The Role of Structural Health Monitoring in the Life-Cycle-Management of Bridges

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Abstract
Following the initial success of structural health monitoring the industry saw some setbacks due to the differences between customers' expectations and the practical performance.

These differences are mainly attributable due to the lack of integration between monitoring and the engineering expertise for structures. Monitoring does not replace visual inspection but rather improves it. Therefore it is essential that inspectors understand the benefits from monitoring and applying it. Not enough has been done to offer them services in a way they need it and where the impact is clearly visible.

SHM requires international guidelines that structure the process from the initial concept design to the system installation and the periodic maintenance and updating the life expectancy of the structure. The co-existence of visual inspection and traditional monitoring methods has to be demonstrated.

Finally the communication with the asset owner has to be relevant. Mostly they are neither interested in data nor in complicated explanations. They require information on which decisions can be made regarding the asset cost and value. This has to be targeted with concise expertise that fits into their working process.

The paper will show how monitoring processes can lead to a condition assessment which is needed to improve the life cycle assessment of a valuable asset.

Keywords:
Bridge Management, Life-Cycle assessment, Monitoring, Maintenance Prediction

1. Introduction

Shrinking budgets and ageing structures require beside the assessment also an economic approach that leads to a ranking of the structures to be rehabilitated. The condition of bridges is normally assessed through a condition index, as a ranking of a bridge condition in comparison to others of a bridge stock. The prediction of the remaining service life of a structure is an important issue for decision making.

2. Bridge Management Philosophy

The two basic values budget and function are what bridge management philosophies base on. Aesthetics can be another important driver, but applies mainly to the few flagship structures. The engineering community has accepted the principles of preventive maintenance, meaning that investment into structural health in time keeps the safety level of a structure constant. Another valid strategy is to let bridges deteriorate until they reach the safety limit and are replaced. Both philosophies require SHM. In preventive maintenance it is required to detect the point of intervention, where rehabilitation shows the highest effect. The functional driven philosophy requires SHM in order to detect when safety limits are reached.

The knowledge about the condition of a bridge or its elements is most wanted information. SHM provides the opportunity to quantify the condition and to provide the basis for decisions. The methodology and tools are described on the following pages.

3. Condition Assessment

Determination of the presence, the location and the quantification of damage are included in what can be called condition assessment The prediction of the remaining service life of a structure can be called life cycle assessment and includes predictions and recommendations like a maintenance plan for the future. The key issue for good predictions is a correct condition assessment.

The basic principle of vibration based structural assessment is, that structural performance changes from defects will create changes in the dynamic response that can be detected from the changes in the vibration characteristics. In other words changes in energy distribution, frequencies, mode shapes, vibration intensities and system damping can be used as indicators of the changes of physical properties of structures such as mass distribution, vibration energy contribution, stiffness, connectivity, boundary conditions and energy dissipation.

A well-defined rating system based on ambient vibration monitoring for investigated structures has to be applied. The classification allows a fast identification on the structure's integrity as well as the corresponding risk level based on measured dynamic parameters, an accompanying visual inspection, a Finite Element Model-update and reference data. Furthermore the structure is classified according to a predefined risk level.

4. Rating

The ranking of the bridges is based on one or more rating systems. The rating is better the more information is provided and can be improved if it is based on three approaches, namely

- The existing conventional inspection. Conditional assessment is traditionally based on visual inspections that are used to determine obvious damages and irregularities. The conventional inspection is subjective and the rating is also influenced by the condition rating technique used by the respective administration.
- The computation of a rating out of measured values from bridge tests. The quality of the rating deduced from a measured value depends on the quality of the measured signal. The quality of the measurement is also up to the sensor types, the monitoring system as well as on the monitoring layout.
- The rating arising from comparison of measurements with computed models. Using numerical methods a reference model can be created, e.g. FE-model, which should reflect the behaviour of a real structure. By modifying selected structural parameters and boundary conditions of the FE-model in order to come to an agreement of the measured and simulated results, this method can also be used in order to provide information about damages of a structure by identifying deficiencies of the structural properties.

Structural Parameters, like the type of the structure, the material properties, the load transfers and redundancy as well as environmental conditions like the temperature and the location of the structure influence the prediction of the remaining lifetime considerably.

To select a suitable observation concept for the measurement campaign depends on the structure itself, the available budget, the condition and the importance.

5. Dynamic Parameters for Structural Monitoring

Out of the measured signature various parameters/damage indicators can be derived.

The most common method for determining the structural parameters is the Ambient Vibration Monitoring; this means monitoring the vibration behaviour of the structure under ambient influences, like wind, traffic, waves, etc. The response of the structure is recorded with highly sensitive sensors and the resulting dynamic characteristics can be used to check the calculation models as well as for observing of the chronological development of the load-bearing capacity. Systematic assessment is therefore a necessity to be able to detect damage as early as possible and to provide a proper basis for remaining service life estimation. The parameters which should be taken into consideration for evaluation of the structural health conditions are generally the Key Performance Indicators ((see Figure 1 and [1]).

Eigenfrequencies are the most fundamental dynamic characteristics of a structure. Matters to be considered are: any changes in a) the lowest frequency and b) the most predominant frequency, and c) other frequencies. Identification of the modal shapes, if they are detected, and their changes would be very informative but their measurement may not be precise enough.

Damping characteristics are also most fundamental data regarding the structural conditions. Any changes particularly of damping values associated with any of the eigenfrequencies would be important.

Spectral pattern obtained through the spectral analysis of dynamic behaviour of the structure contains a large amount of information. In fact, all of the above mentioned parameters can be identified from the spectral presentation. The results can be presented in the form of normalized spectra and also as the cumulative spectra. Information that can be extracted from the spectral results could be limited by conditions of the structure, loading and also of the measurement.

Vibration intensity can be defined by the relationship between the vibration amplitude and its frequency. Experience has indicated that when the product of these two is beyond certain level, there is likely a development of local structural problems.

Long term trend of the spectrum is often identified by looking at the windowed average of the obtained data. Windows are applied to obtain smoother data so that the physical interpretation of their trend could become easier.

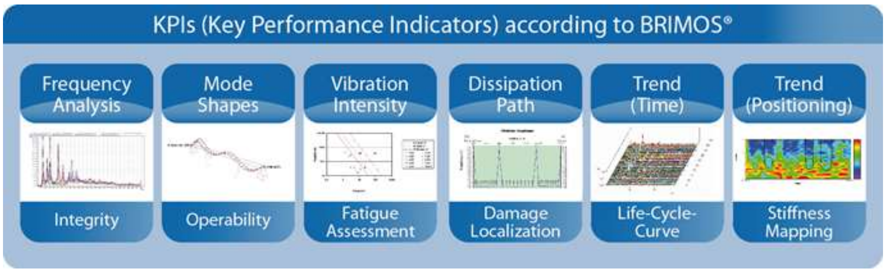

Figure 1: Parameters for structural monitoring: Key Performance Indicators

6. Life Cycle Assessment

Current practices in risk assessment and management for our infrastructure are characterised by methodical diversity and fragmented approaches. In retrospect these risk and safety paradigms resulted from diverse industries driven and limited by available knowledge and technologies. The European stakeholders recognise their obligation to reconsider risk and safety policies, having a more competitive industry and more risk informed and innovation accepting society in focus.
As managing assets is about making decisions, the current and future condition of a structure is wanted to be known as precise as possible. The European FP 7 Research Project IRIS [2] was mainly devoted to the development of Methodologies for the management of the constructed infrastructure.

The basis is the consideration of the entire lifecycle of a structure. The current development is based on the following strategy:

- The basis shall be a generic degradation model which represents an average performance as experienced and documented in various sources
- A broad set of parameters is defined that influences the actual condition. This set is kept flexible to accommodate any future parameters that might appear
- The parameters are grouped in a way that existing assessment routines like visual inspection, system identification by monitoring or damage detection methodologies are covered

• National or local conditions have to be considered separately covering the subjects of design philosophy or extreme micro climates on the other hand
• Analytical results like the comparison of design codes at the time of construction compared to current use profiles have to be introduced
• The utilization of the structure (load demand) and the respective history are to be introduced

The latest research covers all aspects of appropriate lifecycle analysis for engineering structures. In order to meet the governing requirements regarding integral life cycle analysis, durability, the real degradation process and residual lifetime considerations the following major aspects are to be considered for life cycle modelling:

a) The determination/estimation of the design life of new structures
b) The determination/estimation of the residual life of existing structures
c) Assessment criteria whether the real degradation process – determined by
  • Dynamic Bridge Monitoring
  • Visual Bridge Inspection
  • Material tests assessing chloride intrusion, compressive strength, carbonatisation (Durability)
corresponds with the assumed and applied life cycle model, in order to take corrective measures in cases of accelerated ageing
d) Maintenance instructions to guarantee the original design life and preservation of functions

Ad a) The determination/estimation of the design life of new structures

The starting point of the bridge's service life – in terms of the safety level – is according to the initial overdesign and depends on the applied design code and certain safety consideration in the course of the static calculations.

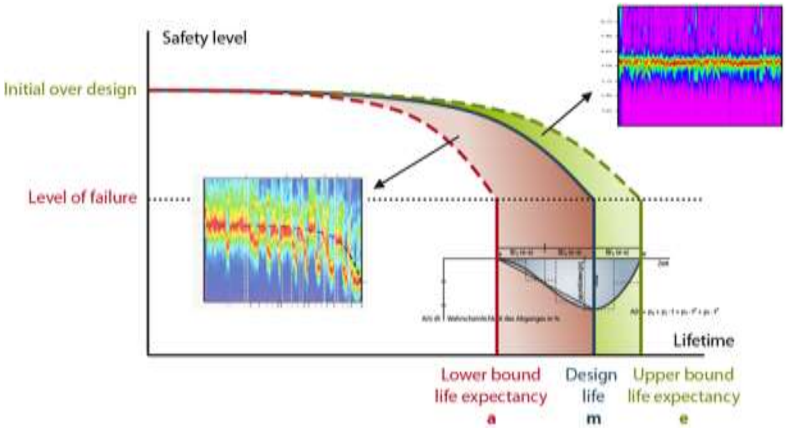

Figure 2: Expected (analytical) lifeline of new structures [2]

To estimate the range of lifetime in the first step, statistical analyses using probability density functions are applied (see
Figure *2*). A basic model covering the operational lifetime of every investigated structure is composed out of the following parameters: year of construction / static system / material / cross section type.

To guarantee these stated ranges of theoretical design life of new structures, the assessment is refined by the consideration of the following additional aspects regarding individual minimum requirements: concrete cover / concrete quality / environment influences / maintenance history / monitoring activities.

To address the deterioration process properly, the following sources of impact affecting the Structural Performance (t) are to be considered in detail: freight traffic volume / level of freight traffic impact /

environmental influences (temperature, radiation, frost action) and also degradation due to chemical exposure.

The approach from the authors [2] is already well-established and covers all the major sources of deterioration impact. Due to given project demands the methodology always has to be adapted and refined based on the major issues listed above.

It has to be mentioned, that a structure usually consists of a number of components which interact. For each of the components individual performance curves are determined, see Figure 3. The structural lifecycle curve is the combination of the individual component curves.

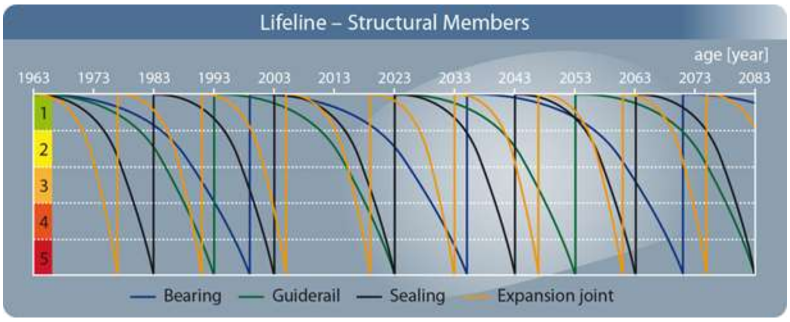

Figure 3: Telescoping of the individual structural members lifelines in the course of the whole timeframe of service life of the bridge itself - causing numerous theoretical points of intervention [2]

Ad b) The determination/estimation of the residual life of existing structures

Basically for primary load bearing members as well as for secondary load bearing members the same methodology and the same sources of impact are utilized. What makes the difference for the analysis itself is the fact, that design assumptions are replaced as good as possible by everything, supporting a deeper understanding about the previous lifeline of the investigated structure, see Figure 4.

For the determination of a methodically refined prediction of the lifecycle curve any additional information will be used, which is able to contribute to a better understanding of a structure. These are:

A) Original Static Calculation (Structural Design)
   Possible reduction of safety level reflecting a paradigm change from previous binding codes to the current ones
B) Judgement / Rating from Bridge Inspections (Reports)
C) Performed Monitoring Campaigns
D) Schedule of Performed Maintenance and Rehabilitation Measures
E) Loading History (Historical Traffic Data)
F) Material Tests (Chloride Intrusion / Compressive Strength, Carbonatisation, etc.)
G) Data on the Environmental Conditions

These datasets are merged via maintenance condition matrix in order to determine the respective lifecycle curve analytically [2]. The corresponding safety level is defined as the offset between the initial safety level in the year of construction until the present date of judgement.

Any change in assessment, for every element separately, generates a new assessment routine and changes the character of the life curve. The continuative progression is derived in a similar way to new structure – but of course depends on the former impact. Eventual improvements through upgrade or repair works are also considered.

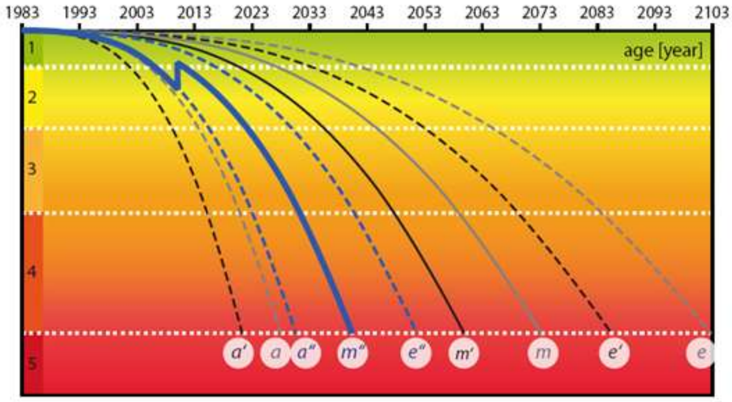

Figure 4: Enhanced lifetime prognosis of an existing bridge by means of integral structural assessment in 2010 leading to proposed maintenance interventions => new range of life expectancy [3]

The model is constructed in a fully dynamic manner and runs the life curve processing any time after a parameter update is received. Depending on the quality of the received information the standard deviation is increased or decreased respectively.

Ad c) Assessment criteria whether the real degradation process which corresponds with the assumed and applied life cycle model in order to take corrective measures in case of accelerated ageing

Continuous condition assessment is a basic prerequisite for an adjusted maintenance planning within the upcoming service life. In the course of being exposed to operational service life new structures are becoming existing structures. Thus the methodological approach based on section a) has necessarily to be used and adapted due to section b).

A constant comparison between expected and measured structural integrity (multi-level assessment of the investigated lifeline) is done to be aware of the velocity of structural ageing.

Ad d) Maintenance instructions to guarantee the original design life and preservation of functions

Regarding Life Cycle and Maintenance projects – the contractors are usually obligated to supply principal maintenance instructions for the investigated infrastructure to guarantee that the original design life of the structures can be achieved.

In the course of the life cycle analysis maintenance plans by means of intervention schedules and by means of corresponding bill of quantities are prepared for the existing and the new structures.

7. Conclusion

Decision support and Life Cycle Assessment has been observed to become a necessity in times of shrinking budgets and ageing infrastructure. The shown methodology can also be applied with a few available data, but a better reliability and more accurate predictions can be made the more information about the structure and its condition are available and incorporated.

Structural data, condition assessment by visual inspection and structural health monitoring as well as maintenance history can help to optimize both condition and costs. The Life Cycle Management Tool, that has been proposed in this paper, can be adapted to different questions with different inputs.

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