F08b

Guideline for Structural Health Monitoring

Dir. u. Prof. Dr. W. Rücker, Dipl.-Ing. F. Hille, Dipl.-Ing. R. Rohrmann

Federal Institute of Materials Research and Testing (BAM),
Division VII.2 Buildings and Structures
Unter den Eichen 87, 12205 Berlin, Germany

CONTENTS

1 INTRODUCTION

To guarantee safety and reliability of civil engineering structures, permanent assessment of the structural condition is essential during the complete life span in combination with maintenance actions. For assessment, actual loading as well as the structural condition must be taken into consideration. The most important premise for an assessment is the availability of actual information.

Besides introduced methods of visual inspections in the last two decades experimental procedures have been developed delivering extensive information. These procedures which support computational analysis by specific measurements regarding actual loading and lifetime expectation have proved their practical suitability in many applications. Advances in sensor technology together with applications of information technology and data analysis have contributed to this development. Thus, complex instruments for providing extensive information throughout the structure lifetime are available to the structural engineer. This lifetime begins with construction, continues with operation, reaches to specific applications of maintenance action and ends with the demolition of the structure.

2 OBJECTIVES AND OUTLINE OF THE GUIDELINE

The purpose of this Guideline is to introduce existing procedures and technologies and to give recommendations for their application. These are shown systematically corresponding to the necessity of extensive information acquisition for structural assessment.

The focus is on the description of a systematic approach for building diagnosis, outgoing from available building documents up to the application of measurement technology. Thereby, a variety of proved methods for structure condition analysis and monitoring are presented. The procedures are exemplified and experiences are imparted.

The second important assumption for an assessment is a comprehensive analysis of the actions. Only by the knowledge of type, dimension and durance of loading assessment of structural strain as base for structural diagnosis is possible. Preceded by classification of actions on the structure the potentialities of load monitoring distinguished by type, dimension and character are discussed.

The third part of the guideline contains the structural damage analysis. The knowledge of damage and its development in terms of dimension and complexity allows for assessment focused on future maintenance. Besides a description of damage, procedures for damage identification and damage assessment are introduced. This section points out potentialities, but also difficulties, arising with the utilisation of measurement data in connection with mathematical procedures for damage analysis. In the appendix of the guideline practical examples for the mentioned procedures and techniques are given.

Within a coherent concept new but already applied procedures for obtaining information about existing structures are introduced. With them, the responsible engineer is enabled to understand and decide dependently about the application of such procedures. The available methods and their future improvement will importantly contribute to economic and safety oriented maintenance actions.

3 ANALYSIS OF ACTIONS

3.1 Classification of actions

3.1.1 *Type of actions*

Actions are structure-depending and utilization-depending loads and deformations as well as displacements which result from the interaction of structures with their environment. They cause strain in material and hence deformations of the components. Maximum actions were used for the design of the structure. The occurrence of extreme actions is handled by risk assessment and can then be accounted for in the design process. Assumptions about dimension, direction and durance of actions during the design are based on estimates and experience. Therefore they must not necessarily correspond with real actions on the structure.

Actions on structures can be classified in mechanical, thermic and physical-chemical actions. They act as external loads or develop internally, e.g. corrosion. External actions are divided with regard to their cause in an interaction of a structure with their surrounding, their technical environment and their utilisation. Generally, actions are temporally and spatially variable and, hence, only statistically predicable and describable.

Actions can cause static and dynamic load effects. Static effects cause no negligible mass forces. Dynamic effects are originated not only by rapid load changes, but also by sudden structural changes (damage).

The most important effects which cause structural strain arranged after their causes will be presented in the following section.

3.1.1.1 Static loads

- Structure-depending loads:

  Self weight of the structure and their components and installations, support forces, prestress, abutment changes, shrinkage, creeping, construction loads, constrains

- Utilization-depending loads:

  Traffic and transportation loads, construction material, silo loads, crane loads, loads from service pipes

- Natural environmental loads:

  Earth and rock pressure, static fluid pressure, flow pressure, groundwater pressure, pore water pressure, snow and ice load, wind loads, foundation - soil settlements, thermic loads, humidity, corrosion, carbonation

3.1.1.2 Dynamic loads

- Utilization-depending loads:

  Traffic loads, machine loads, brake and centrifugal forces, human excited loads,

- Loads from the natural surroundings:
  Wind, waves, earthquake loads, avalanches, water
- Loads from the technical surrounding
  Vibrations, collision loads (vehicles, airplanes, ships), explosion loads

3.1.2 *Character of actions*

Regarding data recording, the computational treatment of the data and the modelling of loads, actions are distinguished in dead loads and live loads.

3.1.2.1 Dead loads

Dead loads are actions which are stationary, slow changing in respect to their average value (e.g., self weight, column settlement, prestress, earth pressure, corrosion)

3.1.2.2 Live loads

Actions which exist not constantly and whose temporal and spatial changes are essential and frequent, concerning their character and dimension belong in this category. This concerns many effects caused by usage of structures as well as wind, temperature, snow, and others.

3.1.3 *Loads and load effects*

Effects are stochastic quantities concerning their temporal and spatial distribution. Hence, it is necessary to describe character and magnitude of the loads by suitable statistical models and characteristics.

In many cases, not the load L but the load effect S is of immediate interest for structural components. The connection between S and L is defined with the surface of influence I

$$S_j(A,t) = \int_A I_j \cdot L dA$$

whereas A considers the contact area between load and surface.

Often, the load L is of interest only if their local load effect matters (examples of the load L are bicycle loads on directly used components like orthotropic plates or wind pressure on small facade components). Dynamic load components of vehicles on a bridge are an example of S.

3.2 Objectives and approach to action analysis

The exact knowledge about acting loads is the basis for realistic evaluation 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 fatigue strength and residual life time of endangered structural components. Finally, administrative arrangements for live load constraints can be derived.

The objective for determination of external influences (load observation) is the consistently acquisition of loads acting on the structure. This requires the knowledge about the behaviour of the system, as it can be obtained with examination on structural models or with experimental methods. The reactions or the computed loads can then be used for following tasks:

- Measurement based permanent observation of traffic load (e.g. traffic intensity density and vehicle weight); those examinations can also be used for verification of existing load models or for development of alternative load models.
- Statistics about the long term trend of increase and decrease of traffic loads.
- Determination of load collectives and dynamic factors by acquiring of acting loads depending on kind, location, amplitude, duration and frequency. Thereby influences from wind and temperature are allowed for. Such fine load models also admit statements about fatigue strength and residual life time of vulnerable structural components.
- Improvement of load models, which within the design process could only be estimated roughly (e.g. dynamic wind loads at cable restraints, at hanger or at wind bracing of bridges).
- Conclusions about environmental loadings like aerodynamic excitation, temperature influences and dynamic loading.
- Derivation of specific action for reduction of load effects by change of loading or structural resistance.

Loads can usually only indirectly determined with structural and load effect models. Basis information provide the measuring parameters described in section 2.3. Often not the absolute size of actions is of interest, but their temporal and spatial change in connection to state or strain monitoring. This applies particularly to damage analysis. Cause-effect connections of damage based on monitoring data can often determined only with additional knowledge of simultaneous actions.

3.3 Determination of actions based on dimension, duration and local effect

3.3.1 *Measurands for characterisation of actions*

Measurement values for the determination of load effects are adjusted according to physical conditions of the respective effects and to the underlying load model which has to be adapted for structural design or assessment.

Characterizing parameters for dead / static actions are for instance mass distributions of self weights. The volume and spatial distribution of structural, non structural components and dead loads has to be guaranteed, possibly within the scope of the structural analysis according to section 3.2. The spatial scatter of specific weight of construction material can be determined by material tests. Changes of the specific weight are ascertained by monitoring parameters of influence (e.g., moisture penetration) or characterising quantities (ground compaction and friction angle of earth materials).

Well known earth pressure models are applied to determine loads on horizontal surfaces and side walls (silo loads, earth pressure and rock pressure etc.). The pressure is used as the central measuring size.

Prestressing loads of externally prestressed structures, guyed masts and towers of suspension bridges can be determined only indirectly by measurement of cable forces, possibly with the help of dynamic properties (natural frequency).

Premise for determining thermal effects is the knowledge about measured temperature distributions in a structure. With the crossectional temperature distribution and the associated statically model load effects can be derived. For statically undetermined structures a mechanical model is necessary to predict the qualitative and quantitative structural behaviour.

Constraint forces as a result of enforced displacements caused by settlements or abutment changes are usually results of simultaneously constant and variable loads. For the evaluation of constraint forces a metrological investigation of the respective displacement is necessary.

If structures are flowed by air or water resistance and hence structural reaction forces result. The dimension of these loads is proportional to the kinetic energy of the flow media and the streaming surface. For identifying these loads from actions like wind, waves, which can cause static and dynamic effects, determination of the flow velocity distribution by measurement is necessary.

Variable loads can cause static and dynamic load effects. As a rule, traffic loads have static and dynamic components and their effect on the structure can be measured with an installed balance. Generally, accompanying measurement values are deformations (strains, displacements) of the structure as a scale or comparable value. In addition, information about the traffic flow, shown by driving speed and distance of vehicles, are of importance.

Vibrations, collision loads, explosion loads and disaster loads cause dynamic load effects which correspond in magnitudes and dynamic properties with loads as well as with the structure. Measuring dimensions for such processes are vibration velocities and accelerations. These describe mass forces and/or strains. This applies to all other dynamic loads in an identical way.

3.3.2 *Determination of actions*

3.3.2.1 Monitoring pattern

Actions should be determined by measurement according to their dimension and frequency, their temporal and spatial distribution and character. The necessary measurement equipment for load monitoring is chosen according to the task.

Monitoring is distinguished in continuous, cyclic, event dependent and load dependent monitoring. Extensive information is gathered with a continuous monitoring. All effects with their temporal allocations are registered. If only recording of load exceedance is required, inactive monitoring can be activated with trigger signals based on threshold values. For monitoring slowly variable quantities like static loads a brief monitoring in regular intervals is often sufficient. Also an event-dependent monitoring is applicable where the inactive monitoring is controlled by load independent values.

To determine maximum strains such approaches can be used for load combinations (section 2.3.3).

3.3.2.2 Wind loads

An important application area in practice is the monitoring of structures, which are easily excited by wind loads due to their system characteristics. Pylons, towers, chimneys, cranes and long span bridges belong to these structures. The mechanisms, leading to excitation of the structure, can be of different nature and are listed below:

- Very slim structures with low natural frequencies can, when with low damping, be excited into vibrations with large amplitudes by the gust structure of the wind.
- At circular cross sections the cyclic flaking of turbulences (Karman's turbulences) can excite the structure to large amplitudes.
- Aerodynamic instable cross sections, like e.g. rectangle sections can cause galloping vibrations. But also circular cross sections, which in general are not able to gallop, can become aerodynamic unstable under external influences like one-sided icing. Recent research has shown that already rain water, running down bridges hangers, can cause extreme galloping vibrations, which can lead to fatigue in structural connections.
- Bridges with cross sections, whose natural frequencies of torsion and transverse reaction lying close to each other, can be excited to flutter vibrations under certain circumstances.

The complexity of excitation mechanisms and the fact, that some effects occur only under certain circumstances result in a difficulty to predict the loading safely in the design state. With data analysis of long term measurements wind load models can be calibrated for particular locations. These models can then be used as a basis for a refined estimation of the expected wind loading. The simultaneous monitoring of the weather situation is necessary.

3.3.2.3 Wave loads and swell loads

Loads from waves and swell have effects on maritime buildings like harbours and offshore structures. Such loads can usually not be determined by direct measurement. They can only be determined indirectly with load models. Besides geometrical data of the inflowed structural component, these models need knowledge about kinematics of the moved water particle as arithmetic values. Input values for those calculations are the location dependent parameters wave height and wave length. Linear and non-linear theories can be applied depending on application, dimension and type of waves plus water depth. Concerning load effects on structures static and dynamic components have always to be considered.

3.3.2.4 Traffic loads

Traffic loads on structures possess static and dynamic components. They arise, e.g., with the crossing of vehicles on bridges or from moved loads on crane rails. Traffic loads have local and global effects on the strain of structural components (section 2.1.3). They cannot be measured directly, but must be determined computationally with validated load models. There is a variety of purposes to determine traffic loads.

The knowledge about traffic flow effects in a statistical sense, the validation of realistic load models or the determination of extreme loads are examples of it.

Acting traffic loads on bridges are computed from permanently measured strain, together with calibration functions, describing the structural performance (e.g. influence line). The influence line can be determined preliminary with proof loading or on numerical ways. The determined global load values are then classified according to the weight of the passing vehicles at each lane and the frequency is calculated for each loading class afterwards. The objective is to obtain a representative overview of the traffic occurring over a longer time period.

Identically dynamic traffic loads are determined. It has to be noted that these dimensions have a structure specific component, because the measured dynamic strains are the result of the interaction between the structure and every vehicle. On the other hand measured static strains are specific for the vehicle and correspond to the weight.

It has to be taken into consideration that strain, measured under traffic, represents the complete respective load of a structure, for example the distributed static load of all vehicles on a bridge. Hence, for an automatic load recognition of single vehicles it is important to calibrate the measurement with different traffic situations, i.e. combinations of load positions, influence lines or to simulate these loads computationally. Then pattern recognition can be applied.

Axle loads and axle configurations of moved vehicles can be investigated with WIM-systems (WIM - weight in motion). It has to be noted that axle load measurement results of such methods in actual traffic are overlaid with dynamic components due to the vibrations of the vehicles. Such results can lead to falsification of statistics of traffic loads. With dense, slow moving, traffic up to traffic jam load measurement with WIM-systems is more precise, since then determination of single vehicle weights is not applicable with strain measurements.

3.3.2.5 Loading by displacements

Elevations and settlements of supports as a result of changes in soil reaction, construction stage et cetera cause load effects which are always proportional to the respective deformations. The determination of these loads is done computationally based on measured displacements.

3.3.2.6 Weight loads

Mass-depending loads from dead weight, construction material, ice and snow are determined by volume and specific weight. Changes of these loads on buildings are to be determined by measurements of volumetric changes (e.g., height measurements with snow) and/or the changes of specific weights (e.g., by moisture absorption). Changes of load effects can also be determined by measurement of respective deformations (deflections, strains etc.).

3.3.2.7 Impact and collision loads; vibrations

In case of collisions an exchange of kinetic energy to deformation energy occurs. In exceptional situations the load effect is mostly dynamic and non-linear. Hence in general, the load cannot be separated from the structural response and requires suitable models for determination. A starting point are models of elastic and plastic action effect with measured dynamic values.

3.3.2.8 Temperature loads

Temperature loads can cause much higher strains in comparison to traffic loads, depending on structural design. If distributed non-linearly, they cause constraint forces and residual stresses. They entail deformation, and can lead to irreversible damage (e.g., cracks). Generally, they occur together with other effects (section 2.3.3) as combination loads. In connection with dynamic loads temperature loads on concrete structures lead to higher fatigue strains.

Strains caused by thermal expansion can be determined computationally only if temperature distribution is known. Hence, the prior measuring task is the determination of temperature fields and their temporal development with distributed sensors. Within the scope of inspections temperature fields on surfaces of components can be determined with thermo-graphic procedures (section 3.2.4).

Stationary and transient temperature fields inside buildings can be determined using computational procedures if thermal material parameters and dimensions for thermic boundaries are known (outside temperature, radiation and convection conditions). The initial conditions for temporal progression must be determinable by measurement.

3.3.2.9 Effects caused by physical - chemical processes

Besides mechanical quantities, a variety of other physical and chemical processes exist. Corrosion of reinforcement bars leads to an early deterioration of concrete structures and reduces the service life. It causes a reduction of the reinforcement cross section, the cracking of concrete cover by expansion of corrosion products and the loss of bond between steel and concrete. The main reasons of corrosion in concrete structures are chloride contamination and carbonation. The corrosion velocity within concrete structures depends substantially on the exposition and in particular on concrete humidity, the electric conductivity, temperature and oxygen concentration. Spalling of concrete as a result of carbonation processes accelerates the corrosion process. Sensors are introduced for measurement of these quantities. The interpretation of the results requires great experience and expert knowledge.

3.3.3 *Load combinations*

For design of structures the effect of load combination is usually assumed. In practice the overlaying load components result from constant and variable loads, exceptional loads and prestress. Loads in situ are usually determined by measured reactions of the structure (deformations, deflections, vibration amplitudes) which are the result of load effects caused by load combinations. To be able to separate single load components from these results, the character of the single load component in direction, propagation, duration and temporal progression as well as further typical properties must be known. With this knowledge load components can be separated by data analysis procedures.

Example: For a combination of loads from traffic, temperature and settlement, the measured strains can be split in five components: a static and dynamic component from traffic load, a component from the change of the average temperature and temperature gradient and a component from settlement. All these components have a characteristic durance which is used for the component separation. The durance of partial load in the time domain corresponds in the frequency domain to a typical frequency. If this frequency is known, the measured total deflection can be separated into load specific components by application of filter functions and can then be processed in accordance to sections 2.3.2.4, 2.3.2.5 and 2.3.2.8.

3.3.4 *Use and analysis of measurement data*

Measurement data for slow variable processes are recorded cyclically or continuously. They are described by statistical dimensions like maximum values, gliding averages and variances and are stored together with the associated measuring time. Fast variable processes, for example effects from traffic loads, wind, waves and shocks are continuously measured, so that possibly all load processes can be recorded. Then data must be processed by procedures adapted to their contained information. If load combinations are processed at first, data separation in respect to loads must be performed (section 2.3.3). These data are additionally analyzed regarding their dynamic characteristics, apart from the description by statistic characteristic values. Here the information about frequency contents of the signals is of special interest. For these procedures, Fourier analysis and wavelet transformations are used among others.

Traffic loads, wind loads and wave loads are separated in their static and dynamic components and are used for further statistical value identification. Subsequent to the calculation of maximum values and averages as well as variances this data is used to determine frequency distributions. For the determination of wind loads specific values of wind speed based on main values for specified periods (e.g., 10 minutes), are processed. The turbulence intensities are calculated from variances of these averages and depicted in power density spectra. For the description of dynamic traffic loads maximum dynamic components of strain are applied to the simultaneously measured static traffic load. For load statistics frequency distributions, classified in load classes, are determined. They are based on ascertained vehicle weights.

3.3.5 *Load models*

Load models not necessarily represent the physical reality of load effects, but contain a filter effect in more or less distinctive shape, as described in section 2.1.3. Load models describe loads in a way, such that the effect on the structure corresponds to that of the real load. Generally, the maximum value of this equivalent action is chosen with a fixed probability and the fixed return period.

In codes for loading assumptions ([13], [14]) the elected probability level follows the return period which is associated with the averaged actual life span of the structure. If load models are updated by constant observation of effects (load-monitoring), the safety level can be adjusted contemporarily to typical values of the respective effects. Besides, it has to be noted that, considering section 2.1.3, the filter effect Ij of the structure determines the actual loads and thus the load effects. Here, compliant load models have to be developed, depending on design and construction method, as well as regarding to further use of the data (e.g., assessment of the load-carrying capacity or the residual life span).

3.3.5.1 Calibration of load models

The calibration of load models has to be done with load monitoring results as described in section 2.3.2. It refers to the statistical basis of the data (e.g., return periods) and to calculation of loads from measured load effects (e.g., strains) with the help of load-structure models.

4 DIAGNOSTIC OF STRUCTURES

4.1 Preamble

The extraction of comprehensive information about structures stands in the centre of this section which contains the parts Structural Condition Analysis, Monitoring of Structures and Numerical Analysis.

Outgoing from gathering and assessing information by means of structural condition analysis, methods for metrological investigations are introduced which complement and verify the available information. This concerns processes which are used predominantly locally, as for example NDT process. Information which describes the structures as a whole is obtained by application of field tests. Load bearing capacity and global structural qualities are superficial. Nevertheless, for this information it is characteristic that it applies only to the time it was obtained.

Time variant values can be measured by application of monitoring methods. This succeeds with repeated investigations. Monitoring methods are applied in irregular or regular time intervals up to continuous operation. They allow to ascertain changes and to issue limited prognostic statements.

Besides metrological investigations computational results are required. Nowadays with the help of arithmetic models comprehensive and very precise statements of the structural behaviour under any effects can be given. The premise for such simulations is, that the model parameters are adapted to reality as exactly as possible. The information for this process can be obtained from results of metrological investigations of structural condition analysis and monitoring of structures.

4.2 Structural Condition Analysis

4.2.1 *Description of design and construction of the structure*

Aim of the survey is the dimensional and constructional ascertainment of the structure and its condition in preparation of advanced structural investigations. These results serve among others as basis for an assessment of the load bearing capacity under present loading, for utility changes with increased load level, for maintenance repair and structural upgrading as well as for the assessment of existing damage under static and dynamic aspects. The purpose of the dimensional ascertainment is the actual and exact record of all geometrical values, necessary for the description of the structure and its structural environment. It starts with the review of existing design documents and will be supplemented by an as realistic as possible geometrical measurement of the existing stock of structures. For those parts of the structure, which can be accessed only with difficulty, tools like laser or tacheometer should be used. The realistic dimensions of the structural members, including their cross sections, should be determined, also under considering the loss of material by corrosion. For thickness measurement, radiographic methods like x-ray and ultrasonic are supposed to be used besides conventional methods. The constructional ascertainment serves the static and dynamic analysis of the structure with consideration of all members and the structural environment taking part at the load bearing behaviour. An actual system description and condition ascertainment stands in the foreground under the following aspects:

- identification of the load bearing and stabilising structural members
- identification of coupling and connecting elements and their mechanic properties
- specification of constructive details (type of prestress, coupling joints, anchors, et cetera)
- determination of material properties (strength, mass allocation, damping properties, humidity, chemical values, et cetera)
- specification of the structure and configuration of the structural environment (ground, restrain systems, fill masses, et cetera)
- evaluation of the functioning of bearings and joints
- specification of existing loads and their spatiotemporal effect
- recording of possible problematical spots and deficiencies
- specification of existing damage and damage causing circumstances.

For information acquisition the listed methods in the described order are available:

- visual inspection
- non destructive testing (NDT)
- testing with low destruction
- destructive testing (DT).

4.2.2 *Determination of threshold values for position stability, serviceability and load bearing capacity*

Threshold values for condition describing values of structures can be gathered from applied codes and guidelines or they can be determined taking local circumstances into consideration. In the second case, the accuracy of the assumptions needs to be ensured and, if necessary, be reviewed after specified periods.

<u>Position stability:</u>

In general, position stability has to be ensured within the ultimate limit state. Further on, global changes of positions through settlement and tilting of foundations of structures have to be limited within the serviceability limit state. For specific types of structures like railroad bridges, threshold values are defined by codes.

Generally, threshold values for position stability within the ultimate limit state can be determined on structural models. Threshold values for position stability within the serviceability limit state have to be determined considering all boundary conditions, influencing the unconfined usage of the structure.

<u>Serviceability:</u>

The limitation of deformation values and vibration under service loading is often regulated in codes and guidelines. This is especially true for structures, where deformations inserted by loads are constricting the serviceability. Otherwise, threshold values for deformation and dynamic behaviour can be constituted discretionary. For covering the durability and serviceability of the structure, deformations, stress values and damages like cracks need to be limited. The according threshold values are often specified in design codes, but can also be self determined.

<u>Load bearing capacity:</u>

Within the ultimate limit state threshold values of measurable condition values are only rarely specified in codes and guidelines. In fact, limits for condition values are defined, but within the ultimate limit state they cannot be used as thresholds for monitoring of the serviceability state. Condition values, which indirectly indicate the limit of the state, can be developed using structural models. Fatigue stress is an exception, since here the ultimate limit state can be reached by service loading. In these cases the amplitudes of the cyclic stress are limited in dependence of the number of cycles.

4.2.3 *Structural identification*

Structural identification provides the most reliable system of characterizing a structure for analysis and decision-making. Therefore, the structural identification principle gives guidance to civil engineers for determination of an optimised measurement system. Herewith, a structure can be characterised accurately and completely in order to reliably establish its health at serviceability and ultimate limit states. To conduct structural identification application systematically, the following steps are specified:

- Collecting information and a-priory modelling

  If necessary for the determination of the static system, all design documents has to be consulted for checking the geometric values and the characteristic values of the building material. Missing details have to be completed by measurement as well as by non destructive testing on the structure and on samples. A model which represents the initial knowledge about the structure is often incomplete and coarse and has therefore to be refined.

- Evaluation of the actual condition

  To assess the actual condition of the structure, the special structural features, existing documentation, known damage, results of visual inspection as well as of non-destructive and/or destructive tests, have to be considered.

- Assessment of the existing bearing capacity

  For the present use or intended change of the use of a structure the bearing capacity has to be proved based on all existing information and the assumption of a safety concept for loads and structural resistances.

- Preparations for experimental analysis

  In preparation of performing full scale tests a sensitivity analysis by the a-priory model has to be required to determine optimal excitations and responses for dynamic tests and to select acceptable ranges of measurements. Based on analytical and preliminary experimental studies the configuration of loads for static tests, the kind, number and locations of sensors should be optimised.

- Full scale tests

  Static load tests should be performed on account of insufficient knowledge about the structural model, the interaction of components, the effect of known damage, the effectiveness of remedial actions. Dynamic tests can be performed to verify global system behaviour and the critical mechanisms that affect the global modes of vibration. For fatigue tests the dynamic behaviour of structure needs to be known.

- Processing of experimental data

  The processing and conditioning of measurement data from full-scale test is an important step to a higher confidence level of information about the structure.

- Model calibration

  Mechanical properties, boundary conditions and continuity conditions of the model are adjusted. Model configurations agree with the physical insight observed during the experiment and obtained from the processed experimental data.

- Utilisation of calibrated models

  The field-calibrated analytical model serves as the best measure of the actual conditions of the structure. This may be used for load bearing capacity rating, load permitting and evaluating internal forces, stresses and deformations under operational conditions,.

4.2.4 *Application of NDT techniques*

In structural analysis and damage analysis non destructive testing methods are applied successfully. With combined application of the described processes, using methods of data fusion, various verifying problems can be solved economically. By application of surface scanners non destructive measurement can be increasingly automated. In addition, a tendency towards image producing analysis, using tomographic methods, is clearly recognizable.

4.2.4.1 Steel structures

For locating flat separations (e.g. cracks) and for thickness determination of structural steel sections high-frequent ultrasonic technology (usual frequency: 2 and 4 MHz) is applied successfully. The same applies to the radiography which is employed for locating volume defects (e.g. pores, inclusions, blowholes) as well as for locating cracks in junction plates of historic trusses. To trace the temporal and spatial of crack development in steel structures sound emission analysis is used. Not only material conditions but also material specific values can be determined non-destructively. Thus, for instance, the spark-induced emission spectral analysis permits the determination of steel composition without sampling.

4.2.4.2 Reinforced and prestressed structures

For reinforced and prestressed structures numerous non destructive testing methods are often combined applied. Especially for locating of near-surface reinforcement, magnetic static magnetic field and alternating field processes are employed up to a maximum component depth of approximately 12 cm. Locating reinforcement or tendons in bigger component depth will mainly be done with radar. For the localisation of tendon ruptures the remanence process must be applied additionally after a successful non destructive discovery. This is based on magnetisation of the tendons and the sizing of the magnetic field. Indicator for a tendon rupture is the change of the polarity. Checking of the diagnosis is possible, for instance, with a minimum-invasive intervention. With a drill an artificial opening can be created for a specific endoscopic investigation. Alternatively, the interesting tendon area can be investigated radiographically. For extensive corrosion condition investigations of the reinforcement the potential field method, based on electro-chemical basis, can be applied.

Also various acoustic methods are applied for solid structures. Because of the dispersing effect of the rock granulation, low frequency ultrasound (usually 50 to 100 kHz) is used. Herewith, the coating thickness as well as the defects (gravel nests, hollow cavities and others), also with unilaterally accessible components, can be detected. Furthermore, the ultrasonic technology is employed for checking of the concrete compression resistance. Additionally, the impact echo process is used for various applications. This process is employed for checking of pile integrity as well as for coating thickness determination of tunnel shells.

4.2.4.3 Masonry structures

An important non destructive testing method for wide ranged damage in masonry is radar. Objectives are the determination of the composition of the masonry (thickness, alignment, hollow cavities, metal ties and others) as well as the determination of moisture conditions. Within wide range moisture investigations the IR-thermography is often employed. For selective structural investigations endoscopy, ultrasound and microseismics are used. Herewith, the compressive strength and homogeneity of natural stones and clay bricks can be evaluated. For selective moisture investigations various electric methods (resistor methods, capacitive methods, microwave methods etc.) as well as radiometrical methods (NMR, neutrons back litter and radiographic methods) are employed.

4.2.5 *Field tests*

Field testing as part of structural identification is used as an inspection approach as well as part of monitoring in the way of cyclic or intermittent observation. The purpose of static field testing is predominantly to check the load bearing capacity of a structure. During dynamic examinations the determination of the dynamic properties of structures and the interaction between the dynamic loads and the structures behaviour is in the focus of attention.

<u>Static tests</u>

Static loads are considered to be those loads that are brought onto or placed on the structure very slowly, so as not to induce dynamic effects in the structure. Static field tests can be subdivided into behaviour tests, diagnostic tests and proof tests.

Behaviour tests are carried out either to study the mechanics of structural behaviour or to verify certain methods of analyses. The objective in the latter case is to verify that analytical methods can be used for the design and evaluation of structures with confidence. A behaviour test provides information regarding how the load is distributed among various components of a structure. Results from these tests can be used to calibrate analytical methods.

A diagnostic test denotes a test that is carried out to diagnose the effects of component interaction. For example the diagnostic test may be conducted to establish the rotational restraint conditions at the end of a bridge column. Through a large number of tests, it has been confirmed that diagnostic testing can be used with advantage: to locate the sources of distress that might exist in a structure due to inadvertent component interaction, and to determine the positive effects of interaction. Diagnostic testing has the benefit of explaining why the structure is performing differently than assumed.

A proof test is carried out to establish the safe load-carrying capacity of a structure. During this test, the structure is subjected to exceptionally high static loads that cause larger responses in the structure than the responses that are induced by statically applied maximum service loads. Because of the very high loads applied to the structure in proof testing, there is always the possibility that the structure may be permanently damaged by the test. A well-planned proof test is carried out with gradually increasing loads, ensuring that the loads are not allowed to be beyond the limit of linear elastic behaviour.

Dynamic tests

Dynamic testing of structures can be subdivided into the following distinct categories

- Stress history tests
- Dynamic load test
- Modal tests

Concerning their characteristic and their spatial distribution, dynamic loads are often complex and computationally not sufficiently to describe. Then stress history tests are accomplished, in order to determine those stresses experimental in dynamically highly stressed ranges of structures (e.g. joint connections), which are substantial regarding the fatigue loading. After preliminary numeric investigations, for the determination of "hot spots ' at structures, a larger number of sensors are attached the stresses under operating conditions are measured. From the results of these investigations optimal sensor configurations for a continuous fatigue monitoring are determined. Stress history tests are accomplished whenever the dynamic actions in combination with the examined structure are too complex to obtain sufficiently exact results by numeric simulations.

Dynamic load tests serve to determine the dynamic increment from traffic loads. Realistic information is needed in order to control design acceptance after completion. Likewise, with same traffic volume, structural changes can lead to changed dynamic stresses in parts of the structure. Also a change of use due to planned passages of vehicles with changed dynamic characteristics lead to measure the new dynamic loads in advance. If during design the dynamic load effects are regarded as an increase of the static stresses, dynamic load tests are to be accomplished by the measurement of strains at those structural parts, which are of importance for the design.

Modal tests are used for determination of modal properties of structures. The knowledge of the modal characteristics is used for damage identification, for quality control of structures after completion, for planning and assessment of repair work, for the assessment of structural safety, after extreme loading as well as for the calibration of structural models.

The procedures for the determination of the natural frequencies, the mode shapes and the modal damping are differentiated regarding to the excitation of the structures in:

- ambient vibration test
- forced vibration test

In the first case the tests are accomplished under operating conditions. The excitation energy comes from the dynamic operating load of the structures (wind, weather, traffic, ground vibration). Therefore ambient vibration tests can also be accomplished with large structures, also under loads, which lead to changes of the dynamic characteristics. It is assumed, that this kind of the excitation has a stochastic character with a broadband spectrum. If this is not the case, a complete identification cannot be accomplished, since only those frequencies become excited, which are present within the exciter spectrum. Ambient vibration test are to be accomplished comparatively fast and inexpensive. Since the systems responses due to natural excitation are often small, highly sensitive sensors must be used to their ascertainment.

The usual kinds of excitation with forced vibration test are impulse (impulse hammer, drop weight et cetera) and Heaviside function as well as regulated excitations (harmonic, periodic and stochastic) by electro-dynamic and electro-hydraulic exciter systems. The selection of the type of exciter depends on the dynamic characteristics of the structures as well as on the existing site conditions. Using the Heaviside function the input energy is concentrated within the low-frequency range. Impulse excitations are unsuitable for large buildings. During regulated excitation arbitrary long measurement times are possible, with which higher frequency resolution can be achieved. Disadvantageous is the fact that equipment and operation of such exciter systems are substantially more expensive and require the exclusion of the normal operating conditions (traffic). The advantage is the almost complete identification of the modal characteristics of the structures.

4.3 Monitoring of structures

4.3.1 *Objectives*

The aim of automatic and permanent monitoring in the context of this guideline is the improved knowledge of the current state and long-term behaviour of structures or structural components as well as of the causing influences and loads. With that the results of previous procedures for structural monitoring are supposed to be improved and completed. Permanent monitoring is generally indicated by continuously recorded measurands, i.e. without time interruption, with permanent applied sensors. Additionally results are compared with previously established reference data of the loading and the structural properties.

The procedures described here can be used for structure-related damage analyses. For instance, in cases of an overload, of arithmetical exceeding of the operational life time or of pre-damage, which forbid normal inspection intervals, permanent monitoring procedures can allow a further use of the structure. Then, it must be guaranteed, that for such safety relevant monitoring the measuring and data processing works reliable using redundant technology. Also it is necessary to evaluate the results of the permanent monitoring constantly or in sufficient short time intervals.

4.3.2 *Specification of monitoring task*

4.3.2.1 Monitoring of load effects

Permanent observation and assessment of the current load effect become highly important with strongly fluctuating and external loadings which cannot be determined sufficiently exact (e.g. wind, traffic) and with complex structural behaviour which can not be modelled or modelled only with large effort (e.g. spatial effects).

4.3.2.2 Condition monitoring

During condition monitoring of structures global and local structural properties are evaluated based on continuously measured values. Objective is to evaluate the current condition and to predict the future development of the structural condition with adequate accuracy. Another objective is to identify and record gross changes in the structural behaviour.

Local structural properties are monitored if there is a local pre-damage or a structural component which is exposed to special loading conditions. If preset threshold values e.g. from codes, from experience or an arithmetical analysis, are exceeded, further specialized investigations are usually necessary.

Generally, structural changes in single components like the fracture of a single prestress tendon cause only local effects. Therefore the monitoring success depends on the local basis of measurement points.

4.3.2.3 Definition of performance parameters and threshold values for monitoring

The identification of extreme load and resistance parameters is of great importance after traffic loads (e.g. heavy traffic, accidental impact, etc.) or environmental actions (e.g. storm, floods, earth quakes) since those single events can result in considerable damage at the structure. To record such events, threshold values need to be defined based on experience, measurements or calculations. Recording of events is carried out by storing time, maximum and other defined parameters and if reasonable, the entire response of all sensors applied. The storage of the complete time response can be advantageous in these cases since possible damage can often be identified by the kind of response.

The determination of the dynamic loads can besides the determination of the static loads be of great importance for realistic evaluation of the load bearing capacity and the remaining life time of a structure and also for the definition of maintenance intervals. For that reason the dynamic factor needs to be determined. It is calculated depending on pre-defined load classes from the ratio of the maximum value of a strain signal to the static part of the signal (determined by low-pass filter).

For risk assessment of material fatigue the local stress is besides material parameters the significant parameter. It is allocated in stress collectives. Stress collectives are established by a permanent analysis of the stress (strain) signal with rainflow algorithm. This corresponds to classical storing of hysteresises which comprises stress signals. Amplitude and shape of a stress collective signify the fatigue potency of the stress. The mean stress amplitude should be included in the assessment for non-welded structures compared to welded structures.

For examining current load effects the following tasks can be of practical importance:

- monitoring of allowable static and dynamic load effects,
- determination of dynamic load effects (dynamic factors),
- classification of load effects (e.g. permanent stress analysis),
- determination of extreme stresses and the frequency of its appearance,

Based on permanent observation of load effects following tasks can be processed:

- evaluation of maintaining life time
- evaluation of the actual structural safety e.g. according EC 1.1 based on the reliability index β
- determination of maintenance intervals depending on the loading and the actual condition of the structure.

At structural condition monitoring in terms of this guideline the actual structural state is evaluated inter alia by:

- measurement of strain, deflection, curvature, inclination on selected sites; this may result in conclusions about e.g. foundation settlement, global changes in stiffness, loss of continuous beam effect etc.,
- observation of selected resonance frequencies (conclusions about changes in global stiffness),
- selective monitoring of changes in dominating vibration modes.

Examples of monitoring of local structural parameters are:

- evaluation of length and width of known single cracks
- observation of structural parts with increased danger of cracking
- strains on points with increased stress concentration
- static deflection and vibration caused displacement of structural components (e.g. restraints of cranes and pylons)
- foundation settlements (e.g. on bridges)
- strains of prestress tendons

4.3.3 *Experimental design of the monitoring task*

4.3.3.1 Preliminary procedures

The monitoring of technical systems is based on knowledge about structural characteristics of the system under observation. Only if the system behaviour is sufficiently known, sensors can be applied on the right positions and an evaluation of the measurement data concerning relevant parameters for system identification can be successful. For localisation of the most stressed structural region computational and metrological methods can be suitable.

The knowledge about the structural system, obtained by methods of experimental and theoretical modal analysis, or analysis of the structural dynamics is the best premise for configuration of the measurement equipment of a monitoring system. It is to proof, if the application of this method is possible and economic on the structure to be monitored.

4.3.3.2 Data acquisition and signal analysis

All values are measured continuously as analogous signals. The necessary sampling rate for the analogue – digital conversion needs to be carried out at the maximum frequency range of interest. If the data analysis takes place in the frequency domain, the sampling rate needs to be at least twice the maximum frequency. Generally, this upper limit is ensured before digitalising by low-pass filter. For data analysis in the time domain, a higher sampling rate should be used. In practice a sampling rate of around five times the highest frequency of interest has proved to be reasonable.

Of all recorded measurement signals characteristic values or parameter functions have to be provided continuously. For interpretation it is important that the collected data be cleansed or intelligently processed. Following methods can be used to perform that task:

- *High- and low - pass filter:* filtering of quasi-static and high frequent signal parts from e.g. temperature variation, cable movements or measurement noise.
- *Band – pass filter:* they are used to filter out other than determined frequency contents of the signal for which the structure is sensitive.
- *Integration:* integrators are used to convert acceleration signals into velocity and displacement. Integrators can be realised by analogue networks in digital ways.
- *Parameter generating:* calculation of mean, standard deviation, peak value from the (probably pre-processed) signal.
- *Frequency analysis:* determination of the spectral content of the time response signal. The frequency resolution f_0 can be determined from the length of the time range T by $f_0 = 1/T$.
- *Statistical analysis:* determination of the probability density function of a variable or determination of the maximum of the signal. Results are represented here in histograms and density functions.

The continuous data acquisition needs a direct processing on site with the aim to reduce the amount of data. Although with that the flexibility of subsequent data analysis is reduced.

In cases of slow-moving changes of the observed performance parameters it can be reasonable to record only their moving mean values. It is also possible that a combination of data acquisition algorithms may be required so that only peak values are recorded as a general operation mode, and continuous data is recorded for discrete periods of time, if a threshold is exceeded.

Selection of the most appropriate data acquisition algorithm is an important component of SHM and will affect both the amount of stored data and the type of diagnostic information that can be obtained.

Processing of data is also important when multiple sensory systems are used in the same SHM project. Many of these sensors may have quite separate signal conditioning and demodulation systems for acquiring the raw data from the respective sensors. It is important that the system is able to process the data from all inputs and relate it to a common reference such as a time stamp.

4.3.3.3 Measurement and service conditions

Within monitoring the measurements are taken under service conditions, where the structure is stressed by traffic loads, vibration emission, wind, temperature and micro seismic influences. While the acquisition of loads for load and load effect monitoring corresponds exactly with the monitoring request, arise for condition monitoring limitations for the wanted measured values. This needs to be allowed for selection of the sensors and their application at the structure. Further on this can have consequences on the methods of data analysis.

The temperature range, on which parts of the installed measuring and data analysis facilities might be exposed, reaches approximately from -40 to 50 degree Celsius. It has to be estimated, when temperature compensation needs to be provided within a measuring chain. Other important climatically influences are humidity and moisture. The electrical protection class of the measuring equipment (sensors, plugs, cable, control devices and computer hardware) needs to be customised to the service conditions. Generally, an electrical shield is necessary for sensors and data lines to protect against electromagnetic fields and currents, especially an adequate protection against lightning. Cable for the transfer of analogue signals should be as short as possible.

For application of sensors, cables and electronic hardware has to be considered, that in general civil structures are not protected against vandalism.

To operate the measuring system durable and economic, all components should be easy replaceable.

4.3.3.4 Sensors and sensor characteristics

Essential for the monitoring of structures are sensors which are robust and operate stably and reliable. It has to be assured that the characteristic qualities are not modified by environmental influences, like temperature, humidity, mechanical influences as well as electric and magnetic fields. At knowledge of these influences the sensors have to be protected or the effect on the measurands has to be compensated.

Sensors can be subdivided in such which concentrate on the monitoring of local properties like material and in those which observe structures from a global point of view. Some are embedded within the structure others are only placed on the surface of the structure.

According to the measurands geometry and dimension, deformation, strain, force, weight, dynamic parameters, temperature and durability parameters the most important sensors currently used within structural health monitoring are:

– *Strain gauges;* at its use it needs to be considered, that the right strain gauges in type and length are applied depending on the structural material (concrete, steel, etc.). Advices for correct application, protection against environmental influences and the right choice of cables are given in [1]. Depending on the measuring amplifier a frequency range from 0 Hz to some kHz can be covered. Constrained to the measuring chain a strain with a resolution up to 0,1 µm/m can be measured.

– *Fiber – Bragg – gratings;* this sensors are suited for strain measurements up to 10000 µm/m and for a temperature range from -50 to 200 degree Celsius within a frequency range from DC to the MHz - range. The sensors can be applied in the structural material as well as on its surface. The sensors length can be adjusted to the measuring task. They have a very good linearity and a small hysteresis and they are non-sensitive against electromagnetic perturbation. Because of the sensors thermal sensitivity temperature compensation needs to be installed during strain measurements.

– *Piezofilm sensors for strain measuring;* piezofilm sensors have, unlike strain gauges, high pass characteristics, i.e. they measure dynamic strain beyond a limiting frequency. This threshold frequency can be established by an adaptation of the charge amplifier directly at the sensor. With copper coated synthetic film a threshold frequency of 0,2 Hz can be provided. The size of the sensor is variable and has generally dimensions of approximately 12 x 90 mm including the charge amplifier and the voltage amplifier. Piezofilm sensors including integrated amplifiers are applied with epoxy resin.

– *Displacement sensors for deflections;* the main types of those sensors which measure the relative displacement between two points based on the inductive principle are the different types of LVDT with measuring ranges between ±1 mm and ±50 mm and a quasi infinite resolution within a temperature range between –20°C and +120°C. For other comparable sensors basing on similar physical principles but with different technical parameters see [1].

– *GPS based displacement sensors;* the determination of deflection in general requires a stable accessible reference location for each measurement. In cases in where this is not practical satellite based sensors are available which measure the movement of structures. Sensor nodes mounted on the structure at sites of interest are able to observe the settlements of foundation as well as long-time period movements of bridges and high rise buildings. Each sensor node consists of a GPS receiver, micro controller and data radio. Precisions less than 10 mm are achievable with the evaluation of the phase information of the satellite signals and use of DGPS.

– *Hydrostatic leveling systems (HLS);* this sensor system applicable for displacement measurements is based on the classical physical law of connected vessels. It consists of two ore more interconnected fluid cells mounted on a structure at selected locations in which one cell is designated to be the datum reference. HLS only can be used for static or quasi-static events. Within a measuring range a resolution of 0,02 mm can be reached.

– *Displacement sensors for relative vibration measuring;* displacement sensors are usually applied to measure crack widths. According to the measuring principle one can distinguish between conductive, inductive and capacitive sensors. Depending on those principles displacements from 0,1 to 10000 µm in a frequency range of 0 Hz to some kHz can be measured.

– *Vibrating wire strain gauges;* this kind of sensors are utilizing the physical law that the square of the natural frequency of wire is proportional to their strain. These sensors encased in sealed steel tubes can be used for measuring strain, strength, pressure and temperature, fixed on the surface of a structure or produced for embedment in concrete for static and dynamic measurements. The long-time-stability is very good. The resolution is about 0,025% of the measuring range.

– *Vibration velocity sensors;* for measurement of absolute motion values this sensors are applied directly at the vibrating object. They do not need a reference point. They can be used in a limited frequency range of approximately 2 Hz to 1000 Hz. Though in the lower frequency range deviances in amplitude and phase could occur. Depending on the integrated mechanic-electric conversion element the sensors can be classified into absolute displacement sensor (inductive, capacitive or strain gauge converter) and vibration velocity sensor (electrodynamic converter).

– *Vibration acceleration sensors;* they are also applied directly at the vibrating object. Depending on the integrated mechanic-electric conversion element they can be used from 0 Hz (strain gauge or inductive converter as well as servo-acceleration sensors) or above a low threshold frequency (piezoelectric sensors). The upper threshold frequency in both cases is at some kHz.

- *Laser detector for vibration measurements;* with these sensors non-contact measurements over relatively wide distances can be carried out. Usually so called position sensitive detectors (PSD-sensors) are applied. The source is mostly a semi-conductive laser with low intensity. The measurable frequency range reaches from 0 Hz to 300 kHz, depending on the measuring system. The resolution goes up to 10 µm, depending on the size of the PSD, the light intensity and the measuring system.
- *Inclinometers for angular displacement measurements;* for frequencies up to 5 Hz sensors can be applied, using the capacitive principle. For higher frequency applications servo-acceleration sensors are more adequate. The resolution of those sensors lies usually within the range of 0,1 to 0,001 degree.
- *Fibre optic sensors;* depending on the applied measuring equipment these sensors are suitable for crack width measurement, for crack detection and localisation. Crack width measurement and crack detection use the physical law that with weakening the fibre cross-section the incoupled light is more absorbed. The weakened light measured at the end of an optical fibre is then a measure for the existence of a crack or for the changed width of the crack. It needs to be noticed, that with reaching a certain crack width the sensor can be destroyed. To localise cracks, one needs to measure the reflection runtime within the optical fibre. This however results in a large procedural investment in equipment and data analysis technique.
- *Temperature, humidity and corrosion sensors;* for permanent acquisition of these measurands commercial obtained sensors are suitable. For that these sensors can be used within long term measurements, they need to be applied and eventually encapsulated with greatest care.

The basic criteria for selection of sensors are minimal change of the measurand (resolution, linearity, accuracy), measuring range, type of measurement (static, dynamic etc.), test duration (long-term stability), test environment, installation environment and financial resources.

4.3.3.5 Measurement equipment

In general long term monitoring measurement equipment contains of the following components:

- signal amplifier (voltage amplifier, charge amplifier, carrier frequency measuring amplifier, bridge amplifier)
- analogue antialiasing filter (tuned to the necessary cut-off-frequency)
- measurement data acquisition system with analogue – digital conversion (16 – 24 bit conversion depth)
- data analysis computer for managing, processing, data reduction and storing
- data storage (semi-conductor, flashcard, disc, floppy, streamer tape, etc.)
- uninterruptible power supply
- unit for remote data transmission with telecommunication devices (phone line for data or fax machine, mobile phone or transceiver for satellite communication) or data channels for traffic management systems

4.3.4 *Treatment and organisation of monitoring data*

4.3.4.1 Static measurands

Measured displacement values like deflection, inclination, settlement, crack width and crack length as well as environmental measurands (temperature, humidity, corrosion etc.) are predominantly quasi-static since they vary only slowly in time. It has been proved to analyse these values in form of hourly mean values with the associated standard deviation. Additional it is recommended to record sudden strong amplitude changes with time using pre-defined threshold values.

The appearance of cracks in (fully) prestressed concrete structures and in major structural elements of steel structures or the crossing of a limit crack width is often a signal for a critical structural state. The permanent monitoring of changes in width of known cracks or the determination of cracks at known weak points of a structure or at points with high stress concentrations is therefore an important element of early damage detection. For characterisation purposes determining and storing hourly maximum values has been practically proved. To correlate the crack state with acting loads (live load, temperature), strain and temperature measurements need to be monitored in the same time pattern.

4.3.4.2 Dynamic measurands

Changes in the load bearing behaviour of structures are always associated with changes in the vibration characteristics. Changes of the static system and associated parameters of the examined structure affect the natural frequencies as well as the mode shapes. They have to be determined by experimental modal analysis.

Within an automated long term monitoring the estimation of the above mentioned values can also be carried out without artificial excitation. Therefore time responses of each measurement point have to be analyzed by a Fourier transformation. Peaks of the power density spectrum describe approximately the natural frequencies. Further on the associated operational mode shapes need to be determined by simultaneous or successive measurements for various measurement points. The operational mode shapes are similar to the natural modes of the structure.

In practice results of multiple successive measurements should be averaged, to eliminate interferences, outside influences and other parts of the signal which are not dependent on the structural state. ANPSD plots can be regarded as the signature of the structure. A change in the stiffness or mass of the structure should be indicated by changes in the pattern of ANPSD. By comparison with a reference state it is possible to get qualitative information about the location and extent of structural changes.

A quantitative assessment needs updating of structural models under consideration. In many cases it is recommended to use additional knowledge from expert systems.

The location of the measurement points as well as the considered natural frequencies and operational mode shapes should be selected in such a way that expected structural changes are reflected as good as possible. This can be achieved by an experimental pre-examinations or numerical simulations.

4.3.4.3 Selection, management and presentation of measurement results

A permanent monitoring system needs to be applied intelligently on site. Everything within a defined range can be recorded by specific parameters or counting values. Those values become stored in defined intervals. Outstanding results will be stored separately with time correlation. The stored data will be transferred continuously or in fixed time intervals via a permanent data transfer line to the monitoring computer. Here all actual information is stored about the measuring setup, the measurement points and the sensors as well as the channel names, the settings and the calibration factors. Further on, the monitoring computer performs conditioning of the results, the management of all data, creates monitoring reports and graphical result presentations as well as necessary trend analysis. By linking to a database with all residual structural information about construction and inspections, possibilities for global use of the measurement data arise, for instance for assembling a technical information system or for development of expert systems. Furthermore this data can be a basis for quality management.

4.3.5 *Review of monitoring parameters and consequences*

4.3.5.1 Status report

The measurement data must be examined in regular time intervals regarding functionality and optimal behaviour of the hardware. Additionally, the monitoring results must be checked regarding their physical reality for correctness and compatibility. This happens on the one hand on the basis of measured time series of selected results (typical, maximal, event-oriented et cetera). On the other hand the results are reviewed on the basis of statistic nominal values (maximum of minimum values, RMS values, mean values, sliding RMS) in the considered periods. During monitoring of dynamic values frequency spectra are compared as well as determined natural frequencies, frequency frequentness and frequency changes in their course are shown and examined for plausibility. Results of load determination are represented over the monitoring time, distributed in load classes. Furthermore, the load distributions within significant time periods are computed and compared. Fatigue-effective stresses are allocated in rainflow matrices and compared to respective stresses in analogous time periods.

4.3.5.2 Analysis of effect coherences

The determination of effect coherences in form of correlations is important for the analysis of monitoring results, besides their temporal development. With that, important information about dependency of the monitoring values from assessable process variables or actions can be won, which could be controlled during monitoring. Errors or faults of sensor technology or in measuring technique, which develop during the monitoring, become fast visible by the representation of correlations for different physically connected measured variables.

4.3.5.3 Alerting

Besides periodic data transfer from the data acquisition computer on site to a central computer an additional event orientated data transfer can become reasonable. This is the case when in consequence of special events like excess of threshold values, significant changes of the structural system and deterioration in parts of the monitoring system immediate information need to be sent to the central computer or a fax machine.

4.4 Numerical analysis

A numerical structural analysis requires an adequate model, which contains structural stiffness, mass distribution and support conditions sufficiently exact.

For structural evaluation, the most accepted technique for modelling and comparing measured and calculated data is the finite element approach. Once the finite element model has gained a certain level of completeness and validity it provides best the basis for analytical prediction and simulation.

Substantial tasks of the numerical analysis are the identification of structural characteristics and the simulation of the structural behaviour with the following options:

- determination of modal parameter
- verification of measurement results
- simulation of structural properties with action, which would be difficult and expansive to realise experimentally
- realisation of parameter studies
- modelling of damages

Sources for inaccuracies of models are assumptions about the structure of the model (net sizing, type of the elements, boundary conditions, linear or nonlinear behaviour) as well as the model parameters (material parameters, continuous and discrete stiffness, masses and moments of inertia). The correct specification of the loads and other action is a substantial assumption for close-to-reality simulation of the structural behaviour.

The following proceeding is recommended for an examining the correctness of simulation results:

- review of the program code / input macros
- review of analysis results, e.g. by:
  - modelling of experiments with definite boundary conditions
  - extreme value analysis, estimation of effects
  - statistic analysis of values with variable parameters
  - comparison with alternative systems
  - quantitative estimation of results

4.4.1 *Calibration of structural models*

The integration of analytical modelling followed by experiment for the calibration and verification of the analytical model for reliable simulation is termed structural identification. Structural identification serves the starting point and core of health monitoring.

Calibration is conducted by progressively adjusting numerical values of groups of parameters that define the material, geometry, boundary and continuity conditions until the discrepancies between measured data and simulated behaviour of the analytical model are minimized with respect to an objective function. The calibrated model has to be checked with measured data which are not applied for calibration.

Even if the most parameter identification processes that are based on linearity, idealized boundaries, supports and release conditions cannot fulfil the real structural conditions, field-calibrated linear model serves as the best possible starting point for simulations by non-linear finite element analysis in order to predict possible failure modes.

- Model calibration
  Mechanical properties and boundary conditions and continuity conditions of the model are adjusted. Model configurations agree with the physical insight observed during the experiment and from the processed experimental data.
- Sensitivity analysis
  Sensitivity can be defined as the local gradient information obtained from an analytical formulation, adjoint differentiation or numerical computation via finite difference schemes. Sensitivity information is very valuable whenever optimisation problems are solved. For model calibration the input parameters should be screened to analyze which ones produce the greatest change in several response features over a range of possible values.
- Utilisation of calibrated models
  The field-calibrated analytical model serves as the best measure of the actual conditions of the structure. This may be used for load-capacity rating, permit loading and evaluating internal forces, stresses and deformations under operational conditions.

5 DAMAGE IDENTIFICATION

5.1 Objectives and procedures of damage identification

The purpose of the damage identification is the intention of attaining as early as possible comprehensive knowledge of damage of structures. Beyond that the local and global effects of the damage with consideration of damage process have to be estimated. A further goal of the damage identification is finding causes for the occurrence of damage.

On the basis of a definition for damage the procedure in principle of the damage identification is described. A typology of the substantial damage at civil structures and their causes is useful. The methods which can be used differ depending upon level of knowledge of the existing or expected damage in local and global procedures. For the global procedures established methods are described, which are based on results of static and dynamic measurements.

5.2 Definition of damage

Damage is defined as changes introduced into a system that adversely affects current or future performance.

This definition is limited to changes to the material and/or geometric properties of structures, including changes to the boundary conditions and systems compatibility.

Changes of the system in the sense of damage develop either directly (time-invariantly) or due to time-variant processes. Time-variant damage can accumulate incrementally over long periods of time such as that associated with fatigue or corrosion damage accumulation. Discrete events as for instance earthquakes, live loads and others can lead according to scheduled or unscheduled events to direct, i.e. time-invariant, damage. In the sense of their spatial expansion damage has a local effect or can be recognized as distributed. The severity of damage takes place either via a geometrical description (crack geometry etc.), by its effect on the load-carrying capacity of structures (e.g. loss of stiffness or mass) or by changes of the energy dissipation properties of a system.

5.3 Classification of damage and damage mechanisms

Damage can be defined as partly or fully destruction of the material structure and therefore a weakening of the resistance of the affected structural component or the whole structure respectively. Damages can be caused by several influences. Predominantly, damages are the effect of deterioration processes. Those are mainly corrosion and fatigue. Furthermore, damages are caused by excess of material strength though unplanned high loading.

5.3.1 *General causes for damage*

Following, general causes for damage are listed:

1.) Overstressing (loading) with time invariant resistance

Possible cases:

- accidental and seismic loads (impact, earthquake, explosion)
- exceptional high variable loads (excessive live load, extreme wind, wave and snow)

2.) Regular loading with reduced resistance

The decrease of the member resistance, as considered in the design, is generally a time depending process, which can initiate damage by:

- deterioration through chemical loading
  - surface corrosion of steel
  - pitting corrosion of steel
  - alkali silica reaction in concrete
- deterioration through mechanical loading
  - sub microscopic crack formation and crack growth until excess of the lower cross sectional limit by alternating loading of structural steel and reinforcement in concrete (fatigue)
  - stress corrosion cracking of prestress tendons
  - fretting corrosion of steel members
  - microscopic crack formation in concrete leads to reduction of the transverse tensile strength and for this reason to a decrease of the concrete compressive strength (fatigue).
- deterioration through physical loading
  - damaging of polymers by ultraviolet radiation
  - damaging of concrete by frost
  - damaging of materials by heat/fire
- creeping, shrinkage, relaxation
  - reduced shear strength through loss of prestress by creeping

3.) Combination from 1) and 2)

5.3.2 *Specific causes for damage*

Parts of the damage mechanisms, described in section 4.3.1 have specific causes like

1.) Corrosion of steel, caused by

- damaged anti corrosion coating
- cracks in concrete and other mechanical damage of structural concrete (plus moist environment), caused by
  - accidental loads
  - poorly configuration of reinforcement
  - constraints through changes in bearing conditions (foundation settlement and rotation, reduction of degree of freedom)
  - loss of prestress
- carbonation of concrete

- chloride ions (from thaw salts, from see water)

2.) Crack formation and crack growth in structural steel as well as microscopic crack formation in concrete, caused by
  - alternating loading above the fatigue strength through
    - high cyclic loading
    - cyclic loading plus reduced cross section (cracks)

5.4 Concepts of damage identification

The identification of damage generally is described by the indication of a four Level process:

1. Determination that damage is present in the structure (Level 1: Detection)
2. Determination of the geometric location of the damage (Level 2: Localisation)
3. Determination of the severity of the damage (Level 3: Quantification)
4. Prediction of the remaining service life of the structure (Level 4: Prognosis)

5.5 Variables and indicators for damage identification

Experimental investigations have the purpose to obtain information for tasks mentioned in section 3.1. It happens either by single investigation in the sense of field tests mentioned in section 3.2.5 or by periodical or continuous measurement with automatically working monitoring systems. The used processes are distinguished by whether knowledge about damages is expected or available leading to a local damage monitoring or whether on the basis of global structural behaviour information have to be gathered. The measuring data are based on static as well as on dynamic investigations. A number of different analytical techniques have been developed for the identification of damage within the structural health monitoring process.

5.5.1 *Local procedures*

The application of local procedures to the weak point analysis is sensible in following cases:

- With the knowledge of type and location of existing damages the dimensions of the damage have to be determined and the development has to be monitored (Level 3). Then the local situation and global consequences are assessed. This applies to the present condition as well as in sense of a prediction for future conditions (Level 4, section 4.4).

- Likewise, this procedure applies to the situation that on the basis of preliminary existing knowledge a damage at a certain location of the structure is expected, e.g., by overloading or fatigue (Level 1). This task can be fulfilled using load monitoring (section 2).

- An additional task for local monitoring of damages is to find causes of damage. Furthermore, besides damage parameters the damage affecting values are monitored. Information about the character of damages and damage causes can be obtained through correlations in temporal context as well as between the magnitudes of the measurement results. An example is the surveillance of crack widths, which can be affected by temperature influence, vibrations, settlement or other causes.

- If local damages have global consequences (e.g., the settlement of a bridge pillar) local observations at other places than the damaged areas can be sensible (Level 1 to 3).

With local procedures measurement values are used, which are sensible for the type of damage or for damage effects by suitable indicators (e.g. crack widths, strains, inclinations et cetera). Here continuously working systems are favourably used.

5.5.2 *Global procedures*

Always, if neither the existence of damage nor the possible damage position is known, sensitive global system parameters have to be controlled and determined. This can be done both via continuous and periodic monitoring, as well as with uniquely accomplished field tests.

5.5.2.1 Dynamic procedures

Vibration characteristics are global properties of the structure and, although they are affected by local damage, they may not be very sensitive to such damage. As a result, the change in global properties may be difficult to identify unless the damage is very severe or the measurements are very accurate.

The identification of a possible damage site and severity of damage on basis of a change in global properties derived from measurements at a limited number of sensor locations, is a problem which may not be underestimated. Sophisticated and complex mathematical techniques, including non-linear programming, need to be employed to obtain the most probable solution. Global vibration characteristics are often affected by phenomena other than damage, including environmental effects such as a change of mass and thermal effects caused by temperature variation. Additionally boundary conditions in a structure may lead to a change in vibration if these boundary conditions are prone to changes with the age.

The information about the condition state of the structure is provided from measured changes in vibration properties. The more commonly used techniques are based on

- Natural frequencies methods
- Mode shape and operational deflection shape methods
- Modal strain energy methods
- Residual force vector method
- Model updating methods
- Frequency response functions
- Statistical methods

There is no optimum method for using measured vibration data for damage detection, localisation and quantification. No algorithm has yet been proposed, which can be applied universally to identify any type of damage in any type of structure. Additionally no algorithm is yet available which can predict the exact service life of a structure. Besides application of the dynamic procedures extensive experience is required in this area.

<u>Natural frequencies methods</u>

Changes in stiffness and masses as well as the dynamically effective support and transition conditions of structures will usually lead to measurable changes of the natural frequencies. Usually, the associated measuring expenditure is small. Often only few reasonable placed sensors are sufficient for the achievement of the desired information. For simple structures the measured differences of the natural frequencies already form a sufficient sample for the localisation of damage. Therefore this method is suitable for online monitoring of structures for Level 1 and 2. The largest frequency changes can be expected with those natural frequencies, where the locations of the associated maximal curvatures of the mode shape match with the damaged ranges of the structures. The assumption of a linear relationship between frequency shifts and damage is no longer appropriate when the severity and the number of locations of damage is increasing. Due to the strong environmental influence on frequency shifts such and ambient effects have to been filtered out.

Mode shape and operational deflection shape methods (ODS)

Reasonable results of damage localisation tasks (Level 2) are to be expected only if the number of measurement points is adequate in relation to the dimensions of the structure. Usually, this is only achievable by field tests (section 3.2.5). Damage indicators, computed through measuring of mode of shapes, are based on the comparison of the amplitude changes in relation to a starting point. Two commonly used methods to compare two sets of mode shapes are the Modal Assurance Criteria (MAC) and the Coordinate Modal Assurance Criterion (COMAC). Depending upon the location of structural changes the direct comparison of mode shapes can lead to better information for the tasks damage detection and localisation than frequency shifts. Furthermore the sensitivity due to environmental influences is less. Good experiences were made with the comparison in cases of structural tests before and after repair. During the investigation of large structures the application of artificial excitation is often not possible. Here, measured ODS are used for the computation of damage indicators. ODS must also be measured in cases, in which damage becomes recognisable only if operating loads are applied.

For damage identification with presence of localized damage the use of mode shapes curvatures is more meaningful, for damage occurs here theoretically highly localised. Curvatures cannot be measured directly; they have to be calculated from measured displacement modes ore can be derived from measured strains. In both cases the requirements on accuracy and number of measuring points for global investigations of buildings are difficult to realize. Damage indicators CDF based on modal curvatures are computed in comparable way as COMAC.

Modal strain energy methods (MSE)

The extension of the modal curvature method by the formulation of a modal strain energy leads to a damage indicator which is defined by the ratio of the modal strain energy of elements of a structure before and after the damage. The indicator employs modal curvatures computed from measured mode shapes by the second order derivative. Taking noisy data into account it is necessary to use interpolation polynomials for the calculation of the derivatives in combination with smoothing procedures by means of regularisation methods to avoid rough curvatures. The MSE is tested on beamlike structures and plates successfully. There are also some enhancements of the original method by variations the damage indicator for multiple damage scenarios.

Residual force vector method (RFV)

Utilizing measured natural frequencies and mode shapes for the damaged system and using initial baseline model for the structure an over-determined system of equations is formulated. This allows determination of unknown correction parameters for the initial model describing the structural damage. Expanding the measured mode shapes successfully the RFV method seems to be a robust method for damage localisation and sizing.

<u>Frequency response and transmissibility function methods (FRF)</u>

Modal parameters are extracted either from input-output measurements or output-only results. In order to exclude errors within damage identification procedures which emerge from modal identification indicators can be defined directly by using FRF measurements or measured transmissibilities. The differences between initial and damaged state are recognized by a shift of resonances and anti resonances in the spectrum as well as by different large amplitudes. Indicators for damage detection are formulated by differences from FRF amplitudes in the initial and damage state. For localisation of damage, ratios of FRF and transmissibilities are used. Measurement results for FRF can be obtained from filed tests whereas transmissibilities can be measured by online monitoring.

<u>Model updating methods (MUM)</u>

Many methods in model updating are used for damage identification procedures. Theoretically MUM are able to provide solutions for the damage identification Level 1 to 3. The determination of damage requires true changes in the physical properties. Problems arise with the non-uniqueness of resultant model in matching the measured data. When damage is affecting both mass and stiffness properties the parameter cannot uniquely identified only by using modal measurements. In general it is not recommended to use only natural frequencies for updating procedures. An advantage is to use FRF measurements directly for damage identification. Modal parameters do not have to be identified as additionally FRF data provide much more information in the desired frequency range. Ill-conditioned matrices from adjacent points in the FRF data have to be avoided. To overcome those problems it is often recommended to make assumptions about the location and type of damage.

<u>Statistical methods (SM)</u>

The basic idea of these methods exists in the acceptance that all substantial information about the condition of a system, which affects the dynamic behaviour, are contained in the measurable responses of the system. On this assumption damage identification is a problem of the statistical pattern recognition that can be solved with non model based recognition methods. Any information can be concentrated in appropriate features representing the actual state of damage. This features derived from output-only measurements taken under normal operating conditions have a distribution with an associated mean and variance. A change in the distribution characteristics of the features will indicate damage, whereby it is presupposed that effects change the systems performance not characteristically. These methods are applicable to Level 1 and 2 identification.

5.5.2.2 Static procedures

Not all kinds of damage are detectable with sufficient reliability by dynamic methods. In cases of small modification of the initial structure and when damage emerges in the proximity of bearings the sensitivity of dynamic damage indicators is low. With the overlaid influence of temperature changes on the measurable dynamic parameters damage identification is very difficult.

Static measurements always require a load situation where the damage identification can be done using measured global parameters. Deformation measurements in most cases refer to a reference position. A proved method for damage identification of beamlike structures is proposed using differences of measured inclinations (Level 1 and 2 identification). Inclination sensors do not need any reference position. The location of only a few sensors is robust regarding the quality of the results of measurement. The load is applied by a slowly moving truck crossing the structure. The damage indicator is determined from the difference of the influence lines of the inclinations in a damaged condition in relation to an initial condition. Influence lines can be measured regarding the local resolution arbitrarily exactly. For the data analysis noise reduction of the measured signals is very important. The method is suitable also for the localisation of multiple damage.

5.6 Determination of damage indicators by measurement

With the determination of damage indicators a redundant approach is recommendable regarding, e.g., damage detection (Level 1) with dynamic processes additional on the damage focused sensors are installed to enhance the informative capability of the results. Additionally is to be paid attention to the fact, that the recorded damage indicators usually contain environmental effects, which must be "cleaned" computationally. A high spatial resolution for measurement of mode shapes is reached either by the concurrent utilisation of many sensors or a few, but moved sensors dependent on a stationary exciter. Here measurement technology based on scanning processes is used.

5.7 Damage assessment in the sense of condition specification

The description of the condition of a structure firstly has the purpose of qualitative evaluation of observed i.e. already existing, or new discovered damages concerning

- the damage magnitude
- the damage consequences
- the damage development
- the damage cause

Additionally their effects for technical systems (e.g., change of the static model) as well as the resulting load capacity, functionality, stability and safety have to be considered. On the basis of knowledge about type and magnitude of essential defects and damages as well as the respective damage mechanisms evaluations regarding the topical load capacity, possible rehabilitation actions as well as the utilisation and safety planning are to be done.

5.8 Damage assessment using threshold values

A simple and approved method for assessing measured condition values is the comparison with preliminary defined threshold values. Those values can be constituted in codes and guidelines as well as determined on the base of investigations and experience.

5.8.1 *Threshold values by codes and guidelines*

Numerous thresholds to be kept during erection and usage of a structure are specified in design codes for structures.

If assessment values are measurable, they can be used directly for assessment of monitoring results. This applies in particular to the limitation of deformation at the serviceability limit state. Further values for providing serviceability and safety against fatigue are limited in codes.

5.8.2 *Determination of threshold values*

If condition threshold values are not defined in codes or guidelines, they can be determined on the base of preliminary examinations. These are primarily examinations and analysis on structural models as well as material testing.

The determination of threshold values requires well-founded knowledge about the structural coherences and the underlying safety level.

6 QUALIFICATION OF TEST PERSONNEL

The procedures described in this guideline can only lead to usable results if before the measuring program, the equipment, the analysis hardware and especially the analysis software and the following interpretation of the results and the assessment is carried out by experienced staff. This requires an expert knowledge in structural engineering as well as experiences with structural proving and testing and with the measurement technique.

To guarantee reliability of the measurement results, the application of sensors, the realisation of measurements and the maintenance of the technique needs to be carried out only by skilled personal under supervision of the for the measurement responsible experts. The measurement personal has to be permanent available. The state of measurement technique has to be recorded.

7 REFERENCES

[1] fib- bulletin 22, Monitoring and safety evaluation of existing structures, CEB-FIP, 2003
[2] ISIS Canada, Guidelines for structural health monitoring, Design Manual No.2, 2001
[3] Merkblatt B9, Merkblatt über die automatisierte Dauerüberwachung, Deutsche Gesellschaft für zerstörungsfreie Prüfung, 2000 (in German)
[4] Sohn, H. et.al.: A review of structural health monitoring , literature 1996-2001,Los Alamos Laboratory Reports LA-13976-MS,2003
[5] Farrar, C.R. et.al.: Damage prognosis:Current status and future needs ,Los Alamos Laboratory Reports LA-14051-MS,2003
[6] Inman, D.J. et.al.: Damage Prognosis, Wiley 2005
[7] Balageas,D. et.al: Structural Health Monitoring, ISTE-HERMES SC. Publ., 2005
[8] ISO 13822 Bases for design of structures – Assessment of existing structures
[9] ISO 14963 Mechanical vibrations and shock - Guidelines for dynamic tests and investigations on bridges and viaducts
[10] ISO 16587 Mechanical vibrations and shock – Performance parameters for con dition monitorung of structures
[11] ISO 18430 Condition assessment of structural systems from dynamic re-sponse measurement
[12] ISO 18649 Mechanical vibrations - Evaluation of results from dynamic tests and investigation s of bridges
[13] EN 1990: Basis of structural design
[14] DIN 1055-100 Einwirkungen auf Tragwerke (in German)
[15] DIN 1076 Ingenieurbauwerke im Zuge von Straßen und Wegen – Überwa-chung und Prüfung (in German)
[16] DAfStb-Richtlinie: Belastungsversuche an Betonbauwerken (in German)
[17] Carden, E.P., Fanning, P.: Vibration based Condition Monitoring, Journal SHM 3(4), 2004
[18] Farrar, C.R., et al.: Dynamic characterization and damage detection in the I-40 bridge over the Rio Grande. Los Alamos National Laboratories, Tech. Rept. No. LA-12767-MS, 1994.
[19] Fritzen,C.-P., Bohle, Parameter selection strategies on model-based damage de-tection, Proc. Structural Health Monitoring, Stanford, CA, Sept. 8-10, 1999

ANNEX A
SENSOR CLASSIFICATION, APPLICATION AND EXPERIENCES

Annex A1: Sensor classification according to different measured values

meaured value	sensor type	measurement range [mr]	resolution	linearity	supply	frequency range	influences
displacement	LVDT LVDT calliper triangulation sensor cable extension transducer	1- 50 mm 1- 50mm 2- 200 mm 50- 40000 mm	1‰ mr 1‰ mr 1‰ mr	0.1% mr 0.1% mr 0.3% mr 0,05%mr	AC/DC AC/DC DC DC	0Hz-0,1kHz 0Hz-0,05kHz 0Hz-10kHz 0Hz- 0,5kHz	cross forces measurement frequency reflecting surfaces, soil cross forces
inclination	bubble level pendulum	±10 grd ± 1 grd	1‰ mr 1‰ mr	0,1 grd 0,05% mr	DC DC	0,5 Hz 0,5 Hz	vibrations
settlement	hydrostatic leveling system PSD	0- 60 mm 0- 90 mm	0,01mm < 0,05 mm	<1% mr	DC DC	static 0Hz-0,5kHz	atmosph. pressure, temp.gradients moisture
strain	strain gauges fiber bragg gratings Fabry- Perot fiber sensor Sofo- system optical string	1 - 10000µm/m ±10000µm/m ±5000µm/m 0,5% sensor length 0,5% sensor length	1µm/m 1µm/m 1µm/m 2µm/m	<1% <1%	DC/AC laser light broadband white light laser light laser light	0Hz-100 kHz 0Hz-100 kHz 0Hz-1kHz static 0Hz-0,1kHz	ΔT, leakage ΔT, transverse stress ΔT transverse stress
acceleration	piezoelectrical sensors MEMS-A640 B12(differential choke)	±100g ±1g ±20g	10µg 5µg	<1% <1% 1%	DC DC AC	0,1Hz - 2kHz 0Hz-0,25kHz 0Hz -0,1kHz	fixing
vibrating velocity	geophon laservibrometer	100 mm/s 10 m/s	5µm/s 1µm/s	< 1% < 1%	DC/AC	4Hz - 1kHz 1Hz- 20kHz	fixing
temperature	thermocouples Pt 100	-185 to 300°C -200 to 600°C	50µV/K 400µV/K	1% <1%	DC		leads temperature gradients

Annex A2: Sensor application and experiences

measured value	sensor type	mounting	experiences
displacement	LVDT LVDT calliper triangulation sensor cable extension transducer	simple simple simple simple	avoiding cross forces small operating frequencies avoiding reflecting surfaces avoiding impacts
inclination	bubble level pendulum	simple simple	small operating frequencies
settlement	hydrostatic leveling system PSD	complex complex	
stress	strain gauges fiber bragg gratings Fabry- Perot fiber sensors Sofo system optical string	complex complex complex complex simple	for short term measurements of strain for long term measurements
acceleration	piezo ellectric sensors MEMS-A640 B12(differential choke)	simple simple simple	rugged pick- up
vibrating velocity	geophon laser vibrometer	simple simple	reliable and rugged pick- up robuster Aufnehmer inapplicable for monitoring systems
temperature	thermocouples Pt 100	complex simple	

ANNEX B
TRAFFIC LOAD IDENTIFICATION ON BRIDGES

Task:

At a seven span prestressed concrete bridge the static and dynamic live loads are to be determined and classified depending upon lanes

Procedure:

The fundamental idea for the represented method is to use the bridge as a balance. On the basis of measured strains on suitable locations at the main girders of the bridge the loads of vehicles are acquired.

In a first step a validated load model has to be developed. For this purpose the influence lines of the strains are measured during the passage of a vehicle of well-known geometry and axle loads. In a second step those influence lines are measured and stored which contain the most important possible combinations of vehicles when passing the bridge. Possibilities of these combinations are: one vehicle behind the other, one next to each other, one behind the other + next to each other, etc. This information form the basic patterns for a later automatic pattern recognition.

In operation strains effected by the weight of the passing vehicles are measured and the combinations of vehicles are identified using the pattern recognition. Afterwards the static and the dynamic portion of the traffic loads are identified by a separation of the measured signals using fourier analysis. Performing a low-pass filtering of the signals with a frequency below the first natural frequency of the bridge the static values of the measured strains are obtained. Appropriate procedures applies to the dynamic portion (Figure 3). The dynamic factor is defined as the relationship of the maximum total amplitude regarding the associated maximum value of the static amplitude.

Results:

One of the results of the load identification is a representative static load for every lane. Figure 4 shows exemplarily the frequency of the ascertained traffic loads separated into load classes for the years from 1994 till 2004. With such continuously recorded data load models updated for each bridge can specifically be determined.

In the same way the dynamic factor φ is determined. Figure 6 shows the temporal change of φ within a period of ten years. φ is determined as a function of the magnitude of the weight of the vehicles. This information about traffic loads can be used for calculating the actually arising entire stresses at bridges in their temporal development by means of finite element models. From these results the residual life time of structures can be derived. Figure 5 shows that the size of the dynamic factor φ can be described regarding the frequency of its occurrence by a statistic distribution. This distribution is varying over time and gives information over the size of the fatigue-conditioned stresses. Figure 6 shows that the dynamic factor can reach absolutely considerably larger values besides his main value although with reduced frequency.

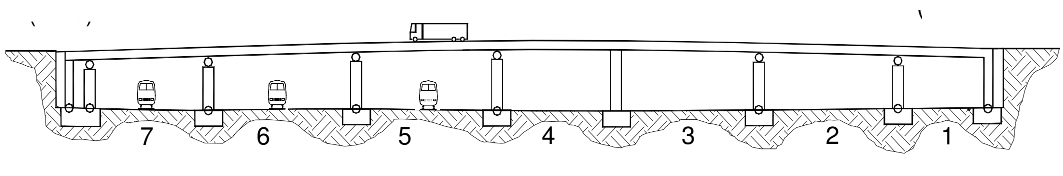

Fig. 1: Westend Bridge Berlin, Germany

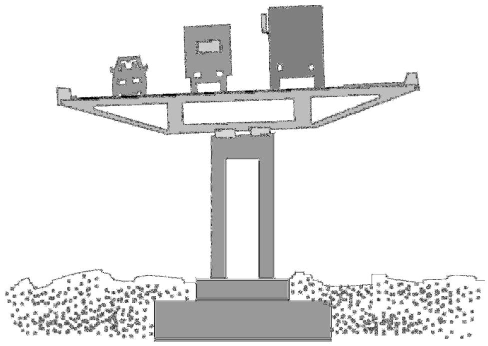

Fig. 2: Cross section of the tested bridge

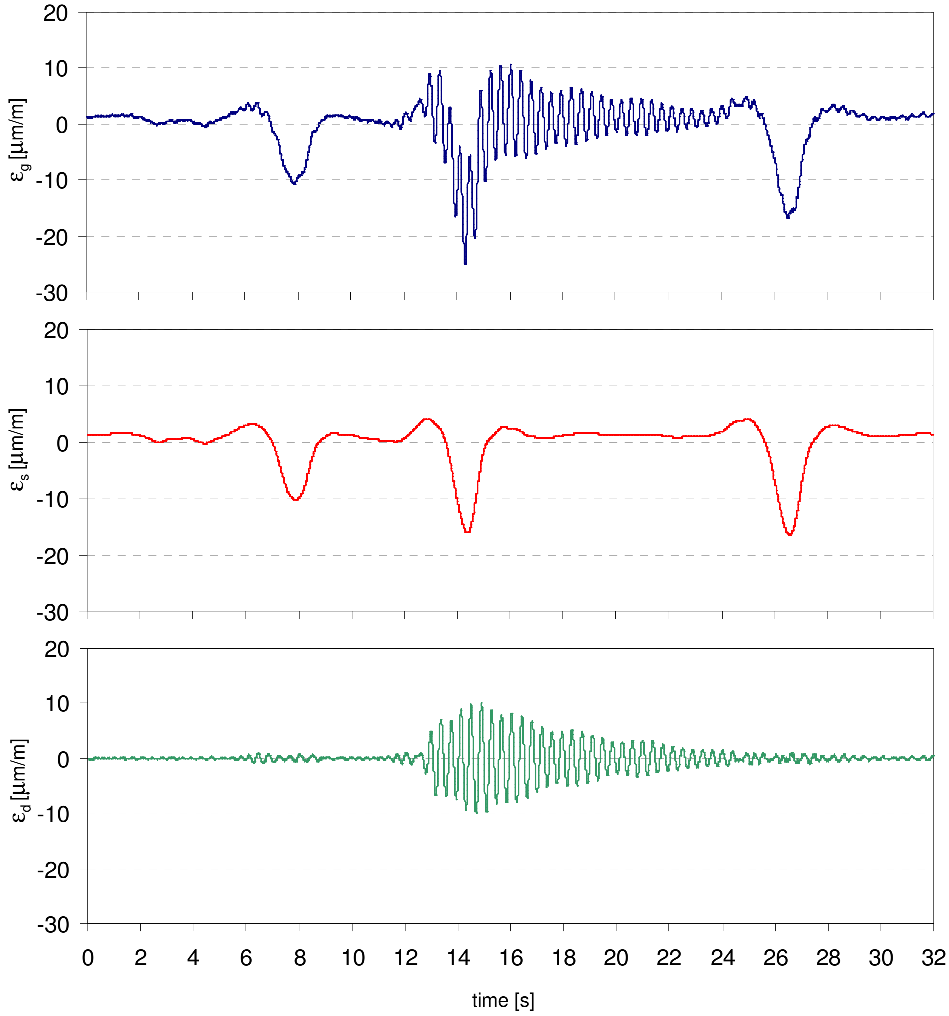

Fig. 3: Separation of the combination load (above) into its static (centre) and dynamic (down) portion

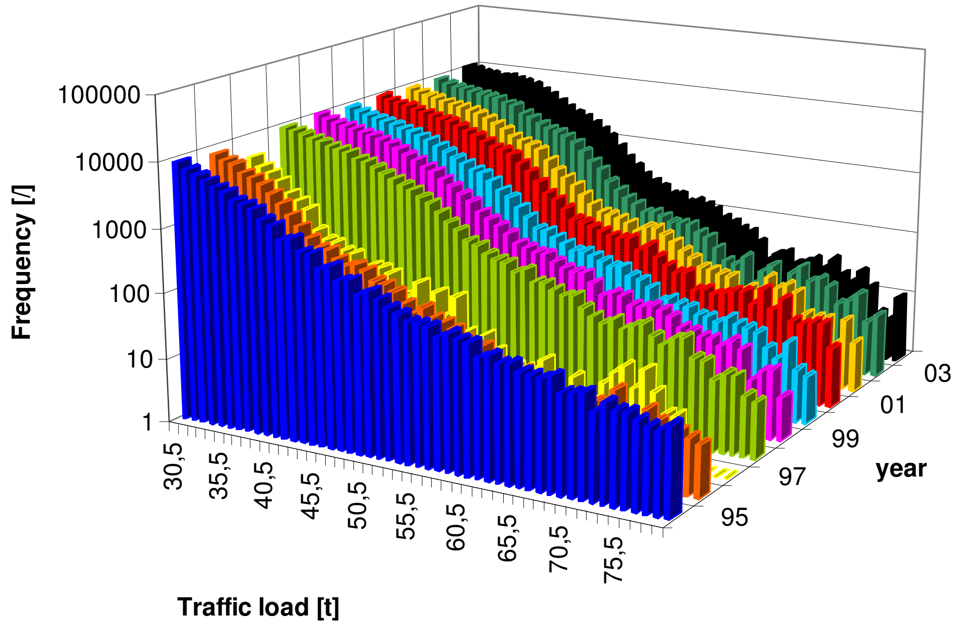

Fig. 4: Frequency of identified traffic loads within the range between 30 and 80 tons over the time between the years 1994 and 2004

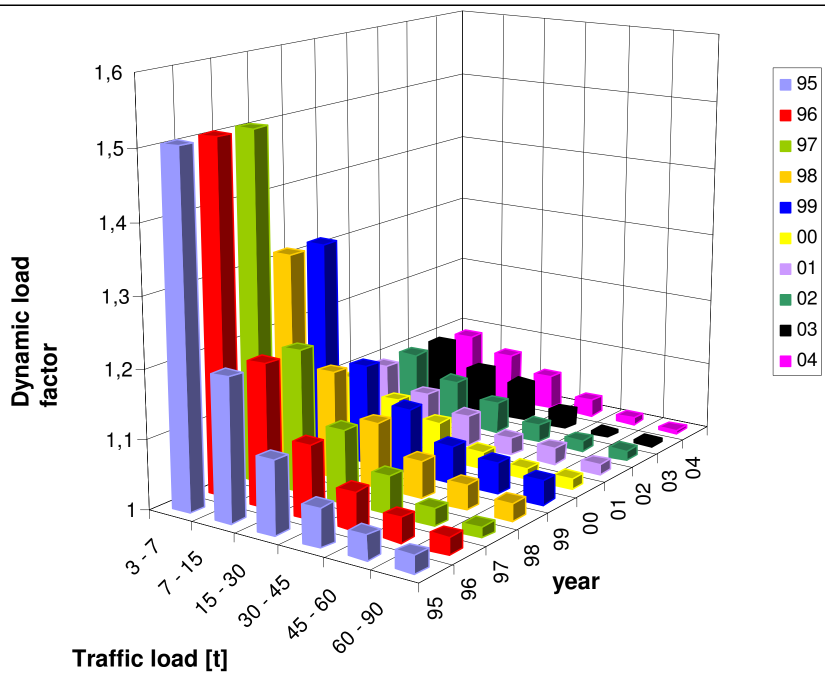

Fig. 5: Development of the dynamic load factor □ depended on measured traffic loads over the time between the years1995 and 2004

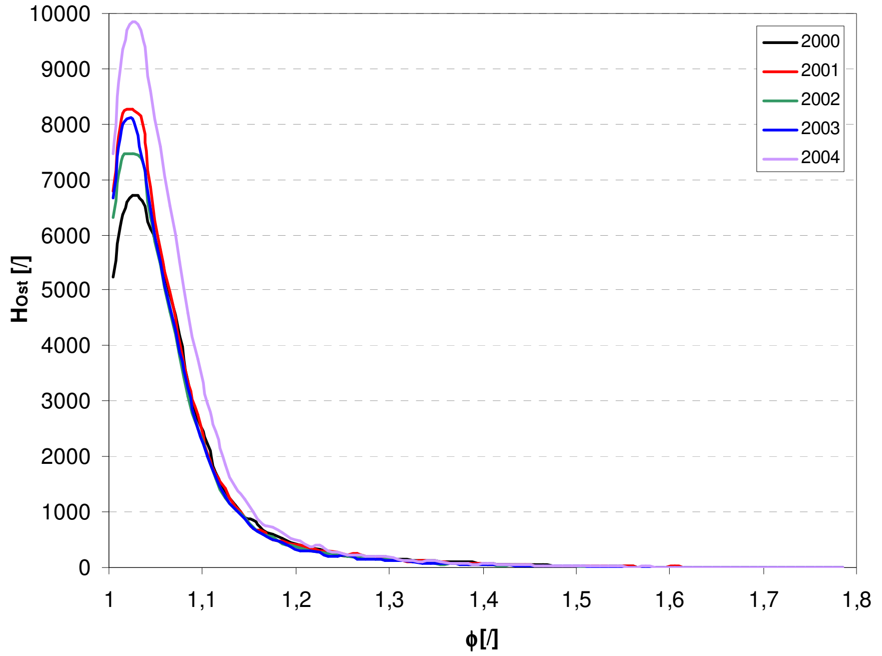

Fig. 6: Frequency distribution of the load factor and their variations within the time period of the years 2000 and 2004

ANNEX C
CONDITION MONITORING OF HERITAGE BUILDINGS

Task:

Beneath the Brandenburg Gate construction work (tunnelling) for a new underground line is carried out. During this time permanent condition monitoring of the monument is to be accomplished with the goal of discovering changes and damage to the structure and the foundations.

Procedure:

Tunneling in the soil in general causes vibrations at the monument and settlements of the foundations. This can cause damage to the carrying structure or to the historical foundations. Therefore additional to the local monitoring of already existing cracks predominantly dynamic sensors for the global surveillance are used. With the results of the vibration monitoring damage identification on the basis by observed natural frequencies is accomplished. In addition, before beginning and after ending the construction work experimental modal analysis is carried out to obtain information about structural damage from variations of the mode shapes in comparison to the reference state. The vibration amplitudes of the building's response excitated by normal traffic before beginning and after ending of the construction work are used as further indicators for changes in the vicinity of the foundations.

Results:

Monitoring results show changes of the dynamic characteristics of the Brandenburg gate approximately to that time, when the tunnelling in the soil had reached the foundations (Figure 4). From the power spectra (Figure 3) a decrease of the natural frequencies is recognizable. Table 1 shows that this change amounts to about 10% for the first natural frequency and up to 25% for the fourth natural frequency. The represented results of measurement were obtained in the context of the respective experimental modal analysis. From Figure 6 it is recognizable that mode shape No. 1 exhibits changes regarding to the directions of the movement. Before beginning of the work mode shape No.1 had a horizontal component exclusively. After ending of the construction work this mode shape contained an additional lateral component and thus an additional modal degree of freedom (Figure 6).

This trend is also confirmed by the results of the vibration measurements at the foundations of the monument. Figure 5 shows the correlation of the vibration amplitudes FR (horizontal) and FL (lateral). These results contain all frequencies of the excitation spectrum. They show also the trend of increasing amplitudes in the lateral direction after completion of the construction work.

It is assumed that tunnelling changed the condition of the foundation stiffness. Such changes can be detected particularly sensitively in the global dynamic behaviour. Advanced information necessary for the assessment of these changes is to be achieved by additional inspections of the foundations and by finite element simulation.

Fig. 1: Construction work close to the Brandenburg Gate in Berlin, Germany

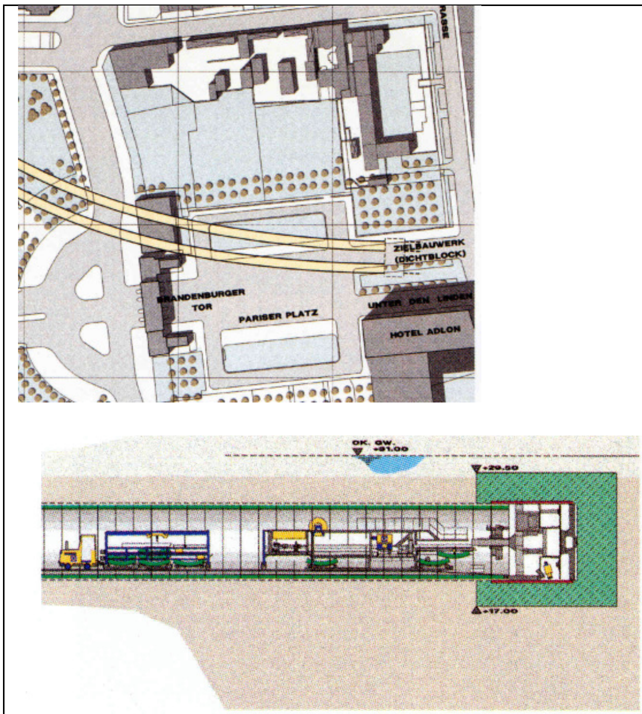

Fig. 2: Tunnelling of a new metro line underneath the monument

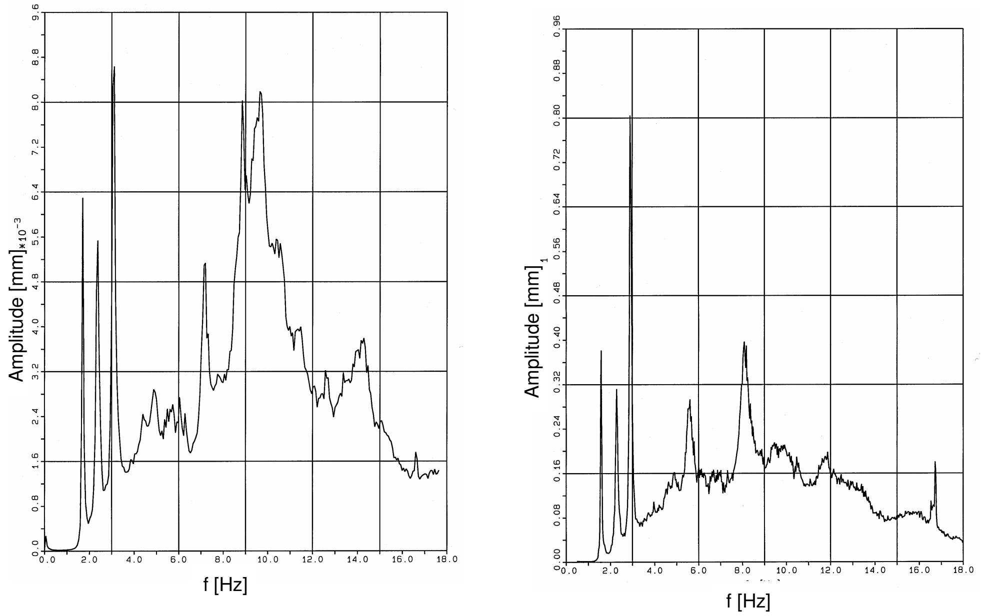

Fig. 3: Power spectra and natural frequencies of the monument in comparison before (left) and after (right) the construction work

	Natural frequencies [Hz]	
Nr.	before	after
1	1.77	1.59
2	2.44	2.29
3	3.17	2.90
4	7.26	5.80
5	8.91	8.2 - 8.4

Table 1: Results from the natural frequency method indicating changes of the dynamic behaviour

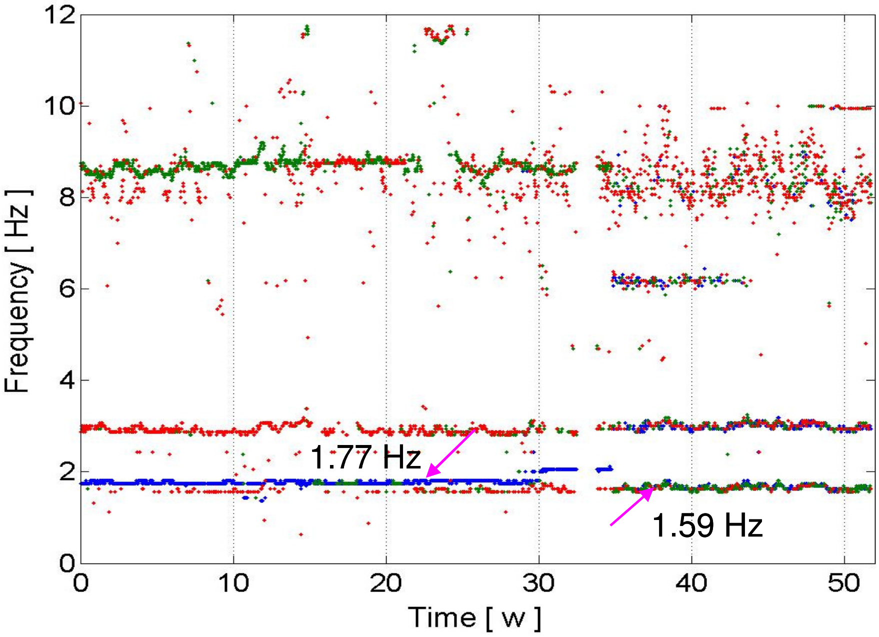

Fig. 4: Results from continuously monitoring show changes of the first natural frequency after approximately 30 weeks observation time

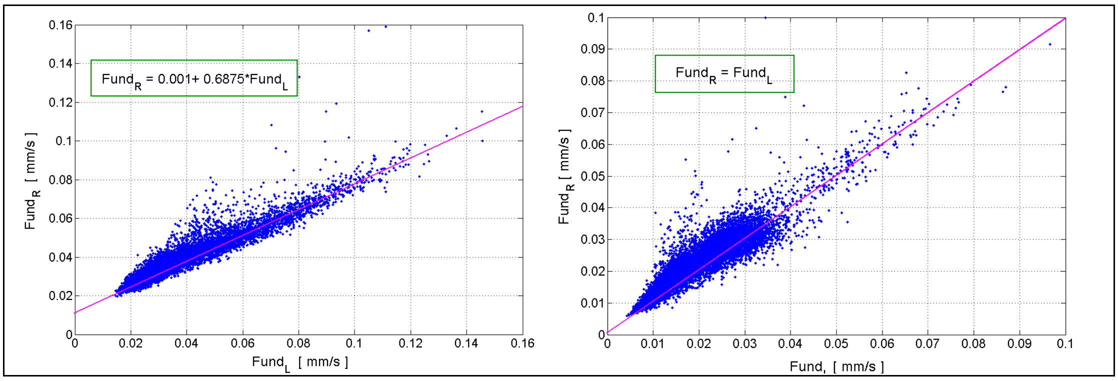

Fig. 5: Ratio of vibration amplitudes FR/FL measured at the foundation indicates structural changes

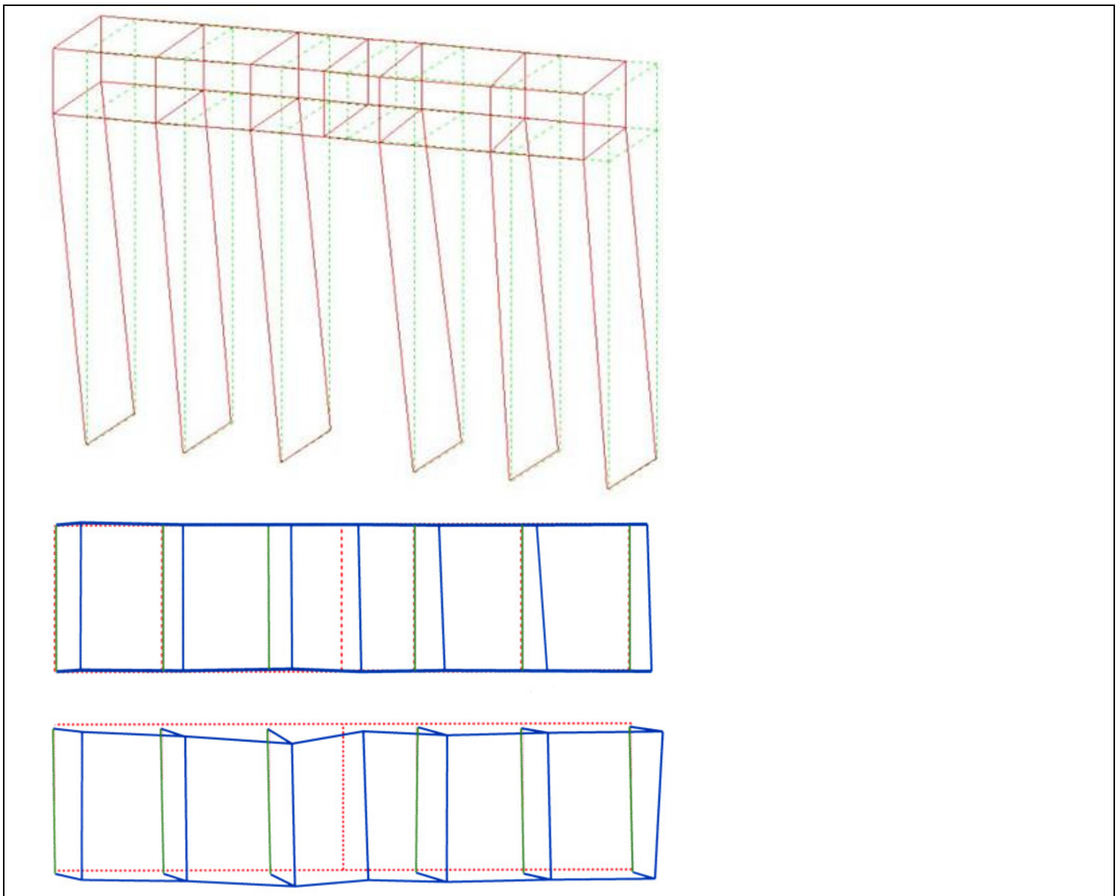

Fig. 6: Comparison of measured first mode shape before and after construction work

ANNEX D
IDENTIFICATION OF LOCAL DAMAGES AND THEIR EFFECT ON STRUCTURES

Task:

By visual inspections cracks in the superstructure of a masonry railway bridge were discovered. With the help of a monitoring system the change of the crack widths under the influence of live loads and temperature should be observed. In addition trends for the damage development should be determined. Beyond that the static stresses should be measured due to the dead loads as well as possible changes of the load-carrying capacity as a function of structural changes (cracks and settlements) and the influence of temperature.

Procedure:

The viaduct has an overall length of 750 m and is build by 34 arches (Figure 1). The sensors and the measurement equipment for the continuous monitoring are located within two of these arches (Figure 2). The measured variables used for monitoring were changes of crack widths, stresses, vibrations and temperatures. The settlements of the piers were determined by geodetic measurements in certain time intervals. The data acquisition was carried out continuously and without any gap. A first evaluation of the data for the purpose of data reduction already took place in-situ. Predominantly statistic characteristic values were determined. Using fourier analysis the results of measurements could be separated depending upon effect (setting, temperature, traffic). The causes of the damage could be analyzed using correlation functions.

Results:

Generally it applies that the supervised changes of crack widths are predominantly temperature-dependent and reversible. Changes of crack widths under the passage of trains were also measured, but these are comparatively small and do not contribute to changes of structural characteristics. The maximum changes of crack width under temperature amount to 9 mm in the yearly cycle whereas those under live load were measured with 0.13 mm. It was stated that the whole cross-section is cracked and is moving like a rigid body (Figure 3), whereby w1 and w2 are crack widths at the two opposite sides of the superstructure. Repair work does not has any effect regarding to the cracks. Changes of crack width can be described in good approximation by a linear correlation with the building temperature: $w \cong -0.3 \cdot T$. An effect of the measured settlements on the changes of crack width was not determined.

Representative strain measurements at the masonry were difficult to perform due to local, temperature-dependent change of the distributions of stress (Figure 5). Sensors with a sufficient measuring length compared with the dimensions of the masonry are important for good monitoring results.

Comparing the measured strains due to live loads and temperature it can be recognized that the ratio of both is 1:100. With this fact it becomes clear that temperature is the crucial load case for the assessment of the viaduct concerning to stress (Figure 4).

Dynamic measurements allow to control the train traffic concerning to the schedule and model of trains operating (Figure 6). This knowledge is necessary for comparing results induced by traffic loads. Traffic induced vibrations are able to excite the natural frequencies of the viaduct (Figure 6). Modal data measured by condition monitoring process as basic information for damage dependent structural assessment.

Fig. 1: Railway bridge 'Neiße Viaduct', Germany

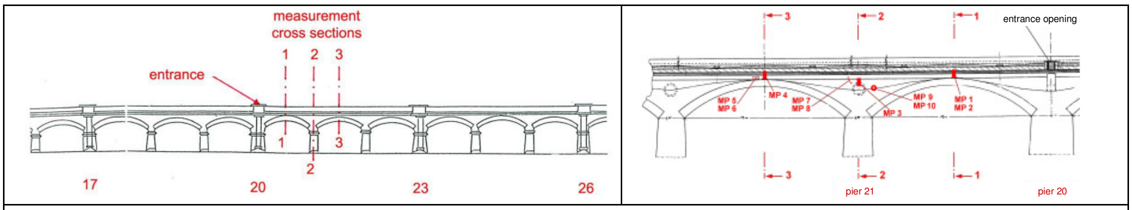

Fig. 2: Cross sections (left) and locations (right) for the attachment of sensors

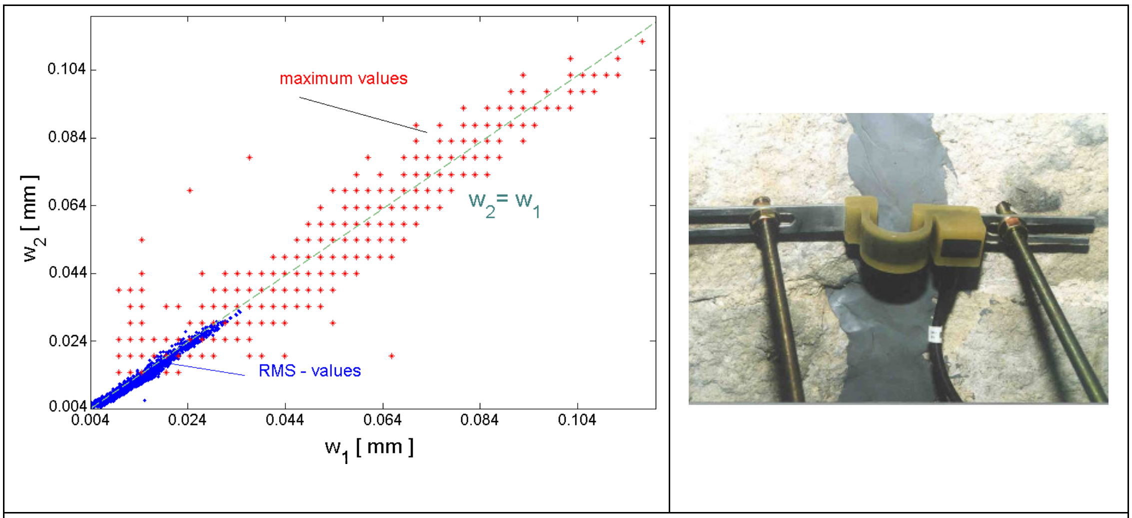

Fig. 3: Comparison of crack widths w_1 and w_2 (left), utilized sensor for measuring large crack widths (right)

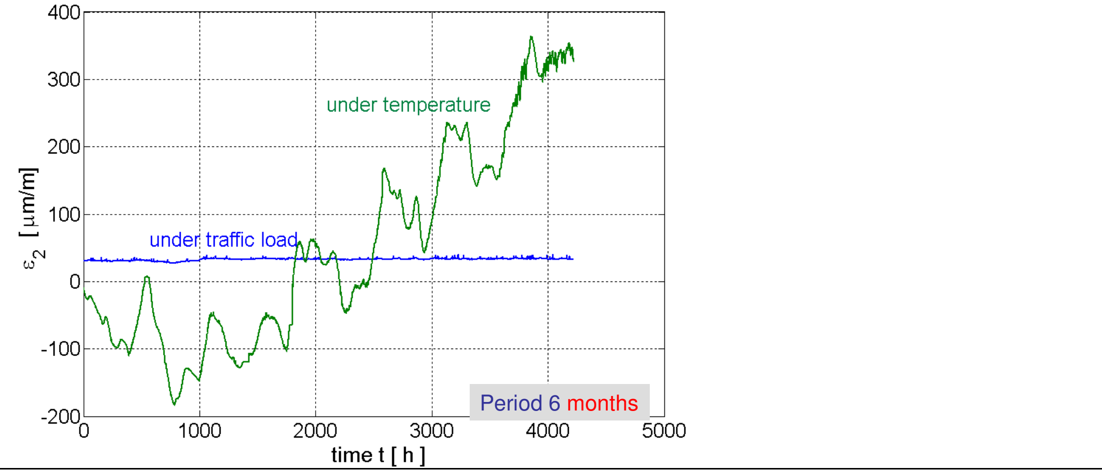

Fig. 4: Measured strains due to the impact of traffic loads and temperature

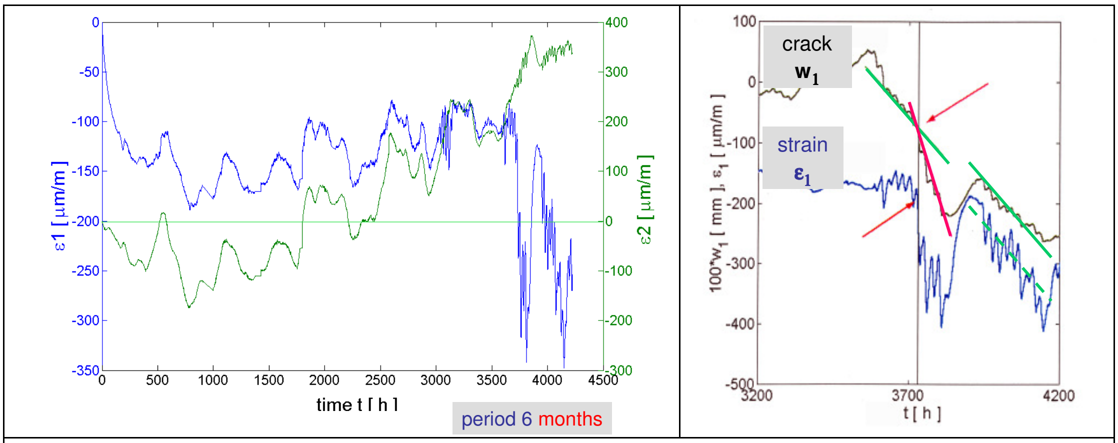

Fig. 5: Measured strain at two locations of the same cross section due to temperature (left), observed rapid change of strain caused by rapid change of crack width (right)

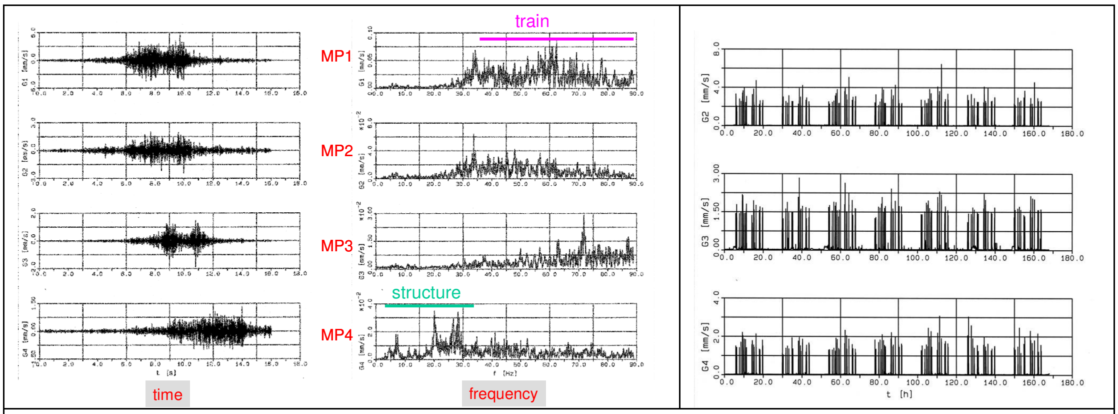

Fig. 6: Passage of a train and the associated frequencies excited (left), controlled passages of trains during the time period of one week

ANNEX E
DAMAGE IDENTIFICATION OF A STEEL BRIDGE BY DYNAMIC PARAMETERS

Task:

At a three span steel bridge artificially increasing damage was generated in order to simulate developing fatigue cracks at welding seams (Figure 1 and 2). From the results of dynamic measurements in the undamaged and damaged state the location and severity of the damage should be determined [18].

Procedure:

The bridge was excited by a shaker within the range of 2-12 Hz with maximum force amplitude of approx. 8900 N. On 26 measuring points accelerations in vertical direction were measured (Figure 3 and 4). From these results by means of experimental modal analysis the natural frequencies and mode shapes were determined. Modal parameters were used to validate finite element models for the undamaged condition. The frequency response (Figure 4) functions show the degree of agreement regarding the dynamic characteristics of the model with the reality. For the damage analysis a residue vector with six natural frequencies and the first two mode of shapes is used. The number of free parameters for the damage localization amounts to 1080 in a first step. For the reduction of the number of free parameters and thus for the localization of damage a two-stage decomposition procedure was used [19].

Results:

In relation to the finite element model Figure 5 shows the result of the damage localization based on the parameter reduction process. By means of a consecutively updating process the finite element model in the damaged condition is enhanced. With the knowledge of the sensitive parameters the extent of the damage is quantified. The results of calculation reproduce the technical reality of the damage to the bridge very well.

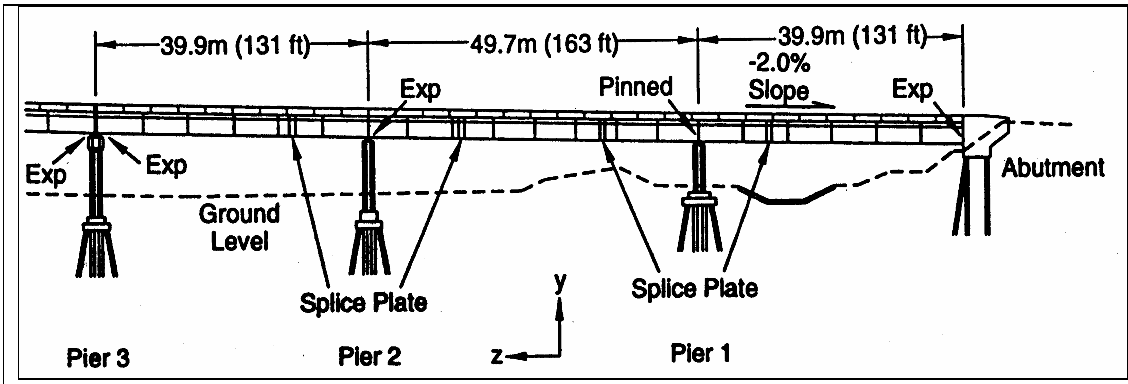

Fig. 1: I-40 highway bridge, New Mexico, USA

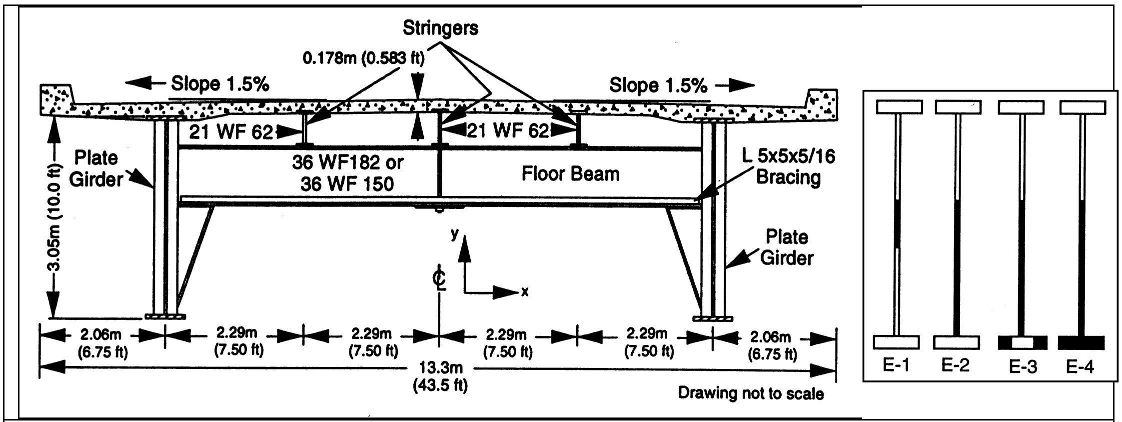

Fig. 2: Cross section of the tested bridge (left), Damage scenarios (right)

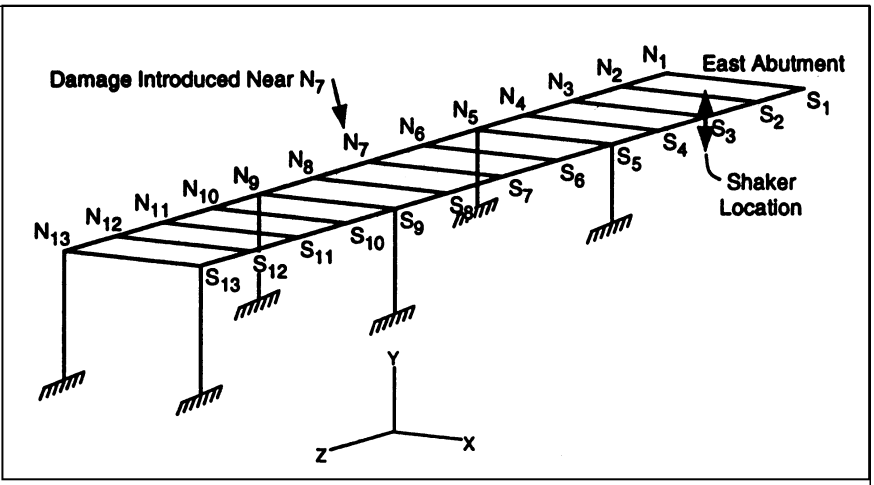

Fig. 3: Mesh grid along the bridge section

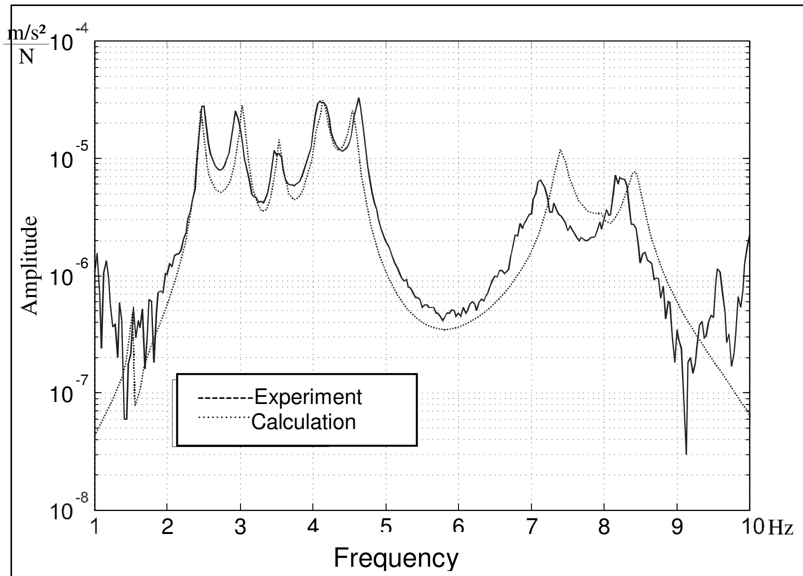

Fig. 4: Frequency response function at measurement point N7

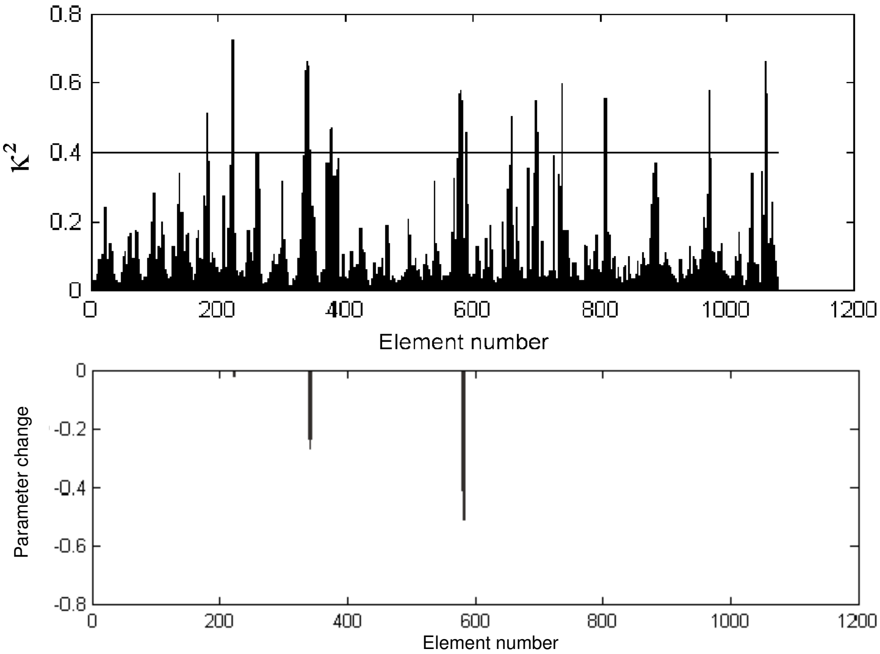

Fig. 5: Damage indicatorκ² in correlation with model parameters (above), Damage localisation: results after parameter reduction (below)

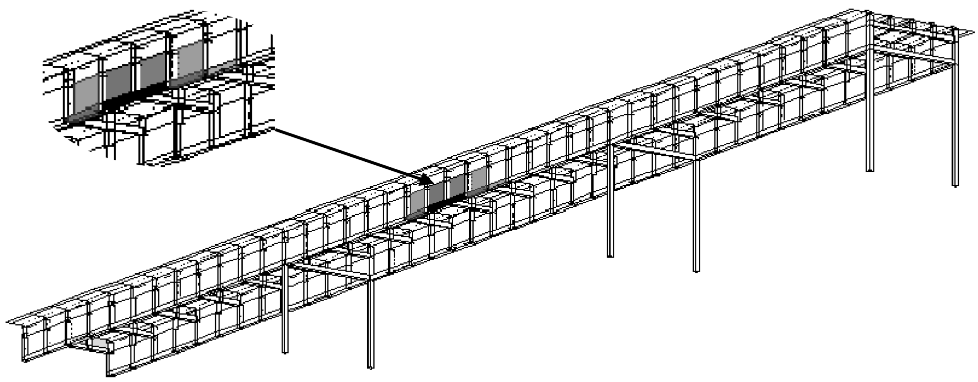

Fig. 6: Detected damage and calculated changes of stiffness obtained by FE-model updating