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AIFIT- USER ORIENTED IDENTIFICATION FOR INFRASTURCTURE SARA- PART V

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Abstract

A majority of structurally relevant damages in reinforced concrete structures create cracks (Bergmeister 1990). Especially on an early stage these cracks are difficult to detect and visual inspections as the only widely-accepted method to localize and evaluate cracks is time consuming and limited to accessible areas of the structure. Most global identification methods narrowing down the area of probable damage show a high dependency on environmental parameters or demand extensive measurements and engineering interpretation (Bolle & Bernd 2003). The project AIFT aims at methods resulting in simple identification and localization of local bending stiffness reductions in reinforced concrete bridges as significant help for detailed inspection. The paper demonstrates nonlinear studies on the correlation of cracks and bending stiffness changes which help to interpret identified local bending stiffness reductions. New approaches for such reduction identification and localization based on directly measured influence lines of load reaction at the bearings are introduced. First results of laboratory tests on two span reinforced concrete beams are presented. Prospects for further analysis of the laboratory tests and complementary field tests using influence lines and modal characteristics based identification methods are given.

INTRODUCTION

BOKU University proposed together with its partners Schimetta Consult, ÖBB (Austrian railway) and Maurer Söhne for funding of a research project by the Austrian research foundation FFG. The proposal presents a project for the user orientated identification systems for engineering structures, called AIFIT. By July 2006 the FFG accepted the project. The research project is divided into the following 8 work packages plus project management and accompanying control:

WP 1 - Influence of Stiffness Changes

The work package is designed for the compilation of parameters influencing stiffness changes or distributions of structures. The correlation of stiffness changes and damage mechanisms of concrete structures is studied. The main results of this work pack-age are presented in the following chapter of this contribution.

WP 2 - Studies on Laboratory Beams

Different damages and levels of damage are applied to a total of 8 test beams. Analyzing the stiffness distribution for the different states of the test beams by various methods allow the identification of major influence parameters for the stiffness changes and the verification of the single methods among them. Addition material tests will give the basis for further numerical simulations. The tests are conducted in two blocks, starting from February 2007.

WP 3 - Numerical Simulations

Based on WP 1 and 2 non linear models are generated and calibrated. This gives a basis for further numerical studies on different structures. Different options for the involvement of identified damages to the models and the assessment of reliability of structures will be analyzed and evaluated.

WP 4 - Calibrating of Upload Measuring Devices on Bridge Bearings

Existing measuring devices are studies according the demands for damage identification. They are tested on realistic conditions in the laboratory and adapted to identification systems.

WP 5 - Field test on a Bridge

The conclusions from WP 1 to 4 are applied to a real bridge. The bearings of the bridge are instrumented and ambient traffic is used for the identification of the systems behavior. Applicable systems for the data management and logging are developed and installed.

WP 6 - Data Evaluation for the Damage Identification

The data obtained from WP 5 are evaluated based on the conclusions of WP 1 to 4. The stiffness distribution is identified and the results interpreted. The reliability level of the structure is assessed.

WP 7 - Field Test with Upload Measurements by Semi-Active Dampers

Already installed semi-active dampers are used for the measurement of cable forces. This information of the structures bearing condition is used for analysis according WP 6.

WP 8 - System Identification by Sensitivity Based Approaches

The data of the modal behavior obtained in WP 2, 5 and 7 is used for a sensitivity based approach. Influences of ambient conditions are analyzed. The approach is completely automated and compared to the results obtained in WP 6.

Identification Methods Analyzed within AIFIT

Within the research project AIFIT different methods are used for the identification of stiffness changes or distributions. Besides the methods using quasi-static information like the direct measurement of influence lines (Hoffmann et al. 2006) and deflection lines (Preslmayr 2006) of structures presented in this contribution, several dynamic approaches offer interesting options.

A method called “direct stiffness method” (Maeck 2003) uses the internal forces from the eigenform of an actuated structure and the knowledge of its mass distribution. The detailed measurement of the eigenform for the first few eigenfrequencies allows the determination of the curvature of the structure in its actuated state. By the knowledge of the internal forces and the curvature the single unknown is the stiffness distribution of the structure and can be calculated directly. Nevertheless using this method in a direct way requires input data of very high quality, which makes the use of smoothing or filtering functions most of the time inevitable. In order to prevent this interference to the raw data based on engineering judgment the method was implemented in a curve fitting algorithm using only raw data. One method completely developed at BOKU University following the claim for user orientated and simple to handle identification is called STRIDE (Strauss et al. 2006). The method executes a finite element model update dependent on the sensitivity of the single input parameters. Based on the same finite element model another approach called OPTI (Strauss et al. 2006) generates a set of structural response data for the training of a neural network, which allows analyzing the measured data. Still all of the mentioned dynamic approaches require a high accuracy in the determination of the modal behavior of the structure like eigenfrequencies and the deflection of the single eigenforms. Therefore one important challenge of the project AIFIT will be the optimization of the dynamic measurement technique to the demands of the bridge owners in accordance with the identification methods.

INFLUENCE OF STIFFNESS CHANGES

At BOKU University stiffness reductions have been studied for reinforced and prestressed concrete structure. The study made use of the research work widely-used non linear finite element software ATENA (Červenka et al. 2001). This software allows the modeling of reinforced concrete structures with or without prestressing by sophisticated material models representing the crack behavior of the concrete and yielding and hardening of the reinforcement. Within the complex finite element model the generated cracks change the bending stiffness of the model and will lead to redistribution of the forces and moments. Nevertheless the modeling of such structures is highly dependent on the various input parameters of the model, which are not all known from experimental data. Furthermore the model itself is subject to inevitable uncertainties, which have to be compensated as far as possible.

Stiffness Analysis

Based on calibrated FEM models of reinforced (Dilger 1966) and prestressed (König et al. 1993) T-beams the deflection behavior can be monitored in more detail, than was done in the laboratory tests. The moment distribution along such beams can be calculated independently of its stiffness distribution by the knowledge of the bearing reaction forces of the beams under load. A close grid of monitoring points for the deflection additionally allowed for the identification of the absolute stiffness for any partition in segments by the use of equation (1), based on the general equation for the influence line (Rubin & Schneider 1996) adapted for the deflection line. The segments have been chosen in a way that the end points of each segment coincide with a monitoring point in the model. These monitoring points have been used as supporting point $w_{i,\ left}$ and $w_{i,\ right}$. Introducing the moment at these points $M_{i\ ,left}$ and $M_{i,\ right}$ into equation (1) leaves the segment's stiffness EI_i as single unknown for different known deflections w(x) between the support points.

$$w(x) = (1-\xi)w_{i,left} + \xi w_{i,right} + \frac{(2-\xi)M_{i,left} + (1+\xi)M_{i,rigth}}{6EI_i}\xi(1-\xi)l^2 \qquad (1)$$

where $\xi = x/l$ and l is the length of the segment

A minimal over determination is required, because the identification according to this procedure is very sensible and the results of the deflection taken from the finite element model are subject to uncertainties caused by the iterative solving process. Using several single deflections w(x) per segment for an optimization of the theoretical vs. the monitored deflection line leads to an adoptable grade of robustness and accuracy of the process. Naturally this is limited by the computational effort for the finite element model. In this way the secant stiffness for the single segments were determined for single load steps or sets of accumulated load steps.

Application Example

Experience from the calibration of models of the T-beams and their stiffness analysis was used to obtain a most realistic model for a stiffness analysis of a real structure (Preslmayr 2006). The chosen structure is a crossover of a 7.5 m wide village street over the railroad Vienna – Laa just about 15 km north of Vienna. This structure lends itself to such an analysis, because it is a simple indetermined 3 span structure with well-defined supports by free deformable elastomer bearings on the abutments and fixed linear rocker bearings on the piers. Furthermore the bridge has no horizontal curvature and the abutments are placed normal to the gradient of the bridge. A maximum slenderness of L/d = 21.67 is given by single span lengths of 10 m at the rear and 13 m at the middle vs. a structural height of 0.6 m. This high slenderness of a non prestressed reinforced concrete plate structure causes a significant crack pattern of the structure already on lower loads as can be seen in figure 1 for a total traffic load of 481 kN distributed to all 3 spans.

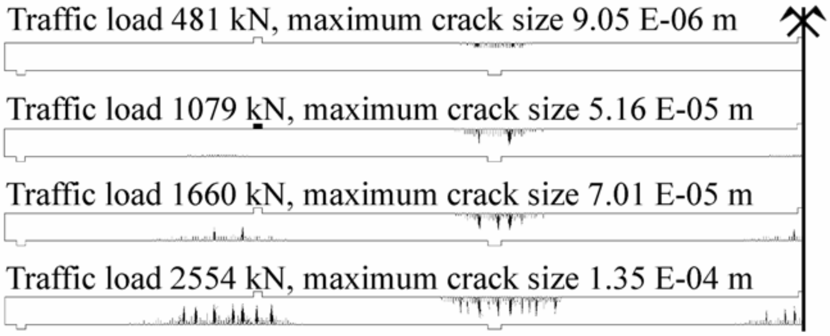

Figure 1. Crack patterns from finite element model for different load steps

The explained method for the stiffness analysis by monitoring the deflection of the finite element model was conducted on this structure with a partition into 33 segment of 1.0 m length each. The identified stiffness reductions correspond with the crack pattern shown in figure 1. As well the maximum stiffness loss of theoretically 77.7% corresponds with the results obtained. The model was used to analyze the influence of degradation like area loss of the cross-sections of the reinforcement bars. The effect even of a loss of 30% is limited and causes mainly a slightly earlier reduction of stiffness for the sections remote of the moment maxima. Much more significant changes are caused by loss of prestressing force, loss of cross-section of the tendons or loss of entire tendons, which has been analyzed on the models of the T-beam No. 1 (König et al. 1993) used for the calibration. The stiffness loss of sections remote to the moment maxima occurs much earlier and faster for this prestressed structure. Nevertheless the method has a very limited accuracy for the identification of absolute stiffness of the section. However it shows that most of the stiffness loss occurs within a small load range, already with the very early development of the cracks. Such significant changes at an early stage of damage favor the application of global identification methods. The analysis used ATENA version 2 for the identification of the segmental stiffness, which allowed only analysis of the structures under load. By reducing the load in the model, the cracks closed again and the stiffness of the uncracked cross-section was regained. Therefore the results of the presented analysis are limited in their transferability to structures damaged by overload and returned to their normal load conditions. Especially prestressed structures have the tendency to regain almost all of their stiffness by closing the cracks after the load has been removed. These structures keep this performance till the yield strength of the prestressed steel is reached and significant plastic elongation occurs. The current ATENA version 3 resumes some of the cross section's initial stiffness when the cracks lose in width by increased interlocking, but will never return to its uncracked state similar to the real behavior.

STUDIES ON LABORATORY BEAMS

Early November 2006 a total of 9 reinforced concrete beams according figure 2 have been concreted right in front of the test facility at BOKU University. Care was taken not only for the preparing and curing of the beams. Thus all beams are lifted into the experimental rig by hand in order to prevent initial cracks in the test specimens.

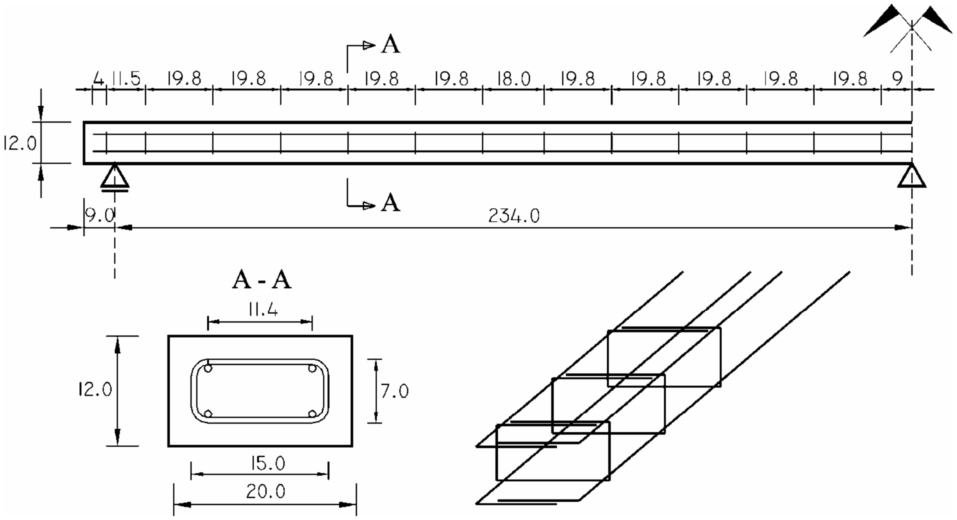

Figure 2. Tests beams of WP 2:

In February 2007 the first block of the tests of WP 2 have been started and are finished by the first week of March 2007. At that time the first four beams are damaged progressively only in one span or simultaneously in both spans. After each load step a full set of measurements is conducted to determine the modal and static characteristics.

Measurements on the Laboratory Beams

The static deflection line is measured in close grid by a defined displacement of a vertical laser sensor on linear guides underneath the beam. For the quasi-static influence line precise force transducers are placed under each bearing recording the reaction forces while a constant load travels over the entire length of the beam. Most efforts are necessary for the precise survey of the modal behavior of the beams. Thanks to arsenal research in Vienna a laser vibrometer can be used which allows maximum precision for the direct measurement of the modal deflection of the beams. The laser vibrometer is placed outside the test rig, while holes in the bearings allow adjusting the laser beam along the linear guides. A surface mirror mounted to the very stiff guides deflects the laser beam vertical to the concrete beam and back to the laser vibrometer (see figure 3.), providing a precise measurement of deflection in a grid of optional density. During the test a distance of 9 cm between two measurement points, leading to a total of 50, showed to be sufficient. In order to ensure similar excitation during the measurement in each point an extensively stable excitation is given by two moving coil actuators connected to the beam according to the specific modal shape and kept in resonance of the beam.

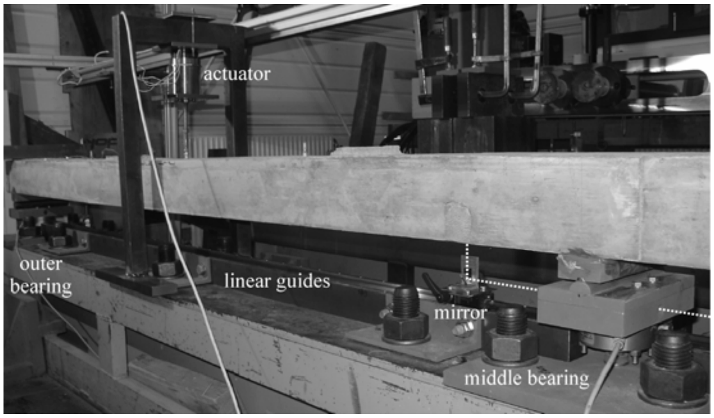

Figure 3. Test beam excited by moving coil actuators and monitored by a laser vibrometer accelerometers and force transducers

In addition accelerometers are placed on both sides of the beam underneath the connection to one actuator to control and avoid torsion modal behavior of the beam. Furthermore these accelerometers allow to control and consider possible changes of the excitation during the measurement. These dynamic measurements are conducted only for the first two eigenmodes as a realistic adjustment of the excitation to higher modes with only two available actuators turned out to be impossible. Finally yielding of the reinforcement is controlled by strain gages at 4 of the 8 beams.

Identified Stiffness Reduction

Due to many innovations of the test set up and identification methods several improvements were necessary during the realization of the first block. Therefore some of the measurement data does not meet the expectations. Meanwhile the measurement technique and test set up are adjusted far enough to gain satisfactory first results. After some improvements to the bearing conditions introduced since beam n°3 both static and modal behaviors lead to much better results. As well the algorithms like the least square curve fit of the analytical formulation of an influence line for the load reactions at the bearings to measured influence lines (Hoffmann et. al 2006) had to be adapted to the specific requirements of the laboratory tests. For this method the beam is sub-divided into 12 sections of same length. The results for all 6 load steps plus the beam in its initial state are shown in figure 4.

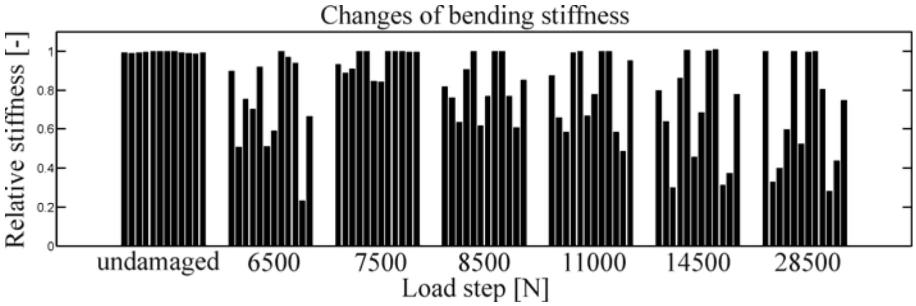

Figure 4. Changes of bending stiffness relative to maximum stiffness

The inconsistent identification for load step number 1 with a load of 6,500 N is attributed to measurement mistakes, which is confirmed by additional tests meanwhile. The results for load step 2, identify stiffness loss above the middle support, where the highest bending moments occur. A crack pattern with noticeably bigger cracks direct left to the middle support corresponds with the significant higher loss of stiffness in this area. It is remarkable, that load step 1 and 2 caused cracks of width almost invisible with the naked eye; while a stiffness loss of app. 16% is identified. Likewise the following stiffness loss is identified close to the symmetrically applied load in the middle of each span. All identification has been conducted on the released beam, exposed only to the dynamic excitation, the traveling load of app. 300 N or two times app. 400 N for the deflection line survey beside its body force. As the cracks opened to more than 0.8 mm under load they showed less than 0.1 mm width after unloading up to load step 5 with a total of 14,500 N. Not until load step 6 yielding of the reinforcement occurred and the cracks reached the service limit state of 0.3 mm width even without any additional load. First comparisons to the results taken from the dynamic analysis seem to be promising, taking into consideration that these methods consider dynamic young's modulus instead of the static young's modulus applicable for the influence line and deflection line surveys. The early status of WP 2 allowed no interpretation of the deflection line so far.

CONCLUSIONS

The project AIFIT showed considering the results of the first two work packages, that at least for reinforced concrete structures global identification methods can provide a valuable tool for inspections. Both numerical models and laboratory test demonstrated, that cracks caused by bending lead to a considerable loss of bending stiffness of the affected cross section. This loss can be identified as smeared stiffness loss of a section, which identifies not only a possible damage in the structure, but also allows narrowing down the area of possible occurrence. Furthermore the loss is detected already at a very early damage state of short and narrow cracks and has no need for baseline values.

The first identification by direct measurement of influence lines produced promising results. Still the method holds opportunities for additional improvement ready. Nevertheless the still ongoing tests allowed no reasonable comparison of the different methods examined within the project AIFIT, which will be available briefly. Furthermore the methods will have to prove their real user orientated practicability in the field test of WP 5 and the really necessary effort for a modal survey, as well as the capability load measuring at the bridge bearings (Hoffmann et. al 2006) have to be analyzed.

New ground has been broken for the modal analysis under laboratory conditions by the efficient use of a laser vibrometer in combination with a specific actuator. New ways of applying loads have been found for the direct measurement of influence lines for the reaction forces at the bearings.

OUTLOOK

The work plan for the laboratory tests will be enhanced based on detailed analysis of the measured data from the first block of WP 2. With this experience the second block will start in March and will end by the end of April 2007. This full data set will allow comparing and validating the single identification methods. Furthermore WP 2 will give important input for the numerical simulations of WP 3 and useful experience for the field tests of WP 5. Additional parameter studies on the measured influence lines will help to formulate the requirements of upload measuring devices implemented to bridge bearings in WP 4. AIFIT targets to have a functioning identification system using upload measuring bearing on hand by the end of 2007 and enhance this and all other examined methods till the end of the project in January 2009.

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