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Model updating for structural health monitoring using static and dynamic measurements

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Abstract

Structural health monitoring is tracking static or dynamic characteristics of a structure to identify and localize stiffness reductions for damage detection. Different damage indicators are used and any indicator presents advantages and drawbacks. Hence the idea comes up to combine them in a model-updating procedure using a finite element model. In a first step, a model is fit to match the healthy reference state of the examined structure. Therefore it relies on minimizing a special objective function adding and weighting the differences between measured and calculated static and dynamic structural characteristics. For doing structural health monitoring the measurements are repeated in distinct time intervals and the finite element model is updated again, using the same objective function and minimization procedure. Damage can be identified and localized by highlighting reductions in the stiffness matrix of the model compared to the initial model.
The efficiency of the method is illustrated by in-situ tests, where a single beam is examined that was part of a real prestressed concrete bridge. For static tests, 8 displacement transducers were disposed along the length of 40m, while the beam was mass-loaded and the deflection line is analyzed. Modal analysis was performed with swept sine excitation with constant force amplitude to identify eigenfrequencies and mode shapes. Stepwise artificial damage was provoked by cutting multiple prestressed tendons inside the concrete beam.
A finite element model with a mapped mesh was created, allowing a variation of Young’s modulus in grouped sections.
On real bridges temperature is neither homogenous nor constant over time, which often has a considerable influence on measured static and dynamic characteristics as the stiffness of asphalt and/or bearings can be affected. The proposed methods show their efficiency when temperature effects were excluded or compensated after measurement, which is a topic on its own and not discussed here.

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Keywords: detection, damage, model update, static, sagging, temperature, compensation

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1. Introduction

Damage detection in mechanical systems can be based on dynamic features namely eigenfrequency, mode shape, Modal Assurance Criterion (MAC) or on static measurements like displacement, inclination or strain. Visual inspection is state-of-the-art, but localization and assessment of existing damage is not always possible, for example when damage is hidden by a coating layer or when access is difficult or when only small cracks are visible. Therefore researchers look for alternatives as for instance model updating which links the behavior of the measurements on real structures with a numerical model. Once the latter fits well to a healthy reference state, the updating of a new set of on-site measurement may localize and assess damage that happened later to the structure.

Therefore, the set-up of a validated model is often sophisticated and the model updating including an optimization procedure may be difficult. The choice of core variables for the objective function becomes crucial. Moreover, temperature effects on the measured variables have to be removed prior to model-updating, as their influence may be in the same order of magnitude than damage [9].

Eigenfrequencies or/and mode shapes from dynamic testing are well known as input variables for model updating. Using both eigenfrequency and mode shape, damaged cables in the Lanaye Bridge [1] between Liege (Belgium) and Maastricht (Holland) were detected based on sensitivity matrices from perturbation method. Damage in the I-40 highway bridge in New Mexico (USA) was localized by a sensitivity analysis in the frequency domain [5] and further by mode shape sensitivities [6].

On the other hand, the size of the analytical model was reduced by a substructuring method in [3] that allowed also decreasing uncertain parameters. As a result, the optimization process based on flexibility revealed a more rapid convergence by reproducing extracted substructural flexibility matrices. But only a laboratory test was illustrated with a 2D frame.

Recently, a merging statistical analysis was combined with mathematical technique (response surface) and introduced into structural evaluation and assessment in [2]. A temperature updating model was utilized to exclude the model frequency variation from the baseline temperature field (20 °C) for data measured during 1 year in the Xiabaishi bridge (China). However, the temperature correction by regression was not shown in this problem of model validation.

Lately, the substructure method has combined with the response surface model updating method in [4]. Through the statistical analysis, the relationship between temperature fields was found, which induced strains of the stiffening girder of the Aizhai Suspension bridge (Chine).

In another study, both dynamic and static features were considered in the model updating. The input in [7] includes eigenfrequency, strain, displacement and hanger force. Temperature effects were reminded but their elimination from static quantities was not described. The idea of taking into account both dynamic and static data in the model updating procedure is appealing, but the decline of eigenfrequencies is not always clearly observed while the smoothness of mode shapes is rarely assured. Static data are often straightforwardly abundant and the elimination of temperature effect from statistics is easier in practice, so their data appear more stable which is an advantageous. At first in this paper, static measurements with temperature compensation are introduced to validate a numerical finite element model for reference. Artificial damage was then introduced in several steps and measurements were repeated. It is shown that model-updating is capable to discover and localize damage.

The analysis is performed on a prestressed concrete beam, which was a part of a real bridge in Luxembourg before.

2. Model updating - objective and damage function

An optimization problem is involved in model updating, by minimizing an objective function $f(\{p\})$ [10]:

$$min_{\{p\}\in\mathbb{R}^n} f(\{p\}) \tag{1}$$

that $\{p\} \in \mathbb{R}^n$ comprises n unknown or uncertain parameters p. The model updating aims to minimize the deviation between simulated results and real measured values. Practically, the deviations should be calculated in a dimensionless way, i.e. by normalization. Here the following objective function is proposed:

$$f(\{p\}) = \frac{1}{N}\frac{1}{\Delta}\sqrt{\sum_{i=1}^{N}\left(r_i(\{p\})\right)^2} = \frac{1}{N}\frac{1}{\Delta}\sqrt{\sum_{i=1}^{N}\left(\left|\ {}_iy_{exp} - {}_iy_{sim}(\{p\})\right|\right)^2} \qquad (2)$$

where deviation vector $r(\{p\})$ is evaluated from ${}_iy_{exp}$ and ${}_iy_{sim}$, which present values of a considered characteristic physical quantity y_i, measured once in well-defined tests and once computed from a finite-element model. N and Δ are introduced for normalization purpose, taking into account of the number of measured quantities N and the measurement accuracy Δ of the considered physical quantity together with the used measurement system. Thus we normalize to one measurement with reliable "digits" or "units".

Once the objective function f has been defined, certain parameters in p should be varied within physical reasonable limits to minimize f during model updating. The idea here is finding the location and the amount of stiffness reduction due to damage. In the present bridge structure, this means a reduction of bending stiffness in narrow slices which can be modelled by decreasing the Modulus of Elasticity of the concerned elements. In the literature, it is often recommended (e.g. in [11-12]) to take a relative rather than an absolute physical quantity, i.e. change it with respect to the initial value.

$$a_k = \frac{E_{k0} - E_k}{E_{k0}}$$

$$\text{So, } E_k = E_{k0}(1 - a_k) \qquad (3)$$

E_{k0} and E_k denote the original and adapted Modulus of Elasticity for slice k, and hence a_k is a dimensionless parameter. To reduce computational effort, Teughels et al. [12] proposed to combine several adjacent elements into one damage element. A so-called *damage function* then establishes a relationship between the *E*-moduli of these elements. More specifically, it defines the modulation of parameter a along the length of each damage element. This also avoids abrupt changes to the *E*-modulus. According to an *x*-axis from -1 to 1, a damage function a (x) is defined. The function itself can be adapted with relatively few parameters, which form vector $\{p\}$ for the optimization.

$$a(x) = p \cdot e^{-0.5\left(\frac{x-\mu}{\sigma}\right)^2} \qquad (4)$$

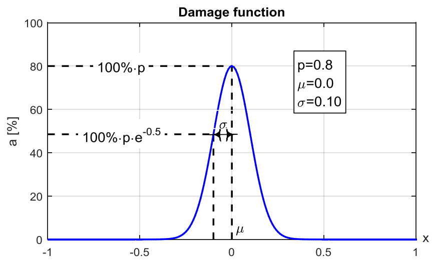


Figure 1: Damage function defined by a Gaussian bell curve

In the present work, the beam is modelled with uniform hexahedral SOLID elements. Divided to equidistant slices, their E modulus is varied to find locations with decreased the stiffness. To reduce the number of parameters, several adjacent slices are combined to form *damage elements* where for each of them a *damage function* is defined. This function should describe in a realistic way the reduction of stiffness due to a crack. The damage function shows highest value at the crack's position, but decays quickly. While a sum from Legendre polynomials was chosen in [12], a Gaussian bell curve with maximum value p, expected or mean value μ and standard deviation σ is proposed here by Eq. (4) and as illustrated in Figure 1. μ gives the location of the simulated crack, while σ and p define the severity.

Before any simulation the E-moduli are calculated by Eq. (3) according to $\{p\}$ for each element by inserting the x-coordinate of the centre of gravity of the element into the damage function a.

3. Application

3.1. Description of the tested structure

The tested structure was a part of a bridge built between 1953 and 1955 and crossed the river Mosel between Grevenmacher (Luxembourg) and Wellen (Germany). After demolishment of this bridge this beam was transported in a nearby harbor (Mertert) and jacked up for the series of experiments. The beam had a total length of 46m as presented in Figure 2 and was prestressed by 19 steel tendons along the longitudinal direction. More details on prestressed tendons with subsequent grouting and the testing procedure can be found in reference [8].

The idea of this testing series was to simulate service-life of the bridge and to measure structural responses after artificial damage was introduced in multiple steps. One end of the beam was fixed to avoid movement in any direction. For the sliding bearing at the other end, two steel plates were placed between the beam and a concrete block and lubricated with grease. In fact, this was not a perfect sliding bearing, because some friction still existed. But we clearly measured and documented longitudinal stick-slip movement of the beam, for instance due to thermal expansion.

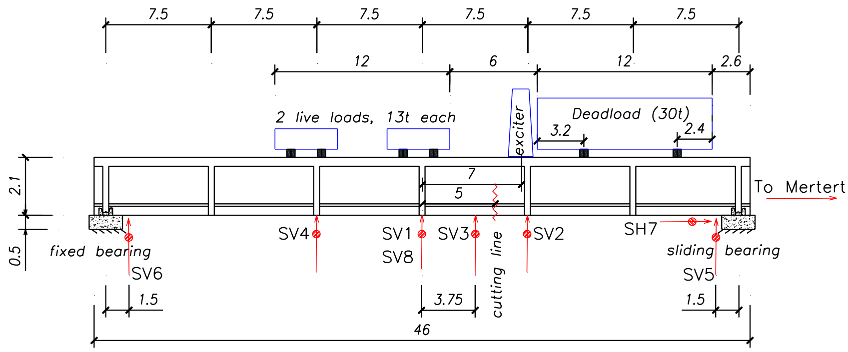


Figure 2. Configuration of the beam and positions of transducers for static measurements

In order to simulate additional dead load (traffic lane with asphalt layer, sideway and other additions), a mass of approximately 30t was cut and positioned on top of the structure. It is referred as dead load and stayed onto the beam during the whole testing period. Although it was not distributed equally over the whole beam length like an asphalt layer, its induced stresses were checked and considered as an equivalent approximation.

On the other hand, two concrete blocks with a mass of 13t each were used for repeated static testing purposes with always the same mass loading, subsequently denominated as live load. The beam was subjected to similar charging due to high traffic loading during its life, i.e. the 26t stayed within the permitted service loading. They were positioned on predefined and fixed wooden pads and removed again after at least 24 hours. Displacements were recorded in several locations as detailed in Figure 2, in the vertical direction (SV1-SV6, SV8) to capture the deflection line and in the horizontal direction (SH7) for control purposes of the horizontal movement of the sliding bearing.

All static tests were performed within one month and the beam was loaded and unloaded 7 times with the two live-loads of 13 t each in 5 different damage scenarios (states #0 to #4 as indicated in Figure 4). These different subsequent increasing damage scenarios were artificially provoked by cutting tendons at the "cutting line" indicated in Figure 2 and in Figure 3. The initial healthy state is numbered as #0 and considered as reference. Four damage states #1 to #4 correspond to the cutting of 2, 4, 6 and equivalent 9 tendons respectively. During the whole period the deflection of the beam (SV1) and the ambient temperature condition were permanently registered. Structural temperature was monitored within a hole of 10cm depth inside the concrete.

As predicted by a Finite Element (FE) model with software ANSYS, the first visible vertical crack appeared after cutting 6 of 19 tendons in scenario #3 under loading of the beam with the two life-loads.

3.2. Static results - Deflection

Deflection lines of the beam were established, referring to the initial (=zero) position of unloaded (UL) configuration in state #0. The first loading in the healthy state #0 is then called #0, L1 and so on (ref. to Figure 2 and Figure 3).

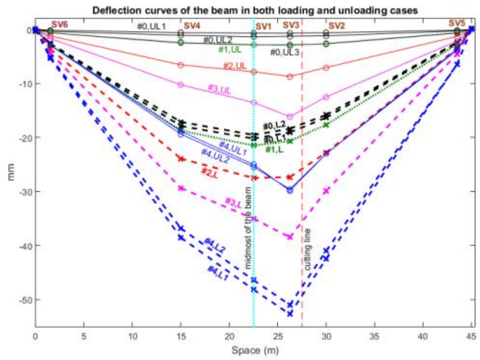


Figure 3. Deflection of the beam in unloaded and loaded states, interpolated with straight lines

By connecting simply the measured values of displacement sensors SV1 to SV6, the deflection lines of the beam are shown Figure 3 for both unloading (solid lines) and loading states (thick dashed lines) for all damage scenarios #0 to #4. Two zero points are assigned to the two outer bearings, though there was no sensor. As already mentioned, the first vertical cracks appeared by the loading of state #3, so-called #3-L. Prior to this state, the deflection curves are quite smooth in the overall view. With this first cracking in #3-L, maximum deflection moves from the middle (SV1) to nearly the cutting line between SV2 and SV3, proving that the monitoring of the deflection curves from the initial state to all the damage states allows localizing damage.

3.3. Temperature compensation

Absolute temperature changes can lead to vertical deflection, especially when there is friction in the sliding bearing which happens quite often. Furthermore, relative temperature differences between top and bottom of the bridge also lead to vertical movement. This temperature movement must not be confounded with deformation due to loading with or without damage and hence must be removed from the measured data. A compensation algorithm was proposed in reference [8] in order to remove the effect of temperature variation in displacement measurements and trace measured data back to a constant temperature. An illustration is given in Figure 4 with sensor SV1 and the temperature measured in concrete (in the bottom of the beam) for the whole measurement campaign. The compensation algorithm calculates back to a constant reference temperature, here chosen at 5°C – the average temperature of the testing period. Each state is not compensated as a unique set, but categorized into different sub-intervals without horizontal movement of the sliding bearing.

In Figure 4 the differences between loaded and unloaded deflection after the temperature-compensation are introduced as red numbers. For damage states #0 and #4, we see a decrease between loading L1 and L2 by the effect of non-reversible residual strain within the first loading due to cracking/plastification.

Nevertheless, from #0-L2 to #4-L2 that are both the second loading of two different scenarios, an increase of 6 mm (from 17 to 23 mm) can be seen indicating progressive damage or reduced stiffness. This increase of step height could be analyzed further and used as damage indicator. But here we skip this indicator and focus on the sagging, which can also be directly seen. After loading 2 the sensor SV1 shows an absolute position approximately 15 mm in state #0-UL2, while it offers 35mm in unloaded condition in state #4-UL1, i.e. a sagging of 20 mm. This sagging, besides the eigenfrequencies, will be serve for model updating in the following.

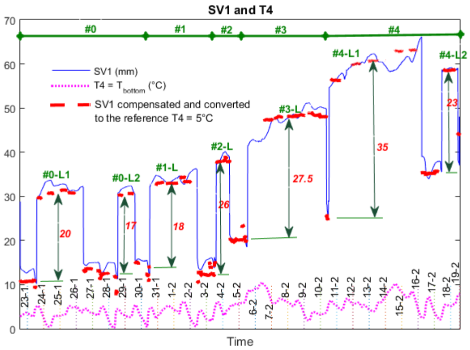


Figure 4. Vertical signal SV1 as measured (continuous blue) and compensated (thick red)

3.4. Model updating procedure

As already stated here the sagging and the eigenfrequencies are used separately for the objective function. The temperature compensated measurements are also indicated in Figure 4, which were used to assess the sagging. Furthermore eigenfrequencies of the first two bending modes identified at 2.9Hz and 7.5Hz were considered. While using the saggings, the number of measurements N = 6 and the measurement accuracy Δ = 0.1mm. On the other hand, the use of eigenfrequencies goes with N = 2 and Δ = 0.01Hz.

The values measured from the on-site monitoring are correlated with results obtained from the simulated model built with SOLID elements in the ANSYS software. Figure 5 shows the model including the main beam, the 'dead load' and the supports (fix and sliding bearings) as well as a zoom showing regular meshing in axial slices.

Figure 6 presents the objective functions $f=f(p, \sigma, \mu)$ examined in different stages of the optimization by selecting values of parameters corresponding to the minima of the objective function based on the sagging. As the quantities in Eq. (4) are dimensionless μ varies from -1 to 1, which represents the two ends of the beam, while coordinate 0 is set at its middle. For instance by starting with an arbitrary value σ=0.02, all considered value of p result in minima at μ = 0.2 corresponding exactly to the location of damage, as shown in Figure 6a for the case of damage #4. Considering now for this damage a set of parameters: p =0.9 and μ = 0.2, a new standard deviation σ can be found at 0.07 in Figure 6b. Going from the new set of parameters: σ=0.07 and μ = 0.2, the objective function is Figure 6c shows clearly optimal value of p is about 0.9 for damage #4. Finally, the objective function is re-checked by different values of p in Figure 6d. From this last image, we can distinguish three classes according to the minima of the objective function. Class 1: p<0.9 (from 0.5 to 0.9) – every minimum befalls at the right location of cutting line μ = 0.2; Class 2: p = 0.9 – the minimum is shifted to μ = 0.13 towards the middle of the beam; Class 3: p>0.9 – a maximum occurs at μ = 0.2 instead of a minimum while the minimum presents far away from the cutting line.

So from Figure 6d for damage #4, it reveals that 0.9 can be seen as a 'critical' value of parameter p. An accurate localization is straightforward with a smaller p than the 'critical' one.

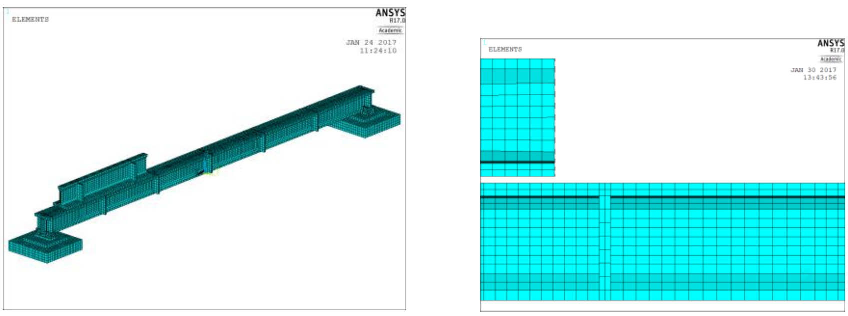
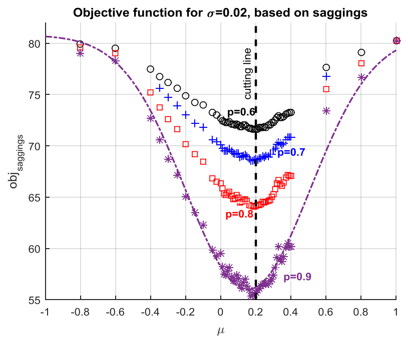
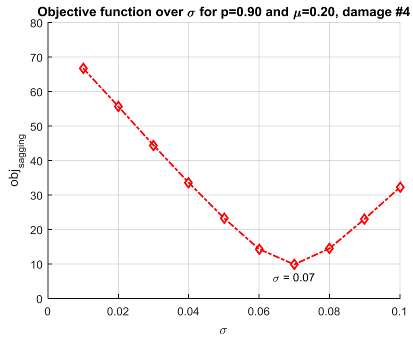


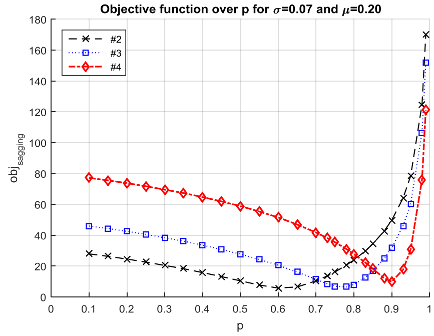
Figure 5: Model by SOLID elements in ANSYS



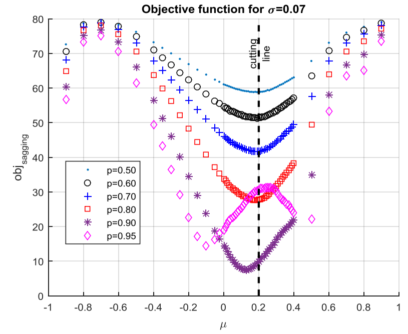
a) Start with an arbitrary value of σ to find damage location μ=0.2



b) Finding the optimal value for σ at 0.07



c) Finding the optimal value of p at 0.9 for damage #4



d) Check damage localisation by μ with optimal σ =0.07 in case of #4

Figure 6. Objective functions based on sagging with the main stages of optimization

Similarly, based on eigenfrequencies, the optimal values for σ and p are 0.03 and 0.88 respectively in case of damage #4. The objective functions are given in Figure 7 with p varies from 0.6 to 0.95. If p = 0.88 is called 'critical' value, $p\in[0.6\text{-}0.7]$ lead to minima about the right side of μ = 0.2 while $p\in[0.8\text{-}0.9]$ allow detecting exactly the location of damage at μ = 0.2. Again, with bigger p, a minimum presents no longer at the right location. Moreover, based on eigenfrequencies, the localization is less consistent than based on sagging owing to the presence of some secondary minima between abscissa μ from -0.2 to -0.05.

As a representative illustration, the reduction of Young's modulus calculated by using the parametrized damage function as described is shown in Figure 8. The two curves result from using the optimal/'critical' parameter sets based on sagging and eigenfrequencies respectively. . The Gaussian curve based on eigenfrequencies allows facilitating the localization of damage at μ = 0.2 corresponding to x=27.6m. The Gaussian curve based on sagging, with the 'critical' p value points out damage slightly nearer toward the middle of the beam. It may be explained by two assumptions: 1) either at *damage scenario #4*, the damage was developed largely toward the middle or 2) there was no sensor measured at the cutting line, the maximum deflection is recognized at sensor SV3 which is also near μ = 0.13.

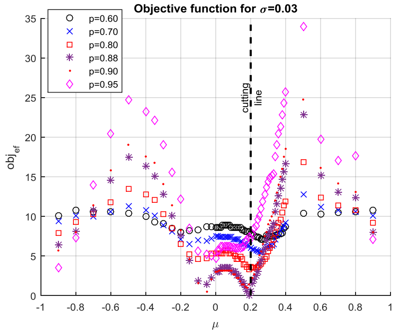


Figure 7: Objective functions based on eigenfrequencies

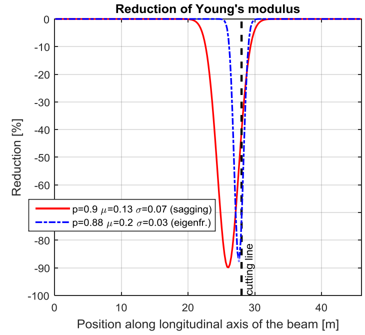


Figure 8: Reduction assessment of Young's modulus along the beam

4. Conclusion

In this paper, a novel technique is proven robust for discovering and evaluating damage in real bridge structure, based on both ambient measurements and finite element simulations. Of course an adequate model is crucial and the model updating is only reasonable if temperature effects have been excluded by appropriate algorithms from measurements.

Sagging and eigenfrequencies have been considered separately for the updating process. In next steps a combination of these features could be checked and further damage indicators taken into account, such as step-height of repeated static testing with identical loading.

A Gaussian bell-curve damage function was used to reduce the numbers of variables in the optimization function. Nevertheless the optimization problem is still rather costly, why only linear modelling was used so far.

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References

[1] A. Mordini; K. Savov; H. Wenzel, The Finite Element Model Updating: A Powerful Tool for Structural Health Monitoring, Structural Engineering International 17(4):352-358 · November 2007.
[2] Zh. Zong, X. Lin, J. Niu, Finite element model validation of bridge based on structural health monitoring - Part I: Response surface-based finite element model updating, Journal of traffic and transportation engineering (english edition) 2015; 2 (4): pp. 258-278.
[3] Y. Xia. Sh. Weng. Y.-L. Xu. A Substructuring Method for Model Updating and Damage Identification. Volume 14, 2011, Pages 3095-3103 The Proceedings of the Twelfth East Asia-Pacific Conference on Structural Engineering and Construction - EASEC12.
[4] Sheng Yu, S.M.ASCE; and Jinping Ou, Structural Health Monitoring and Model Updating of Aizhai Suspension Bridge, Journal of Aerospace Engineering, 7-2016.
[5] V.H. Nguyen, J.-C. Golinval, Localization and quantification of damage in beam-like structures using sensitivities of principal component analysis results, Mechanical Systems and Signal Processing 24 (2010): pp. 1831–1843.
[6] E. Parlo, P. Guillaume, M. Van Overmeire, Damage assessment using mode shape sensitivities, Mechanical Systems and Signal Processing, Volume 17, Issue 3, May 2003: pp. 499-518.
[7] H. Schlune, M. Plos, K. Gylltoft , Improved bridge evaluation through finite element model updating using static and dynamic measurements, Engineering Structures (0141-0296). Vol. 31 (2009), 7: pp. 1477-1485.
[8] V. H. Nguyen, S. Schommer, S. Maas, A. Zürbes, Static load testing with temperature compensation for structural health monitoring of bridges, Engineering Structures (2016), 127(2016):pp. 700-718
[9] S. Maas, S. Schommer, V.H. Nguyen, D. Waldmann , J. Mahowald, A. Zürbes, Some remarks on the influence of temperature-variations, non-linearities, repeatability and ageing on modal-analysis for structural health monitoring of real bridges, EVACES'15, 6th International Conference on Experimental Vibration Analysis for Civil Engineering Structures, 19-21 October 2015, EMPA Zürich Switzerland.
[10] J. Nocedal, SJ. Wright, Numerical Optimization. New York, NY: Springer Science+Business Media, LLC; 2006.
[11] B. Jaishi, W.-X. Ren, Damage detection by finite element model updating using modal flexibility residual, Journal of Sound and Vibration 2006; 290(1-2): pp. 369–387.
[12] A. Teughels, J. Maeck, G. De Roeck, Damage assessment by FE model updating using damage functions, Computers & Structures 2002; 80(25):1869–1879.