Damage detection for bridge structures based on dynamic and static measurements

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Abstract

Some results of damage detection for real bridge structures are reported in the present paper based on both dynamic and static measurements. Dynamic analysis relates to the identification of modal parameters and deduced variables… The processing of static data is based on the analyses of deflection line and its derivatives, i.e. slope and curvature.

Detection methods were applied in several real concrete bridges in Luxembourg. The results are encouraging and useful for Structural Health Monitoring in civil engineering structures.

Keywords: bridge, damage, modal identification, deflection, temperature

1 Introduction

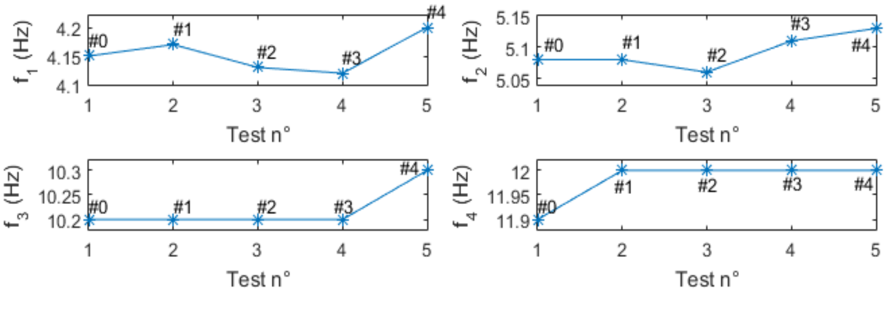
As bridges are structures of big size and subjected to varying temperatures, their structural health monitoring is quite difficult. Typically their inspections are done visually and static load testing is sometimes performed. Furthermore, especially in the last years, monitoring of modal features like eigenfrequencies, mode shapes or damping ratios is in vogue. These features can be used for subsequent analyses like model-updating and stiffness or flexibility assessment to identify and localize stiffness changes (Reynders & De Roeck, 2010; Huth et al., 2005; Nguyen & Golinval, 2010), even to predict remaining life (Khan et al., 2015). On the other hand, static load tests providing important information on deformation, displacement, tilt and strain (Inaudi, 2010) are still an appropriate alternative with a long tradition.

In the last decade, the Research Unit in Engineering Sciences at the University of Luxembourg had the opportunity to investigate several real bridges as well as to analyze the consequence of artificial introduced and hence known damages prior to their final demolition for different reasons. Some revealed issues are reported in the present paper, including both static and dynamic analysis. Different damage detection methods were tested and some results are reported in the present paper, including both static and dynamic analyses.

2 Dynamic investigation

Since corrosion and fatigue can induce cracking in concrete and hence stiffness reduction, the health condition of a structure may be reflected via its modal parameters, namely eigenfrequencies, mode shapes, modal masses and damping ratios. For example in any numerical model, damage or a reduction of structural stiffness normally leads to a reduction of eigenfrequencies. However, for real bridges, the damage detection based on the variation of eigenfrequencies is not always straightforward, because the reduction of frequency due to damage may be even lower than its variation due to environmental influences or due to measurement noise. It is for instance known that temperature influences Young's modulus of asphalt or bearings including the sub-soil, which hence changes considerably the stiffness. This can be illustrated by the two following examples.

The "Deutsche Bank" Bridge (Maas et al., 2012) was a three-span concrete bridge with a total length of 51m, post-tensioned by 29 tendons with subsequent grouting. In order to simulate damage, several prestressed tendons were cut according to 4 damaged scenarios #1 to #4 (1 to 27 of 29 tendons locally cut) and scenario #0 denotes the intact state. Under the excitations of an electric shaker with swept sine excitation of constant amplitude, vibration responses of the bridge were captured by 12 sensors allocated on two sides of the bridge deck. Eigenfrequencies identified for the first 4 modes are depicted in Fig. 1.

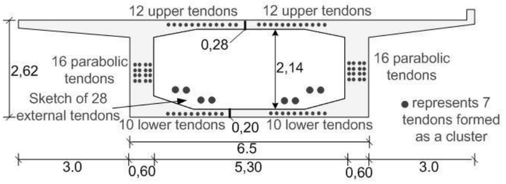


scenario	situation
#0	intact
#1	1 tendon cut
#2	5 tendon cut
#3	9 tendon cut at one location
#4	9 tendon cut at 3 locations

Figure 1 : “Deutsche Bank” Bridge – eigenfrequencies measured for healthy state and increasing levels of damage

Though considerable local damages from condition #1 to #4 were stepwise increased, the eigenfrequencies do not reveal obvious decrease, above all as no visible cracking in concrete was observed.

In a second example, the Champangshiel-Bridge, artificial damages induced cracking in concrete but no monotonous decrease of eigenfrequencies. It was a pre-stressed concrete bridge that the total length is 102 m with two spans of 37 m and 65 m (Nguyen et al., 2014). A cross-section of the bridge is given in Fig. 2 and the position of sensors in Fig. 3; the distance between them along the bridge’s length was about 10 m. Before its complete destruction, the bridge was monitored and a series of damages were artificially introduced as summarized in the table in Fig. 2.



State	Damage
#0	Undamaged state
#1	Cutting straight lined tendons in the lower part
#2	Cutting 8 straight lined tendons in the upper part
#3	Cutting external tendons
#4	Cutting 16 straight lined tendons in the upper part and 8 parabolic tendons

Figure 2 : Schematic cross section of the box girder with location of the tendons and the execution of damages in the Champangshiel bridge

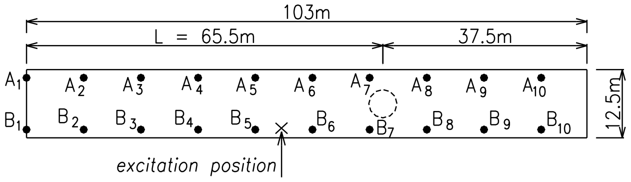


Figure 3 : Location of the sensors on the deck of the Champangshiehl bridge

Vibration monitoring under swept sine and impact excitation were performed for the healthy structure and for each damage state. The identification of eigenfrequencies from these two types of excitation gave quite similar results which are shown in Fig. 4.

For this bridge, reduction of the eigenfrequencies due to damages is clearly visible, though not strictly monotonous. Especially for damage scenario #2, an increase of the eigenfrequencies f_2 and f_4 is apparent.

These two examples show that the detection by simple observation of frequencies is not always evident. Furthermore it should be noted that any perturbation due to excitation was avoided because the structures were always excited with the same manner and level. But for instance temperature variation was unavoidably present, due to the size of the bridge, due to solar radiation and day-night changes.

Other useful alternative can be the analysis of deducted dynamic features, e.g. the flexibility matrix or the use of Principal Component Analysis (PCA), a statistical method to remove noise and even temperature influence. Mode shapes are known as less sensitive to global change (e.g. due to temperature) but more perceptible to local change (e.g. due to damage). The flexibility matrix, i.e. the inverse of the stiffness matrix, is often computed in practice based on a limited number of measured eigenfrequencies, mode shapes and modal masses. This may allow observing an increase of flexibility of structure with damage. As presented in Fig. 5a, the diagonal elements of this matrix show clearly the distinction between the different levels of damage (Mahowald et al., 2012).

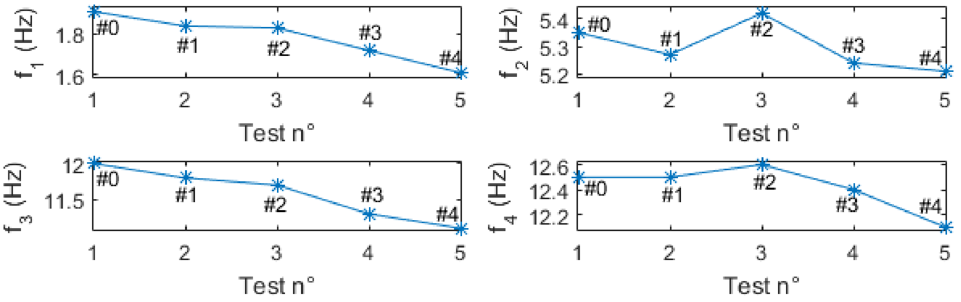
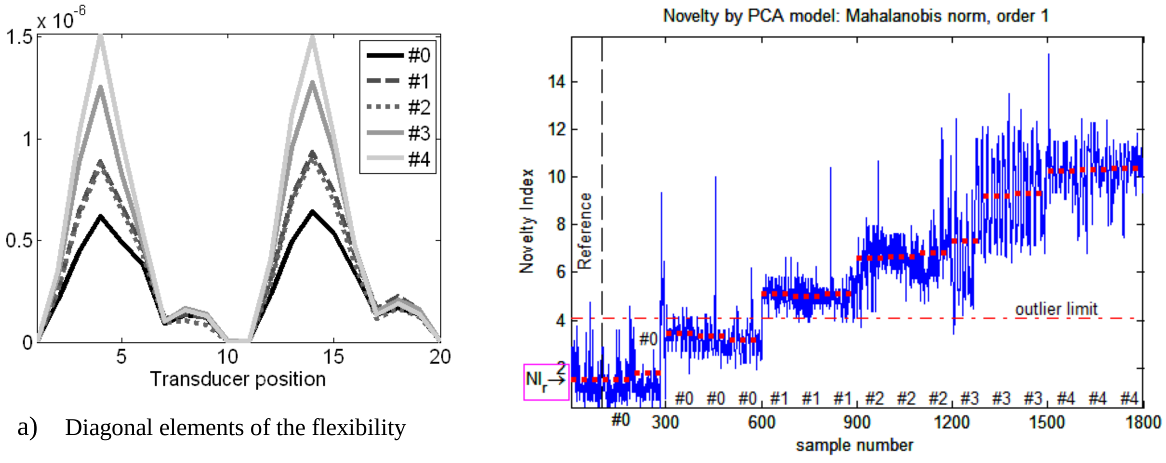


Figure 4 : Champangshiehl bridge - eigenfrequencies measured for every state

Principal Component Analysis (PCA) is a statistical method that enables damage detection including environmental effects by considering for instance dynamic features as input, for example the identified eigenfrequencies (Nguyen et al., 2014). A particular advantage of this method is its ability to separate ambient influence from changes caused by damage, provided the number of samples is sufficient. A damage indicator called Novelty Index can be used as efficient tool for evaluating the difference between healthy and damaged states. Fig. 5b presents the PCA detection based on the first four eigenfrequencies and 300 samples in any damage scenario. In order to enable the detection on a broad basis and to avoid false alarm, the data in the healthy condition #0 are enriched and gathered from different days and different excitations (hammer impact and swept sine). The damaged states are examined under the swept sine excitations with constant excitation force amplitude. In total, Novelty Index *NI* is computed for 1800 samples for all the states. A red bold dotted line shows the mean value of every 100 samples. The dash-dot horizontal line indicates a statistical outlier limit $OL = \overline{NI}_r + 3\sigma$ where $\overline{NI}_r$ and σ are the mean value and the standard deviation of Novelty Index in the reference state.



a) Diagonal elements of the flexibility

b) Monitoring by Novelty Index and Principal Component Analysis

Figure 5 : Damage detection for the Champangshiehl bridge

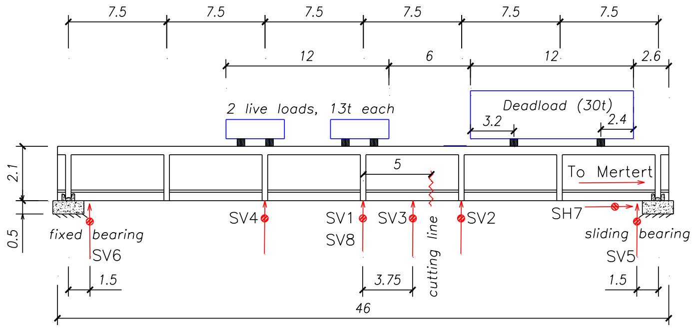
An overall look at Fig. 5b reveals an interesting result: despite the variation of the *NI* for the undamaged state #0 (which results from the variation of the eigenfrequencies with the temperature), most of the *NI* values lie below the outlier limit line. The few samples crossing this line are influenced by other factors, e.g. the presence of nonlinear effects or measurement noise. The small variation of the mean values in the healthy state #0 comes from simply the difference of excitations. On the contrary, all the damaged states are clearly detectable by exceeding the outlier limit. They are well classified and increasing in accordance with the respective damage levels.

3 Static investigation

Beside vibrational inspection, static testing provides helpful and reliable information for assessing the actual condition of a bridge by discovering local change of stiffness through shape deformation and through the absolute values of deflection line for a given loading.

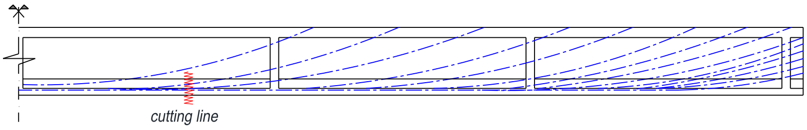
It consists in register displacements at several points in the structure and thus the deflection line is established for every state. This method is subsequently illustrated by a third test-object, the Grevenmacher-Bridge. The old bridge had 5 independent fields that each consisted of 5 parallel pre-stressed concrete beams. It was demolished in 2013 and two of these beams each with a length of 46 m and a mass of about 120 tons were shipped to a nearby port for test purposes.

In order to simulate the loading situation during its operational life, the dead-load of asphalt, pavement, guard railing, etc. had to be modeled. Hence one beam was cut in pieces and used for charging the second one, our test-object (Fig. 6.). One fixed and one sliding bearings were realized by cast-in-place concrete onto nearby railroads, which provided a solid foundation.



a) Configuration of the beam and positions of transducers SV1-SV8

State	Cutting of
#0	0 tendon
#1	2 tendons
#2	4 tendons
#3	6 tendons
#4	6 tendons+ half of 6 others tendons



b) Disposition of tendons shown in a half of the beam's length

Figure 6 : The test set-up of the beam and description of damage scenarios #0 - #4

So to simulate this additional dead load, a part of the second beam with a mass of approximately 30t was set on the top of structure. This mass stayed onto the beam during the whole test period and is therefore referred to as permanent load. Although it was not distributed over the whole beam like an asphalt layer, it was considered as an admissible approximation. Additionally, two concrete blocks, each with a mass of 13t, were used to represent live loads due to high traffic loading on the bridge. They were put on for static tests and removed again after at least 24 hours. Displacements due to these loads were recorded in several locations, as detailed in Fig. 6a, along the vertical (SV1-SV6, SV8) and horizontal directions (SH7).

The beam was prestressed by 19 steel tendons along the longitudinal direction of the beam as illustrated in Fig. 6b for a half of the beam. Different damage scenarios were simulated by cutting the tendons at the cutting line indicated in Fig. 6. Static tests were carried out by loading and unloading the structure always with the two live loads, in total 7 times. Hence two principal situations have to be distinguished: loading (L) and unloading (UL). In total, 7 loadings are considered from #0 to #4 as #0-L1; #0-L2; #1-L; #2-L; #3-L; #4-L1 and #4-L2.

The aim here is to establish deflection lines of the beam, distinguished from zero position of reference configuration #0, UL1. Fig. 7 presents deflection lines of the beam for both unloading and loading states by connecting simply measured points SV1 to SV6. Two zero points are assigned according to the two border bearings. The data are picked up according to 8 unloading times and 7 loading times from scenario #0 to #4. Before the appearance of vertical cracks around the cutting line from scenario #0 to #2, the deflection curves are quite regular and smooth in an overall view. After that, the future breaking point became maximum deflection point and is clearly shown by the sensor SV3, which was close to the cutting line. The maximum deflection moved from SV1 (in the middle) to SV3, near the cutting line of the beam. This proves that the drawing of deflection curves from the initial state to all the damage states allows localizing damage.

For comparison purposes, the deflection lines were also smoothed by the cubic spline interpolation. To improve the visibility only the loaded states are presented in Fig. 8.

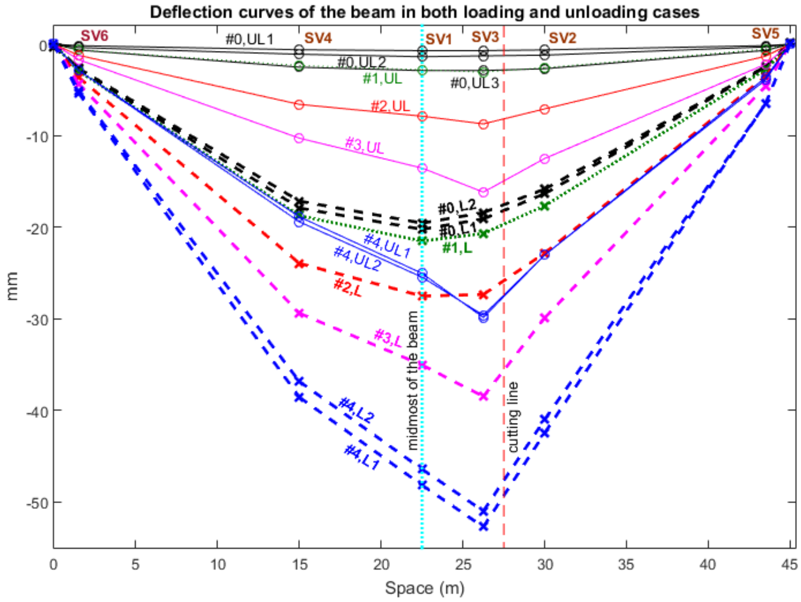


Figure 7 : Deflection of the beam in unloaded and loaded states

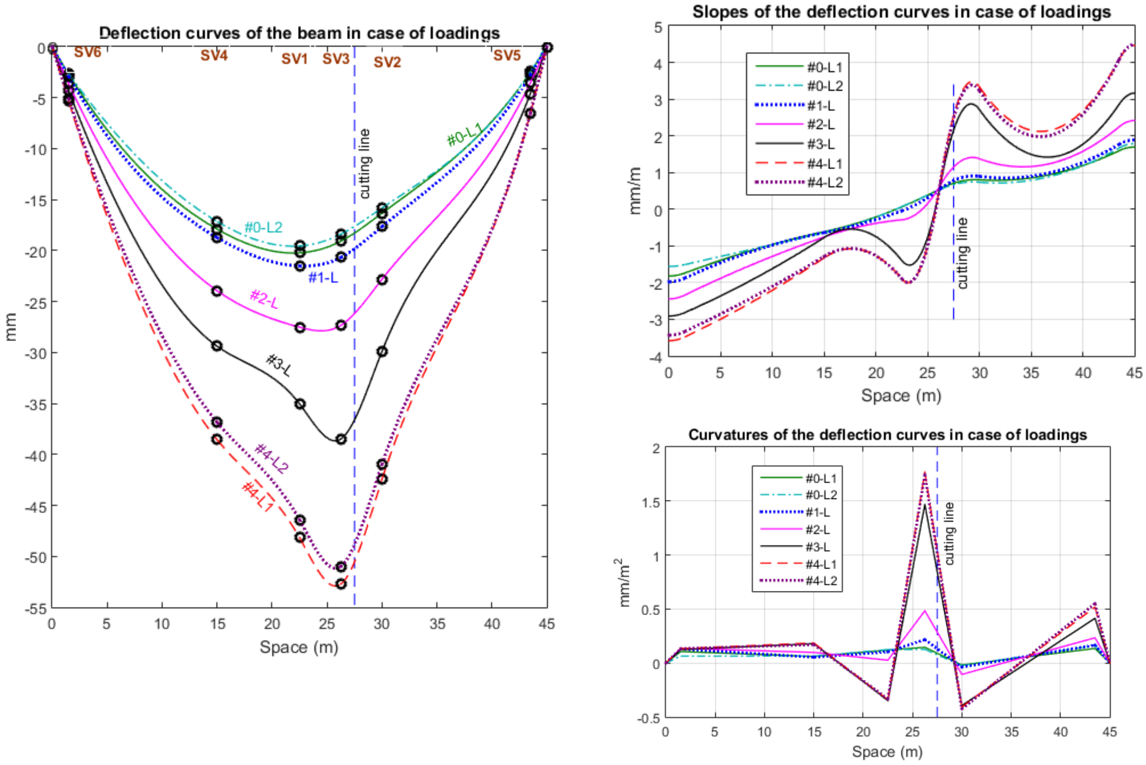


Figure 8 : Results from the cubic spline interpolation: Deflection lines, Slopes and Curvatures

While damage can be detected and localized already by the raw deflection lines in Fig. 7, it can also be localized by important change of shape of the curve and by the increase in displacement near the cutting line. The absolute values in Figs. 7-8 can already be used as damage indicator. Looking at only loaded or only unloaded state near the crack (position SV3), an increase of at least 30mm can be detected with respect to the healthy reference state. This very important change indicates as well the presence of damage.

Naturally, the derivatives of the deflection curve, namely the slope (1st derivative) and the curvature (2nd derivative) are also helpful for localization. Damage can be identified by strong variation of the slopes around the cutting line. These variations lead to high values of curvatures near the cutting line. Damages are accurately localized as the curvatures near the cutting line show dominant values compared to other positions. It shows that the damage localization is efficient and accurate from damage state #2.

4 Conclusion

Several techniques from dynamic and static data for damage detection in bridges are presented in this paper. Dynamic methods are based on eigenfrequencies, mode shapes, flexibility, and Novelty Index. They showed different performance with respect to ambient and operational influences as for instance temperature variation and excitation level. Alternatively, the establishment of static deflection curves from load testing is an effective means to localize damage. Around breaking line, an increase of flexibility is observed and important changes of shape as well as amplitude of the deflection curves are revealed. Furthermore, their slopes and especially curvatures allow localizing damage by showing sudden changes along the structure.

The combination of dynamic and static methods provides an exact basis for the assessment of bridge health condition and may also be used for model updating techniques.

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