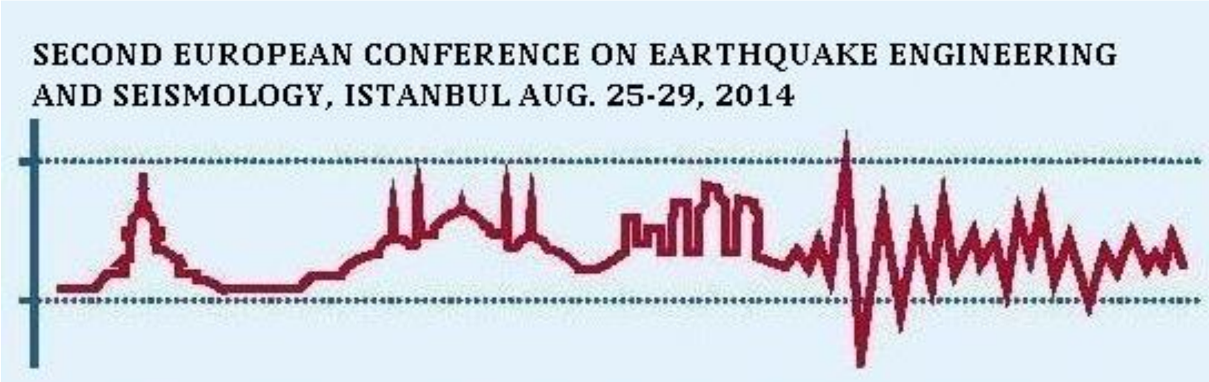


TESTING A NEW PROCEDURE FOR DAMAGE DETECTION ON FRAMED STRUCTURES SUBJECTED TO STRONG MOTION EARTHQUAKES

Rocco DITOMMASO[1], Felice Carlo PONZO[2], Gianluca AULETTA[3] and Chiara IACOVINO[4]

ABSTRACT

Structural Health Monitoring and Damage Detection are areas of current interest in civil, mechanical and aerospace engineering. For many years, experimental modal testing has become a significant topic in the field of structural assessment, not only with regards to typical structures of mechanical engineering, but also of civil engineering.

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). Structural damage exhibits its main effects in terms of stiffness and damping variation. As a consequence, using a permanent dynamic monitoring system becames possible to detect and, if suitably diffused on the structure, to localize structural and non-structural damage occurred on the structure during a strong earthquake.

In this paper a new methodology to detect and localize a possible damage occurred on a framed structure after an earthquake is presented.

INTRODUCTION

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.

The process of implementing a damage identification strategy for aerospace, civil and mechanical engineering infrastructure is referred to as structural health monitoring (SHM). This process involves the observation of a structure or mechanical system over time using periodically spaced measurements, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of system health. For long-term

[1] Postdoctoral Fellow, University of Basilicata, Potenza, Italy, r.ditommaso@unibas.it
[2] Associate Professor, University of Basilicata, Potenza, Italy, felice.ponzo@unibas.it
[3] Postdoctoral Fellow, University of Basilicata, Potenza, Italy, gianluca.auletta@tiscali.it
[4] Master Degree, University of Basilicata, Potenza, Italy, iacovinochiara@libero.it

SHM, the output of this process is periodically updated information regarding the ability of the structure to continue to perform its intended function in light of the inevitable aging and damage accumulation resulting from the operational environments. Under an extreme event, such as an earthquake or unanticipated blast loading, SHM is used for rapid condition screening. This screening is intended to provide, in near real-time, reliable information about system performance during such extreme events and the subsequent integrity of the system. Structural health monitoring aims to determine and track the structural integrity and to assess the nature of damage. The earliest and wide spread methods are those that are based on the use of vibrational data from permanent or temporary arrays of sensors. The ability to monitor remotely the health of an instrumented structure, detect damage as it occurs, and issue an early warning after an extreme event (earthquake, explosion or some other natural or man made disaster), before physical inspection is possible, has immense potential benefits in reducing loss of life and injuries, in emergency response, and in recovery following the disaster.

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 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 on 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.

Pandey et al. (1991) highlighted on the possibility to use the structural mode shapes to extract useful information for structural damage localization.

In this paper a new procedure for damage detection on framed structures based on changes in mode curvature is proposed. The proposed approach is based on the use of Stockwell Transform, a special kind of integral transformation that became a powerful tool for nonlinear signal analysis and then to analyze the nonlinear behaviour of a general structure (Stockwell et al., 1996). Compared with the classical techniques for the time-frequency analysis, this transformation shows a much better resolution and also offers a range of fundamental properties such as linearity and invertibility (Ditommaso et al., 2012). Aim of this paper is to show, through practical examples on reinforced concrete framed structures, how it is possible to identify and to localize damage on a structure comparing mode shapes and the related curvature variations over time. It is possible to demonstrate that mode curvature variation is strongly related with the damage occurred on a structure (Pandey et al., 1991).

METHODOLOGY

In this paper, using few sensor installed inside a structure (one three directional accelerometer for each floor) it is defined a new methodology that is able to assess the presence of any damage on the structure providing also information about the related position and severity of the damage and it is based on a band-variable filter able to extract the nonlinear response of each mode of vibration.

The Band-Variable Filter, Ditommaso et al. (2012), 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. It gives the possibility to extract from a nonstationary 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 behavior of each mode of vibration. In this way, it is possible to evaluate both frequency and mode shape variation during an earthquake.

In this section, we will discuss about the opportunity to use the band variable filter to evaluate the mode shapes during the non-stationary phase. As mentioned before, the basic idea is to isolate, by mean the band-variable filter, the fundamental mode shape over time and evaluate its changes in terms of shape and related curvature. Here we show how, using the proposed band variable filter, it is possible to extract the mode shapes of a system also during the phase of maximum nonlinearity.

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 structural response acceleration at the last floor;
- Defining the filtering matrix on the vibration mode considered (calibrated signal recorded on the last floor);
- Convolution of the filtering matrix with the Stockwell transform of the signals recorded at each level and in the same direction;
- Evaluation of the mode shape over time and its curvature.

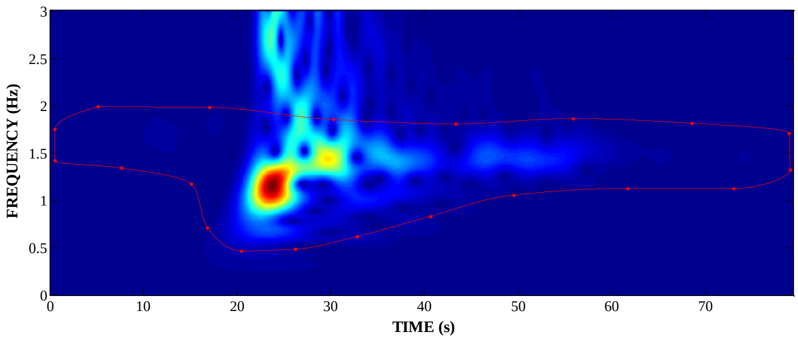


Figure 1. Selection of the fundamental mode of vibration

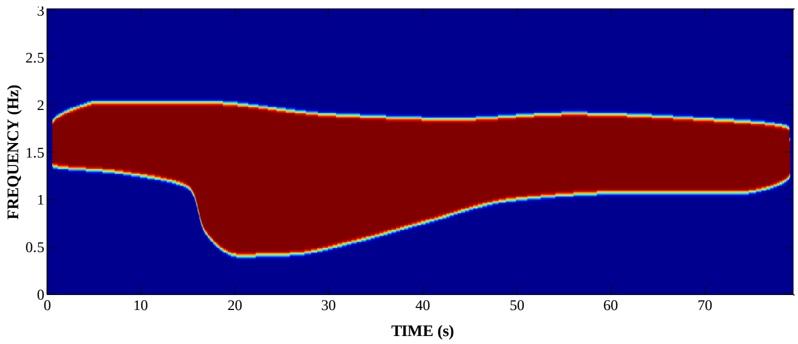


Figure 2. Filtering matrix

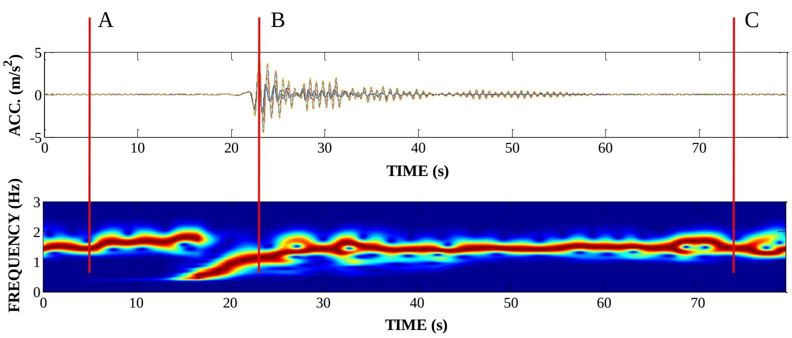


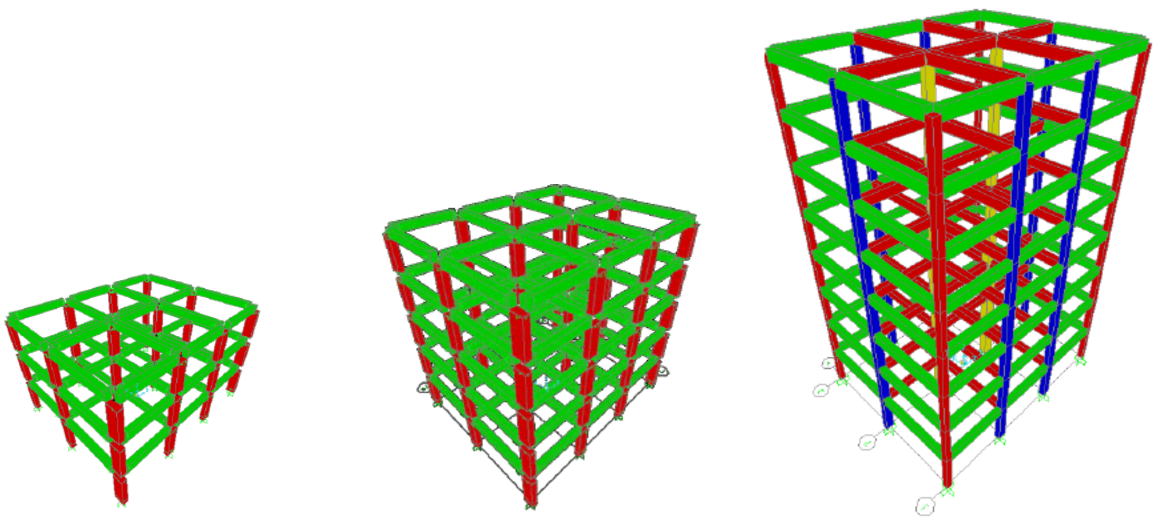
Figure 3. Normalized S-Transform and selection of the instants A, B and C

Fig. 3 shows the frequency evolution of the fundamental mode extracted by means of the band variable filter and the time-point from which the mode shapes were evaluated. 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 time-instant where the damaging structure exhibits the minimum fundamental frequency and (C) one instant after the earthquake. Comparing the mode shape characteristics evaluated in the instant A, B and C it is possible to understand is 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.

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. 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.

APPLICATIONS

This paper resumes the main outcomes retrieved from many numerical non linear dynamic models of reinforced concrete framed structures characterized by 3, 5 and 8 floors with different geometric configurations and designed for gravity loads only. 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 (NTC2008).



(a) (b) (c)

Figure 4. Numerical models regular in plan: (a) 3 floors, (b) 5 floors, (c) 8 floors

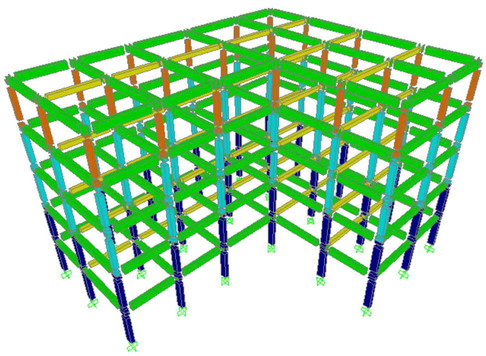
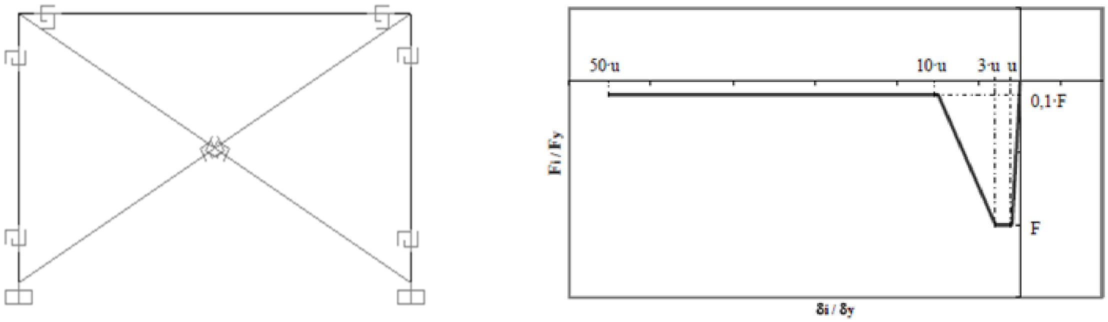


Figure 5. Numerical model with 5 floors irregular in plan

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 by inserting two equivalent structural elements in the models. The mechanical characteristics of these elements were evaluated considering the Mainstone model (Mainstone, 1974). This relationship is valid for rectangular shape panels only. In the simulation a 12+8cm thick panel was considered. Using SAP2000 finite elements program, these elements were modelled by mean multi-linear plastic link. The Force-Displacement behaviour for Mainstone model is depicted in Fig. 6b.



(a) (b)

Figure 6. Model of infill panel elements and respective displacement-force behaviour

RESULTS

İn this section the main outcomes retrieved from structure with 5 floors regular in plan subjected to natural accelerograms compatible with the Italian code (NTC2008) are presented.

The following figures show the mode shapes, the respective curvatures and the curvature differences among floors evaluated over time in the instant before the earthquake (A), in the time-instant where the damaging structure exhibits the minimum fundamental frequency (B), and in the instant after the earthquake (C).

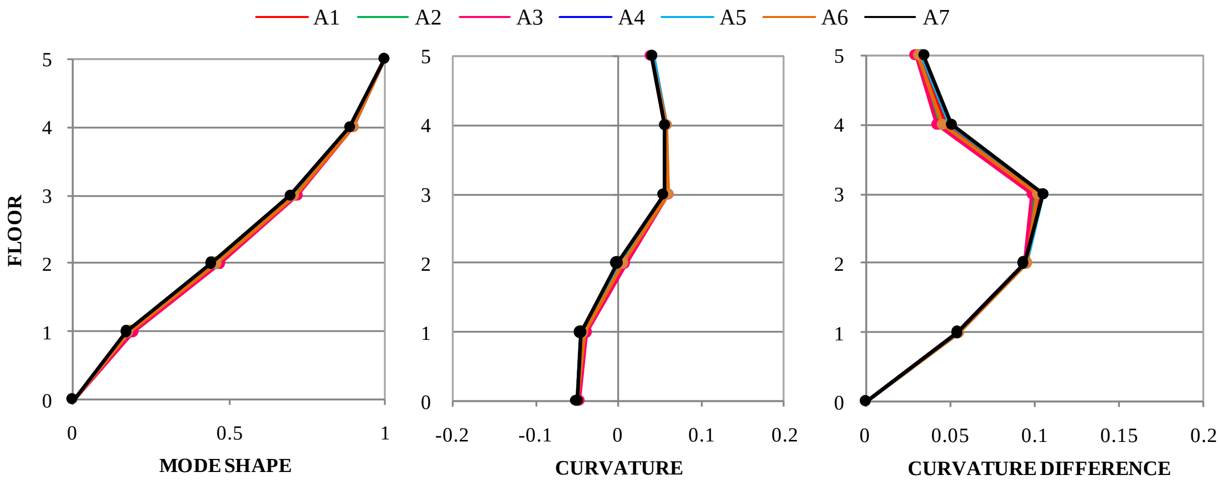


Figure 7. Mode shapes, mode curvatures, curvature differences among floors in the time instant (A) before the earthquake for the structure with 5 floors

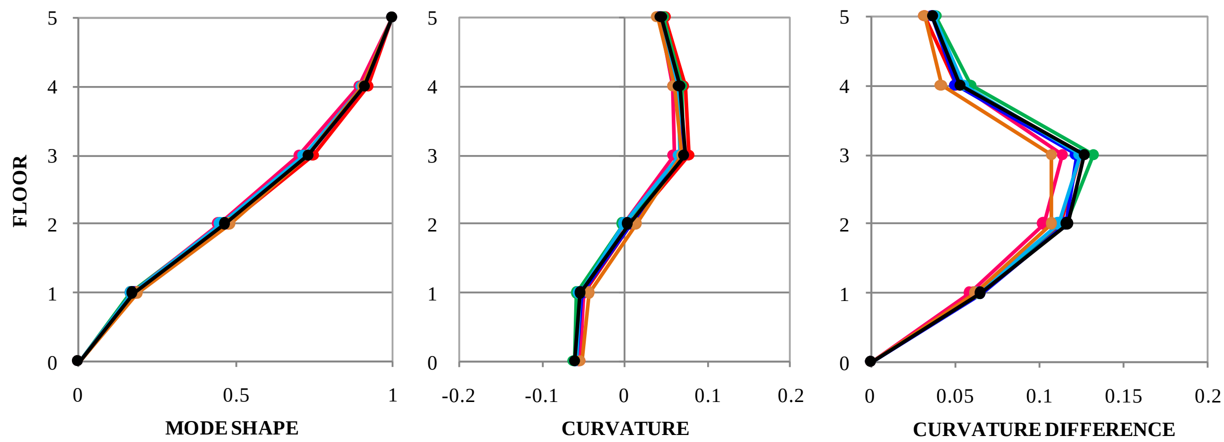


Figure 8. Mode shapes, mode curvatures, curvature differences among floors in the time instant (B) of minimum fundamental frequency for the structure with 5 floors

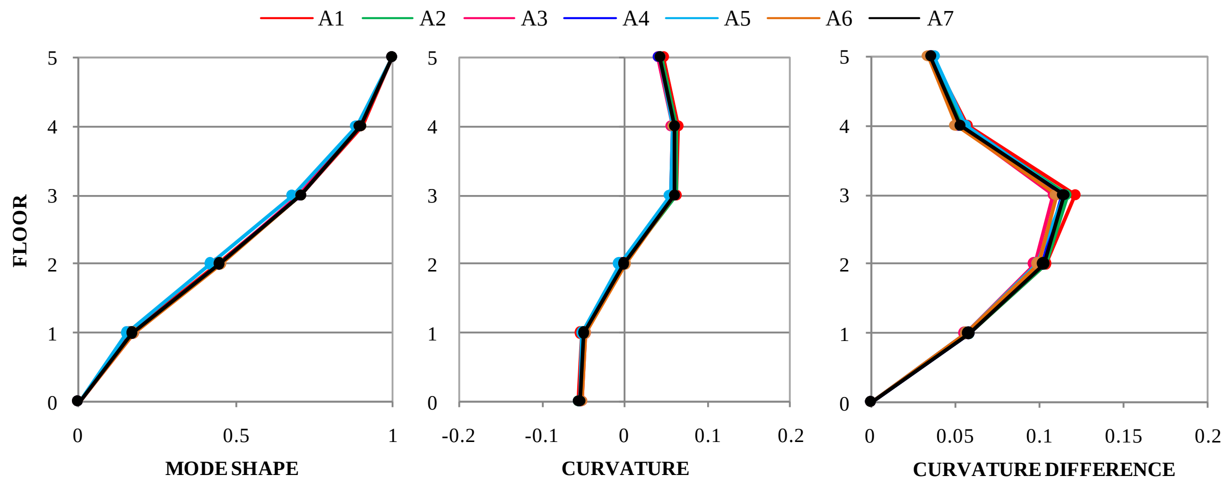


Figure 9. Mode shapes, mode curvatures, curvature differences among floors in the time instant (C) after the earthquake for the structure with 5 floors

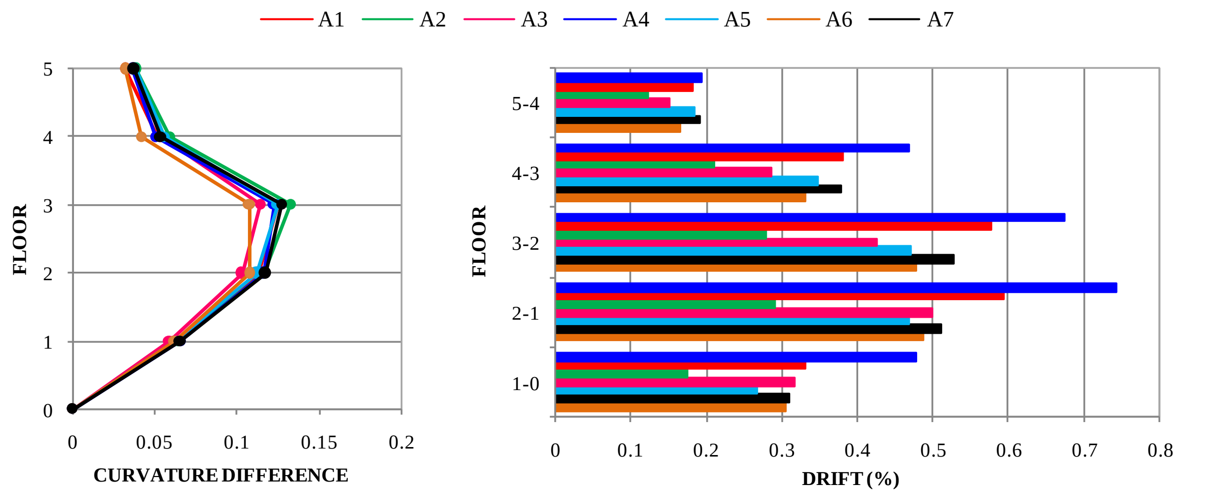


Figure 10. Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 5 floors

Analyzing figures 7-8-9, we can 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. Fig. 10 shows that drift, an efficient damage indicator, is agree with the curvature difference indeed the maximum inter-story drifts are in correspondence to the second and the third floors. These parameters allow to achieve a better understanding of the mechanisms of damage as well as a more precise location of the mainly damaged floor.

Another important parameter is the difference in terms of mode curvature between the time-instant where the damaging structure exhibits the minimum fundamental frequency (B) and the instant before the earthquake (A). A correlation between maximum inter-story drift and maximum curvature difference has been defined. This Fig. 11 shows the outcomes for the structure regular in plan with 5 floors subjected to natural accelerograms (A1, A5, A6) refered to a soil type B and an artificial accelerogram refered to a soft soil type D to grow seismic intensity.

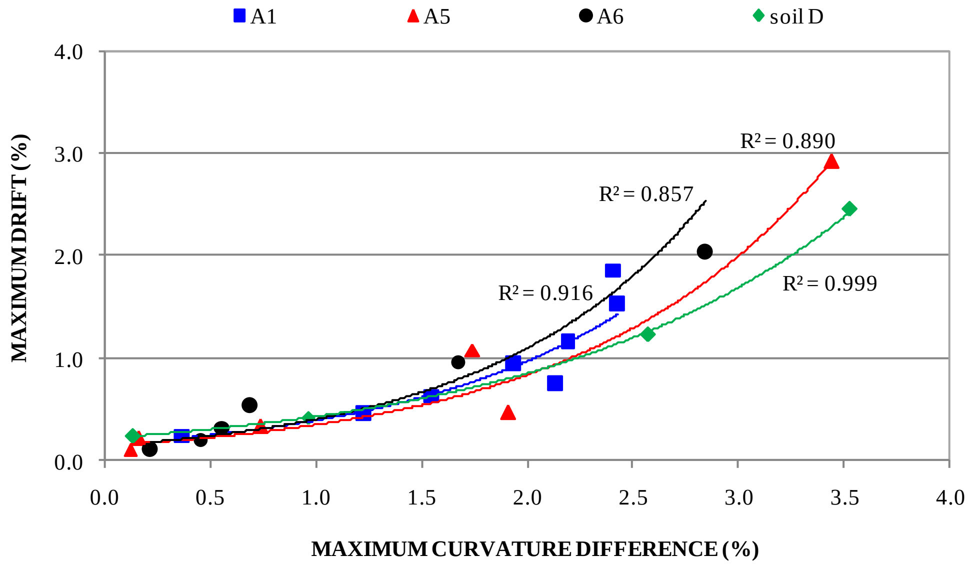


Figure 11. Correlation among maximum inter-story drift and maximum curvature difference

As shown in Fig. 11, the difference in mode curvature is strongly related to the maximum inter-story drift, a useful indicator for structural and non-structural damage occurred on a structure. It is interesting to observe a quasi-linear behaviour between 0 and 0.5% of maximum inter-story drift, a range where the structure exhibits a linear behaviour, after this limit it is possible to note a slight nonlinear behaviour that increases with the importance of nonlinear effects occurred on the damaging structure. It is very important to highlight the limited dispersion of the data. This trend can be seen in all structures analyzed.

From the preliminary analyses performed by using nonlinear numerical models it seems possible to obtain useful information for structural damage detection and localization just using the data provided from the fundamental mode of vibration of the monitored structure.

CONCLUSIONS

As demonstrated by several works in the field of structural health monitoring, the dynamic characteristics of a structure, such as frequencies, damping and mode shapes can be defined as the "fingerprint" that any structural system has. The change of these characteristics may be correlated to the presence of damage in the structure, so that many identification techniques are based on the measurement of the variation of such characteristics and allow to evaluate the presence of damage and to provide also information about the related position.

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. 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 if you intend to run an extensive and continuous monitoring of a large number of structures.

In this paper the results of the methodology show the possibility to localize the damage occurred on framed structures subjected to strong motion earthquakes through analysis of parameters such as the mode curvature and the curvature difference among floors.

It is emphasized that the proposed method is based on the evaluation of mode shape calculated from the accelerations and not from the displacements, so it is possible to avoid problems of divergence in the operation of double integration.

This is very important to understand the mechanisms of damage during an earthquake and to implement strategies of damage localization based on the change in the modal curvature, as presented in this work.

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 correlation between maximum inter-story drift and maximum curvature difference between the time-instant where the damaging structure exhibits the minimum fundamental frequency and the instant before the earthquake has been defined. This last step is crucial because it allows the method to evolve towards a third level, according to the classification of Rytter (1993) of the identification of the damage and to provide more precise and accurate information about both location and severity of the structural damage.

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.

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