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SENSOR DISTRIBUTION ON A MONITORED STRUCTURE: OPTIMIZATION OF A PROCEDURE FOR DAMAGE DETECTION AND LOCALIZATION

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Abstract

Damage detection approach based on dynamic monitoring of structural properties over time has received a considerable attention in recent scientific literature. In earthquake engineering field, the recourse to experimental research is necessary to better understand the mechanical behaviour of various structural and non-structural components.

Aim of this paper is the optimisation of a methodology based on the evaluation of the mode curvature to detect and localize a possible damage occurred on a framed structure after an earthquake. The methodology is based on the use of accelerometric sensors, one station for each floor, to record accelerometric time-histories and directly evaluate the fundamental mode shape variations from filtered signals. In order to reduce costs and computation, this paper focuses on the possibility to reduce the number of stations installed on the monitored structures. In this study, the attention has been concentred to minimize the number of sensors, as a function of the number of floors, and to optimize their distribution along the monitored building. This paper resumes the main outcomes retrieved from many numerical nonlinear dynamic models of reinforced concrete framed structures.

Keywords: Structural Health Monitoring; Damage Detection; S-Transform; Band-Variable Filter

1. Introduction

Structural Health Monitoring and Damage Detection Techniques, especially for structures located in seismic prone areas, have assumed a meaning of great importance in last years, for the possibility to make a more objective and more rapid estimation of the damage occurred on buildings after a seismic event.

Damage Detection approach based on dynamic monitoring of structural properties over time has received a considerable attention in recent scientific literature. The basic idea arises from the notion that spectral properties, described in terms of the so-called modal parameters (eigenfrequencies, mode shapes, and modal damping), are functions of the physical properties of the structure (mass, energy dissipation mechanisms and stiffness). In the most general terms, damage can be defined as changes introduced into a system that adversely affect its current or future performance. Implicit in this definition is the concept that damage is not meaningful without a comparison between two different states of the system, one of which is assumed to represent the initial, and often undamaged, state. This theme issue is focused on the study of damage identification in structural and mechanical systems. Therefore, the definition of damage will be limited to changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the current or future performance of these systems.

In the last twenty years, significant efforts have been devoted to the field of Non-destructive Damage Evaluation (NDE) using the variation over time of the dynamic characteristics of structures such as eigenfrequencies, mode shapes and global dissipative characteristics (equivalent viscous damping factors). In the last years many researchers are working to set-up new methodologies for Non-destructive Damage Evaluation based on the variation of the dynamic behavior of structures under seismic loads ([1], [2], [3], [4], [5]). The NDE methods for damage detection and evaluation can be classified into four levels, according to the specific criteria provided by the Rytter [6]. Each level of identification is correlated with specific information related to monitored structure: increasing the level it is possible to obtain more information about the state of the health of the structures, it is possible to know if damage occurred on the structures, it is possible to quantify and localize the damage and to evaluate its impact on the monitored structure. Pandey et al. [7] discussed the possibility to use the mode shape curvature to detect and localized damage on structural elements. Sampaio et al. [8] extended the idea of Pandey et al. [7] by applying the curvature-based method to frequency response function instead of mode shape and demonstrated the potential of this approach by considering real data. The techniques for damage identification based on vibration and, in particular, those based on changes in modal parameters have been widely applied to the assessment of the health status of the existing structures, ([9], [10], [11]).

The limit of this approach lies in the fact that all these experimental methods require that the proximity to the damage is known regardless, and that the portion of the structure to be inspected is readily accessible. In order to overcome these limitations it is necessary to have methods with a global character, and which allow a first level of screening instead of more sophisticated methods. In order to increase the performance level of damage detection and localization on monitored structures, it is necessary to sup-port the theoretical criteria with numerical and experimental tests on both real and scaled structures, using in laboratory and in situ tests.

Over the last years, in order to localize and quantify the damage occurred on both single structural elements and structures, several authors proposed to use the modal curvature variation over time ([7], [8], [10], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]). Practically, comparing the geometric mode shape curvature exhibits by the elements, and/or by the structure, over time it is possible to detect the damage position.

In this paper it has been focused the attention on the detection and localization of structural damage on framed structures after a strong motion earthquake. In the first part of the work a procedure for damage evaluation, based on changes in modal curvature and on the use of accelerometric sensors, is presented. Than the result retrieved optimizing the methodology are showed. Particularly we have considered the possibility to minimize the number of sensors, as a function of the number of floors, and to optimize their distribution along the monitored building. The method has been applied to nonlinear numerical models of reinforced concrete framed structures.

2. Description of the methodology

In this section the methodology for structural damage detection is presented. The proposed procedure is based on the use of a band-variable filter able to extract the nonlinear response of each mode of vibration. The Band-Variable Filter [22] is used to extract the dynamic characteristics of systems that evolve over time by acting simultaneously in both time and frequency domain. The filter was built using the properties of convolution, linearity and invertibility of the S-Transform [23]. It gives the possibility to extract from a non-stationary and/or nonlinear signal just the energy content of interest preserving both amplitude and phase in the region of interest [22].

The filtering method, here discussed from the mathematical point of view, is based on the algorithm described in the following steps:

- Assessment of *S*-Transform $S(\tau, f)$ of the signal $h(t)$;
- Generating the filtering matrix $G(\tau, f)$, selecting the time-frequency subdomain directly from the *S*-Transform result;
- Calculating the convolution in the time-frequency domain $M(\tau, f) = G(\tau, f) \cdot S(\tau, f)$;
- Retrieving the filtered signal $h\,f(t)$ through the calculation of the inverse *S*-transform matrix $M(\tau, f)$.

So the complete process can be written as:

$$h_f(t) = \int_{-\infty}^{+\infty} \left(\int_{-\infty}^{+\infty} [S(\tau, f) \cdot G(\tau, f)] d\tau \right) \cdot e^{-i \cdot 2 \cdot \pi \cdot f \cdot t} df \qquad (1)$$

Using this kind of approach it is possible to extract from a nonlinear signal recorded on a damaging structure during an earthquake, the time-varying behaviour of each mode of vibration. In this way it is possible to evaluate both frequency and mode shape variation during an earthquake.

The proposed procedure has been applied on reinforced concrete framed structure to detect and localize the damage occurred after an earthquake. The algorithm involves the following steps:

- Evaluation of the acceleration time-histories at the top floor of the monitored structure (Fig. 1a);
- Definition of the filtering matrix following the time-frequency evolution of the fundamental mode of vibration of the monitored structure (Fig. 1b);
- Convolution of the defined filtering matrix with the Stockwell Transform of the signals recorded at each level and in the same direction (Fig. 1c);
- Evaluation of the mode shape and its curvature variation over time (Fig. 1d).

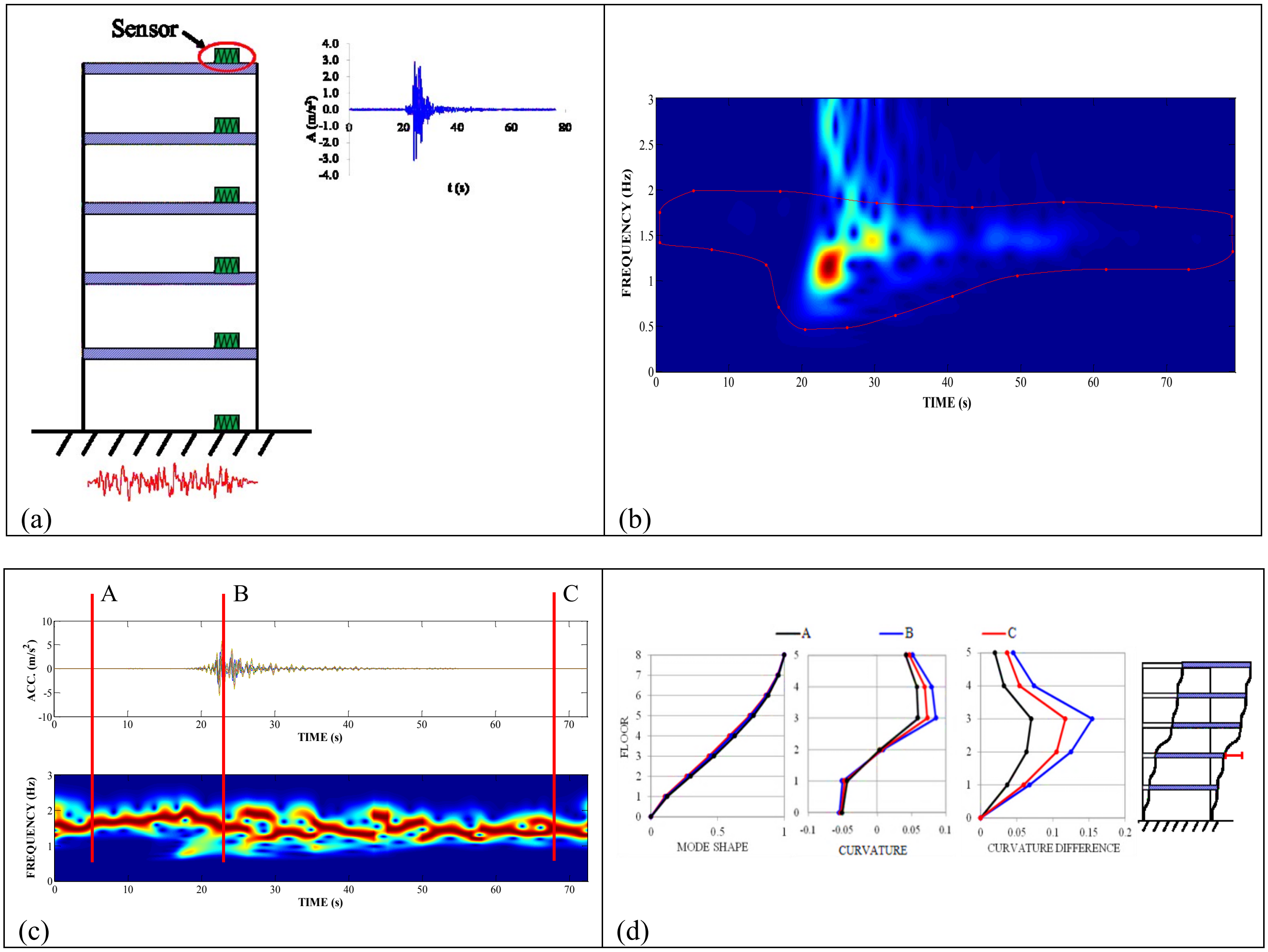


Fig. 1 – Algorithm for damage localization

It is worth noting that by applying the Band-Variable Filter it is possible to follow the frequency evolution over time and to focus the attention on three important time instants: (A) one instant before the earthquake, (B) the time-instant where the damaging structure exhibits the minimum fundamental frequency and (C) one instant after the earthquake. The first version of the methodology described in this section has been presented in Ditommaso et al. [24], where the mode curvature were evaluated and the difference were calculated just among different time instants. On the contrary, the new approach is based on the evaluation of the mode curvature and the difference is evaluated, at first, among different floors and, secondly, among different time instants. In order to full automatize the procedure for damage detection several studies are being carried out. Particularly it can be possible to automatize the filtering matrix selection by using the STIRF procedure [25].

3. Numerical applications

The procedure presented in this work has been applied to the responses of nonlinear numerical models of reinforced concrete framed structures characterized by 3, 5 and 8 floors with different geometric configurations and designed for gravity loads only (Fig. 2).

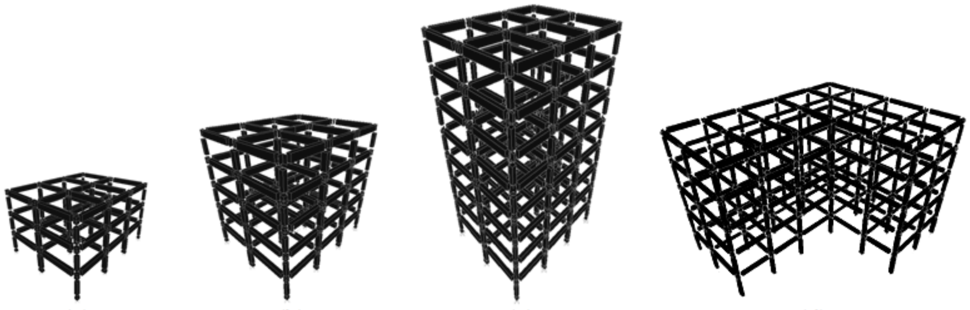

(a) (b) (c) (d)

Fig. 2 – Numerical models regular in plan with 3 floors (a), 5 floors (b), 8 floors (c) and numerical model irregular in plan with 5 floors (d)

A software based on nonlinear finite element (SAP2000 non-linear) has been used to model the 3-D structure. In order to simulate a structural nonlinear behaviour during a strong ground motion, link elements and plastic hinges have been added at the end of beam and column elements respectively. Link elements have a Pivot hysteretic behaviour, while plastic hinges have an axial load-dependent one. The numerical campaign was conducted using both natural and artificial accelerograms compatible with the Italian code for a soil type B and a soft soil type D [26].

Furthermore the numerical campaign has been extended considering the presence of infill panels within the structural R/C frames and their interaction with the columns, both the masonry strength and stiffness contribution by inserting two equivalent structural elements in the models [27]. The mechanical characteristics of these elements were evaluated considering the Mainstone model [28]. Using SAP2000 finite elements program, these elements were modelled by mean multi-linear plastic link.

4. Results

In this section have been presented the main results obtained by applying the procedure for damage detection to the numerical models. The mode shapes, the mode curvatures and the curvature differences among floors evaluated over time have been analysed. The following figure show the results for the five story building subjected to natural accelerograms compatible with the Italian Seismic Code [26] in the time-instant where the damaging structure exhibits the minimum fundamental frequency (B).

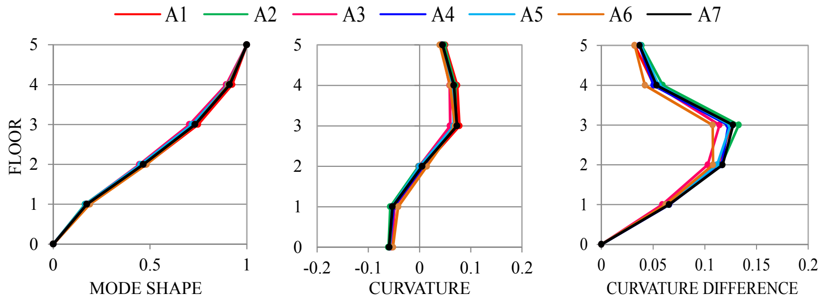


Fig. 3 – Mode shapes, mode curvatures, curvature differences among floors in the time instant (B) before the earthquake for the structure with 5 floors [29]

It can be possible to note a change of the trend of mode curvature among the third and the second floor and among the second and the first floor. Also the major curvature difference is among the third and the second floor. Furthermore it has been analysed the inter-story drift, an efficient damage indicator, that gives information about the damage and the characterization of the seismic behaviour of a building [30].

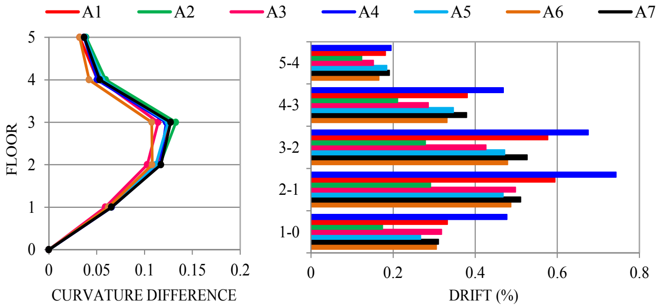
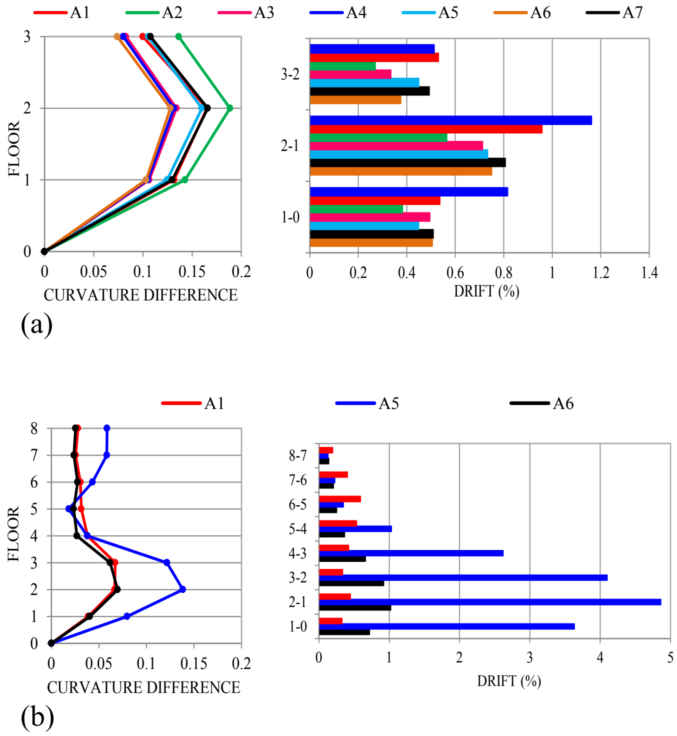
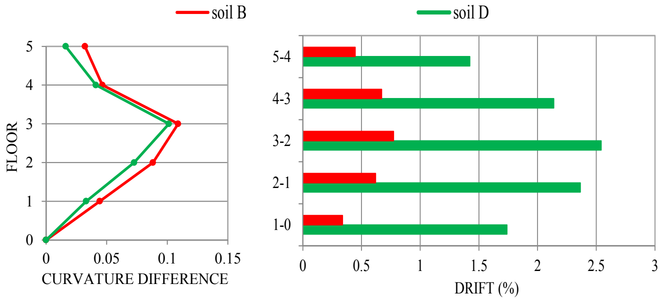


Fig. 4 – Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 5 floors [29]

Fig. 4 shows that drift is agreement with the curvature differences, indeed the maximum inter-story drifts are in correspondence to the second and the third floors. The proposed methodology for damage detection and localization has been applied also to the other numerical models with different number of floors and configurations.





(c)

Fig. 5 – Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 3 floors (a), 8 floors (b) regular in plan and for the structure with 5 floors irregular in plan (c)

In order to define the damage threshold of even the non-structural component, the campaign of numerical simulations has been extended by modelling the effects caused by the presence of infill panels within the frames structures. Fig. 6 shows the results of the five story structure with infill panels subjected to three natural accelerograms, relating to the type of soil B (A1 - A5 - A6), and to an artificial one relating to the type of soil D.

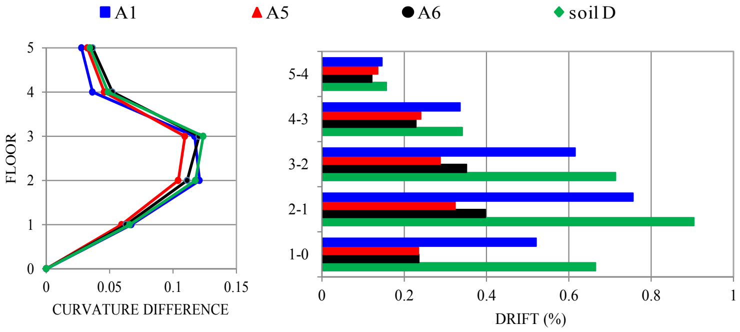


Fig. 6 – Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 5 floors with infill panels

Finally from the different results obtained it can be considered that the curvature variation is able to localize damage occurred on structures and identify the most damaged floor after strong motion earthquake.

In order to optimize the presented procedure the attention has been focused on the possibility to minimize the number of sensors installed on the monitored structure, as a function of the number of floors, and to optimize their distribution along the building. Therefore starting from the initial distribution of the accelerometers installed, one for each floor of the structure, we started to reduce the number of sensors until we reach the optimal number that allowed us to evaluate the best mode shape of the structure.

Fig. 7 shows the different positions of the sensors on the five story building. The last one resulted optimal for the analysis (Fig 7d). From the results obtained for the five story building, it has been found that the minimum number of sensors to be installed to better follow dynamic behaviour of the structure is equal to four.

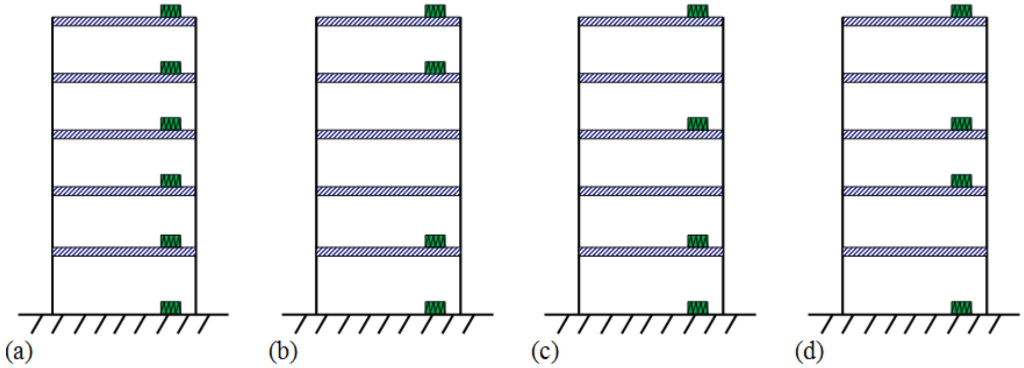


Fig. 7 – Different tested configurations for damage localization for the structure with 5 floors

The following figure shows the main results obtained optimizing the procedure for the five story building without and with the presence of infill panels. Particularly Fig. 8 shows the comparison between the curvature difference obtained starting from the accelerations recorded at each floor of the structure and the curvature difference obtained from the accelerations recorded at only 4 floors.

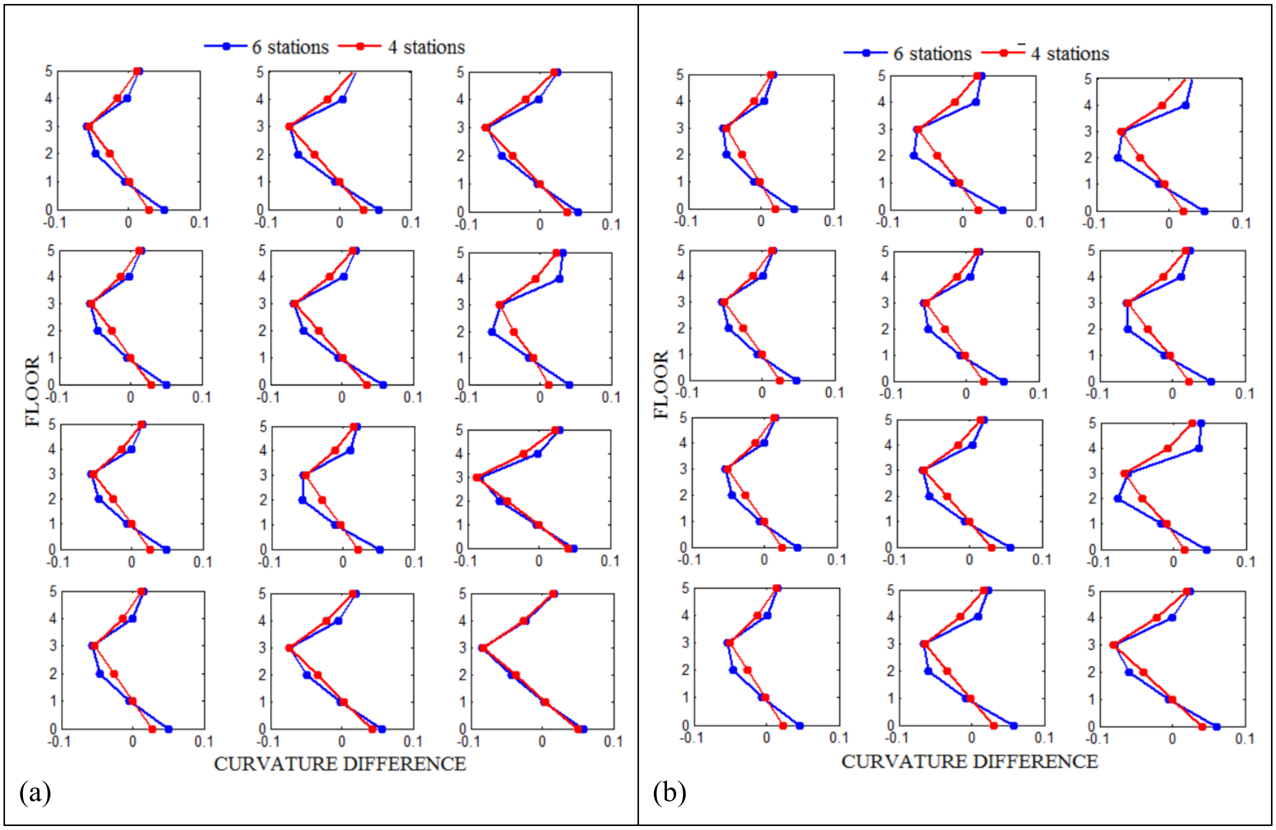


Fig. 8 – Curvature difference obtained starting from recordings with all the accelerometric stations and with only four accelerometric stations for the structure with 5 floors without infill panels (a) and with infill panels (b)

Fig. 8 shows that in most cases reducing the number of sensors from 6 to 4 for the five-story structure the results are in agreement with each other. Therefore from the first results it can be noted that also reducing the number of sensors installed on the monitored structure, the curvature variation still managed to locate the structural damage and identify the most damaged level. Similar results were obtained by reducing the number of sensors also for the other different numerical models.

5. Conclusions

In this work a procedure for damage detection on framed structure based on mode curvature variation is presented and it is showed the possibility to optimize the methodology reducing the number of sensors installed on the monitored building.

Starting from the properties of the S-Transform and of the band-variable filter, the ability to isolate individual modes of vibration of a building makes possible to explore their variation over time, evaluating the change in mode curvature. Most of vibration based procedure and methodologies for damage detection on existing structures are based on the evaluation of just stationary or “stationarized” structural modal parameters. The proposed procedure is based on the use of the Band-Variable Filter that allows to separate the variable contribution of each mode of vibration within both on linear and nonlinear fields. The capability to separate each single contribution allows to better understand how damage propagates on the structure and which are the main mode involved into the damage process, during the nonlinear behavior of each excited structure. Therefore, being able to evaluate the mode curvature during the maximum excursion in nonlinear field and isolating it from superimposed signals, allows for a better understanding of the mechanisms of damage as well as for a more precise location of both structural and non-structural damage.

Several authors showed that also the variations of the modal curvature are strictly related to the damage occurred on a structure. Moreover, using the mode curvature as a control parameter it is also possible to localize where the damage occurred on the structure. At the moment many of the methods to evaluate structural damage, found in the bibliography, require a large number of instrumental recordings, which are obtained by placing a number of sensors at each level of the structure to be monitored. Therefore, these procedures may be very expensive if you intend to run an extensive and continuous monitoring of a large number of structures.

The results obtained in this work show the possibility to localize the structural damage and identify the most damaged floor after strong motion earthquake through analysis of parameters such as the mode curvature and the curvature difference among floors.

One of the advantage derived from the use of the proposed method for damage detection and localization is related to the possibility to retrieve all necessary information directly from the acceleration time-histories (and not from the displacements), so it is possible to avoid problems of divergence in the operation of double integration. From the results obtained for the different structures can be noted that the mode curvature and the curvature difference among floors are able to locate, in a fast and intuitive level, the mainly damaged floor.

The next step will be the extension of the study to a larger set of structures, using numerical simulations, experimental models and experimental campaigns on real structures, in order to better improve the methodology and provide damage estimates more accurate. Finally the peculiarities of the method may be useful to monitor a large number of strategic structures, to evaluate real time the possible damage after a strong motion earthquake and to contribute to the determination of damage scenarios.

6. Acknowledgements

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7. Copyrights

8. References

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