SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

VALIDATING OF A NEW PROCEDURE FOR DAMAGE LOCALIZATION USING SHAKING TABLE TESTS ON A 1:15 SCALED STRUCTURE

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ABSTRACT

In Earthquake Engineering field, due to the complexity of the phenomena that characterize the behaviour of structures and their interaction with the foundation soil, the recourse to experimental research is necessary to better understand the mechanical behaviour of the various structural and non-structural components, to validate new techniques for Structural Health Monitoring and for damage detection and localization. Aim of this paper is to present the preliminary results retrieved from an experimental campaign performed on a five-floor 1:15 scaled structure excited using several shaking-table tests in order to validate an innovative methodology for damage localization.

INTRODUCTION

Studies on the Structural Health Monitoring (SHM) are mainly aimed at deepening understand on dynamic behaviour of structures subjected to seismic action, in order to develop strategies for accurate analysis and safety assessment. Particularly, Structural Health Monitoring, especially for structures located in seismic prone areas, has assumed a meaning of great importance, for the possibility to make a more objective and more rapid estimation of the damage occurred on buildings after a seismic event. These tools are also useful to analyse the dynamic behaviour of structures, taking into account their interaction with soil, and to study the damage mechanisms in order to develop effective strategies for seismic retrofit of existing buildings and to reduce their economic impact. In the last years there have been significant advances both on the theoretical approach, concerning new techniques for the building dynamic identification (Safak, 1998a, 1998b, 1999; Ivanović *et al*., 2001; Snieder e Safak, 2006; Todorovska and Trifunac, 2008a, 2008b, 2008c; Trifunac *et al*., 2008;. Todorovska 2009a, 2009b; Ditommaso *et al*., 2010; Mucciarelli *et al*., 2011; Picozzi *et al*., 2011) and on development and application of new techniques based on time-frequency analyses (Parolai 2009; Ponzo *et al*., 2010; Ditommaso *et al*., 2010; Mucciarelli *et al*. 2011; Puglia *et al*., 2011, Ditommaso *et al*. 2012).

In the last twenty years, significant efforts have been devoted to the field of Non-destructive Damage Evaluation (NDE) using the variation in time of the dynamic characteristics of a structure such as frequencies, mode shapes and global dissipative characteristics (equivalent viscous dampng factor). The NDE methods for damage detection and evaluation can be classified into four levels (Stubbs *et al*., 2000), according to the specific criteria provided by the Rytter (1993). Each level of

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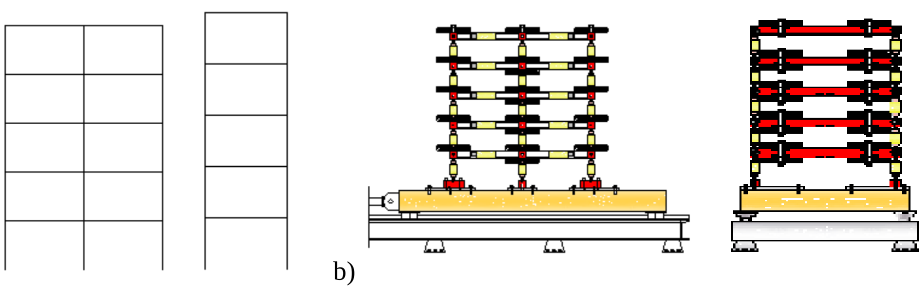
identification is correlated with specific information related to monitored structure: increasing the level it is possible to obtain more information about the state of the health of the structure, it is possible to know if damage occurred on the structures, it is possible to quantify and localize the damage and to evaluate its impact on the structure.

In order to increase the performance level of damage detection and localization on monitored structures, it is necessary to support 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 mode curvature variation over time. Practically, comparing the geometric mode shape curvature exhibits by the elements, and/or by the structure, over time it is possible to localize in an accurate way where the damage occurred. Most of these techniques are based on the variation of the mode shape curvature related to the fundamental mode of vibration of the structure (Bisht and Mahendra, 2012; Ditommaso *et al*., 2012a and 2012b). Pandey *et al*. (1991) proposed the mode shape curvature to be a sensitive parameter for damage localization. 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. Radzienski *et al*. (2011) performed an experimental campaign on an aluminium cantilever beam to identify the modal parameters. It was found in these studies that mode shape curvature is a useful parameter for damage detection and localization. Dilena *et al*. (2011) demonstrated that mode shape curvature could be a useful term for damage location on a reinforced concrete single span bridge. Roy and Ray-Chaundhuri (2013) provide a mathematical basis to show the correlation between a structural damage and a change in the fundamental mode shape and its derivatives. For a cantilever shear beam this approach demonstrates that the change in the fundamental mode shape due to any damage is an excellent indicator of damage localization. Further, also the change in higher derivatives of the fundamental mode shape could be used to increase the performance of damage localization techniques. Aim of this paper is to describe the main scientific results retrieved from an experimental campaign of shaking table tests performed on a 1:15 scaled structure and conducted at the Seismic Laboratory of the University of Basilicata (SISLAB). One of the main goal of the shaking table tests performed on the five floors scaled structures was to validate a new procedure for damage detection and localization on framed structure (Ditommaso et al., 2014). The proposed procedure is based on the study of the fundamental mode shape curvature variation over time, when subjected to strong motion earthquake. In the experimental campaign the proposed approach for damage localization is based on the use of a band-pass filter. From the preliminary results retrieved from the analyses performed on the experimental data it seems possible to confirm the capability of the methodology to localize the position of the maximum inter-story drift used as damage indicator.

NUMERICAL ANALYSIS FOR CALIBRATION OF EXPERIMENTAL 1:15 SCALED STRUCTURE

To understand the seismic behaviour of experimental model, both in terms of damage mechanisms, both in terms of seismic performance, it has been designed a five-floor 1:15 scaled numerical model named 5_M1. The model consists of two spans and two frames (Mossucca,2008) in the x direction and by one span and three frames in the Y direction. It is regular in plan and in elevation. The other characteristics of the scaled model are descripted in Table 1.



a) b)

Figure 1 - a) prototype model c.a.; b) 5_M1 experimental model in 1:15 scale.

Table 1 - Main characteristics of the Numerical Model

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
Mechanism of plasticity	Pillar floor 3

In the numerical scaled model, pillars and beams were modelled using linear elements and using plastic hinges to simulate the static nonlinear characteristics. Each hinge has been defined using the nonlinear moment-rotation behaviour derived from experimental test performed on single elements. The numerical analyses have been performed using the finite element software SAP2000 (Computer and Structures) and to perform the nonlinear dynamic analyses NLlink Plastic Wen elements (calibrated using experimental data) have been used in the model.

The numerical campaign started performing on the scaled structure several nonlinear static analyses used also to calibrate the nonlinear link used on the dynamic numerical analyses. An example of the results retrieved from the pushover analyses has been depicted in the Figure 2.

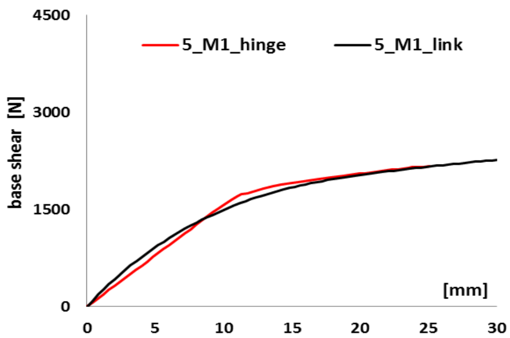


Figure 2 - Comparison pushover model 5_M1.

In order to investigate the dynamic behaviour of the numerical 1:15 scaled structure, before to start with the analyses, an accurate selection of the seismic input has been done. Particularly, the seismic inputs used for the experimental campaign have been selected from the ITACA database (http://itaca.mi.ingv.it). In the preliminary phase seven earthquake 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. 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.

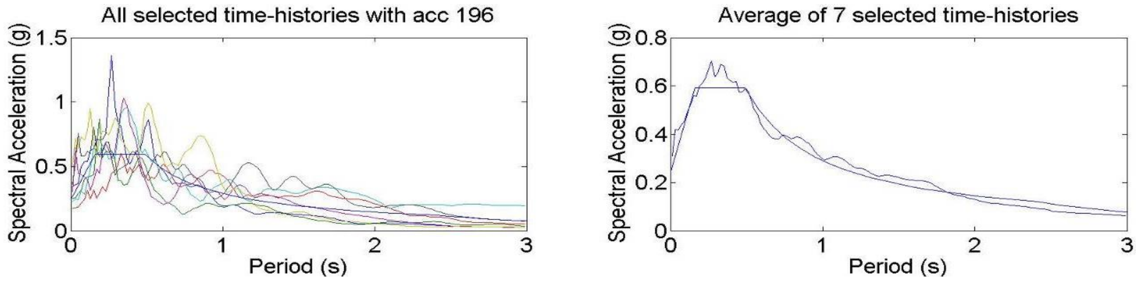


Figure 3 - elastic acceleration response spectra in 1:1 scale.

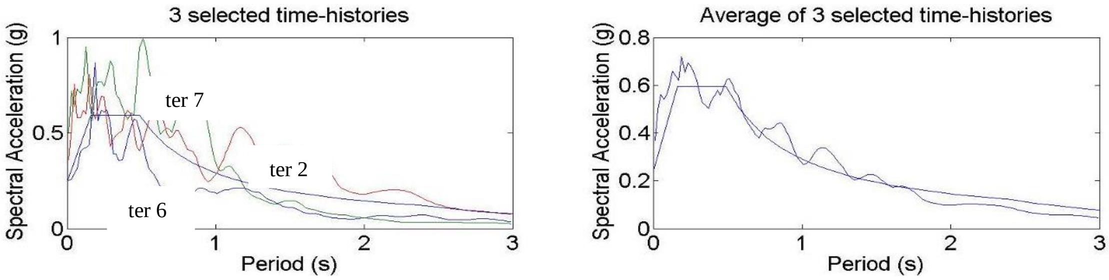


Figure 4 - elastic acceleration response spectra selected for testing in a 1:1 scale.

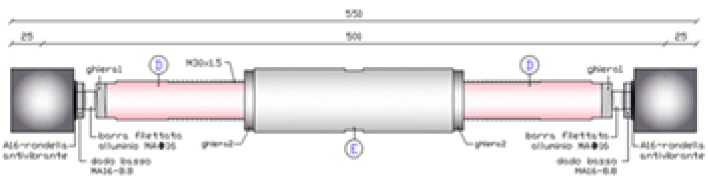
After the selection of the seismic database (7 earthquake), in order to reduce the number of the shaking table test, following the criterion based on the target spectrum described before, only 3 earthquake have been selected and as shown in Figure 4, there is a very good agreement between the average of the selected earthquake and the target spectrum.

EXPERIMENTAL 1:15 SCALED MODEL AND EQUIPMENT FOR THE DYNAMIC TESTS

In order to test and to verify the algorithm for damage localization a five-story 1:15 scaled model has been realized. The model has been designed using elements that allows to easily change the mass, stiffness and geometric configuration. It is made by means of modular elements in steel and aluminium bars, differently tapered, replaceable and resistance and calibrated stiffness. The designed framed structure can be assembled following several king of configuration in order to reproduce the seismic behaviour of several kind of reinforced concrete framed structures: a) designed using different codes; b) several number of floors; c) to simulate different collapse mechanism; d) change the regularity characteristics both in plan and in elevation.

Figure 5. Frontal and lateral visualization of the shaking-table and the five floor 1:15 scaled structure.

As described before, the experimental model (see Figure 5) is composed of beam and pillar elements appropriately assembled and made by the systems shown in Figure 6 and 7. 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.



a)

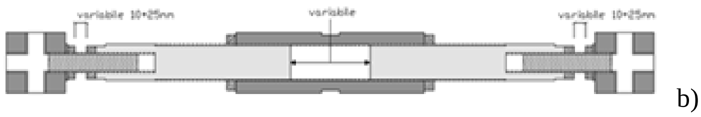


Figure 6. a) Beam geometry b) section

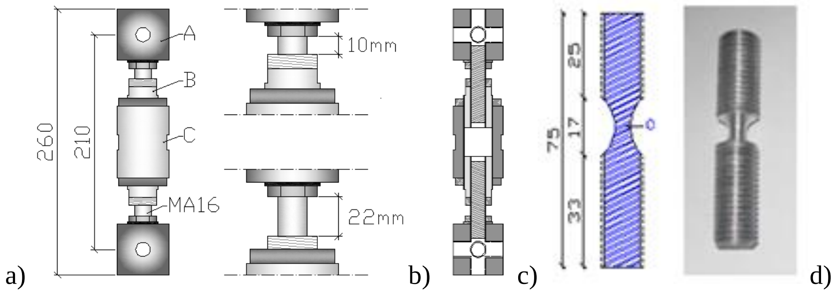


Figure 7. a) Geometry pillar b) configurations height varied c) section of the pillar d) special threaded rod.

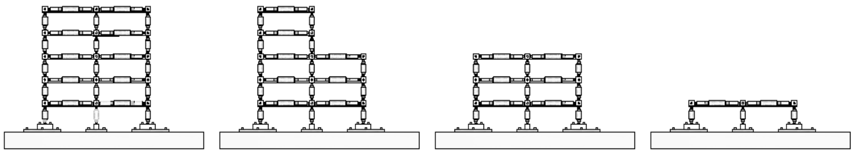


Figure 8. Geometric configurations realizable by exploiting the modularity of the components.

Taking the advantage to use a modular structure it is possible to easily change the damaged elements after a strong motion test. Furthermore, using this system, the experimental model lends itself easily to the change of the geometrical configuration introducing also torsional effects locating on asymmetric position several additional masses.

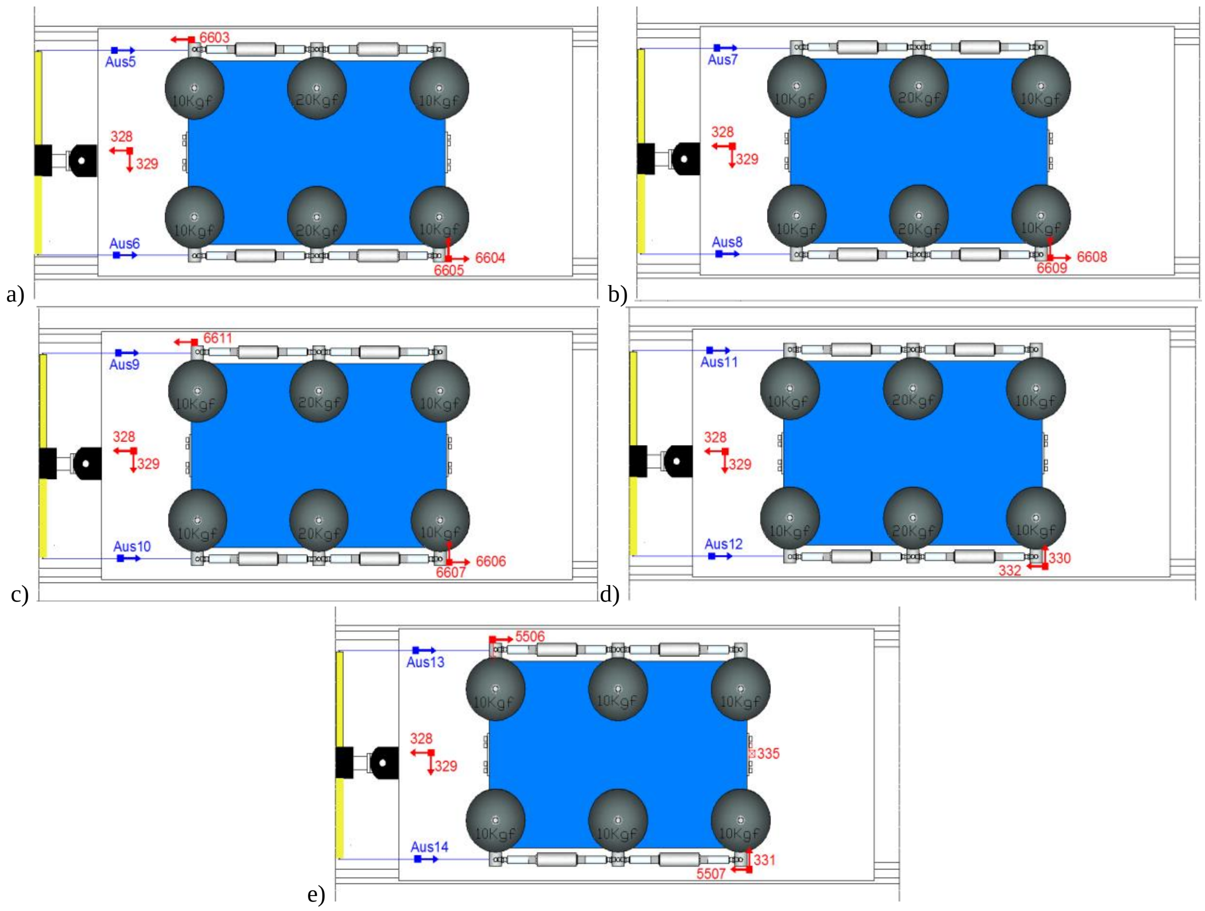


Figure 9 - Configuration of acquisition channels of the model 5_M1-a) configuration plane 1 (P1); b) configuration plane 2 (P2); c) configuration plane 3 (P3); d) configuration plane 4 (P4); e) configuration plane 5 (P5).

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 and it has the following geometric characteristics: 1m x 2m. The motion is impressed by 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. 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 9 and their characteristics are detailed in Tables 2 and 3.

Table 2 – Configuration of acquisition channels of the model 5_M1.

N° Channel	Name Channel	Position	Magnitude Recorded
1	Aus 5	P1 - Right	DISPLACEMENT_DirX
2	Aus 6	P1 - Left	DISPLACEMENT_DirX
3	Aus 7	P2 - Right	DISPLACEMENT_DirX
4	Aus 8	P2 - Left	DISPLACEMENT_DirX
5	Aus 9	P3 - Right	DISPLACEMENT_DirX
6	Aus 10	P3 - Left	DISPLACEMENT_DirX
7	Aus 11	P4 - Right	DISPLACEMENT_DirX
8	Aus 12	P4 - Left	DISPLACEMENT_DirX
9	Aus 13	P5 - Right	DISPLACEMENT_DirX
10	Aus 14	P5 - Left	DISPLACEMENT_DirX

Table 3 – Configuration of acquisition channels of the model 5_M1.

N° Channel	Name Channel	Position	Magnitude Recorded
1	328	Shaking-Table	ACCELERATION_DirX
2	329	Shaking-Table	ACCELERATION_DirY
3	6603	P1 - Right	ACCELERATION_DirX
4	6604	P1 - Right	ACCELERATION_DirX
5	6605	P1 - Left	ACCELERATION_DirY
6	6608	P2 - Left	ACCELERATION_DirX
7	6609	P2 - Left	ACCELERATION_DirY
8	6611	P3 - Right	ACCELERATION_DirX
9	6606	P3 - Left	ACCELERATION_DirX
10	6607	P3 - Left	ACCELERATION_DirY
11	332	P4- Left	ACCELERATION_DirX
12	330	P4- Left	ACCELERATION_DirY
13	5506	P5 - Right	ACCELERATION_DirX
14	5507	P5- Left	ACCELERATION_DirX
15	331	P5- Left	ACCELERATION_DirY
16	335	P5- Left	ACCELERATION_DirZ

Figure 10 - a) displacement transducers b) accelerometer transducers installed on the scale model c) Poseidon disposed on the shaking table.

DYNAMIC IDENTIFICATION OF MODEL

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 compare the dynamic characteristics of the experimental model with those of the numerical one. Particularly, eigenfrequencies, equivalent viscous damping factors and mode shapes have been considered for the comparison. 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 11 shows a comparison between experimental and numerical model considering the first three mode shapes. In Table 4 a comparison between experimental and numerical fundamental period of the structure is proposed.

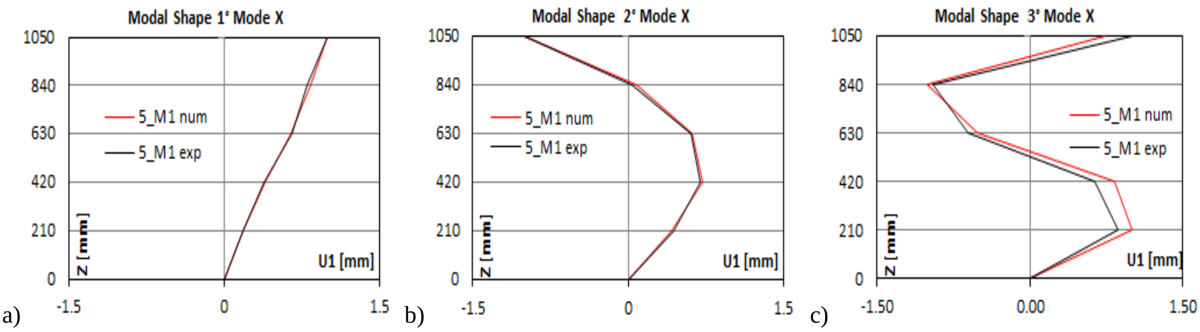


Figure 11 - Comparison of numerical and experimental mode shape model 5_M1 a) 1° mode shape b) 2° mode shape c) 3° mode shape.

Table 4 - Comparison period model 5_M1

PERIOD [sec]		
Mode	**Numerical**	**Experimental**
1 °	0.253	0.238
2 °	0.095	0.098
3 °	0.062	0.063

It is possible to observe a good agreement between numerical and experimental data both in terms of structural fundamental period and mode shapes.

After the comparison in terms of dynamic characteristics of the structure using ambient vibration tests and white noise, on the five-story 1:15 scaled structure 21 dynamic tests have been performed. The input motion has been scaled in terms of intensity allowing us to analyse the seismic response at the same earthquake but with different PGA (Peak Ground Acceleration).

The dynamic behaviour of the structure has been analysed using time-frequency analyses based on the Stockwell Transform, named S-Transform. In order to retrieve the fundamental mode shape during both linear and nonlinear behaviour of the structure, the band-variable filter made by Ditommaso *et al*. (2012) has been used. The nonlinear behaviour predicted from the nonlinear numerical model implemented in SAP 2000 has been confirmed during the shaking table tests.

APPLICATION OF THE PROCEDURE FOR DAMAGE LOCALIZATION

The basic idea of the procedure proposed by Ditommaso *et al*. (2014) is to isolate, thanks to the band-pass filter, a single mode shape and to analyse their changing over time in term of modal curvature variation. In fact, structural damage if generally associated to a stiffness reduction that implies some changes both on eigenfrequencies and mode shapes. Analysing the changes over time of the curvature related to the fundamental mode shape it is possible to retrieve useful information to localize the damage occurred on a monitored structure after an earthquake. The curvature related to a mono-dimensional elastic can be evaluated using the following expression:

$$v'' = \frac{M(x)}{EI}$$

where M(x) is the bending moment, E is the elastic modulus, I the moment of inertia of the cross section and $\upsilon(x)$ is a mode shape. If any damage occurred on the structure there is a reduction of the denominator that increases the curvature values.

The algorithm used to estimate the mode curvature variation of the structure involves the following steps:

- Evaluation of the structural response in acceleration at the last level (Figure 12);

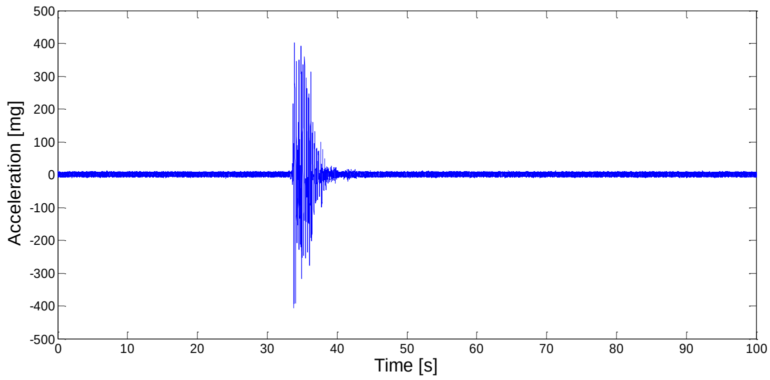


Figure 12 - acceleration records on the fifth floor of the model 5_M1.

- Identification of the fundamental frequency of oscillation and calibration of the band-pass filter around the considered frequency that could changes over time (Figure 13);

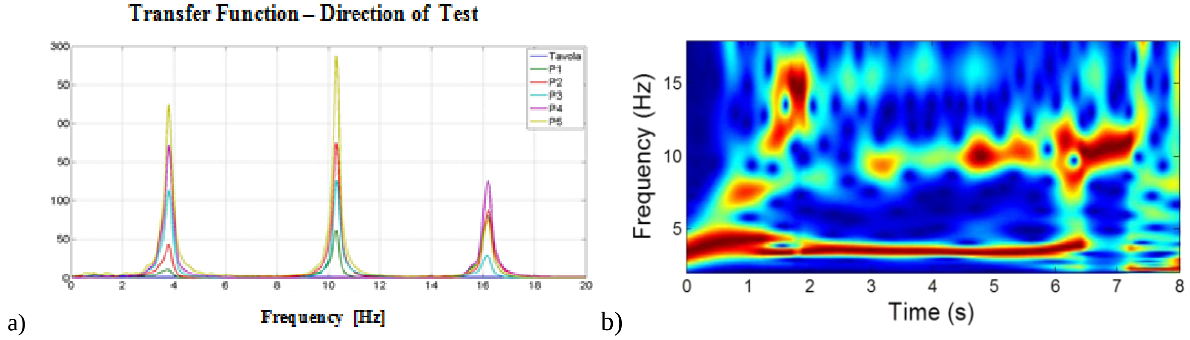


Figure 13-a) Transfer function of the accelerometer signal on the fifth floor of the model 5_M1 b) S-Transform of the accelerometer signal on the fifth floor of the model 5_M1.

- Filtering all accelerometer signals recorded at different levels of the structure (Figure 14);

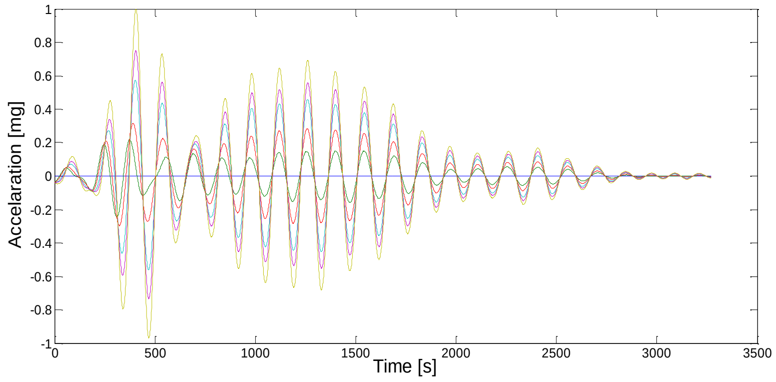


Figure 14 - Story of the accelerations filtered.

- Evaluation of the mode shape relative to the first mode and its variations over time;
- Evaluation of the mode curvature at any instant of time;
- Evaluation of the curvature variation by the difference of curvature among floors (Figure 15).

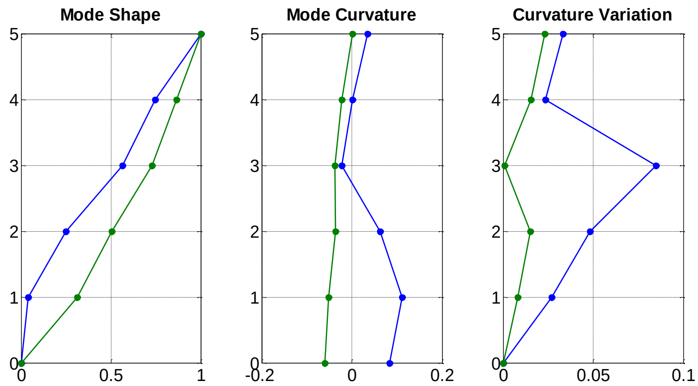


Figure 15 - Evaluation of the mode shape, curvature and its variation.

The algorithm was applied both on numerical and experimental data obtained from the experimental campaign performed using shaking table tests. During strong motion tests on the five-story 1:15 scaled model, structural damage occurred at the third floor of the model as depicted in Figure 15, using the maximum curvature variation as damage indicator, and also depicted in Figure 16 where it is possible to see the importance of the inter-story drift directly on the picture.

Figure 16 Mechanism pillars plasticized on the third floor of the model 5_M1 so as estimated by the method for damage localization.

DISCUSSION AND CONCLUSIONS

The preliminary results of the analytical and experimental study carried out at the Seismic Laboratory of the University of Basilicata are described in this paper. Aim of the work is to validate using several shaking table tests performed on a five-story 1:15 scaled structure a fast procedure for damage localization on framed building subjected to earthquakes. The work started with a nonlinear numerical campaign used to calibrate the model with static and dynamic analyses. During the experimental campaign 21 dynamic tests were performed using one degree of freedom shaking table and using three selected real earthquakes scaled in time, to consider the scale factor of the model, and scaled in amplitude to investigate the seismic response of the model when subjected to the same earthquake at different intensities.

In order to localize the damage occurred on the scaled structure during the shaking table tests, a method based on the maximum curvature variation has been applied. The method, proposed by Ditommaso *et al*. (2012 and 2014), is based on the evaluation, using the S-Transform and a band variable filter, the dynamic characteristics of the monitored structure and their changes over time due to nonlinear effects.

The method has been applied on both numerical and experimental data and produce interesting results confirmed also from visual inspection of the model. Further analyses are necessary to automatize the methodology and to upgrade the classical approaches for damage detection.

ACKNOWLEDGEMENTS

This study was partially funded by the project DPC-RELUIS 2010-2013 financed by the Italian Department of Civil Protection.

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