Damage localization on Reinforced Concrete Structures

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SUMMARY:
It is known that the occurrence of structural damage, for any kind of structure, it is able to changes its dynamic characteristics over time. Generally, the main parameters conditioned by this problem are periods of vibration, damping factors and mode shapes. 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. In order to analyze the nonlinear behaviour of a general structure, and localize a possible damage, we propose a band-variable filter based on the Stockwell Transform. This paper shows through many examples as comparing mode shapes and the related curvature variations over time it is possible to easily identify the damage and also localize it on the structure.

Keywords: Damage Detection, S-Transform, Band-Variable Filter, Structural Health Monitoring, Nonlinear Dynamics

1. INTRODUCTION

Structural Health Monitoring (SHM) points to increase the knowledge about linear and non linear dynamic behavior of structures in order to develop accurate strategies of analysis for the safety assessment (Brownjohn et al., 2011). Particularly, structural monitoring, especially for structures located in seismic prone areas, has assumed a meaning of great importance, for the ability to provide useful information about the state of the health of strategic structures and infrastructures over time, and the possibility to perform an objective quick estimate of the damage occurred on structures just after a seismic event. SHM performed on both weak and strong motion also facilitates the understanding of structural behaviour during earthquakes and related damage mechanisms. It allows the possibility to study and develop both effective time-spending and protection strategies. The growing number of demand for a widespread of health monitoring for strategic structures in seismic areas has emphasized the need to realize in-depth scientific studies, in order to verify the feasibility of economic and fast methods to detect anomalous vibrations, to execute post earthquake warning and monitoring, damage assessment and first damage scenarios. Generally, an effective system for structural health monitoring requires an appropriate number of sensors, suitably located in the structures, and complex elaborations of big amounts of data. The experience of damage, even catastrophic, occurring throughout the world as a result of strong seismic events succeeding each other in years, has increasingly highlighted the need to adopt new technologies and new theoretical tools to understand and improve the behavior of civil construction and to assess quickly and as efficiently as possible, the mitigation strategies. Aim of the engineers is to develop new integrated detectors and techniques for SHM and Eartly-Warning (EW) systems.
In the last two decades several innovative techniques (Weaver et al., 1991; Donoho and Johnstone, 1994; Donoho, 1995; Douglas, 1997; Mallat, 1998; Safak, 1998a, 1998b and 1999; Galiana-Merino et al., 2003; Pinnegar and Eaton, 2003; Askari and Siahkoohi, 2007; Simon et al., 2007; Parolai, 2009)have been proposed to identify the dynamic characteristics of real structures (Ivanovic et al., 2001; Snieder and Safak, 2006; Todorovska et al., 2008a, 2008b, 2008c, 2009a, 2009b; Trifunac et al., 2008; Mucciarelli et al., 2011; Picozzi et al., 2011; Omrani et al., 2011a and 2011b; Bisht and Singh, 2012; Dinh et al., 2012; Ditommaso et al., 2012). Moreover, thanks to the time-frequency analysis

technique proposed by Stockwell et al. (1996), a new nonlinear filter has been proposed (Ditommaso et al., 2012) for both traditional SHM and to analyze the nonlinear behaviour of structures under seismic loads. Thanks to this tool we proposed a new methodology to detect and localize a possible damage occurred on a reinforced concrete structure after an earthquake.

2. SIMPLIFIED METHODS FOR MONITORING OF STRUCTURES

In the last years many researchers are working to set-up new methodologies for Non-destructive Damage Evaluation (NDE) based on the variation of the dynamic behaviour of structures under seismic loads (Ponzo et al., 2010; Dinh et al., 2012; Omrani et al., 2011a and 2011b; Bisht and Singh, 2012).

The NDE methods can be classified into four different levels (Stubbs et al., 2000) as a function related to the type of information provided by the different approach (Rytter, 1993):

- **First level methods:** only able to evaluate the presence of a possible damage to the structure;
- **Second level methods:** able to assess the presence of any damage on the structure providing also information about the related position;
- **Third level methods:** able to identify any possible damage occurred on the structure by providing information about both location and severity of the damage;
- **Fourth level methods:** able to detect the presence of damage on the structure, estimate severity and position as well as providing information related to the impact that impairment has on the structure.

Each method, according to the level where it takes place, requires accurate information and algorithms characterized by an increasing in complexity when increasing the level. Therefore, the development of refined methodologies requires, in general, high costs, it is computationally expensive and it needs experts people to interprete the complex results. Using a complex approach it is impossible to control a relevant number of structures and infrastructures. This kind of approach is necessary to perform scientific studies or to control a limited number of structures. Then, it is clear the importance to set-up fast and simplified methodologies for SHM and NDE. These methodologies must be based exclusively on few sensors installed within the structure and related to the main modes of vibration characteristics. Most of methods proposed in the past were based on the eigenfrequencies variations of the structure, but now it is clear that frequency variation could be related also to the external temperature variations (Xia et al., 2012).

Aim of a part of the research projects RELUIS-DPC 2005-2008 (research line 9) and RELUIS-DPC 2010-2013 (Task AT3.1), both funded by the National Department of Civil Protection (DPC), is to define fast and integrated mothodologies for SHM, NDE and EW systems. These methodologies must be based on just few sensors installed inside each building and must provide useful information about the health state of the monitored structure over time and synthetic information about a possible damage occurred after an earthquake. Ponzo et al. (2010) proposed a fast method for SHM and damage evaluation using just one three-directional accelerometer located on the top of the building. The procedure is based on 4 parameters (maximum top acceleration, two kinds of fundamental frequency variation and equivalent viscous damping variation) directly extracted by the recording and related to the maximum inter-story drift (used as damage indicator) by mean an empirical relationship. In this paper, using few sensor installed inside a structure (one three directional accelerometer for each floor) we defined a new methodology for damage detection and localization based on a band-variable filter able to extract the nonlinear response of each mode of vibration.

3. THE STOCKWELL TRANSFORM AND THE NONLINEAR FILTER

This paper discusses the possibility to use a Band-Variable Filter (Ditommaso et al., 2012) 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. As discussed in Ditommaso et al. (2012), the proposed band-variable filter can be written as:

$$h_f(t) = \int_{-\infty}^{+\infty} \left(\int_{-\infty}^{+\infty} [S(\tau, f) * G(\tau, f)] \, d\tau \right) \cdot e^{i \cdot 2 \cdot \pi \cdot f \cdot t} \, df \tag{3.1}$$

where $S(\tau, f)$ is the S-Transform of the signal *h(t)*, $G(\tau, f)$ is the filtering matrix and $h_f(t)$ is the filtered signal. A generic *k*-th column $G(\tau_k, f)$ identifies a filtering window at a given time step. In order to better clarify the filtering procedure a worked example will be provided in the next section. Defining the filtering matrix could be a time-demanding operation, since each filtering window should be defined over a varying frequency recursively with a fixed time lapse. Moreover, the band-pass portion of the filter must be enlarged or reduced for each time step according to the desired bandwidth and the rectangular shape of the matrix. In order to simplify this process, it is convenient to try to automate it. We propose an implementation that defines the filtering matrix using a graphical user interface (GUI) that visualizes the amplitude spectra of the S-transform of the signal allowing for a point-and-click selection of the desired portion of the time-frequency domain. The routine is designed so that the user can select a few points and the computer performs a cubic spline interpolation. In order to build the filtering matrix we used the *pimf* function of MATLAB©, which is a convenient approximation of a boxcar function. This spline-based curve is so named because of its Π shape. It is possible to obtain more details about this function from www.mathworks.com. It is possible to download the matlab routine related to the proposed Band Variable Filter from http://roccoditommaso.xoom.it.

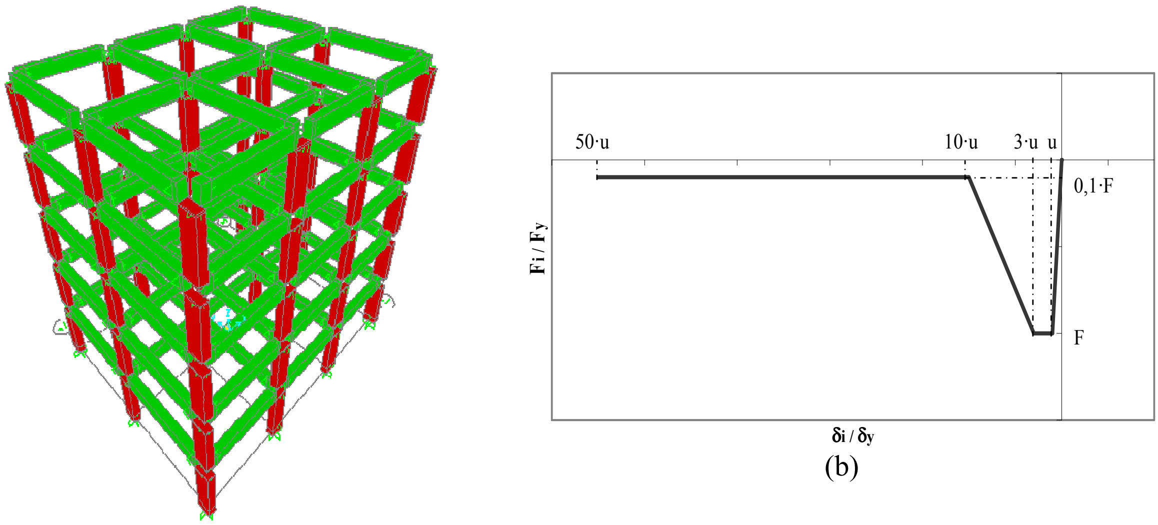
4. MODE SHAPES EVALUATION AND DAMAGE LOCATION

The band-variable filter discussed in the previous section 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 as discussed by Ditommaso et al. (2012). 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.

As mentioned before, the basic idea is to isolate, using the band-variable filter (Ditommaso et al., 2012), the fundamental mode shape over time and evaluate its changes in temrs of shape and related curvature. It is possible to demonstrate that mode curvature variation is strongly related with the damage occurred on a structure (Pandey et al., 1991). To apply the proposed procedure it is necessary to focus the attention on three most important instants for a structure subjected to an earthquake: (A) one instant before the earthquake, (B) the instant of maximum inter-storey drift and (C) one instant after the earthquake. Comparing the mode shapes characteristics evaluated in the instant A, B and C it is possible to unserstand if damage occurred after the earthquake and localize it on the structure. Instant A is the reference instant and it is necessary to compare the difference in terms of mode curvature between B-A and C-A.

In order to better explain the proposed procedure two examples have been considered. The former is related to a nonlinear numerical model of a reinforced concrete framed structure (plant 15x12m), regular in plan and in elevation, with five floors and composed by four frames along the longitudinal direction (X) and three frames along the transversal direction (Y) as shown in Figure 1a. The considered structure has been designed following the criteria of the Italian seismic code (OPCM 3431/2005) for high ductility class (CDA), high seismic intensity (PGA 0.35g) and for soft soil type D. The height of each storey is 3m, for a total height of the building equal to 15m. In order to take into account the presence of infill panels within the structural R/C frames and their interaction with the columns, both the masonry strength and stiffness contribution have been considered (Dolce et al., 2004) by inserting two equivalent structural elements in the models. The mechanical characteristics of these elements were evaluated considering the Mainstone model (Mainstone, 1974) through the eq. 4.1. This relationship is valid for rectangular shape panels only. In the simulation a 12+8cm thick panels were considered. The Force-Displacement behaviour for Mainstone model is depicted in Figure 1b.

$$b_w = 0.2 \cdot d_w \cdot \sin(2\vartheta) \cdot \left(\frac{E_w \cdot t_w \cdot h_w^3 \cdot \sin(2\vartheta)}{E_c \cdot I_p}\right)^{-0.1} \cong 0.1 \cdot d_w \tag{4.1}$$



(a) (b)

Figure 1. (a) Numerical model (b) Displacement-Force behaviour for infill panel elements

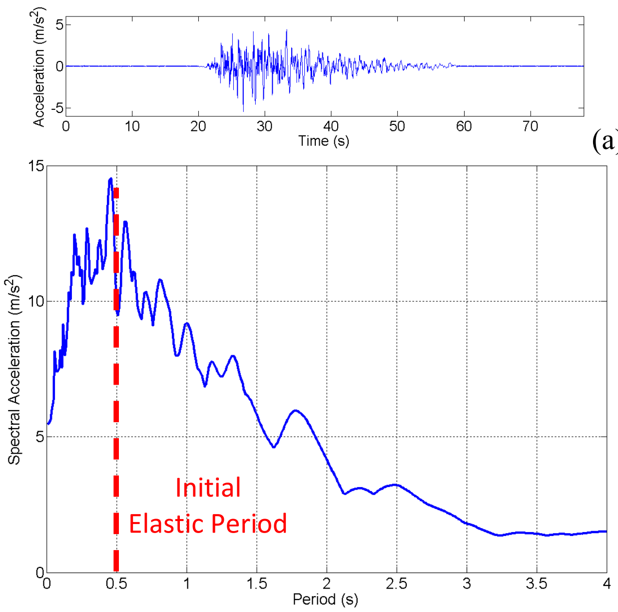


Figure 2. (a) Input used for numerical analyses (b) Acceleration response spectra

Using SAP2000 finite elements program, these elements were modelled by mean multi-linear plastic link. In order to consider the presence of doors and windows, the effective area of the infill panels considered in the analyses was reduced at 80% of the total area. Beams and columns have been modelled with frame elements, assuming 20MPa cylindrical strength of concrete and 430MPa yield strength of steel. In order to simulate a structural nonlinear behaviour during a strong ground motion, link elements and plastic hinges have been used at the end of beam and column elements respectively.

Link elements have a Takeda hysteretic behaviour, while plastic hinges have an axial load-dependent one. It is possible to find more details about this numerical model in Ponzo et al. (2010).
With reference to the nonlinear dynamic behaviour, mode shapes related to the fundamental mode of vibration were extracted using the signals filtered by mean the band variable filter following these steps:

- evaluation of structural response at the last floor where the fundamental mode is very clear;
- creation of the filtering matrix based on the S-Transform from the accelerometric recording;
- convolution of the filtering matrix with signal recorded at each level;
- evaluation of the mode shape over time.

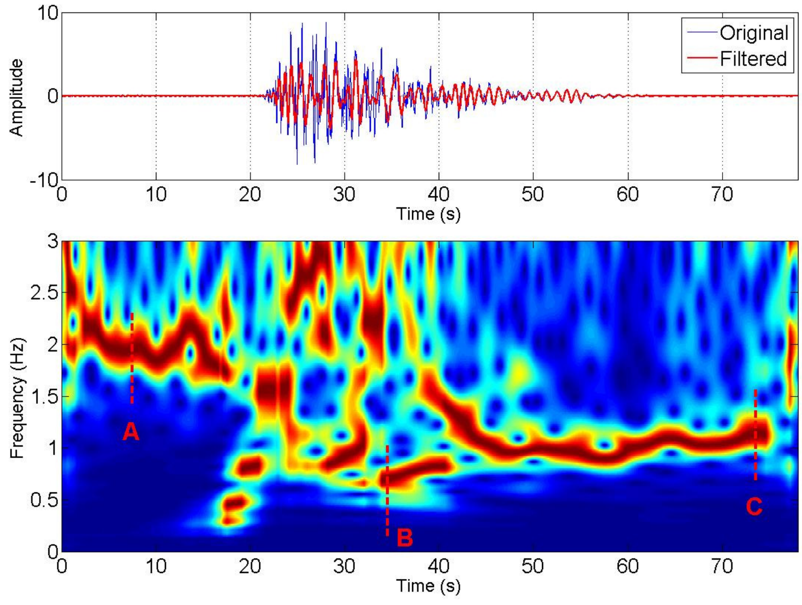


Figure 3. Normalized S-Transform and selection of the instants A, B and C

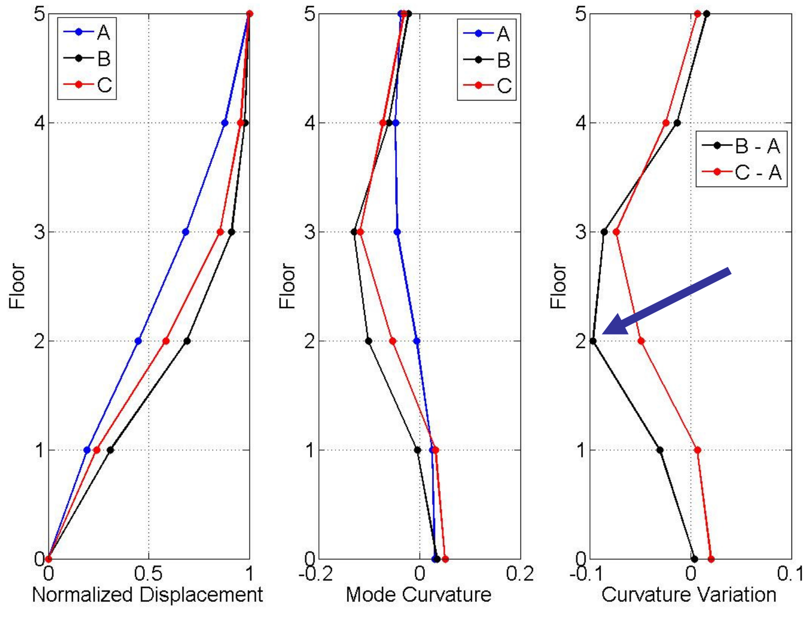
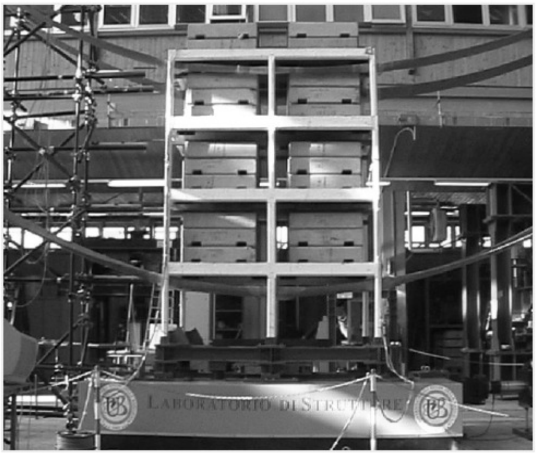


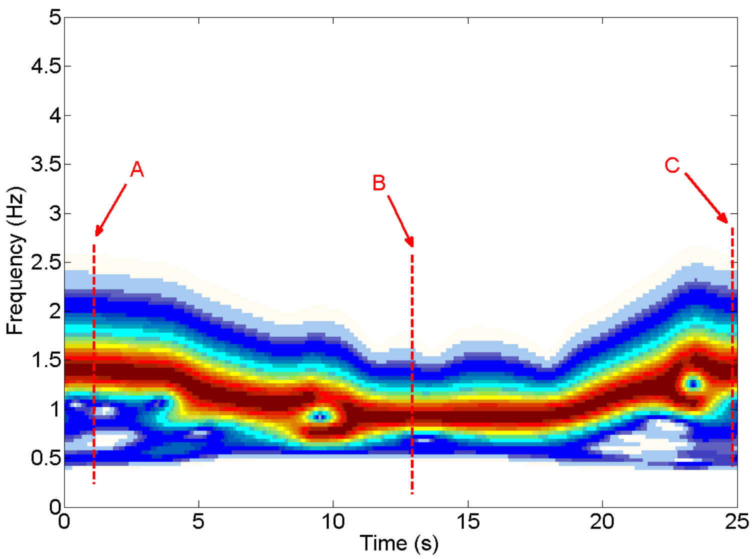
Figure 4. From The Left: Mode Shapes And Curvatures evaluated at time instances A, B and C, And Curvature Variations B-A And C-A

Figure 3 shows a comparison between the original signal (blue) recorded on the top of the building (along the fundamental mode direction) and the signal filtered using the procedure described above.

Also the normalized S-Transform of the signal is depicted. The behaviour of the structure is clearly non-stationary, with a change over time of the frequency related to the fundamental mode. The starting frequency is 2.0Hz, the minimum frequency is 0.65Hz and the final frequency is 1.15Hz. Figure 6a shows the frequency evolution of the fundamental mode of the structure extracted using the band variable filter and the time-point from which the mode shapes were evaluated: Mode Shapes A (related to the starting frequency), B (related to the minimum frequency) and C (related to the final frequency). It is worth noting that using the standard approach it would have been possible to evaluate only the starting and final mode shapes. On the contrary, using the band variable filter it is possible to evaluate also the mode shape related to the minimum frequency recorded during the maximum excursion in the plastic field (mode shape B). Figure 4 shows the mode shapes evaluated over time as indicates in Figure 3: Mode Shape B has a curvature bigger than Mode Shapes A and C. It is known that mode curvature is strongly linked to the building damage during a seismic event (Pandey et al., 1991). Therefore, being able to evaluate the mode curvature during the maximum excursion in nonlinear field and isolating it from superimposed signals, we can achieve a better understanding of the mechanisms of damage as well as a more precise location of the damage on the structure. In this example the maximum curvature variation (B-A) is located at the second floor where the maximum interstory drift occurred. On the contrary, using the curvature variation associated to the mode shapes A and C, related to the stationary behaviour before and after the earthquake, the maximum curvature variation is associated to the third level, but it is in contrast with the maximum measured intersory drift (Figure 4).



(a)



(b)

Figure 5. (a) POP model from Ponzo et al. (2010) (b) Normalized S-Transform and selection of the time instants A, B and C

The latter example is related to a ¼ reinforced concrete scaled model designed for vertical loads only and tested at the Structural Laboratory of the University of Basilicata in Potenza, within the POP, project (Dolce et al. 2005), through mono-axial shaking table test (Figure 5). The model was tested using two different conditions: fixed base (phase I) and with isolation system (phase II). With regards to the tests in the fixed-base configuration mentioned above, the effective peak acceleration of the table was progressively increased from 0.05 up to 0.35 g, using different spectral shapes. All floor displacements were measured through Temposonic digital transducers, fixed to an external steel reference frame. The floor accelerations were acquired through a system of horizontal servo accelerometers.

Following the same approach described for the numerical model also the fundamental mode shape related to the POP model has been evaluated. Figure 5b shows the S-Transform related to the accelerometric recording at the last level of the structure. The starting frequency is 1.4 Hz, the minimum frequency is 0.90 Hz and the final frequency is 1.35 Hz. Figure 5b shows also the time-point from which the mode shapes were evaluated: Mode Shape A, B and C (starting frequency, minimum frequency and final frequency). In order to highlight the frequency evolution of the POP model a normalized S-Transform has been used. Figure 6 shows the mode shapes evaluated over time. It is worth noting that also for the experimental model the Mode Shape B, evaluated during the maximum excursion in the nonlinear field, has curvature bigger than Mode Shapes A and C. Also in this case the curvatures obtained from the mode shapes opportunely cleaned from the noise and the effects of higher modes thorough the S-Transform give the best information on the damage intensity and location. Moreover, the evaluation carried out on curvatures confirmed the location of the damage observed directly on the experimental model.

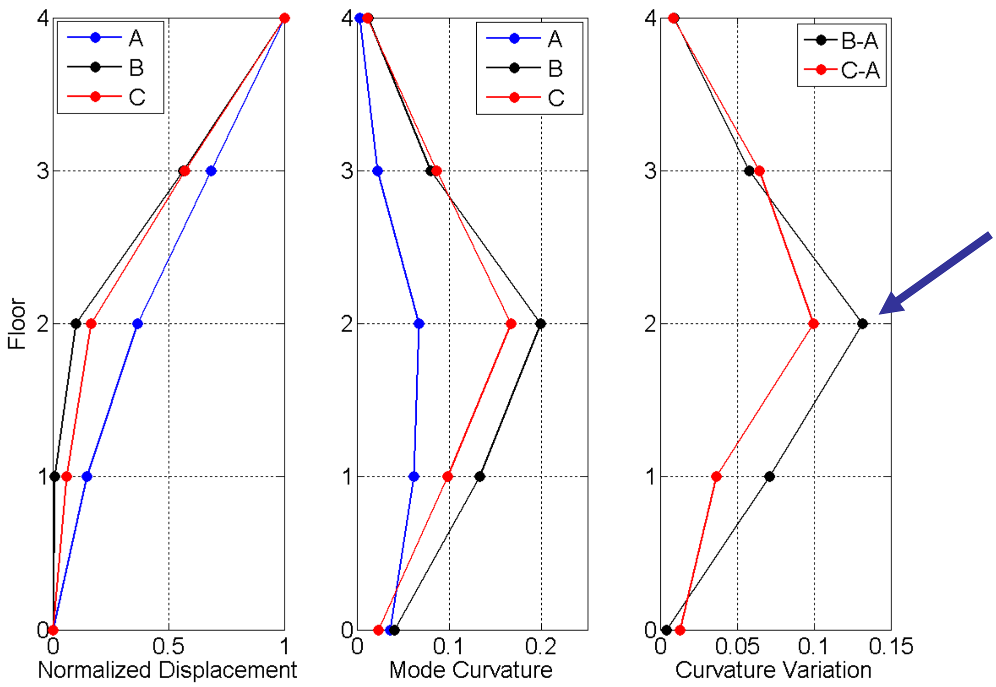


Figure 6. From The Left: Mode Shapes And Curvatures evaluated at time instances A, B and C, And Curvature Variations B-A And C-A

In order to compare the performance related to the proposed technique with those related to the classical approach (using a classical band-pass filter to isolate the dynamic characteristics related to the fundamental mode) the modes curvature variations were calculate for both numerical and experimental models (not shown here for sake of brevity). The results obtained using the classical approach are coherent with those related to the time-instants A and C, but are very different from those related to minimum frequency (B) reached during the nonlinear phase of the motion. This kind of result was expected because the classical approach is very useful to analyze the stationary motion of a system, but fails when it is used to analyze the nonstationary behaviour of the same system. Starting from the results obtained for both numerical and experimental models, the possibility to

evaluate the fundamental mode shapes during the maximum excursion in the plastic field (minimum frequency reached over time) is a crucial aspect for a correct detection and localization of the damaged occurred on the structure during the strong motion phase. In fact, the results obtained from the experimental model shown that also using the modal curvature variation (C-A) it is possible to localize the damaged floor, but the amplitude of this kind of variation is very different from those obtained using the modal curvature variation evaluated using the approach proposed in this paper (B-A) that is the real variation reached during the nonlinear motion.
Using the band-variable filter, taking into account the possibility to evaluate the maximum mode shapes variation over time, further study are necessary to find an empirical relationship to link the damage level with the maximum modal curvature variation reached during the nonlinear motion of the structure forced by a strong earthquake.

5. DISCUSSION AND CONCLUSIONS

Techniques based on Fourier transform provide good results when the response of the system is stationary, but fail when the system exhibits a non-stationary, time-varying behaviour. To hamper classical techniques, it is not necessary that a building reaches damage: even the non-stationarity of the input and the possible interaction with the ground and/or adjacent structures can show the inadequacy of classic techniques (Ditommaso et al., 2010). In 1996, Stockwell introduced a new powerful tool for the signals analysis: the S-Transform (Stockwell et al., 1996). Compared with the classical techniques for time-frequency analyses, this transformation shows a much better resolution and also offers a range of fundamental properties such as linearity and invertibility (Ditommaso et al., 2012). By exploiting these properties, it was possible to develop a filter whose band varies both in time and in frequency domains, being very useful to study the characteristics of non-stationary signals (Ditommaso et al., 2012). As discussed in the previous sections, this tool becomes necessary when one wants to isolate the response of individual time-varying modes of vibration of soil and buildings (e.g., when their dynamic characteristics evolve over time as a result of seismic events). The ability to investigate the non-stationary response of structures opens new scenarios, giving the opportunity to explore new possibilities. For example, the ability to isolate individual modes of vibration of a building make possible to explore their variation over time, evaluating the change in mode curvature. It is known that this parameter is strongly linked to the building damage during a seismic event (Pandey et al., 1991). 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.
In this paper the results of the porposed procedure for damage detection and localization have been proposed. The methodologie appears able to localize the damage occurred on a reinforced concrete framed structure after a strong earthquake. Particularly, the methodologie has been tested on both a numerical model and a ¼ reinforced concrete scaled model damaged using several shaking table tests. It is worth noting that the procedure is completely based only on accelerometric data. Then, it is not necessary to integrate the data to evaluate velocities or dislacements. In this way the damage localization is very fast and the results could be sent directly to monitoring central station.
Using the band-variable filter, taking into account the possibility to evaluate the maximum mode shapes variation over time, further study are necessary to find an empirical relationship to link the damage level with the maximum modal curvature variation reached during the nonlinear motion of the structure forced by a strong earthquake.

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