Bridge Maintenance, Safety, Management, Life-Cycle Performance and Cost

Editors

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International Association for
Bridge Maintenance and Safety

Comparison between damage detection methods applied to beam structures

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ABSTRACT: Damage detection methods based on the dynamic measurements of structures are one of the most important techniques for damage evaluation in bridges. The methods considered in this study have been recognized as the most promising tools for damage detection in these structures. Some of these methods were applied during the deliberate damage of Z24 Bridge in Switzerland and I-24 Bridge in USA. These methods have been evaluated in different cases and therefore it is difficult to decide which method is the best for the particular purpose. The comparison of these methods will be done using simulations performed in a composite simply supported bridge. Almost all the methods provided good results when noise was not taken into account. However, accuracy of these methods is still limited when noise is present during acquisition of the dynamic response.

1 INTRODUCTION

The structural evaluation of bridges has become an essential topic since many of these structures have achieved their service life and some damage may occur. The current methods for detection of damage are visual inspection and local non destructive evaluation (NDE) methods. In order to be efficient, these techniques need a priori global location of the damage and easy access to the damage zone. For global damage detection, methods based on dynamic monitoring have been proposed. They can be categorized into four different levels: 1) detecting if the structure is damaged; 2) finding the location of damage; 3) estimating the severity of damage and 4) evaluating the remaining service life of the structure. A review of those methods was provided by Sohn et al (2003).

The first attempt to detect damage using vibration based methods was the comparison between the natural frequencies. Salawu (1997) carried out a review of these methods. Those methods were not efficient principally because cracking in beam structures provokes only a small change in natural frequencies. One of the first methods for comparison of mode shapes was the Modal Assurance Criterion (MAC), which gives a value 1 if two vectors (mode shapes) are the same and 0 if they are completely different. The coordinate modal assurance criterion (COMAC) compares the change of the mode shapes in different points of the structure. Pandey et al (1991) found that the second derivative of the mode shapes (curvatures) is more sensitive than simple mode shapes for detecting damage. Based on the curvature method, Stubbs and Kim (1994) proposed the damage index method, which is the comparison between square curvatures of the structure before and after the damage.

One of the most promising techniques for detecting damage is based on Wavelet Analysis. For those methods, it is not always necessary to know the undamaged condition of the structure and the numerical differentiation of the dynamic response is not required. Liew et al (1998) was the first to apply the Wavelet Analysis for detecting damage in civil engineering structures considering the mode shapes of cracked simply supported beam obtained from modifying its stiffness matrix. Hong et al (2002) presented a method based on Continuous Wavelet Transform and Holder Exponent. The severity of the damage using Wavelet Analysis was obtained for the first time with this method. Another procedure for identification of damage uses the Wavelet Packet. Chang et al (2005) proposed a method that consists of decomposition of the dynamic response into wavelet packet components. The energy for a given component and level of decomposition is obtained for all the measuring points. Finally, the curvatures of these energies are calculated and the damage is detected as a local disturbance along the beam.

The damage detection methods evaluated in this study were: COMAC, curvature, damage index, discrete wavelet analysis (details), continuous wavelet transform, wavelet packet transform and Holder exponent methods. All of them are level 2 methods. Also, level 1 methods were used as comparison between principal frequencies and MAC method. The comparison was done on the first five mode shapes of the structures.

2 BRIDGE STRUCTURE

The bridge considered for the evaluation of the damage detection methods was designed following the AASHTO bridge code 1994, Salgado (2000). It is a composite simply supported bridge with two steel I beams (HE800B) and concrete slab with 300 MPa of compressive strength and 215 mm of depth. Its total length is 20 m. Figure 1 illustrates the geometry of the bridge.

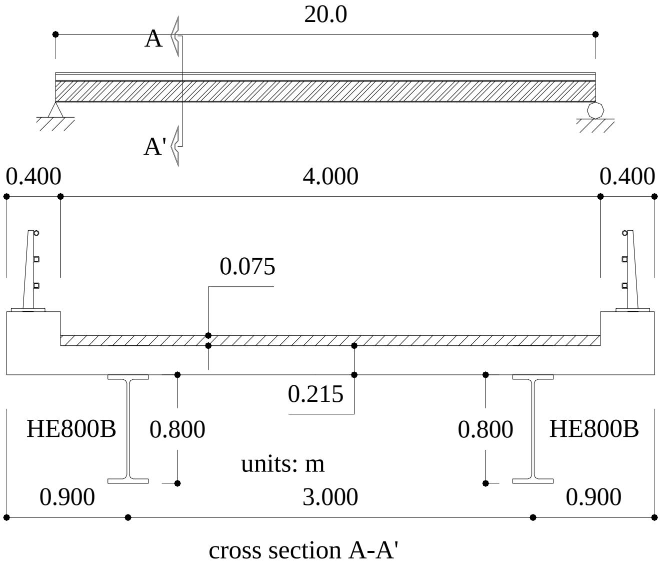

Figure 1. Geometry of the bridge adopted as example.

3 DAMAGE SCENARIOS

In this study, damage scenarios representing fatigue damage caused by heavy traffic were considered. This damage was simulated with open cracks located in the mid-length region of the steel I beams. For this purpose, two general cases were evaluated. Firstly, the severity of damage was considered with four crack depths. The first crack has a depth of 8 mm appearing along the bottom flange of the steel beam trying to simulate a light damage scenario. In the second case, the crack propagates to 17 mm along the bottom flange. In the third case, the crack covers the entire bottom flange. Finally, in the last case, the crack has propagated to the half of the total depth of the steel I beam and it represents a severe damage scenario. In the second general damage case, the extension of damage was evaluated using three crack patterns. One crack in the middle length of the steel beam was simulated for the first damage pattern. Two cracks appear equidistant 500 mm to the first crack in the second damage pattern. Finally, additional six cracks which are equidistant 500 mm appear over the steel I beams. The proposed damage scenarios are shown in Figure 2.

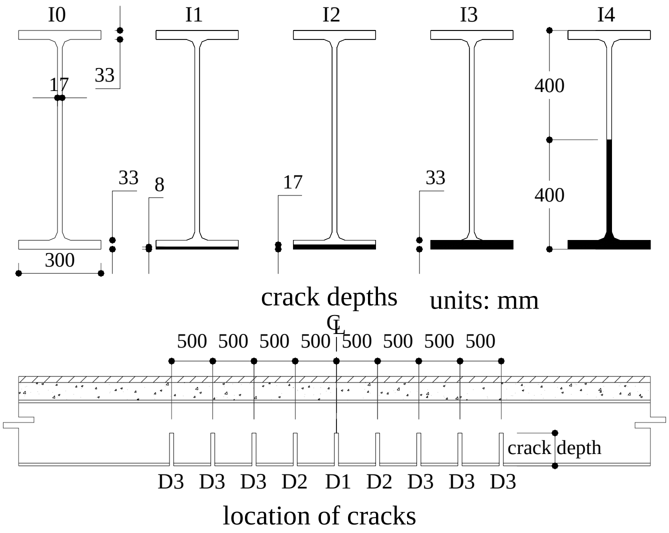

Figure 2. Assumed damage scenarios.

4 DYNAMIC SIMULATIONS OF THE BRIDGE

The analyzed bridge was modeled as one dimensional simply supported composite beam according to the Euler Bernoulli hypothesis. Only heavy traffic was considered in the simulations. For this case, triple punctual loads are considered, independent from each other and representing a lorry passing over the bridge with a constant axle separation of 4 m between the first and second load and 6 m between the second and third load. The magnitude for the front axle load was 50 kN and the remaining two loads were variable with a uniformly distributed load variation between zero and the maximum load (P=120 kN). The distance between lorries was defined as the minimum safety distance necessary for avoiding a crash, which for this problem was 31 m, Salgado (2000).

The dynamic response for cracked beams is obtained with the procedure proposed by Salgado et al (2005) which considers that cracks cause a local change of stiffness near to the location of damage. This small perturbation is taking into account during the assemblage of the general stiffness matrix. The updated mode shapes are calculated finding the eigensolution for the undamped free vibration of a typical mode considering that the mass of the beam does not change.

In some cases, artificial noise was added to the dynamic response in order to simulate errors during the acquisition of the data. Noise was considered as a normal distribution with a standard deviation equal to the chosen error on the maximum root mean square (RMS) of the response. The noise level used was 1.0%, referred as N1. Dynamic response with moving loads is variable enough to rule out higher noise levels, therefore this noise level is considered suitable for this evaluation.

5 DAMAGE DETECTION METHODS

5.1 *Methods of level 1*

Two methods of level 1 were evaluated in all the damage scenarios. The first method is based on the change of resonant frequencies. As mentioned above, cracking in structure provokes small changes in the resonant frequencies and in practice; it is difficult to detect these changes. In fact, ambient factors, errors during acquisition and precision of the instrumentation can give variability of the frequencies around 5%. Resonant frequencies obtained from simulations have high numerical precision; therefore, it is possible to identify changes in frequencies in almost all the evaluated cases. The change of frequency in the damage scenarios is defined as the rate of damaged and undamaged circular frequencies as shown in the Table 1.

Table 1. Damage identification with changes in frequencies

	Damage pattern D1				Damage pattern D2				Damage pattern D3			
Mode	I1	I2	I3	I4	I1	I2	I3	I4	I1	I2	I3	I4
1	1	0.99	0.97	0.88	0.99	0.98	0.94	0.76	0.98	0.95	0.85	0.57
2	1	1	1	1	1	1	1	0.99	1	0.99	0.97	0.86
3	1	0.99	0.98	0.9	0.99	0.98	0.95	0.84	0.98	0.96	0.91	0.81
4	1	1	1	1	1	1	0.99	0.97	0.99	0.98	0.93	0.74
5	1	0.99	0.98	0.92	0.99	0.98	0.95	0.89	0.99	0.98	0.94	0.83

From Table 1, it can be concluded that mode 1 is the most sensitive to the damage and mode 2 has the least variation with this method. Because highlighted values in Table 1 have more than 5% of frequency change it is possible to indicate damage detection in real case. These results show us that damage was identified for all the damage patterns for the most severe damage scenario I4. Damage could be also detected for the damage scenario I3 and damage pattern D3.

The other method of level 1 evaluated in this study was the modal assurance criterion (MAC) method. This method compares the mode shape vectors with and without damage and gives a value of 1.00 if these two vectors are the same and 0.00 if they are completely different. Its mathematical representation is given by

$$MAC_i = \frac{\left| \{\varphi_o\}_i^T \{\varphi_D\}_i \right|^2}{\left| \{\varphi_o\}_i \right| \left| \{\varphi_D\}_i \right|}, \tag{1}$$

where $\{\varphi_D\}$ and $\{\varphi_o\}$ are the mode shape vectors with and without damage respectively. The subscript i refers to the ith mode and the superscript T refers to the transpose of the vector.

The obtained results applying this method to the damage scenarios are shown in the Table 2.

Table 2. Damage identification with MAC method

	Damage pattern D1				Damage pattern D2				Damage pattern D3			
Mode	I1	I2	I3	I4	I1	I2	I3	I4	I1	I2	I3	I4
1	1	1	1	0.999	1	1	1	0.998	1	1	0.999	0.996
2	1	1	1	1	1	1	1	1	1	1	0.999	0.983
3	1	1	0.999	0.992	1	1	0.998	0.982	1	0.999	0.996	0.979
4	1	1	1	1	1	1	1	0.995	1	0.999	0.99	0.91
5	1	1	0.998	0.98	1	0.999	0.994	0.962	0.999	0.998	0.99	0.894

According to Table 2, MAC method cannot distinguish if damaged mode shape vectors have enough variation for being able to identify the damage in most of the cases. Only in the damage scenario D3I4, this method showed values that point out possible damage in the structure.

5.2 *Methods of level 2*

5.2.1 *COMAC method*

The Coordinate Modal Assurance Criterion (COMAC) method is a linear combination of the two evaluated vectors and it gives local information combining the data from different modes. If the modal displacement of the jth node from two sets of vectors is the same, the COMAC value is equal to 1.00. The mathematical representation of this method is given by

$$COMAC_j = \frac{\sum_{i=1}^{N} \left| \{\varphi_o\}_i^j \{\varphi_D\}_i^j \right|^2}{\sum_{i=1}^{N} \left[\{\varphi_o\}_i^j \right]^2 \sum_{i=1}^{N} \left[\{\varphi_D\}_i^j \right]^2}, \tag{2}$$

where $\{\varphi_o\}_i^j$ and $\{\varphi_D\}_i^j$ are the displacements for the jth node of the ith mode for the baseline and damaged condition respectively.

5.2.2 *Mode shape curvature method*

Curvature mode shapes were found to give good damage detection in structures. This method proposed for the first time by Pandey et al (1991) considers that the curvature mode shapes are related to the flexural stiffness of the beam at any point by

$$\kappa = \frac{d^2\varphi}{dx^2} = \frac{M}{EI}, \tag{3}$$

being κ the curvature mode shape, M the bending moment of the cross section, E the young's modulus, I the moment of inertia and $d^2\varphi/dx^2$ is the second derivative of the mode shape with respect to the longitudinal distance, x.

In this way, if a crack appears, the flexibility of the beam (EI) will decrease causing an increment in the magnitude of the curvature. Two methods have been proposed for obtaining mode shape curvatures. The central difference method and the mixed approach method proposed by Maek (2003). Mathematical formulation of these curvature methods are given in Equations 4 and 5 respectively

$$\kappa = \frac{\varphi_{i+1} - 2\varphi_i + \varphi_{i-1}}{\left(L^e\right)^2} \tag{4}$$

$$\left[f(\alpha,\beta,L^e)\right] = \begin{bmatrix} v \\ \psi \\ \kappa \end{bmatrix} = \begin{bmatrix} \varphi \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

in which L^e is the length of the element, φ is the displacement mode shape, v is the smoothing mode shape, ψ is the modal rotation and κ is the modal curvature. α and β are the penalty factors.

5.2.3 *Damage Index Method*

Stubbs and Kim (1994) proposed the damage index (DI) method which calculates the change in the strain energy stored in the beam when it deforms in a particular mode shape, as defined for its numerical evaluation in the Equation 6.

$$\beta_{i,j} = \frac{\{\kappa_{Di}\}_{i,j}^2 + \sum_1^N \{\kappa_{Di}\}_{i,j}^2}{\{\kappa_{oi}\}_{i,j}^2 + \sum_1^N \{\kappa_{oi}\}_{i,j}^2} \frac{\sum_1^N \{\kappa_{oi}\}_{i,j}^2}{\sum_1^N \{\kappa_{Di}\}_{i,j}^2} \tag{6}$$

Here, $\beta_{i,j}$ indicates the evaluation of damage at ith mode at location j, N is the total number of nodes in the beam, and o and D indicate the baseline and damage conditions respectively.

5.2.4 *Wavelet Analysis methods*

Wavelet analysis methods have become popular because they do not require differentiation of the measured data and it is possible to detect damage only with the existing damaged information. These methods, based on Continuous Wavelet Transform (CWT) and considered as an improvement of Fourier Transform, have the ability to analyze the measured data with variable size windows making possible detection of small singularities related with damage. Theirs mathematical background is described below,

5.2.4.1 Wavelet Analysis theory

Wavelets are defined as functions that contain waves which drop to zero after some oscillations. These functions have one independent variable. The function with these characteristics is called "mother wavelet". Different sets are generated from this mother wavelet translated by *b* and dilated by *a*, represented as $\Psi_{a,b}$. The main idea of this analysis is based on Continuous Wavelet Transform (CWT) which is the integral over time of the wavelet convolution. Its mathematical representation is shown in Equation 7.

$$CWT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(x)\Psi\left(\frac{x-b}{a}\right)dx = \int_{-\infty}^{\infty} f(x)\Psi_{a,b}dx \tag{7}$$

The results of this transformation are called wavelet coefficients and show how well the function correlates with the signal. It has been found that damage due to a sudden loss of stiffness and the moment when it occurs, creates wavelet coefficients with large amplitudes like a spike or an impulse. This procedure is the base of the Wavelet Analysis damage detection. Because CWT has redundant information, it is possible to use discrete values of dilations and translation without loss of accuracy. For this purpose, dilation is defined as *a=2j* and translation parameters as *b=k2j*. In this way, the discrete reconstruction of the function can be expressed by

$$\begin{aligned} cD_J(k) &= \int_{-\infty}^{\infty} f(x)\Psi_{J,k}(x)dx \\ D_J(x) &= \sum_{k=-\infty}^{\infty} cD_J(k)\Psi_{J,k}(x) \end{aligned} , \tag{8}$$

where cD_j is the level J detail coefficients and $D_j(x)$ is the level J detail function. The most important is to detect the singularities in the signal, particularly on the finest scale details.

The Wavelet Packet Transform (WPT) is a generalization of the wavelet transform defined as the linear decomposition of the evaluated function. In WPT the signal is decomposed in approximations and details, these two results are themselves decomposed into another level of decomposition. Then this process is being repeated until the required level of accuracy is achieved. A variant of this method called Wavelet Packet Signature (WPS) was proposed by Chang et al (2005). This method obtains the entropy energy of the dynamic response at measured points and obtains the second derivative of the entropy energy along the beam. Here, this method was modified applying the CWT in the finest scales instead of the second derivative. Two cases were considered for this method. WPS was applied to dynamic displacements and to accelerations referred as *WPSu1* and *WPSac1* respectively.

5.2.4.2 Holder Exponent

Holder exponent is a procedure that has the ability to give information about the regularity of the signal, i.e. identify the differentiable order of a function. Applying this method to the function *f(x)* at x_0, it can be expressed as follows,

$$\left| f(x) - P_n(x - x_0)\right| \le C\left|x - x_0\right|^{\alpha}, \tag{9}$$

in which C is a constant and P_n is an approximation polynomial to the function *f(x).*

A transformation is needed to eliminate the polynomial part in the last equation. If a wavelet transform with *n* vanishing moments that ignore polynomials up to order *n* is applied to the last equation, Equation 9 can be expressed as follows,

$$\left|CWT(f(b,a)\right| \le Ca^{\alpha} \tag{10}$$

However, for the evaluation of damage, it is more convenient to recast the previous equation as,

$$\alpha = \log_2\left(\left|CWT(f(b,a)\right|\right) \tag{11}$$

5.3 *Comparison of damage detection methods of level 2*

Damage was considered successfully identified when a clear spike, several spikes or local disturbance were detected in the damage region. 24 different damage scenarios were evaluated. In Figure 3 an example of the damage detection methods is shown. All of them successfully identified the damage. Moreover, Tables 3 and 4 show the sensitivity evaluation of the damage detection methods to severity of damage, extension of damage and noise level.

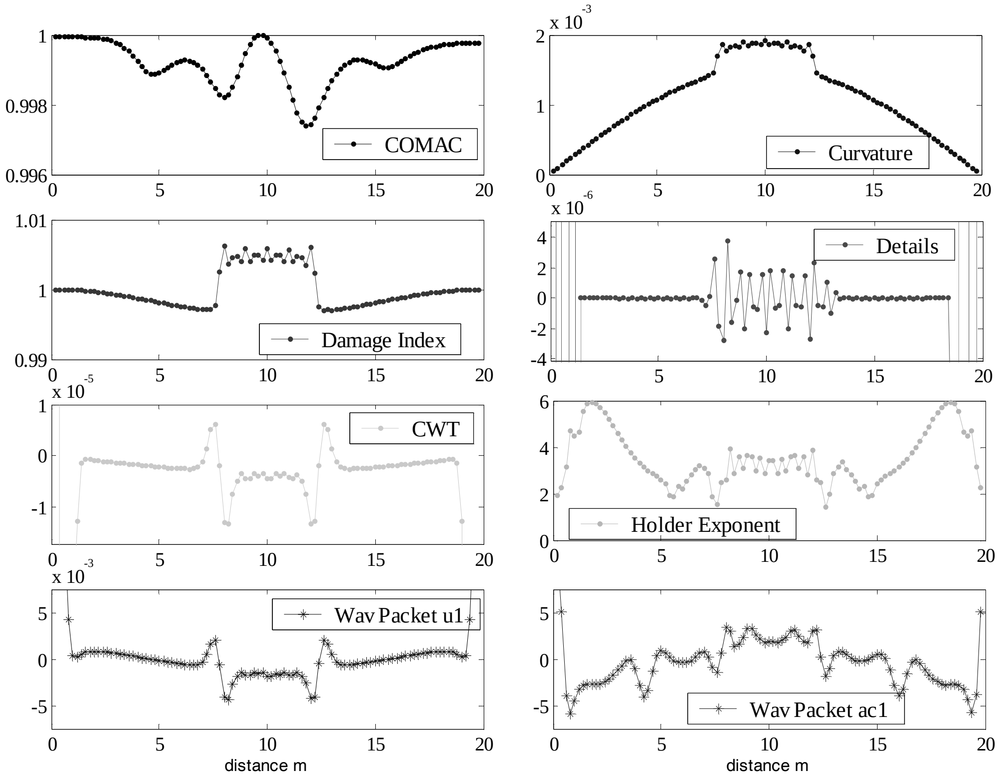

Figure 3. Typical comparison of level 2 damage detection methods (case I2D3 without noise is shown)

Table 3. Comparison of damage detection methods without noise.

N0	Damage pattern D1				Damage pattern D2				Damage pattern D3				Overall
Method	I1	I2	I3	I4	I1	I2	I3	I4	I1	I2	I3	I4	Classif.
COMAC	G	G	G	G	G	G	E	E	G	G	E	E	G
Curvature	E	E	E	E	E	E	E	E	E	E	E	E	E
DI	E	E	E	E	E	E	E	E	E	E	E	E	E
Details	E	E	E	E	E	E	E	E	E	E	E	E	E
CWT	E	E	E	E	E	E	E	E	E	E	E	E	E
Holder	G	G	G	-	G	G	G	E	G	G	G	E	G
WPSu1	E	E	E	E	E	E	E	E	E	E	E	E	E
WPSac1	G	E	E	G	-	-	-	E	E	E	E	E	G

(E) excellent, (G) good and (-) no damage identification

According to Table 3, curvature, DI, details, CWT and WPSu1 method could successfully identify damage location for all the cases. COMAC, Holder exponent and WPS ac1 method were less precise in the damage location identification.

If a noise level of 1.0% is added to the dynamic response, damage identification is evidently affected in all the methods (see Table 4). Details and CWT could not identify damage in any case. The reason for this behavior is that damage identification is done in the finest scales composed by high frequencies, the same as the added noise that hides the singularities peaks. Curvature, DI, WPSu1 and WPSac1 could identify the damage for the most severe damage cases. COMAC method showed in many cases local perturbances but they were not in the

COMAC method showed in many cases local perturbances but they were not in the damage region, indicating false detections.

Table 4. Comparison of damage detection methods with noise level N1=1.0%

N1	Damage pattern D1				Damage pattern D2				Damage pattern D3				Overall
Method	I1	I2	I3	I4	I1	I2	I3	I4	I1	I2	I3	I4	Classif.
COMAC	-	-	-	G	-	-	G	G	-	-	G	G	G
Curvature	-	-	-	E	-	-	G	G	-	-	-	E	G
DI	-	-	-	E	-	-	G	G	-	-	E	E	G
Details	-	-	-	-	-	-	-	-	-	-	-	-	-
CWT	-	-	-	-	-	-	-	-	-	-	-	-	-
Holder	-	-	-	-	-	-	-	-	-	-	-	G	-
WPSu1	-	-	-	E	-	G	G	G	-	G	G	G	G
WPSac1	-	-	-	G	-	-	-	-	-	G	G	G	G

(E) excellent, (G) good and (-) no damage identification

6 CONCLUSIONS

In this paper, a comparison of several damage detection methods was presented. With respect to level 1 methods, changes in resonant frequencies and MAC method were found to be not reliable damage detection methods. Changes in resonant frequencies method was successful only for the most severe damage cases, whereas MAC did not provide a clear change in the evaluated mode shape vectors. Level 2 methods successfully identified the damage location when noise was not evaluated. Exception were COMAC, Holder exponent and WPSac1 methods. When noise was added to the dynamic response, an abrupt decrement in the damage location for all the methods was noticed. Curvature, DI and WPSu1 showed the best behavior when noisy data information was given. More research should be done including experimental results in order to have a more reliable damage detection method. The authors are currently working in these tasks and the results will be presented in a future communication.

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