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SENSITIVITY FACTOR BASED DYNAMIC DAMAGE IDENTIFICATION SARA - PART III

Alfred Strauss
University of Natural Resources and Applied Life Sciences, Austria

Konrad Bergmeister
University of Natural Resources and Applied Life Sciences, Austria

Roman Wendner
University of Natural Resources and Applied Life Sciences, Austria

Drahomír Novák
Institute of Structural Mechanics
BUT University, Czech Republic

David Lehký
Institute of Structural Mechanics
BUT University, Czech Republic

Abstract

Non-destructive inspection methods are in general ordered by owners of systems, structures, bridges etc. Most of these methods are point inspection methods, that means they provide only information in discrete points in space and time. Therefore for most of these inspection methods there is a risk to not detect already damaged zones in space and time. Alternatives are structural monitoring systems. They provide data (e.g., static and dynamic mechanical quantities) in several points of a structure. They allow the assessment of the behaviour of the whole structure. Changes of the responses or the violation of threshold values reflect a process in the structure. The proposed sensitivity factor based approach can be used to assign the changes to a structural characteristics like shear weakness etc. The developed algorithm of the proposed approach, emphasizing its characteristics with regard to the characterization of basic variables and the inclusion of the monitoring results, is presented. The selection of the sensitivity factors and the orientation of the correction process are presented. The algorithm is based on a special randomization technique which allows a very large reduction in the computational efforts and therefore the treatment of even large engineering structures.

INTRODUCTION

Structural monitoring systems provide data (e.g., static and dynamic mechanical quantities) in several points of a structure. The outcomes of monitoring systems should serve for the detection of degradation processes as well as potential failure zones. There are already existing methods for detecting changes in structural properties that are based on monitoring outcomes. In general they rely on concepts based on calibrated values of the measurements of structural behavior. Well-known techniques are heuristic fitting methods, curve-fitting methods, grey systems methods, and neural network approaches (Novák and Lehký (2005), Cichocki and Unbehauen (1993), Teughels and De Roeck (2004), Maia et al. (2003)). The first two of these techniques are engineering-based methods. The experience and knowledge of the user are responsible if the technique succeeds. Local minimum problems will be not detected by these methods and they do not rely on automatic strategies. Nevertheless they have the advantages that these techniques can be understood easily and that singular illogical results can be excluded from the decision process.

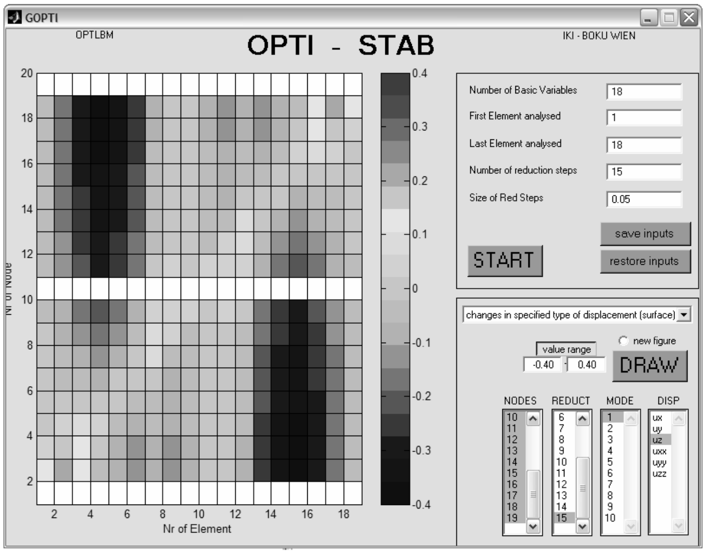
The last two of the methods mentioned above are based on scattering data sets (e.g. random variables). The random variables are used to establish a detection network which together with the random data from real measurements can serve for detecting structural damages (Novák and Lehký, 2005). More details about this method are given in the consequent paper – Part IV. The advantage of these methods is that the user does not have to make any decisions during the optimization/detection process. On the other hand it takes an experienced user to set up a suitable network (structure of the network) for each individual task.

An identification method characterizing the inputs as random variables and using the stochastic outputs for the identification of elements with high sensitivity to the response changes is an alternative method called STRIDE (Strauss et al., 2006). Unfortunately, reliable statements regarding the sensitivity of elements require traditional techniques (e.g. the crude Monte Carlo technique) and, therefore, a large number of simulations. The Latin Hypercube Sampling, as presented in the consequent paper Part II, allows the substantial reduction of the number of simulations. There are two software packages, OPTI and STRIDE that originates from the philosophy of STRIDE. The features of these packages are presented in the following.

FEATURES OF THE SOFTWARE OPTI

“Optimizing Identification” OPTI is a rather basic tool to determine and visualize correlations between certain input parameters and dynamic structural response. Like STRIDE OPTI is developed in MATLAB and equipped to interface with FEM software packages like SOFISTIK. This tool enables the user to better understand the influence of damage to the dynamic behavior of larger and more complex structures and thus allows for a better choice of suitable monitoring points and verification of plausibility of results of more sophisticated identification methods.

The basic idea is the variation of one or even several chosen input parameters such as the young’s modulus of certain subsections of a structure followed by the analysis of the resulting change in dynamic structural response. At the moment only an ordered approach is considered, which means that the chosen property is altered stepwise for one subsection after the other. Consequently no interaction between several damage scenarios can be taken into account. Fig. 1 shows the graphical user interface for OPTI. On the right hand side the input parameters for calculation and the relevant output values can be chosen. On the left hand side an example for a two span bridge is shown. In this case the sensitivities to damage for the first mode can be seen, where the x-axis shows the damaged element and the y-axis the effected element.



Number of Basic Variables: 18
First Element analysed: 1
Last Element analysed: 18
Number of reduction steps: 15
Size of Red Steps: 0.05

changes in specified type of displacement (surface)
value range: -0.40 - 0.40
○ new figure

NODES: 10, 11, 12, 13, 14, 15, 16, 17, 18, 19
REDUCT: 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
MODE: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
DISP: ux, uy, uz, uxx, uyy, uzz

Figure 1. Graphical User Interface GUI of the software OPTI

FEATURES OF SOFTWARE STRIDE

STRatified IDEntification (STRIDE) is the software associated with the sensitivity factor based approach. It is developed under the scientific software package MATLAB and provides a Graphical User Interface GUI that allows the experienced user to set up individual identification tasks. The Start Surface is divided in three main parts:

- the pre-processing part (i.e., set up of the simulation properties)
- the processing part (i.e., running the numeric identification algorithm)
- the post-processing part.

The user is mainly involved in the first part, the simulation properties. These are in turn structured in the search strategy, the number of iterations, the number of load cases, the standard deviation and the randomization technique. The numerical part is characterized by the discretization and the iteration process which is active until the difference between simulations and monitoring results D_o is smaller than a predefined limit. The monitoring can for instance be used for geometrical, mechanical and dynamical structural parameters, or any combination of these.

Pre-Processing

Search strategy - The current state of the code is restricted to one of two search strategies (i.e., decreasing or increasing the basic variables *B*). This restriction was included since it is crucial that the correction process is not being captured in local minima. The correction process without constraint is a complex system due to the fact that the proposed sensitivity factors are acting in both directions (plus, minus) and their correlation under certain circumstances can cause errors. The selection of one correction direction allows the proper handling of the influence of the sensitivity factors and their correlations on the correction process. Enabling the direction free correction is a target of the next developments.

Number of iterations – At each iteration (a) the basic variables to be identified are randomized and are delivered to the FEM Model or Mathematical Model, (b) the sensitivity analysis is performed, (c) the correction algorithm is started, and (d) the correction due to the sensitivity factors is performed. Since the relation between the simulation outputs and the *B* inputs is in most cases nonlinear, the correction process is running step wise. The user has the ability to select the number of iterations to be performed. Initially an automatic stop criterion was considered but since the sensitivity factors are also influenced by the loading of the system, it is possible that a selected monitor point is not activated during a correction process. Instead a graphical illustration of the progress of the process was installed to provide the user with a decision basis for the requested number of iterations.

Number of load cases - The current version of STRIDE is already prepared to include the correction processes relying on several load cases. The correction information of each load case is treated herein with the same weight. However, the weight differentiation tool is already available.

Standard deviation - There are processes where the correction of the standard deviation is faster than the correction of the mean value. If within this kind of processes the standard deviation of one or more basic variables *B* get very small the correction process could die, since the sensitivity analysis rely on the scattering of *B*. In such cases it is recommended to use a constant standard deviation (i.e., a more stable behavior of the process is provided).

Randomization technique - The design of the realizations from selected basic variables relies in general on the LHS technique and can be done by three included tools. The tools differ in their ability as follows: (a) LHS-PERMUTATION: uses the permutation method based on the LHS philosophy to create the realizations. Only normal probability density functions can be used. The correlation between the basic variables *B* cannot be considered, (b) LHS-GENERAL: follows fully the theoretical concept of McKay et al. (1979). Only normal probability density functions can be used. The correlation between the basic variables *B* cannot be considered, and

(c) FREeT is used for the LHS. In this case correlation between the basic variables *B* can be considered, and in addition, any pdf can be used.

Processing

The main parts of the processing can be itemized as follows:

- The deterministic model of the structure is prepared and checked within ATENA (Červenka, 2003) or other FEM software packages.
- Uncertainties of the input parameters are modeled as random variables described by their pdf. The result of this step is the set of input parameters for STRIDE (random variables are generally described by mean value, standard deviation and pdf).
- Randomized input parameters are generated according to their pdf using LHS sampling (by one of the previously mentioned methods).
- Generated samples of random parameters are used as inputs for ATENA or other FEM computational models. A linear or nonlinear calculation is performed and selected results (structural response) are saved and taken for the sensitivity analysis and, therefore, for the correction process.
- The differences between the simulated outputs and the measured outputs are evaluated and weighted according to the sensitivity factors.
- The random input parameters are corrected according to the results provided in the above steps.
- Previous four steps are repeated until the differences between the simulated and the measured outputs become as small as required.

The algorithm includes several already existing software packages, like FREeT, ATENA, Sofistik etc. They are activated during the correction process.

Post Processing Part

The post processing provides the user with the graphical illustration of

- basic variables after their correction
- sensitivity factors after each iteration

The graphical outputs can be demonstrated in 2D or 3D histogram format.

APPLICATION ON EXISTING STRUCTURES

The above presented methods have already been applied to laboratory as well as real structures. Since the laboratory outcomes were very promising the step to real structure applications stand to reason. The numerical identification methods were performed together with a stochastic neural network approach, which is discussed in the consequent paper Part IV. The parallel testing of both approaches follows the intention to find out the strong and weak points of both of these concepts. In general it could be concluded, based on these studies, that the results of both approaches were comparably good. Beyond the laboratory tests, as shown in the consequent paper Part IV, there is a big interest in the following discussed structures, since the outcomes of the health monitoring programs, as sketched in the consequent paper Part I, will be in consequence included in the identification methods.

Colle Isarco Viaduct

The first of the structures of interest is the Colle Isarco Viaduct. It is a cantilever beam bridge in Italy with a total length of 1,000 m. The structure was erected in 1969, it is a fully post-tensioned box-girder bridge and is part of the Brenner Highway in Italy. Several objects of this type are found in the two separated lanes which form this bottleneck crossing the Alps. The northern cast-in-place balanced cantilever beams are the most sensitive elements of bridge systems. Therefore, these elements, with varying box girder depths, have been chosen for the analyses.

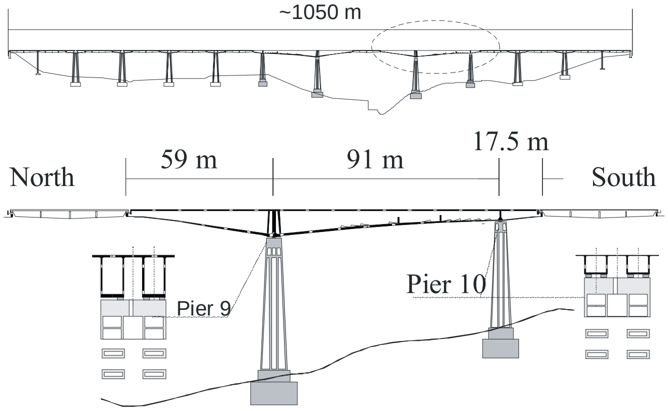


Figure 2. Side elevation of the Colle Isarco Viaduct

The total length of the beams is 167.5 m. They are subdivided by the mid-span with a length of 91 m and the cantilever beams with a length of 59 m and 17.5 m, see Fig. 2. The lane slab has a width of 10.60 m and the lower girder slab a width of 6.00 m. Both of them have a thickness of about 0.20 m. The height of the box girder varies from 10.80 m over the middle support to 2.85 m at the end of the cantilever beams.

OPTI related to the basics of *STRIDE* was initially used for the currently discussed bridge to assess the influence of damage modelled as decrease of the young's modulus on the dynamic structural response. This was done for all 30 elements along the axis of the structure each in 15 reduction steps of about 5%. Based on a model of this structure eigenfrequencies and eigenformen were studied. Figure 3 exemplarily shows the relative changes in vertical deflection due to damage for the 5th mode – a main bending mode. The results clearly show which nodes are affected most by damage and thus are for instance suitable for deployment of monitoring sensors.

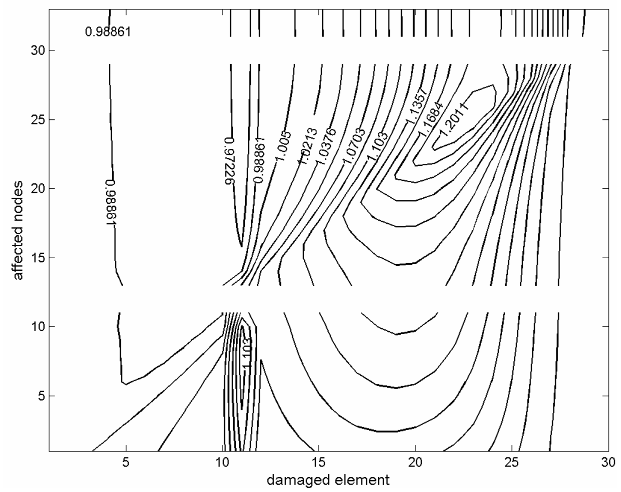


Figure 3. Relative changes to u_z for 5th mode

STRIDE

The STRIDE identification studies are based on the results of health monitoring program of the Colle Isarco Bridge performed by Santa et al. (2004). The above discussed results obtained by OPTI served as a preliminary study which allows checking the sensitivity of the measured structural or mechanical quantities. First steps of the STRIDE identification at the Colle Isarco Bridge showed the location of critical zones over the higher pile in flexure and over the smaller pile in shear. The extended comparison of the numeric identification with the measured one is in progress and will be completed soon.

Z24 BRIDGE

The second of the structures of interest is the Z24 Bridge. It is a structure in Switzerland which was subjected to damage tests and thus much dynamical data is available for analyses. The overall width of the cross-section is 9.00 m and the height 1.10 m. The structure is a continuous-system with four point supports, see Fig. 4. The lateral fields have a length of 14.00 m and the middle field a length of 30 m.

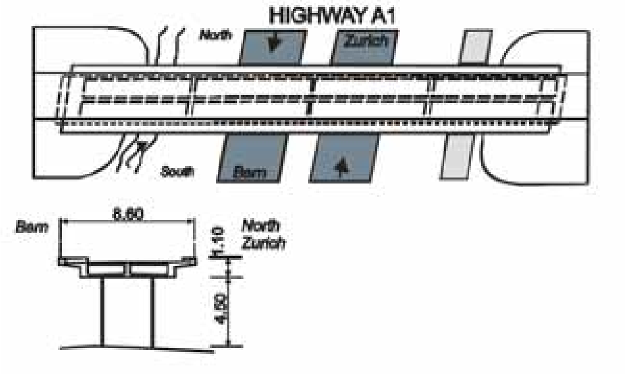


Figure 4. Top View and Cross Section of the Z24 Bridge
(adapted from Teughels and De Roeck (2004))

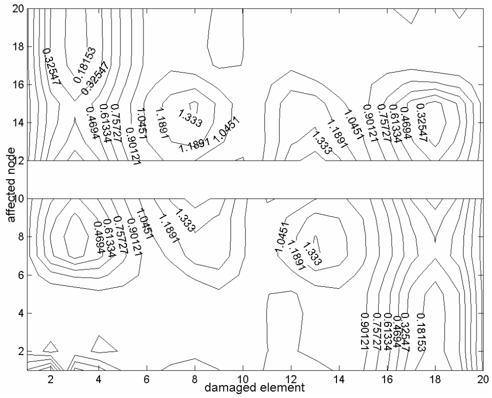


Figure 5. Relative changes to u_z for 7th mode

OPTI study: A linear FEM Package was used, as for the Colle Isarco Bridge, for a preliminary study of the sensitivity of measured data. The studies were based on the measurements performed by Teughels and De Roeck (2004). The Z24 was discretized in 30 cross section elements which serve as basic variables for the following stochastic identification. The *OPTI* investigation was performed according a stepwise reduction of the section modulus of elasticity for both bending and torsion. The modulus of elasticity of bending and torsion are fully correlated. The basic variables (physical properties of the selected cross section) were stepwise continuously reduced to 5% of their stiffness (15 steps per element). Fig.5 shows the relative changes in vertical deflection for the 7th mode, which is a pure bending mode, resulting from a stiffness loss of 75% in element i. The x-axis shows the damaged element and the y-axis the affected nodes where the displacement is calculated. As can be seen in this figure the 7th mode is rather sensitive to damage in elements of the outer spans. Damage to element 3 for example leads to a reduction of vertical displacement u_z in node 8 of about 67%. On the other hand a stiffness reduction in an element of the main span has virtually no effect on this bending mode.

STRIDE The studies on the Z24, are focused on the identification of damaged zones. STRIDE was used to determine from frequencies as well as mode shapes the location of weak zones and the stiffness reduction of those weak zones. The identification was based on three frequencies and four mode shapes. Fig.6 shows the used FEM model and the first mode shape.

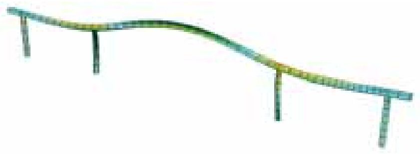


Figure 6. FE Model showing first mode shape

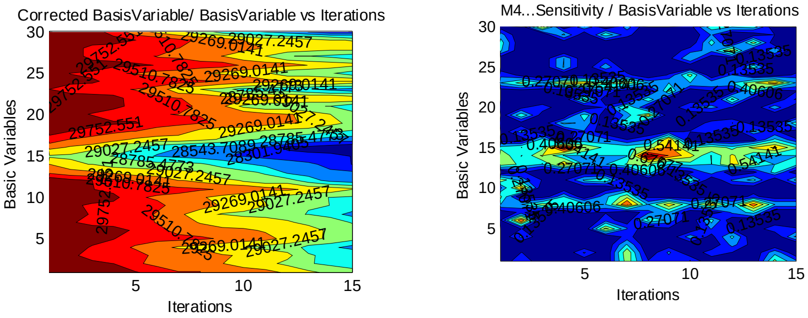


Figure 7. Corrections in the basic variables and sensitivity factors of the 1st mode shape (M4)

With the proposed algorithm and provided dynamic qualities it was possible to identify the damaged zones in the midfield (element 15). The critical zones could already be detected within the first iteration steps, see Fig. 7 (left picture). Beyond the development of the element stiffness the development of the sensitivity factors between the basic variables and the measured dynamic qualities gave an interesting insight in the correction process. Constant sensitivity fields, as shown in Fig.7 (right picture), participates more than the fluctuating ones. Further details and studies already finished and partially in progress are provided in the consequent paper – Part IV.

CONCLUSONS

Monitoring concepts dealing with dynamic and displacement measurements to detect and predict degradation processes of structures gain on meaning. Nevertheless they have to be combined with identification concepts in order to answer the locations and the levels of damages. It is very important for the assessment of residual capacity of structures. The proposed approach of inverse analysis using virtual statistical simulation and sensitivity factor based algorithm appeared in that context to be as very promising technique.

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