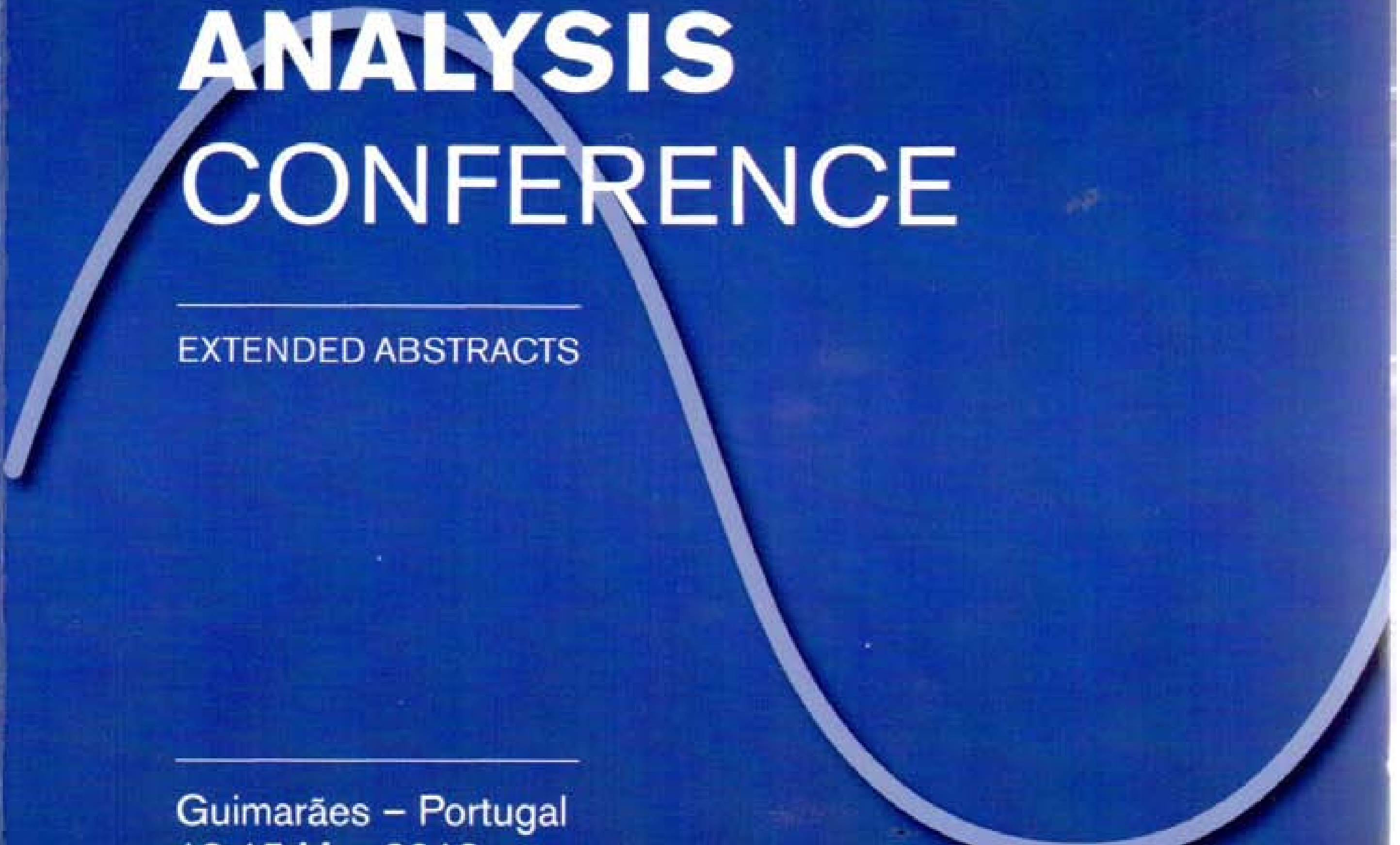
5th IOMAC INTERNATIONAL **OPERATIONAL MODAL ANALYSIS** CONFERENCE



EXTENDED ABSTRACTS

Guimarães – Portugal
13-15 May 2013

Editors:
Álvaro Cunha
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STRUCTURAL EVALUATION OF BRIDGES THROUGH VIBRATION MONITORING: A NEW COMPREHENSIVE PROPOSAL

Rolando Salgado[1]*, Sergo Zamora*[1] *,Gustavo Ayala*[2] *and Ulises Zúñiga*[3]

ABSTRACT

An important part of the operating costs of existing bridges lies in their corrective maintenance. For this reason, it is imperative to have more precise structural evaluation procedures in bridges. To do that, several damage detection methods based on vibration monitoring have been applied. These methods have showed better performance than traditional ones. However, up to now, it has not been proposed a comprehensive procedure that can give us the structural integrity of the bridge at any time and with high precision. In this research, trying to propose a more rational method to evaluate bridges, AVT on one scale model of a bridge (a steel mesh structure) was carried out with different damage scenarios. Using vibration based damage detection methods, a comparison of the dynamic parameters before and after damage was done for localising and identifying damage in the scale models. Moreover, it was evaluated the proposed comprehensive method for detecting the induced damages. The results found in this work makes possible to have a procedure that optimizes the process of damage detection giving a more rational method to evaluate the structural behaviour of bridges.

Keywords: structural evaluation, damage detection, Structural Health Monitoring.

1. INTRODUCTION

Nowadays, civil infrastructure is near its service life and it has more probability to suffer structural damage. Build new infrastructure in all cases is expensive and impractical. Another option consists in increase the service life of the structure taking account an adequate safety level. This represents, in many cases, to carry out rehabilitation works and good plan maintenance. To do that, it is needed a precise structural condition of the structure which mostly considers doing 4 main steps according to Rytter [1]: I) detect damage in the structure, II) determine its location, III) severity of the damage and IV) remaining service life. For gathering all this activities in one general procedure a more comprehensive structural evaluation method needs to be proposed.

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A more rational proposal of structural evaluation procedure cannot be understood without the contribution of the Structural Health Monitoring (SHM). The SHM process involves the observation of a system periodically or continuously using a specific array of sensors [2]. Acquired measurements are processed to detect unusual behaviour of the system that can be associated with damage.

Carrión [3] developed an SHM method applied to bridges based on the wave propagation analysis and the modified minimum rank perturbation theory. Additional, a bridge administration system (currently applied in Mexico) was proposed which includes structural capacity and residual life modules based on probabilistic and deterministic models according to the bridge type.

Afterwards, Magalhães *et al.* [4] implemented an SHM procedure in the Infante D. Henrique Bridge. This structure is located in the city of Porto, at north of Portugal and it consists of an arch concrete bridge with 371 length. Results from dynamic monitoring determined the influence of the ambient factors in the dynamic parameters of the bridge and it was possible to predict damage scenarios by a numerical regression model.

Other application of structural evaluation procedures in bridges can be found in Ortiz *et al.*[5]. Here, the structural condition of Antonio Dovalí Jaime (best known as Coatzacoalcos II) cable stayed bridge was carried out. This bridge is located in the southeast of México City and cross the Coatzacoalcos River. It has 1170 m length with 280 m of main span. Two different structural evaluation procedures were done in this bridge, namely, static and dynamic tests. Moreover, a numerical model of the bridge was done which was updated with information obtained from the dynamic tests. Results indicated that the considered bridge has an acceptable safety level to continue be in service.

In this paper, a more comprehensive methodology for the structural evaluation of bridges was proposed. For doing that, several damage scenarios of different severity were induced in a scale model steel mesh bridge. Damage was intended to be detected in all cases by changes in its dynamic parameters. Finally, the proposed methodology of structural evaluation was proved to the case study presented here.

2. PROPOSED METHODOLOGY FOR EVALUATING THE STRUCTURAL BEHAVIOUR OF BRIDGES

The methodology for the structural evaluation has been proposed as general as possible; i.e. it can be applied to any bridge topology and made of any material. The main elements recommended by authors for achieving a better structural evaluation of these structures are given below:

2.1. Operational Modal Analysis (OMA)

Operational Modal Analysis is a technique for extraction of the modal parameters where acquisition of the input forces is not required compared to the traditional modal analysis techniques. This technique allows performing tests in structures under operating conditions or in conditions where the input forces are difficult to acquire. Performing tests under operating conditions is desirable in highway bridges where, in many situations, cause a disturbance of their normal operating is not desirable. Actually, this force excitation represents real service condition of the bridge avoiding having big and expensive exciters. Acquiring output signals only from natural or ambient excitation, such as vehicles passing over the bridge, is better known as Ambient Vibration Tests (AVTs). This acquired dynamic response needs to be processed using techniques known as OMA methods.

2.2. Numerical model

The numerical model tries to represent the structural behaviour of the bridge. To achieve a good approximation, it is suggested to consider the dynamic simulations theory of cracked structures. Salgado *et al.* [6] assessed several of these methods and proposed the best procedure to be applied in bridges. A more realistic dynamic simulation of the cracked bridge considers the dynamic simulations of vehicles passing over the bridges. It is recognized the influence of many factors in this phenomenon such as dumping dampers and surface pavement rugosity which are difficult to evaluate. However, good approximations in this topic have been obtained by Laduscher [7] which did a parametric evaluation of many of these methods and they determined a simplified model possible to take into account the most relevant variables. Salgado *et al.* [6] proposed also a simplified vehicle-bridge interaction based on the mass moving method. Either of both procedures can be applied to the crack bridge model to simulate the dynamic response of the bridge.

This proposed numerical model can also being used to determine the preliminary dynamic parameters of the structure necessary to determine the sampling frequency and time interval to acquire the output response. Moreover, this numerical model is used to determine the optimal location of the sensors in order to maximize the probability of damage detection.

2.3. Vibration based damage detection methods

Salgado [8] carried out an evaluation of the most promising damage detection methods applied to bridges. Author found that those methods based on Wavelet Analysis are the most suitable for bridge structures. These methods can work in two different ways. Comparing a priori baseline dynamic condition of the bridge with its current structural condition and, just using its current structural condition. As thought, first procedure is more accurate; however, in many cases is not available a priori baseline condition which turns out these methods in the best option in such as conditions. These methods have the disadvantages to be very sensitive to noise always present in the dynamic response especially in AVTs.

The proposed procedure to maximize the possibility of true damage detection consists to applied several of these damage detection methods of level I, II and III and verify if clear disturbance repeats in two or more methods. The occurrence of this condition indicates high probability of damage detection. The main inconvenient is given in the identification of clear disturbances. Between the procedures to determine disturbances those based on statistics parameters seem to be the best option.

All the suggested methods work better where number of measuring points increase. One way to do that is interpolating the dynamic response using spline interpolation. According to Zhou [9] better results than spline interpolation may be obtained using Beizer interpolation.

2.1. Prognostics

A second part of the proposed structural evaluation procedure is the Prognostics of damage. It can be defined as a discipline focused on predicting the time at which a structure or its components will no longer perform its intended function [10].This can be done by determining the extent of deviation of a structure from its expected normal operating conditions. Analysis of failure modes, detection of early signs of wear and aging, and fault conditions are some of the techniques used for determining the extent deviation of the structure. These signs should be correlated with a damage propagation model. Considering that damage is caused basically by fatigue, an empirical damage evolution law, such as the Paris law for crack growth may be used.

2.1. Remaining service life

Once damage was detected, located and its severity was determined, the remaining service life of the structure needs to be determined. The safety evaluation of the structure can be done using Reliability Analysis taking into account the obtained structural condition. An important advance in this field can be obtained from the remaining fatigue life of structures as mention by Xuefei [11].

2.1. Probability of damage detection

Due to the vast number of damage detection methods available in the literature, it is important to define the probability of damage detection as a representation of the probability that a given damage detection method will be able to detect a specific damage in a given structure. This can be done by a Probabilistic of Damage (POD) curve which shows the probability of a damage detection method as a function of damage size for a specific inspection technique as mention by Achenbach [12].

The proposed methodology above described is better understood with the help of Figure 1.

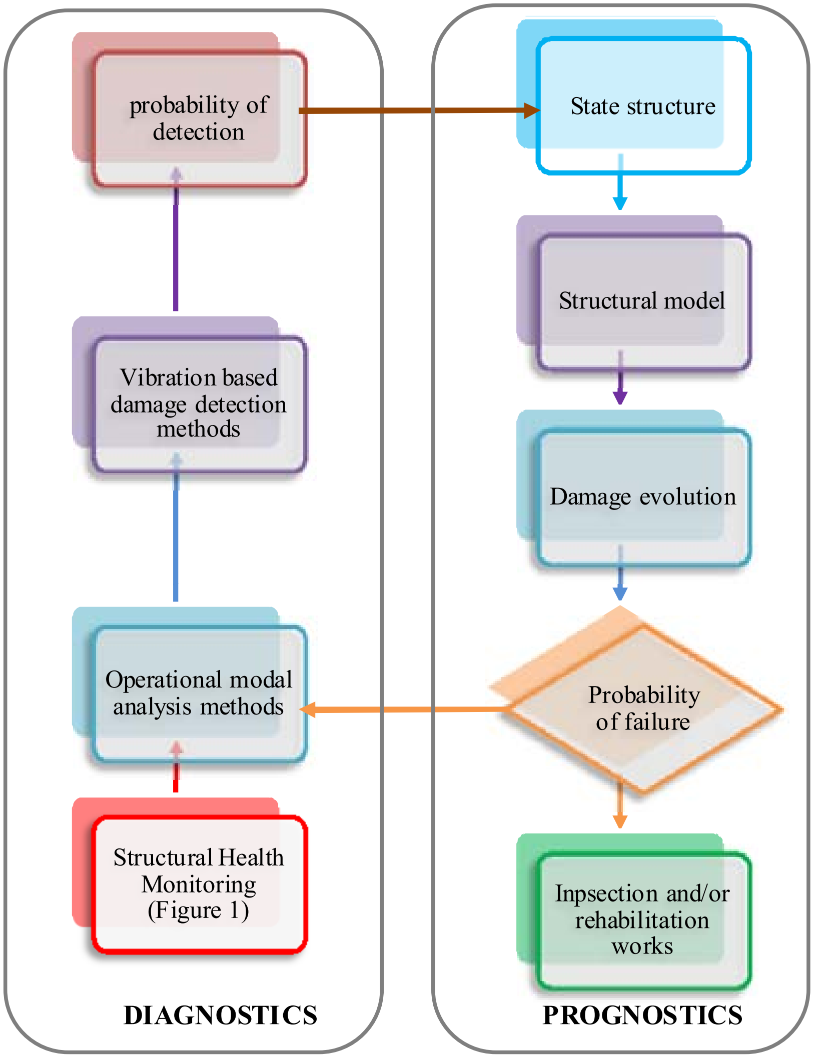

Figure 1 A detailed steps of the proposed procedure.

3. APPLICATION EXAMPLE

For evaluating the proposed methodology, a scale model of a steel simply supported bridge was made. This structure consisted of rectangular hollow cross sectional elements with geometry indicated in Figure 2. Its dimensions were considered in order to obtain its first natural frequency between 2 to 12 Hz where most of the bridges with 6 to 100 m span are expected to fall.

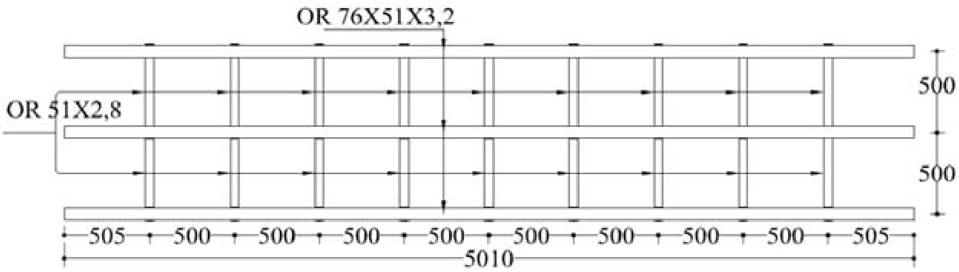

Figure 2 Geometry of the scale steel bridge adopted as example (units: mm)

3.1. Simulated damage scenarios

Damage was simulated as vertical open cracks done by saw cuts. Three different severities of damage were evaluated:

- **Light damage**: It was simulated as an open vertical saw cut in all cross section of the element. It has a depth equal to the lower flange depth of the element.
- **Moderate damage**: The same than before but now crack increases till ¼ of the overall depth of the element.
- **Severe damage**: Saw cut includes the overall depth of the element.

In total, 5 damage scenarios were simulated. More detail description of damage scenarios is given in Table 1.

Table 1 Description of damage scenarios

	Damage scenarios									
	1		2		3		4		5	
	X	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*	*X*	*Y*
Position from lower left corner (mm).	2500	270 810	2750	270	2250	540	2250	0 540 1020	3750	0
Crack depth (mm)	3.2		3.2		13		13		51	
Severity	Light		Light		Moderate		Moderate		Severe	

X means longitudinal distance while *Y* means transversal distance.

3.2. Structural Health Monitoring by ambient vibration tests

According to the preliminary analysis done with the numerical model, the sampling frequency was defined to be 500 Hz in order to determine the first three mode shapes and the acquisition time was set to 1000 s. 33 measuring points were defined to obtain a good representation of the mode shapes and high possibilities of damage detection. Ambient vibration tests (AVTs) were performed in all damage scenarios using only 6 accelerometers at the same time. Therefore, it was necessary to do 8 set ups where 2 accelerometers were fixed in the place of maximum amplitude and the remaining 4 were roved to cover all the remaining measuring points.

3.3. Operational Modal Analysis

Modal parameters for the 6 different damage scenarios (including no damage case) were obtained using the Enhanced Frequency Domain Decomposition method [13] which was implemented for the authors in a computer program. The frequencies and damping ratios for the selected mode shapes are given in Figure 3 and mode shapes are depicted in Figure 4.

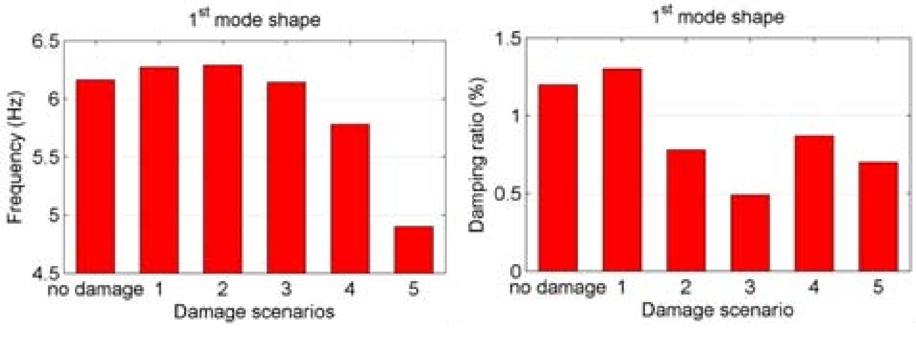

Figure 3 Evolution of the a) Frequency and b) Damping ratio through damage scenarios for the first mode shape

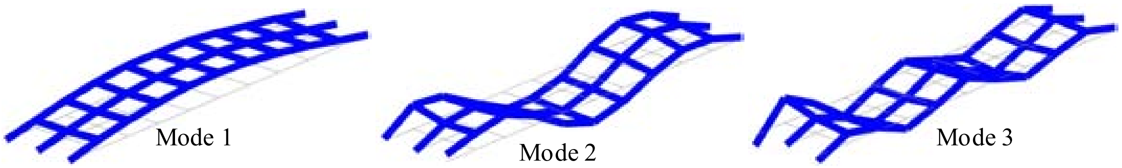

Figure 4 Mode shapes calculated for the undamaged case

From Figures 3 and 4 it can be concluded that damage can be deduced for an important decrement of frequency that it was observed for the first mode shape and for the cases 4 and 5 (moderate and severe cases).

3.4. Vibration based damage detection methods

The applied damage detection methods used in this study were, for the level I methods: the Frequency Change method and the Normalized Modal Difference (NMD), a variant of the Modal Assurance Criterion (MAC) method. For the level II methods, the Curvature of mode shapes, the Continuous Wavelet Transform (CWT), the Discrete Wavelet Analysis (DWA) and the Wavelet Packet Signature (WPS) methods. For detecting and locating damage in the scale model, two vibration parameters were selected, namely, the (normalized) mode shapes and the acceleration response obtained from the AVTs. The WPS method used, for the process of damage detection, the energy of the acceleration response while the other methods used the mode shapes of the footbridge.

To simplify the process of damage detection, the mode shapes and energy acceleration mode shapes were shown in a one dimension continuous graph. First line of measuring points goes from 0 to 5 m, second line goes from 5.1 m to 10.1 m and third line goes from 10.2 m to 15.20 m.

Successful damage detection was considered when frequency change is bigger than 4%. Damping ratio change has big variations to propose a consistent lower limit for damage detection, but it can be used to confirm the presence of damage done by others methods. NMD criterion damage has been established to 20% for damage detection. In the case of level II methods, damage is successfully detected when a sharp peak and/or disturbance zone with coefficient values clearly above those of its neighbourhood were found in the graph. Exceptions are the zones near the supports (0 m; 5.0 m-5.1 m; 10.2 m) where disturbance is always present due to discontinuity of mode shapes. Results of applying the damage detection methods to the most sensitive mode shapes and energy shapes are shown in Figures 5 and 6 for the 5th damage scenario.

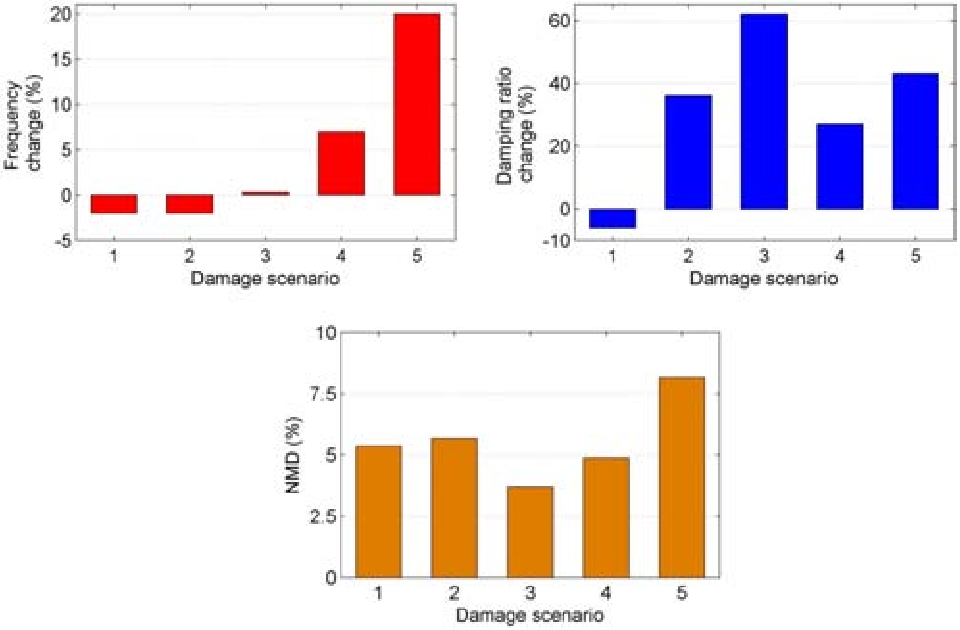

Figure 5 Application of level I damage detection methods to the first mode shape

From Figure 5 it can be observed that damage can be detected only for the frequency change method, in the damage cases 4 and 5, which are the most severe cases. This level I methods are not confident to detect damage alone. They need to be confirmed by level II methods.

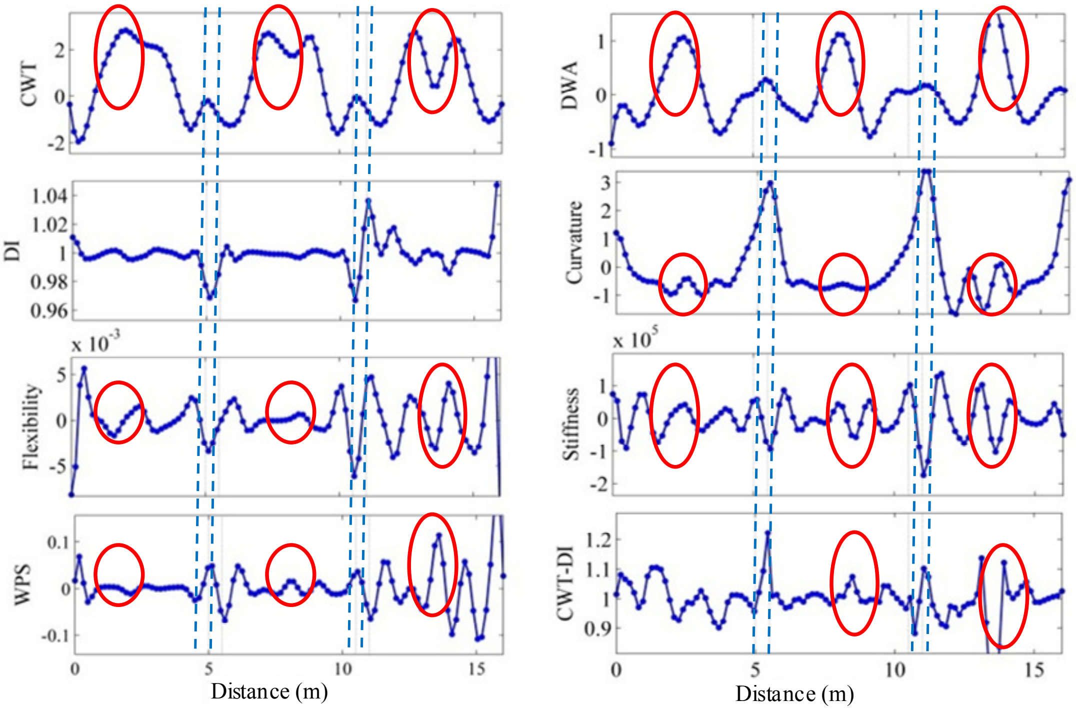

Figure 6 An example of application of level II damage detection methods

From Figure 6 it is possible to detect damage in the most severe location. At midspan of the three longitudinal elements where 7 saw cuts were done. In the two less severe cases, damage was not detected. Simulated damage was induced always between two sensors and it has been proved that damage caused a very local disturbance of its stiffness. Therefore, only in the most severe damage scenario was possible to detect damage.

The second part of this study concerns to prognostics (see Figure 1). This is still under development and it will be presented in further communications.

4. CONCLUSIONS

In this paper, it was proposed a more rational methodology for the structural evaluation of bridges. This procedure proposed the use of advanced damage detection methods based on vibration monitoring with the help of new sensors and data acquisition systems technology. It is also to taken into account the use of advanced dynamic simulation of bridges. The remaining service life of the bridge is proposed to be determined by Structural Reliability methods using procedures already proposed for fatigue analysis. This methodology was evaluated, in its first part (diagnosis), by a scale model of a simply supported steel bridge. Results indicated that damage could be detected for the most severe cases. Better results can be obtained using other sensor locations closer damage places. Damage detection methods of level III are going to apply to the acquired data and the safety level of the scale model will be determined. Results indicate that is possible to determine the structural condition of bridges in more consistent way.

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