# Testing the dynamic behaviour of floor diaphragms for the seismic assessment of URM buildings

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## *Abstract*

The dynamic behaviour of horizontal diaphragms plays a fundamental role in the seismic response of existing buildings. Indeed, it is well known that the floor diaphragms are responsible for the dynamic coupling and collaboration among the resistant elements, as well as for the redistribution of the seismic action in the nonlinear regime. The fulfilment of these fundamental structural tasks, which depends on the diaphragm in-plane stiffness and on the effectiveness of the boundary connections, can be particularly critical in existing masonry buildings, which are often characterised by timber floors or vaults that tend to exhibit a nonrigid in-plane behaviour. An in-depth knowledge of this subject is mandatory to guide the engineering judgment in the a priori assumptions governing the mechanical modelling, as well as to enable the a posteriori validation of the seismic assessment. To this purpose, the authors have developed a model-driven procedure to investigate the dynamic behaviour of the diaphragms by means of ambient vibration measurements. The procedure, employing at least two biaxial sensors for each floor diaphragm, solves an inverse kinematic problem to discriminate and estimate the diaphragm rigid rotation and macroscopic angular deformation from vibration data. A perturbation approach can be employed to run the procedure also in the typical operational case of minimal sensors availability. The rigid, quasi-rigid or deformable diaphragm behaviour of the observable structural modes is evaluated in the frequency domain, comparing the magnitudes of the power spectral densities associated to the rigid rotation and macroscopic angular deformation. Although the algorithm has already been successfully validated by means of laboratory data and tested through pseudo-experimental simulations against adverse field conditions, this paper investigates its application to full-scale measurements acquired on two existing unreinforced masonry (URM) buildings in Italy: the Pizzoli (AQ) town hall, in Abruzzo region and the Sanremo (IM) town hall, in Liguria region (Northwest Italy). The first application is supported by recordings from a permanent monitoring system installed by the Italian structural seismic monitoring network, whereas the latter by in-situ ambient vibration measurements. Emphasis is given not only to the capability of the procedure to support the calibration of numerical models, but also to its possible repercussions on the seismic assessment, in particular for simplified vibration-based approaches adopting the rigid diaphragm assumption. With this purpose, a more refined equivalent frame model of each structure – suitably calibrated to match the experimental modal parameters identified from the experimental measurements – is used to verify how finer rigid-diaphragm discretisations can improve the estimation of the mass participation factors, even for diaphragms commonly assumed as perfectly rigid.

*Keywords: deformable diaphragms; seismic engineering; existing buildings; structural models; ambient vibration tests.*

## 1. Introduction

The seismic assessment of existing buildings is a task of fundamental importance in earthquake-prone regions. Following the economic and life losses caused by recent earthquakes (discussed in [1] for those that hit Italy), this research field is currently attracting a growing interest from the scientific community. Among the other construction techniques, unreinforced masonry (URM) is a widespread solution in the longstanding building tradition of urban areas particularly vulnerable to the seismic hazard [2],[3],[4]. Unfortunately, recent earthquakes also revealed how the safety of strategic buildings can be critical in seismic-prone areas [5].

Given the large number of structures exposed to the risk, simple and reliable seismic assessment techniques are mandatory to put in place risk-mitigation strategies at large scale, guaranteeing both the safety and the preservation of the built heritage. In the perspective of efficient assessments, a quite common modelling choice for buildings – adopted by both the professionals and the researchers – is to consider the floor diaphragms to behave dynamically as perfectly rigid bodies in their plane. The rigid diaphragm assumption enables the use of reduced-order models, ensuring lighter and time-saving computations. This is the case of simplified methods for the seismic assessment of civil buildings based on experimental modal parameters [6]. In this framework, the Italian Civil Protection Department (CPD) developed the Seismic Model from Ambient Vibrations (SMAV), a simplified kinematic model to assess the operativity level of strategic buildings at the national scale [7]. Employing the so called Multi Rigid Polygon (MRP) model, the procedure is able to estimate the mass participation factors of the identified modes necessary for the simulation of the seismic response [8]. However, its adoption can be problematic in the case of masonry buildings, which are often characterised by deformable diaphragms such as timber or vaulted floors. The influence of deformable diaphragms on the seismic response of masonry buildings has been extensively studied in the past decades, both from the analytical [9] and experimental [10] point of view and is still being widely investigated nowadays [11], [12]. The technical circumstances in which the floor deformability has to be taken into account or – on the contrary – it can be neglected without compromising the reliability of the seismic assessment are still object of an open debate. Therefore, the matter is usually left to the expert judgment of the analyst.

Attempting to fill this gap, a previous research of the authors provided some operational tools to support the analyst choices, exploiting ambient vibration measurements on the floor diaphragms [13]. The developed procedure discriminates and estimates the diaphragm rigid rotation and the macroscopic angular deformation from vibration data, exploiting a perturbation approach in case of minimum sensor availability. The rigid, quasi-rigid or deformable diaphragm behaviour of the observable structural modes is identified in the frequency domain, comparing the magnitudes of the rigid rotation and angular deformation power spectral densities. The paper illustrates the procedure application to two real case studies, emphasising the possible repercussions on the seismic assessment. In this regard, focus is made on the role played by the diaphragm deformability on the estimation of the mass participation factors according to SMAV. In particular, the strategic URM buildings selected as case studies are the Pizzoli (AQ) town hall, in Abruzzo region and the Sanremo (IM) town hall, Liguria region. In the first case the analyses are based on the ambient vibration recordings from a permanent monitoring system, installed by the Italian structural seismic monitoring network (OSS) [14] in strategic buildings of Central Italy [15]. In the second case, the application exploits the in-situ vibration tests carried out in several strategic buildings in Liguria [16], a region in Northwest Italy.

## 2. Data-driven identification of diaphragm deformability

The ambient vibration data acquired by two or more bi-axial sensors on a floor diaphragm can be employed to estimate its in-plane displacement field. Assuming the linear relationship

$$\mathbf{v}_{\mathrm{j}} = \mathbf{v}_0 + \mathbf{H}\boldsymbol{\Delta}\mathbf{x}_{\mathrm{j}} \tag{1}$$

where, as first approximation, the displacement vector $\mathbf{v}_{\mathrm{j}} = (\mathrm{u_j}, \mathrm{v_j})$, measured by the *j-th* sensor in the position $\mathbf{x}_{\mathrm{j}} = (\mathrm{x_j}, \mathrm{y_j})$ is assumed to depend – through a linear relation governed by the proportionality matrix $\mathbf{H}$ – on the position difference $\boldsymbol{\Delta}\mathbf{x}_{\mathrm{j}} = \mathbf{x}_{\mathrm{j}} - \mathbf{x}_0$ with respect to the position $\mathbf{x}_0$ occupied by a reference sensor measuring the displacement vector $\mathbf{v}_0$. The identification of the diaphragm deformation can be stated as an inverse problem aiming to determine the four components $H_{hk}$ (with $h, k = 1, 2$) or, equivalently, the physical quantities

$$\Omega = 1/2(H_{21} - H_{12}), \qquad \Gamma = H_{21} + H_{12}, \qquad E_{xx} = H_{11}, \qquad E_{yy} = H_{22} \tag{2}$$

which, by virtue of a formal analogy with the linear kinematic of deformable bodies, can be mechanically interpreted as *rigid rotation* $\Omega$, s*hear strains* $\Gamma$ and *normal strains* $E_{xx}, E_{yy}$. The macroscopic shear and normal strains, if not null, describe the global changes in shape and volume of the deformable floor diaphragms, respectively. Introducing the column vector of the unknowns $y = (\Omega, \Gamma, E_x, E_y)$, if vibration data from $N \geq 2$ biaxial sensors are available, the general identification problem reads

$$\mathbf{Ay} = \mathbf{b}, \qquad \mathbf{A} = \begin{pmatrix} \mathbf{A}_1 \\ \vdots \\ \mathbf{A}_j \\ \vdots \\ \mathbf{A}_{N-1} \end{pmatrix} \quad \mathbf{b} = \begin{pmatrix} \mathbf{b}_1 \\ \vdots \\ \mathbf{b}_j \\ \vdots \\ \mathbf{b}_{N-1} \end{pmatrix} \tag{3}$$

where the matrices $\mathbf{A}_j, \mathbf{b}_j$ are related to the identification problem $\mathbf{A}_j\mathbf{y} = \mathbf{b}_j$ of the *j-th* sensor. Assuming that the sensors are *well placed* (so that $\mathbf{A}$ is full row rank) and remembering that $n = 4$ is the number of unknowns, in the case of minimum sensor availability in which $N = 2$, since $\text{rank}(\mathbf{A}|\mathbf{b}) < n$, the linear system (3) is underdetermined. Nevertheless, a solution can be obtained by adopting a suited perturbation approach [13]. Indeed, defining the auxiliary small parameter $\varepsilon \ll 1$ a proper variable ordering can be introduced

$$\Omega = \varepsilon\Omega' + \varepsilon^2\Omega'', \qquad \Gamma = \varepsilon^2\Gamma'', \qquad E_{xx} = \varepsilon^3 E_{xx}''', \qquad E_{yy} = \varepsilon^3 E_y''' \tag{4}$$

which states that the shear strain $\Gamma$ and the normal strains $E_{xx}, E_{yy}$ are respectively small and extremely small with respect to the rigid rotations $\Omega$. Solving the perturbation problem up to the third $\varepsilon$-order, reconstructing the general solution and then reabsorbing the auxiliary parameter $\varepsilon$ leads to the approximate solution

$$\Omega = \frac{1}{2}\left(\frac{\Delta v}{\Delta x} + \frac{\Delta u}{\Delta y}\right), \qquad \Gamma = \frac{\Delta u}{\Delta y} + \frac{\Delta v}{\Delta x}, \qquad E_{xx} = 0, \qquad E_{yy} = 0 \tag{5}$$

where the normal strains $E_{xx}, E_{yy}$ are found to be identically zero.

From a practical point of view, at least two *well placed* ($\Delta x, \Delta y \neq 0$) bi-axial sensors are required to estimate the rigid rotation $\Omega$ and the shear strain $\Gamma$, preferably located at the opposite corners of the diaphragm. Furthermore, the sensors should be properly fixed to the supporting walls at the floor height or to the structural part of the floor itself. Additional sensors placed in the mid-span could allow investigating possible differential shear deformations (in-plane *bending* deformation of the diaphragms) relevant for the seismic assessment. Finally, to synthetically judge about the diaphragm in-plane rigidity or deformability, the power spectral densities (PSD) of $\Omega$ and $\Gamma$ should be estimated and compared in the neighbourhood of the natural frequency of the identified natural modes. A perfectly rigid diaphragm is expected to return an ideally null shear strain spectrum. Assuming a negligible effect of the measurement noise, the $\Omega$-spectrum of a rigid torsional mode can be expected to be at least two order of magnitude greater than the corresponding $\Gamma$-spectrum. Thus, the $\Omega$ and $\Gamma$ modal amplitudes should differ for at least one order of magnitude. Although essentially conventional, this quantitative threshold is however fully consistent with the assumed ordering of the perturbation solution (4). Deformability modes of the diaphragm, on the other hand, should determine significant amplification peaks in the shear strain spectrum, quantitatively comparable with the rigid rotation in the limit case.

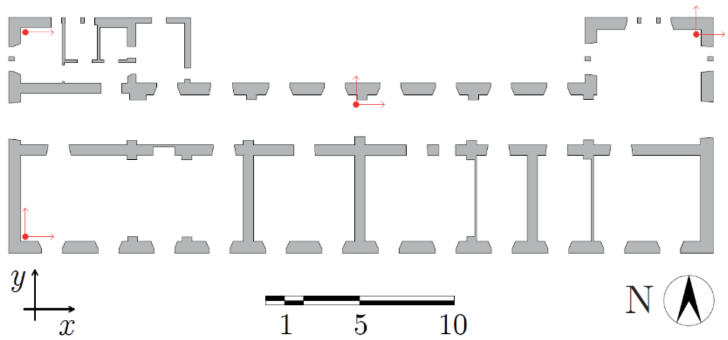
## 3. Full-scale ambient vibration measurements on URM buildings

### 3.1 Description of the case studies: the Pizzoli (AQ) and the Sanremo (IM) town hall buildings

The Pizzoli town hall building (labelled ‘PZ’ in the following) is a two-storey masonry building permanently monitored by the Italian structural seismic monitoring network (OSS) [14], located in the homonymous city in Abruzzo region, Central Italy. The strategic structure rises in the city centre (42 26'10.1"N 13°18'05.2"E) with two floors above the ground level and a non-habitable rooftop (Fig. 1a). The building plan has a rectangular shape of dimensions 36.75 m x 11.9 m, with the longest side oriented in the East-West direction. The inter-storey height increases from 3.6 m at the ground level to 4.25 m at the first level. Two external bearing walls and a central spine wall run along the whole building. The spine wall is crossed by three secondary walls in the front part of the building, creating a continuous rear corridor (Fig. 1b). Nevertheless, the structure maintains the symmetry with respect to the North-South direction. The masonry piers are built with a cut local stone varying in thickness from 65 cm to 75 cm at the first level, from 30 cm to 65 cm at the second level and from 45 cm to 65 cm at the rooftop. A structural survey provided valuable information about the typology of the floor diaphragms [15], which are composed of thin iron beams and hollow bricks capped by a reinforced concrete slab whose thickness is 16.5 cm and 12 cm at the first and the second level respectively. Furthermore, some thermographic images revealed the presence of perimetric reinforced concrete beams at the floor level.

*Bellevue Palace* ('SR') was a luxury hotel built at the end of the 19th century in Sanremo (IM), a city located on the west coast of Liguria region, Northern Italy. Today the building houses the city town hall, which holds the strategic role to coordinate the rescue operations in the municipality in the event of an earthquake. The structure rises on a gentle slope with four floors above the ground and a habitable rooftop (43°49'20.9"N 7°47'12.3"E, Fig. 2a). The building sides dimensions are 66 m x 16,90 m and the inter-storey height ranges from 4.75 m at the ground floor to 4.10 m at the top floor. The rectangular plan develops smoothly in the East-West direction, symmetrically with respect to the North-South direction, with a central spine wall running along the whole length of the building (Fig. 2a). similarly to the Pizzoli case. Four connecting walls orthogonal to the spine divide the plan in five parts, of which the middle and the two outermost are slightly projecting from the main façade. The entire western wing of the building is connected to a rear building for the whole height of the ground level (Fig. 2b). The constraint also extends to the second level in the midspan.

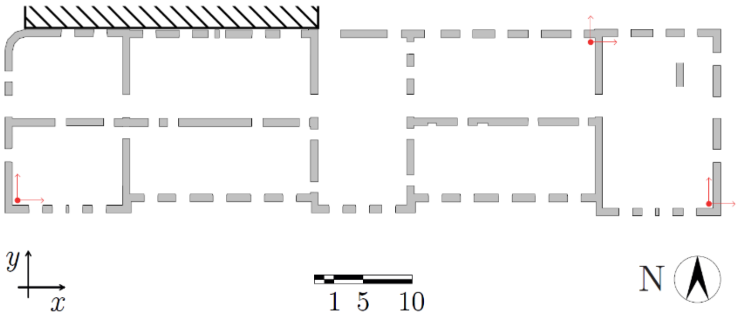
(a)




(b)

Fig. 1 a – Lateral view of the Pizzoli town hall building. b – Structural layout of the bearing walls and measurement setup (common to each floor).

(a)




(b)

Fig. 2 a – Front view of the Sanremo town hall building. b – Structural layout of the bearing walls highlighting the rear constraints and measurement setup (common to each floor).

For what concern the masonry walls, they are built with a cut local stone with good bonding, are 70 cm thick at the ground and become thinner with the height, down to a minimum of 50 cm at the rooftop, in which a timber structure supports the pitched roof. The horizontal diaphragms are probably composed by reinforced concrete slabs. However, no detailed documentation is available to confirm this hypothesis. In this regard, it should be noted that the eastern wing of the building has undergone several structural interventions, including the removal the spine walls at every floor and the replacement of floor slabs of the last two floors with cast-iron beams. These reasons motivated the employment of one additional sensor in this area (Fig. 2b).

### 3.2 Measurement setup and modal identification

The recordings of the ambient response of the Pizzoli town hall building, which have been provided by OSS, are acquired from one mono-axial and three bi-axial accelerometers permanently installed at each level of the building (Fig. 1b), with a sampling frequency of 250 Hz for at least one hour. The signals are then decimated by a factor of 5 and de-trended due to a linear increase of their mean value in some measurement channels.

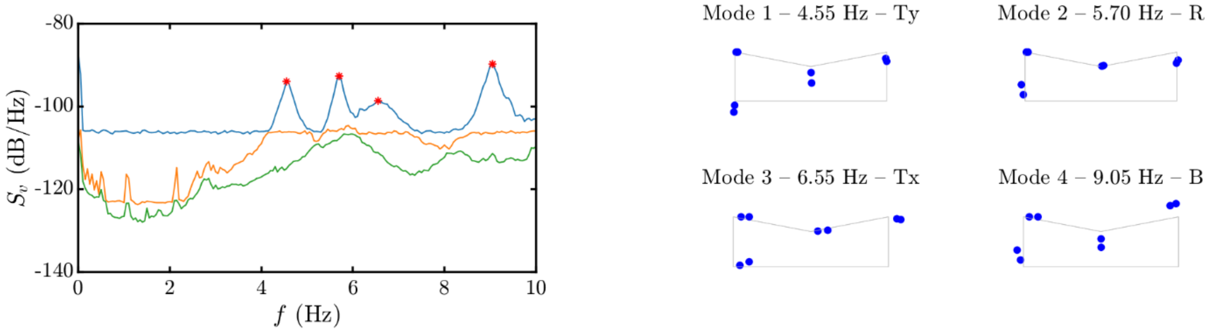
The ambient response of the Sanremo town hall building, on the other hand, is measured employing eight seismometers *Lennartz 3D/5S*, each paired with an independent data acquisition recorder MarsLite equipped with a 20 bit A/D converter, an SD card for data storage and a GPS receiver for time synchronisation. The measurement setup involves three sensors at each level of the building with two reference sensors on the rooftop, deployed in two partial configurations (Fig. 2b). The sensors are laid directly on diaphragm flooring close to the walls. The ambient vibrations – in terms of velocities – are acquired with a sampling frequency of 250 Hz for at least one hour for each measurement configuration. The processing involves the decimation by a factor of 5 and, according to the frequency response of the seismometers, the high-pass filtering below 1 Hz. For both the case studies, the frequency band investigated ranges therefore from 1 Hz to 25 Hz. Natural frequencies and mode shapes are identified using the Frequency Domain Decomposition (FDD) technique [17]. The auto- and cross-power spectral densities are estimated employing the Welch method [18] with 20 s Hamming windows and 50% overlap, resulting in a frequency resolution of 0.05 Hz.

Four modes below 10 Hz have been identified from the recordings of the ambient response of the Pizzoli building (named 'PZ' in the left columns of Table 1), as shown by the amplification peaks of the first singular value of the spectral density matrix (Fig. 3a). As shown by the mode shapes (Fig. 3b), the first identified mode at 4.55 Hz involves the translation of the floors along the y-direction ('Ty'), with modal displacements increasing with the height of the building. The second identified mode at 5.7 Hz appears as a torsional mode ('R'), with the maximum modal displacement located in the western part of the building. The third mode, identified at 6.55 Hz, shows again a translational behaviour but along the x-direction ('Tx'). Finally, the fourth identified mode at 9.05 Hz seems to be dominated by the bending of the floors in the horizontal plane ('B').

The ambient vibration tests on the Sanremo building were able to catch four natural modes below 10 Hz ('SR' in the right columns of Table 1), as highlighted by as many resonance peaks in the first singular value of the spectral density matrix (averaged over the two measurement configurations, Fig. 4a). The global mode shapes (Fig. 4b) are obtained scaling and merging the partial mode shapes based on the modal amplitude identified on the reference sensor(s). At 3.05 Hz and 3.65 Hz, the first and third identified mode both show a torsional behaviour of the structure in which the floor diaphragms rotate in their plane ('R') around the eastern and western part of the building respectively. The second identified mode at 3.35 Hz, on the other hand, is dominated by the translation of the floors ('T') along a diagonal direction, linearly increasing with the height.

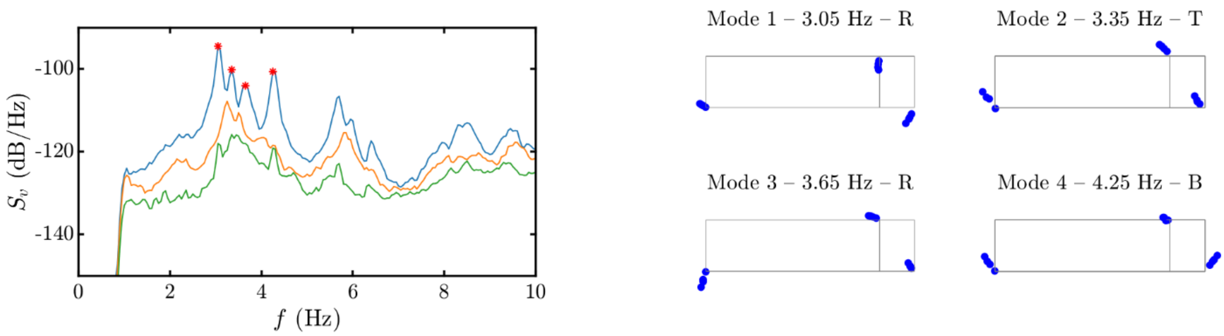
Table 1. Natural frequencies and mode shape types identified by FDD on the Pizzoli ('PZ') and Sanremo ('SR') town hall buildings.

| | PZ | | SR | |
|---|---|---|---|---|
| Mode | f (Hz) | Type | f (Hz) | Type |
| 1 | 4.55 | Ty | 3.05 | R |
| 2 | 5.7 | R | 3.35 | T |
| 3 | 6.55 | Tx | 3.65 | R |
| 4 | 9.05 | B | 4.25 | B |




(a) (b)

Fig. 3 a – Pizzoli town hall building: first three singular values of the spectral density matrix. b – Global mode shapes of the first four identified modes.




(a) (b)

Fig. 4 a – Sanremo town hall building: first three singular values of the spectral density matrix (averages of the two measurement configurations). b – Global mode shapes of the first four identified modes.

The unusual presence of multiple torsional modes at very close frequencies, as well as the absence of a pure translational mode along the direction of minimum stiffness *y*, can be explained by the rear constraint imposed by an adjacent building (see § 3.1, Fig. 4b). Higher-frequency modes are affected by spatial aliasing due to the small number of sensors deployed. Nevertheless, the mode shape of the fourth identified mode – at 4.25 Hz – shows significant deformation components of the floor diaphragms, involving their in-plane bending (‘B’) as in the Pizzoli case.

## 4. Identification of the diaphragm dynamic behaviour

For both the buildings the rigid rotation $\Omega$ and shear strain $\Gamma$ are estimated at each level employing N = 3 sensors (in the Pizzoli town hall the mono-axial sensor is discarded), whose number is sufficient to evaluate the axial strains $E_{xx}$, $E_{yy}$ as well according to the exact solution of the identification problem [13].

Concerning the Pizzoli town hall building, even if the first identified mode ‘Ty’ appears to be a rigid translation of the floors along the *y*-axis (Fig. 3b), the presence of a small amplification peak in the PSD of the shear strain $\Gamma$ highlights a non-negligible deformation component (Fig. 5a). This shear deformation is even more significant at the first floor (Fig. 5b) and concurrent with the axial deformation component $E_{yy}$ (Fig. 5d). On the other hand, the motion exhibited by the diaphragms in the second ‘R’ and third ‘Tx’ identified modes can be considered as quasi-rigid in the plane, given the absence of any $\Gamma$-peaks (Fig. 5a,c). It has to be noted, however, that for the rotational mode ‘R’, the spectral ratio $G_{\Omega\Omega}/G_{\Gamma\Gamma}$ is around 20 at the ground level and it decreases to 10 at the first level. Thus, the modal amplitude of the rigid rotation is only 3 to 4.5 times greater than the one of the shear strain, failing to achieve a significative difference. The fourth identified mode ‘B’ is characterised by the highest deformation peaks in the shear and axial strains along the *y* direction, consistently with the bending of the diaphragms recovered by the mode shape (see § 3.2, Fig. 3b). The modal decomposition is thus able to identify the in-plane bending of the diaphragm as a superposition of shear and axial strains.

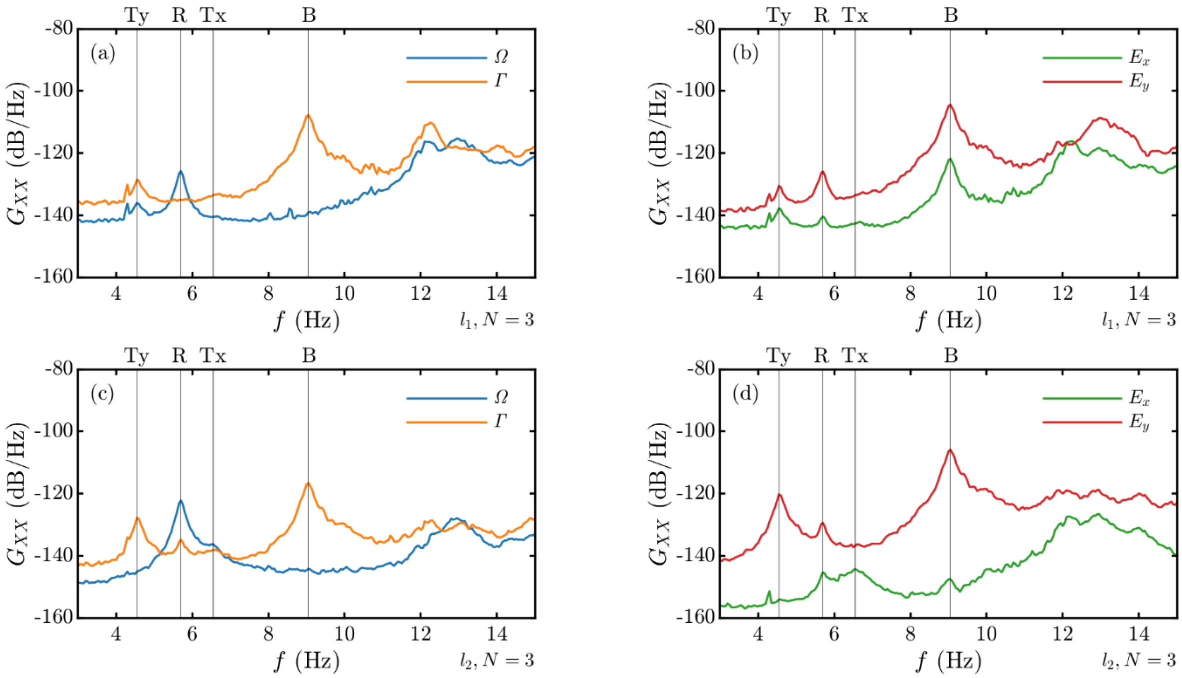
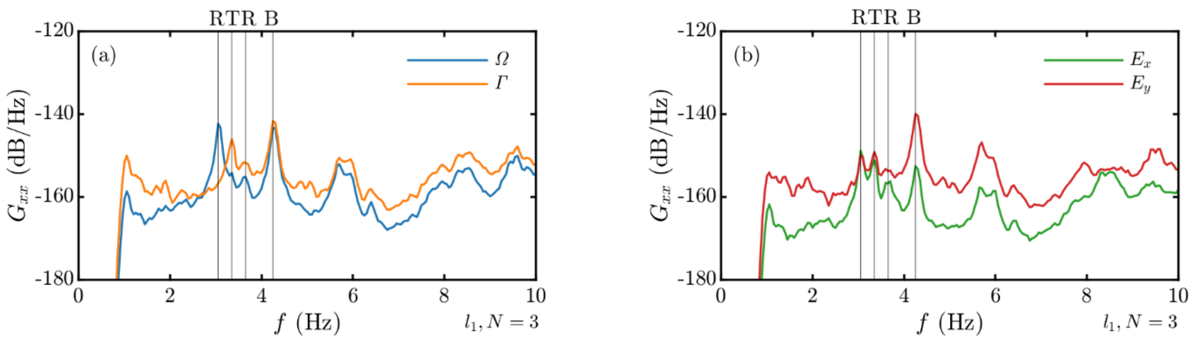



Fig. 5 Power spectral densities a,c – of the rigid rotation Ω and shear strain Γ and b,d – of the axial strains $E_{xx}, E_{yy}$ at the ground and first level of the building for N = 3.

In the case of the Sanremo town hall building, the PSDs shows that the first identified mode 'R' involves a rigid rotation of the first two levels, since Ω is two order of magnitude greater than Γ (Fig. 6a,c). More precisely, the spectral ratio $G_{\Omega\Omega}/G_{\Gamma\Gamma}$ is maximum at the second level, with a value higher than 100. This means that the amplitude of the rigid rotation is at least one order of magnitude greater than the shear strain, suggesting a substantial rigidity of the diaphragms. The second identified mode 'T', given the absence of particular amplification peaks, can be considered as a rigid translation of the diaphragms (at least at the second and fourth floor, Fig. 6c,g). The rigid-diaphragm behaviour, however, seems to vanish at the upper floors (Fig. 6e,g), where the axial strains $E_{xx}, E_{yy}$ become more and more relevant (Fig. 6f,h). This can be reasonably explained considering the structural interventions realised in the building, which include the removal of some reinforced concrete slabs at the last two floors (see § 3.1). In the neighbourhood of the bending mode 'B', the PSDs highlight the importance of the shear (Fig. 6a,c,e,g) and axial (Fig. 6b,d,f,h) deformation components with respect to the rigid ones, as already suggested by the mode shapes (see § 3.2, Fig. 4).



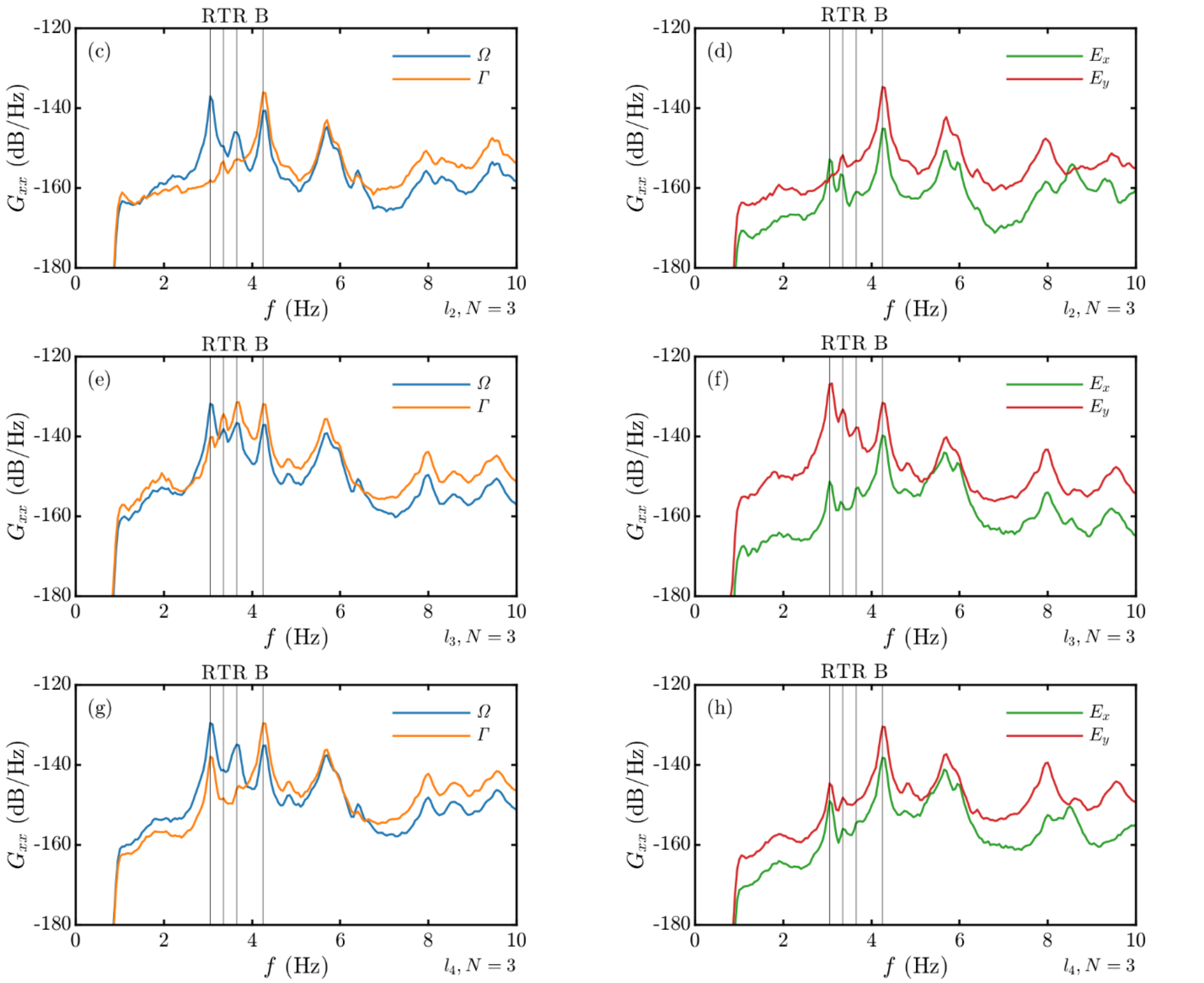



Fig. 6 Power spectral densities a,c,e,g – of the rigid rotation Ω and shear strain Γ and b,d,f,h – of the axial strains $E_{xx}$, $E_{yy}$ at the first, second, third and fourth level of the building for N = 3.

## 5. Influence of the diaphragm deformability on the seismic assessment

Based on the above considerations, the possible adverse effects of diaphragm deformability on the simplified seismic assessment carried out according to SMAV [7] deserve to be investigated. It may be worth recalling that the SMAV procedure, adopting the so-called multi rigid polygon model (MRP) [8], by-pass the common impossibility to recover a complete modal model of the building from output-only measurements, i.e. to obtain mass-normalised mode shapes. To this purpose, the model assumes that each floor behaves in its plane as one or more rigid bodies of known mass, according to their mechanical properties, geometry and constraints. This simplification allows to build a reduced-order mass matrix of the structure and to recover the mass participation factors of each mode shape, which are necessary for the simulation of the seismic response. Indeed, a finer discretisation of the floors in rigid-behaving portions allows a more reliable estimation of the modal masses, especially in complex-shaped buildings and even more in the presence of deformable diaphragms. On the other hand, since two bi-axial measurements for each polygon are required to recover its translational and rotational motion (§ 2), this reflects in a larger number of sensors, raising considerably the efforts of vibrations tests.

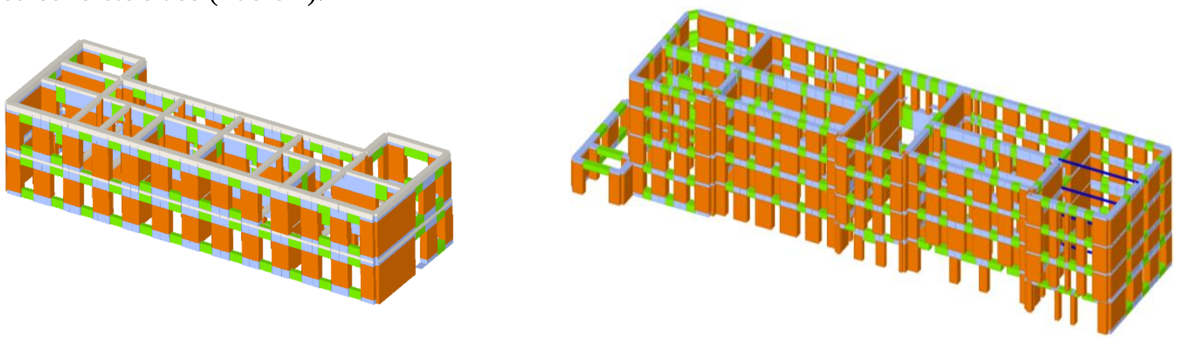
Once the complete set of experimental modal parameters (i.e. the identified natural frequency $f_k$, the mass-scaled mode shape $\phi_k$ and the damping ratio $\xi_k$ for each of the *k-th* identified mode) are known, SMAV estimates the response of the building to a given seismic input through a linear procedure with superposition of the effects. To compensate this simplification, the procedure brings into play some frequency-drift decay curves related to the nonlinearity of the structure [7]. This topic, however, will be discussed in future works. Assigned a pseudo-acceleration response spectrum $S_a$, the response $\boldsymbol{u}_k$ of the structure is evaluated trough

$$\boldsymbol{u}_k = \phi_k S_d(T_k, \xi_k)\boldsymbol{\Gamma}_k \tag{6}$$

where, for the *k-th* mode, $S_d = S_a/(2\pi f_k)^2$ is the displacement response spectrum, $T_k = 1/f_k$ is the natural period, $\xi_k$ is the identified (or assumed) damping ratio and $\boldsymbol{\Gamma}_k$ the modal participation factor.

It is clear from (6) that any error in the estimation of the modal participation factors directly reflects on the computation of the seismic response and thus on the reliability of the safety assessment. For this reason, to better understand the effect of different rigid-polygons discretisations and the potential influence of the diaphragm deformability (§ 4), the mass participation factors computed from MRP are compared with those estimated through more detailed equivalent-frame (EF) models of the buildings [19], suitably calibrated to match the experimental modal parameters identified from the experimental measurements. The EF technique is a common methodology in the modelling of URM buildings, especially in the seismic engineering field. If compared to more refined finite element models, EF models can be preferable by virtue of the computational advantages in the nonlinear simulations. The structural mesh is composed by deformable elements, namely *piers* and *spandrels* (respectively orange and green in Fig. 6), which are connected by undeformable *rigid nodes* (light blue in Fig. 6). According to the hypotheses of the software package [19], the horizontal diaphragms are modelled as orthotropic membranes with defined axial and shear stiffness.

The EF models of the Pizzoli and Sanremo town hall buildings have been developed based on the information acquired from the existing documentation, previous researches and in-situ surveys. Respecting the reasonable ranges of variation from the literature [20], the mechanical parameters which govern the stiffness of the masonry and the rigidity of the diaphragms are calibrated to match the identified experimental modal parameters. The calibration achieved a good agreement with the experimental results (Table 2), both for the natural frequencies (with a relative error |Δf| lower than 5% in the first three modes) and for the mode shapes (MAC ≥ 0.9). The final values of the Young moduli of the masonry $E_m$ are compatible with the observed masonry typology of cut stone and good bonding, whereas the equivalent shear stiffness moduli of the floor diaphragms $G_{eq}$ (for a conventional membrane thickness of 0.05 m) are consistent with the presence of reinforced concrete slabs (Table 2).



(a) (b)

Fig. 7 Equivalent frame (EF) mesh of a – Pizzoli and b – Sanremo town hall buildings.

Table 2. Natural frequencies of the EF models of the Pizzoli and Sanremo town hall building, relative error in frequency and values of the MAC with respect to the experimental results.

| | PZ | | | SR | | |
|---|---|---|---|---|---|---|
| | $E_m$ = 2450 MPa, $G_{eq}$ = 14250 MPa | | | $E_m$ = 2000 MPa, $G_{eq}$ = 4500 MPa | | |
| Mode | f (Hz) | \|Δf\| (%) | MAC | f (Hz) | \|Δf\| (%) | MAC |
| 1 | 3.40 | 4.3 | 0.98 | 3.04 | 0.3 | 0.95 |
| 2 | 4.30 | 3.4 | 0.94 | 3.34 | 0.3 | 0.9 |
| 3 | 5.24 | -3.6 | 0.94 | 3.48 | 4.6 | 0.97 |
| 4 | 8.62 | -8.5 | 0.95 | 4.26 | 0.2 | 0.94 |

The calibrated models have been then employed to generate pseudo-experimental mode shapes, simulating three different measurement setups for each building. Such configurations correspond to as many rigid-polygons discretisations (Fig. 8a and Fig. 8b). Regarding the Pizzoli rigid-polygons model, the three simulations named 1P, 2P, 4P account for one, two and four rigid polygons and require two, three and five bi-axial sensors respectively (red dots in Fig. 8a). As shown by the comparison with the EF model, the rough 1P discretisation generally tends to overestimate the mass participation factors with a percentage difference around 10% (Table 3). Indeed, one rigid polygon does not suffice to capture the behaviour of the fourth mode involving the bending deformations of the diaphragms (see § 4). The 2P and 4P models, on the other hand, seem to provide more reliable results, improving the mass participation factor of the first mode and succeeding in describing the fourth mode.

The Sanremo rigid-polygons model simulations are named 1P, 3P, 5P and account for one, three and five rigid polygons, requiring two, four and six bi-axial sensors respectively (red dots in Fig. 8b). From the comparison with the corresponding EF model, the 1P discretisation is again greatly overestimating the mass participation factors (Table 4). Finer discretisations, however, seem to have a significant influence only on the second mode. The discrepancies between the EF and the MRP models are probably due to the interaction with the adjacent building (§ 3), which can significantly affect the experimental mode shapes (as discussed in [8]). Indeed, the 3P and 5P are able to describe the fourth mode. Nevertheless, its effect on the seismic response is not appreciable given the negligible mass participation factor. To evaluate the influence of the different discretisations on the seismic assessment according to SMAV, two different seismic input, representative of 101 years and 475 years return periods, are employed in the form of local pseudo-acceleration spectra.

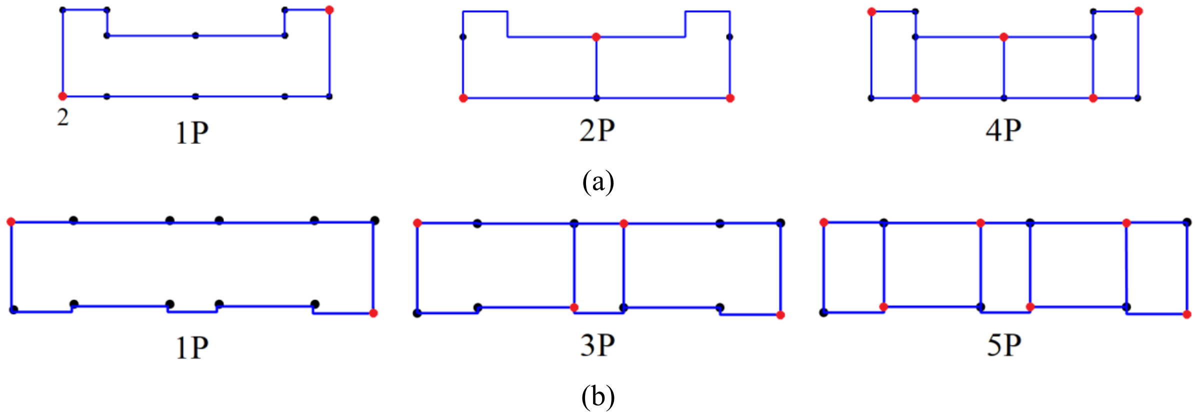



Fig. 8 Simulated measurement configurations (in red) for the MRP discretisation of – (a) Pizzoli with one, two and four rigid-polygons and of – (b) Sanremo in one, three and four rigid-polygons.

Table 3. Pizzoli town hall building: mass participation factors estimated from the calibrated EF model and from the MRP model with different rigid-polygons discretisations.

| PZ | | | EF model | | MRP model | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1P | | 2P | | 4P | |
| Mode | f (Hz) | Type | $m_x$ | $m_y$ | $m_x$ | $m_y$ | $m_x$ | $m_y$ | $m_x$ | $m_y$ |
| 1 | 3.40 | Ty | 0 | 0.85 | 0.01 | 0.97 | 0 | 0.91 | 0 | 0.90 |
| 2 | 4.30 | R | 0 | 0 | 0 | 0 | 0 | 0.01 | 0 | 0.01 |
| 3 | 5.24 | Tx | 0.89 | 0 | 0.99 | 0 | 1.00 | 0 | 0.99 | 0 |
| 4 | 8.62 | B | 0 | 0.10 | // | // | 0 | 0.08 | 0 | 0.09 |
| Total: | | | 0.89 | 0.85 | 1.00 | 0.97 | 1.00 | 1.00 | 0.99 | 1.00 |

Table 4. Sanremo town hall building: mass participation factors estimated from the calibrated EF model and from the MRP model with different rigid-polygons discretisations.

| | | | EF model | | MRP model | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1P | | 3P | | 5P | |
| Mode | f (Hz) | Type | $m_x$ | $m_y$ | $m_x$ | $m_y$ | $m_x$ | $m_y$ | $m_x$ | $m_y$ |
| 1 | 3.04 | R | 0.23 | 0.15 | 0.59 | 0.11 | 0.57 | 0.13 | 0.56 | 0.08 |
| 2 | 3.34 | T | 0.18 | 0.49 | 0.14 | 0.86 | 0.15 | 0.83 | 0.15 | 0.74 |
| 3 | 3.48 | R | 0.43 | 0.03 | 0.27 | 0.03 | 0.27 | 0.03 | 0.27 | 0.05 |
| 4 | 4.26 | B | 0 | 0 | // | // | 0 | 0 | 0 | 0 |
| Total: | | | 0.85 | 0.67 | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 | 0.87 |

Table 5. Pizzoli town hall building: maximum Inter-storey Drift Ratio ($IDR_{max}$) estimated by SMAV for two return periods of the seismic event.

| PZ | Tr = 101 years | | | | Tr = 475 years | | | |
|---|---|---|---|---|---|---|---|---|
| MRP model | $IDR_{max}$ (‰) | Input (%) | Level | Node | $IDR_{max}$ (‰) | Input (%) | Level | Node |
| 1P | 6.5 | 30x,100y | 1 | 2 (y) | 19.6 | 30x,100y | 1 | 2 (y) |
| 2P | 5.7 | 30x,-100y | 1 | 2 (y) | 16.8 | 30x,-100y | 1 | 2 (y) |
| 4P | 4.9 | 30x,-100y | 1 | 2 (y) | 14.8 | 30x,-100y | 1 | 2 (y) |

For the Sanremo town hall building, due to the negligible differences in the mass participation factors, the variations of the estimated seismic response have been found to be not significant. In the Pizzoli case, instead, a finer discretisation of the MRP provides an appreciable reduction in terms of maximum inter-storey drift ratio ($IDR_{max}$). The decrease of the estimated $IDR_{max}$ is around 13% going from 1P to 2P and around 25% from 1P to 4P, for both the seismic events (Table 5). However, this decrease partially mismatches with the corresponding decrement in the participant mass, which is generally more limited and negligible from 2P to 4P. A possible explanation can be related to a more appropriate modelling of the deformation components of the first mode, which has been previously highlighted by the evaluation of the diaphragms rigidity (§ 4).

## 6. Conclusions

The paper discusses the role of the diaphragm deformability in vibration-based procedures for the seismic assessment of URM building, referring in particular to SMAV [7]. Taking advantage of a simple technique previously developed by the authors [13], the dynamic behaviour of the floor diaphragms of two URM strategic buildings is investigated through ambient vibration tests. The analysis of in-plane rigid rotation and shear strain estimated from vibration data of the diaphragms, while confirming the rigid behaviour of some modes, highlights the presence of deformation components in some low-frequency modes. Despite the presence of reinforced concrete slabs, both the buildings exhibit an in-plane bending mode of the diaphragms below 10 Hz. This information is useful to enhance the calibration of the equivalent frame models of the structures, which are employed to evaluate the reliability of the rigid diaphragm assumption employed by SMAV. In this regard, the simulations carried on the Pizzoli EF model highlights how finer rigid-polygons discretisations can improve the estimation of the mass participation factors, even for diaphragms commonly assumed as perfectly rigid. This certainly implies a wider network of employed sensors and a greater experimental effort. Nevertheless, these findings suggest that this strategy can be recommended in building with geometrically elongated or complex plans. The results of the SMAV seismic assessment, although still preliminary, seem to be significantly sensitive to the different discretisations, thus justifying a further exploration of the subject.

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