SHM at the Civil Infrastructure: Applications, recent Progress and future Demands

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INTRODUCTION

Health monitoring for civil engineering structures is a challenge. Our structures are a prototype each and show small safety margins and a great exposure to the public. Bridges for example were the backbone of powerful empires from China to Rome and the Incas in America. Currently the transportation infrastructure is directly related to economic success of a nation. All these facts make structural health monitoring of civil engineering structures more difficult than any monitoring of a well defined mechanical structure. The major number of uncertainties in geometry, material properties and the influence of the environment might have a higher impact on monitoring results than any minor damage. Therefore only complex approaches under consideration and compensation of the already known phenomena will be successful.

HEALTH MONITORING FOR CIVIL ENGINEERING STRUCTURES

In civil engineering the procedure and tools are best developed for bridges. Some kind of structural health monitoring always existed in this sector. The following figure shows how these procedures have developed from simple inspection routines to highly sophisticated monitoring campaigns.

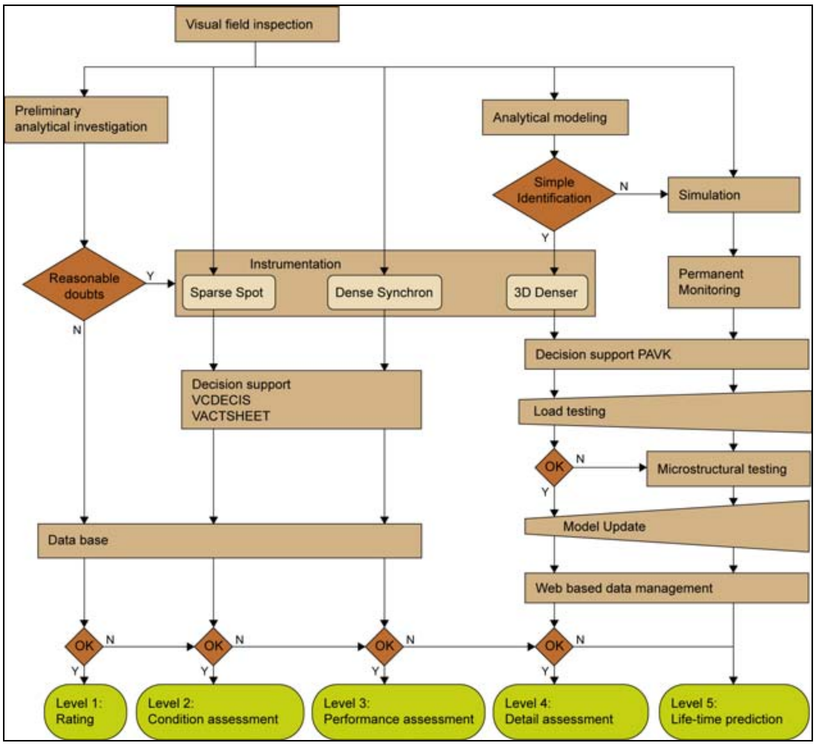

Figure 1: Typical hierarchical concept for the SHM procedure for bridges

The extent of monitoring is mainly depending on the required results. Currently 5 levels are used in order to determine the depths of investigation. These are:

Level 1: Rating

It represents the conventional assessment of the structure starting with a visual field inspection that provides a subjective impression of the condition of the structure. Some preliminary analytical investigation is performed in order to provide a rating as a basis for decisions. This would be the typical application of a bridge management system like PONTIS or DANBRO. Many bridge owners use databases to store the results.

Level 2: Condition Assessment

A rough visual field inspection has to be an element of any SHM campaign. After that a decision has to be made whether the conventional approach is satisfactory or an extended or even sophisticated additional approach is taken.

This determines the type and quantity of instrumentation. For condition assessment a simple instrumentation is sufficient and a simple decision support system will provide the necessary additional information. Storage and treatment of data should also be done in the existing database. A link to existing conventional tools is available. The monitoring can be performed at single spots only.

Level 3: Performance Assessment

This intermediate level uses the same procedure than described under level 2. The level of assessment and performance elaboration in the decision support process is considerably higher as additional information like mode shapes is measured and elaborated. This provides additional indicators for the assessment and will demonstrate the performance of the structure. It obviously requires a denser instrumentation and synchronous monitoring.

Level 4: Detail Assessment and Rating

The next step will be to establish an analytical model representing the structure. The model will be compared with the monitoring results. In case that identification is simple a step back towards level 3 might be taken. In case that phenomena are detected that can not be explained from the records further steps have to be taken to clear the situation. The most obvious thing is to introduce a permanent record over some period of time to capture the necessary phenomena valid for this specific case. Load testing also has been proven successful to establish performance parameter. With these results a simple model update can be performed to assess the results and provide a rating. Extensive monitoring is required. The records shall cover at least 24 hours, but shall rather be much longer to capture environment and traffic situations.

Level 5: Lifetime Prediction

For a serous lifetime prediction the records available have to be long enough to cover at least 3 cycles relevant for the structure. This is normally in the order of 3 years. Simulation should be run from the analytical model in order to achieve a theoretical performance to be compared with. To handle the major quantity of data special software for decision support is required. Load testing will be done targeted and extensive. In addition micro structural testing might be useful in order to look into the performance of single elements of a structure. The update process will be extensive and considering several conditions of the structure. This includes particular the loaded and unloaded case and all the nonlinearities involved. In case of reasonable doubts this monitoring system shall be operated online and web based with a warning computed by the decision support. The final lifetime prediction can then be performed as described under chapter 7.3.

The costs related to these procedures are given in the following figure. These costs are mainly depending on the extent of the monitoring campaign and the number of man hours to be invested in modeling, simulation and update procedures. The figures provided in the graph are based on prices 2006 for a typical 3-span bridge with an average length of 150m. The price can also be influenced by the number of spans, by the type of the structure and also particular by the condition for the monitoring campaign. It is expected that the prices will be rather reduced than increased. This can happen through the introduction of time saving modeling procedures and sophisticated monitoring software. Nevertheless these are still to be developed.

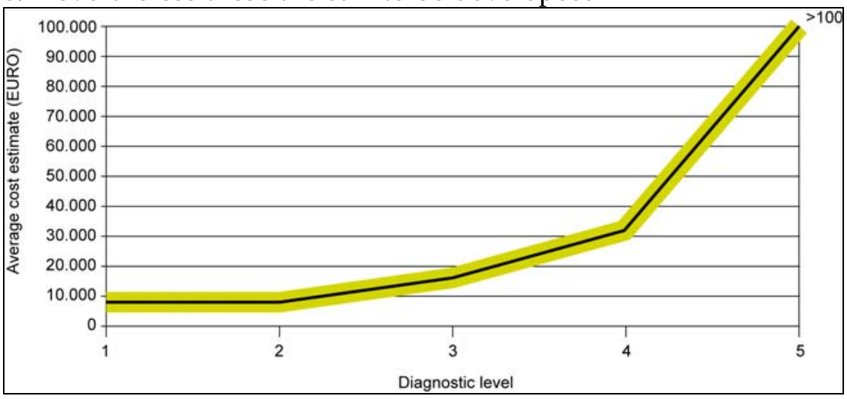

Figure 2: Cost development of monitoring campaigns for a typical 3-span bridge (€, base 2006)

HEALTH MONITORING

Structural Health Monitoring (SHM) is the implementation of a damage identification strategy to the civil engineering infrastructure. Damage is defined as changes to the material and / or geometric properties of these systems, including changes to the boundary conditions and system connectivity. Damage affects the current or future performance of these systems.

The damage identification process is generally structured into levels:
1.) Damage detection, where the presence of damage is identified
2.) Damage location, where the location of the damage is determined
3.) Damage typification, where the type of damage is determined and
4.) Damage extent, where the severity of damage is assessed

The global higher transportation network operates about 2,5 million bridges. The current bridge management systems are rating them by various methodologies and approaches. This results in very inhomogeneous figures. The U.S. Federal Highway Agency (FHWA) stated in 2005 that 28% of their 595.000 bridges are rated deficient. Only a portion of it (about 15%) has structural reasons. In Europe this figure varies around 10%. No figures are available from the Asian networks. Nevertheless if we consider an average of 10% deficiency, we look at 250.000 bridges that definitely require structural health monitoring.

Extensive literature has developed on SHM over the last 20 years. This field has matured to a point where several accepted general principles have emerged. Nevertheless these principles are still challenged and further developed by various groups of interest. The strategies in mechanical engineering or aerospace are taking different approaches. Nevertheless the civil engineering community can considerably benefit from these efforts.

Separate approaches to consider that civil engineering structures are a prototype each, are necessary.

CLIENT REQUIREMENTS AND MOTIVATION

The construction sector is conservative. The implementation of new technologies needs a clear requirement and motivation to be accepted by owners and operators. It has been recognized that the current practice does not satisfy the needs of shrinking budgets and aging structures. Nevertheless they satisfy valid codes and standards. Before a breakthrough in implementation of new technologies can happen the requirements and motivation has to be clearly understood and argued against potential clients.

Three main drivers might be approached in the promotion of structural health monitoring. The motivation to apply and order services based on the new technologies can be:

- Responsibility driven, which means the new methods to become standard applications supported by codes, standards and guidelines
- Economically driven motivations, such as situations where a ranking of structures to be rehabilitated is necessary because of insufficient budget available or the need to use a structure for a certain time period longer than designed
- Curiosity driven motivations comprise those cases where clients would like to know more about their important and complicated structures. Results can also lead to better planning for future structures.

From above mentioned motivation the following requirements can be derived. These are typical services requested from the technology providers:

- A certificate that a structure satisfies the requirements from codes, standards and guidelines comprises a main business opportunity. Many recommendations already consider the increase of maintenance periods in case those measurements are taken. The provision of such certificates by engineers is common practice in Europe. Other parts of the world don’t apply this system. It has led to an impressive evolution of bridge technology in Europe, which has been exported worldwide. It creates the environment for quality construction.

- The transfer of liabilities and responsibilities for structures in terms of technical and operational matters takes place with the huge privatisation drive we can observe currently. Clients are systematically transferring the stock of structures into private hands. The new players involved are open to new applications which are able to support innovative and economic maintenance strategies.
- Special structures require special attention. The necessary top expertise can not always be available with every owner or operator. The top experts for each region will require offering the newest technologies for their work.
- A shortage in capacities of personnel to carry out the routine maintenance and assessment works at the bridge stock also leads to new opportunities. As these services are normally tendered new technologies might have an economic and technology edge.
- In case of emergency or accidents the generation of a secure situation is desired by affected owners. Any assessment based on the results of measurements is more likely to be accepted than subjective assessment by the expert. The clients want to sleep well because somebody else is permanently watching and assessing their structures.
- Ad hoc assessment in case of doubts or emergency also comprises this application area. The subjective conventional assessment produces too many negative scores on structures and doubts are raised. A quantitative assessment is desired.
- The optimization of maintenance concepts requires input on which this process can be performed on. The more data are available the better the organization will be and the better maintenance concepts will be available. The reduction of the remaining risks helps to make decisions with lower safety margins.
- The determination of priorities, through a quantification based on measurements, helps to satisfy the growing demand in combination with shrinking budgets. This assessment can come up with better scores, minimizing the number of structures requiring immediate intervention. Decision support for investment planning can be offered on the basis of above mentioned services. Every new measurement improves the database and as such improves the quality of the results and supports the necessary decision making.
- Lifecycle cost determination helps to increase the periods where budgetary planning is necessary. The demand for retrofit and maintenance can be estimated over the whole life period of a structure or even of a fleet of structures.
- The direct link of structural performance to operation of a structure can be established. Very often information about an optimal speed or frequency in the traffic can be determined which shall be used by the operation personnel of a transportation infrastructure and communicated to the drivers through telematic devices.
- Hot spot identification technologies are very often requested in case that the weakest point of the system or a significant accumulation of

incidents is observed. Clients would like to know where to look first and what the background of certain phenomena could be.
- The prediction of structural performance for future loading scenarios is a further specific item requested. Particular when a non linear behaviour can be expected special expertise becomes necessary.
- Fleet observation when the number of structures is huge is desired to improve the quality of assessment. For this the conception has to be subdivided into stages depending on the depth of information required.

The selection of a suitable observation concept has to be based on mainly external factors. These are the number of structures to be observed in combination with the budget available. For this purpose it is necessary to offer services on increasing quality levels. The levels can be subdivided into spot, periodic, permanent and online assessment campaigns at structures. The respective features are:

- A spot observation shall comprise a very quick measurement campaign with a few simple to handle sensors only. It shall bring information on the general condition of a structure in order to create a ranking.
- Periodic assessment means a measurement campaign on a structure, which is repeated after a specified period of time, to generate information on the performance over time. This spot information might comprise rather long periods.
- Permanent observation and assessment of structures becomes necessary when certain limits are passed. This observation allows a very detailed assessment based on permanent recordings and can help to implement quick decision making.
- Online observation and assessment allows warning through electronic media, be it an SMS in the simple case or an online status through the internet. Decisions might be taken by the computer based on the measurement data. These alert systems will only be applied at extremely critical structures.

PERIODIC REPORTS

In general it has to be stated that clients need and desire a support of their work and not issues that makes it more complicated. In this respect also the procedures have to be carefully watched and permanently improved. The information policy also plays a major role in the client - consultant relationship. The new methodologies are rather complex and require a deep understanding of structural dynamics, physics and measurement techniques. Due to the fact that this expertise is rarely available at the owners engineering department, the fear to be exposed to unknown black box applications has to be taken from their shoulders. On the other hand they are spending considerable amounts of money and would like to be informed frequently about progress and results. Therefore we have to ensure them that the technology part is in good and competent hands and that they will receive the necessary information they desire. The best success has been achieved with very simple reporting techniques. A periodic report received by email comprising single page information is preferred. The example shown in figure 3 provides such a typical weekly report. The main information is provided in a single window, where upper and lower normalized thresholds are given and the measurement results within this period are placed within these thresholds. With one look at this graph the personnel can immediately see whether any of the thresholds has been exceeded. The client is satisfied because all indicators are green and the ordered observation is permanently working.

The periodic report should provide on this single page the following information:

- A photo and a system plot of the structure under observation for easy and quick identification
- A window with the periodic results placed within the relevant thresholds over the observation period
- Eventually a 2nd window with special information required by the client, such as wind speed information or any other quantity desired
- Finally a rating shall be provided which is based on the measurements taken in the reporting period. This rating shall enable the client to immediately see whether any changes have happened.
- Eventually the specification of a remaining life capacity can be provided if the necessary data are recorded.

Besides this 1-page record for the client a scientific report shall be generated by the system for the expert. This shall enable a quick assessment of all the single measurements in order to write necessary expertises or learn from the performance. Every year in average the system shall be calibrated with the information gained. This might also comprise a change in the rating and will update the remaining life capacity based on existing knowledge.

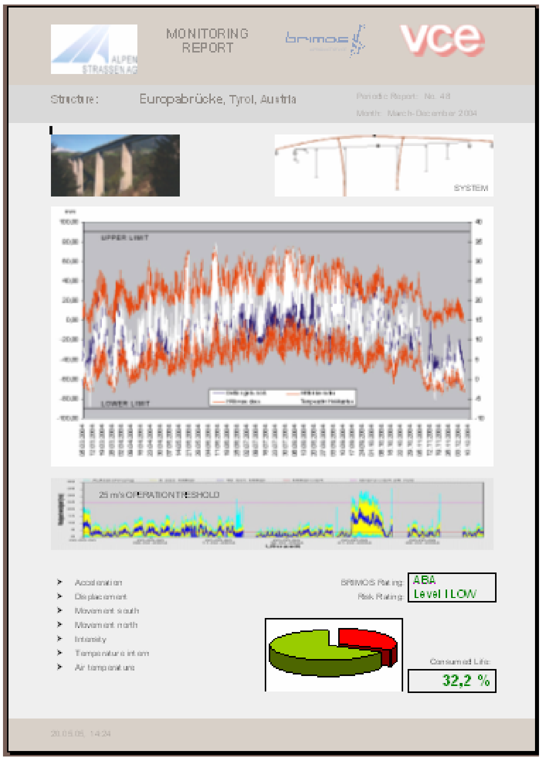

Figure 3: Typical periodic report for a bridge structure

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