Ambient vibration monitoring

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ABSTRACT: Not only Bridges but also other structures have a strongly developed vibration behaviour, which can be described by the eigenfrequencies, the respective mode shapes and damping values. The aim of *AVM* is to use dynamic behaviour of a structure for the assessment of its condition and capacity.

1 SYSTEM IDENTIFICATION

Calculation models for the determination of stresses and consequently for the measuring of structures only represent an approximation to reality and have to be calibrated. For the determination of the conformity between the calculation model and the actual load-bearing behaviour up to now frequent stress tests (for example at railway bridges) have been carried out and the measured deformations (flexures) were compared with the calculated reference values. From this conclusions are drawn on the load-bearing safety and performance capability of the structure.

A simpler method for the determination of these parameters is based on the determination of the dynamic characteristic by so-called ambient vibration measurements. By these measurements the vibration behaviour of a structure is recorded, evaluated and interpreted under ambient influences, i.e. without artificial excitation, by means of highly sensitive acceleration sensors.

The methodology to make conclusions on the load-bearing capacity of a structure by measuring its dynamic behaviour and to check mathematical model assumptions is already very old. In [1] there is a report on stress tests between 1922 and 1945 in Switzerland where tests by free oscillations at the aerial *Beromünster* in 1941 are described. The results were used for checking the calculation assumptions, deviations between measured and calculated results were interpreted and statements for similar future towers were done.

The checking of structures by means of dynamic measuring methods has a long tradition in Switzerland and was carried out until the beginning of the 1990s in the form of tests by free oscillations by means of initial strains or intermittent stresses and by means or excitation with unbalance exciters or hydraulic shakers. Such tests were also carried out in Austria and Germany for scientific purposes but at a smaller scope, they were, however, not extensively applied for system identification or check and calibration of calculation models. In [2] it is, however, suggested to further develop dynamic procedures for the assessment of the maintenance condition of structures.

The rapid development of measuring technology on the one hand and computer technology as well as software on the other enables us to carry out dynamic measurements of ambient structure vibrations and their evaluation very quickly and with relatively low expenditures today. Vibrations influencing the structure due to natural excitation sources like micro-seismic phenomena, wind, waves etc. are regarded as ambient causes. The measuring and evaluation system *BRIMOS® (Bridge Monitoring System)* developed by the authors takes advantage of these progresses and opens a wide field of application to technology.

The dynamic characteristic of the structure cannot only be used for a single check of calculation models but statements on the chronological development of the load-bearing capacity and therefore estimates on the remaining service life duration are enabled by measurements at certain intervals. Measurements at any moments supply snapshots of structural integrity and can be used in combination with parallel mathematical analyses for the determination of possible damages to the structure.

Below the decisive dynamic parameters to be determined for system identification are shortly described. During monitoring all analyses of system identification are applied. In addition to the procedures of structure mechanics and dynamics statistic

methods have to be used which determine trends from large data quantities. The use of so-called trend cards, which clearly represent an eventual change of individual parameters by means of the time-frequency diagram, has proved successful.

This trend card shows the shift of eigenfrequencies over time due to the damage of individual prestressed cables in a test at the motorway flyover *Regau* (*Object S123a*).

1.1 *Eigenfrequencies and Mode Shapes*

The eigenfrequencies are an essential parameter for the description of the vibration behaviour of a structure in the linear elastic field. A mode shape– i.e. a

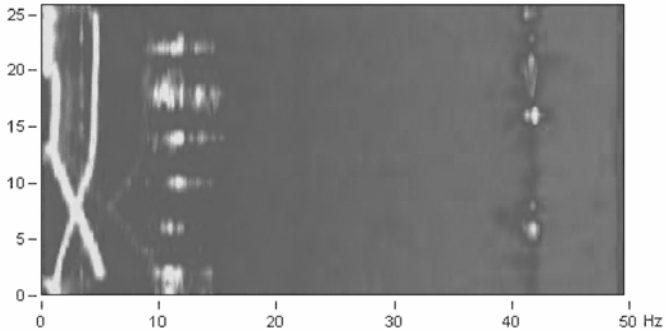

Figure 1 Transposition of the system according to damage, moment of failure

vibration form in which the structure oscillates with the respective eigenfrequency – belongs to every eigenfrequency. The actual oscillation of a real structure is composed of the respective shares of the individual mode shapes.

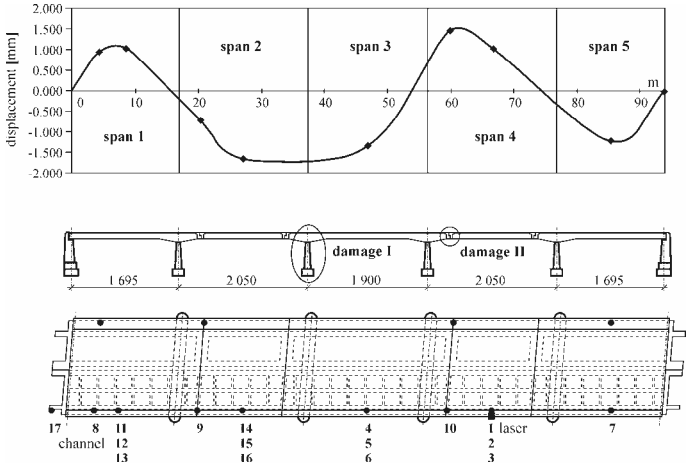

Figure 2 Measured first mode shape of a defect structure (settlement of supports due to heavy traffic)

The mathematical modal analysis supplies both the eigenfrequencies and the mode shapes of a structure – in experimental modal analysis the eigenfrequencies are obtained as well, the mode shapes can be determined point by point (at the measuring points). Both analyses have to be carried out for system identification. The actual static system is obtained by comparing the measuring results with the calculated values and adaptation of the calculation model to the measurements. In order to get a correct image on the actual load-bearing system, it is required to consider not only the first eigenfrequency and the respective modal form but also higher frequencies and the respective forms.

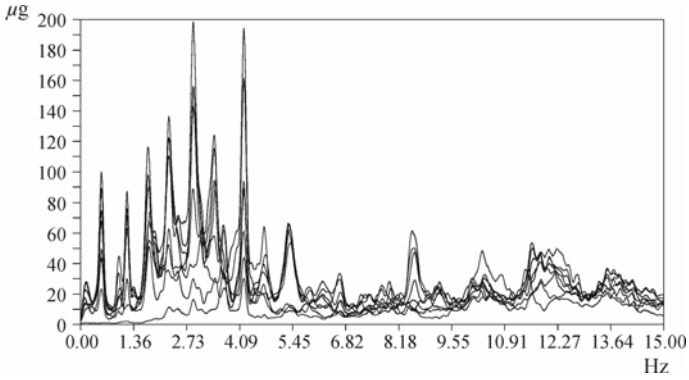

Figure 3 Frequency spectrum vertical 0 - 15 Hz

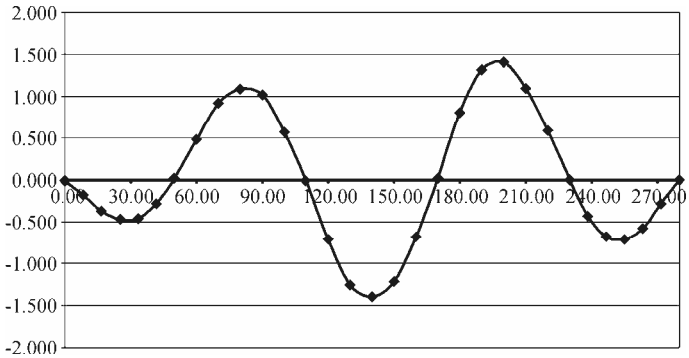

Figure 4 First vertical eigenform of a five span bridge

1.2 *Damping*

All real structures have a damping which results in a continuous decay of vibrations after excitation until a static equilibrium is reached. The damping properties are dependent on frequencies and represent a significant value for system identification. In particular they are an indicator for the current degree of exploitation of the load-bearing capacity of a structure as in case of increasing exploitation of the maximum load-bearing capacity – i.e. at the transition from the elastic into the elastoplastic range – the damping coefficients considerably rise [1]. In addition the dampings have an influence on the eigenfrequencies themselves, which is negligible in case of the usual damping values of structures in use, which, however, gains in importance with increasing exploitation of the load-bearing capacity.

In the course of a dynamic test of a structure the determination of the damping properties is therefore necessary to obtain a complete picture on the load-bearing behaviour.

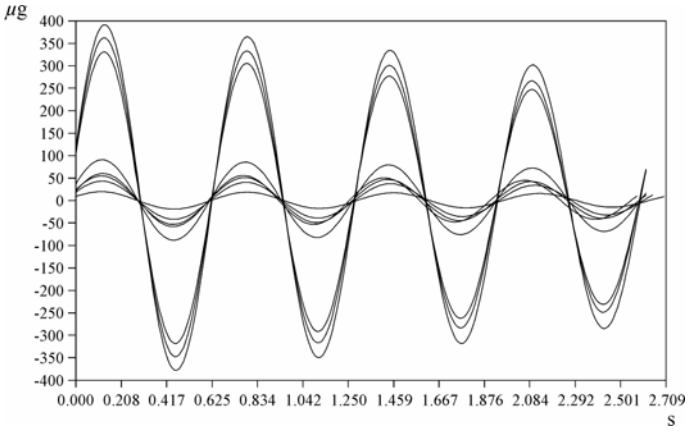

Figure 5 Damping window, first vertical eigenfrequency

1.3 *Deformations and Displacements*

Up to now the traditional measuring methods mainly measured deformations under defined loads and the latter were afterwards compared to calculated forecast values (for example test loads on railway bridges). The information content of this method is essentially limited to the flexural stiffness of the tested structure but the latter is definitely an important assessment criterion.

Dynamic measurements also include information on the structure deformations during the measuring period. By registering the three-dimensional vibration behaviour it is even possible to extract these deformations from the measurements in all three directions in space. Therefore not only vertical flexures but also horizontal (transversal and longitudinal) displacements are finally available for the assessment of the structural integrity.

1.4 *Vibration Intensity*

The vibration intensity is a very good indicator for the stress of a structure by dynamic loads. High intensities of a structure or individual structural members are very susceptible with regard to fatigue relevant damage mechanisms. The measuring values are recorded and classified in an intensity chart. This is appropriate in particular for the localization of detailed inspections at especially sensitive parts of the building. In case of the *Voest Bridge* in Linz the decisive sections could be localized on a small part of the total structure. On the other hand it becomes possible to develop the contribution of the perpetrators (traffic monitoring system) more justly in future by observing them.

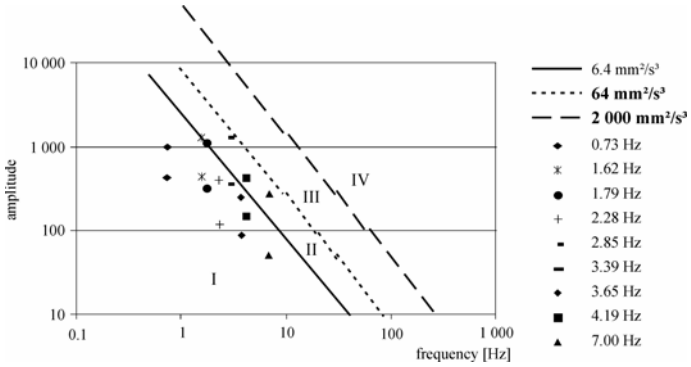

Figure 6 Intensity chart at the Europa Bridge of the Brenner Motorway

1.5 *Trend Cards*

Trend cards represent a signal in the frequency-time domain by means of area mapping. In order to be able to distinguish the individual frequency peaks, a colouring of the card is required so that the energy content of the vibration and therefore the respective intensity can be determined. A detailed representation of this technology can be found in chapter 2.5.2.

2 STRESS TEST

The knowledge of the current stress condition of a structure and its individual load-bearing elements is often particularly interesting. The examination is required on the one hand to determine the existing current load-bearing safety and to be able to introduce possibly necessary immediate measures. On the other hand it is an essential basis for the forecast of the future maintenance expenditures. An important assessment criterion to be mentioned in this connection is the evaluation and interpretation of the vibration intensity of the respective structure. By application of classification the endangering of a structure with regard to damage can be derived.

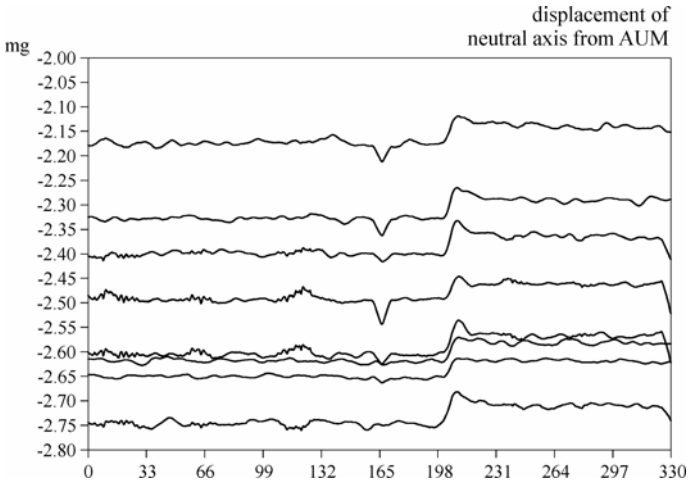

Figure 7 System displacement due to bearing reset forces of the flyover *St. Marx*

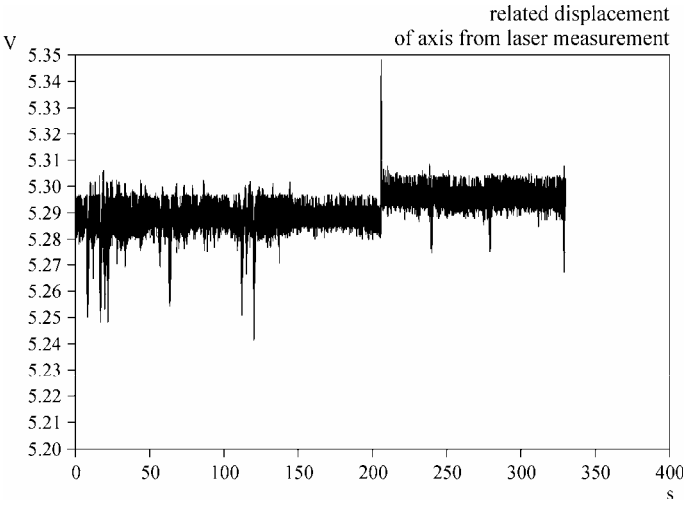

Figure 8 System displacement due to bearing reset forces of the fly-over *St. Marx*

2.1 *Determination of Static and Dynamic Stresses*

The global stress condition has to be determined statically and dynamically. From the knowledge of these two stress types the dynamic enlargement ratio for the traffic loads can be determined. This is not only an indication of the dynamic sensitivity of the structure; its knowledge allows also the establishment of specific measures for the reduction of the stress level (for example by speed limits).

Figure 9 Flyover *St. Marx* – section of the *A23 motorway*

2.2 *Determination of the Vibration Elements*

Individual elements of a structure frequently show particularly strongly developed vibration behaviour (e.g. rim beams of deck cantilevers, stay cables of guyed constructions). Such structural members have a decisive influence not only on the convenience for the use of a building. They are also particularly susceptible to fatigue fractures caused by the continuous changes in stress in the load-bearing elements concerned. The recognition of such structural members by modifying the vibration behaviour within the scope of a dynamic measuring programme enables a timely rehabilitation and therefore prevents greater damages.

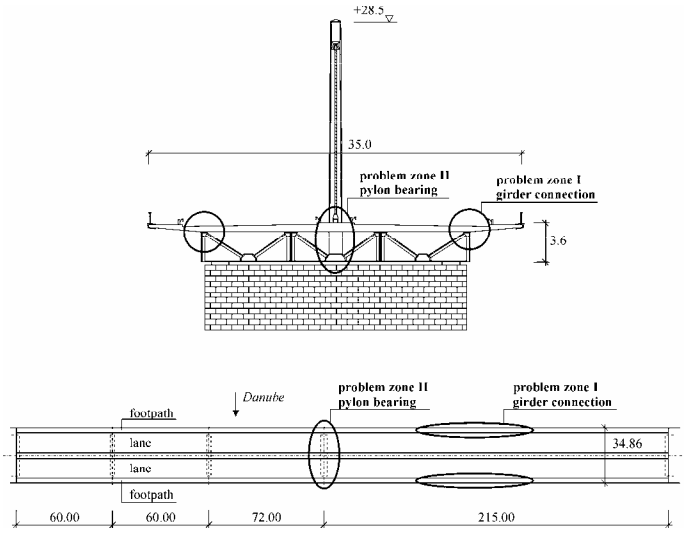

Figure 10 Vibration intensive areas at the *Voest Bridge* across the Danube

A simple dynamic analysis already supplies information on such elements in a structure and thus enables a specific measurement.

2.3 *Stress of Individual Structural Members*

Apart from the global stress situation and the tests on individual structural members particularly susceptible to vibrations, a specific stress determination for individual structural members is required in the scope of an extensive test of the building. For all load-bearing elements with a direct relation between eigenfrequency and stress level (stay cables, tendons, tension members under compression) a determination of the stress by means of an evaluation of the vibration measurement is possible. If the relations are more complicated, it is more advisable to determine the stresses by means of the optimized calculation model drawn up in the scope of system identification.

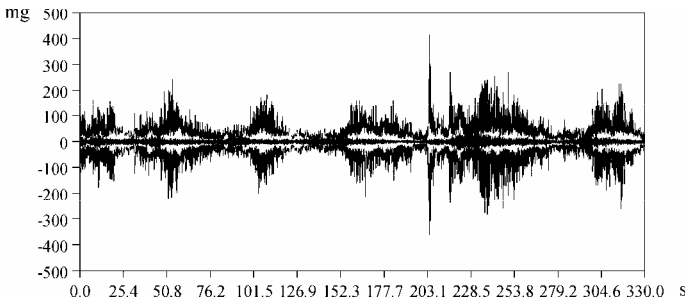

Figure 11 Acceleration signal of a bridge cross-section with high values for the cantilever vibration

2.4 *Determination of Forces in Tendons and Cables*

The knowledge of the actual tensile forces in the tendons of guyed structures (e.g. pylons, pyramid type roofs) or in the cables of cable-stayed bridges,

Figure 12 Annual inspection of all cables at the *Rosen Bridge* in Tulln

in the suspenders of arched bridges or in external tendons is required for the assessment of these elements themselves but also for the examination of the global stress of the structure. The determination of these forces by lift-off tests is connected with considerable expenditures as well as the danger of damages. The mounting works at the anchorages can unfavourably influence the durability of these critical elements.

Therefore fast and non-destructive methods for the determination of the forces are required. The measurement of the vibration characteristic is an approach for a solution because there is a simple, quasi linear relation between the eigenfrequencies of a cable and the inherent force.

3 ASSESSMENT OF STRESSES

An essential task to be solved is the assessment of stresses of the total system as well as of individual structural members. This assessment must be carried out with regard to the actual structural condition and consider the predicted future development of the structural condition.

AVM offers the possibility to carry out the assessment on the basis of objective parameters. If these measuring results are combined with calculation models very good predictions can be made by applying probabilistic approaches. Statements with varying accuracy are possible here and the scope of the executed test determines their expressiveness.

3.1 *Structural Safety*

The dynamic characteristic contains information on the global structural condition as well as on local phenomena. During the assessment of the structural safety the whole system is viewed and its behaviour analysed. The system identification concentrates on the lower frequencies in the spectrum. The scope of tasks is the determination of the frequencies and the respective mode shapes of the whole system and to calculate damping values which describe the system behaviour. The total structure can be assessed by means of these results.

For safety consideration there are numerous excellent models in literature. Above all the models by *Frangopol* (USA) and by *Das* (England) should be emphasized. They analyse the service life of a bridge starting from construction up to the slow decline of resistance by use and finally to the so-called intervention points where activities have to be taken to keep the safety level above a critical limit. Such a chart is shown in Figure 2.13. A curve for the theoretical service life can, however, not be transferred to reality. A simple approach is the assessment of the existing load-bearing safety by the system identification of the eigenfrequencies. It results in a value – in relation to the planned value – which existed at the moment of measuring. After consideration of the environmental influences as well as on the basis of periodic measurements, values can be determined, which lead to a curve. Future models will consider further values from parameter classification apart from the assessment of the modal parameter eigenfrequency and therefore enable even better predictions.

Aim of these considerations is finding out the structures requiring rehabilitation most urgently from a big random sample of structures. The current development of the *BRIMOS® recorder*, which can register and assess a big number of structures with low expenditures, complies with this aspect.

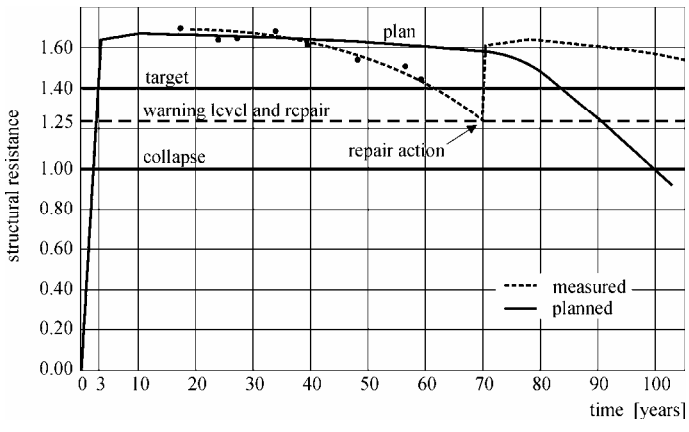

Figure 13 Theoretical service life chart of a structure

3.2 *Structural Member Safety*

The bases of the structural safety can be analogously applied to individual structural members, too. Every member has its own characteristic which can be isolated from the total measurement. So for example the vibrations of decks are discernible very distinctly. During a sufficiently accurate measurement, i.e. check points at every member, their characteristic can be unequivocally determined. This isolation makes it possible to make statements on the quality of individual structural members. An isolated local damping value is calculated, which gives information on the quality of the respective structural member.

Measurements at several cross-sections of the structure were carried out at the *Europa Bridge* with the individual elements instrumented according to the sketch in Figure 2.14. By this both the load displacement and individual stress can be derived.

3.3 *Maintenance Requirements and Intervals*

The increasingly ageing engineering structures in the field of traffic infrastructure entail the growing significance of maintenance problems. Bridges are checked by periodic monitoring measures with the aim to minimize the safety risk on the one hand and to keep the costs for the maintenance as low as possible on the other hand by carrying out rehabilitation measures at the right moment. In Austria the bridge tests in the area of the federal road network are carried out on the basis of the guideline for the monitoring and checking of road bridges at periodic intervals. In order to fix an optimum duration of the intervals, it is advisable to combine conventional bridge tests and dynamic monitoring.

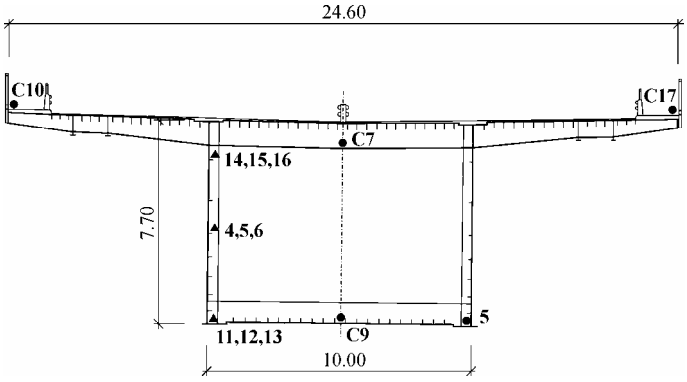

Figure 14 Cross-section of the *Europa Bridge* with sensors

On the one hand parameters are better and more objectively quantified by dynamic tests; on the other hand also a qualitative statement is possible. This would make it possible to extend the inspection intervals for bridges with a good maintenance condition.

A further attractive possibility is the application of simple verifications, which supply information on changes in the system by means of comparison to the basic measurement. In this way the requirement of a main inspection can be determined at a relatively low cost. So essential maintenance costs could be reduced without having to accept a lower safety level.

Special cases in this connection are the cable-stayed bridges where information on the structural condition can be gained by simply monitoring the cables at shorter intervals.

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3.4 *Remaining Operational Lifetime*

For the maintainer and the user of a structure the question of the expected remaining operational lifetime has an essential significance. As already described under chapter 2.3.1, the remaining operational lifetime can be extracted from measurements at periodic intervals. Safe forecasts are possible on the triple period of the measurements, i.e. in case of measurements over three years, an extrapolation on nine years. From this point of view it seems important to carry out first measurements as soon as possible even if there is no immediate reason (problem) for them. This type of application of the system will be significant only after several years of employment.

4 LOAD OBSERVATION (DETERMINATION OF EXTERNAL INFLUENCES)

The objective of the determination of external influences (also called load observation) is the complete registering of traffic loads or other influences acting on the structure. In this connection the induced loads are not registered by means of a special balance but by the dynamic reaction (response) of the structure. This requires the knowledge of the dynamic system behaviour of the structure as it can be acquired by model calculations and/or experimentally (measurement). The dynamic reactions and the determined traffic loads can be used for the treatment of further tasks.

4.1 *Load Collective*

This is the determination of load collectives by recording the acting stresses according to location, type, size, duration and frequency. Influences by wind and temperature can be additionally considered. Sophisticated load models allow more precise statements on the service limit state and remaining lifetime of damaged structural members.
Load Collective

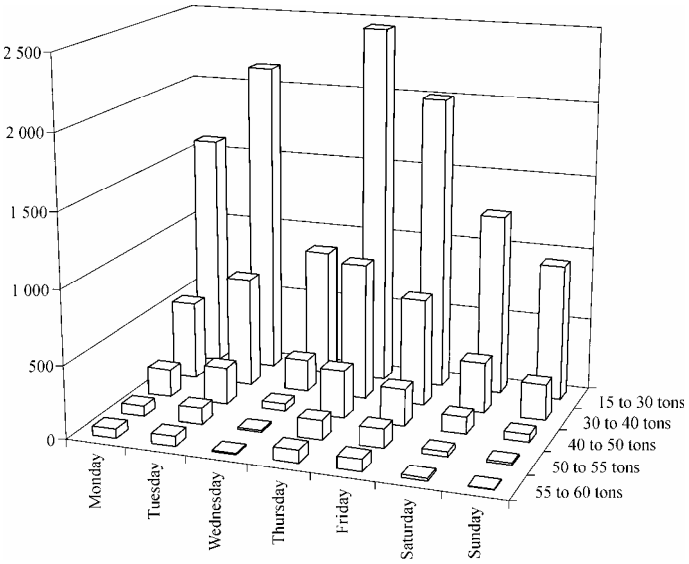

Figure 15 Passage events during a week (4 to 10 January 1999)

4.2 *Stress Characteristic*

Load models which can be only difficultly estimated in the design phase (above all special structures like cable guyed structures, suspenders or lateral braces of bridges) can be essentially improved due to measuring data. The knowledge of the stress characteristic enables improved and clearly more efficient designs.

An example is a railway bridge for which the load displacement was followed by measurements.

Figure 16 Detailed examination at the *Rohrbach Bridge*

The reason was the particularly high noise radiation of the structure because no ballast existed at the structure. The contribution of the individual elements to the total sound spectrum was to be determined. The aim was to apply damping measures at the right location; therefore the vibration intensive structural members were to be determined.

4.3 *Verification of Load Models*

A further application of the method is to check how far the theoretically applied load models correspond to reality. This is especially important for older structures where the standards required evidence for lower traffic loads. The proof whether the structure is up to the current actual loads can be done on the basis of dynamic measurements. Furthermore the method can be applied for the assessment with regard to the widening of the structure. The permanent observation of the traffic data by measurements, as for example traffic intensity and density as well as conclusions on the total vehicle weights, become increasingly significant for the strategic planning. A further possibility is the monitoring of important roads with regard to overloaded vehicles.

The actual dynamic factor affecting the structure is dependent on several parameters, essentially, however, on the driving speed, the vehicle weight and the pavement condition. From the measurement the respective values can be extracted and be included into a security check.

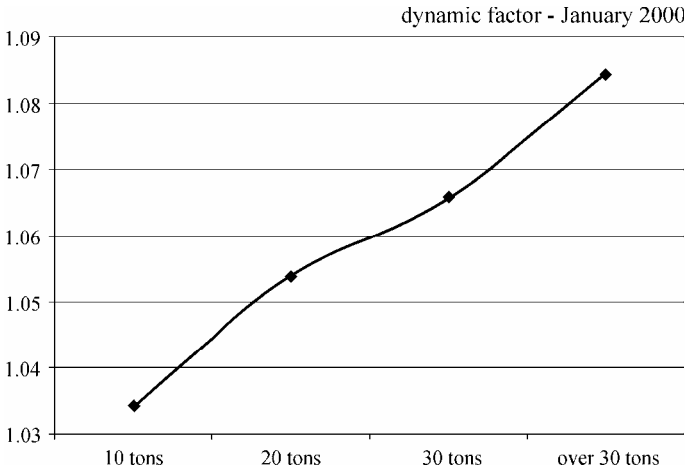

Figure 17 Dynamic factor of the flyover *St. Marx*

One of the most important findings of the tests was the fact that in most cases the actual dynamic factor is considerably lower than prescribed by the standard. For individual structural members, however, also considerably higher factors were discovered (for example 1.90 for the cantilevers of the *Europa Bridge*). In particular for old structures where the standards still prescribed relatively low stresses, such an assessment is often the last possibility for being able to prove the load-bearing safety.

4.4 *Determination of Environmental Influences*

Conclusions on the influences from the environment, like aerodynamic vibrations, running waters, shocks from neighbouring industrial plants or other excitations are enabled by dynamic measurements. An external influence often leads to the unusual behaviour of a structure. In areas prone to earthquakes it is

possible to determine dominant site frequencies, which are to be avoided in the design of the structure.

The influences from the environment are determined by means of an external sensor in the scope of the measurement. This sensor is located outside the system and measures the vibrations transferred via the ground. This has proved particularly successful in the vicinity of a quarry (*Mur Bridge Kraubath*). The registering of the ground spectrum is regarded as one of the most essential development steps of the system considering above all the safety of buildings with regard to the introduction of *Eurocode 8*. In the scope of a big project in West-Java (Indonesia) the functioning of this approach for an earthquake mapping based on dynamic measurements has been proven.

4.5 *Determination of Specific Measures*

In case of problems or changes of the requirement (for example extensions) the method can be applied for the deduction of specific measures for the stress reduction. This can be realized by the reduction of the stress or the change of the construction, which enables the utilization of still existing reserves. An example to be mentioned in this connection is the structure of the *F9 Donnergraben Bridge* on the *Tauern Motorway* where a damaged concrete deck led to increased vibration intensity at the structure. If this value is outside of the safe area, measures have to be taken, for example the rehabilitation of such defective spots. The scope of the measure can be localized very specifically by the examination.

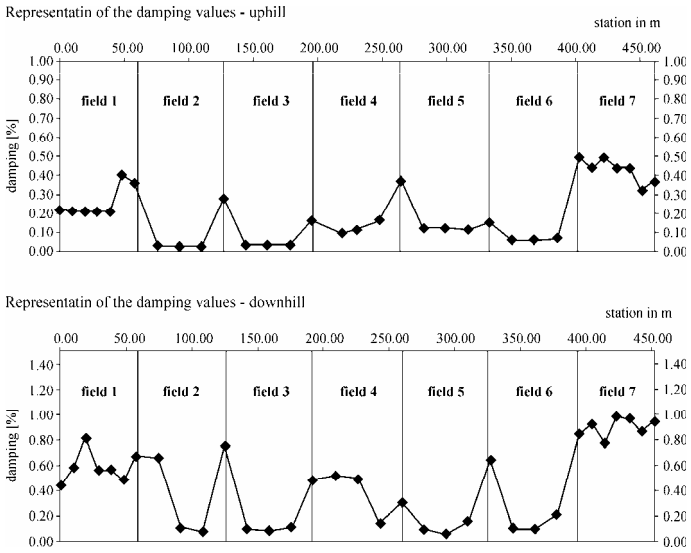

Figure 18 Damping progress of the *F9 Donnergraben Bridge*

4.6 *Check on the Success of Rehabilitation Measures*

By measurements before and after rehabilitation information on the quality of the works and the success of the rehabilitation can be gained. This is possible by a simple comparison of the dynamic characteristic.

An example to be mentioned in this connection is the *Inn Bridge Hall-West* where a clear deviation from the system was noticed during the basic measurement. This could be attributed to the unintentional fastening of the system in area of the abutment. After the removal of this fastening the calculated and expected frequency value was measured in the verification measurement. The measure could therefore be classified as successful and was correspondingly proved.

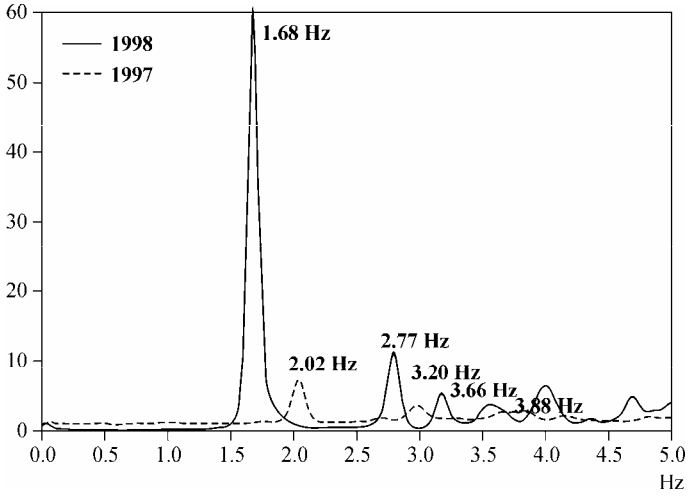

Figure 19 Frequency Spectrum of *Inn Bridge Hall West* 1997 - 1998

4.7 *Dynamic Effects on Cables and Tendons*

The dynamic behaviour of a cable is clearly defined by its free vibration length, cable mass and the inherent force according to the *cable theory* if the cable is without any bending stiffness. Since a typical cable which is used in civil engineering does have a considerable stiffness a method was developed for *AVM* cable force determination which partly bases on the *beam theory*. Bending stiffness increases the frequencies especially in higher modes because higher curvature in the mode shapes cause nonlinear relation between eigenfrequency and its respective order. Furthermore the stiffness of a cable is shortening its free vibration length (*effective length*) due to fixed support conditions entailing an increase of the eigenfrequency in all orders.

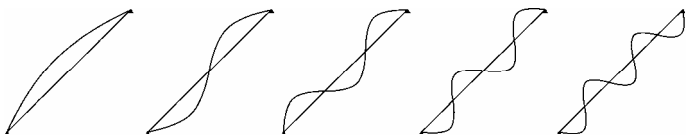

Figure 20 Increasing curvature in raising mode orders

Since bending stiffness is unknown for almost every measured cable but consideration of bending stiffness is indispensable for exact cable force determination, the stiffness has to be determined in analyses of the dynamic characteristics before the actual calculation of the cable force. The method used for the *AVM* cable force determination was developed within the European project *IMAC* (Integrated Monitoring and Assessment of Cables) were not only a high number of cables were measured in field tests but also investigations and verification on tendons and stay cables were performed under well-known laboratory conditions.

Determination of cable forces enables accurate, quick and cheap quality control under construction, after pre-stressing procedures as well as periodical supervision for safety and maintenance reasons.

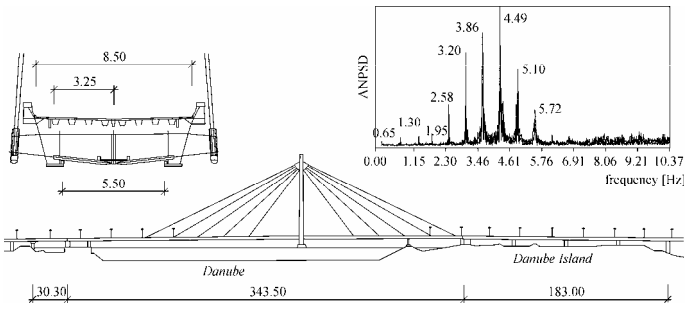

Figure 21 Characteristics of cables of the *Donaustadt Bridge*

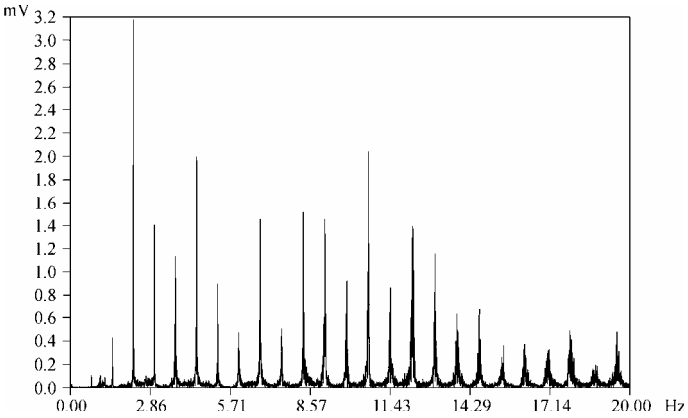

Figure 22 Spectrum of a cable of *Donaustadt Bridge*

4.8 *Parametric Excitation*

Problems with the vibration behaviour of individual structural members like cables, struts or delicately proportioned elements can often be attributed to parametric excitation. In this process the eigenfrequency of a structural member is stimulated by a frequency of the total structure. Consequently an uncontrolled vibration of cables or a fracture of individual stays in steel construction occurs. These phenomena can be quantified by measurements so that the assessment basis for rehabilitation can be derived.

Parametric excitation was particularly observed in the higher eigenfrequencies of cables. Therefore it is not sufficient to harmonize the first eigenfrequencies (basic frequencies) of the cables with the deck frequencies. The fact that cables permanently oscillate (as for example in case of the *Erasmus Bridge* in Rotterdam) is attributed to the constant supply of energy via parametric excitation at a higher eigenfrequency. The cable vibration itself mostly takes place in the second eigenfrequency with superimposed, higher frequencies. It is, however, inadmissible to draw conclusions on the energy transfer from the visually recognizable vibration form.

The possibilities and examinations mentioned up to now do not represent the whole potential of the dynamic vibration method for cables and tendons. In future probably further phenomena will be identified and covered. An extension, above all on the behaviour of road joints, has already occurred (*TU Innsbruck, Prof. Tschermanegg*) and other members, which are frequently damaged, are included. Therefore a continuously growing extension of the application field is to be expected.

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