Damage detection and bridge classification by ambient vibration monitoring – application of BRIMOS at two stay cable bridges in China

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Abstract: In this paper the application of BRIMOS (Bridge Monitoring System) on two cable stayed bridges in China is described. Harbin Institute of Technology has provided two bridges for these tests, one is Shandong Binzhou Yellow River Bridge and the second is Harbin Songhua River Bridge. Both bridges are equipped with health monitoring systems with various advanced sensors. VCE tested its mobile monitoring equipment on both bridges in May and June 2006. Mobile monitoring equipment for quick and easy bridge assessment might be a useful compliment to the many big and sophisticated monitoring systems at bridges in China. The focus of the paper is on the technical performance of the monitoring equipment and on the quality of results. The experience of the monitoring campaign is a win-win situation for both partners with regard to monitoring system development and measurement data interpretation. By the collaboration of different universities and companies of different countries and continents, a fruitful discussion can develop.

Key words: Cable stayed bridge, Structural health monitoring, Vibration monitoring, Permanent Monitoring, Periodic monitoring

INTRODUCTION

Owners of structures realised the need for quality control tools to be applied for maintenance and rehabilitation planning 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. The base for this type of monitoring is that each structure has its typical dynamic behaviour which may be addressed as vibrational signature. Any changes in a structure, such as all kinds of damages which lead to a decrease of the load-carrying capacity have an impact on the dynamic response. This suggests the use of the 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 current conditions and helps in planning of rehabilitation budgets.

Therefore different monitoring systems based on the analysis of the dynamic characteristic have been developed recently. Owners of concrete bridges require assessment tools
for those components which cannot be inspected visually. The BRIMOS technology (Bridge Monitoring System), developed by VCE in the last few years, provides additional information for the bridge inspector to carry out an accurate assessment of the condition and the remaining lifetime of the bridge.

Figure 1. Costs vs. maintenance effort of bridges.

THE BEGINNING OF THE BRIMOS DEVELOPMENT

Prestressing Steel with a yield strength of 145/160 kP/mm² was used in early post-tensioned bridges until the year 1965 in Germany and Austria. These tendons were called “Sigma Oval” and “Neptun N40”. Tests performed on this steel quality raise doubts that specific early charges show a proneness to stress crack corrosion. After a sudden spectacular failure of a prestressed beam of an industrial building in Germany in 1993 detailed investigations have been done. Due to an additional damage on a highway bridge in Austria in 2000 all structures built with the specific type of prestressing steel were assessed very carefully.

This was done by conventional methods and in addition with the vibration characteristic method BRIMOS developed by VCE. During these tests on 28 bridges in Austria, 5 of them turned out to be in a critical condition. In the framework of an Austrian research project VCE had the chance to introduce artificial damages to this 5 structures and to study the effects to dynamic response. The damages on one structure were possible until failure.

Figure 2. Location of bridges with problematic condition.

INTRODUCTION TO AMBIENT VIBRATION TESTING

Ambient Vibration Testing does not require a controlled excitation of the structure. The structure’s response to ambient excitation is recorded in a large number of points. By the application of system identification (SI) techniques the frequency response functions are determined and analysed. For large and flexible structures, such as suspension bridges, cable-stayed bridges and high-rise buildings it becomes too difficult and costly to provide controlled excitation (forced testing) 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 (white noise). Then the natural frequencies and mode shapes of the structures as well as the other remaining modal parameters can be identified. The main
advantage of this method is that normal operation, such as traffic, is not influenced or interrupted during testing. Traffic is a welcome source of excitation which usually provides good wide-band excitation but also deserves attention on additional effects.

The bases for the assessment of structures by the ambient vibration method are the so-called modal parameters, i.e. natural frequencies, mode shapes, damping values and vibration intensities. In addition a new development, the trend cards, are a very good indicator for assessment.

BENCHMARK TESTS

During tests on 28 bridges in Austria 5 of them turned out to be in a critical condition. It was decided to replace them because rehabilitation would have been too costly and therefore not desired. The experience from the BRITE-EURAM project SIMCES was studied in detail before the field tests were planned in detail. The possibility to apply artificial damages to 5 post-tensioned structures in real scale was a great chance to improve the existing knowledge. Therefore all tests had to be planned very carefully. Main focus was put on the identification of damages in prestressing tendons, which are currently assessed by visual or very local inspection techniques.

A global assessment of the structure pointing out prospective damages and damage locations is urgently required for the bridge owners. Before the structures were damaged detailed vibration tests were performed, using a sensor setup with high density. A second measurement sequence was performed after removing the pavement in order to quantify the effect caused by the additional load. It was shown that the pavement only has influence on the natural frequency due to the additional load. There was no stiffening effect recognizable. System Identification was performed with the simple but effective peak picking method.

![Figure 3. Ambient vibration testing of a structure.](image)

The assessment of the capabilities of dynamic methods was done by introducing artificial damages to the embedded tendons. For the first bridge, this was done by cutting the tendons which turned out to be a very complicated and time-consuming task. The other bridges were damaged by drilling cores to the structure. This was a very sensitive method for damaging tendons in a sequence.

DAMAGE ASSESSMENT

System identification (SI) means extracting the dynamic characteristics of bridges or other civil engineering structures from vibration data. Vibration characteristics serve as input to modal calibration and damage identification algorithms. Technical development work is carried out all over the world on this subject.

One of the recent projects was the BRITE-EURAM project SIMCES (System Identification Methods for Civil Engineering
Structures) which focuses on the subject of damage identification based upon ambient vibration measurements. During this project good results have been obtained, and an extensive amount of new knowledge was created.

PEAK PICKING

The simplest approach to estimate the modal parameters of a structure subjected to ambient loads is the so-called Peak-Picking (PP) method. The method is named due to the key step of the method: the identification of the eigenfrequencies form the spectrum plot (Fig. 6). The method is widely used and practically implemented by VCE, EMPA, BAM. Probably because of its simplicity it is the most widely used method in civil engineering. Recent applications make use of the high sophisticated Maximum Likelyhood Identification or the Stochastic Subspace Approach.

MAXIMUM LIKELIHOOD IDENTIFICATION (FREQUENCY DOMAIN)

Maximum Likelihood (ML) identification is an optimization based method that estimates the parameters of a modal by minimizing an error norm. A discussion on the use of the ML estimator to identify parametric frequency-domain models can be found in (Schoukens & Pintelon, 1991). The ML method results in equations that are non-linear in the unknown parameters. This requires an iterative procedure with related problems such as convergence, local minima, sensitivity and high computational effort. Recent applications have overcome this problem, thus ML identification is a robust method to find the modal parameters of a structure from large and noisy data sets.

STOCHASTIC SUBSPACE IDENTIFICATION (DATA DRIVEN)

The main advantage of data-driven algorithms is that they do not require any further preprocessing in order to obtain spectra or covariances. These methods identify models directly from the time signals. The data-driven subspace method is closely related to the covariance-driven subspace method. Recently a lot of research effort in the system identification community was spent to subspace identification (Overschee & De Moor, 1996).

Subspace methods identify state-space models from (input and) output data by applying robust numerical techniques such as QR factorization, Singular Value Decomposition (SVD) and least squares. As opposed to the covariance-driven SSI, the data driven Stochastic Subspace Identification method avoid the calculation of covariances between the outputs. It is replaced by projecting the row space of future output into the row space of past output. In fact, the covariances and projections are closely related. They both are aimed to cancel out the uncorrelated noise.

MODE SHAPES

The real vibration shapes of a structure consist of the mode shapes corresponding to the natural frequencies. Therefore mode shapes are - beside the natural frequencies - the second important quantities describing the dynamic behaviour of a structure. Measurements of the global vibrations in discrete points contain contributions of single mode shapes to the
global dynamic behaviour 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 computed ones using MAC techniques (Modal Assurance Criteria).

VIBRATION INTENSITY

Those vibration a structure may be subjected is usually considered with respect to its effect on the structure itself, and not on its occupants, equipment or machinery. Modern structures are less massive and have lower damping than in the past. More sophisticated design and analysis techniques now generally lead to less redundancy. The consideration of vibration limits therefore becomes increasingly important for the maintenance of structural integrity. Structural vibration limits for particular damage risks can be classified according to the level of vibration intensity.

DAMPING

Beside the natural frequencies and their 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 un-cracked to cracked state (i.e. due to the 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 70s. It is based on the idea that average segments of time series of the response of a randomly loaded system describe the system properties cleaned from the traces of the stochastic load.

BRIMOS RECORDER

One major result of the artificial damages is the knowledge that only one sensor located at a specific point of the structure leads to a good impression about the structural performance. Using these results a rough ranking of the structures can be done, showing the necessity to more detailed investigations. For this purpose a compact monitoring and assessment system the so-called BRIMOS-Recorder was developed, which should give a first estimation about the structural condition. The system was developed under the assumption being used by the bridge owners and local authorities. Interpretation and assessment of the measurements has to be done by experts. This method enables the assessment of a large number of bridges in one year, which leads to a higher safety level for the users.

The system was developed by VCE in co-operation with several partners in the field of structural dynamics. The system consists of an internal high sensitive 3-dimensional sensor from Kinemetrics, an internal power supply
equipped with a charging circuit as well as a data logger with 32 MB flash memory which is sufficient to run a measurement for 8 hours continuously. The unit further consists of a water-proof box with a display and a keyboard which is the interface to the user. The system was developed under the assumption that it can be used by the bridge authorities and their maintenance crews.

For this purpose several monitoring systems have been installed that provide this information. If it is related to ambient temperatures, rules valid for a certain location can be developed, that allow an easy approximate assessment. If all this measurements could be linked in a European network the dissemination of the methods could be improved and the work of innovative engineers could be supported.

In a first step, the mobile BRIMOS monitoring system was equipped with temperature sensors for air and material temperature and with sensors for measuring radiation intensity and direction. By this way a valuable data pool for further research work will be created (about 50 structures are monitored each year). The environmental parameters acquired by the system can also be used as input for model updating.

ENVIRONMENTAL INFLUENCES

Dynamic monitoring is particular depending on environmental influences. In order to make the assessment of the environmental influence easy, it is aspired to have long time data on for example temperature of a structure.

CLASSIFICATION SCHEME

Classification is used to identify structures which show distinct problems and urgently require maintenance and rehabilitation efforts. A proper budget planning of the responsible bridge authority can be done according to the time schedule set up based upon the measured results of the ambient vibration system. A classification of structures is possible and can be used as a basis for priorities.

From the practical point of view a combined assessment should consist of a first check using the BRIMOS technology in order to classify the specific structure. This classification should be the starting point for further detailed and costly assessment. In this way only those structures classified as critical should be investigated in detail.
This classification was drawn up on the basis of experience gathered from about 400 assessed bridge structures. The results of artificial damages on real prestressed concrete and reinforced concrete bridges were integrated as an important basis for the establishment of the system.

A simple and easy to use classification system is required because of the fact, that in many cases bridge authorities are not familiar with non destructing testing techniques and even have no time to read hundred-page reports. The proposed classification system is very similar to the Moody’s public finance rating. The rating symbols consist of three letters and one number (for example AAA 1). The letters stand for: Visual inspection results, results of ambient vibration monitoring and results of model updating (always from A for very good to C for bad). The number stands for the risk level (from 1 for low risk to 5 for extreme risk).

From this classification system the urgency of any required rehabilitation provisions can be derived, which enables an optimum control of the existing financial sources with simultaneous maintenance of a maximum safety level for the users.

MEASUREMENT OF TWO BRIDGES IN CHINA

Harbin Institute of Technology (HIT) provided two bridges for tests with BRIMOS, one is Shandong Binzhou Yellow River Bridge and the second is Harbin Songhua River Highway Bridge. Both bridges are equipped with permanent structural health monitoring systems with various advanced sensors. This allows a proper comparison of the measurement results. The measurements were carried out in cooperation of HIT and VCE in May and June 2006.

HARBIN SONGHUA RIVER HIGHWAY BRIDGE

This cable stayed bridge with a main span of 336 meters was completed in 2004. The bridge is located near Harbin in Heilongjiang province. It’s equipped with a permanent monitoring system for some of the stay cables.

Within a monitoring campaign of 3 days all 208 stay cables and the bridge deck were measured with two BRIMOS Recorders in May 2006.

BINZHOU YELLOW RIVER HIGHWAY BRIDGE

The Bridge with spans of 84+300+300+84 meters is located near Binzhou in Shandong province. The stay cables are equipped with different types of passive and semi-active MR vibration dampers, developed by HIT.

The highly sophisticated monitoring system of the bridge includes 138 optical fiber strain and temperature sensors, 2 anemoscopes, 38 accelerometers and 4 GPS sensors,
which are distributed on the main pylon, the deck and the stay cables. Data transmission is managed by a wireless communication system and data analysis happens in real time.

All the data and evaluation results are stored in a SQL server 2000 database with a visitor permitted website, which is operating in realtime.

In June 2006 the deck and the stay cables of the main pylon were measured with BRIMOS Recorders.

CONCLUSION

This paper describes the function and performance of a compact mobile ambient vibration monitoring system. With this BRIMOS system measurements on two cable stayed bridges in China were carried out in May and June 2006. Both bridges are equipped with sophisticated permanent monitoring system. The intention of these measurements is a comparison of the results of different systems and to show advantages and disadvantages of permanent and periodic monitoring in the sense of performance and costs.

All the results of this investigation are going to be presented at the “The Fourth China-Japan-US Symposium on Structural Control and Monitoring” in Hangzhou.

References


