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FLOOR SPECTRA VALIDATION THROUGH ACTUAL DATA FROM THE 2016/2017 EARTHQUAKE IN CENTRAL ITALY

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Abstract

Analytical expressions as much as possible reliable to assess the possible amplification phenomena due to the filtering effect of the main structure play a key role for a correct definition of the seismic input induced on non-structural elements in existing buildings. Traditionally, the approach adopted by Codes refers to the definition of the seismic action in terms of floor spectra, which are based on the simplified assumption to neglect the dynamic interactions between primary and secondary structures. Due to the complexity of such amplification phenomenona, furthermore possibly raised by the nonlinearity of the building itself, accurate data on existing structures hit by real seismic events constitute a precious source for a better understanding of the topic and for corroborating the validation of analytical expressions. In this framework, the paper aim is twofold. On one hand, it attempts to interpret the physics of the amplification phenomenon through some experimental evidence coming from both laboratory tests and *in-situ* measurements on existing structures monitored by the Italian structural seismic monitoring network (OSS). On the other hand, it presents the application of an analytical expression for the floor spectra developed by the Authors to a case-study consisting in the Pizzoli Town Hall (L'Aquila, Italy), hit by the 2016/2017 earthquake in Central Italy and permanently monitored by OSS since 2009. With the aim of validating the expression both in the linear and nonlinear fields, the comparison between experimental and analytical floor spectra has been provided for both a minor seismic event and the main event of 18/01/2017, after which the structure exhibited a moderate damage level. Even if the research is still ongoing, the first results appear promising.

Keywords: floor spectra; masonry; existing buildings permanently monitored; seismic analysis; nonlinear behavior

1. Introduction

In the seismic assessment of existing buildings, a crucial and tricky aspect is the proper definition of the seismic input to be used for the verification of non-structural elements (such as parapets, chimneys, or equipment) or of local out-of-plane mechanisms in masonry buildings. Traditionally, the approach prescribed by Codes refers to the definition of the seismic action in terms of floor spectra that, as known, assume licit the decoupling between main and secondary structures ([1], [2]). Although such amplification phenomenon has been already proven in literature (*e.g.* [3], [4]), accurate data on existing structures hit by real seismic events, so valuable to validate analytical expressions proposed in literature, are quite few.

Within this context, the paper firstly describes the physics of the amplification phenomenon by means of experimental and real evidence (§2). In particular, the results of some laboratory tests and the post-processing of some recordings on three masonry buildings are presented. The buildings are the Pizzoli Town Hall (AQ, Italy), the "Pietro Capuzi" school of Visso (MC, Italy) and the former Fabriano Courthouse (AN, Italy). They have been selected within the aims of ReLUIS project founded by the Department of Civil Protection ([5], [6]), since they have the distinctive feature of being permanently monitored by the Italian structural seismic monitoring network (hereinafter named as "OSS" [7]). The monitoring system includes accelerometers placed at the different levels plus a three-axial sensor at the foundation in order to measure the seismic excitation applied to the structure. All of them have been hit by the 2016/2017 Central Italy earthquake exhibiting different damage levels ([6], [8]). Thus, records from the different main shocks, secondary seismic events and ambient noise are available as well. Secondly, these data are used to validate an analytical expression for the floor spectra definition, proposed by the Authors in [9]. This expression allows evaluating the floor spectra in different points of the building and at different levels by considering the contribution of the more relevant modes, when properly combined (§3). For the aim of validation, the comparison of the experimental floor spectra with the analytical ones is presented in the paper for the Pizzoli Town Hall (§4). Since the case-study exhibited a moderate damage level, the comparison allowed validating the expression in the moderate nonlinear field.

2. Experimental and real evidence for a physical interpretation of the amplification phenomenon

The seismic input on an element placed at a certain level of the building is a function of both the ground motion and the dynamic response of the primary structure, which may be affected by the evolution of the latter in the nonlinear range as well. Due to the complexity of the phenomenon, laboratory experimental tests or *in-situ* measurements on existing buildings are very useful to better understand the physics of the phenomenon.

Fig.1a shows, for example, the comparison between the floor spectra (continuous plot) and the ground response spectra (dashed plot) obtained from the acceleration time histories recorded during a shake-table campaign [10]. These tests were performed on a prototype of a half-scale four-story building, built with reinforced concrete (RC) and unreinforced masonry (URM) walls, as bearing system; the vertical bearing systems were connected by RC slabs. In particular, the figure compares the floor spectra obtained respectively: a) from one of the first tests performed (in black), characterized by a peak ground acceleration applied to the shake-table (*PGA*) very low, and by the mock-up still in the linear field and not yet damaged; b) when the structure, significantly damaged, exhibited a nonlinear behavior (in blue). It is worth noting that the actual movement of the shaking table is never exactly equal to the input record, due to the feedback of the equipment. Hence, the actual values of *PGA* at the shaking table are slightly different from the PGA_{nom} (this is why in Fig.1a the shaking table response spectra normalized to PGA_{nom} do not start from 1). Furthermore, Fig. 1b shows the evolution of the equivalent fundamental period (T_1) of the structure for increasing values of the PGA_{nom}. Such values were determined respectively as: the period with the largest dynamic amplification (rhombus indicator); or from the structural dynamic identification performed after each run test (triangle indicator, as illustrated in [10]). These latter are generally shorter than the actual period obtained during the shaking.

As one can see, as long as the response of the building is in the linear phase, significant amplifications can be observed both in terms of peak floor accelerations (*PFA*) and spectral peaks (Fig.1a). Moreover, the maximum amplification occurs in correspondence of the fundamental period of the structure (equal to T=0.13 s), identified in the figure with the grey vertical line. Then, as the structure was increasingly damaged, it is possible to observe an elongation of the fundamental period (T=0.23 s) and a reduction of the peak that, at the same time, tends to be smoother and wider (Fig.1a-b).

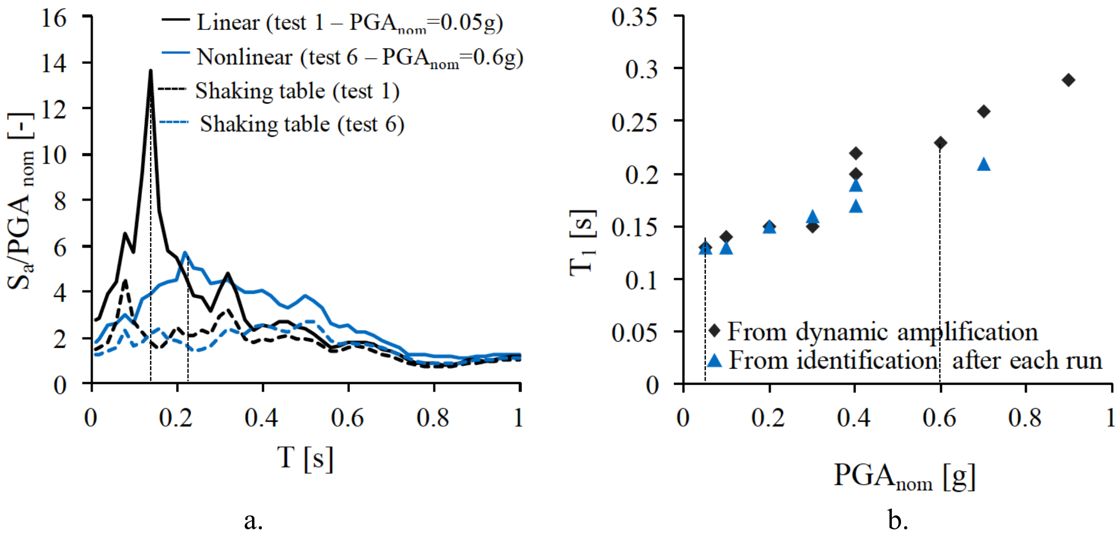


Fig. 1 – a) Comparison between floor (continuous plot) and ground (dashed plot) response spectra obtained in the linear (test 1) and nonlinear field (test 6) of the prototype; b) First period T_1 for different values of the PGA_{nom} (figure adapted from [9])

The same effects have been testified by *in-situ* measurements on existing buildings as well. From the '90s many structures were being permanently monitored in Italy by the OSS, allowing for the collection of very precious data for further understanding the seismic amplification effects in the upper levels of more complex structures and of its evolution with the progressing nonlinear phase. Fig. 2 shows some post-processing of the recordings acquired by the permanent monitoring system on three buildings [6]: the Pizzoli town hall (AQ, Italy), the former Fabriano courthouse (AN, Italy) and the "Pietro Capuzi" school of Visso (MC, Italy). Such structures were struck by the 2016/2017 Central Italy earthquake sequence, exhibiting various damage levels, from slight (the Fabriano Courthouse) to near collapse (the School of Visso).

In particular, Fig. 2a compares, for the first two buildings, the response spectrum measured at the base (dashed plot) with the floor spectra obtained from some sensors placed along the same vertical alignment, but at increasing height (thicker plot lines). The recordings refer to the two main events which mainly damaged the structures: the main event of 18/01/2017 (for the Pizzoli town hall) and the second shake of the main event of 26/10/2016 (for the Fabriano courthouse). This comparison clearly highlights the amplification phenomenon, which is in both cases more pronounced at the top and in correspondence of the fundamental periods. Instead, Fig. 2b shows the effects of the nonlinearity on the floor spectra shapes, by comparing the floor spectra (normalized to the *PGA*) obtained after a minor event (in black) and the main shock of 18/01/2017 (in blue) for the Pizzoli's town hall and the floor spectra measured after different consecutive shocks for the school of Visso. The damage exhibited by each structure is sketched in Fig. 2c.

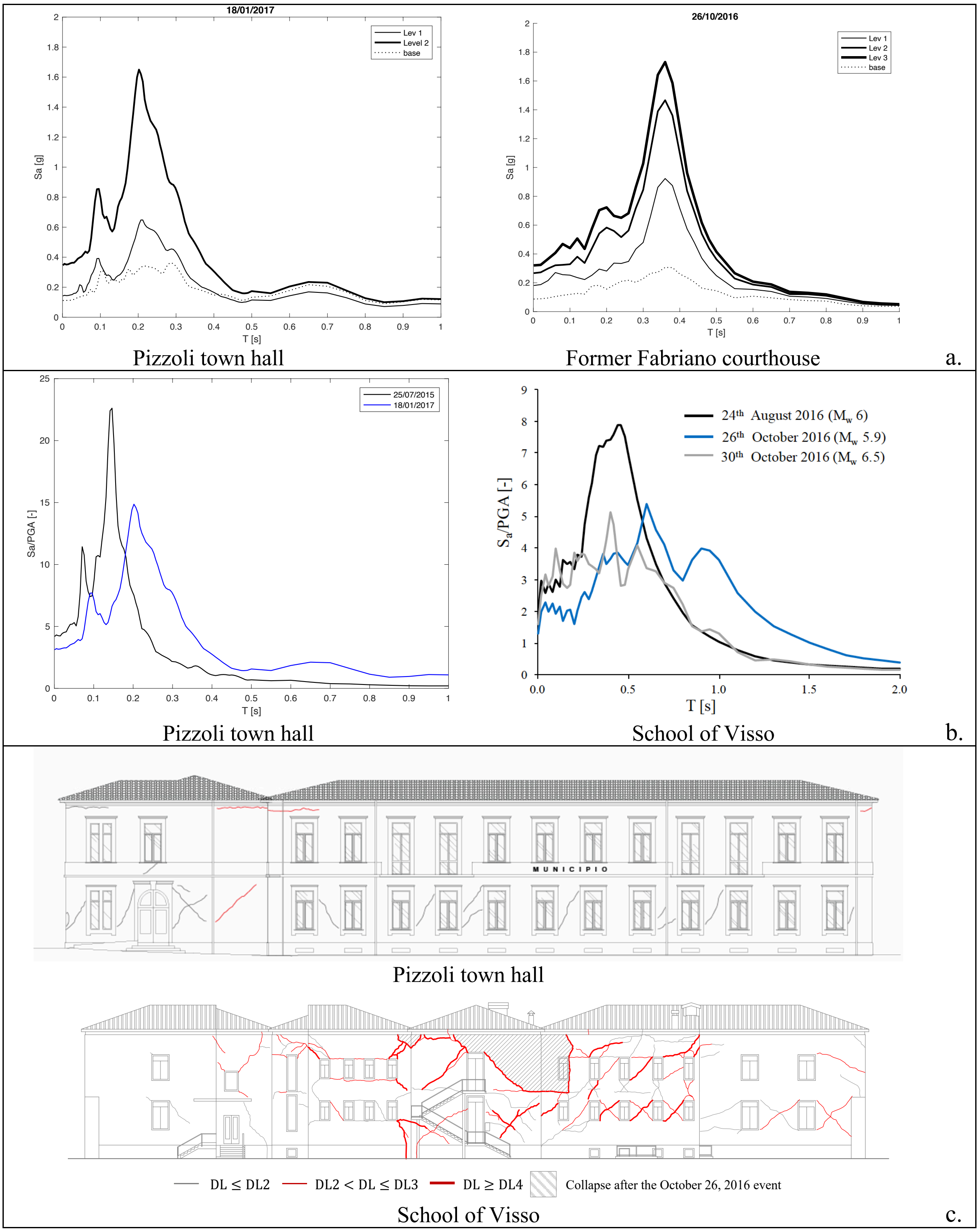


Fig. 2 – a) Amplification phenomenon recorded by the monitoring system on the Pizzoli's town hall (main event of 18/01/2017) and on the former Fabriano Courthouse (main event of 26/10/2016-19:18); b) Effects of nonlinearity on the floor spectra shapes for the Pizzoli town hall and the school of Visso; c) Example of damage exhibited by these latter buildings after the main shocks of 18/01/2017 (Pizzoli's town hall) and of 26/10/2016 (school of Visso) – figures adapted from [11] and [12].

In order to properly interpret the results, it has to be underlined that, while the Pizzoli town hall exhibited a moderate damage only after the main event of 18/01/2017, the school of Visso exhibited a significant damage after the 26/10/2016 second shake, but it remained almost the same during the one of 30/10/2016. Moreover, as discussed in [8], the school in Visso suffered damage cumulation phenomena especially passing from the event of 24/08/2016 to 26/10/2016. Although the floor spectra obtained from i*n-situ* measurements have shapes more irregular than those obtained from the experimental tests (especially when the structure enters in the strong nonlinear field as in the case of the building in Visso), one can recognize the same trend already described in Fig. 1a. Obviously, this trend emerged in a more systematic way from the results of the experimental campaign, where the same record was scaled at the base up to inducing increasing damage in the prototype. Conversely, it is more difficult to be interpreted on existing buildings, since the floor spectra come from different seismic events.

3. Basics of the proposed analytical floor spectra formulation

The expression applied in this paper has been originally proposed by the Authors in [9]. It allows to proper describe the phenomena presented in §2: by evaluating the floor spectra in different points of the building and at different levels; and by considering the contribution of the more relevant modes, when properly combined. The expression needs to know only: the response spectrum at the base; the main dynamic parameters of the selected modes; and the damping features of the main structure and of the secondary element/local mechanism to be verified.

Eq. (1) summarizes the used expression, which gives the acceleration floor spectra at the level Z of the main structure (where the element to be verified of period T and damping ξ is placed) as:

$$S_{aZ}(T,\xi)=\sqrt{\sum_{k=1}^{N} S_{aZ,k}^{2}(T,\xi)} \quad \left(\geq S_a(T)\,\eta(\xi) \quad for\ T>T_1 \right) \tag{1}$$

where: $S_a(T)$ is the acceleration response spectrum of the ground motion; N is the number of considered modes; $S_{aZ,k}(T,z)$ is the contribution of mode k^{th} that is given by:

$$S_{aZ,k}(T,\xi)=\begin{cases} \dfrac{AMP_k\ PFA_{Z,k}}{1+\left[AMP_k-1\right]\left(1-\dfrac{T}{T_k}\right)^{1.6}} & T\leq T_k \\ \dfrac{AMP_k\ PFA_{Z,k}}{1+\left[AMP_k-1\right]\left(\dfrac{T}{T_k}-1\right)^{1.2}} & T>T_k \end{cases} \tag{2}$$

where:

– $PFA_{Z,k}$ is k^{th} peak floor acceleration that depends on the modal parameters of the main structure in terms of natural periods (T_k), modal participation coefficients (γ_k) and modal shapes ($\psi_k\ (x\ y\ z)$) and its viscous damping ξ_k. Furthermore, it depends on the ground spectrum $S_a(T_k)$ calculated in correspondence of the structure natural period T_k and properly reduced through the damping correction factor $\eta(\xi_k)$:

$$PFA_{Z,k}=S_a(T_k)\,\eta(\xi_k)\,\left|\gamma_k\,\psi_k(x,y,z)\right|\sqrt{1+4\xi_k^2} \tag{3}$$

– AMP_k is an amplification factor of the $PFA_{Z,k,}$ defined by two contributions: f_k that depends only on the viscous damping of the main structure, and f_s that depends only on that of the secondary element. The expressions proposed to calculate these latter are:

$$f_k = \xi_k^{-0.6} \tag{4}$$

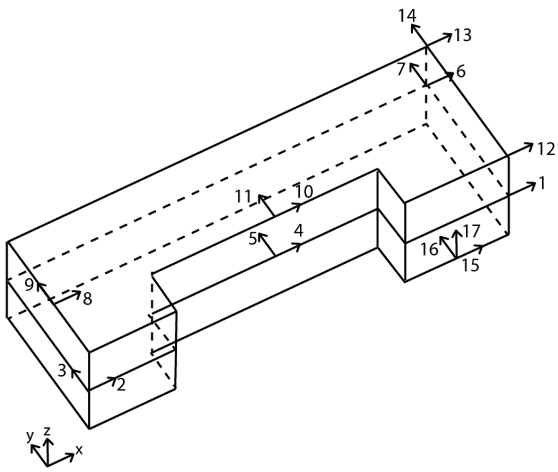
$$f_s = \eta(\xi) = \sqrt{\frac{0.1}{0.05+\xi}} \geq 0.55 \tag{5}$$

This formulation considers linear the main structure. However, it is possible to consider its nonlinear behavior through an equivalent nonlinear system, taking into account the period elongation and an increased damping ξ_k. For more details, the interested reader may refer to [9].

4. Application to the Pizzoli Town Hall

4.1 Overview on the available data

The Pizzoli town hall (Fig. 3a), built around 1920, is a simple structure, quite regular in elevation and with a C-shaped floor plan, whose dimensions are about 38 x 12.5 m. The building has two levels, a basement and a non-habitable attic characterized by a pavilion roof. The walls are built with a quite regular stone masonry and the horizontal floors are characterized by thin iron beams and hollow bricks capped by a RC slab.



a. b.

Fig. 3 – a) Pizzoli's town hall building; b) Sensor layout

The structure has been instrumented since 2009 with a permanent accelerometric monitoring system suitable for recording both strong-motion earthquake and low vibrations and tremors, with accelerations from 10^{-4} to 2 g (where *g* is the gravitational acceleration) [13]. The sensor layout is reported in Fig. 3b. As one can see, some accelerometers are bi-axial and are placed at different levels of the structure; in addition, one three-axial sensor is located at the foundation in order to measure the seismic input applied to the structure. This latter instrument is very important in order to evaluate the amplification effects of the floor accelerations as respect to the ground/base excitation. Records from the different main shocks, secondary seismic events and ambient noise are available as well. However, in this paper, the recordings of the secondary event of the 25th July 2015 (with *PGA* values around 0.001 g) and of the main shock of 18th January 2017 (PGA_x=0.112g; PGA_y=0.100g) were used for the floor spectra evaluation. In particular, after this main shock, the structure exhibited a moderate damage (Fig. 2c), characterized mostly by shear cracking in the piers and some pseudo-vertical cracking at the intersection among some orthogonal walls (justified by a poor quality of the wall-to-wall connection among these walls).

A numerical model of the building was developed in Tremuri ([14], [15]), following the Equivalent Frame (EF) modelling approach, which considered only the in-plane response of masonry walls. According to this approach, each wall is discretized by a set of masonry panels (piers and spandrels), in which the non-linear response is concentrated, connected by a rigid area (nodes). Once set up the EF model, it was firstly calibrated in the elastic field thanks to the dynamic identification data provided under operational conditions [16] and then validated in the nonlinear field by comparing the numerical results with the experimental data recorded by the permanent monitoring system [11]. Fig. 4 shows the modal shapes of the first four modes obtained from the numerical model. In particular, from the figure, it is possible to see that mode 1 is a translational mode in the y direction, while mode 3 is a translational mode in the x direction.

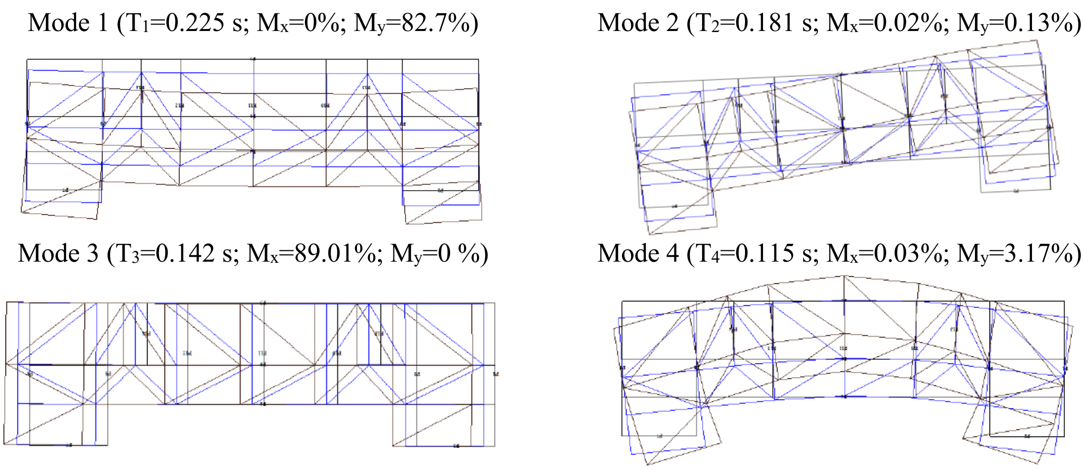


Fig. 4 – Numerical modal shapes of the first four modes

Since the Pizzoli's town hall is quite regular and with stiff horizontal diaphragms, it can be assumed as licit to neglect higher modes in the floor spectra definition and consider only the contribution of the fundamental ones in the directions of interest. For this reason, in the floor spectra evaluation, only the contribution of the first four modes have been considered.

4.2 Floor spectra evaluation

In order to validate the expression recalled at §3, the experimental floor spectra (obtained from the floor accelerations recorded by the monitoring system) have been compared with the analytical ones derived from the application of the analytical expression briefly recalled at §3. In the following, it will be presented how the parameters necessary to compute the latter have been evaluated in the examined case.

The ground response spectrum has been determined from the accelerations applied to the structure recorded by the three-axial sensor placed at the building foundation (sensors n.15 and n.16 of Fig. 3b). Moreover, since in the examined case the floor spectra have been evaluated from the response spectra of ground motion accelerations $S_a(T_k)$ of an actual record, there was a strong sensitivity to the estimation of the period T_k, due to the presence of peaks and valleys. Hence, $S_a(T_k)$ has been evaluated as the integral in a proper range of the periods around T_k, assumed equal to $T_k \pm 0.06$ s.

The dynamic parameters useful to apply the expression for the floor spectra definition are the periods of the selected modes (T_k), the modal shapes (ψ_k) and the participation coefficients (γ_k). In the examined case, they have been assumed as specified below.

- *Concerning the periods:*
  - For the floor spectra evaluation of the secondary event of the 25th July 2015, the numerical periods obtained from the modal analysis performed on the model calibrated in the elastic field have been used.
  - Instead, for the floor spectra evaluation of the main shock of 18th January 2017, the analysis of the occurred damage (Fig. 2c) and of the numerical dynamic response simulated during the

seismic event showed that the structural response was in the moderate nonlinear field. Thus, an elongation of the fundamental periods has been assumed, coherently also with the experimental evidence (§2). In particular, the elongated periods have been computed accounting for a degradation of stiffness properties of masonry. The values have been calibrated considering as target the values obtained from the dynamic identification performed by means of input-output techniques by employing the examined recording (ReLUIS projects, Task 4.1 – [5]).

- *Concerning the modal shapes and the participation coefficients,* they have been assumed for both the considered events by evaluating a complete modal shape from the calibrated EF model developed in Tremuri, by assuming no change in the modal shapes during the seismic shock of 18th January 2017. This latter assumption is licit, since it has been checked that the modal displacements obtained for the different main shocks keep almost unchanged, meaning that no significant variation of the corresponding mode shapes occurred ([5], [17]). This is also coherent with the occurred damage level, that was moderate.

Finally, the damping factor of the building ξ_k (associated to each mode) has been evaluated following a two steps procedure. Firstly (a), the structural damping has been obtained from the experimental data in order to guarantee the best fitting with the peaks of the experimental response spectra. In particular, it has been obtained for each sensor and on the dominant mode, *i.e.* the one characterized by the major contribution in terms of the product P (Eq. (6)) normalized to the maximum one. Then (b), it has been determined only a value for each mode, evaluated as the mean of the damping factors obtained in the previous step.

$$P = S_a(T_k)|\gamma_k \psi_k(x,y,z)| \tag{6}$$

Table 1 collects the damping used for each mode and for each seismic event. It has to be pointed out that, for those modes with a negligible contribution in terms of product *P*, a damping equal to 5% has been assumed (this is the case of modes 2 and 4). As one can see, the values of damping in Table 1 are reasonable, being around 5% in the linear response and a bit higher (around 7%) during the slight nonlinear phase of the response.

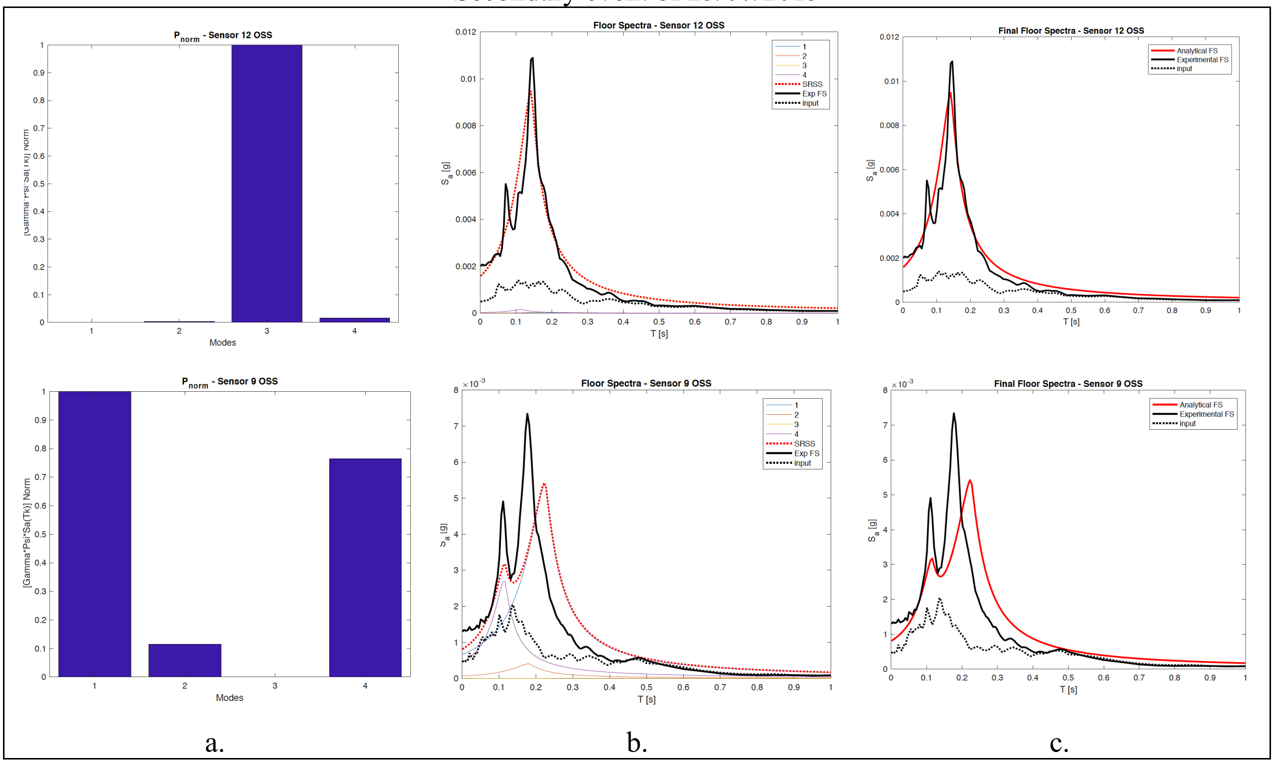
Since the paper's aim was not to evaluate the seismic input for the verification of an atop secondary element, in the examined case a damping factor ξ equal to 5% has been assumed.

Table 1. Damping assumed for each mode in the floor spectra evaluation (step 2)

Event	**Mode 1**	**Mode 2**	**Mode 3**	**Mode 4**
25th July 2015	0.03	0.05	0.05	0.05
18th January 2017	0.06	0.05	0.07	0.05

Fig. 5 shows the comparison between the experimental (in black) and analytical (in red) acceleration floor spectra obtained from two sensors placed at the second level of the building (sensor n.12 and n.9 of Fig.3b). The comparison is provided both for the secondary event of 25th July 2015 and for the main shock of 18th January 2017. In particular, the figure illustrates: a) the importance of the selected modes (in terms of product *P* normalized to the maximum one); b) the floor spectra evaluated for each mode; c) the final floor spectra, evaluated by the SRSS combination. It is interesting to observe that, while for sensors n.12 only the contribution of mode 3 is relevant, instead for sensor n.9 the final floor spectra is characterized by two peaks: the more significant one is due to the contribution of mode 1 (that is the dominant one), while the second one is due to the contribution of mode 4. From these results, it is possibile to observe in both cases a quite good agreement of the analytical floor spectra with the experimental data.

Secondary event of 25/07/2015



Main event of 18/01/2017

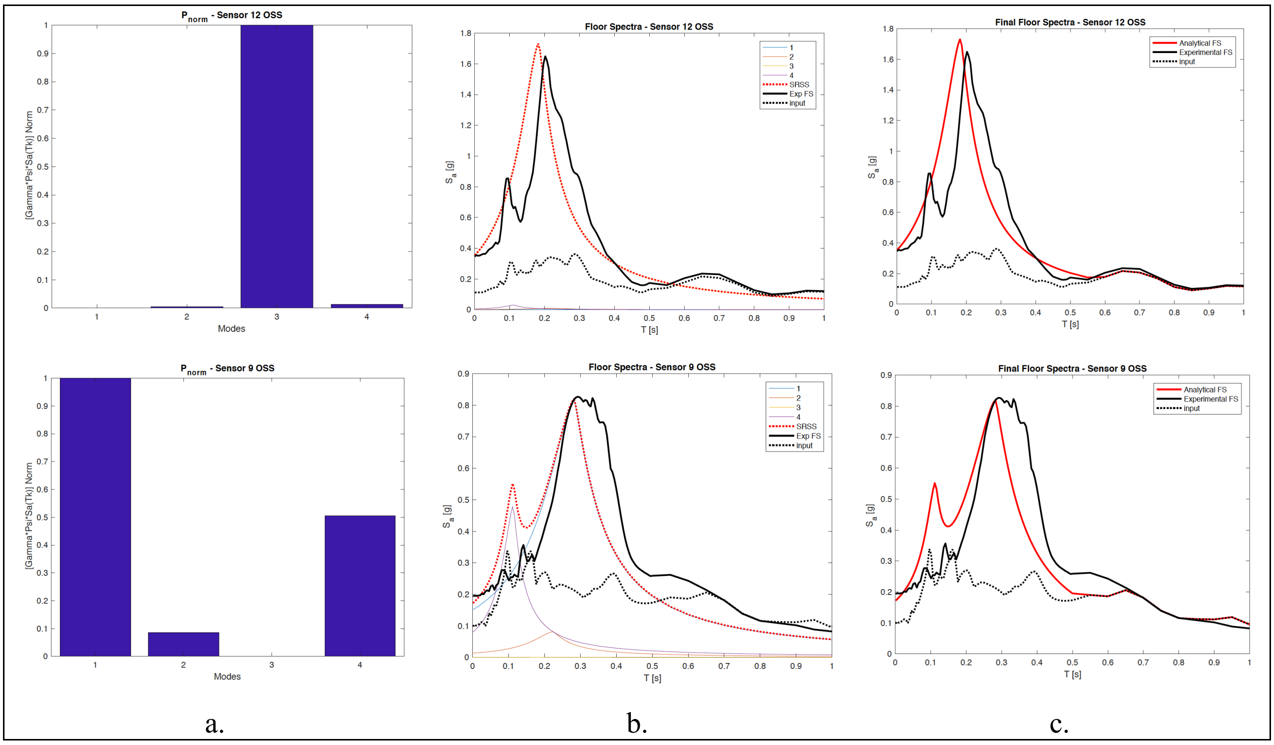


Fig. 5 – a) Contribution of modes in terms of product *P*; b) Floor spectra evaluated for each mode; c) Final floor spectra

5. Conclusions and ongoing research

The paper presents the application and validation of an analytical expression for the floor spectra definition proposed by the Authors to an existing masonry building. In particular, the building consists of the Pizzoli town hall that has been permanently monitored since 2009 by the Italian OSS and it was hit by the 2016/2017 Central Italy earthquake. Records from different main shocks, secondary seismic events and ambient noise were available. These data allowed for the calibration of a numerical model of the building in the elastic field and its validation in the moderate nonlinear phase. A validation of the expression has here been presented, by comparing the experimental floor spectra (obtained from the accelerations time history recorded by the sensors) with the analytical ones obtained by applying the proposed expression. All the parameters necessary to apply the formulation have been directly derived from the numerical model and the *in-situ* measurements. The availability of some recordings acquired during a minor event of 25/07/2015 allowed to validate the expression in the liner field. However, since the case-study exhibited a moderate damage after the seismic event of 18/01/2017 (Central Italy earthquake), the reliability of the expression can be verified in the moderate nonlinear field as well. This research is still ongoing, since it can benefit of many other *in-situ* measures from actual earthquakes on various existing buildings monitored by OSS. These data on other complex structures will constitute essential sources for a better understanding of the rather complex phenomenon.

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