Title: Bridge Classification Based Upon Ambient Vibration Monitoring

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ABSTRACT

Bridges are essential for the transportation infrastructure of any country. The peak of construction of the European Transportation Infrastructure happened in the 1970s. It is estimated that nowadays 760,000 bridges are serving within the Trans-European Network (TEN) and the primary and secondary road network. Owners of bridges expect that the critical age where rehabilitation and retrofit works at bridges become essential starts after 30 years of service. Considering the time of construction a huge peak of repair and retrofit investment is expected for the years starting from 2005 onwards. Studies carried out show that the required effort could be more than tripled compared to present values. In times of shrinking budgets, as prevailing now, alternative methods to deal with this problem are required.

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. Brimos provides additional information for the bridge inspector to carry out an accurate assessment of the condition and the remaining lifetime of the bridge.

In the scope of the dynamic tests a classification system is established. This classification was drawn up on the basis of experience gathered from more than 80 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. From this classification system the urgency of any required rehabilitation measures can be derived, which enables an optimum control of the existing financial sources with simultaneous maintenance of a maximum safety level for the users.

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1. SUMMARY

Owners of structures realize 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 feedback from structures for more economic design and better understanding of the performance. Researcher were always fascinated by the potential of full scale dynamic tests of structures. These common aspects triggered the development of structural monitoring. It is recently well-known that each structure has its 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. 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 planning of rehabilitation budgets.

2. GENERAL

Monitoring the quality of structures comprises a wide field of engineering tasks. The most promising recent developments has been achieved with Ambient Vibration Testing and dynamic System Identification (SI) tools. Ambient Vibration Testing does not require a controlled excitation of the structure. The structural response to ambient excitation is recorded in a large number of points. From these ambient measurements the condition of the structure is derived.

As already mentioned, a huge peak of bridge construction happened in the 1970s, which are reaching their critical age currently. Thus, an enormous maintenance and rehabilitation effort is coming towards the road and bridge authorities (figure 1). To manage this problem, advanced technologies in bridge priority ranking concerning maintenance actions are urgently required.

![Figure 1. Construction of Bridges vs. Maintenance Costs Estimated](image-url)
3. BENCHMARK TESTS

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. 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 study the effects to the dynamic response.

![Locations of Test Structures in Austria](image)

It was decided to replace the 5 critical structures 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 have been planned. Such a possibility to apply artificial damages to 5 post-tensioned structures in real scale is unique in the world until now. Thus, all tests have been planned very carefully. Main focus was put to the identification of damages in prestressing tendons, which are currently assessed by visual and very local inspection techniques, only.

A global assessment of a structure, pointing out prospective damages and damage locations, is therefore urgently required. Before the structures were damaged an initial vibration test was 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. The pavement only has influence on the natural frequency due to the additional load. There was no stiffening effect recognizable.
The assessment of the capabilities of dynamic methods was done by introducing artificial damages to the embedded tendons. This was performed by cutting the tendons which turned out to be a very complicated and time-consuming task. Later on, the damages of the other projects were induced by drilling cores to the structure. This was a very sensitive method for damaging tendons in a sequence.

4. DAMAGE ASSESSMENT

System identification (SI) means extracting the dynamic characteristic of bridges or other civil engineering structures from vibration data. The vibrational characteristic serves 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.
The major tools of the damage assessment are the natural frequencies, the mode shapes, damping values, vibration intensities due to traffic as well as trend cards indicating the structural behavior over time.

5. TREND CARDS

The development of so-called trend cards is a major outcome of the real scale damage tests performed in 2001 in Austria. These cards represent the signal in a frequency-time diagram. Figure 6 shows typical trend cards as they are obtained from several ambient vibration measurements.

In order to distinguish the individual frequency peaks, a coloring of the card is required so that the energy content of the oscillation and therefore the respective intensity can be determined. By this type of representation, damages are already visible in their beginning phase in the frequency spectra. What has to be mentioned, however, is that the basic frequencies with their long-wave vibration forms are insensitive to local damage. Therefore the assessment and interpretation of the whole measured frequency spectrum assumes greater significance.

6. 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 priority ranking of bridges can be done, leading to the classification if more detailed investigations are necessary. 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. Main assumption for design was, that a use of the system is possible for the bridge owners and local authorities by themselves. Interpretation and assessment of the measurements has still to be done by experts. This method makes the investigation of a large number of bridges in short time possible, which leads to a higher safety level for the users. Locating the sensor is one of the major tasks for a correct assessment and classification of the investigated structure. The best location was found by assessing the results from the artificial damage tests. The following rule was defined for placing the BRIMOS recorder to the structure.

![Figure 6. Trend of a structure in a good condition (left) and a damaged structure (right)](image-url)
A generalization with regard to the assessment of the respective frequency band is, however, not admissible, as the behavior is strongly dependent on the respective structure type. Consequently also local damages, for example at bigger structures, could bring about clear changes in natural frequencies and the respective basic vibration forms. In order to assess the chronological development of the structural condition it is required to carry out dynamic measurements of the structure at periodic intervals. In this context a 6-monthly examination interval seems useful but at the beginning of the measuring series a sufficient number of basic values has to be collected over a shortened interval. Based on these basic values the chronological development of the condition can be represented graphically by trend cards.
7. 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. In the following illustration the measuring results of 35 prestressed concrete bridges, which were built between 1955 and 1965, are shown. The condition of the structures is reflected in the measuring values and therefore clearly shows the need for any action required.

![Classification of structures according BRIMOS](image)

Class A represents bridges which are in a very good condition and do not have any problems. Bridges assigned to group B basically show a good condition, however some local problems and small damages may be possible. These bridges are usually exposed to high traffic loads. Bridges classified into C show a critical structural condition and urgently need rehabilitation measures or a total replacement.

From the practical point of view a combined assessment should consists of a rough check using the Brimos-Recorder 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 the structures classified as critical should be investigated in detail.
8. CONCLUSIONS

From the results it was derived that the failure of only few prestressing tendons can be found by the use of the ambient vibration method. Recent assessment procedures failed because only the basic frequencies and corresponding mode shapes had been observed. The tests showed that small changes very often do not lead to a change of the fundamental frequencies in the range up to 10 Hz. The frequencies in the high range as well as the damping values are very sensitive to changes or damages of the prestressing tendons.

The problems and failures with the assessment using the ambient vibration method in the last few years could be caused by the circumstance that a numerical simulation of these effects is nearly impossible. The infected mode shapes in reality are in a frequency range where the calculation results in rough estimations of the frequency.

Bridge classification using the modal parameters natural frequencies, mode shapes, damping values, vibration intensities as well as trend cards is a very effective tool for assessment and priority ranking of the structures. It should be noted in this context that the assessment of all modal parameters together as well as the assessment of the total frequency band of interest is very important. The Brimos Recorder thus can help to increase safety in the traffic network considerably, at the same time reducing the inspection and maintenance costs.

9. REFERENCES

1. www.vce.at
2. www.samco.org