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Evaluation of the performance of different damage indicators in railway bridges

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Abstract

This article describes a damage identification methodology based on a genetic algorithm and its application to the numerical model of a railway bridge. The identification method is based on an iterative process that in each iteration compares the values of the bridge's dynamic response for a test damage scenario with the response values for a reference damage scenario. The introduction of damage to the test numerical model is based on the modification of a preselected numerical parameter values. The genetic algorithm allows the identification of damage by minimizing the residue of an objective function constructed from the responses of the test and reference model, and based on the so-called damage indicators. In this study are defined and tested damage indicators based on modal parameters (frequencies and vibration modes) in parameters built from the modal parameters (modal curvatures and flexibility curvatures), and in dynamic responses under action of impulsive loads from frequency response functions (FRFs). The proposed methodology for identifying damage was tested based on a two-dimensional numerical finite element model of a railway bridge including the railway track. The results allowed evaluating the efficiency and reliability of the methodology and of the damage indicators which, in most situations, showed potential in the detection, location and quantification of the severity of the damage.

Keywords: Damage identification; iterative method; genetic algorithm; damage indicators; railway bridges.

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1. Introduction

Bridges and viaducts are critical components of the railway infrastructure system. The natural degradation of these structures combined with the increased speed of circulation of vehicles and transportation of high intensity loads may lead to the emergence of potentially performance compromising damage. In this sense, there is a growing interest in developing expeditious methods to evaluate structural integrity aiming to reduce the costs of inspection and maintenance.

There are two types of structures damage identification methods: those based exclusively on experimental results (data-based methods) and those based on numerical models (model-based methods). Rytter (1993) [1] classifies these damage identification methods at four levels: level 1 (detection of damage), level 2 (location of the damage), level 3 (quantifying the severity of the damage) and level 4 (estimated residual life). Methods based on experimental results have the advantage of not requiring the support of a numerical model, but can hardly exceed level 2. In turn, the methods based on mathematical models are generally associated with a high computational cost however they typically reach Level 3.

Within the methods based on numerical models it is worth mentioning those based on dynamic response, particularly in terms of modal parameters (frequencies, vibration modes and damping coefficients) [2], the response under the action of impulsive loads and the response under traffic actions [3]. Some of these methods are based on optimization algorithms that allow minimizing the differences between the dynamic responses simulated based on a numerical model of test and reference. In these situations the damage scenarios are reproduced changing the values of numerical parameters. The genetic algorithm has been commonly used in the detection of damage, with the advantage of enabling the detection of the global minimum; allow the use of a large number of parameters and the ease of calculation parallelization [4-5].

This article aims to evaluate the efficiency of different indicators in identifying damage of a numerical model of a railway bridge. To this end an iterative method was used based on a genetic algorithm and based on dynamic responses. Finally robustness of damage indicators to the presence of noise in the dynamic responses and the number of points of modal settings was evaluated.

2. Damage identification methodology

Fig. 1 shows a flowchart illustrating the computational implementation of the iterative method based on a genetic algorithm and which involved the use of two commercial programs: Matlab (2011) [6], and ANSYS (2007) [7].

The damage identification methodology is based on the approach of the values of the modal response / dynamic of the bridge for a damage test scenario with the response values of a reference damage scenario.

The reference damage scenario is defined based on a predefined set of numerical parameters which simulate a deterioration in the condition of the structure. The damage test scenario is defined based on a set of numerical parameters resulting from the application of the genetic algorithm and ranging along the optimization process. The optimization involves minimization of an objective function defined from damage indicators based on modal/ dynamic responses of the structure.

In the first iteration (k=0), the user sets the numeric parameters that reflect the reference damage scenario based on which the numerical model of reference is constructed in the ANSYS program. Within this program a modal or dynamic analysis is performed, depending on the type of damage indicator used, and after calculation reference damage indicators (ID^{ref}) are kept in a text file.

In the following iterations in the Matlab program is initiated the optimization process based on the application of a genetic algorithm. At this stage individuals are generated randomly and constituting the initial population. Each individual is formed by a set of genes in correspondence with the numeric parameters. Population of generation k + 1 individuals are generated from generation k individuals, using three genetic operators: selection, reproduction and mutation.

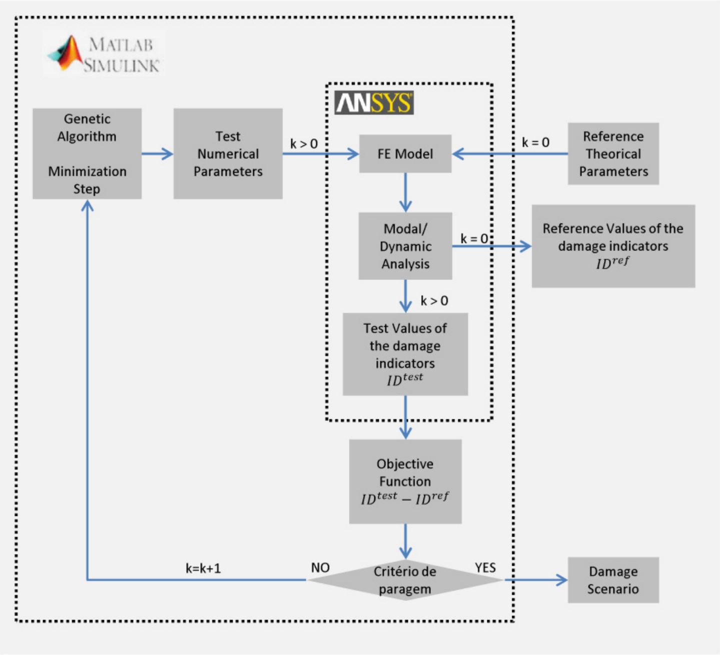


Fig. 1. Flowchart of the iterative methodology.

The numerical parameters that make up each individual are then inserted into the ANSYS program where the numerical model test is constructed and is held the modal / dynamic analysis, allowing the obtaining of the test damage indicators (ID^{test}). Then, for each individual the value of the objective function resulting from the difference between the test damage (ID^{test}) and reference (ID^{ref}) indicators is calculated. This iterative process ends when the stopping criterion is reached. The stopping criterion is typically associated with a limited number of generations or convergence of the optimization, that is, when the objective function value is less than a preset tolerance.

3. Case study: railway bridge

3.1 Numerical modeling

The railway bridge is constituted by a stretch simply supported with a span equal to 15 meters. The deck, which serves as support to only one circulation track is composed of a concrete slab with a constant height and width. The finite element numerical model of the bridge was developed in the ANSYS program, and includes the deck modeling, the supports, the railway track and the track-deck connection (Fig. 2).

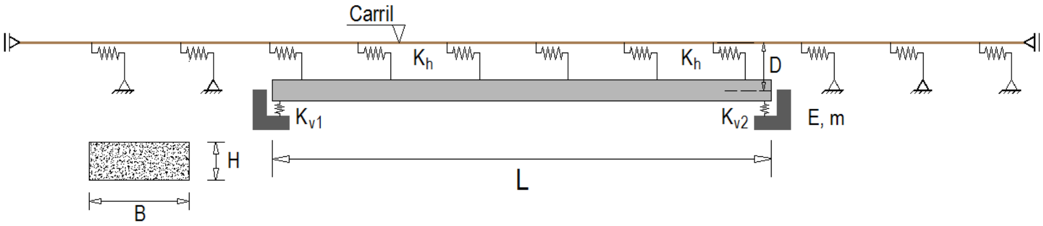


Fig. 2. Numerical model of the bridge including the railway track.

The deck was modeled using finite elements of 2D beam with 0.50 m in length and the supports were modeled by means of spring elements. It was also modeled an extension of the track corresponding to the length of the deck and about 10 meters to each side of the abutments in order to simulate the track continuity over the adjacent embankments. The track was modeled through 2D beam elements positioned at level of the center of gravity of the rails, discretized each 0.50 m. The connection track-deck was modeled through spring elements simulating the longitudinal stiffness of the ballast layer.

In Table 1 are described the main geometrical and mechanical parameters of the numerical model of the bridge, including the designation, the adopted value and its unit. There is also indicated the lower and upper limits adopted in the damage identification presented in Sections 4 and 5.

Table 1. Characterization of the parameters of the numerical model of the bridge

Parameter	Designation	Adopted Value	Unit	Adopted limits (Lower/Upper)
L	Deck span	15	m	-
B	Width of the cross section	5	m	-
H	Height of the cross section	0.85	m	-
m	Mass of the deck	18700	Kg/m	10000/25000
E	Elasticity module	30	GPa	15/30
Kv	Vertical stiffness of support	4	x 10^9 N/m	1/15
Kh	Longitudinal stiffness of the track-deck connection	30	x 10^6 N/m	-
D	Distance between the center of gravity of the deck and the rail	1.075	m	-

The values adopted for parameters L, B, H, m and E were taken or adapted from the final report of the expert committee D214 of ERRI (2001) [8]. The longitudinal stiffness of the track-deck connection was translated, simply, by a linear relationship, according to the indications of standard UIC 774-3 (2001) [9] in case of ballasted tracks. The distance D has been calculated considering a height of ballast layer equal to 0.35 m and the distance from the base of the beam to the neutral axis of the rail equal to 0,30 m.

3.2 Damage scenarios

The application of the damage identification methodology was based on three damage scenarios (C1, C2 and C3). Table 2 lists the considered scenarios, which differ in the number of parameters which reproduce the damage, equal to 6, 8 or 10, for scenarios C1, C2 and C3, respectively.

It is also presented the parameter values for the case in which the model of the bridge is not damaged. In Fig. 3, it is colored in red the parameters whose value was changed to reproduce the presence of damage, namely: the mass of the deck (m) which intends to reproduce mass variations due to possible leveling operations of the railway track, the vertical stiffness of the right side support (K_{v2}), which reflects the effect of the support device degradation and the material's deformability module (E1, E2, E3 and E4) and position (x_1, x_2, x_3 and x_4) of some of the finite elements of the model in order to reproduce the presence of localized damages on the deck.

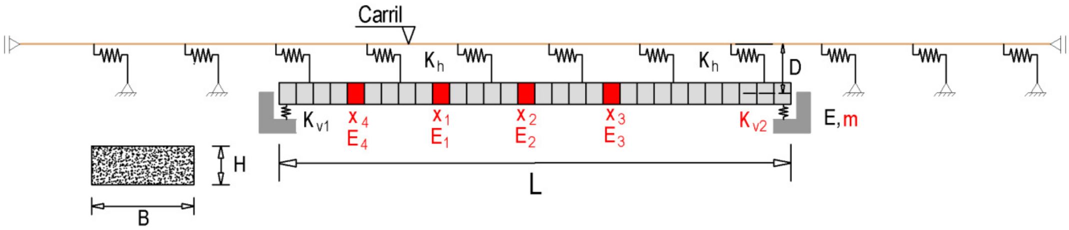


Fig. 3. Numerical model of the bridge indicating the damage parameters.

Table 2. Scenarios with and without damage of the numerical model of the bridge

		Parameters									
		m	K_{v2}	x_4	E_4	x_1	E_1	x_2	E_2	x_3	E_3
Scenario	No damage	18700	4	*	30	*	30	*	30	*	30
	C1	17700	4.5	-	-	10	25	15	20	-	-
	C2	17700	4.5	-	-	10	25	15	20	20	28
	C3	17700	4.5	5	26	10	25	15	20	20	28

* In the no damage state all elements have the same elasticity module

4. Assessment of damage indicators performance

Within this section it is intended to test and compare the efficiency of different indicators in identifying damage of the numerical model of the railway bridge. For this purpose 6 damage indicators were selected: natural frequencies (ID1) [10], vibration modes (ID2) [11], natural frequencies and vibration modes (ID3), modal curvatures (ID4) [12], flexibility curvatures (ID5) [13] and FRFs (ID6) [14].

The application of the genetic algorithm was based on an initial population consisting of 30 individuals, randomly generated and following a uniform distribution, considering 300 generations, in a total 9000 subjects.

In the case of ID1 indicator the natural frequencies of the first 5 vibration modes were considered. In the case of ID2 indicator modal settings were set based on the information from all nodes of the finite element mesh (31 nodes). On ID4 indicator the curvature of modal configuration was calculated based on the central differences method. On ID5 indicator the flexibility curvatures were built on the matrix of modal flexibility of the structure using the first 5 vibration modes. In the case of the ID6 indicator, calculation of the FRFs considered the impulsive action applied near the half-span of the deck and the responses in accelerations measured at 5 different positions, as shown later in Fig. 7(a).

In Fig. 4 are presented the errors of the parameter values that reproduce the damage, in relation to the reference values for the C1, C2 and C3 scenarios, which resulted from the application of 6 damage indicators. In white are illustrated situations in which the identification of the damage was fully successful (no error) and in red situations in which damage identification had significant errors.

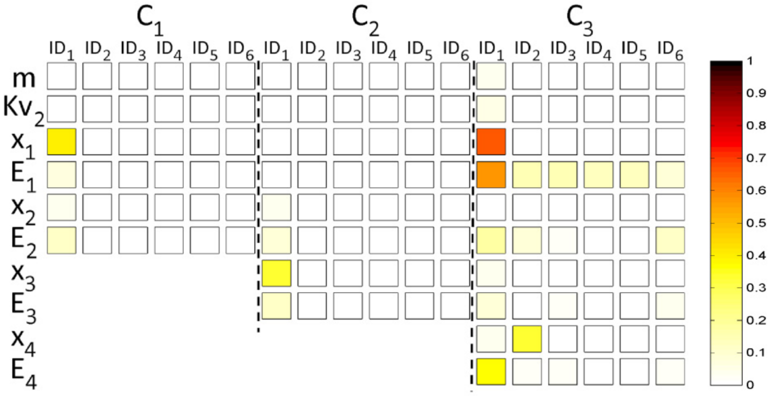


Fig. 4. Errors of numerical parameters regarding reference values, depending on the damage scenario and the damage indicator.

Figure analysis allows assessing that:

i. Comparing the three damage scenarios, and confirming indications pointed by Ribeiro (2012) [15], the greater the number of numerical parameters involved, the greater the difficulty of the algorithm to converge to reference values. In scenarios C1 and C2, with 6 and 8 parameters respectively, the reference value was found for the majority of damage indicators. For C3 setting with 10 parameters, there are slight errors in some parameters, regardless of the damage indicator;

ii. Comparing the performance of different damage indicators, the indicator based on natural frequencies (ID1) is the one presenting the greatest differences regarding reference value, regardless of the damage and parameter setting. For all other damage indicators reference value of all parameters was obtained with nearly null error.

5. Evaluation of the robustness of damage indicators

In this section it is intended to evaluate the robustness of damage indicators in relation to the presence of noise in the signal (5.1), the number of points in the construction of modal configurations (5.2) and the number of control points in the construction of the FRFs (5.3). The robustness analyzes were performed for the C2 damage scenario since for this scenario most damage indicators have reached the reference values.

5.1 Influence of noise level

In the robustness analysis of the damage indicators in the presence of noise, were simulated 3 noise levels (with 1%, 5% and 10% of signal amplitude). Analysis of Fig. 5 allows concluding, as expected, that noise increase leads to an increase of the error in calculation of reference value. Comparing the different damage indicators, it is concluded that the ID3 indicator (frequency and vibration modes) is quite robust even in the presence of noise in the order of 10%. In contrast, ID5 indicator (flexibility curvature) proved to be quite sensitive to noise level, presenting significant errors even for noise level of 1% and above all for the related deformability module parameters.

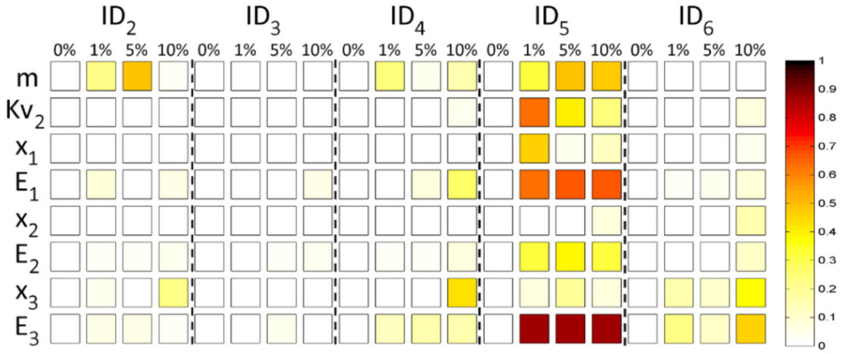


Fig. 5. Influence of noise level on errors of numerical parameters values regarding reference values.

5.2 Influence of the number of points in modal configurations

In the analysis of the behavior of damage indicators dependent on modal settings (ID2, ID3, ID4 and ID5), were held analyzes in which the deformed are built from 31, 16 and 11 points. In Fig. 6 is observed that the ID2 indicator (vibration modes), considering 16 or 11 points, has errors on the order of 20% in the parameters related to the deformability module. The ID3 indicator (frequencies and vibration modes) also presents a small error in quantification of parameters in the case where 11 points are considered. The remaining damage indicators (ID4 and ID5) achieved the reference values regardless of the number of points considered in the modal deformations.

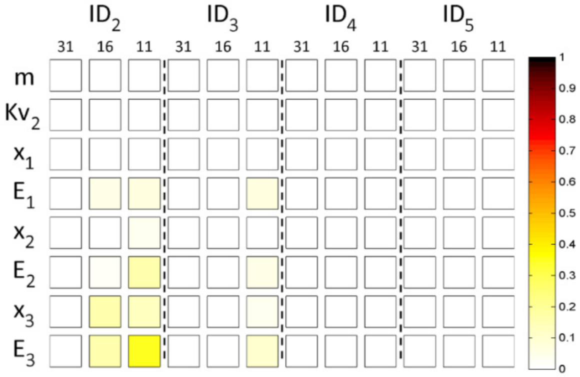
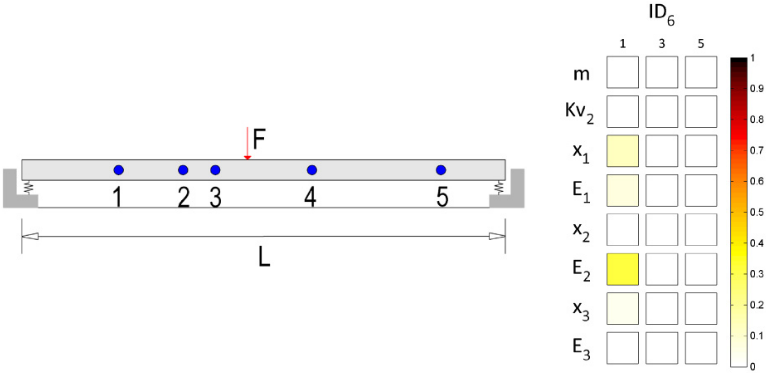


Fig. 6. Influence of the number of points of modal settings on the errors of values of the numerical parameters regarding reference values.

5.3 Influence of the number of control points of the FRFs

In the prospect of simulating real situations where the number of control points of the dynamic response is reduced, dynamic analyzes were performed to calculate the FRFs considering 1, 3 or 5 control points (the latter is shown in Fig. 7 (a)).

In Fig. 7 (b) it can be seen that only in the case where acceleration records are used in only one control point is where errors in the reference values of the parameters occur, and parameter E_2 presents a significant error (30 %) and E_1 parameter assumes an error of about 10%.



(a) (b)

Fig. 7. Influence of the number of control points of FRFs: (a) location of the control points and application of excitement; (b) errors of parameter values with damage regarding reference values.

6. Conclusions

This paper conducted a comparative study of the performance of different damage indicators by applying an iterative identification methodology and based on the case study of a railway bridge. The indicators used were the frequencies, vibration modes, frequencies and vibration modes, modal curvatures, flexibility curvatures and frequency response functions.

The performance assessment of damage indicators revealed the high efficiency of most indicators, with the exception of natural frequencies, the identification of the damage introduced into the numerical model of a railway bridge and involved changing the values of 6, 8 and 10 numeric parameters.

The robustness assessment of damage indicators was performed for the scenario of 8 damage parameters and allowed to observe a very good stability of the indicator based on the frequencies and vibration modes in identifying damage in the presence of noise, unlike what happened with the flexibility curvature indicator. Regarding the influence of the number of points used in modal shapes only the indicator using the modal configurations has been influenced by reducing the number of points. Regarding the number of control points of the FRFs only the situation in which one resorts to a control point had influence on the damage identification.

In the future it is intended to extend this study to further damage indicators specially those related to the dynamic performance of the train-bridge system in operation, and related to the stability of circulation, to the stability of the railway track and to passenger comfort. These new developments will require adjustment of some of the routines of the tools developed to incorporate the resolution of the train-bridge dynamic problem.

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