Identification of local damage in beams and frames

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SUMMARY. Identification of structural damage through dynamical parameters has received in the last decades a continuous attention in civil engineering, but it is still a debated question. Indeed, for an increasing complexity of the structure, the sensitivity of dynamical parameters to damage becomes comparable with the sensitivity to measurement uncertainties or environmental modifications. Following the approach proposed by other Authors for a single beam or arch, the paper investigates the possibility of identifying a localised damage, for more complex structures, using only natural frequencies measured in the undamaged and damaged configurations; a minimum procedure selects the solution in a data base of FE models simulating possible positions and levels of damage. The procedure, whose reliability on a two-span beam has already been confirmed by experimental tests summarised here, can also be successfully applied to frame structures through a substructure approach discussed in this paper by means of numerical simulations.

1 INTRODUCTION

The identification of localized damage on structures through dynamical parameters has received in the last decades a continuous attention in civil engineering, even recently (e.g. [1][2]). Electronic devices (sensors, central units,…) and powerful software for data processing allow today to get accurate experimental data on the structural response in a relatively easy and economical way; it becomes then affordable, even for usual structures, to compare structural characteristics (as dynamical properties considered in this paper) at different times, and use the detected modifications to identify structural variations, e.g. due to damage or deterioration. On the other hand, the modification of dynamical parameters for typical and realistic amount of localised damage is always small and comparable to similar modifications due to different and physiological effects, e.g. related to environmental temperature modifications. For this reason, it is often questioned the possibility itself to perform such a damage identification on the basis of measured dynamical parameters.

Indeed, identification can be effective only if dynamical parameters significantly affected by damage are measured; as a consequence, when a linear structural behaviour can be assumed (as often accepted for low excitations), the experimental identification of first natural modes (or even of their natural frequencies only, as shown in [3][4]) can allow damage identification for very simple structures (e.g. a single beam or arch), because first modes are in this case sensitive to damage. This is not the case for very complex structures (e.g. multi-floor frames), where local damage significantly affect only higher modes; therefore, ambient excitations (wind, traffic, microtremors…) can be not appropriate in this cases for identification purposes, because they typically excite first modes only. However, as shown in this paper, output-only (or "operational") identification techniques (e.g. [5-8]) can still be applied and convenient if used to identify local modes excited by local (although possibly unknown) excitations.

This paper reports some experimental and numerical results on these subjects. In particular, it summarizes numerical and experimental investigations performed on a steel model of a two-span simply-supported beam, subject to impulsive and environmental loads already studied by the writers [9][10]; a localized damage is considered, consisting of a notch (modeled through a bilateral stiffness reduction), obtained with a disk saw. Acceleration records are used to obtain the first six natural frequencies, both in the undamaged and damaged configuration, for several levels of damage and different temperatures.

The location and intensity of damage is found (see Sect.3.4 below) by minimizing the difference (in the least squares sense) between the measured natural frequencies and the corresponding ones given by finite element models (FEM) of the structure simulating each possible position and level of the damage, according to the procedure proposed in [3,4].

As shown in this paper, the proposed procedure can be further extended to more complex structures, provided that its substructures (e.g. a multi-span beam for each floor of a planar frame) are examined one by one; the basic idea is that in this case the FEM data-base of damaged models, to be used in the minimisation of the error function, must refer to the natural frequencies of the local modes of substructures, i.e. the only modes that can be practically detected (provided that local excitations are applied).

2 DAMAGE IDENTIFICATION THROUGH MEASURED NATURAL FREQUENCIES

2.1 *The model of damage*

Different mechanical models have been proposed (see [11] and papers there quoted) both for a crack (that implies a stiffness reduction only when its two sides open, introducing a mechanical nonlinearity) and for a notch, that can be approximately modelled through a (bilateral) stiffness reduction or equivalent means, at least for small curvatures. Here the last case is considered; according to [11], the damaged part of a beam is modelled through a rotational spring connecting the undamaged parts; its flexural stiffness k is related to mechanical and geometrical characteristics (elastic modulus E, Poisson coefficient ν, area moment of inertia I, thickness h) as follows

$$k = \frac{EI}{6\pi\left(1-\nu^2\right)h\Phi_1} \tag{1}$$

where, based on a theoretical formulation, the non-dimensional coefficient Φ_1 can be expressed as a function of the ratio α between the notch depth p and the beam thickness h.

2.2 *Identification of damage by means of frequency measurements*

A technique proposed by Vestroni and co-authors [3][4] assumes as experimental data the variation of an appropriate number of natural frequencies between damaged and undamaged configurations; the identification of damage is obtained by comparing these experimental variations with the numerical ones obtained through a finite elements model (FEM) for the undamaged structure and a data-base of varied FE models for several position and level of damage, modelled as a rotational spring (see Sect. 2.1). The identified solution (position *s* and depth *p* of the notch) corresponds to the FE model whose natural frequencies minimise the error function

$$G(p,s) = \sum_i \left(\frac{\Delta\omega_i(p,s)}{\omega_i^U} - \frac{\Delta\omega_{e,i}}{\omega_{e,i}^U} \right)^2 \tag{2}$$

where $\Delta\omega_i(p,s)$ and $\Delta\omega_{e,i}$ represent the differences between numerical and experimental values of the *i*-th natural frequency in the damaged state with respect to the undamaged one, and ω_i^U and $\omega_{e,i}^U$ are the numerical and experimental values of the undamaged *i*-th frequency.

The number of natural modes to be considered (index *i* in Eq.1) depends on the problem; for the cases discussed in Vestroni and co-authors ([3][4], simple beam or arch), three natural frequencies can be sufficient; however, the accuracy increases with a higher number of natural frequencies, and this can be decisive for practical applications, where data are affected by noise.

3 TWO-SPAN BEAM

3.1 *Experimental setup*

The experimental investigation fully described in [9][10] has been performed in the Material Testing Laboratory of the Department PRICOS of the University “G. D’Annunzio” of Chieti-Pescara; a steel model of a two-span simply-supported beam has been considered, with a total length of 2200 mm and a rectangular cross section 40 mm wide and 8 mm thick (see Fig.1, 2); in Fig.1 three heathers are also shown, used for inducing thermal variations in the beam in some tests not discussed here (see [9][10]). Twelve accelerometers with ± 2g full scale range and operating between -20°C and +80°C have been used; for each case two configurations have been considered, with five repeated sensors:

- configuration A, positions 1, 3, 4, 5, 6, 8, 11, 14, 15, 17, 18, 19 of Fig.2;
- configuration B, positions 2, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16.

Figure 1 : Experimental setup.

To have the same mass distribution for each configuration, the 7 measurement points without accelerometers have been equipped with equivalent added masses (16 g each). Data acquisition has been performed with a 16 channels LEA-DAS unit, equipped with National Instruments technology. A simple forcing has been considered so far, applying impulsive loads with a hammer; accelerations points have been recorded with sampling frequency of 1000 Hz.

Several cases have been considered (two in Table 1). After tests for the undamaged beam at several temperature levels, they have been repeated on the damaged beam; a notch at 501 mm from one of the beam ends (see Fig.2) has been cut with a disk saw, with increasing depth (*p* = 1.6, 3.2 and 4.2 mm); mass reduction is negligible.

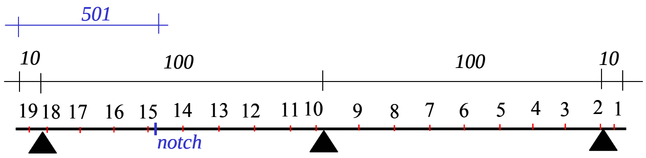

Figure 2 : sketch of measurement points (distances in millimetres) and position of the damage (see Fig. 1)

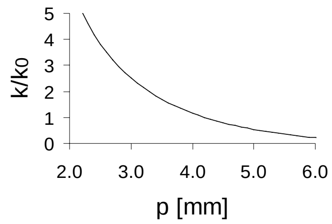

Figure 3 : Stiffness k as a function of p; k_0 is the stiffness for p=4.2 mm

3.2 *FE model*

The steel beam has been modelled through an elastic linear finite element model (FEM) with 109 beam elements 20 mm long. Assumed 7813 kg/m^3 for the mass density and 0.3 for the Poisson coefficient, the elastic modulus E has been chosen as an updating parameter, and its value $E=2.032\cdot10^5$ N/m^2 has been obtained by minimising the difference between the first six FEM natural frequencies and those measured in the undamaged configuration.

According to Chondros [11], the localised damage has been described by means of a rotational spring; its stiffness *k* is shown in Fig.3, normalised with respect to a reference value k_0 corresponding to the depth of the notch cut in the experimental model for the cases described below, p_0=4.2 mm (#2 in Table 1). A data base of the first 6 natural frequencies for 7630 FE models has been built, assuming 109 different positions (step 20 mm) and 70 different depth of the notch between 2 and 7 mm (variable step, average less than 0.1 mm). The solution of the identification problem, in terms of *s* (position) and *p* (depth) of the damage is searched through the minimum procedure (Eq. 2) described in Sect. 2.2.

Table 1: the first 6 natural frequencies for sample cases

									results of identification	
#			**f_1 (Hz)**	**f_2 (Hz)**	**f_3 (Hz)**	**f_4 (Hz)**	**f_5 (Hz)**	**f_6 (Hz)**	**s mm**	**p mm**
1	FEM frequencies. Damaged case corresponds to s=500 mm, p=4.1 mm (see Fig.4)	undamaged	24.38	32.64	76.63	94.28	162.85	188.09	500	4.1
		damaged	24.13 (-1.03%)	32.35 (-0.89%)	76.46 (-0.22%)	93.33 (-1.01%)	162.1 (-0.46%)	186.45 (-0.87%)		
2	Experimental data: s=501 mm, p=4.2 mm 19 measurement points; see Fig.5	undamaged	24.58	32.60	76.76	94.33	165.4	186.8	500	4.7
		damaged	24.15 (- 1.75%)	31.98 (- 1.90%)	76.22 (- 0.70%)	93.72 (- 0.65%)	164.5 (- 0.54%)	184.2 (- 1.39%)		

3.3 *Identification of natural frequencies*

Experimental identification of natural frequencies has been performed in different ways:

- through the well known Goyder technique applied to Fast Fourier Transforms (FFT) of the measured accelerations, with average values assumed as experimental data for each case;

- through the Artemis software [12], that includes different techniques: EFDD (Enhanced Frequency Domain Decomposition), SSI-CVA (Stochastic Subspace Identification - Canonical Variate Analysis), SSI-UPC (Unweighted Principal Components) and SSI-PC (Principal Components); Table 1 reports natural frequencies of the first six modes (SSI-PC) for several cases; a more detailed report of experimental investigation can be found in [9].

3.4 *Identification of damage*

The identification of damage is performed through the minimum procedure described in Sect. 2.2, where unknown parameters are the damage position *s* and depth *p*.

To show the typical trend of the error function G as a function of location and intensity of damage, pseudo-experimental data (generated numerically and therefore exact) are examined first; the natural frequencies assumed as "experimental" data in the undamaged and damaged situation are those reported as "case 1" in Table 1. Fig.4a shows the level curves of G; two different minima are found due to the symmetry of the beam; moreover, being the pseudo-experimental data of this case corresponding to one of the cases of the data base, the minimum of G is equal to zero, and therefore the location and the depth of damage are exactly identified.

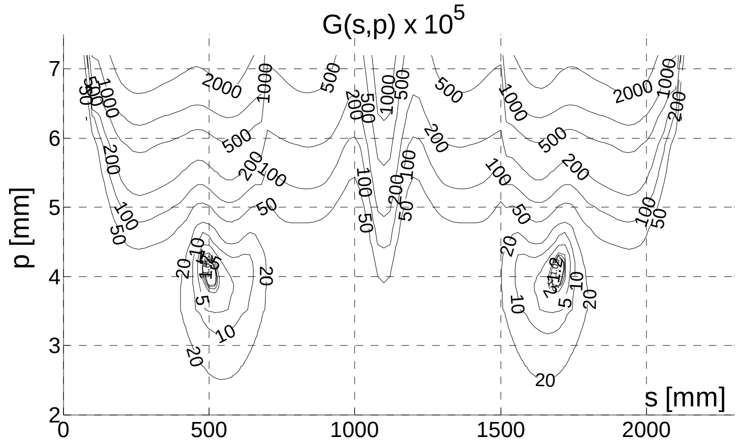

Figure 4 : case #1 in Table 1: pseudo-experimental data, generated with s=500 mm and p=4.1 mm in the FE model. Level-curves of the error function G

Fig.5 shows the identification in case of experimental data (case 2 of Table 1), where now G is normalised with respect to its minimum value G_{min}; for the symmetry reasons already explained, two different minima are found also in this case; therefore, in Fig.5a the level curves are reported for one span only, while Fig.5b reports a zoom around the solution. The identification (s = 500 mm, p = 4.7 mm) turns out to be accurate with respect to the position of damage, while it overestimates the depth of the notch (p = 4.2 mm); in the writers opinion, this error (about 12 % of the effective depth) can possibly be attributed to some difference between the function $\Phi_1(\alpha)$ proposed by Chondros (see Eq.1, where $\alpha = p/h$) and the effective behaviour of the beam tested, although only further investigation can allow to get reliable conclusions.

It is also worth noticing that the procedure searches the minimum within the data base of FEM cases considered, and therefore with the grid spacing introduced to generate the data base (Δs= 20 mm and Δp variable, with an average value less than 0.1 mm); although, in the writers' opinion, the spacing assumed can be appropriate for practical purposes, an iterative approach could easily be considered with a database locally enriched at each step.

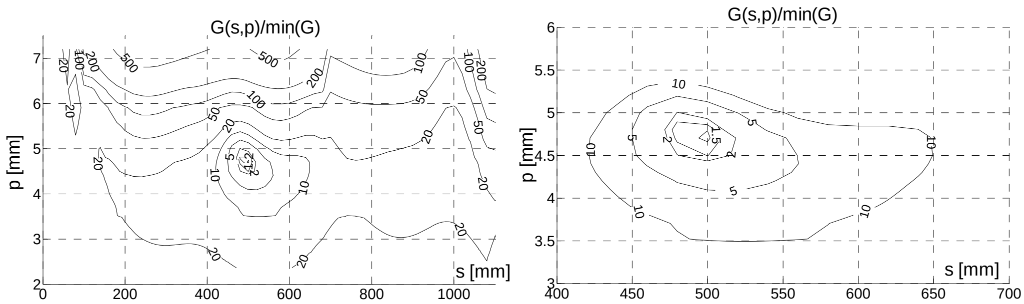

Figure 5 : case #2 in Table 1: experimental data, damage with s=501 and p=4.2 mm. a) level-curves of error function G normalised to its minimum value; b) zoom around identified solution s=500 and p=4.7 mm

Numerical and experimental results [9] confirm the reliability of the described procedure; indeed, it has the advantage of using as experimental data only the frequencies of relatively few modes, i.e. parameters less sensitive to noise or disturbances with respect to other dynamical characteristics, as shown in [9][10]; the procedure allows therefore a satisfactory evaluation of damage even if the damaged span is not directly accessible, evaluating natural frequencies through acceleration records on the adjacent undamaged span, or if data are affected by noise or other disturbances, e.g. thermal variations.

4 NUMERICAL INVESTIGATION ON A PLANE FRAME

As shown in Sect. 3.4, the proposed procedure for identifying position and intensity of damage needs a reference FE model, updated by means of undamaged experimental frequencies, and a data-base of varied FE models, representing all possible damaged configurations.

While for simple structures so far considered (single or multi-span beams) this implies a relatively small computational effort, for an increasing structural complexity the computational burden may be relevant and algorithms to generate automatically the FE data-base should be implemented, as it will be tried in the next future.

Moreover, it can be difficult (or even impossible) to detect localised damage in a complex structure by observing frequency (or shape) modification of global modes, often negligible, while the effect can be more relevant on “local” modes of the substructure affected by damage, provided that local excitations on this substructure are applied.

This motivated the substructure approach discussed in Sect.4.1 below, that uses only a selected set of “local” modes to build the data-base of frequencies for the minimisation procedure.

On the other hand, in case of complex structures (even if relatively simple, as the planar frames discussed below) the problem of modal density arises, i.e. the existence of many structural modes with close natural frequencies while only some of them – as just said - can be really detected and used for identification purposes, i.e. those significantly excited by the local actions acting on the substructure under considerations (see Sect.4.1). This requires appropriate criteria to distinguish natural modes of the FE “damaged” models to be included in the data-base for minimisation procedure - and to be compared with modes of the reference FE model with similar shape - from other modes in the same range of frequencies; in the numerical example discussed below, the selection has been done by means of expert judgement, but an algorithm to perform it automatically is mandatory to extend the procedure to more complex (and more significant) structures.

4.1 *Substructure approach*

A possible approach, here discussed with reference to the simple frame in Fig.6, requires to select – in the data-base of natural frequencies to be used for the minimisation procedure – only local modes excited by local actions on a given substructure, i.e. the only modes that can be practically detected; if (as it usually happens) a detailed location of sensors cannot be extended to the whole structure for practical or economical reasons, the procedure must then be repeated on different substructures one by one, till to explore the whole structure.

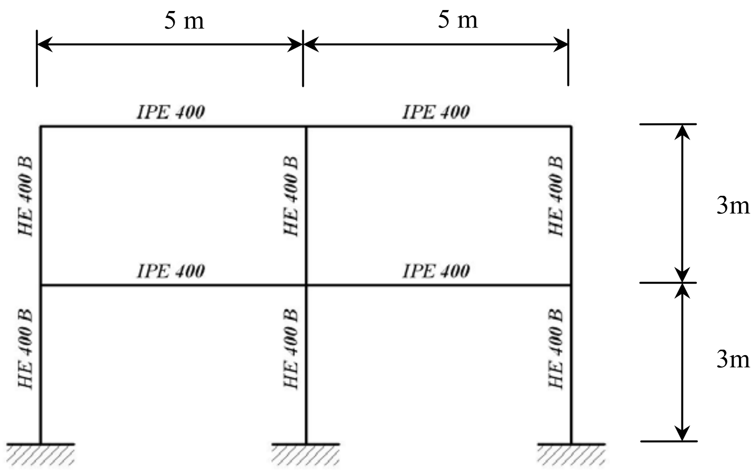

Figure 6: Steel frame (numerical data). For each floor, added mass 2900 kg/m. In the finite element method: damping coefficient 0.5 %.

With reference to the frame in Fig.6, a damage is considered at 1.72 m from the left end of the first-floor beam, corresponding to a 6 cm notch described by a rotational spring according to [11] (see also [9][10]). With an impulsive load at 2/3 of the span of the same beam, numerical time-histories of acceleration have been generated by means of a finite elements model for both the beam of the first floor; distance between "measurements" points is 1/8 of the span.

Modal shapes and frequencies of local modes so identified at the first floor are reported in Fig.7, both for undamaged and damaged configuration, while corresponding modes of the FE models of the frame are reported in Fig.8. Quite obviously, in the numerical case here considered the "experimental" undamaged model coincides with the FE reference one, while in practical cases it has to be obtained by model updating, by means of experimental results in the undamaged configuration.

The FE data-base has been built varying damage position with Δs=0.156 m (1/32 span) and notch depth between 4 and 8 cm.

It is worth noting that the six modes in Fig. 7, the only ones to be detected between 0 and 100 Hz for the assumed local excitation, together with a 7th mode not represented in the picture, correspond with the same order to the modal shapes in Fig.8; the latter have indeed been denoted by letters because separated, for the complete frame, by a ten of modal shapes not relevant for the dynamic behaviour of the substructure under consideration.

According to this and other numerical examples, the procedure seems quite promising for this kind of structures also, as shown by results in Fig. 9 and 10 relative to two different characteristics of damage. The location and intensity of damage are in fact detected with a good accuracy, even for modal frequencies of the damaged case distorted (with ± 30 % of the difference between damaged and undamaged frequencies) to simulate possible noise in experimental data.

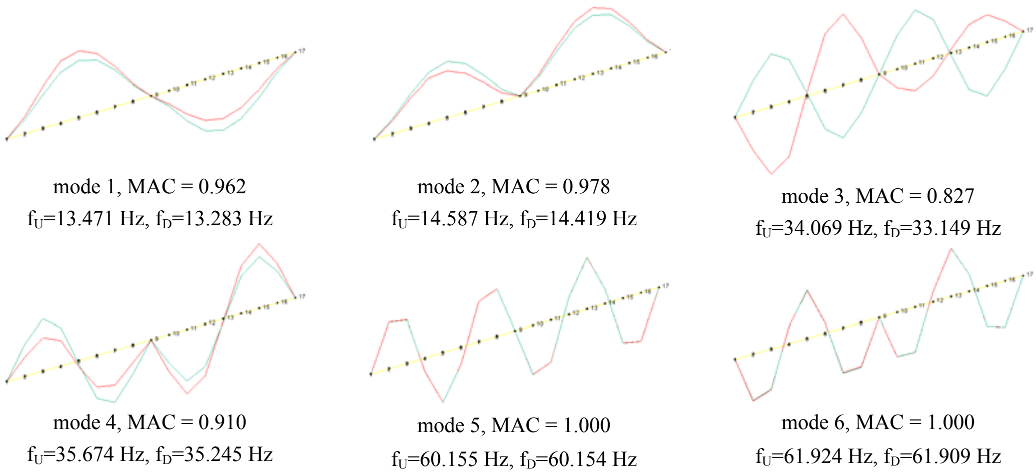

Figure 7. Beam at the first floor of frame in Fig. 6. Modes identified with SSI-UPC technique in undamaged configuration (cyan) and in damaged configuration (red) from simulated time-histories of vertical acceleration under impulsive loads

5 CONCLUDING REMARKS

The paper deals with the identification of localized damages on structures through dynamical parameters, following the procedure proposed by Vestroni and co-authors [3][4] for a single beam or arch. The possibility is investigated of identifying a localised damage, for more complex structures, using only natural frequencies measured in the undamaged and damaged configurations.

In the first part of the paper, the reliability of the procedure is shown for a two-span beam by means of numerical and experimental results. Previous papers of the writers [9][10] have also shown that identification of damage can be obtained even if the measures do not include the damaged span or if data are affected by noise or other disturbances, e.g. due to temperature variations. As shown in the paper, the proposed procedure can be further extended to more complex structures, provided that its substructures (e.g. a multi-span beam for each floor of a planar frame) are examined one by one; the basic idea is that in this case the FEM data-base of damaged models, to be used in the minimisation of the error function, must refer to the natural frequencies of the local modes of substructures, i.e. the only modes that can be practically detected (provided that local excitations are applied). Preliminary numerical results are quite promising. However the idea, so far explored only by means of numerical data (*pseudo-experimental*), will certainly require an experimental validation in the next future, at least to the laboratory scale.

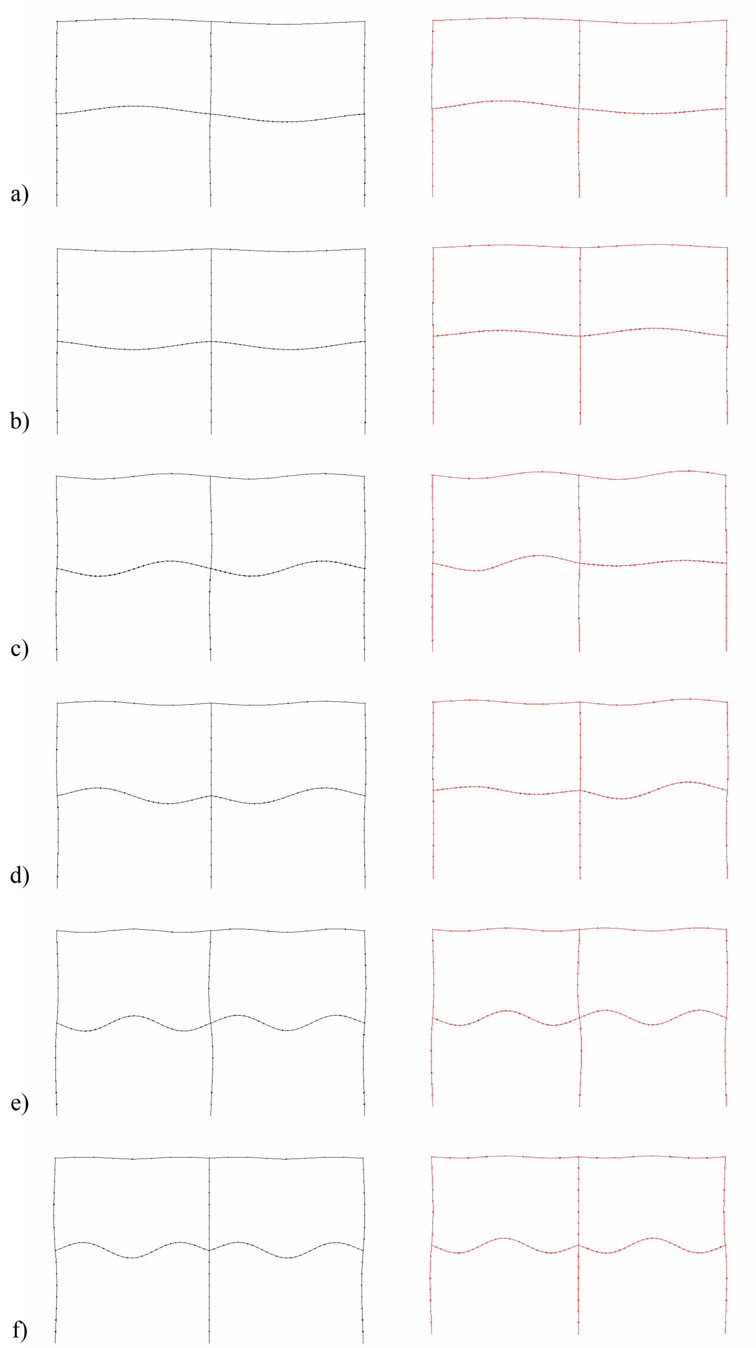

Figure 8: Natural modes of the frame in Fig. 6 (FEM model): undamaged configuration (black, on the left) and damaged configuration (red, on the right) with concentrated damage at s = 1.72 m, depth p=6.0 cm.

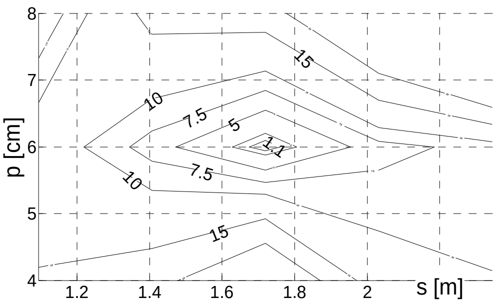

Figure 9: frame in Fig.6, pseudo-experimental data, generated with damage s=1.72 m, p=6 cm. Level-curves of the error function G/Gmin

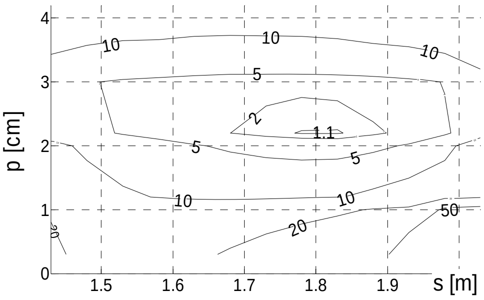

Figure 10: frame in Fig.6, pseudo-experimental data, damage s=1.78 m, p=2.2 cm. Level-curves of error function G/Gmin

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References

[1] Catbas F.N.,Gul M. and Burkett J.L.“Damage assessment using flexibility and flexibility based curvature for structural health monitoring”,*Smart materials and struct.*, **17**, pp.1-12 (2008)

[2] Chellini G., De Roeck G., Nardini L. and Salvatore W. “Damage detection of a steel-concrete composite frame by a multilevel approach: Experimental measurements and modal identification”, *Earthquake Engineering & Structural Dynamics*, **37** (15), p. 1763-1783 (2008).

[3] Cerri M.N. and Vestroni F. "Identification of damage due to open cracks by changes of measured frequencies", *16th Proc. Conf. of Theoretical and App. Mechanics AIMETA (*2003).

[4] Greco A., Pau A. and Vestroni F.. “Damage identification in a parabolic arch”, *Proc. 18th Conf. Italian Association for Theoretical and Applied Mech. AIMETA*, Brescia, Italy (2007)

[5] Perry M. J. and Koh C. G. “Output-only structural identification in time domain: Numerical and experimental studies”, *Earthquake Eng. & Struct. Dynamics*, 37 p. 517-533 (2007).

[6] Benedettini F. and Gentile C. "Ambient Vibration Testing and Operational Modal Analysis of a Masonry Tower", *Proc. 2nd IOMAC*, Copenhagen, Denmark (2007).

[7] Brincker R., Ventura C.E. and Andersen P. "Why Output-Only Modal Testing is a Desirable Tool for a Wide Range of Practical Applications", *Proc. 21st IMAC*, Florida (2003).

[8] Zhang L., Brincker R. and Andersen P. “An Overview of Operational Modal Analysis: Major Development and Issues”, *Proc. 1st IOMAC*, Copenhagen (2005).

[9] Bellizzotti G. *PhD Thesis on damage identification*, Dottorato in Strutture, XXI ciclo, Univ. “G. D’Annunzio” Chieti-Pescara, advisor V. Sepe (*in Italian*) (2009).

[10] Sepe V. and Bellizzotti G. "Identification of damage in structural elements not directly accessible", *Proc. 3rd IOMAC*, May 4-6 2009 Portonovo-Ancona, Italy (2009)

[11] Chondros T.G. and Dimarogonas A.D. “A continuos cracked beam theory”, *Journal of Sound and Vibrations*, 215(1) p.17-34 (1998).

[12] ARTeMIS (Ambient Response Testing and Modal Identification Software), Structural Vibration Solutions A/S, Denmark, *www.svibs.com*