned would be costly and complex from the point of view of installation and data assessment. This is why it is preferrable to use only a limited number of monitoring systems and types of sensor.

In order to extract maximum data from the system it is necessary to place the sensors in representative positions on the structure. The sensor network to be used for monitoring depends on the geometry and the type of structure to be monitored, parameters and monitoring aims. The design of sensor networks is developed and presented in Chapters 4 and 5.

The installation of the monitoring system is a particularly delicate phase. Therefore, it must be planned in detail, seriously considering on-site conditions and notably the structural component assembly activities, sequences and schedules.

The components of the monitoring system can be embedded (e.g. into the fresh concrete or between the composite laminates), or installed on the structure's surface using fastenings, clamps or gluing. The installation may be time consuming, and it may delay construction work if it is to be performed during construction of the structure. For example, components of a monitoring system that are to be installed by embedding in fresh concrete can only be safely installed during a short period between the rebar completion and pouring of concrete. Hence, the installation schedule of the monitoring system has to be carefully planned to take into account the schedule of construction works and the time necessary for the system installation. At the same time, one has to be flexible in order to adapt to work schedule changes, which are frequent on building sites.

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

Structures have different life periods: construction, testing, service, repair and refurbishment, and so on. During each of these periods, monitoring can be performed with an appropriate schedule of measurements. The schedule of measurements depends on the expected rate of change of the monitoring parameters, but it also depends on safety issues. Structures that may collapse shortly after a malfunction occurs must be monitored continuously, with maximum frequency of measurements. However, the common structures are designed in such a manner that collapse occurs only after a significant malfunction that develops over a long period. Therefore, in order to decrease the cost of monitoring, the measurements can be preformed less frequently, depending on the expected structural behaviour. An example is given below

for static monitoring of concrete structures:

- *Early and very early age of concrete.* Possible only if low-stiffness sensors are embedded in the concrete (Glišić, 2000). The monitoring schedule of early-age deformation is one to four sessions of measurements per hour during the first 24–36 h and four measurements per day to one measurement per week afterwards, depending on concrete evolution ('session' means one measurement for each sensor).
- *Continuous monitoring for 24–48 h.* This is recommended in order to record the behaviour of the structure due to daily temperature and load variations. This session of measurements is to be performed at a pace of one measurements session per hour during 24–48 h, at least once per season of each year.
- *Construction period.* The schedule must be adapted to construction work. It is recommended to perform at least one measurement session after each construction step that changes the loads in previously built elements (pouring of new storeys of a building, assembling of elements by prestressing, transportation, etc.).
- *Testing load (if any).* Generally a minimum of one measurement session after each load step.
- *Period before refurbishment, repair or enlargement.* These measurements will serve to learn about the structural behaviour before reconstruction. They are to be performed several times per day (e.g. one session in the morning, noon, afternoon and night) during an established (representative) period. In addition, several continuous 24 h or 48 h monitoring periods (session each hour) are recommended in order to determine the daily influence of temperature and loads.
- *During refurbishment, repair or enlargement.* In general, the same schedule as for construction, combined with four times per day and 24 or 48 h sessions.
- *Long-term monitoring during service.* At least one to four sessions per day are recommended for permanent static monitoring and at least one per week to one per month for periodic static monitoring. Yearly periodic 24–48 h continuous sessions (at least one session every hour during 24 h) are also recommended.
- *Special events.* Measurement sessions during and after strong winds, heavy rain, earthquakes or terrorist acts.

The data management can be basic or advanced. Basic data management consists of execution of measurements (reading of sensors), storage of data (local or remote) and providing for access to data. The monitoring data can be collected manually, semi-automatically or automatically, on site or remotely, periodically or continuously, statically and dynamically. These options can be combined in different ways; for example, during testing of a bridge it is necessary to perform measurements semi-automatically, on site 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. Possible methods of data collection (reading of sensors) are presented schematically in Figure 1.2.

Data can be stored, for example, in the form of reports, tables and diagrams on different types of support, 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 (data stored in a 'central library' with backups) and that 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 possible manners of storage and access to data are presented in Figure 1.3.

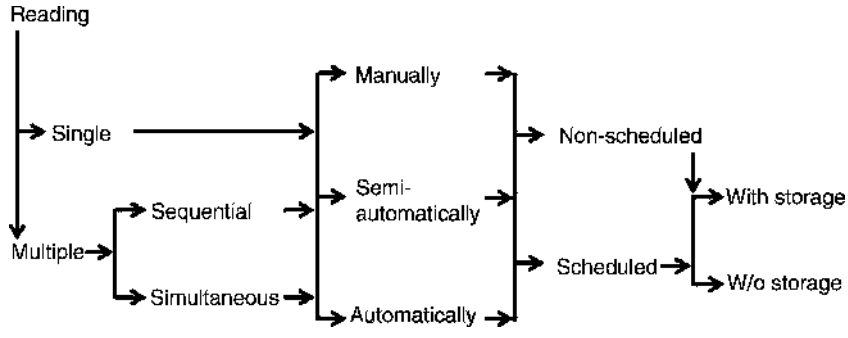


Figure 1.2 Methods of collecting the data (courtesy of SMARTEC).

The software that manages the collection and storage of data is to be a part of the monitoring system. Otherwise, data management can be difficult, demanding and expensive.

Advanced data management consists of interpretation, visualization, export, analysis and the use of data (e.g. generation of warnings and alarms). Collected data are, in fact, a huge amount of numbers (dates and magnitudes of monitoring parameters) and have to be transformed to useful information concerning the structural behaviour. This transformation depends on the monitoring strategy and algorithms that are used to interpret and analyse the data. This can be performed manually, semi-automatically or automatically.

Manual data management consists of manual interpretation, visualization, export and analysis of data. This is practical in cases where the amount of data is limited. Semi-automatic data management consists of a combination of manual and automatic actions. Typically, export of data is manual and analysis is automatic, using an appropriate software. This is applicable in cases where the data analysis is to be performed only periodically. Automatic data management 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, planned actions can be undertaken (e.g. warnings can be generated and exploitation of the structure stopped in order to guarantee safety).

The data management has to be planned along with the selection of the monitoring strategy. Appropriate algorithms and tools compatible with the chosen monitoring system have to be selected.

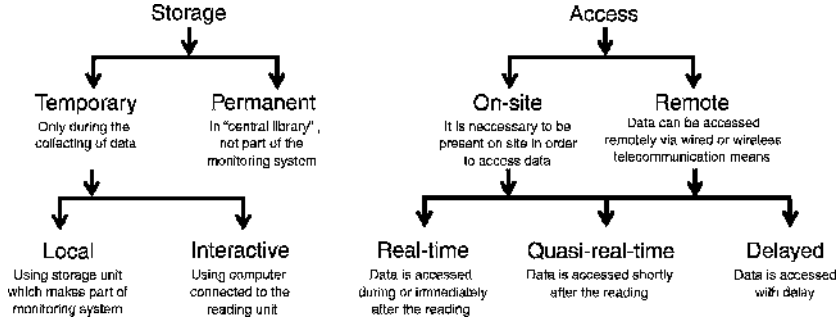


Figure 1.3 Possible methods of storage and access to data (courtesy of SMARTEC).

The monitoring strategy is often limited by the budget available. From a monitoring performance point of view, the best is to use powerful monitoring systems, dense sensor networks (many sensors installed in each part of the structure), software allowing remote and automatic operation. On the other hand, the cost of such monitoring can be very elevated and unaffordable. That is why it is important to develop an optimal monitoring strategy, providing good evaluation of structural behaviour, but also affordable in terms of costs. There are no two identical structures; consequently, the monitoring strategy is different for each structure. Methods used to develop a monitoring strategy that is optimal in terms of monitoring performance and budget are presented in the following chapters of this book. Based on our experience of applying the proposed methods, an estimated budget for monitoring of a new structure ranges between 0.5 % and 1.5 % of the total cost of the structure.

1.2.2 Actors

The main actors (entities) involved in monitoring are the monitoring authority, the consultant, the monitoring companies and the contractors. These entities must collaborate closely with each other in order to create and implement an efficient and performing monitoring strategy. These entities need not necessarily to be different; for example, a monitoring company can also have a role of consultant or contractor.

The monitoring authority is the entity that is interested in and decides to implement monitoring. It is usually the owner of the structure or the entity that is, for some reason, interested in the safety of the structure (e.g. legal authority). The monitoring authority finances the monitoring and benefits from it. It is responsible for defining the monitoring aims and for approving the proposed monitoring strategy. The same authority is later responsible for maintenance and data management (directly or by subcontracting to the monitoring company or contractor).

The consultant proposes a monitoring strategy to the monitoring authority. This strategy consists of performing the necessary analysis of the structural system, estimating loads, performing numerical modelling, evaluating risks and creating another monitoring strategy if the initial one is rejected by the monitoring authority. After the delivery of the monitoring system, the consultant may perform supervision of the installation and commissioning of the monitoring system.

The company devoted to monitoring (monitoring company) is basically responsible for delivery of the monitoring system. However, the same company can often have a role of consultant (development of the monitoring strategy in collaboration with the responsible authority) or contractor (implementation of the monitoring system).

The installation of the monitoring system is performed by a contractor with the support of the monitoring company and the responsible authority. The interaction between the core activities of the monitoring process and the main actors is presented in Figure 1.4.

As an illustration of the topics and processes presented in Sections 1.1 and 1.2, an on-site monitoring example is presented in the next section.

1.3 On-Site Example of Structural Health Monitoring Project

Once every generation, Switzerland treats itself to a national exhibition commissioned by the Swiss Confederation. Expo 02 was spread out over five temporary *arteplages* built on and around Lake Biel, Lake Murten and Lake Neuchâtel, located in the northwest of Switzerland

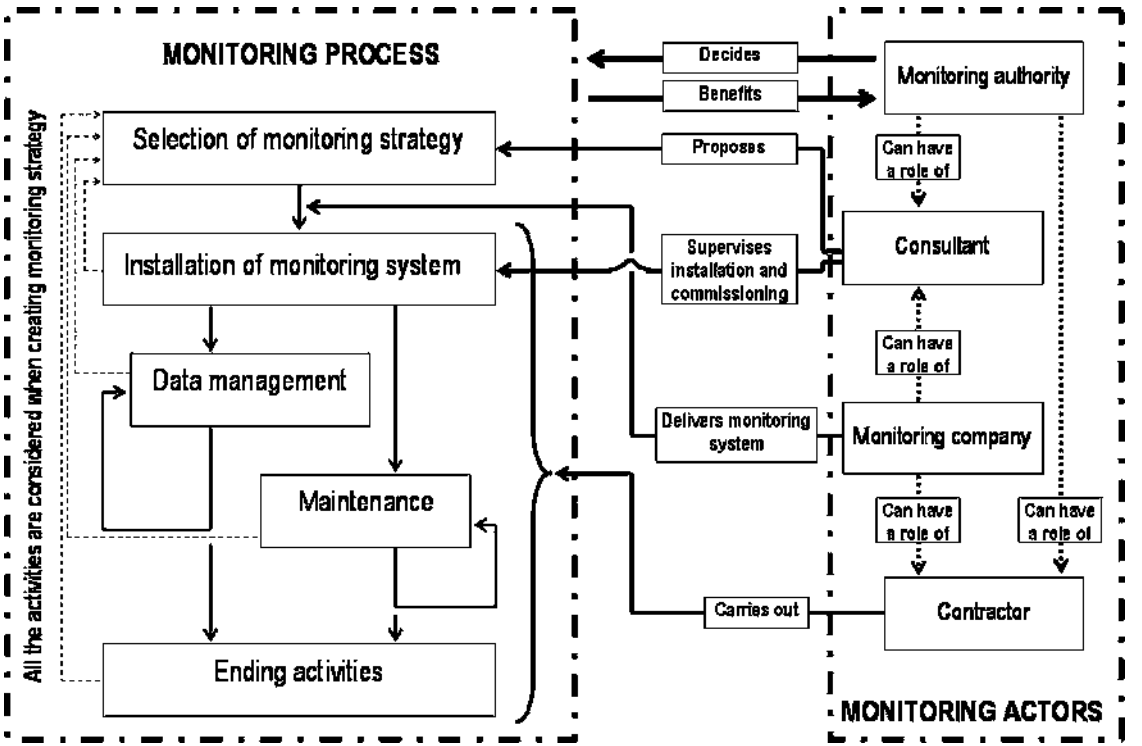


Figure 1.4 Interaction between monitoring core activities and monitoring actors (courtesy of SMARTEC).

(Cerulli *et al.*, 2003). Each *arteplage* was related to a particular theme, which was reflected in its architecture and exhibitions. The 'arteplage' at Neuchâtel was related to 'Nature and Artificiality'; a big steel and wooden whale eating a village represented *The Adventures of Pinocchio* fairy tale from the Italian writer Collodi. The belly of the whale held an exposition dedicated to robotic and artificial intelligence, while the rest of the village was developed on two floors with steel piles/beams and wooden walls and floors. The 'Piazza Pinocchio' was built together with other exposition buildings on one large artificial peninsula (platform), approximately 50 m from the shore and 5 m above the lake water level. A large textile membrane was used to cover the Piazza Pinocchio. After Expo 02, the peninsula was dismantled. The global views of Expo 02 in Neuchâtel and the whale structure are shown in Figure 1.5.

The peninsula consisted of a steel grid platform structurally supported by underwater steel columns. One of the architects' aims was to allow visitors to walk over the two exposition floors without restrictions. A concentration of visitors at one exhibition place, combined with temperature variations and differential settlements of columns, could create a redistribution in the structural elements that would be difficult to predict. Numeric simulation of the structural behaviour would have been too laborious without giving an indisputable feedback on the real structural behaviour. In order to ensure structural safety and optimal serviceability of the peninsula structure during the opening and in service, the Expo 02 committee (monitoring authority) decided to monitor the Piazza Pinocchio.

The monitoring company selected also had the roles of consultant and contractor; that is, the company was also in charge of developing the monitoring strategy and implementing the monitoring system. The monitoring specifications were as follows:

1. To ensure structural safety and optimal serviceability of the peninsula structure during the opening and in service
2. Identified representative monitored parameters are normal (axial) forces in the columns; they are determined for average strain and temperature monitoring
3. An optical-fibre monitoring system with high accuracy allowing for quasi-real-time, automatic and remote operation was selected
4. A so-called scattered simple topology combined with parallel topologies was used to monitor the columns (see Figure 1.6 and Sections 4.2 and 4.3)

Figure 1.5 View of the artificial peninsula hosting the 'Piazza Pinoccio' (left) and whale structure (right) (courtesy of SMARTEC).

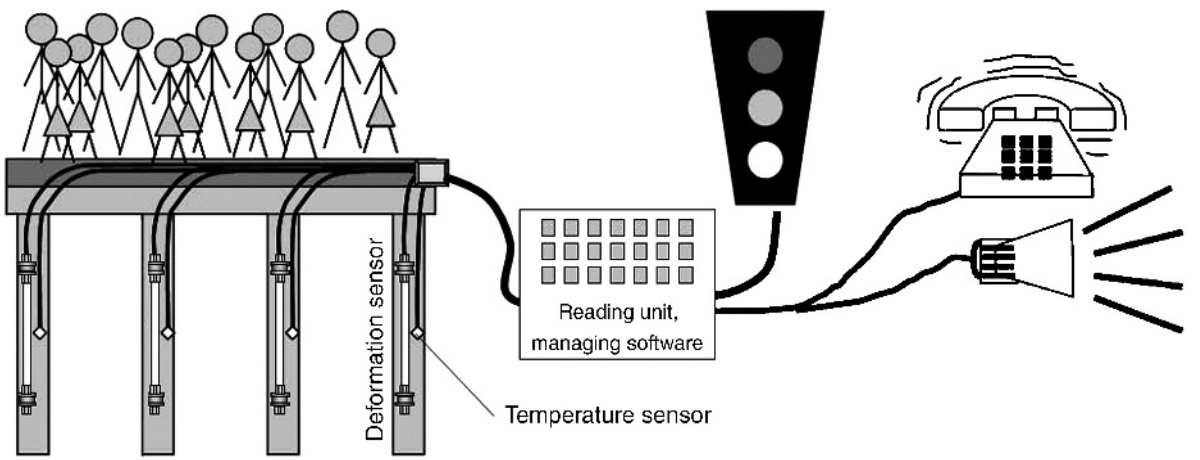


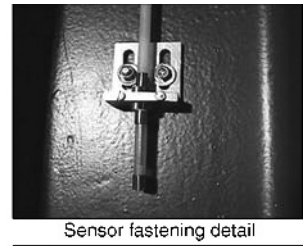
Figure 1.6 Schematic representation of monitoring strategy (courtesy of SMARTEC).

5. Monitoring is performed continuously during the exposition's opening hours
6. The data received from the monitoring is used to stop overloading of the platform by visitors and to evacuate the exhibition area in the case of structural malfunction
7. To make monitoring costs affordable, taking into account the temporary purpose of the structure, the monitoring system was simply rented from the monitoring company.

The monitoring strategy was developed in collaboration with engineers responsible for the structural design, with architects to decide on the aesthetics and logistics, and with the Expo 02 Security Department to develop warning procedures.

The technical aims were to enable detection of small load changes, to identify thermally induced strains and to detect bending on representative columns. The resolution of the

Sensor fastened to the column web



Sensor fastening detail

Temp.sensor fastening detail

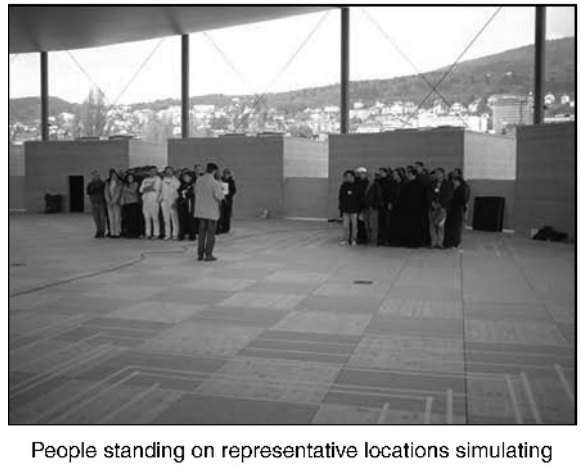
Sensor in the cross-section edges

Figure 1.7 Photographs taken during the installation (courtesy of SMARTEC).

monitoring system selected is 2 $\mu\varepsilon$, which allowed the detection of the weight caused by 10 people ($\sim$700 kg) carried by one column (which corresponds to about 20 kg m^{-2}). Deformation sensors with a 1 m long gauge-length were selected. To detect biaxial bending moment effects, four sensors were installed at the edges of the cross-section of one representative column. To determine thermal strain and separate it from elastic strain, compatible conventional temperature sensors were used. The monitoring concept is represented schematically in Figure 1.6.

Continuous measurements were carried out over 5 months during the daily opening hours (about 18 h per day). In the morning, before visitors were on site, a measurement was taken. This measurement was useful for comparing the measurements without live loads. After each measurement session was completed, the forces in the columns were calculated in quasi-real time and compared with predefined thresholds obtained using the algorithms developed. If the warning threshold was reached, then the alert status was activated.

People "free movement" test



People standing on representative locations simulating concentrated load

Figure 1.8 Photographs taken during the tests (courtesy of SMARTEC).

Sensor installation was carried out in different stages. To help the main contractor to maintain the construction work schedule, the sensors were installed on columns during construction and the connecting cables were installed at a later date inside the first-floor wooden pavement.

The central measurement point consisted of one reading unit, one optical channel switch and one computer connected to the telephone line. The central measurement point was installed in the control room (on the first floor) together with other devices used to manage and control the Piazza Pinocchio's shows and performances. Photographs of the installation are presented in Figure 1.7.

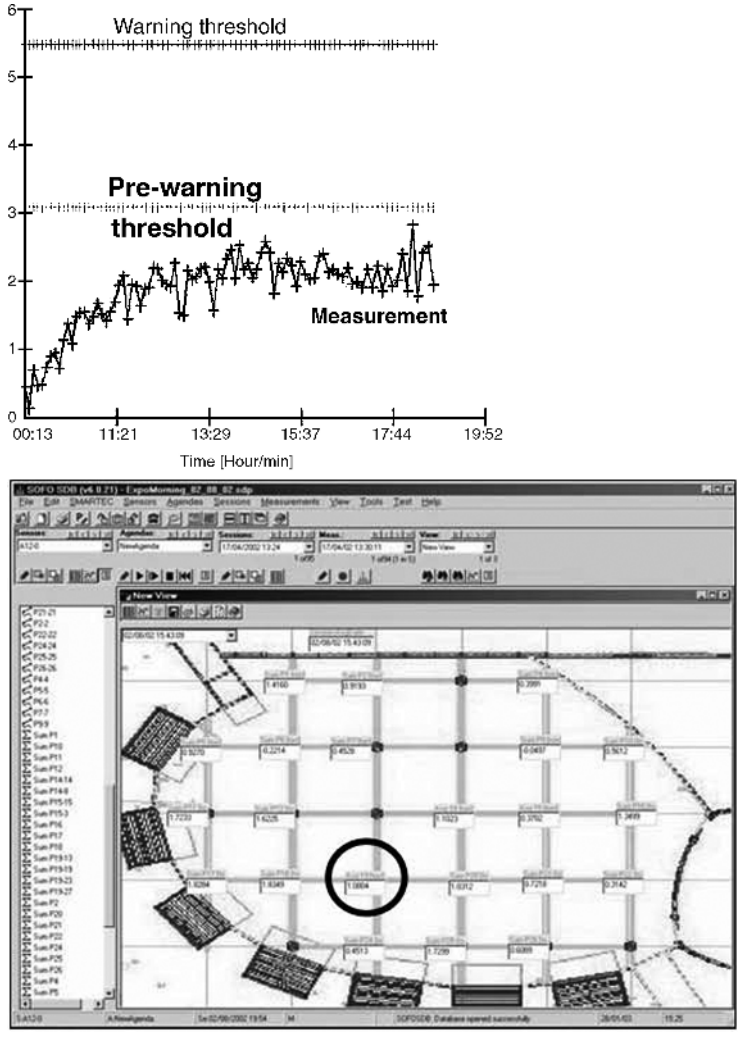


Figure 1.9 Visualization of a single measurement (left) and plan view of whale floor with 'windows' showing the actual value of the force in the corresponding column; if the threshold is reached, the colour of the window changes to yellow (pre-warning) or red (warning) (courtesy of SMARTEC).

Since some sensors were installed in rooms accessible to visitors, it was necessary to hide them in order to provide good aesthetical impact and protection. Moreover, neon lamps were installed in certain columns, so protection against unintentional accident was necessary. For these reasons the architects decided to protect the column by using an aluminium grating. The thermocouple heads were covered using polystyrene to provide ambient thermal isolation.

Before the national exposition started, the committee decided to test the structure and the monitoring system. More than 1000 people had been asked to visit the exposition area freely and to consent to a trial load test, where people had to stand very closely for a few minutes at certain locations. The tests were performed with high safety precautions. The monitoring system passed the tests successfully and was commissioned and put in service. Photographs taken during the tests are shown in Figure 1.8.

The data management consists of sensor readings, analysis of results, storage of results on a local computer, comparison with predefined thresholds and visualization of both measured values and warnings. To enable access to the monitoring system from different locations, the remote monitoring option was provided via a telephone line. Every day, at closing time, the system automatically executed a backup of the database and generated an Excel file (as an official results document). After that, it prepared the new configuration file to be used the following morning and switched off. Examples of data visualizations are given in Figure 1.9.

After Expo 02 closed the peninsula structure and the monitoring system were dismantled. The monitoring system was returned to the monitoring company.

An example of the complete monitoring process and interaction with monitoring actors has been presented in order to illustrate the notions developed and presented in the previous two sections.

Index

Some of the words in the index occur in several pages, and the authors believe that the listing of all the corresponding page numbers may not be beneficial to the readers. For such words, the authors decided to highlight in bold the most important pages (if possible to discriminate them) or simply to list only the most important ones highlighted in bold and to omit other occurrences. Thus, if the number after a word is either a normal character or mixed bold/normal character, then the list is exhaustive (e.g. the words 'Activity' and 'Analysis' respectively); if the full list of pages after a word is only presented in bold, then it is not exhaustive, but only the most important occurrences are listed, while the others are omitted (e.g. the word 'Bridge').

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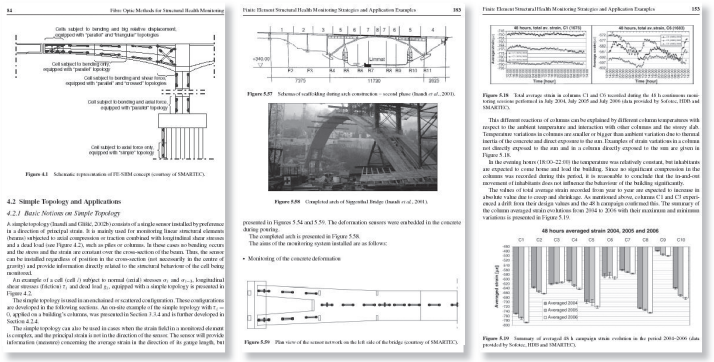

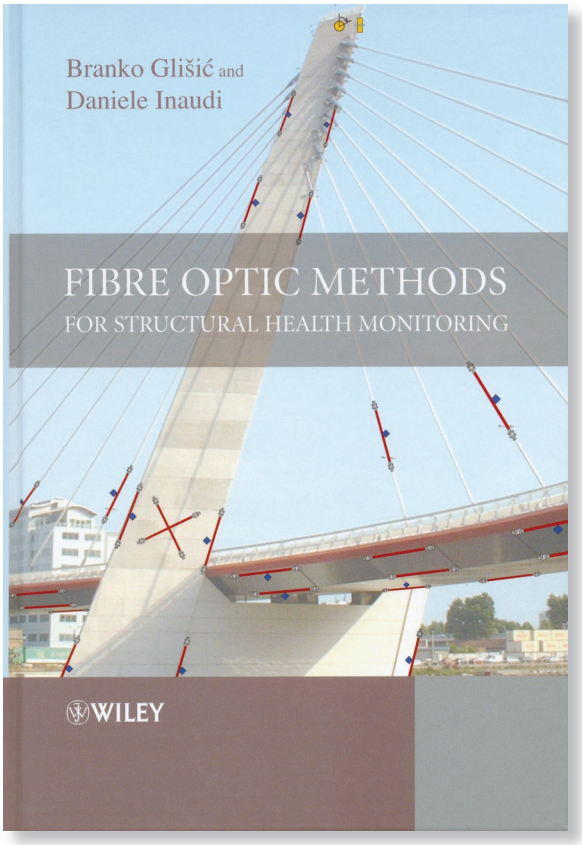

GENERAL DESCRIPTION

Book entitled:

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TECHNICAL DESCRIPTION

Fibre Optic Methods for Structural Health Monitoring is organised as a step-by-step guide to implementing a monitoring system and includes examples of common structures and their most-frequently monitored parameters. This book:

- presents a universal method for static structural health monitoring, using a technique with proven effectiveness in hundreds of applications worldwide;
- discusses a variety of different structures including buildings, bridges, dams, tunnels and pipelines;
- features case studies which describe common problems and offer solutions to those problems;
- provides advice on establishing mechanical parameters to monitor (including deformations, rotations and displacements) and on placing sensors to achieve monitoring objectives;
- identifies methods for interpreting data according to construction material and shows how to apply numerical concepts and formulae to data in order to inform decision making.

Fibre Optic Methods for Structural Health Monitoring is an invaluable reference for practising engineers in the fields of civil, structural and geotechnical engineering. It will also be of interest to academics and undergraduate/graduate students studying civil and structural engineering.

FEATURES

- **Introduction to structural health monitoring**
- **Fibre-Optic sensors**
- **Fibre-Optic Deformation Sensors: Applicability and Interpretation of Measurements**
- **Sensor Topologies: Monitoring Global Parameters**
- **Finite Element Structural Health Monitoring Strategies and Application Examples**
- **Monitoring of Pile Foundations**
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- **Monitoring of Tunnels**
- **Monitoring of Heritage Structures**
- **Monitoring of Pipelines**

The use of fibre optic sensors in structural health monitoring has rapidly accelerated in recent years. By embedding fibre optic sensors in structures (e.g. buildings, bridges and pipelines) it is possible to obtain real time data on structural changes such as stress or strain.

Engineers use monitoring data to detect deviations from a structure's original design performance in order to optimise the operation, repair and maintenance of a structure over time.

The book starts with an introduction to Structural Health Monitoring and fiber optic technologies. The methods of application of fibre-optic sensors and interpretation of the results are then presented in a clear and comprehensive manner, and illustrated with real, on-site examples.

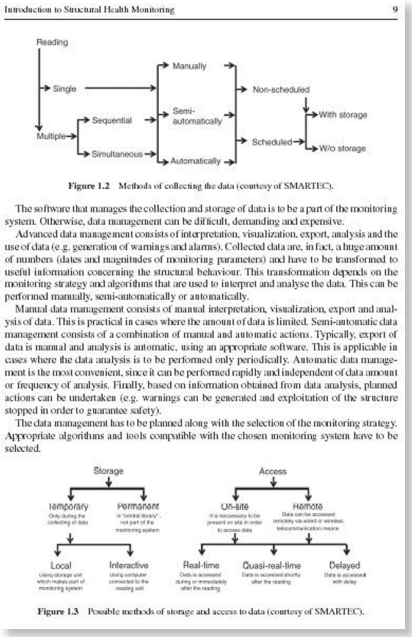

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Figure 1.2 Methods of collecting the data (courtesy of SMARTEC).

The software that manages the collection and storage of data is to be a part of the monitoring system. Otherwise, data management can be difficult, demanding and expensive.

Advanced data management consists of interpretation, visualization, export, analysis and the use of data (e.g. generation of warnings and alarms). Collected data are, in fact, a huge amount of numbers (dates and magnitudes of monitoring parameters) and have to be transformed to useful information concerning the structural behaviour. This transformation depends on the monitoring strategy and algorithms that are used to interpret and analyse the data. This can be performed manually, semi-automatically or automatically.

Manual data management consists of manual interpretation, visualization, export and analysis of data. This is practical in cases where the amount of data is limited. Semi-automatic data management consists of a combination of manual and automatic actions. Typically, export of data is manual and analysis is automatic, using an appropriate software. This is applicable in cases where the data analysis is to be performed only periodically. Automatic data management 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, planned actions can be undertaken (e.g. warnings can be generated and exploitation of the structure stopped in order to guarantee safety).

The data management has to be planned along with the selection of the monitoring strategy. Appropriate algorithms and tools compatible with the chosen monitoring system have to be selected.

Figure 1.3 Possible methods of storage and access to data (courtesy of SMARTEC).

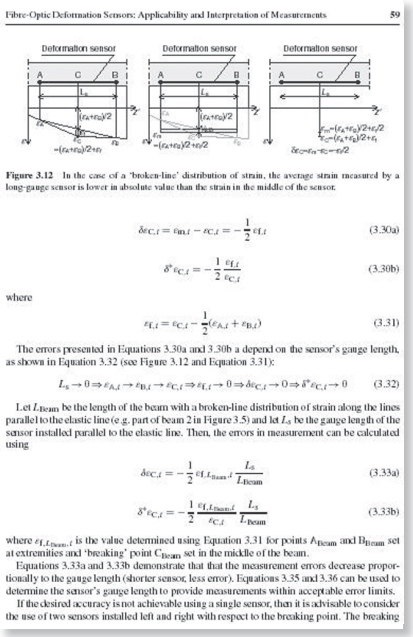

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Figure 3.12 In the case of a 'broken-line' distribution of strain, the average strain measured by a long-gauge sensor is lower in absolute value than the strain in the middle of the sensor.

$$\delta\varepsilon_{C,i} = \varepsilon_{m,i} - \varepsilon_{C,i} = -\frac{1}{2}\varepsilon_{I,i} \tag{3.30a}$$

$$\delta^{*}\varepsilon_{C,i} = -\frac{1}{2}\frac{\varepsilon_{I,i}}{\varepsilon_{C,i}} \tag{3.30b}$$

where

$$\varepsilon_{I,i} = \varepsilon_{C,i} - \frac{1}{2}(\varepsilon_{A,i} + \varepsilon_{B,i}) \tag{3.31}$$

The errors presented in Equations 3.30a and 3.30b a depend on the sensor's gauge length, as shown in Equation 3.32 (see Figure 3.12 and Equation 3.31):

$$L_s \to 0 \Rightarrow \varepsilon_{A,i} \to \varepsilon_{B,i} \to \varepsilon_{C,i} \Rightarrow \varepsilon_{I,i} \to 0 \Rightarrow \delta\varepsilon_{C,i} \to 0 \Rightarrow \delta^{*}\varepsilon_{C,i} \to 0 \tag{3.32}$$

Let L_{Beam} be the length of the beam with a broken-line distribution of strain along the lines parallel to the elastic line (e.g. part of beam 2 in Figure 3.5) and let L_s be the gauge length of the sensor installed parallel to the elastic line. Then, the errors in measurement can be calculated using

$$\delta\varepsilon_{C,i} = -\frac{1}{2}\varepsilon_{I,L_{Beam},i}\frac{L_s}{L_{Beam}} \tag{3.33a}$$

$$\delta^{*}\varepsilon_{C,i} = -\frac{1}{2}\frac{\varepsilon_{I,L_{Beam},i}}{\varepsilon_{C,i}}\frac{L_s}{L_{Beam}} \tag{3.33b}$$

where $\varepsilon_{I,L_{Beam},i}$ is the value determined using Equation 3.31 for points A_{Beam} and B_{Beam} set at extremities and 'breaking' point C_{Beam} set in the middle of the beam.

Equations 3.33a and 3.33b demonstrate that that the measurement errors decrease proportionally to the gauge length (shorter sensor, less error). Equations 3.35 and 3.36 can be used to determine the sensor's gauge length to provide measurements within acceptable error limits.

If the desired accuracy is not achievable using a single sensor, then it is advisable to consider the use of two sensors installed left and right with respect to the breaking point. The breaking

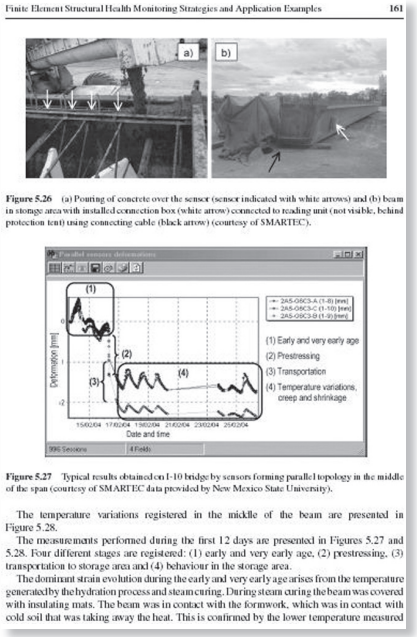

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Figure 5.26 (a) Pouring of concrete over the sensor (sensor indicated with white arrows) and (b) beam in storage area with installed connection box (white arrow) connected to reading unit (not visible, behind protection tent) using connecting cable (black arrow) (courtesy of SMARTEC).

Figure 5.27 Typical results obtained on I-10 bridge by sensors forming parallel topology in the middle of the span (courtesy of SMARTEC data provided by New Mexico State University).

The temperature variations registered in the middle of the beam are presented in Figure 5.28.

The measurements performed during the first 12 days are presented in Figures 5.27 and 5.28. Four different stages are registered: (1) early and very early age, (2) prestressing, (3) transportation to storage area and (4) behaviour in the storage area.

The dominant strain evolution during the early and very early age arises from the temperature generated by the hydration process and steam curing. During steam curing the beam was covered with insulating mats. The beam was in contact with the formwork, which was in contact with cold soil that was taking away the heat. This is confirmed by the lower temperature measured

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