Summary

The integrity of structures that form part of our Cultural Heritage is difficult to assess. During disasters, such as earthquakes precious objects are destroyed and loss of life (i.e. Cathedral of Assisi) often occurs. In case the structural performance under ultimate conditions is known reasonable strengthening could be undertaken in time. Bridge and Mechanical Engineers have developed non destructive test methods for the assessment of structures and components. They are based on ambient vibration tests that provide the so called “Vibrational Signature” of a structure from which weaknesses or hidden damage can be located. There are three major branches developed, which attract interest for the assessment process:

- Assessment of the structure itself and damage detection (church towers etc.)
- Assessment of structural details and members by laser spectrography (statues etc.)
- Assessment of surfaces by spectrography (frescos and mosaics)

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

1. General

Structures vibrate permanently in their natural frequencies. This displacements of micro millimetres are recorded and processed that it can be compared to theoretical FEM calculations. The spectral analysis and random decrement technology for damping determination reveal the weak points. The success of strengthening or retrofit can be measured as well.

The existing monitoring systems have been further developed to suit the low level of vibration in massive structures. Suitable filter and amplifier technology are developed to suit the high standards required. The evaluation and assessment algorithms require intensive further development to suit these most complicate cases. The now applied method are reduced to plain problems and have to be extended to complex structures.

1.1 Ambient vibration testing

Each structure has its typical dynamic behavior which may be addressed as vibrational signature [16]. Changes in a structure such as all kinds of damages leading to decrease of load carrying capacity have effects on the dynamic response. This suggests the use of the dynamic response characteristic for evaluation of a structural integrity. Monitoring of the dynamic response of structures makes it possible to get very fast knowledge of their actual condition.
Ambient vibration testing is under development since many years and has been applied successfully particular on bridge projects. It has been demonstrated that monitoring results can support the structural engineer in the assessment process and provide a quantification of structural properties. Research and development now concentrates on the definition of damage laws, that allow an automatic diagnosis of structures. The process of elaborate instrumentation, measurement and analysis of dynamic response data supplemented by immediate or long-term maintenance and rehabilitation programs can be considered as health monitoring.

1.2 Application on the cultural heritage

The basic principals of a health monitoring are the same in bridges or any other structure. The difficulty with the structures of the cultural heritage is, that they are built from less defined materials, that their behavior under heavy load is particular nonlinear and damages occurred earlier, influence the behavior considerably. Furthermore it is a fact that these structures are in most cases considerably stiffer than a typical bridge and therefore do not show this clear behavior. The aim of recent research projects was to create a better understanding of the structural behavior and its representation in the measured data.

2. Technologies

The structures of the cultural heritage vary in their characteristics considerably. It is therefore necessary to have a wide range of monitoring methods available for selection. A key requirement of the owners is the absolutely non destructive testing.

2.1 Assessment of massive structures

In churches or castles typical structural elements are towers, arches or combined elements that are often consisting of material with dry joints. Here the classical ambient vibration testing methods are applied by the positioning of accelerometers in pre-determined suitable positions. Due to the low level of excitation these instruments just have to be laid on top of the structure. By measuring and combining the necessary number of points the eigenfrequencies and eigenmodes can be determined accurately. These have to be compared with the finite element model to be established for the structure. Opposite from bridges, where the finite element model can be pre-determined expressing the will of the designer, in structures of the cultural heritage often the finite element model is calibrated by measurement. This means that an updated, as close as possible to reality, model is available for the assessment. Here in particular the value of the analysis of the eigenmodes is demonstrated. It was shown that particular cracks or open joints are much better represented in the eigenmodes then in any other dynamic property.

2.2 Assessment of structural details and members

Many of our famous churches show a huge number of pinnacles around the towers and all over the structure. They are mainly composed of natural stone erected with dry joints and only partly equipped with metal bolts. The fact that there are in most cases a huge number of similar pinnacles the application of statistical method makes an assessment possible. By simple comparison of eigenfrequencies and eigenmodes of similar pinnacles those who are damaged (different) can be easily identified. To be of use the measured natural frequencies need to be compared with another dynamic property and this may belong to one of the following 3 groups:

- The average frequency of similar simple structures
- The frequency of the structure measured previously
- A calculated frequency of the structure

Each type of comparison has its own application and limitation. BRE (British Research Establishment) of England has carried out non-destructive tests to evaluate the integrity of 534 stone pinnacles of the Palace of Westminster. It has been shown that only 5 of these huge number of pinnacles have to be assessed as suspect. They will be further assessed by other methods and intensified maintenance will be applied. By this measures the safety of the structure was quantified. [6]
2.3 Assessment of surfaces

The smaller structural elements become the higher frequencies are involved. Anyhow the basic principals of ambient vibration testing are applicable as well. In case of surfaces, this includes also paintings and mosaics, vibrations are measured by laser spectography and assessed by the same principles mentioned above. In many cases it becomes useful to introduce power at a low level by application of sound through acoustic actuators. The response of the surface is measured and analyzed by FFT analysis. The eigenmodes are plotted in 3 dimensional way, where inconsistent behavior of any part of the structure is immediately visible. This can be used for the assessment of necessary rehabilitation methods for frescos and mosaics, where the cost may vary in the magnitude of a hundred times. A very interesting research project in this field has been carried out by the University of Ancona. [4]

2.4 Nonlinear acoustic diagnosis

The most innovative approach to the problem of damaged detection comes from acoustics. The idea starts from the actual fact that in many materials, like steel, concrete, rock, soil and many other, the nonlinear elastic properties are linked with the level of damage. [9] By mastering the nonlinear elastic process and their coupling it is possible to pull out information from an experiment. In case that the input is known (i.e. a modulated low frequency produced by a localized shaker), than the elastic nonlinearity of the medium lead to modification of the output spectrum (13). Most of the structures are subject to continuous random vibration noise due to traffic, river-flow etc. This level will be the low frequency spectrum of excitation and will be monitored by the normal ambient vibration methods. The high frequency inspection will be supported by a mobile vibrating source, for example a high frequency piezo electric shaker, which is mounted at the structure at characteristic points. The Sensors read the 3 groups of signals, the low frequency ambient spectrum, which represents the source of continuous fatigue and future damage, the high frequency spectral response to the shaker and the high frequency modulated signal coming from nonlinear sources located in the damaged area. The damage is then identified by the knowledge of the structure, the behavior of the structural elements under dynamic loads and the level of low and high primary frequencies. This method is still in the conceptual phase and is intended to become a subject for a major research project under the 5th framework program of the European Union.

The nonlinear stress – strain relationship intended to be used is on the one side the atomic (nanoscale) nonlinearity, where crystals and crystal-like materials, symmetries and coupling with other physical properties lead to higher order tensors of elasticity (Curie law). Most of active materials are likely to share that behavior. On the other hand the mesoscale nonlinearity represents the fact that most of natural and handmade materials are produced in complex processes leading to mesoscale structure (grain, polycrystalline clusters etc.) and to a large family of defects (voids, grainbond, flow etc.). The very first origin of nonlinear elastic behavior belongs to the mesoscale structure, that leads to odd symmetry stress-strain, to hysteric response and even to end point memory behavior. These properties are met in rocks, concrete, ceramics and even in metallic alloys. Experimental experience has been gained in Russia on that subject.

3. Applications

A number of applications have been carried out. The following examples are representative for the trend in the monitoring community.

3.1 St. Laurentius Church Vienna

During the extension of the underground U3 network the church at Breitensee was subject to tunneling works close to their foundation. To monitor the influence of the tunneling on the structure existing cracks have been instrumented and watched throughout the works. Using standard methods very good results have been achieved. Correlation with ambient influences like temperature has been found and documented.
3.2 Statue of Erzherzog Karl in Vienna

The methods of vibration analysis have been applied not only to bridges and towers, but also monuments of the cultural heritage. The exceptional bronze statue of Erzherzog Karl at the Heldenplatz in Vienna represents one of two largest statues with a horse-rider situated on the two back-shoes only. This 12 m high bronze statue is surrounded by thousands of tourists daily. The material properties of the structure, formed 160 years ago, can be assessed by the application of the vibrational characteristic method. Consecutive measurement over a period of time provides information on the development of the structural integrity.
3.3 Stone Pinnacles on the Palace of Westminster

The Palace of Westminster is a historic landmark in London and of great national importance as it houses the parliament of the United Kingdom. At BRE in England Brian Ellis introduced a remarkable method for assessment. The maintenance of the Palace is a continuous and interesting task. A conservation policy has been established including the following two items:

- To retain and conserve as much of the original fabric and decorative detail as possible
- To use non-destructive testing where possible to avoid the loss of original fabric.

A particular problem is the integrity assessment of the decorative stone pinnacles that adorn the Palace. Pinnacles, which are made of limestone and contain a central vertical metal dowel, can be quite substantial structures with a height of several meters and like all structures the pinnacles will deteriorate with time. Over many years several pinnacles have failed with consequential damage to the structure. A total of 534 stone pinnacles are recorded.

The solution to the problem was to monitor the fundamental natural frequency of the pinnacles. This is a relatively simple parameter to measure, yet provides basic information on the relative overall stiffness and mass of the pinnacle. Initially a number of pinnacles were tested using impact tests to proof the method. While the impact tests were satisfactory and could be used on the smaller pinnacles, they where not suitable on the use on the larger pinnacles, which could not be approached safely unless scaffolding was provided. For these pinnacles a laser-test system was used. The key of the test system is the photometry laser interferometer, which is a long range laser capable of measuring sub-micrometer vibration at distances of up to 150m from concrete surfaces. The system has been developed for measuring vibrations inline with the laser beam. The laser beam is focused on a position near to the top of the selected pinnacle. The main output is an analog voltage which is proportional to velocity and hence the vibration velocity of the pinnacles can be monitored remotely. The analog output is digitized at a selected sampling frequency.

The assessment is mainly done through comparison of frequencies and spectra of similar pinnacles. In addition finite element models have been introduced to predict the response.

Fig. 3 Laser-monitoring and velocity record of damaged vs sound pinnacle
3.4 Assessment of Frescos and Mosaics

At the University of Ancona non invasive measurements of damage of frescos, paintings and icons by laser scanning vibrometer have been carried out by Paolo Castellini et alia.

Fig. 4 Local delamination record and monitoring equipment

Frescos and icons show analogies in terms of defects, both present layer to layer detachments and delaminations as well as surface cracks. The target of the work was to develop a diagnostic system for the measurement of the defect’s position and size. After initial measurements setups based on accelerometers and impact hammers a novel system based on laser vibrometers and acoustic stimulation of structures to allow full remote and contact-less investigation of detachments and delamination have been developed.

Fig. 5 Measurement results on a fresco in a church near Ancona - (a) fresco photo (b) fresco RMS vibration map (c) fresco defects map as supplied by the restorer.

A new kind of exciters, namely Piezo Actuators, have been introduced in the measurement chain and its effectiveness in finding defects in icons have been demonstrated. The project has been developed within the LASERART project which is an EC founded research program.

First tentative in situ measurements have been carried out in a chapel near Ancona. The results are quite encouraging because the feasibility of the technique was demonstrated and it showed fair correlation between the work of the restorer and a vibration map obtained by the vibrometer.

4. Conclusion

A number of state of the art technologies have been developed over the past years for structures, bridges and buildings. The methodologies applied there have been transferred and refined by engineers working at the cultural heritage. Great effort was given by the research programs of the European Union, particular under the 4th and 5th framework program. The results of these works are
very encouraging and suggest the practical use of these methods. Anyhow the applications are still singular cases but deserve to be picked up by engineers working in practice. Further interesting works can be expected in the near future.

References