Guidelines for monitoring and assessment - A SAMCO initiative as a basis for the international standardization

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ABSTRACT: To remove the major obstacle in the application of the already existing methods guidelines shall be drafted to form a basis for a public order of such services. This is the demand which the EU Commission has placed at the SAMCO network with the expectation that the guidelines will be the base for an international code to be worked out. There isn't a comprehensive international standard yet which describes the use of methods and procedures of SHM according to comparable results. The paper explains the concept and the contents of that guideline for monitoring and assessment of engineering structures which is developed at BAM currently and brought into the international standardization process (CEN or ISO) for the processing until March 2006.

1 INTRODUCTION

Structural assessment is an essential part of the management of structural networks and the development of strategies and procedures for achieving an optimum balance between cost and safety as well as cost and serviceability is becoming a major objective for authorities, operating buildings, bridges, tunnels, dams and industrial structures.

The determination of the conditional state of structures is in most cases still based on visual inspections and described by subjective indices. Beside those traditional methods permanent monitoring will be more and more applied in future for observation of the structural state. The required technique is by now available and the adopted procedures are state of the art in a wide range. Nevertheless it needs to be pointed out, that these tasks require a multidisciplinary cooperation between the specialists of civil-, electrical- and computer engineering. To obtain comparable results from monitoring for further use as input values of the assessment process, a standardised concept for monitoring is necessary. Such a standardised concept is supposed to be developed with the monitoring guideline.

Structures are then typically assessed by the same idealized models and procedures as used for their design. These traditional methods have been indicated as the most critical technical barrier to effective infrastructure management. Maintenance needs should be based on quantitative values like objective safety and serviceability rather than on the qualitative values of the visible condition state of the structure. There is a wide range of assessment procedures with different sophistication developed worldwide. Especially in recent years, based on the progress in sensor and computer technology, the stochastic character of structural state influencing values can be considered in the assessment process. The wide range of possible assessment procedures need to be described and structured in dependence to the assessment objective. This is supposed to be done in a guideline for structural assessment with the major ambition to give an outline of possible methods to allow the practicing engineering community to pick up the method, adequate for the assigned task.

2 SUMMARY OF SPECIFIC OBJECTIVES

2.1 Monitoring Guideline

Related to the international context of the monitoring guideline being established within this work package (ISO, CEN) an attempt will be made to compare the European with the Non-European state of the art in Structural Health Monitoring. The ambition is to find out actual tendencies in used and researched technologies to include those results in the proposed guideline.

For the draft of a monitoring guideline existing national and international codes and standards on allied subjects of structural monitoring need to be considered. That means to collect information about how national rules consider basic knowledge of structural state from (mostly visual) inspections in Europe, North America and Asia. For seven coun-

tries in Europe, the USA and Hong Kong the codes and guidelines are evaluated comparable with the German code DIN 1076 (inspection of highway bridges). Further on improved techniques from visual inspection to the use of non-destructive procedures will be integrated.

The monitoring of structures is applied in various fields of civil engineering with a various effort in time and equipment. Also, the applied techniques stand in an environment of fast technological changes. To consider all those aspects, a structured approach is required for establishing the draft of the guideline. In a first step information need to be provided and processed, concerning mostly:

- the state of the art,
- the state of research and
- the state of application.

That has to be done to rise the future acceptance of the monitoring guideline. In a second step the substance of guideline will be generated considering existing recommendations and guidelines within this field.

2.2 Assessment Guideline

To process information from monitoring and structural control within structural assessment, different methods with varying sophistication have been developed and applied worldwide. Objectives for working on structural assessment are:

1. Enquiry of strategies and procedures for structural assessment; these, commonly used by practicing engineers as well as these, developed recently and assuming high standard of technology and knowledge.
2. Analysis and classification of these assessment procedures depending on the sophistication of input data, of calculation processes and of the safety evaluation methods.
3. Creating of a guideline for assessing load carrying capacity and serviceability of existing structures, based on developed assessment procedures. The guideline is supposed to conduct practicing engineers through the process of utilising structural data, to evaluate the level of safety and compare it with common and/or standardised safety limits.

The proposed guideline offers a methodological framework for assessment. A stepwise procedure is assumed, beginning with simple methods and, if necessary, going on more sophisticated**.** It is intended to describe the coherency and difference of various methods to provide an understanding for practising engineers and hep them, finding the suitable assessment procedure in dependency on the objectives and other boundary conditions.

3 OVERVIEW OF THE TECHNICAL PROGRESS

3.1 Monitoring Guideline

3.1.1 Basic essentials

Main objective of Structural Health Monitoring is the supply of information, which allows for assessing the structure. This goal can be achieved only when the information contain all necessary aspects for an adequate structural assessment. For this the knowledge of the current material characteristics, the load effects as well as the current structural behaviour and their further temporal development is necessary. The frame of the proposed monitoring guideline will be described for that reason by the following subjects:

1. Load analysis
2. Structural diagnostics
3. Damage analysis

With the according partitions the described concept attends an application area of the monitoring guideline, with which a great number of different structures can be covered. The structure of the guideline orientates fundamental at the code ISO 16587 and the German Guidelines for Monitoring of Structures (German Society for Non-destructive Testing 1999).

3.1.2 Objectives

The basis for the arrangement of the guideline is a concept for providing of information regarding load effects, loadings and condition (Mehdianpour et.al 2003). It is possible to keep information for all stages of assessment represented in Figure 1. The structural diagnosis here differentiates with respect to ‘condition analysis’ and ‘monitoring’. The first covers all those experimental methods, which are used in the sense of inspections (also periodic). Monitoring is used as long-term observation and supplies realizations, which are used on the one hand prognostically for life span evaluation. On the other hand it permits the acquisition of data during long periods in which the influence of more diversely, even more combined, impacts on the observation parameters becomes visible. Also changes in condition due to developing damage are recognized and can be considered in the used numerical models. The exact knowledge about the acting loads is the basis for a realistic evaluation of the utilization of the structural load bearing capacity. Further on their exact determination allows the derivation of realistic load models which then can be used for realistic statements about service strength and residual life time of endangered structural components. Finally administrative arrangements for live load constraint can be derived.

The guideline contains a classification of the acting loads after kind and character as well as load and

load effect as well as recommendations for the determination in accordance with its size, duration and local effect. Combination loads as well as load models and their calibration are described.

For the condition analysis recommendations are given regarding the description of the draft and the construction of the structure. The definition of limit values considers situation security, the adequacy and load-carrying capacity.

Structural identification provides the most reliable manner of characterizing a structure for analysis and decision-making. Doing this the proceedings with the documentation of well-known damage and structural characteristics, the use of NDT procedures and the execution of field test are called.

The monitoring part contains those topics, which are linked with the expectations of the long-time observation like the definition of performance parameters and associated limit values. For the experimental arrangement information are given concerning data acquisition, signal analysis as well as measurement and service conditions, sensors and measurement equipment. Here is also a subpart foreseen regarding to for the treatment and organization of the monitoring data as well as the examination of the monitoring results and consequences.

In the damage analysis part damages and damage mechanisms are classified and possible measuring and/or indicators for the description of damage are described Well-known methods for damage detection, localization and quantification and their application are called. Suggestions are made for the evaluation of damage in the sense of limit values and for a description of the condition of damaged structures.

3.1.3 State of the guideline

It is intended, to structure the above mentioned main subjects of the monitoring guideline so, that all fields influencing Structural Health Monitoring and the acquisition of information for structural assessment are mentioned. This concerns definitions, classifications, equipment, methods and recommendations.

It is not intended to fill out all structuring points within the scope of this guideline in a first step. Next the draft will be discussed within SAMCO. Via SAMCO workshops the draft has been introduced to the members of the network. Further presentation of the guideline with all details will be accessible via the SAMCO data base.

Investigation of basics for provision of material and knowledge for the guideline has the following state of work: Representatives number of national inspection-codes und guidelines is evaluated for the countries: Austria, Denmark, France, Germany, Norway, Slovenia, UK, US/Texas and Hong Kong.

For the SAMCO monitoring guideline the “Guideline of Monitoring of Structures” (German Society of Non-destructive Testing), the “Guidelines for Structural Health Monitoring” (ISIS Canada) and the “fib – bulletin 22” (International Federation for Structural Concrete) preparative abstracts are established so, that therein are those elements adopted.

All important ISO codes which are essential have been analysed and described concerning their structure and their textural elements. ISO codes of interest are ISO 16587 “Performance parameters for condition monitoring of structures”, ISO 14963 “Guidelines for Dynamic Tests and Investigations on Bridges and Viaducts”, ISO 18649 “Evaluation of Results from Dynamic Tests and Investigations on Bridges”

There is an extensive set of case stories about the present application of Structural Health Monitoring. Following data was requested: kind of structure, monitoring objective, monitoring technique, kind of sensors, data and analysis, monitoring results.

Of the worldwide spread survey answers came from 11 European countries and the USA. The assemblage of currently 48 case studies concern structures in 19 European and 3 Asian countries as well as the USA and Russia. An integrating report about the evaluation of the case stories information will be provided. It is intended to continue and actualise the survey. The integrated results of the single case stories integrated into the SAMCO – data base and can be used via internet by interested scientists and clients.

3.2 Assessment Guideline

In a first step a review of existing regulations like codes and guidelines has been carried out to get a general knowledge about how assessment is ruled by existing standards and also to obtain a summary about assessment procedures applied in current practice. Further, recently developed methods have been investigated for their usage in structural assessment. This has been done under the aspect of processing mainly site specific structural data obtained by health monitoring and control.

3.2.1 Existing regulations

Despite the general lack of regulations for structural assessment, a few do exist and have been analysed within the project work. Although most of the investigated standard work is valid only on national level and makes allowance only for specific classes of structures, the recently published international standard ISO 13822 "Bases for design of structures - Assessment of existing structures" regulates assessment generally. The basics and principles of the safety estimation process are stipulated in the code ISO 2394 "General principles on reliability for structures". It also contains a chapter for describing the principals of the assessment of existing structures. In 2001 the International Organization for Standardization (ISO) has released the guideline ISO 13822. This standard

regulates the principles of structural assessment, recommends the general course of action as well as few calculation methods. It also provides target reliability values as possible acceptance criteria. On a national level, in the U.K. the highway authority has developed a whole series of codes for assessing existing highway bridges (BD21/01 & BA 16/97). In Germany the railway authority has also published a guideline for assessing older railway bridges (DS 805).

3.2.2 Recent research on structural assessment

The ideal structural assessment is based on a realistic representation of the existing mechanical and chemical processes of a structure being loaded. In recent years, many new methods based on high tech sensors have been developed to be able to determine the realistic structural state. Further on new generations of structural models have been developed, able to picture real structural behaviour, in the service state as well as in the state of failure (ultimate state), where the structural material behaves non-linear. There is also a great research interest in the verification of the structural reliability. Mainly because of the much faster computer technology the allowance of stochastic characteristics in the parameters of structural resistance and loading as well as a more refined mathematically acquaintance with structural uncertainties can reduce conservatism in the reliability verification process. The European research project BRIME "Bridge Management in Europe" has developed a framework for the management of bridges on the European road network. The reports of this project has been used for a review on the assessment practices currently used in the European countries, as well as for newly developed methods and techniques (BRIME, 2002).

3.2.3 Objectives for assessment

In general structural assessment is a process to determine, how reliable the existing structure is able to carry current and future loads and to fulfil its task for a given time period. The first step of the assessment process must always be the clear specification of the assessment objective. This is essential to identify the most significant limit states. Associated with the limit states are the structural variables to be investigated and with those the assessment procedure to be applied. A wide range of different assessment procedures exists with varying complexity and the choice of the appropriate procedure depends highly on the specified requirements of assessment. There are two main objectives to conduct assessment of existing structures, the assurance of structural safety as well as serviceability and second the minimization of costs.

Safety and serviceability can be evaluated for a variety of reasons, among others for changes in use or increase of loads, effects of deterioration, damage as result of extreme loading events and concern about design and construction errors and about the quality of building material and workmanship. Increases of the maximum live load limits and changes of use are probably the main reasons for structural assessment. For buildings such changes could result in the need to support higher floor loadings. For bridges there is a world wide demand to raise the limits for traffic loads. Any structure is undergoing some degree of deterioration. The effects of deterioration are structure and site specific. Concerning structural strength, corrosion and fatigue are the main deterioration processes. Spalling, cracking, and degraded surface conditions are typical indications of deterioration. Impact, earthquake or wind storms can result in structural damage. The remaining load carrying capacity needs to be analysed after such events.

In the last decades systems for managing structures have been developed for minimizing the overall cost by optimizing inspection, maintenance and repair work. A main task within this decision making process is the assessment of the structural conditions to determine the current state and to assume the future performance of a structure. The objective of assessment within structure management is to provide information about the structural state for optimization of the point in time and the extent of inspection, maintenance and repair work (maximum operation effect at minimum costs) and for priorisation of maintenance and repair work within a stock of structures or parts of a structure. Further on it needs to be achieved to minimize economic losses by disruption of operation of the structure.

3.2.4 Classification

The assessment of existing structures can be carried out with methods of varying sophistication and effort. The core objectives, as described above, are to analyse the current load carrying capacity and to predict the future performance with a maximum of accuracy and a minimum of effort. Unduly conservatism but also too lax restrictions should be avoided. In most cases it is common to start with simple conservative routines and use more sophisticated routines only, when the evaluated load carrying capacity is insufficient. Generally, structural assessment should be carried out using limit state principles with characteristic values and partial safety factors. If more refined methods are necessary and economic, the probabilistic approach has to be applied. In general, within one applied assessment procedure the sophistication of the individual components should be of around the same level. For instance, there is no sense to achieve resistance and load parameters with simple but imprecisely methods and use full probability based methods for the verification. Admittedly, there may be cases were a mixture of methods with low and high complexity is advis-

able. For instance when a first step low level assessment failed and in a second step the structure specific resistance and load parameters are achieved by more refined investigation methods like NDT, the structural analysis and the verification can be carried out with the same simple methods as in the first step and the assessment may now result in sufficiency.

In general assessment procedures can be classified into three groups: non-formal assessment, measurement based assessment and model based assessment.

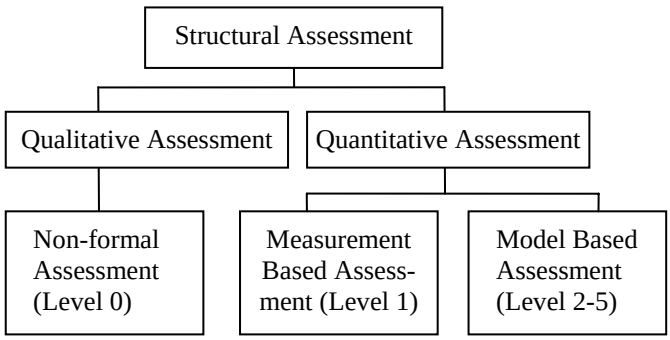

Figure1. Classification of Structural Assessment

Besides these three approaches to assessment a system of different assessment levels has been developed. It considers that the different procedures vary in sophistication. In general it is recommended to start the assessment with simple but conservative low level methods and, in case the assessment failed, move on with more refined upper levels.

3.2.5 Non-formal assessment (Level 0)

In this category fall assessment routines which are based on the experience and the judgment of the assessing engineer. They are qualitative and more or less subjective and are applied only exceptional. Most non-formal assessment takes place within structure management for a pre-evaluation of the structure. The structural condition is evaluated on the base of visual inspections.

3.2.6 Measurement based assessment (Level 1):

The most straightforward formal assessment routine is the comparing of directly measured performance values with defined threshold values. The load effects are not determined by structural analysis but by measurement (e.g. performance monitoring, proof load tests). The threshold values can be given in codes or specified individually. Since only serviceability measures can be determined directly, the method is only able to verify structural sufficiency within the Serviceability Limit State. It is a two-component procedure where the components are the measurement of load effects and the serviceability verification. Measurement based assessment routines are in general simple. Example applications are serviceability tests after construction and the evaluation of displacement or dynamic behaviour after a new utilization of the structure. The assessment of nearly insufficient and monitored structures may also be based on this method.

3.2.7 Assessment based on document review and visual inspection (Level 2)

Information about load and resistance is taken from design documents and codes with exception of specific values, leading to the assessment (damage, extraordinary load). Knowledge about structural condition from visual inspection may also enter the assessment.

Within this routine the structural analysis is based on the same techniques, used in the design process. If necessary, more refined analysis techniques (e.g. FE analysis) may be used. Common applications are the validation of safety and serviceability after extreme-load-damage (damages can result from extreme traffic, impact, earthquake, windstorm, etc.), validation of safety and serviceability after deterioration-damage (damages are results of fatigue, corrosion or other deterioration processes), determination of safety and serviceability for utility changes (e.g. new use of buildings and extreme heavy vehicle crossing of bridges).

3.2.8 Assessment based on supplementary investigations (Level 3)

When a structure or components could not be assessed as sufficient with Level 2 methods, accurate information about material properties and dimensions from in situ and lab tests may lead to a successful verification of safety and/or serviceability. Typical parameters to be analysed are geometric dimensions, mechanical and chemical material properties and hidden damages or inhomogeneities.

To be able to make a sufficient conclusion about a material property, tests have to be carried out on an adequate number of samples. Statistics of the test results can than be used for determining the site-specific characteristic value of the tested property. Geometrical measures are generally applied with their nominal value.

When it becomes necessary to use more refined analysis methods and models (e.g. FE models) the structural properties of the model need to be adapted to the reality. For that reason it is useful to determine performance measures and compare them to those of the model. Structural parameter need then to be adapted at the model to reflect the real structure in a sufficient manner. Structural parameters within model adaptation are cross sectional stiffness (e.g. module of elasticity, dimensions, stiffness of superstructures and attachments), hinge and bearing flexibility, mass distribution and damping behaviour as well as constraints which affect structural performance (e.g. external prestressing).

General assessment is carried out with the same code based loading requirements as for all structures. These load models allow for the worst credible happenstance, in case of bridges based on estimated maximum dynamic impact effects, worst overloading of vehicles and maximum lateral bunching of vehicles on a bridge. Also, they often allow for future increases in live loading and are inappropriate for safety evaluation of short time periods. With bridges taking into account different traffic conditions on different types of roads, different impact characteristics, or the lower probability of maximum impact effects occurring at the same time as lateral bunching, leads to site specific live load models with reduced magnitudes (Das, 1997). To develop a site specific live load for assessment, statistical data needs to be collected from a range of structures of the same type. Then probabilistic load models have to be generated based on the collected data. With reliability analysis the load model will be calibrated for defined sets of structures. This work needs to be done in preliminary stages of the assessment by a technical authority.

3.2.9 Modified partial safety factors (Level 4)

Based on structure-specific safety characteristics, target reliability as assessment criteria can be modified. Within the partial factor based safety format those factors need to be changed to represent the adjusted safety margin. Specific safety characteristics are loading history, consequences of failure, reserve strength and redundancy, warning of failure by inspections and monitoring. For modifications based on loading history the underlying assumption is that if the structure has been in service for a sufficiently long period of time, it can be reasonably assumed that it will have been subject to some extreme loading. For modifications based on consequences of failure structures can be classified according to the consequences, if failure occurs (e.g. low, medium, high, very high hazards to life and economic consequences). The classification is based on the ratio defined as between total costs (i.e. construction costs plus direct failure costs) and construction costs. For modifications based on reserve strength and redundancy structures can be classified according to the type of failure if it occurs (e.g. ductile and redundant with high reserve strength, brittle failure). For modifications based on warning of failure the magnitude of the target reliability can be reduced, if early warning by periodic inspections or a monitoring system is intended. Modifying partial safety factors based on adjusted target reliability is a probabilistic procedure and should be carried out for sets of structures and structural specifics by technical authority.

3.2.10 Probabilistic assessment routines (Level 5)

The main result of a probabilistic assessment routine is the calculated probability of failure or the equivalent reliability index of a structure or structural member. Unlike in the partial safety factor concept, where design parameters are definite and uncertainties are guarded by safety factors, the probability of failure depends directly on the uncertainties in the load and resistance parameters (and on other factors such as gross errors, etc). Uncertainties are modelled using appropriate probability distribution functions for each basic variable and for defined limit states. The probability of failure or equivalently the reliability index is then calculated for structural components or for the overall structure.

4 CONCLUSIONS

Within the scope of the SAMCO network BAM is developing guidelines for monitoring and assessment of structures which should be the outlines for future international standards. The guidelines introduced in this paper serve as basis for clients and as help for the practicing engineer.

Starting from already existing codes and recommendations on the basis of an extended concept of monitoring a guideline is developed. It covers all those ranges, which are necessary for providing all information for the assessment of existing structures. The paper describes the concept and the approach.

Several procedures for the assessment with different sophistication and complexity have been presented together with their relationship to the assessment objectives. Because of the reduced conservatism a special attention is concentrated on probabilistic methods, since those can allow for more realistic measures of uncertainties than code based methods and therefore are able to reflect a realistic condition state of the single assessed structure. That of course requires the use of realistic structural and load parameters which can be also obtained by monitoring.

5 REFERENCES

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