LOCALIZATION OF DAMAGE OCCURRED ON FRAMED STRUCTURES: ANALYSIS OF THE GEOMETRIC CHARACTERISTICS OF THE FUNDAMENTAL MODE SHAPE

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SUMMARY: Damage detection techniques based on data acquired using permanent and/or temporary monitoring systems directly installed on structures, and/or infrastructures, have received a significant attention in the recent scientific literature. The recourse to experimental methods it is necessary also with the aim to characterize the seismic linear and nonlinear behaviour of real structures excited by earthquakes. Structural Health Monitoring (SHM) systems provide also the possibility to better understand the effects of the dynamic soil-structure interaction, together with the role played by the non-structural components on both linear and nonlinear behaviour of the monitored structure. A new methodology for damage detection and localization on framed structures, based on the maximum modal curvature variation related to the fundamental mode of the monitored structure, is proposed in this paper. Particularly, the main outcomes retrieved from several numerical nonlinear dynamic models, and from several shaking table tests, performed at the University of Basilicata using a scaled framed model, have been discussed.

KEYWORDS: damage detection; s-transform; band-variable filter; nonlinear dynamics; signal processing

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.

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 (Dinh et al. 2012; Omrani et al. 2011a,b; Bisht and Singh, 2012; Ponzo et al. 2010). The NDE methods for damage detection and evaluation can be classified into four levels, according to the specific criteria provided by the Rytter (1993). 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. (1991) discussed the possibility to use the mode shape curvature to detect and localized damage on structural elements. Sampaio et al. (1999) extended the idea of Pandey et al. (1991) 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, Doebling et al. (1996); Poudel et al. (2007); Limongelli (2014). Roy and Ray-Chaudhuri (2013) provide a mathematical basis to show the correlation between a structural damage and a change in the fundamental mode shape and its derivatives. Today, despite the progress made in the field of structural diagnostics, most of the approaches used in the evaluation and localization of damages are based on visual inspections.

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.

In 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 (Pandey et al. 1991; Sampaio et al. 1999; Poudel et al. 2007; Lee et al. 2008; Cao et al. 2009; Radzienski et al. 2011; Dilena et al. 2011; Zhu et al. 2011; Bai et al. 2012; Ditommaso et al. 2012; Roy and Ray-Chaudhuri 2013; Xiang et al. 2013; Cao et al. 2014; Limongelli 2014). 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 a new procedure for damage detection on framed structures based on changes in modal curvature is discussed. 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 behavior of a general structure (Stockwell et al. 1996).

Aim of this paper is to show, through practical examples on 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, before, during and after an earthquake. Furthermore, the main scientific results retrieved from an experimental campaign of shaking table tests performed on a 1:15 scaled structure and conducted at the University of Basilicata (SISLAB) are described.

2. **Methodology**

In this paper, a new simplified methodology able to assess and quantify a possible damage on a monitored structure, it has been defined. 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 proposed by 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 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).

The S-Transform (Stockwell et al. 1996) is a time-frequency localization spectral method similar to the short time Fourier transform (Gabor 1946) characterized by a Gaussian moving window whose width scales inversely, and whose height scales linearly, with the frequency.
The S-Transform of a function *h(t)* is defined as:

$$S(\tau,f)=\frac{|f|}{\sqrt{2\pi}}\int_{-\infty}^{+\infty}h(t)\cdot e^{-\frac{(\tau-f)^2\cdot f^2}{2}}\cdot e^{-i\cdot 2\cdot\pi\cdot f\cdot t}\,dt \qquad (1)$$

Where *t* = time; *f* = frequency, and τ = a parameter that controls the position of the Gaussian window along the *t* axis. The seismic structural behaviour is analysed using a band-variable filter (Ditommaso et al. 2012) based on the S-Transform.
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(τ, f)* of the signal *h(t)*;
- Generating the filtering matrix *G(τ, f)*, selecting the time-frequency subdomain directly from the *S*-Transform result;
- Calculating the convolution in the time-frequency domain *M(τ, f) = G(τ, f)·S(τ, f)*;
- Retrieving the filtered signal *h f (t)* through the calculation of the inverse *S*-transform matrix *M(τ, f)*.

So the complete process can be written as:

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

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.
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 excursion in the plastic field.

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).

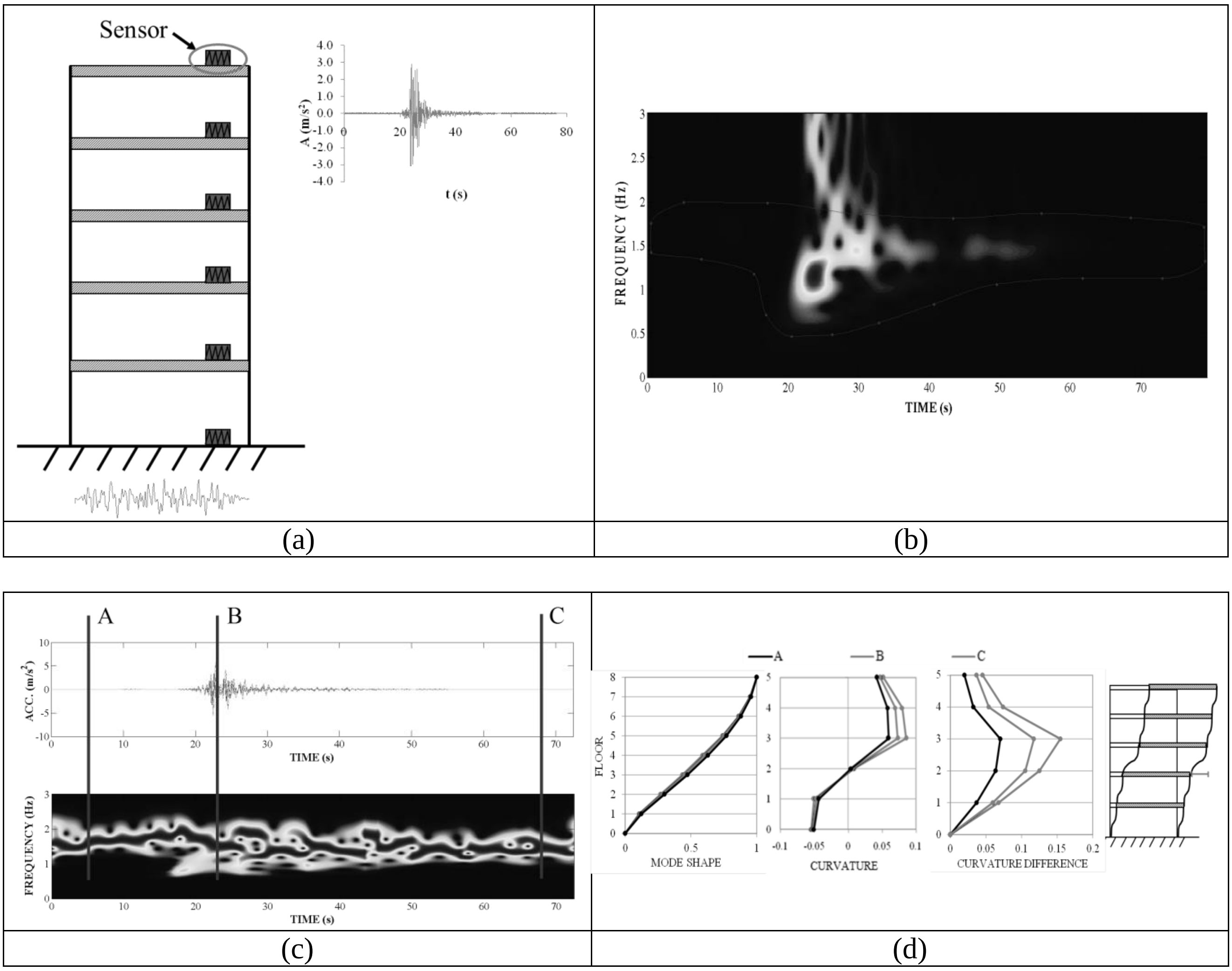


Figure 1. *Algorithm for damage localization*

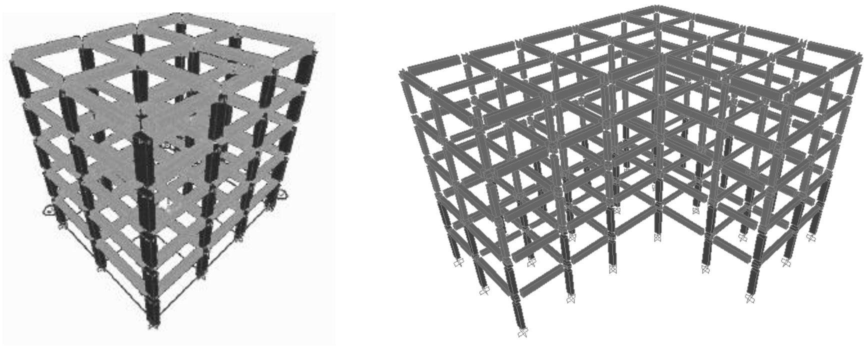
As described in Cao et al. 2014, it is possible to consider a framed structure as a beam and using the following relationship it is possible to correlate the curvature with the bending moment:

$$W''(v) = -\frac{M}{EI(v)} = \frac{W(v-h)-2W(h)+W(v+h)}{h^2} \quad (3)$$

Where M is the bending moment, $EI(v)$ is the bending stiffness, $W(v)$ is the displacement and $W''(v)$ is the related curvature. Considering the fundamental mode shape of a framed structure as a beam displacement, following Cao et al. (2014), it is possible to localize the damage analysing the singularity on the curvature of the fundamental mode shape. In this paper, following the evolution over time of the singularity on the curvature related to the fundamental mode shape the damage is detected and quantified.

3. **Numerical simulations**

In order to verify the proposed procedure, an extensive campaign of numerical simulations, considering the results obtained using different types of reinforced concrete structure modeled using finite element program SAP2000, was carried out. Tests have been conducted using both natural and artificial accelerograms, compatible with the elastic spectra provided by the Italian Seismic Code [NTC 2008]. Two structural typologies, designed for vertical loads only, the former, regular in plan, and the latter, with an irregular shape (L), have been considered. For typology 1, structures characterized by three, five and eight floors have been considered, while, for typology 2, only a five floors structure has been used. In order to determine the damage of even the non-structural components, the campaign of numerical simulations has been extended by modeling the effects caused by infill panels on the structural frame.



(a) (b)

Figure 2. *Numerical models: (a) Type 1, (b) Type 2*

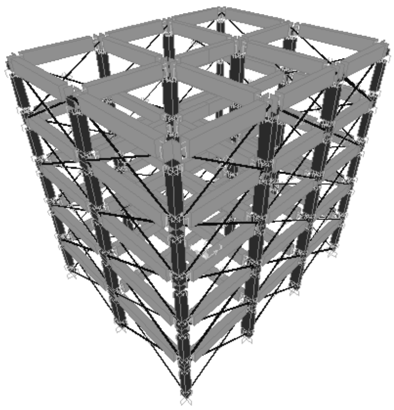


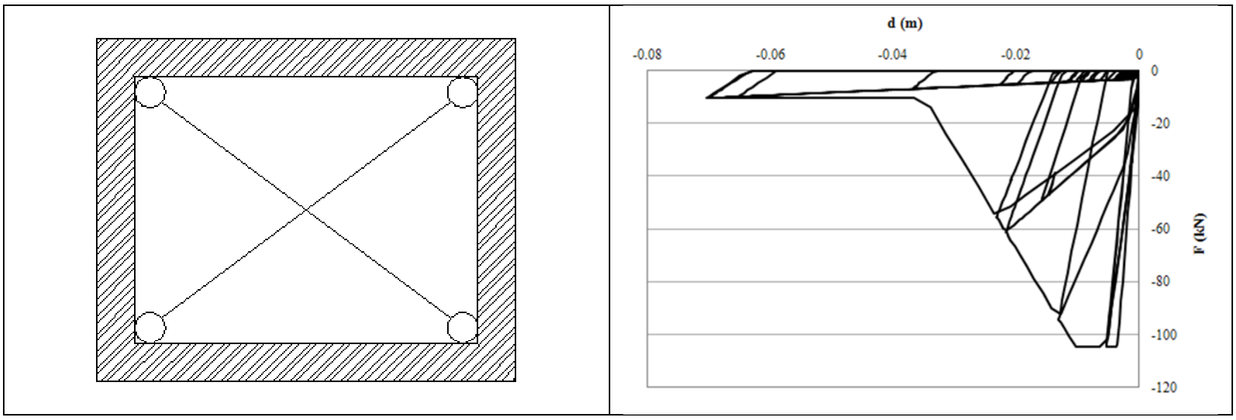
Figure 3. *Numerical model with infill panels*

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. 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 with a hysteretic behaviour, depicted in Fig. 4b.

$$b_w = d_w \cdot 0.20 \cdot \sin 2\theta \cdot \left(\frac{E_w \cdot t_w \cdot h_w^3 \cdot \sin 2\theta}{E_c \cdot I_p}\right)^{-0.1} \cong \frac{1}{10} d_w \quad (4)$$

where:
b_w the equivalent width;
h_w the panel height;
d_w the strut length;
t_w the panel thickness;
θ the angle that the strut forms with the horizontal line;
E_w the elastic modulus of the panel, chosen as 2000 N/mm^2;

E_c elastic modulus of the concrete;
I_p moment of inertia of the columns.



(a) (b)

Figure 4. *Hysteretic behaviour of infill panel*

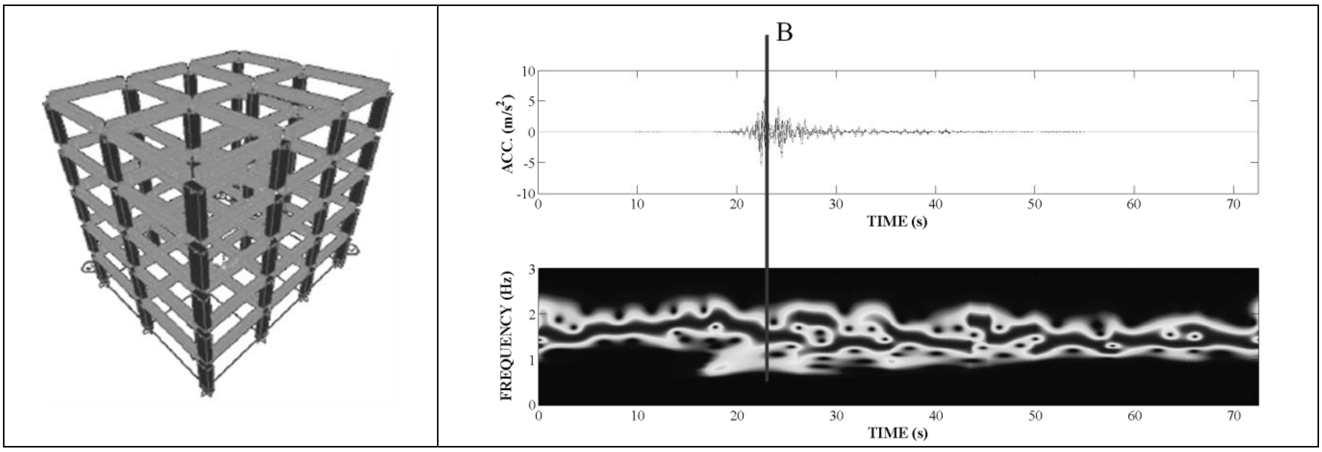
The numerical campaign was carried out using both natural and artificial accelerograms compatible with the Italian code for a soil type B and a soft soil type D (NTC2008). The natural accelerograms (Table 1) were extracted from the European database (European strong motion database). The artificial accelerograms were generated with the program SeismoArtif starting from the response spectrum.

Table 1. *Natural accelerograms*

	data	ora	stazione
A1	06/05/2009	20.00.12	TLM1
A2	06/05/2009	09.21.18	FRC
A3	23/11/1980	18.34.53	BGI
A4	23/11/1980	18.34.53	CLT
A5	23/11/1980	18.34.53	STR
A6	06/04/2009	01.32.39	AQG
A7	06/04/2009	01.32.39	AQK

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

The following figure shows the mode shapes, the respective curvatures and the curvature differences among floors evaluated in the time-instants where the damaging structure exhibits the minimum fundamental frequency (B).



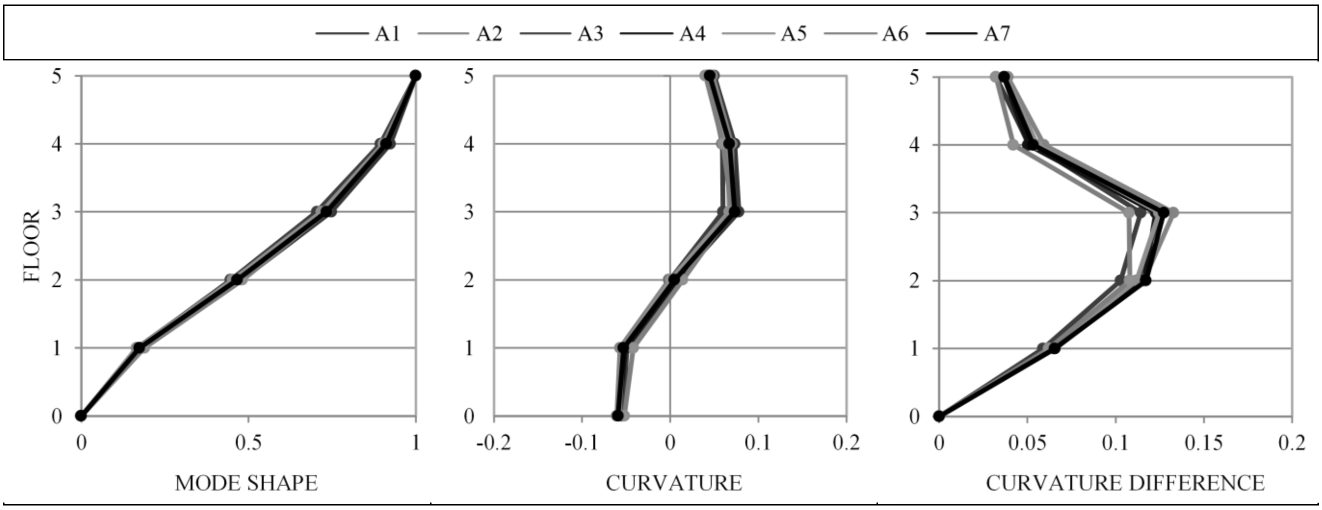


Figure 5. *Mode shapes, mode curvatures, curvature differences among floors in the time instant (B) of minimum fundamental frequency for the structure with 5 floors – Type 1 (Ditommaso et al., 2014)*

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. A similar result is obtained by subjecting the structure to seven artificial accelerograms. After the evaluation of the curvature variations related to the fundamental mode of vibration, the inter-story drift, use as damage index, has been considered. This latter parameter allow us to detect, through the different levels of performance, the expected damage both to structural and non-structural elements (Calvi, 2013).

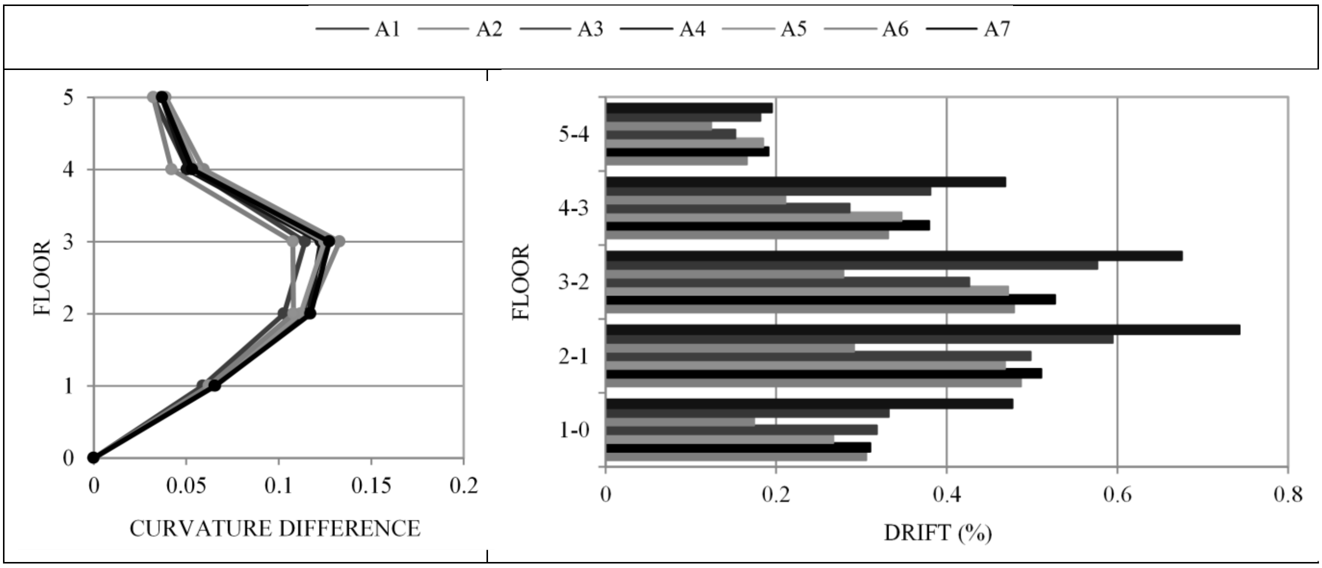


Figure 6. *Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 5 floors – Type 1 (Ditommaso et al., 2014)*

Figure 6 shows that drift is in agreement with the curvature difference, indeed the maximum inter-story drifts occurred 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. Following figures show the main results retrieved applying the proposed procedure on the analyses performed on both regular and irregular structures. Figures 7, 8 and 9 show a comparison of the results retrieved from the application of the proposed procedure and the use of maximum inter-story drift.

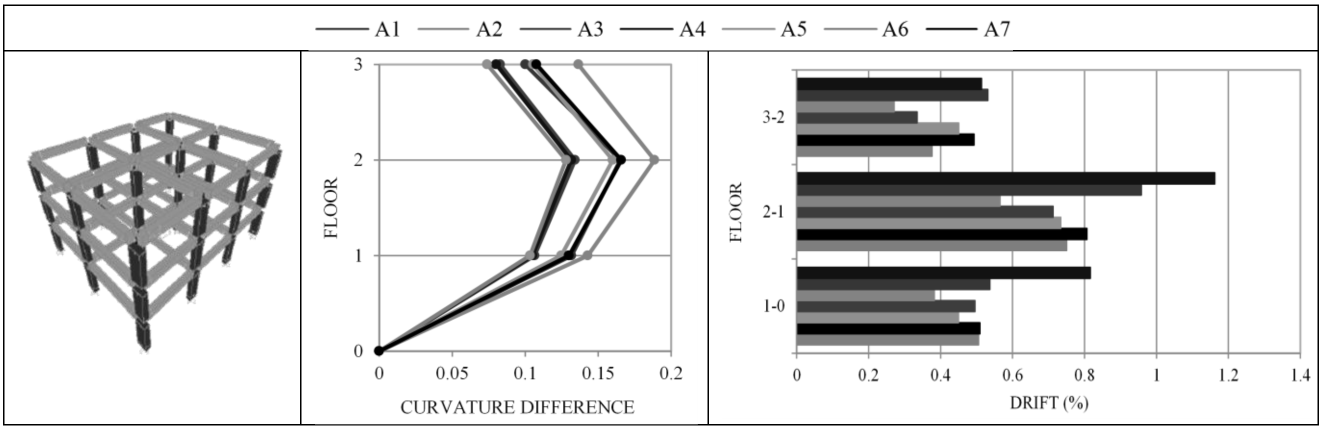


Figure 7. *Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 3 floors – Type 1*

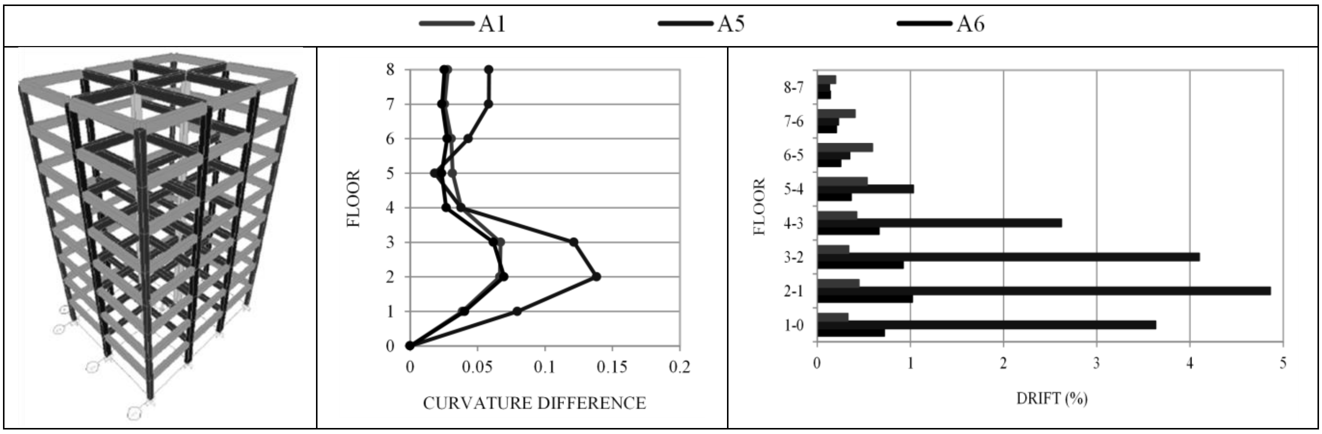


Figure 8. *Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 8 floors – Type 1*

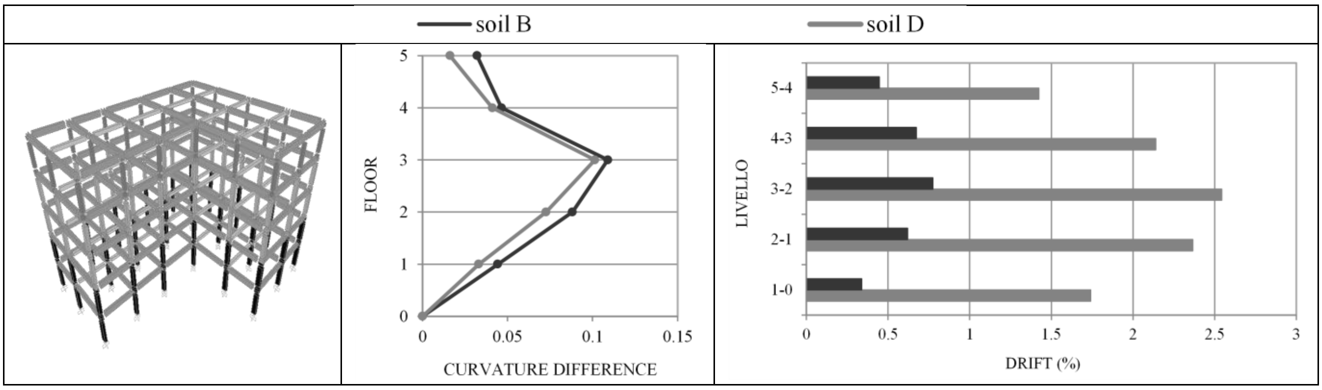


Figure 9. *Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 5 floors – Type 2*

As depicted in the previous Figures, maximum curvature variation and maximum inter-story drift provide consistent results. The advantage derived from the use of the proposed technique is related to the possibility to work directly on the accelerometric acquired data.

In order to determine the damage threshold even for non-structural components, the campaign of numerical simulations has been extended considering also the infill panels. In the follow, the results of a five-story regular structure excited using three natural accelerograms, related to the soil type B (A1 - A5 - A6), and an artificial one related to the soil type D.

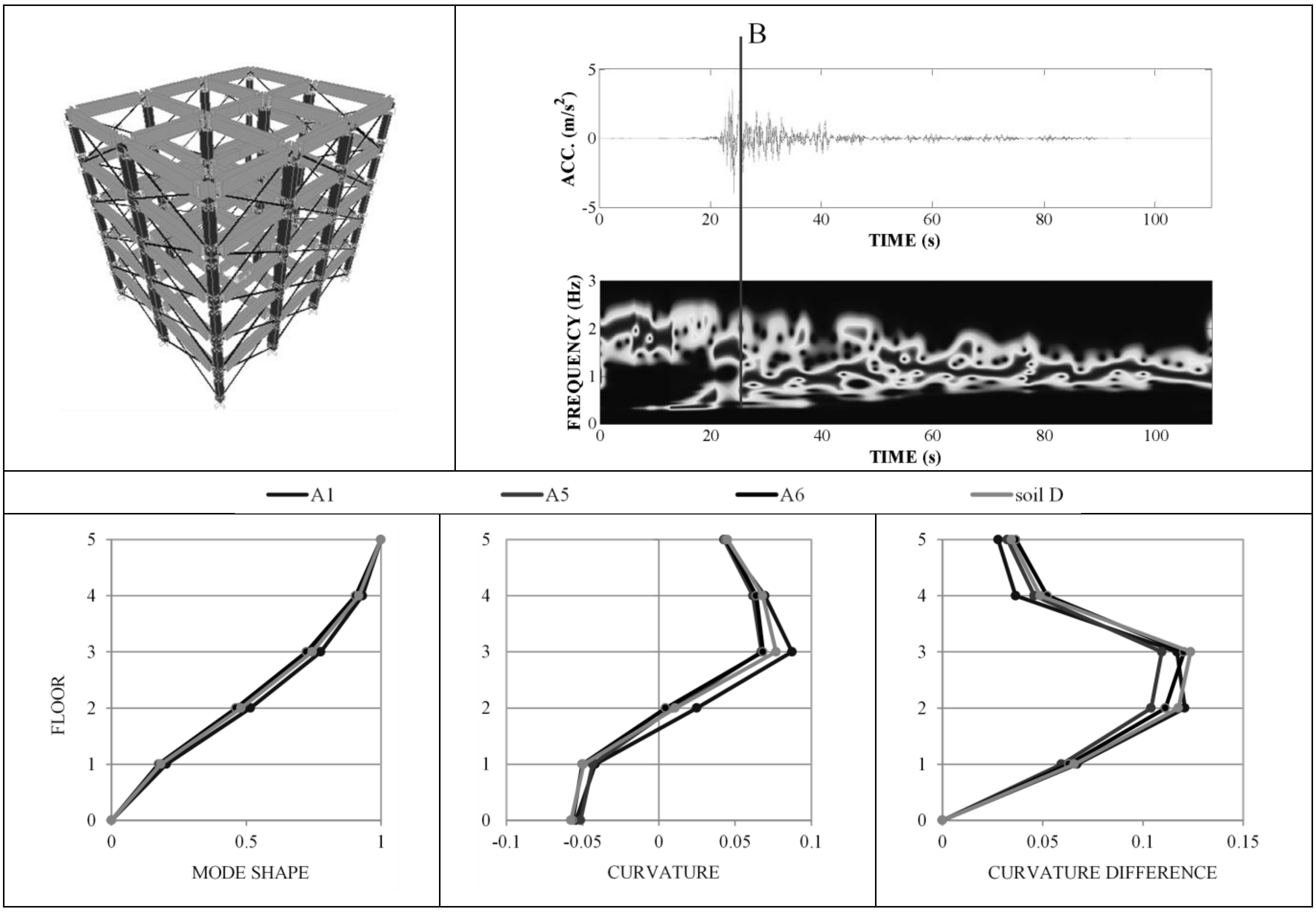


Figure 10. *Mode shapes, mode curvatures, curvature differences among floors in the time instant (B) of minimum fundamental frequency for the structure with 5 floors with infill panels – Type 1*

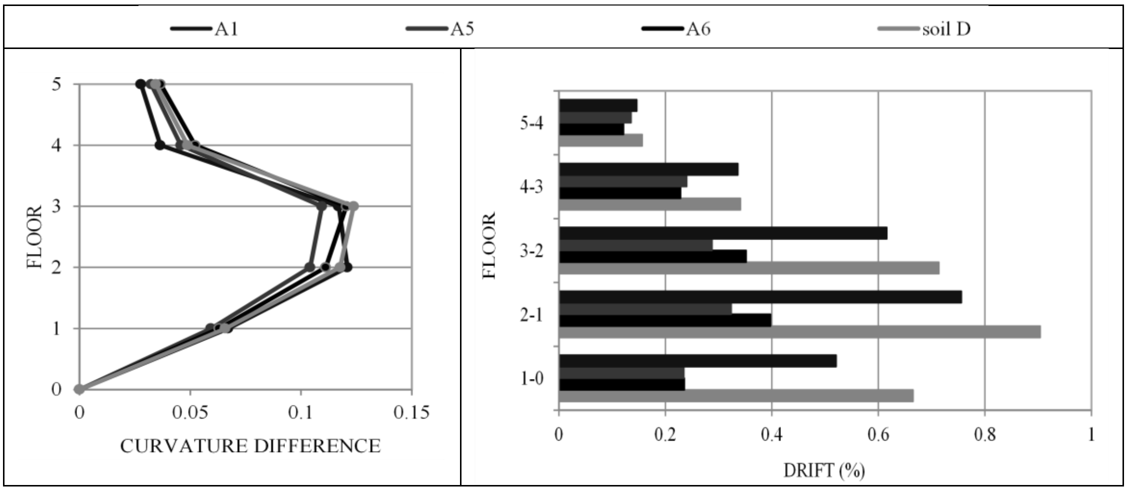


Figure 11. *Curvature differences among floors and maximum inter-story drift in the time instant (B) of minimum fundamental frequency for the structure with 5 floors with infill panels – Type 1*

In order to quantify the structural damage, a correlation between the maximum curvature variation and the maximum inter-story drift, has been defined for the considered structures (Fig.12).

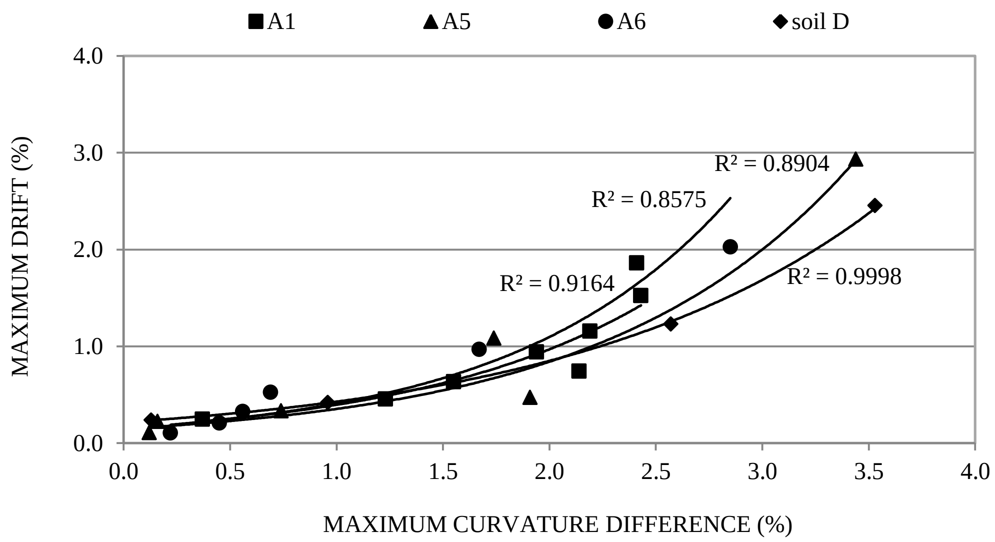


Figure 12. *Correlation among maximum inter-story drift and maximum curvature difference for the structure with 5 floors*

From the first results showed in Figure 12 (Ditommaso et al., 2014), we can observe that the curvature difference is strongly related to the maximum inter-story drift. For reinforced concrete structures it is possible to note a quasi-linear behaviour up to 1% of inter-story drift and then a non-linear trend.

4. **Experimental Tests**

In order to test and to verify the proposed methodology for damage detection and localization a five-story 1:15 scaled model (Figure 13) has been designed and tested at the University of Basilicata (Italy) using shaking table tests. A comparison between the damage estimated using the proposed methodology and the damage detected using classical visual inspections has been performed.

Figure 13. *Frontal and lateral visualization of the shaking-table and the five floor 1:15 scaled structure (Ponzo et al., 2014)*

The model has been designed using modular elements in steel and aluminium bars, differently tapered, replaceable and resistance and calibrated stiffness. The model consists of two spans and two frames in the x direction and by one span and three frames in the Y direction. The other characteristics of the scaled model are descripted in Table 2.

Table 2. *Main characteristics of the experimental model (Ponzo et al., 2014)*

Identification model	5_M1
Regular in plan	yes
Regular in elevation	yes
Number of floors	5
Mass [N/floor]	900
Its total weight model [N]	4500
Total additional mass [N]	3800

The experimental model (Figure 13) is composed of beam and pillar elements appropriately assembled and made by the systems shown in Figures 14-15. Particularly, these systems are constituted by two threaded bars MA16 alloy of aluminium and/or steel. The bars are replaceable and placed in their extremities, 75mm long, with a constant and/or tapered diameter.

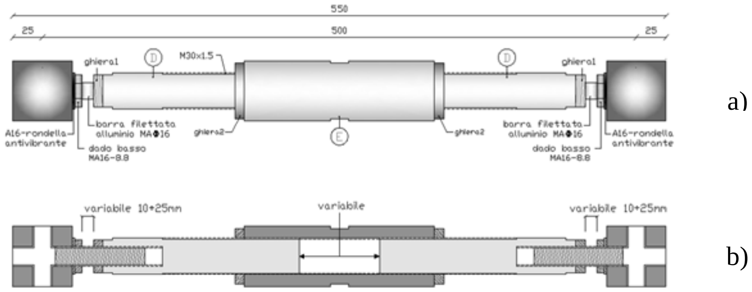


Figure 14. *a) Beam geometry b) section (Ponzo et al., 2014)*

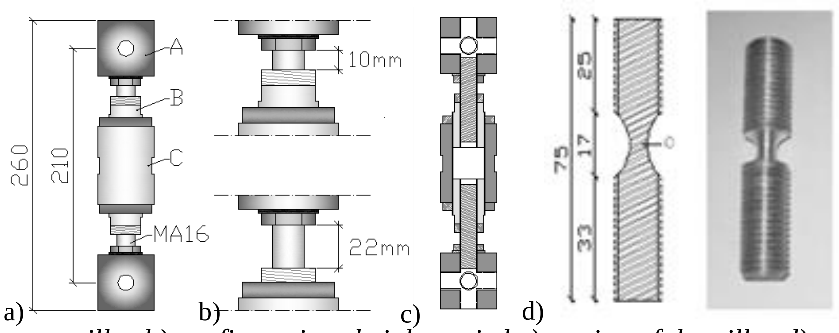


Figure 15. *a) Geometry pillar b) configurations height varied c) section of the pillar d) special threaded rod (Ponzo et al., 2014)*

The experimental model was tested under dynamic conditions on the shaking table available at the Seismic Laboratory of the University of Basilicata. The shaking table is characterized by a one degree of freedom with the following geometric characteristics: 1m x 2m. The motion is impressed by means of a INSTRON Shenck jack (± 125 mm of stroke), maximum force equal to 40 kN, which allows to obtain a maximum acceleration equal to 1g using a mass equal to 15 kN and ranging the frequency from 0 to 20 Hz.

In order to acquire the dynamic behaviour of the model during the shaking table tests several kind of accelerometric sensors (using cable and wireless network) have been distributed both on the structure and on the basement of the table (Fig. 17). In addition, potentiometric transducers have been installed in order to acquire the displacement at all levels of the tested structure. The sensor position is shown in Figure 16 and their number is shown in Table 3.

Table 3. *Acquisition channels of the model.*

Measurement Recorded	Direction	No. Transducers
Displacement	X	10
Acceleration	X	9
Acceleration	Y	6
Acceleration	Z	1

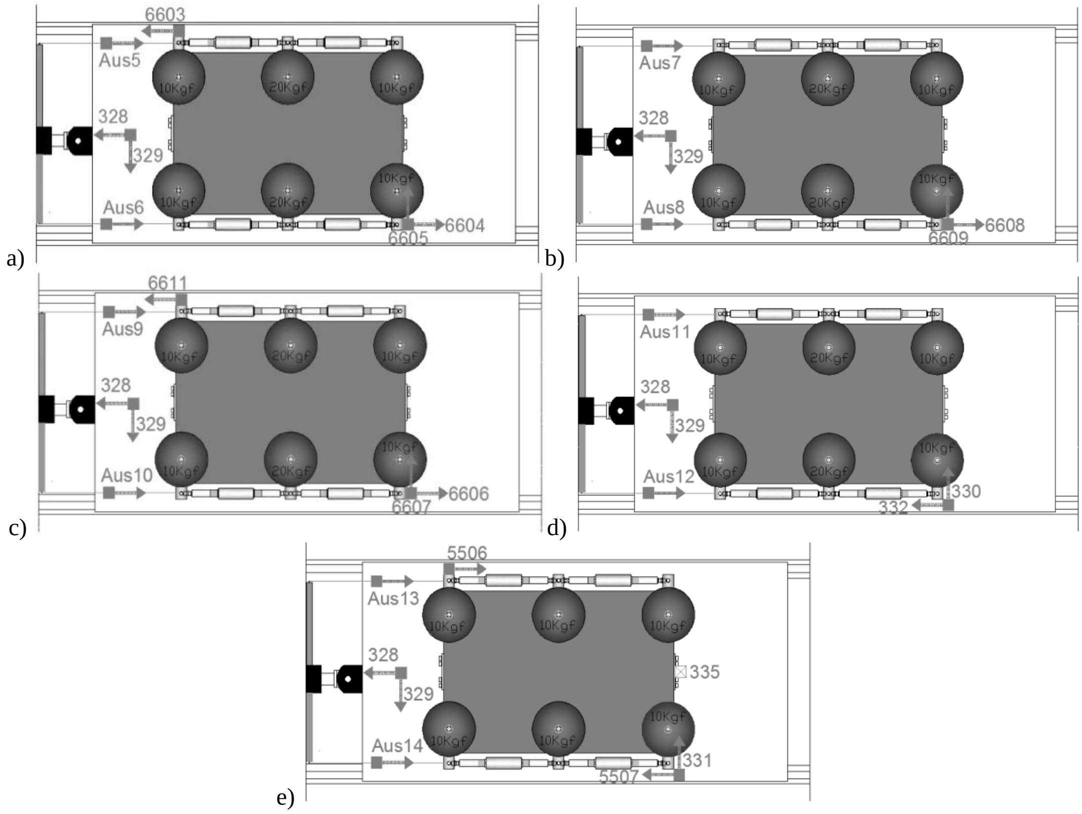


Figure 16. *Configuration of acquisition channels of the model: a) plane 1 (P1); b) plane 2 (P2); c) plane 3 (P3); d) plane 4 (P4); e) plane 5 (P5). In blue the displacement transducers and accelerometers in red (Ponzo et al., 2014)*

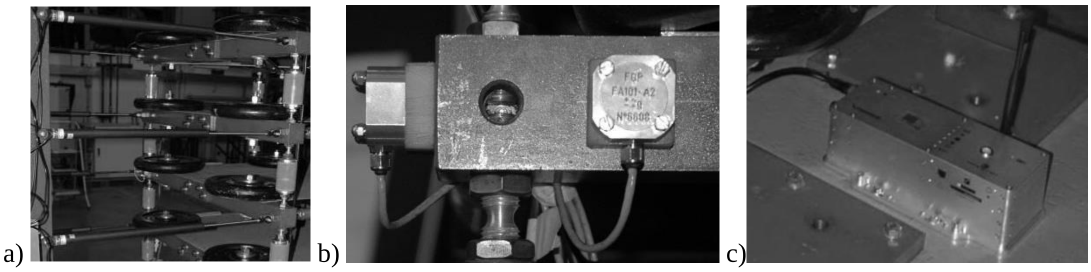


Figure 17. *a) Displacement transducers b) accelerometer transducers installed on the scale model c) accelerometric station three-directional wi-fi disposed on the shaking table*

In the preliminary phase seven earthquakes characterized by response spectra compatible with the target spectrum provided by the Italian seismic code (NTC 2008) related to Potenza City and soil type B (Figure 18), have been considered. After the selection of the seismic database (7 earthquakes), in order to reduce the number of the shaking table tests, following the criteria based on the target spectrum described above, only 3 earthquake have been selected, as shown in Figure 19. There is a very good agreement between the average of the selected earthquake and the target spectrum. With the aim to take into account the scale factor used for the framed structure, the entire selected earthquake database have been scaled in the time domain through a constant equal to the square root of the scale model factor.

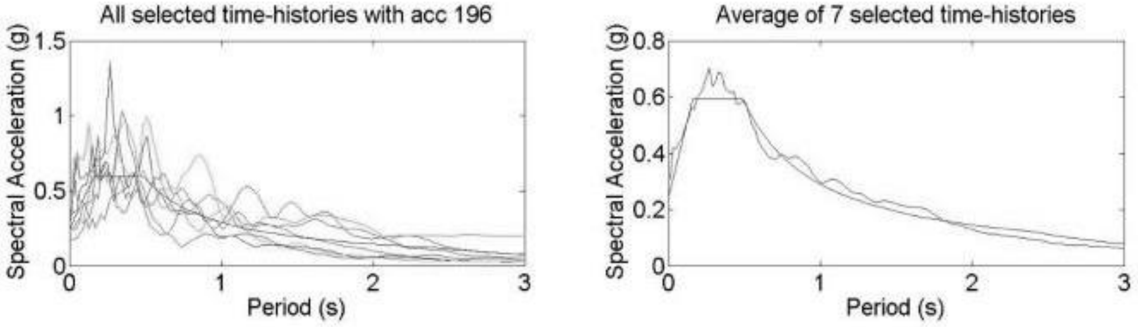


Figure 18. *Elastic acceleration response spectra in 1:1 scale (Ponzo et al., 2014)*

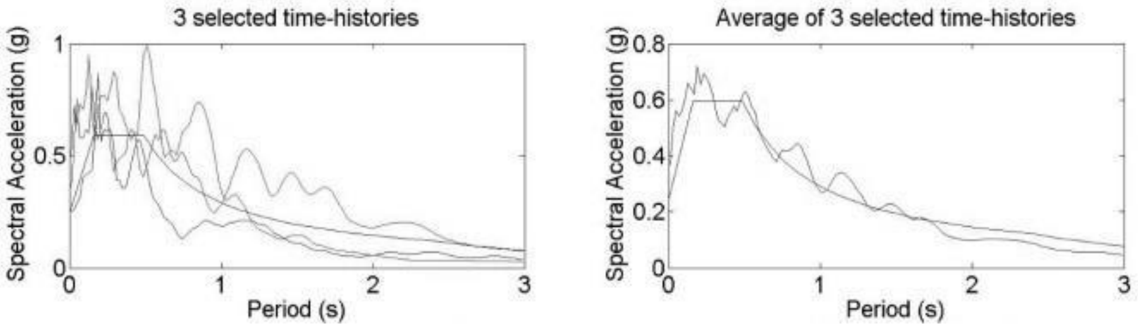


Figure 19. *Elastic acceleration response spectra selected for testing in a 1:1 scale (Ponzo et al., 2014)*

The experimental campaign carried out on the five-story 1:15 scaled model started performing several ambient vibration tests. The results retrieved from these preliminary tests were useful to evaluate the dynamic characteristics of the experimental model the eigenfrequencies, the equivalent viscous damping factors and mode shapes. All the data were analysed using algorithm implemented in MatLab and able to automatic retrieve a preselected number of eigenfrequencies, the related equivalent viscous damping factors and mode shapes also when these characteristics are changing over time due to nonlinear effects. Figure 20 shows the first three mode shapes and in Table 4 fundamental period of the structure is proposed.

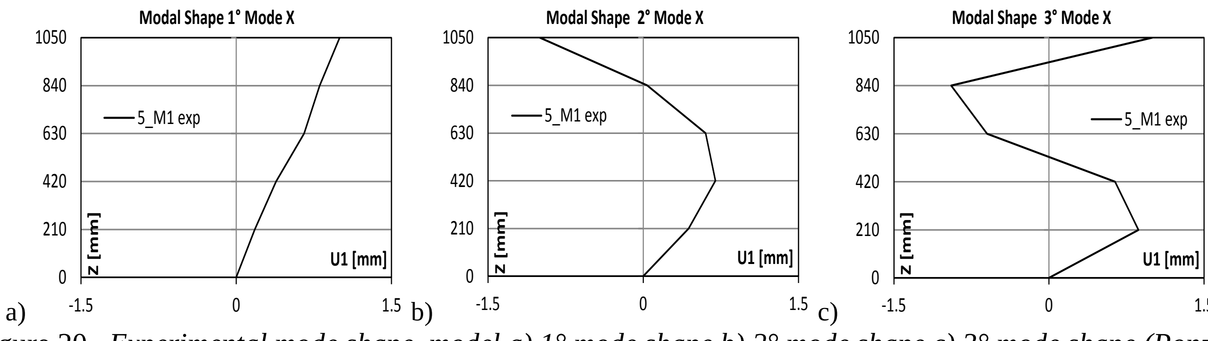


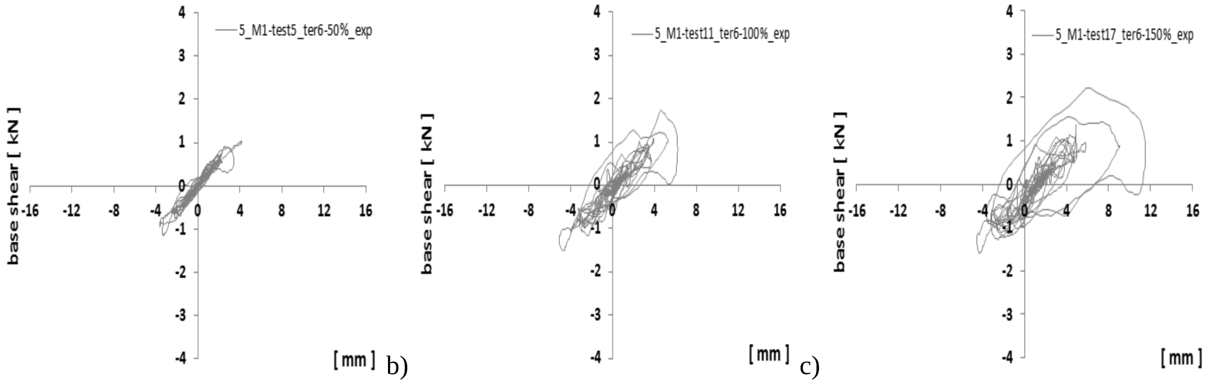
Figure 20. *Experimental mode shape model a) 1° mode shape b) 2° mode shape c) 3° mode shape (Ponzo et al., 2014)*

Table 4. *Period model (Ponzo et al., 2014)*

PERIOD [sec]	
Mode	Experimental Data
1 °	0.238
2 °	0.098

3 °	0.063

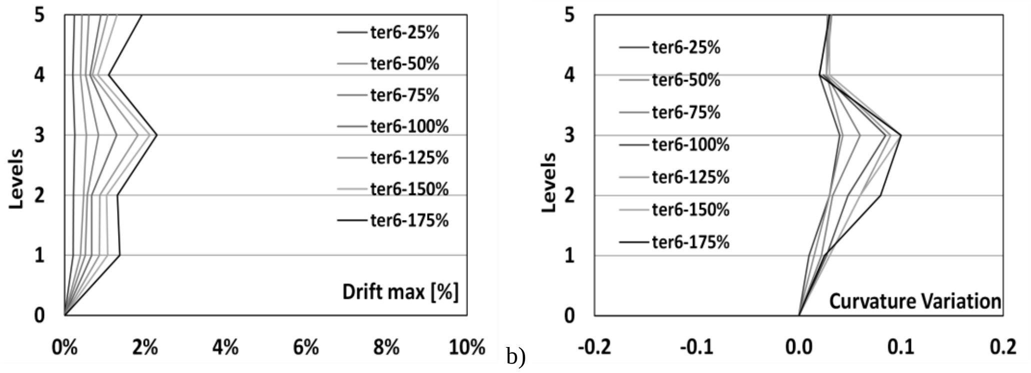
The experimental campaign on the shaking table was performed using the three selected accelerograms increasing the motion intensity and monitoring the response of the model. Considering the top floor displacement and the recorded base shear, Figure 21 shows the cyclic dynamic behaviour of the scaled structure subjected to the accelerogram ter6 with three different intensities.



a) b) c)

Figure 21. *Base shear vs top floor displacement of the experimental model using three different intensities of the ter6 accelerogram*

The algorithm for damage localization was applied on experimental data obtained from the experimental campaign performed using shaking table tests. Figure 22 shows the maximum curvature variation and the maximum inter-story drift evaluated using the accelerogram ter6 and increasing the intensities from 25% up to 175%.



a) b)

Figure 22. *a) Maximum drift evaluated on model; b) Modal Curvature variation evaluated on model*

From Figure 22b, it is observed that the values of curvature variation increases with the intensity of the input. It is also noted that the inter-story drift is in agreement with this result, indeed damage is localized to the third level of the structure (Fig.23).

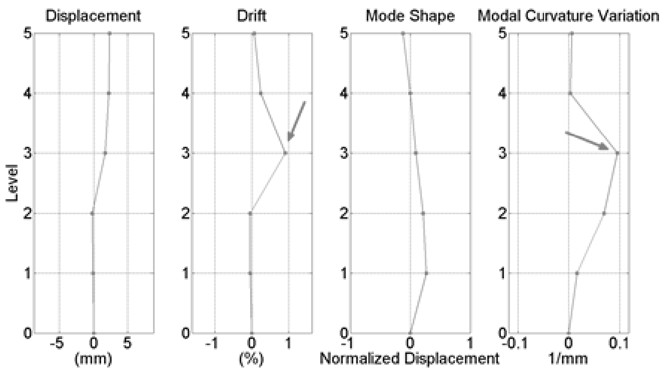


Figure 23. *Comparison among maximum curvature variation and maximum maximum inter-story drift*

In order to test the possibility to use the maximum curvature variation as damage index, Figure 24 shows the correlation among the maximum curvature difference among floors and the maximum inter-story drift. It is worth noting from Figure 24 the good correlation existing between the mentioned parameters (as discussed also for the numerical analyses). For the considered steel framed structure a slight nonlinear behaviour starts after 0.5% (in the plane maximum curvature variation-maximum inter-story drift). Further analyses are necessary to confirm this kind of results for different input motions and different kind of representations. Figure 25 shows the damaged scaled model after the strong motion shaking table tests: the maximum damage occurred at the third floor.

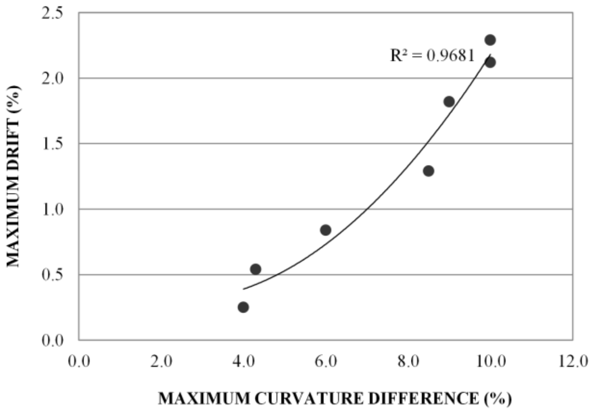


Figure 24. *Correlation among maximum inter-story drift and maximum curvature difference for the model*

Figure 25. *Mechanism pillars plasticized on the third floor of the model so as estimated by the method for damage localization (Ponzo et al., 2014)*

5. **Conclusions**

In this paper, numerical and experimental results derived from the application of the proposed methodology for damage detection and localization on framed structure have been proposed. The methodology is based on the comparison of the maximum curvature variation, related to the fundamental mode of the monitored structure, before, during and after a seismic event. Taking the advantage derived from a combined use of S-Transform and band-variable filter it is possible to retrieve information related to the fundamental mode shape, and its geometric characteristics over time. In the proposed method, the considered geometric characteristic is the modal curvature and its variations before, during and after the earthquake. As proposed from several authors in the recent scientific literature, and confirmed in this study, the modal curvature is a valuable indicator of structural damage, and the analysis of its variation over time allow scientists and engineers to better detect and localize a possible damage occurred on a structure after a seismic event.

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. Aim of this work is also to validate the proposed procedure. Starting from the results obtained from the numerical and the experimental campaign it is worth noting the possibility to use the maximum curvature variation (over time) to detect and localize the damage occurred on a monitored structure just after a strong motion earthquake. Further analyses are necessary to confirm the preliminary results and to better calibrate the proposed procedure also considering the typological characteristics. It is clear that the consequences of structural damage in many existing buildings have a serious influence on the life and work of the people who use it. Consequently, the meaning of the damage control assumes increasingly importance in the process of testing and monitoring of the construction.

6. **Acknowledgements**

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7. **References**

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