23rd International Conference
ENGINEERING MECHANICS 2017
Svratka, Czech Republic, 15 – 18 May 2017

A CONCEPT FOR TESTING AND MONITORING OF BUILDING STRUCTURES – THEORETICAL CASE STUDY

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Abstract: *A mere comparison of measured and analytical deformations, natural frequencies and mode shapes provides us with just a small part of the information contained in the data, especially when component- level damage prevention is needed. The presented analysis studies in detail a few criteria for evaluation of measured data, with the example of simulated plane trusses in respect to the ultimate limit state. It demonstrates the high potential of a systematic approach, while combining several criteria, particularly when using simultaneous strain and deformation measurements, as it documents the proposed Relative Mode Difference (RMD) criterion. On the other hand, the study points out the major limitation of practical applications that is caused by unknown inherent uncertainties of various kinds, providing us with the incentive for further experimental research.*

Keywords: Testing, Monitoring, Building structures, Ultimate limit state, Mode shapes, Strains.

1. Introduction

The motivations for Structural Health Monitoring (SHM) and its state-of-the-art are discussed in detail in (Brownjohn, 2006). It is obvious that SHM (Li, 2016) is a quite complex topic embracing many disciplines, such as system identification (Ewins, 1984), reliability (Gao, 2012), uncertainty estimation [ISO 2394], measurement technologies (e.g. Ye, 2014), data processing, etc.

It is well known that many structural faults are accompanied by a change in the transfer properties of structures, as reflected by measurable changes of deformations, natural frequencies and mode shapes. In the case of the ageing process, these faults quite often have a gradual character. It has been a matter of research in recent years that monitoring can help to assess more precisely the actual condition of building structures. Another sub-problem not yet being resolved satisfactorily is component-level structural information, which is the focus of this case study.

Generally, many load cases must be analysed to assess whether a building structure accommodates the ultimate limit states (further ULS). A final number of critical sections can be determined from this process. By knowing the initial state of a completed structure, the reliabilities or the utilization ratio can be estimated for each of these critical sections. An efficient meaningful SHM presumes that the fault tolerance is clearly observable with the aid of the measured or monitored parameters.

It is not the goal of this study to deal with the observability of various kinds of damage, because it is the matter of individual conditions, depending on applied methods, equipment and environment. However, it is the aim of the study to review a few concepts for the evaluation of measured data and to point out what benefit may be obtained from their combination.

The secondary aim of this study was the testing of the new RMD-criterion for localising damage from mode shapes. The experimental verification is planned during the future years.

2. Analytical models

Plane truss models (cantilever, simple supported beam, and continuous beam) were chosen to save computer time for numerous calculations and because they are well suited for tracing the bending and

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shear effects separately. The numerical results do not have a practical meaning, because mere assumed, fictive uncertainties were always applied to introduce the evaluation method in its complexity.

The Cantilever and Simply Supported Truss models were loaded with the Point Load and dimensioned so that all elements were utilised to 75 % of the ULS. The same applies for the Continuous Truss with the difference that the elements were grouped into five groups of elements out of which only the mostly stressed one was utilised to 75 % of the ULS.

3. Evaluation criteria

There are several types of static and dynamic loading tests that can be applied repeatedly and various types of quantities that can be continuously monitored and of course also numerous analytical procedures to process or evaluate the measured results. A set of experimentally obtained and conceivably analytically evaluated quantities is understood in this article as an evaluation criterion and can also be understood as a point of view on the condition of the structure. The goal is to choose a suitable combination of different evaluation criteria to be able to check or observe all the necessary parts of the structure.

In the following paragraphs, by "damage" is understood the reduction of the cross section of an element so that the stress in this element reaches the ULS.

Influence line:

The influence line, usually in the form of measured displacements or strains at one point of the structure, can easily be measured e.g. by a vehicle crossing a bridge. The change of the influence line is a suitable parameter that can be obtained from repeated loading tests which reflect the changes of stiffness along the structure. A change of the influence line always occurs at the location of the damage. In the case of a change of shear stiffness, there is a step in the influence line, while changes in the bending stiffness cause a change of its inclination. The situation may be less transparent in the case of multiple damage and statically indeterminate structures, especially around the supports.

If we know the precision of measurements, including all kinds of uncertainties, we can also estimate the extent of "observable or identifiable damage". This can be tuned to the current needs by using more measuring points and / or measured quantities. Considering the assumed (fictive) uncertainty of measurements of 2 %, the identifiable extent of damage was less than on half of the elements at any of the three models.

Natural frequencies:

Natural frequencies – it is the frequently used parameter in structural health monitoring (SHM). They can be used for indication of damage and, under special conditions, also for the assessment of its location or its extent. As in the previous case, the analysis was carried out considering the damage of each of its structural elements under the assumption that only 5 natural bending modes can be identified experimentally. If it is further assumed that the average drop of 5 natural frequencies of 0.5 % can be clearly distinguished and the drop of a single frequency can be measured with an uncertainty of 1 %, the identifiable extent of damage could also be estimated.

It should be noted that the minimum changes that can indicate the damage of one of the elements were considered. There is, of course, also the possibility that the cross section of all the structural elements will be reduced, for example, by just 10 % and therefore the ULS will not be exceeded anywhere. The structure will be safe, but the drop of natural frequencies will be considerably greater than the assumed tolerance of 1 %. This implies that monitoring could provide a warning at a safe level, but the condition would need to be checked visually on the site in any case.

Not all the elements could be checked only with aid of natural frequencies under the assumed conditions on the considered analytical models.

Flexibility change derived from the mode shapes:

In this study, it was assumed that the mode shapes could be measured at the nodes of the upper flange only in the vertical direction. According to (Padney, 1994), the flexibility matrix $\boldsymbol{F}$ can be computed from the following equation:

$$\boldsymbol{F} = (\boldsymbol{\Omega})^{-1} \cdot \boldsymbol{\Phi} \cdot \boldsymbol{\Phi}^T, \qquad (1)$$

where $\boldsymbol{\Omega}$ is the diagonal matrix of eigenvalues and $\boldsymbol{\Phi}$ is the matrix of the natural mode shapes scaled to the mass matrix. The negative changes of the main diagonal of the flexibility matrix show maxima at the location of damage analogically to the influence line and the integral of this function reflects the extent of the damage.

Theoretical estimation of the uncertainty of the flexibility changes is even more dubious than in the previous cases, because it will always depend on local conditions. Nevertheless, for our purposes, the value of 0.005 m/N for the global extent of the damage (the integral value!) was assumed to be the resolvable limit.

The flexibility changes resemble very much the character of the changes of the influence. The Flexibility changes could provide the damage indication at another set of elements than in the case of the previous criteria, but again some elements were rather unsensitive to this criterion.

Relative change of the relation between deformations and strains derived from the mode shapes:

If there are elements whose damage does not cause a significant change of the previously discussed criteria, there is still the possibility of local monitoring. The amplitudes of the measured mode shapes can be scaled in respect to strain amplitudes at critical points on the structure. The change caused by local damage can then easily be expressed as the relation of modes on intact and damaged structure, e.g. with the aid of the Modal Scale Factor (MSF) (Ewins, 2000; Allemang, 2003). Measurements of strains are a more demanding task than measuring accelerations or velocities in general (Bayer, 2016). However, new technologies provide us with promising new solutions like Fibre Bragg Grating optical sensors (Ye, 2014).

Thus we suppose that a reference measurement $\boldsymbol{V}r_{i,j}$ of m modes using n degrees of freedom ($i = 1...n; j=1...m$) is available from the intact structure and another corresponding set of modes $\boldsymbol{V}d_{i,j}$ from the damaged structure. The measurement is also available of strains at a single critical point εr and εd coming from the intact and damaged structures. The relative change of modes can then be defined as

$$\boldsymbol{RMD_j} = \frac{\sum_{i=1}^{n} \frac{Vr_{i.j}}{\varepsilon r_j} * \frac{Vd_{i,j}}{\varepsilon d_j}}{\sum_{i=1}^{n} \frac{Vr_{i.j}}{\varepsilon r_j} * \frac{Vr_{i,j}}{\varepsilon r_j}} - 1 \qquad (2)$$

If the damage of an element was not noticed by the previous criteria, but the strain between its nodes could be measured, the critical condition of this element could easily be identified by the RMD criterion.

Using assumed uncertainty of the RMD criterion of 10 % the damage on the continuous truss would be observable on all the elements when applied together with the previous criteria (see Fig. 1).

4. Conclusions

Focusing on the ULS, the case study presents an approach to component-level damage prevention. It demonstrates on a few simple truss structures that it is theoretically possible for the monitoring of static and dynamic deformations to be used as a collapse prevention in the case of gradually progressing damage. An efficient combination of available measured data and appropriate evaluation criteria can be obtained from a systematic analysis of damage scenarios. The reviewed criteria are merely an example for “data mining”. It is, of course, possible to propose or invent others (e.g. Wu, 2004 or Whelan, 2015), with respect to monitoring the goals in individual cases.

It is also obvious that a successful application on real structures depends on inherent uncertainties (concerning the analytical model, local and global environmental effects, measurement equipment, etc.) whose reliable estimation is still a problem that requires further experimental research.

A relative mode difference criterion for damage localisation was proposed, using measured vibration mode shapes and corresponding strains at a few critical points. This implies that monitoring of dynamic strains at low or ambient levels could be a promising field of application.

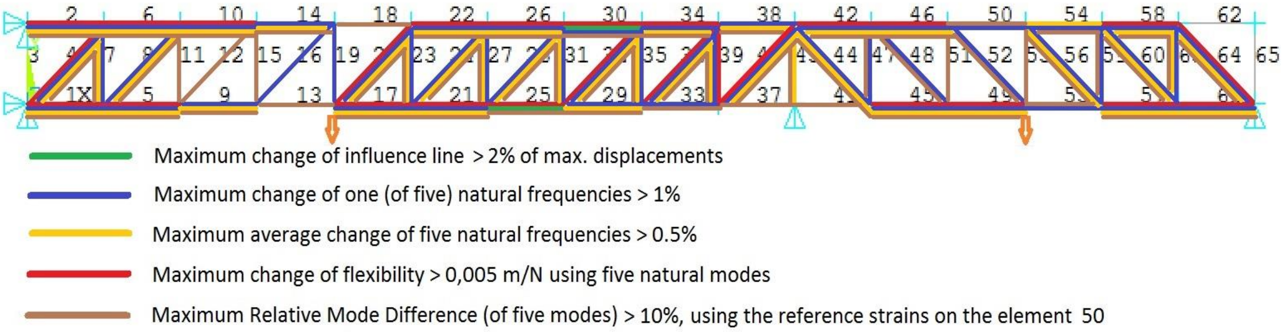

Fig. 1: Observable damage under assumed, fictive uncertainties on the continuous truss.

Acknowledgement

The supports of grants GA CR 17-26353J (identification code AVOZ 68378297) and the institutional support RVO 68378297 are greatly appreciated.

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