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# INTERPOLATION EVOLUTION METHOD: ANALYSIS OF THE INFLUENCE OF HIGHER MODES RETRIEVED FROM NONLINEAR NUMERICAL ANALYSES PERFORMED ON TWO DIFFERENT MODELS OF REINFORCED CONCRETE FRAMED STRUCTURES

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**Keywords:** Structural Health Monitoring; Structural Damage Localization; Higher modes; Curvature Evolution Method, Interpolation Method, Band-Variable Filter

**Abstract.** *Continuous monitoring based on vibrational identification methods is increasingly employed in order to evaluate the state of health of existing structures and infrastructures in operative conditions and after relevant earthquakes. Most of the damage identification methods are based on the variations of damage indices defined in terms modal and/or non-modal parameters. Most of simplified methods for structural health monitoring and damage detection are based on the observation of the evolution of the dynamic characteristics associated to the fundamental mode of vibration of a monitored structure. The contribution of higher modes to the dynamic response of multi degree-of-freedom systems is an issue of relevant importance affecting both the design of new structures and the assessment of existing ones. The contribution of higher modes could be effective also in the inverse procedures for structural damage detection. In this paper the Interpolation Evolution Method, previously applied considering only the contribution of the fundamental mode of vibration, has been applied taking into account the contribution of the higher modes. Preliminary results retrieved from a numerical campaign based on nonlinear finite element models excited by several strong motion earthquakes are presented.*


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# 1 INTRODUCTION

Systems for structural health monitoring could be a relevant tool in seismic regions after a strong motion earthquake performing an objective estimation of possible structural damage. Vibration based damage identification techniques have been widely applied for the assessment of the health state of buildings. Researchers have worked to set-up new methodologies for SHM based on the detection of variations, after a strong seismic event, of the structural dynamic characteristics, namely the modal parameter (frequencies, mode shapes, damping) or non-modal parameters like the operational deflection shapes (ODS) [1]. Damage identification is generally carried out through a comparison between the original (undamaged) state and the (possibly damaged) current state [2]-[4]. Methods based on frequency changes can be reliably applied to detect damage, but they are hardly able to give information about the location of damage. To this aim are more effective methods based on the time-evolution analyses ([5]-[8]) able to detect changes of modal or operational mode shapes and/or of their derivatives such as slopes, curvatures or strain energy [9]-[13].

Most of simplified methods for structural health monitoring and damage detection are based on the analysis of the evolutive dynamic characteristics associated to the fundamental mode of vibration of a monitored structure. The contribution of higher modes to the dynamic response of multi degree-of-freedom systems is a topic of relevance for the design of new structures and the assessment of existing ones, and it could be effective also in the inverse procedures for structural damage detection.

In this paper the Interpolation Evolution Method (IEM), a combination of two existing methods, named Curvature Evolution Method (CEM) and Interpolation Method (IM), has been applied taking into account the contribution of higher modes in the procedure for damage localization. The Interpolation Method [9] is based on a damage feature defined in terms of the loss of smoothness (that is local increases of curvature) of the operational mode shapes, induced by a local reduction of stiffness. The damage feature is defined in terms of the variation of the interpolation error between a reference and a (potentially) damaged configuration. The interpolation error is computed for each configuration by interpolating with a smooth function (namely a cubic spline for a beam-like structure) the operational (or the modal) shapes computed from responses recorded on the structure during vibrations. In the Curvature Evolution Method [10] the damage feature is defined in terms of the mode curvature. This parameter is evaluated overtime from the responses recorded during the earthquake and the comparison of its values at different times allows the detection of its possible variations. In this method it is possible to analyse the nonlinear response of each mode of vibration of the monitored structure through the Band-Variable Filter [14].

The combined approach has been applied to nonlinear numerical models of reinforced concrete framed structures excited by several strong motion earthquakes.

# 2 INTERPOLATION EVOLUTION METHOD (IEM)

The main idea at the base of the combined IEM approach is to jointly exploit the performance of the Curvature Evolution Method with the stability of the Interpolation Method. The interpolation is applied to the fundamental mode shape continuously extracted at each time instant before, during and after a strong motion event. A further advantage connected to the proposed procedure consist in the possibility of computing a set of values of the damage feature (variation of the interpolation error) allowing to recover its statistics thus taking into account its variability due to uncertainties induced by noise in recorded data.

The Curvature Evolution Method [10] for damage localization is based on the use of the Band-Variable Filter [14] able to extract the nonlinear response of each mode of vibration, acting simultaneously in both time and frequency domain. The detection of possible changes occurred during a single earthquake is carried out in terms of a damage feature defined in terms of the mode curvature. The Band-Variable Filter gives the possibility to extract from a non-stationary and/or nonlinear signal just the energy content related to a single mode of vibration, preserving both amplitude and phase over time [15]. The Band-Variable Filter allows to evaluate both frequency and mode shape variations during an earthquake. The basic idea is to isolate, by mean the Band-Variable Filter, the fundamental mode over time and evaluate its changes in terms of both shape and related curvature [16].

The Interpolation Method [9] is based on the observation that the comparison of the operational mode shapes related to the undamaged and damaged phases points out a sharp reduction of smoothness of the deformed shape at the damaged story. The damage feature is thus defined as the variation of the error related to the use of a (smooth) cubic spline function in interpolating the operational or the modal shapes of the monitored structure. A variation of the interpolation error between a reference and a possible damaged configuration indicates the onset of damage. In order to remove the influence of the amplitude of displacements on the evaluation of the interpolation error and to remove the numerical errors related to the estimation of displacements from recorded accelerations, the interpolation error is defined in terms of the difference between the transfer functions of the recorded and interpolated accelerations with respect to the input acceleration [17]. The value of the damage feature at each location equipped with a sensor is computed as the positive difference between the values of the interpolation error in the inspection $E_i$ and in the reference $E_0$ phases.

The combination of the two methods CEM and IM is performed herein using the Band-Variable Filter to extract the non-linear response of the structure and assuming as a damage feature the variation of the interpolation error computed at different times during the strong motion.

In this paper, the Band-Variable Filter has been used in order to extract both the first and the second mode of vibration (in the same direction) of the structure. The structural mode shapes have been evaluated over time and have been interpolated through a spline shape function at each location $x$ and time $t$. After the computation of the interpolation error, the variation of the interpolation error with respect to the initial value have been computed at each location $x$ and time $t$. finally has been selected the damaged location as that corresponding to the highest frequency of detection over the duration of the strong motion.

## 3 NUMERICAL CASE STUDIES

The Interpolation Evolution Method has been applied to nonlinear numerical models of two reinforced concrete framed structures of respectively 5 and 8 floors with regular geometric configuration (Figure 1) and designed only for gravity loads. The height of each story is 3 m, for a total height of the buildings equal to 15 m for the 5 story building and of 24m for the 8 story building (Figure 2).

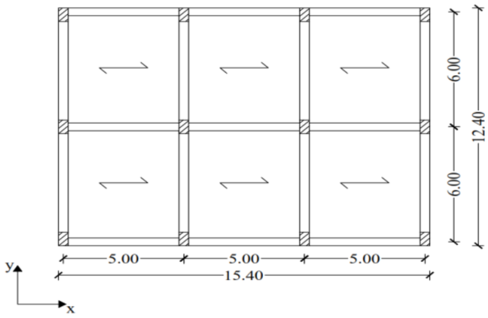



Figure 1: Geometric plan.

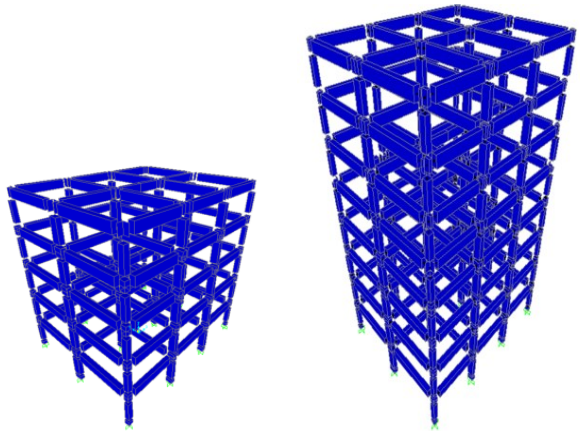


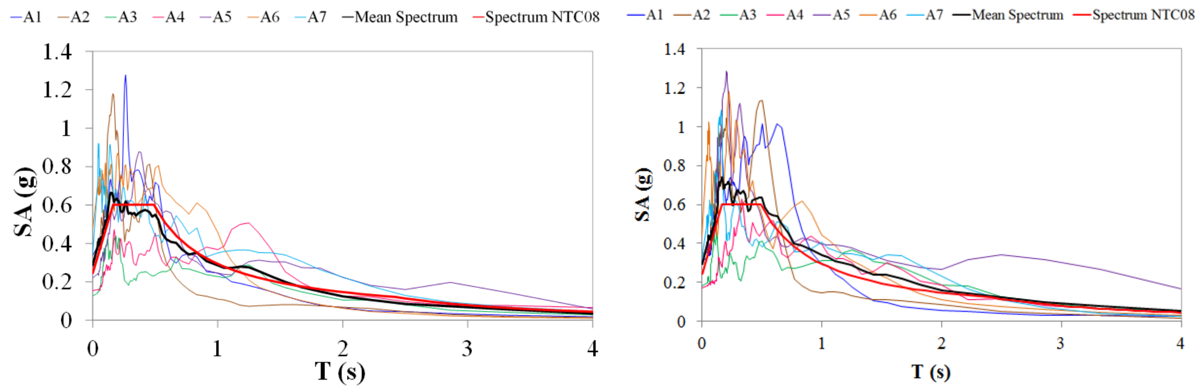
Figure 2: Nonlinear FEM models: (a) 5 story, (b) 8 story.

Nonlinear dynamic analyses have been carried out using a nonlinear 3D model built in SAP2000 non-linear [18]. In order to simulate a structural nonlinear behaviour during a strong ground motion, link elements and plastic hinges were modelled at the ends of both beam and column elements. Link elements have a Pivot hysteretic behaviour, while plastic hinges have an axial load-dependent one. Table 1 shows the Peak Ground Acceleration (PGA) values of the natural accelerograms selected for the numerical simulations.

| | A1 | A2 | A3 | A4 | A5 | A6 | A7 |
|---|---|---|---|---|---|---|---|
| **PGA (g)** | 0.34 | 0.34 | 0.13 | 0.15 | 0.22 | 0.48 | 0.35 |

Table 1: PGA related to the natural accelerograms used for the numerical simulations.

İn order to identify the reference fundamental frequency before the earthquake and the final fundamental frequency after the earthquake, 20 seconds of pink noise have been added at the beginning and at the end of each time-history used as input. Figure 3 shows the response spectra of the seven accelerograms compatible with the Italian Seismic Code for a soil type B [19].




(a) (b)

Figure 3: Response spectra of the natural accelerograms: (a) NS component; (b) WE component.

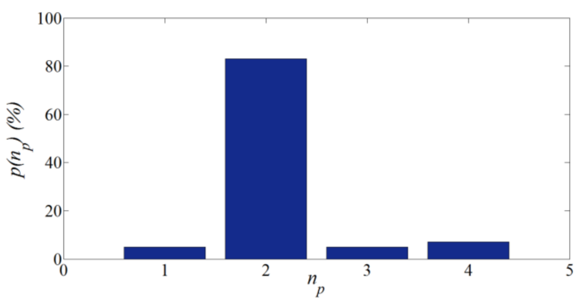
## 4 DISCUSSION OF RESULTS

This section shows the preliminary results obtained by applying the Interpolation Evolution Method to the case data simulated using the 5 and 8 storey nonlinear models. In order to test the robustness of the IEM approach and to perform realistic simulations, each nonlinear numerical analysis has been performed using both NS and WE component of each selected earthquake. After each simulation, as described in section 2, the first step was the identification of the first and the second mode of vibration along the same direction and the computation of the corresponding operational mode shape (evaluated considering just the contribution of the first two modes along a single direction). Then, the interpolation through the cubic spline function has been applied and the time history of the damage feature (variation of the interpolation error) has been evaluated at each instrumented location. At each time instant, the location where the maximum value of the damage feature (among all the instrumented locations) was attained, has been chosen as the damaged one. For each event and for each storey, the frequency of detection (number of times the location was detected as the damaged one over the total duration of the event) was assumed as representative of the probability of detection at the storey. Table 2 shows the initial modal characteristics of the used numerical models and the considered modes (1° and 2° modes along the same direction corresponds to the 1° and 4° modes highlighted in Table 2).

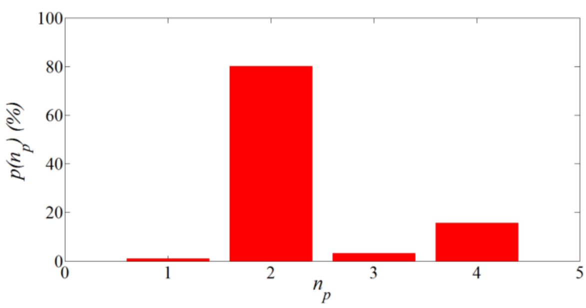
| | 5 story building | | | 8 story building | | |
|---|---|---|---|---|---|---|
| **mode** | **f (Hz)** | **mass particip. (dir. x)** | **mass particip. (dir. y)** | **f (Hz)** | **mass particip. (dir. x)** | **mass particip. (dir. y)** |
| **1** | **0.84** | **78.00%** | **0.00%** | **0.66** | **0.00%** | **66.24%** |
| 2 | 0.59 | 0.00% | 77.00% | 0.80 | 61.23% | 0.01% |
| 3 | 0.58 | 0.00% | 0.76% | 0.86 | 2.16% | 0.15% |
| **4** | **0.27** | **10.00%** | **0.00%** | **1.99** | **0.00%** | **8.57%** |
| 5 | 0.19 | 0.00% | 0.00% | 2.41 | 8.21% | 0.00% |
| 6 | 0.19 | 0.00% | 10.00% | 2.58 | 0.34% | 0.02% |

Table 2: Values of frequency and mass participation of the mode of vibration considered for the analysis.

From Figure 4 to Figure 7, the results obtained by applying the IEM selecting only the first fundamental mode of vibration are compared with the results obtained by considering both the first and the second mode of vibration.




(a)




(b)

Figure 4. Histograms of probability to detect damage at each floor of the 5 story building - accelerogram A1: (a) only first fundamental mode; (b) first and second fundamental mode.

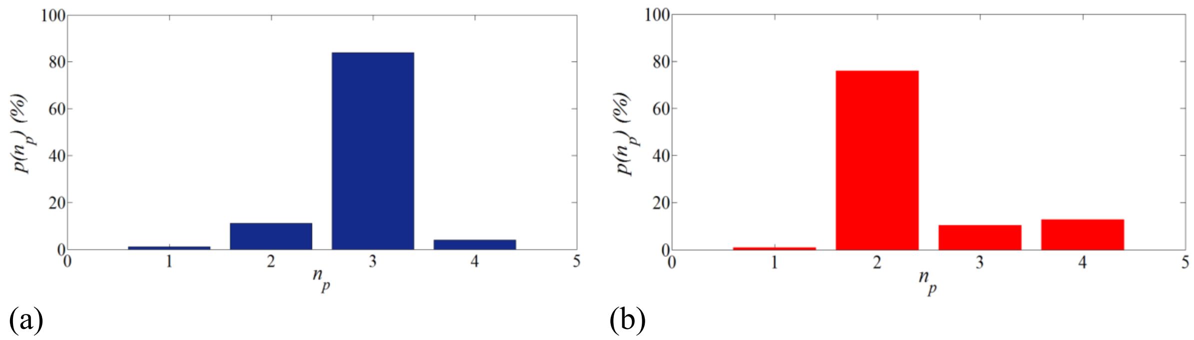



Figure 5. Histograms of probability to detect damage at each floor of the 5 story building - accelerogram A5: (a) only first fundamental mode; (b) first and second fundamental mode.

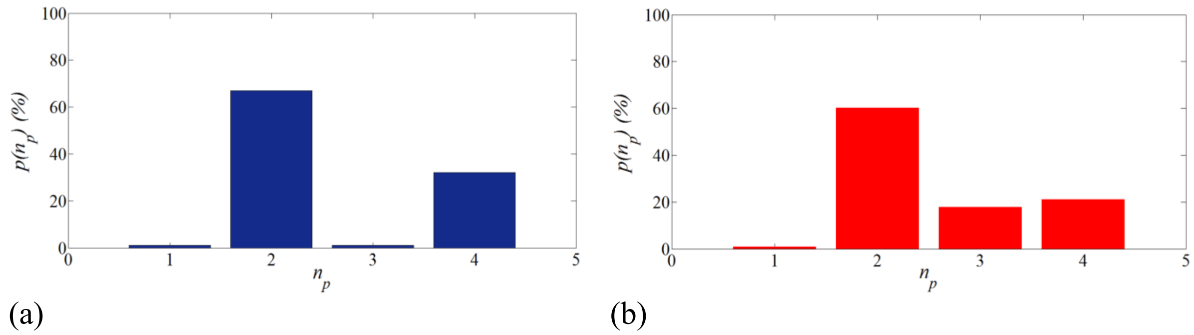



Figure 6. Histograms of probability to detect damage at each floor of the 5 story building - accelerogram A6: (a) only first fundamental mode; (b) first and second fundamental mode.

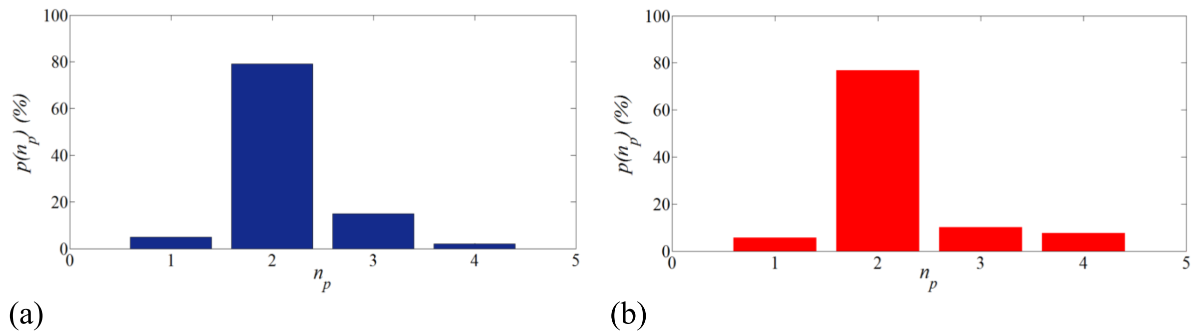



Figure 7. Histograms of probability to detect damage at each floor of the 5 story building - accelerogram A6: (a) only first fundamental mode; (b) first and second fundamental mode.

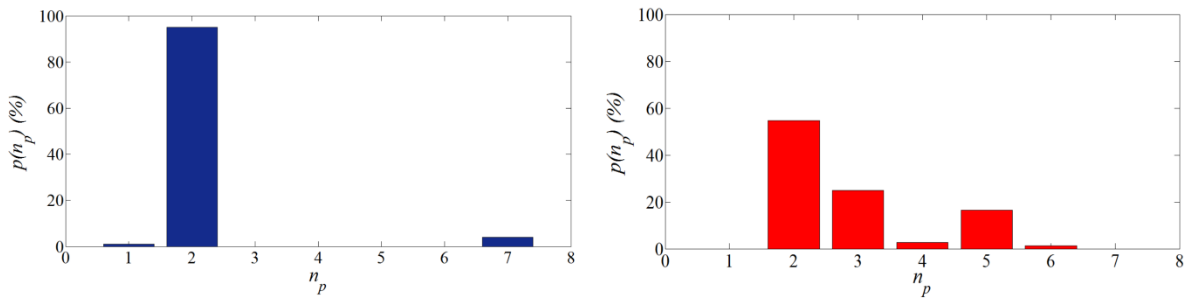
The nonlinear dynamic analysis carried out on the two multi-storey frames show that the different earthquakes caused the formation of plastic hinges at the ends of all columns between the second and third floors for the 5 storey model and between the first and second floors for the 8 storey model. The maximum variation of the interpolation error occurs at the second and the third floor (only for the accelerogram A5) considering the first fundamental mode. By applying the procedure through the selection of both the first and the second mode of vibration, the maximum values are at the second floor of the structure. The highest value of the damage feature is attained at the damaged locations allowing the correct localization of damage.

Table 3 summarizes the probability to detect damage at each floor obtained from data of the 5 story building excited by the selected ground motions.

| | A1 | | A5 | | A6 | | A7 | |
|---|---|---|---|---|---|---|---|---|
| | **1st mode** | **1st + 2nd mode** | **1st mode** | **1st + 2nd mode** | **1st mode** | **1st + 2nd mode** | **1st mode** | **1st + 2nd mode** |
| $n_p$ | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) |
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 5.08 | 1.04 | 0.63 | 0.86 | 0.59 | 0.85 | 4.66 | 5.64 |
| 2 | **83.05** | **80.21** | 10.63 | **75.97** | **67.06** | **60.17** | **76.27** | **76.69** |
| 3 | 5.08 | 3.13 | **84.38** | 10.30 | 0.59 | 17.80 | 14.41 | 10.15 |
| 4 | 6.78 | 15.63 | 4.38 | 12.88 | 31.76 | 21.19 | 1.69 | 7.52 |
| 5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Max Drift | 2° floor | | 2° floor | | 2° floor | | 2° floor | |

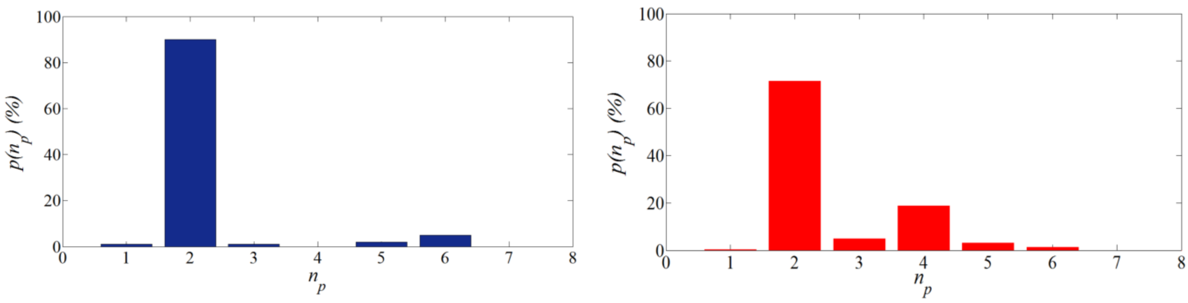
Table 3: Comparison of probability to detect damage at each floor of the 5 story building considering only the first fundamental mode, the first and second modes and the floor where the maximum drift occurred.

The maximum values of the frequency of detection are similar in all the analysed cases and occur at the most damaged floor. The following figures show the comparison between the frequency if detection obtained considering only the first fundamental mode and or both the first and the second modes of vibration of the 8 story building.



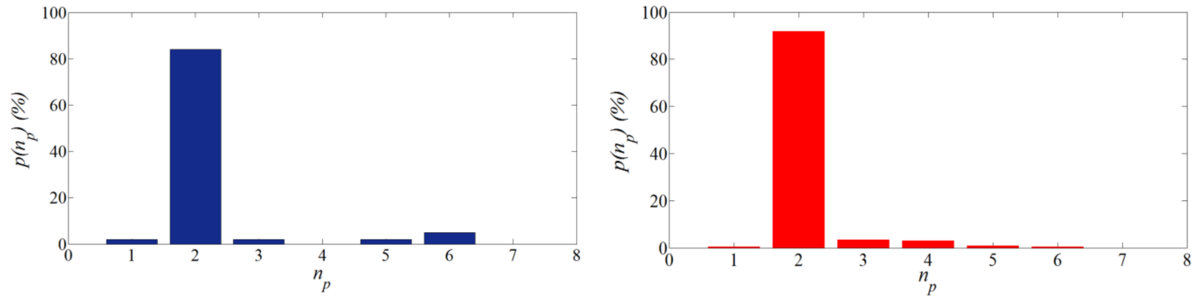

(a) (b)

Figure 8. Histograms of probability to detect damage at each floor of the 8 story building - accelerogram A1: (a) only first fundamental mode; (b) first and second fundamental mode.



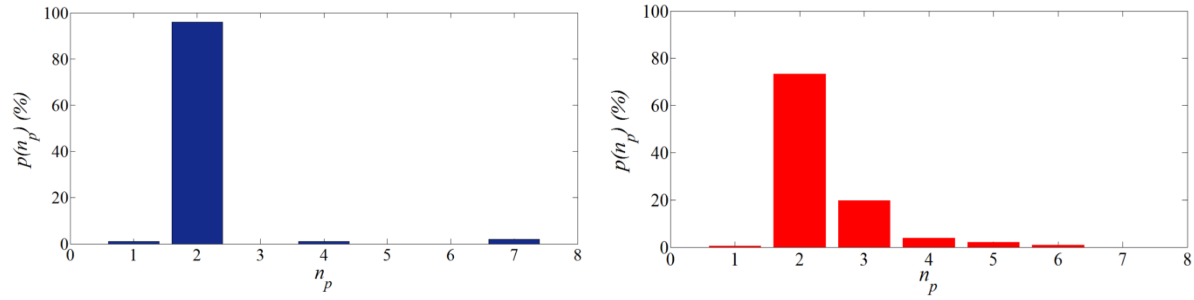

(a) (b)

Figure 9. Histograms of probability to detect damage at each floor of the 8 story building - accelerogram A5: (a) only first fundamental mode; (b) first and second fundamental mode.




(a) (b)

Figure 10. Histograms of probability to detect damage at each floor of the 8 story building - accelerogram A6: (a) only first fundamental mode; (b) first and second fundamental mode.




(a) (b)

Figure 11. Histograms of probability to detect damage at each floor of the 8 story building - accelerogram A7: (a) only first fundamental mode; (b) first and second fundamental mode.

Table 4 summarizes the probability to detect damage at each floor obtained from data of the 8 story building excited by the selected ground motions.

| | **A1** | | **A5** | | **A6** | | **A7** | |
|---|---|---|---|---|---|---|---|---|
| | **1st mode** | **1st + 2nd mode** | **1st mode** | **1st + 2nd mode** | **1st mode** | **1st + 2nd mode** | **1st mode** | **1st + 2nd mode** |
| $n_p$ | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) | $p(n_p)$ (%) |
| 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1 | 1.05 | 0.00 | 1.01 | 0.35 | 2.11 | 0.43 | 0.82 | 0.42 |
| 2 | **94.74** | **54.61** | **90.91** | **71.53** | **88.42** | **91.88** | **95.90** | **73.22** |
| 3 | 0.00 | 25.00 | 1.01 | 4.86 | 2.11 | 3.42 | 0.00 | 19.67 |
| 4 | 0.00 | 2.63 | 0.00 | 18.75 | 0.00 | 2.99 | 0.82 | 3.77 |
| 5 | 0.00 | 16.45 | 2.02 | 3.13 | 2.11 | 0.85 | 0.00 | 2.09 |
| 6 | 0.00 | 1.32 | 5.05 | 1.39 | 5.26 | 0.43 | 0.00 | 0.84 |
| 7 | 4.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.46 | 0.00 |
| 8 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Max Drift | 2° floor | | 2° floor | | 2° floor | | 2° floor | |

Table 4: Comparison of probability to detect damage at each floor of the 8 story building considering only first fundamental mode, the first and second modes and the floor where the maximum drift occurred.

The results are in agreement with those presented above. The maximum values of the damage indices occur at the damaged locations leading to a correct localization of damage. However, for the 8-story structure, the probability values obtained considering only the first fundamental mode of vibration are higher than the values obtained in the second case (1st + 2nd mode of vibration) except for accelerogram A6.

The last circumstance is probably due to the lower reliability of the time evolution of the second mode with respect to the first which is the one that exhibits the higher contribution to the frame response as shown by the values of the modal participation factors.

## 5 CONCLUSIONS

In this work the Interpolation Evolution Method for damage localization has been applied using responses obtained using nonlinear finite element models excited by several real strong motion earthquakes. The novelty of the paper consists in taking into account the effects of higher modes of vibration on the damage localization procedure. The method was applied to two case studies comparing results obtained considering only the first fundamental mode of vibration with those retrieved considering also the second mode of vibration.

Results show that for both the cases, the combined method is able to successfully detect the correct location of structural damage. Particularly, the maximum values of the damage feature occur at the most damaged floor. For the 5 story building, higher modes do not increase the reliability of the procedure but confirm the results obtained by considering only the first mode of vibration. Whereas the maximum probability to detect damage at each floor of the 8 story building decrease if higher modes are considered, therefore the procedure for damage detection is more reliable based only on the first fundamental mode.

## ACKNOWLEDGEMENTS

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