Quality Assessment and Damage Detection by Monitoring

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Summary

Owners of structures realize the need for quality control tools to be applied for maintenance and rehabilitation planing as well as lifetime assessment. Practicing engineers highly desire quality control of construction and a feedback from structures for more economic design and better understanding of the performance. Researchers were always fascinated by the potential of full scale dynamic tests of structures. These common aspects triggered the development of structural monitoring. Each structure has it’s typical dynamic behavior which may be addressed as vibrational signature. Any changes in a structure, such as all kinds of damages leading to decrease of the load carrying capacity have an impact on the dynamic response [5]. This suggests the use of the dynamic response characteristic for the evaluation of quality and structural integrity. Monitoring of the dynamic response of structures makes it possible to get very quick knowledge of the actual conditions and helps in planing of rehabilitation budgets.

Keywords: Quality assessment, damage detection, monitoring, system identification, life-time prediction

1. General

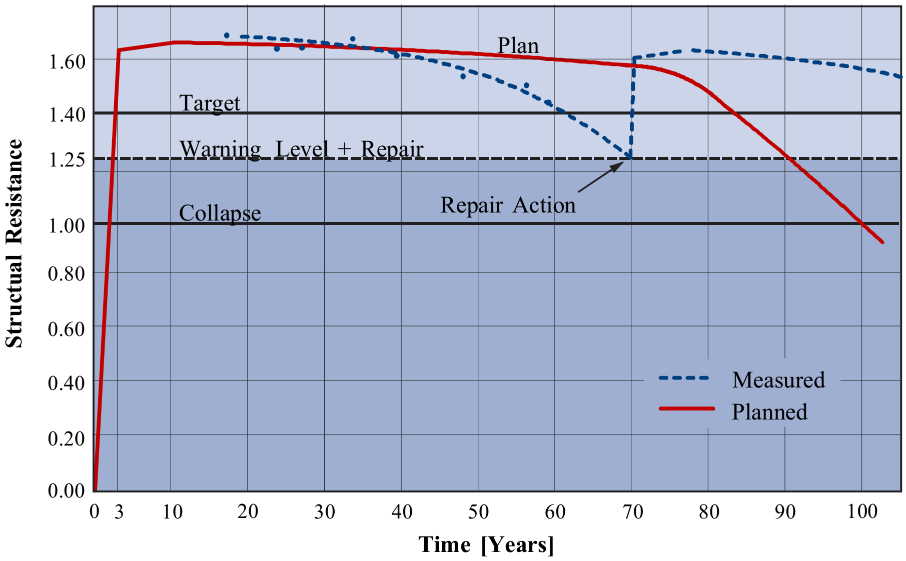

Fig. 1 Development of Resistance over time

Monitoring the quality of structures comprises a wide field of engineering tasks. The most promising recent development has been achieved with Ambient Vibration Testing and dynamic System Identification tools. Therefore this contribution concentrates on this subject.

2. Brief History

Mechanical engineers of the last century already predicted that the vibrational signature of structures and components contains all relevant information for assessment. Tests with simple structures, such as masts, date back to the early twenties. After WW2 the development was guided by the limited means available for testing and calculations. All kind of strain gages were developed and other sensors tested. The seventies brought the first applications of field accelerometers with computer aided data processing. The Forced Vibration Testing (FVT), as applied by EMPA [4] in Switzerland or ARSENAL in Austria, gave remarkable results at small and medium structures. The breakthrough came with the development of powerful PC's and sensors in the nineties. This step was documented by the contributions to the 1995 IABSE Symposium in San Francisco [2,5,8]. Ambient Vibration Testing (AVT) became feasible and powerful. It becomes more and more accepted by practicing engineers and attracts research and development.

3. Introduction To Ambient Vibration Testing

Ambient Vibration Testing does not require a controlled excitation of the structure. The structures response to ambient excitation is recorded in a large number of points. By the application of system identification technologies the frequency response functions are determined and analyzed [6]. For large and flexible structures, such as suspension bridges, cable stayed bridges or high-rise buildings it becomes too difficult and costly to provided controlled excitation at levels which are significantly higher than the excitation provided by ambient sources. The method only requires the measurement of the response to ambient excitation which might be caused by wind, traffic, waves or micro seismic activity. It is assumed that the excitation is relatively smoothly distributed in the frequency band of interest. Than the natural frequencies and mode shapes of the structure can be identified and it becomes possible to estimate damping values associated with individual modes [7]. The main advantage of this method is that normal operation, such as traffic, does not have do be influenced or shut down during testing. Traffic is a welcome source of excitation which usually provides good wide band excitation but also deserves attention on tricky side effects as demonstrated in coming chapters. A typical layout for a monitoring system is shown in Fig. 2.

Several dynamic investigations of large complex civil structures, especially bridges, have been carried out by various research institutes. Research and development activities are recorded in parallel in Europe, America and Japan. A couple of institutions in the U.S.A i.e. the Columbia University and the University of Connecticut are developing prediction methods and are working with damage laws [2,5].

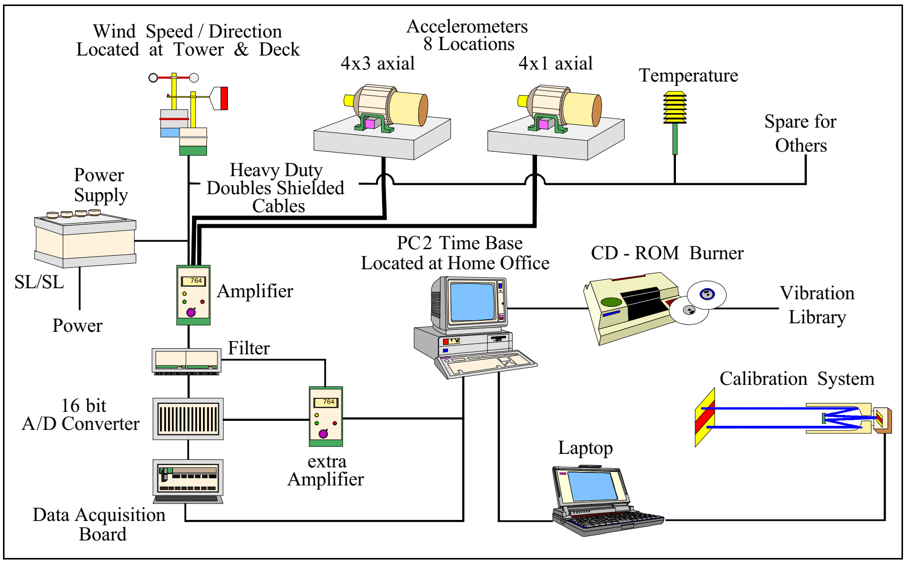

Fig. 2 Mobile system for ambient vibration testing

In Japan and the Far East large monitoring systems are very common and the Sensor technology is advanced [8]. But little has been published on the progress in system identification technologies. In Europe mobile systems have been applied successfully, so that a great number of structures were tested and the request for better system identification tools became imminent [11].

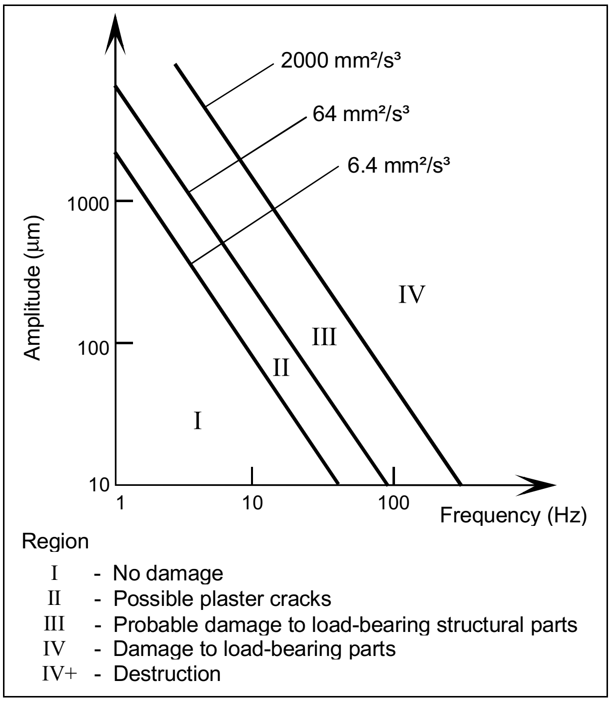

Fig. 3 Structural damage limits [3] acc. Beards "Structural Vibration"

The procedure of ambient vibration testing is straight forward. A theoretical model for the structure to be tested is created and the basic frequencies and mode shapes are determined as desired by the planer. Based on the geometry a layout of measurement points is decided and the measurement is taken under normal operation conditions [12].

Already on site the spectra are determined and compared with the theoretical values. The deeper analysis is than carried out in the home office. The result can be a comparison of desired behavior and actual behavior but also a change of behavior within a time frame, which means development of the structure over time (Fig. 1). The information content of the records is almost unlimited and in most cases the costs determine the depth of investigation.

A classification of results may be done using Fig. 3.

4. System Identification Technologies

System identification means extracting the dynamic characteristic of bridges or other civil engineering structures from vibration data. The vibrational characteristic serves as input to model calibration and damage identification algorithms. Technical development work is carried out all over the world on this subject. For reference the BRITE-EURAM Project SIMCES (System Identification Methods for Civil Engineering Structures) is referred too. Special attention was paid to techniques making use of operational data.

4.1 Peak-picking

A first method to estimate the modal parameters of a bridge based on output-only measurements (accelerations) is the rather simple, but very effective, peak-picking method. The method is widely used and practically implemented by VCE [11], EMPA [7], BAM and others.

In this method the natural frequencies are determined as the peaks of the Averaged Normalized Power-Spectral Densities (ANPSDs). The ANPSDs are basically obtained by converting the measured accelerations to the frequency domain by a Discrete Fourier Transform (DFT). The coherence function computed for two simultaneously recorded output signals has values close to one at the natural frequencies. This fact also helps to decide which frequencies can be considered as natural.

The components of the mode shapes are determined by the values of the transfer functions at the natural frequencies. Note that in the context of ambient testing, transfer function does not mean the ratio of response over force, but rather the ratio of response measures by a roving Sensor over response measures by a reference sensor. So every transfer function yields a mode shape component relative to the reference sensor. Here it is assumed that the dynamic response at resonance is only determined by one mode. The validity of this assumption increases as the modes are better separated and as the damping is lower. The method has been used successfully at VCE and EMPA for a large number of structures.

4.2 Least Square Method

Is has been shown that, under the assumption that the system is excited by stationary white noise, correlation functions between the response signals can be expresses as a sum of decaying sinusoids. Each decaying sinusoid has a damped natural frequency and damping ratio that is identical to that of a corresponding structural mode. Consequently, the classical modal parameter estimation techniques using impulse response functions as input like Polyreference LSCE, Eigensystem Realization Algorithm (ERA) and Ibrahim Time Domain are also appropriate to extract the modal parameters from response only data measured under operational conditions. This technique is also referred to as NexT, standing for Natural Excitation Technique.

4.3 Stochastic subspace identification

Unlike the two previous methods the stochastic subspace identification method directly works with the recorded time signals. The peak-picking method requires frequency domain data while the polyreference LSCE method needs the correlation functions between time signals [10].

The method assumes that the dynamic behavior of a structure excited by white noise can be described by a stochastic state space model (this statement can be justified):

$$x_{k+1} = Ax_k + w_k \tag{1}$$

$$y_k = Cx_k + v_k \tag{2}$$

where x_k is the internal state vector; n_p is the number of poles; y_k is the measurement vector and w_k, v_k are white noise terms representing process noise and measurement noise together with the unknown inputs; A is the state matrix containing the dynamics of the system and C is the output matrix, translating the internal state of the system into observation.

The subspace method than identifies the state space matrices based on the measurements and by using robust numerical techniques such as QR-factorization, Singular Value Decomposition (SVD) and least squares. Loosely said, the QR results and a significant data reduction, whereas the SVD is used to reject the noise (assumes to be represented by the higher singular values). Once the mathematical description of the structure (the state space model) is found, it is straightforward to determine the modal parameters (by an eigenvalue decomposition); natural frequencies, damping ratios and mode shapes.

4.4 Mode Shapes

The real vibration shapes of a structure consist of the mode shapes corresponding to the natural frequencies. Therefore the mode shapes are - beside the natural frequencies - the second important quantities describing the dynamic behavior of a structure. Measurements of the global vibrations in discrete points contain the contributions of the single mode shapes to the global dynamic behavior at these locations. After identifying the natural frequencies in the ANPSD the acceleration records are transformed into displacement records by a double integration process. Transformation of these time domain displacement records into frequency domain and normalisation of the displacement spectra leads to the displacement values for each natural frequency at each measurement location. The measured mode shapes are compared to the computes ones using MAC techniques (Modal Assurance Criteria).

4.5 Damping

Beside the natural frequencies and the corresponding mode shapes the damping coefficients are the third factor used for describing the dynamic response of a structure. The frequency dependent damping ratios are important criteria for structural assessment due to the fact that these ratios increase significantly when the structural resistance decreases – in other words, high damping ratios are an indicator for reduced safety. Especially prestressed concrete bridges show a distinct increase of the damping ratios when the cross sections change from uncracked to cracked state (i.e. due to loss of prestressing force). The damping ratios are extracted from the measured acceleration records by using the Random Decrement Technique (RDT). This technique was developed by NASA in the early 70-ies. It is based on the idea that averaging segments of time series of the response of a stochastic loaded system describe the system properties cleaned from the traces of the stochastic load [12].

4.6 Assessment of the Structure

When dealing with wind the so called "aerodynamic derivatives" are used for assessment. It is proposed to introduced so called **“structural dynamic derivatives”**, which are based on a similar idea. The most desired system parameters are the real stiffness and the damping of the structure. The stiffness varies with time and is influenced by creaking of concrete structures. Material damping represents the actual condition of the material with respect of fatigue and lifetime development, and system damping represents the capacity of the structure to dissipate energy (i.e. friction in bearings etc). When the actual stiffness of a structure, obtained from measurement, is known, it is a simple task to introduce it into the calculation and rerun the structure. This gives a distinct value for the remaining structural capacity. It can be expressed in a percentage.

5. Quality assessment and damage detection

The use of the described tools and the key-points under discussion are most usefully described in examples.

5.1 Assessment of Cables

Cable stays are exited by moderate wind and rain. Out of many cables only a few are concerned. Monitoring is able to identify those cables where the critical damping is below 0.3%. Adequate damping measures can be designed with the data and the effectiveness can be tested after installation. The method was applied at a couple of cable stayed bridges already. One of the most regent cases was the new Donaustadt - Bridge in Vienna which spans the Danube with an eccentric main span of 186 meters. 8 out of 20 cables where effected by the phenomenon and the problem was solved by installation of tiny tie ropes between adjacent cables.

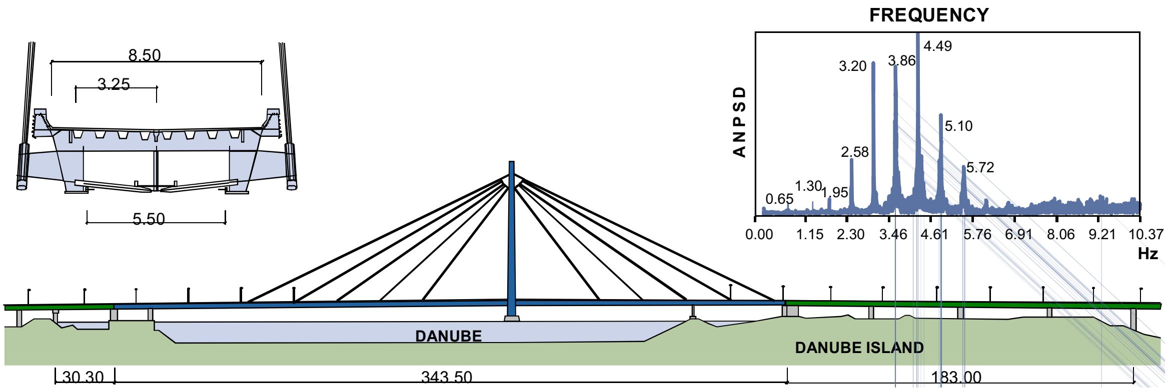

Fig. 4 Elevation, cross section and spectrum of cable 10 N

5.2 Vibration Mitigation

Two reduce noise and particular vibration emissions of railway lines mass spring systems have been developed during the past year. The vibration attenuation capacity of such systems depends on the natural frequency and the damping ratio which are controlled by the mass and the spring stiffness. The effectiveness of such systems can be tested by the described system identification technologies. Series of tests are carried out to conform the design integrity of the system. The thermal behavior of the huge concrete mass, a couple of 100 meters of concrete mass is pureed in one piece, the actual displacement under train loads and the vibrational behavior is monitored. The finite element calculation can be calibrated by the results and the transfer functions from the sources of vibration to the target structures is determined. The quality of a design idea is assessed as well as the function in reality is documented. As and example the 1,176 m long continuos mass spring system of the Zammer Tunnel for the Austrian High Speed Railways is presented (Fig. 5). It was found that the targets have been over fulfilled which provided the basis for more economic design in the 2. case where the technology has been applied.

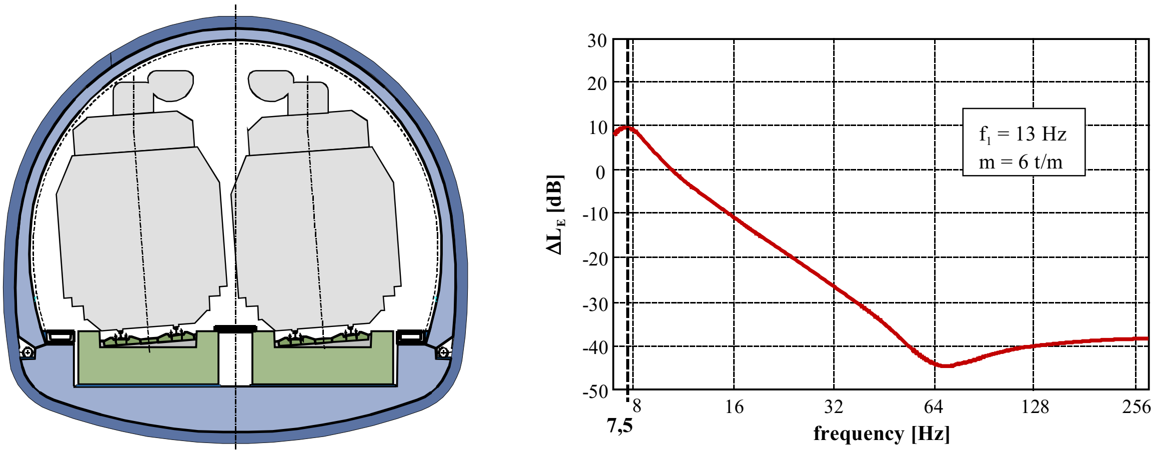

Fig. 5 Mass-spring-system of Zammer tunnel and frequency attenuation

5.3 Damage Identification

Construction joints of concrete bridges built in the 1960'ies represent notorious week points. The Großram – Bridge is a typical continuos structure built by the advancing shoring method. During earlier inspections a defect construction joint was identified. The joint opened under heavy loads exposing the prestressing tendons to moisture and salt attack. The joint was repaired and strengthened by clued fibre plates. The task for the monitoring team was to assess the quality of the strengthening work and the function of this important structure. It was demonstrated that the damage was repaired successfully and the capacity of the structure was restored. The assessment was carried out using Modal Assurance Criteria (MAC) which provide figures for modal fitting between calculations and test data. Fig. 6 shows the superimposed modes in theory and practice.

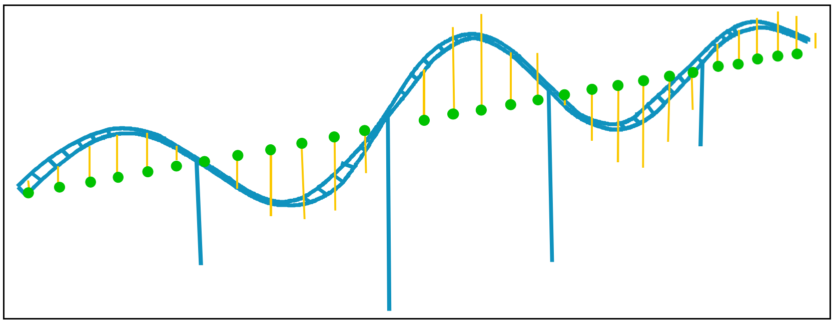

Fig. 6 Comparison between calculated and measured data

4 Pier Settlement

System identification is a most valuable tool for the determination of soil structure interaction phenomena. The most common simple assessment by the engineer, that piers are rigidly connected to the ground can be quantified by measurement carried out under operation.

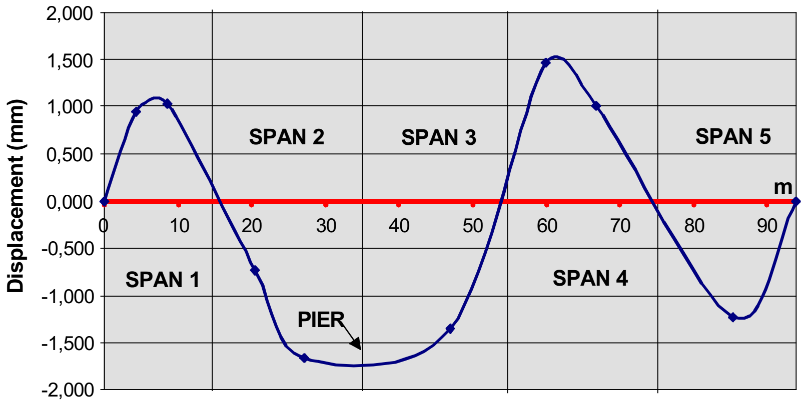

Fig. 7 Displacement of the structure under heavy traffic

The best indicator is a change in mode shape as shown in Fig. 7 for the Gurk – Bridge where a pier settles periodically with heavy loading. This settlement with a period of 20 sec. and a displacement of 8 mm indicates a beginning damage of the foundation. This findings led to immediate action by additional supports to the structure to avoid a collapse. The displacement should be very close to zero of piers in continuous structures. In Fig. 7 the settlement of the pier is obvious.

5.5 High-rise Buildings

The dimensions of the load bearing columns and members of high-rise buildings are depending on the assessment of realistic loading from wind-forces and life-load. When an existing system is measured and the results are compared to the design, experience can be gained for the design of future projects. Another benefit in high-rise buildings is the determination of real displacement, which has influence on the design of the facade and other structural elements. Currently under development is a method to assess glass or precast panels of high-rise structures on instability or their potential of failure. The comparison of the vibrational characteristic of neighboring similar panels provides an easy and quick option for assessment.

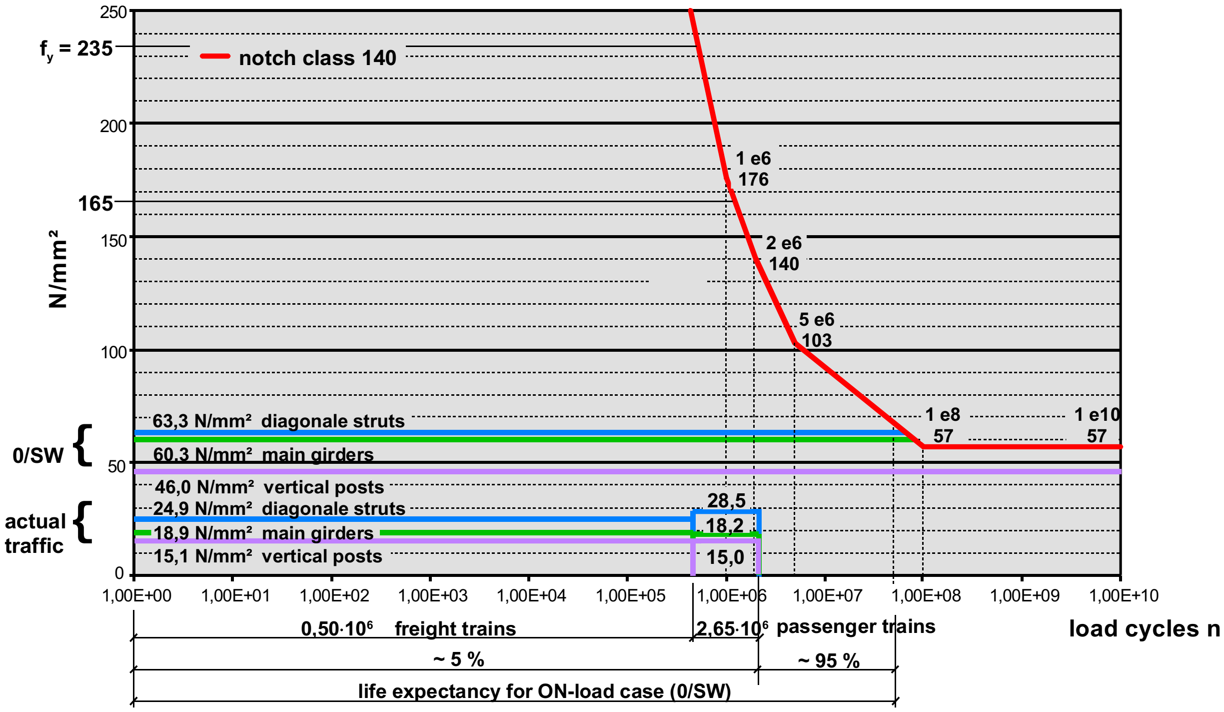

Fig. 8 ÖBB-Bridge Tulln – max. fatigue stress for superstructure 1 and life expectancy

5.6 Assessment of old Steel Structures

There are huge numbers of bridges older than 100 years in our railway systems. The desire for higher axial loads and higher speed of trains requires an assessment of these structures. The fact, that these bridges very often consist of a number of equal single span girders allows a typical qualitative comparison between each other. While monitoring the 5 span railway bridge across the Danube at Tulln differences in the vibrational characteristic could be identified as repair actions after damages during the 2. world-war. The correct acting structural system including the effect of the repair-works could be established and the finite element model now represents the real behavior of the structure.

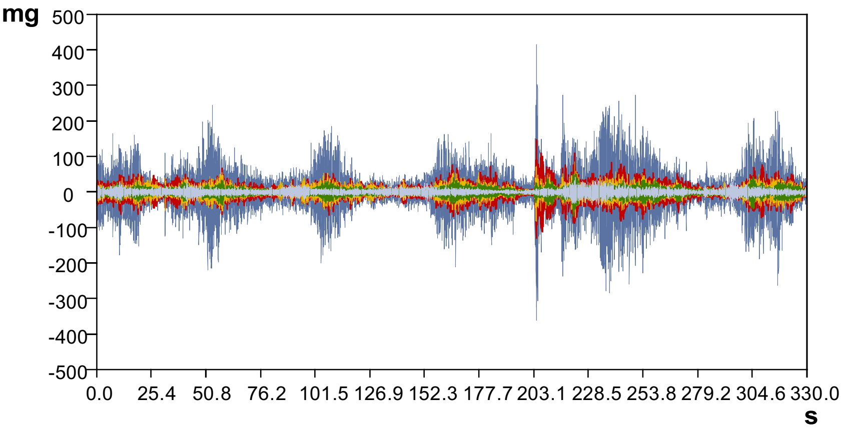

Fig. 9 Peak acceleration of 0,42 g for the cantilever tip of the Europabrücke

In addition the assessment of the remaining life-time of the structure was carried out with the use of the load collective determined from the railway-data and the comparison to typical Wöhler Diagrams. In Fig. 8 a typical life expectancy for a 100 year old railway bridge is shown. It has to be noted that a perfect assessment of the remaining life-time is impossible due to the high scatter of the fatigue tests. Anyhow a secure remaining life-time can be determined.

5.7 Assessment of Structural Elements

Structural elements of steel bridges may experience dramatic changes in loading when bridges are retrofitted or strengthened. System identification also serves for the determination of the behavior of single members within a complex structure (Fig. 9). In case of the record breaking Europa - Bridge an additional lane was introduced and the structure had to be widened by 3 m. This creates unbalanced systems for the orthotropic deck which has considerably larger cantilever arms now. The behavior of the cross-section had to be determined to find out the real loads on diagonal beams.

5.8 Traffic Control by Tele-Monitoring

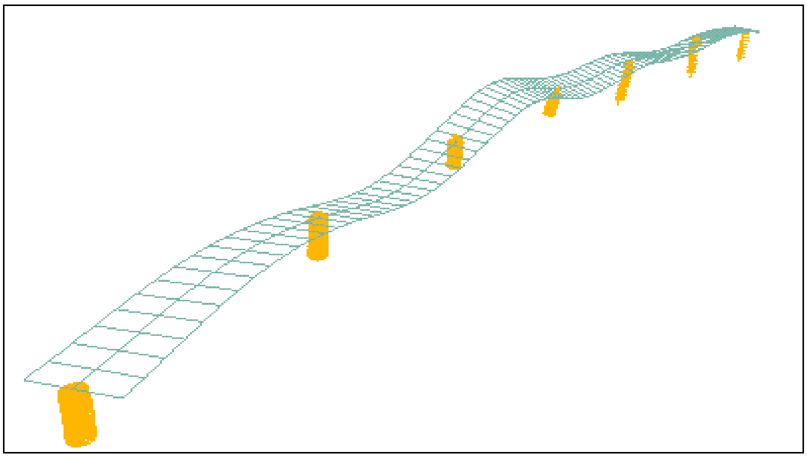

Fig. 10 Animated first mode of the St. Marxer Hochstraße

Permanent monitoring of structures enables the engineer to gather data on the long-term performance of bridges. When the system is clearly identified, each new recorded response can be classified and counted. After a reasonable amount of time sufficient information for a realistic fatigue calculation are collected. A side effect is the identification of extraordinary loads on the structure.

For this purpose a bridge in Vienna was instrumented with a Tele-monitoring system, consisting of accelerometers linked with a Video-system, that provides information on the traffic conditions at certain structural response levels. The well-known thesis, that high-loads at low speed are less harmful to the structure than standard loads at excessive speed, proved to be valid. Furthermore this type of instrumentation provides the chance to get actual traffic information via Internet.

5.9 The Effect of Temperature and Traffic Loads

It was found that the temperature effect might be dramatic in case of very rigid structures with small spans. In case of major bridges this effect can be neglected in the assessment of the vibrational characteristic. At the Schottwien – Bridge with a main span of 250 m and 12 m high girders at the support measurements were taken over a temperature range of 17°. Due to the fact that this bridge is virtually unloaded every night very clear ambient signals have been received. The change of the dominant first Eigenfrequency is within 1% over the full temperature range and can therefore be neglected. This phenomenon has been confirmed on other major structures. In minor structures the strain from temperature changes the characteristic within a range of 5%, which can not be neglected anymore. The results have to be calibrated by statistical means. Therefore it is essential to record the ambient temperature at each monitoring action. The effect of traffic loading on the bridge was tested at the Nordbrücke where 105,000 vehicles pass daily with distinct peaks at rush hour. It was demonstrated that the method can deal perfectly with different load scenarios.

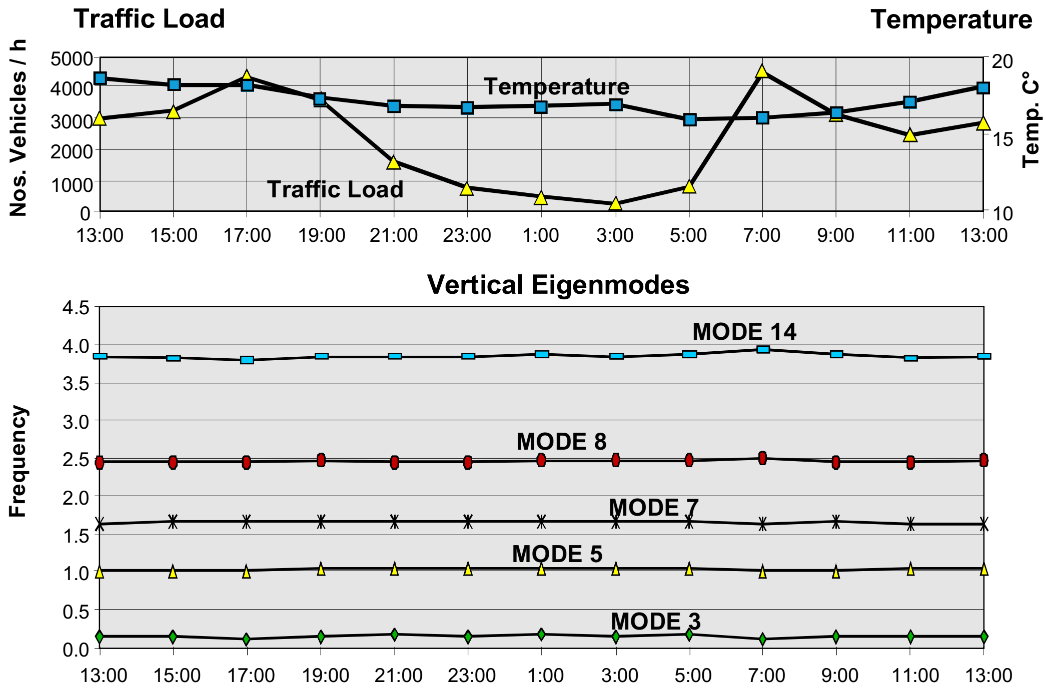

Fig. 11 Effect of vehicle load on the vertical modes (24 hours)

5.10 Quality Control of Construction

The vibrational characteristic changes with each construction stage. Monitoring instruments are able to record these changes and therefore confirm the quality of construction steps carried out. Another benefit is that major impacts are recorded which might influence the quality of the structure. In case of cable stayed bridges the stresses in the cables can be monitored and compared to the desired values. Another application is the check of the removal of temporary fixations during construction. Complex systems can so be checked easily as demonstrated in Fig. 12.

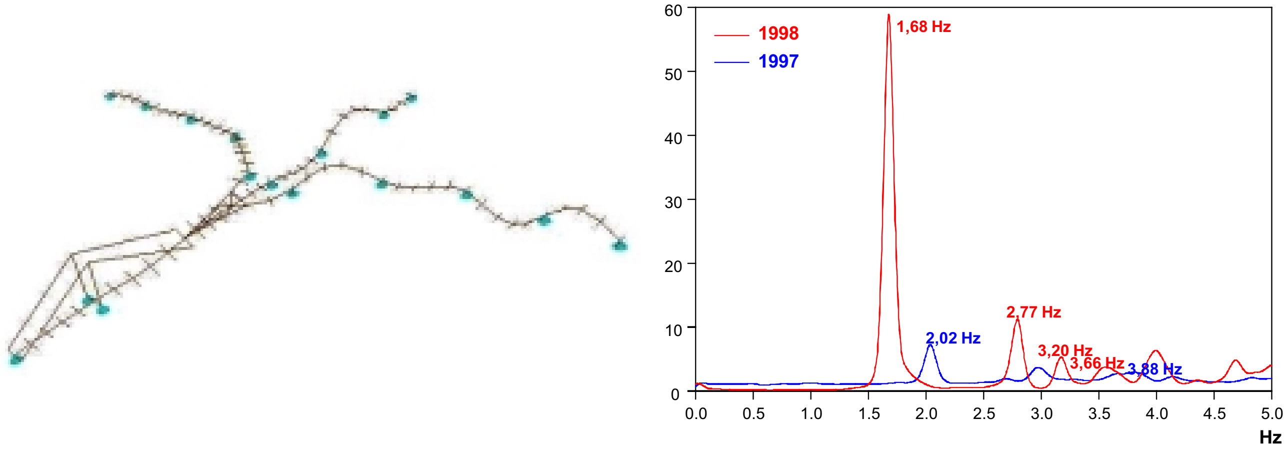

Fig. 12 Hall West Bridge, effect of the release of a horizontal restraint

5.11 Assessment of External Prestressing Cables

Due to the growing importance of external prestressing assessment tools are desired for the existing structures. With the application of similar algorithms as used for stay cables the external prestressing cables can be assessed on the actually existing forces and on the global behavior of the structure, particular after retrofit measures. As an example the Mur-Bridge St. Michael is shown, where excessive displacements have been stopped by external cables. The cables have been assessed one by one by acceleration measurement and the safety of the global system was determined.

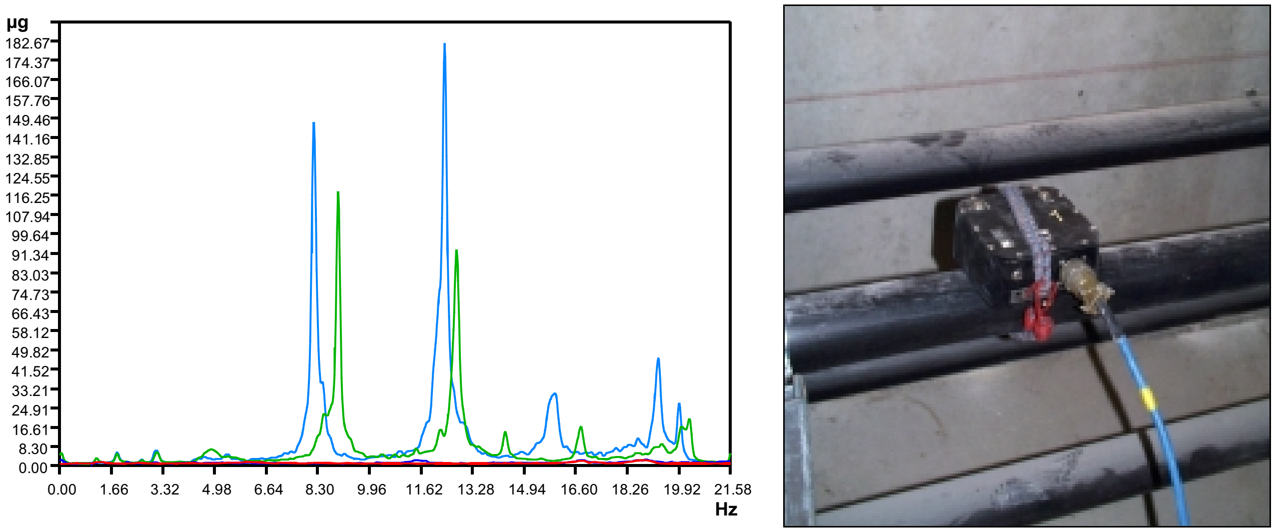

Fig. 13 Simple measurement of spectrum and related cable frequencies

5.12 Structures of the Cultural Heritage

The described method is not limited to bridges and towers, but can also be applied at monuments of the cultural heritage. The exceptional statue of Erzherzog Karl at the Heldenplatz in Vienna represents one of the two largest statues with a horse-rider situated on the two back shoes only. This 12 m high Bronze-statue is surrounded by thousand of tourists daily. The material properties of the structure formed 160 year ago can be assessed by the application of the vibrational characteristic method (Fig. 14). Consecutive measurement over a period of time provides information on the development of the structural integrity. Further application in this respect are the assessment of cantilever staircases built from natural stone, the assessment of the tiny structural members of Gothic churches and the integrity of Frescos and Mosaics.

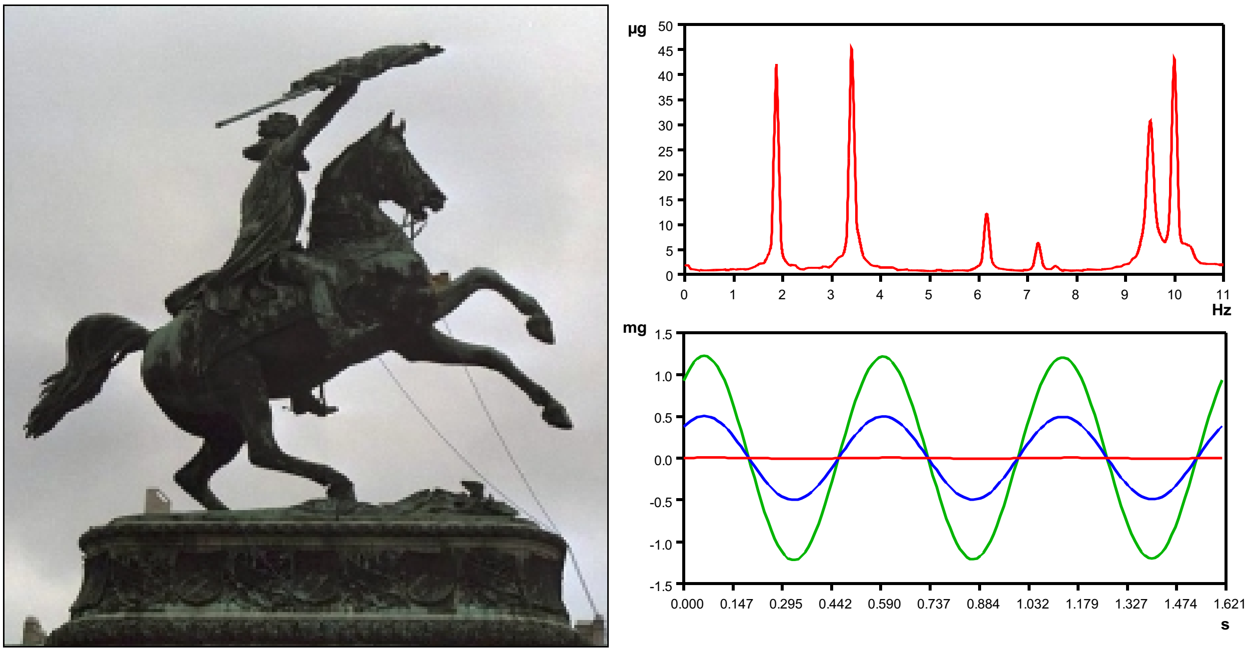

Fig. 14 Erzherzog Karl Statue with ambient spectrum and damping window

6. Outlook

Structural monitoring is in the transition phase from being scientific and educational only to commercial exploitation. The research and development work is still too much concentrated on basic research. In the 5th Framework program of the European Union monitoring plays a key role with the key-words on structural assessment and damage detection. Due to the end-user orientation these projects will come up with practical solutions for the engineering society. It is planed to form a cluster of projects consisting of:

- A bridge monitoring project including damage detection
- A high-rise building monitoring project including wind design optimization
- A cultural heritage monitoring project including detail assessment of surfaces
- A demonstration and data collection project providing free access to data
- A basic research project on damping and related issues

Two main facts are hindering the dissemination of the methods. First of all good equipment is rather expensive and suffers from the rough construction environment. The application requires expensive specialists which increases the costs of the action. The second problem is the absence of monitoring in the education of structural engineers and the related low level of information in the clients organizations. The enormous potential of monitoring is widely unknown.

Considering all this facts future key-actions shall concentrate on:

- The development of reliable, cable-less monitoring systems which can be purchased at reasonable costs
- The development of software-tools for application by concerned engineers without the necessity of expensive specialists
- The education of the engineering society with respect to monitoring and its potential

Considering the experience made with over 60 structures monitored, where 20% of the cases showed considerable differences between design and reality, monitoring should find its way to be a standard tool for structural engineers in future.

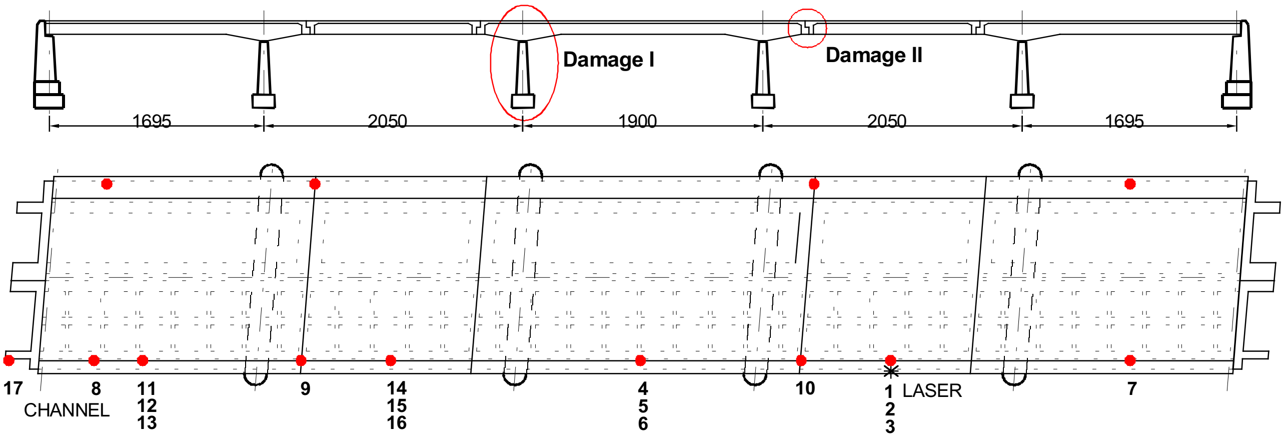

Fig. 15 Area of damage identified by system identification

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