Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 2056-2074

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COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

# EXPLORING SIMULATION TOOLS FOR URBAN SEISMIC ANALYSIS AND RESILIENCE ASSESSMENT

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**Keywords:** Community Resilience, Ideal City, Seismic Losses, Finite Element, Simulations.

**Abstract.** *Nowadays, the refined models of simulation to evaluate the seismic damage in an urban area are becoming of paramount interest for the scientific community. Regional seismic damage simulation can potentially provide valuable information that can facilitate decision making, enhance planning for disaster mitigation, and reduce human and economic losses. However, the application of refined models is limited because of their high computational cost and needs of highly experienced users. For these reasons, these approaches remain academic experiences. This study proposes a straightforward approach to the problem, at the same time competitive, to simulate the seismic response and to assess the degree of damage at urban scale. At first, the simulation of the standard building is performed using an equivalent single degree of freedom model. Subsequently, the same approach is extended to a number of regular buildings from a virtual city sample for time-history seismic response analysis. The first part of this work is devoted to present the methodology to prepare the one-degree-of-freedom model of the standard building by comparing it with a refined multi degrees of freedom model as a target. Finally, a seismic damage simulation of a virtual city sample is implemented to demonstrate the capacity and advantages of the proposed method at increasing seismic intensities for damage assessment. It is the starting phase for further multi-hazards analyses at the regional scale through agent-based models.*


doi: 10.7712/120117.5549.18264

## 1 INTRODUCTION

Civil Engineering structural systems have been usually considered at standard scale level: e.g. the building one, even if of large dimensions. They are usually characterized by classical elements, forces and consolidated computational procedures for their analysis as well. However, recent social developments and economic transformations, related to globalization, with integrated people activities within large urbanized areas, also characterized by high-density living and working, all together has changed the conditions of the last century toward regional dimensions. The current trend involves not only expected standard forces (wind, earthquake, etc.) but also new hazard with higher level components and indirect effects related to interconnections between static and dynamic systems. The resulting scenario leads to a new paradigm of vulnerability and, consequently, new analysis tools are expected to be developed with respect to the urban dimension.

The need of approaching such complex problem with rational tools is the object of this research work. In particular, new approaches to urbanized systems and large-scale simulations within a seismic scenario are explored, by evaluating multipurpose codes for numerical simulation and also simplified numerical approaches.

A sample of a 3-D virtual city is developed for evaluating the seismic effects at increasing intensities. It will be the starting step for further urban loss analyses through agent-based models, which will be updated with respect to performance losses.

Modern cities are systems with a high density of population and buildings. Once they are hit by earthquakes, the damage or collapse of buildings will result in huge economic losses and casualties. Regular multi-story buildings occupy a large proportion in urban areas, therefore they are mainly exposed to seismic damage and collapse due earthquakes. An accurate and efficient regional seismic damage prediction method is required to assess the seismic damage of regular multi-story buildings in order to mitigate the earthquake disasters in modern cities on critical infrastructures.

Several authors have proposed methods for modelling multi-degrees of freedom structural systems (e.g. [1,2]) with a high grade of complicacy the large number of regular buildings. For this purpose, an equivalent single-degree-of-freedom (SDOF) model of regular standard buildings is studied in this work within a multipurpose finite element (FE) code. It includes two main positive aspects: the structural analysis for damage assessment and the real time visualization in a single unit. The structural problem in literature is usually solved separately from the visualization problem (e.g. 3D urban polygonal models [3]).

In this study a single degree of freedom model is proposed to evaluate in details the seismic performance of the regular buildings trying to limit the complexity of the problem, not needing a super computer to conduct the analysis as in [4].

For developing the equivalent single degree of freedom model for the standard regular building a sequence of analyses for comparison has been performed. A refined FE analyses is firstly performed for identifying the multi-degrees-of-freedom (MDOF) system with respect to expected characteristics from guidelines (Eurocode 8 [5]). Then the SDOF is developed with reference to structural dynamics and then implemented in FE code Ansys [6] through beam and solid elements. This last option is promising for a further automatic implementation of the virtual city model by linking the 3D GIS city map and the simulation framework. Finally, we have developed a medium-sized district to assess the overall behaviour during an earthquake at increasing intensities. In particular, the damage assessment is of a paramount importance for subsequent simulations of critical infrastructures losses.

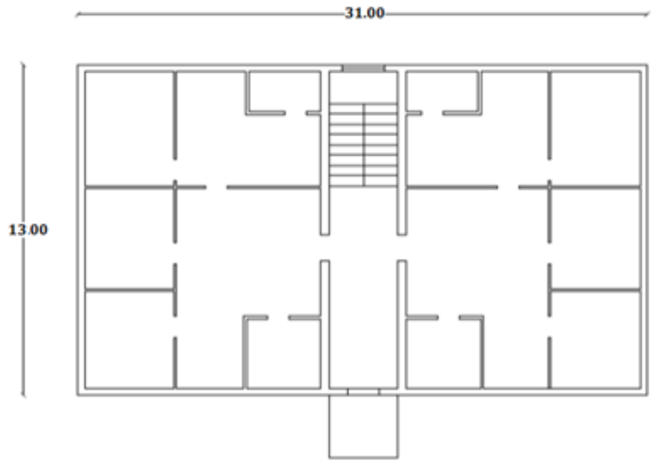
A 3D GIS of the ideal city is in a CAD format and it is imported into a FE code and the geometry of the whole buildings system (e.g. district) in a single step is imported. This procedure is performed accounting for the numbers of the floors of every building, the material and the structural typology (masonry, frame).

According to the Hazus report [7], the seismic damage is classified into five levels: none, slight, moderate, extensive, and complete damages. To assess the seismic damages of buildings, two sets of criteria are in existing literatures: the force-based damage criteria and the deformation-based criteria. Both have their advantages and limitations. As proposed by Xiong et al. [1] and Yin et al. [8] this study defines the damage states by taking the advantages of both the force-based and deformation-based damage criteria. The force-based damage criteria are used for the “slight” and “moderate” damage states, whereas the deformation-based criteria are used for the “extensive” and “complete” damage states. The proposed method has the ability to output the displacement contours for different time steps, thus making it possible to generate an animation of the building seismic responses. This research will provide a reference for the seismic damage prediction of large urban areas.

# 2 METHODOLOGY

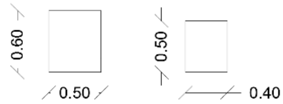
## 2.1 Description of the case study

A finite element model is prepared considering a real residential building in the ideal city with a rectangular footprint and a polygonal shape. It is 11 meters high and the inter-story distance consists in 3.5 meters except the first floor that is to 4.5 meters from the ground. The building has three floors. Figure 1a depicts the dimensions of the plant and Figure 1b the longitudinal section.




(a) - *Plant of the building -*


(b) - *Longitudinal section* -




(c) *Section pier* *Section beam*

Figure 1: Reference building.

The material is the reinforced concrete (C25/30). Figure 1c reports the typical section of the beams and of the piers, constant for all floors.

## 2.2 SDOF FE model of the regular ideal building: beam element approach

To perform the analyses a multipurpose FE software is employed (Ansys [6]). The reference building is firstly represented through a beam (element BEAM188 in Ansys 2 nodes and 6 degrees of freedom per node with cubic shape function). According to [6], the element is based on Timoshenko beam theory, therefore, shear deformation effects are included. The beam is fixed to the ground and a cross section equal to the shape of the footprint of the real building is assigned. The mass of the building is concentrated on the top of the beam (Figure 2). It is worth noting the polygonal shape performed by the FE post-processor (Figure 3). It results very useful for both the polygonal visualization of the virtual city and, at the same time, for low computational costs (low number of degrees of freedom).

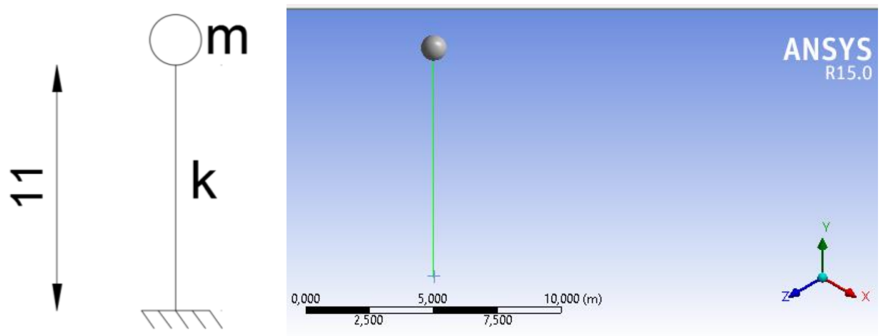



Figure 2: Beam model.

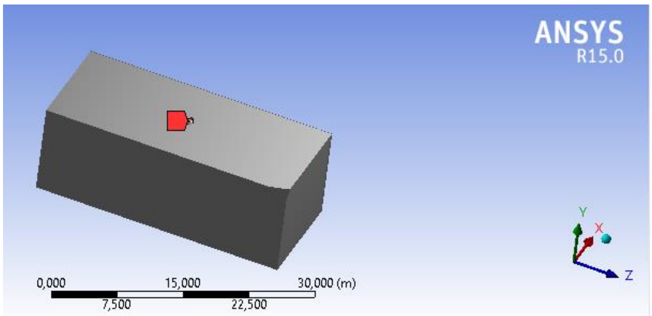



Figure 3: Polygonal output.

According with Eurocode 8 [5] the expected period of the structure is given from the following formula:

$$T = CH^{\frac{3}{4}} \tag{1}$$

Where $C$ is a constant in function of the material and $H$ is the height of the building. In our case the high is 11 meters then:

$$T = 0.075 \cdot 11^{\frac{3}{4}} = 0.45\, sec \tag{2}$$

For this period, the stiffness of the building can be computed. A self-weight of $11\,\frac{KN}{m^2}$ is fixed accordingly with a widely accepted range of $10\,\frac{KN}{m^2} \div 12\,\frac{KN}{m^2}$. Therefore, the total mass and the equivalent SDOF stiffness of the whole building are the following one:

$$m_{tot} = Weight\ for\ floor \cdot n°\ of\ floors \cdot Area\ of\ plant = 11 \cdot 403 \cdot 3 = 13299\ KN \cong 1355.6\ Kg \tag{3}$$

$$K = \left(\frac{2\pi}{T}\right)^2 m_{tot} = 259270850\,\frac{N}{m} \tag{4}$$

The displacement corresponding to the equivalent stiffness is then computed:

$$\frac{F}{K} = \delta^* \tag{5}$$

The cantilever bending stiffness is function of the inertia modulus of the cross section and the modulus of elasticity. The cross section is related to the building foot-print, while the modulus of elasticity can be tuned in the following identification procedure.

Thus, a general constant force $F$ is applied to the elastic model of the structure in the Ansys FE code, reading the top displacement $\delta$. The modulus of elasticity is then modified, within a tuning procedure, until $\delta$ results equal to $\delta^*$. Table 1 summarizes the tuning values.

| Applied force | K | $\delta^*$ | E | $\delta$ |
|---|---|---|---|---|
| 100 kN | 259270.85 kN/m | 3.85E-4 m | 43.6 MPa | 3.85E-4 m |

Table 1: Tuning values.

The same result can be obtained by considering the Timoshenko stiffness closed form:

$$v(z = H) = \frac{FH}{GA_S} + \frac{FH^3}{3EI} \tag{6}$$

Where v in the transversal displacement of the beam, z is the beam longitudinal coordinate, G is the shear modulus, $A_S$ is the shear surface ($A_S$ =0.85$A$) and $EI$ respectively the elastic and inertia moduli.

The mode shape of the first vibration mode for the regular ideal building can be assumed almost linear as depicted in Figure 4.

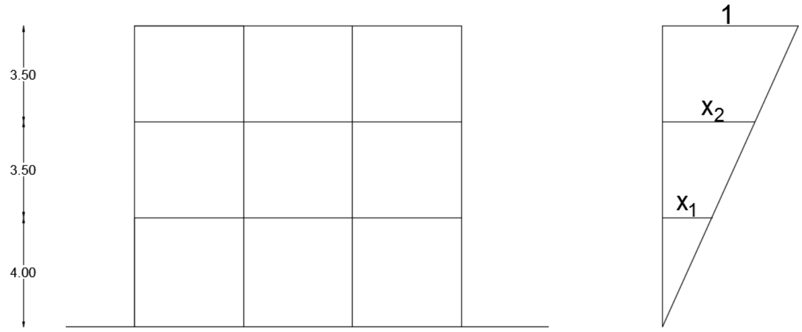



Figure 4: First mode shape of vibration.

Normalized eigenvectors corresponding to every floor can be computed by proportion. Thus, $x_1$ and $x_2$ in Figure 4 result:

$$1:11 = x_2:7.5 \rightarrow x_2 = 0.68 \tag{7}$$

$$1:11 = x_1:4 \rightarrow x_1 = 0.36 \tag{8}$$

A self-weight of $11\frac{KN}{m^2}$ is fixed for all floors except for the last roof floor, where the self-weight is $10\frac{KN}{m^2}$. The foot print area $A_{fp}$ and the modal mass associated to the first mode $m^*$ can be computed as:

$$A_{fp} = 403\ m^2 \tag{9}$$

$$m^* = \sum m_i \cdot \varphi_i = 11 \cdot 403 \cdot 0.36 + 11 \cdot 403 \cdot 0.68 + 10 * 403 \cdot 1 = 8640.2\ KN \tag{10}$$

Where $\varphi_i$ is the value of the eigenvector of $i$ floor. The circular frequency $\omega^*$ associated to the $i$ mode is then computed:

$$\omega^* = \sqrt{\frac{K}{m^*}} = \sqrt{\frac{\left(\frac{2\pi}{T}\right)^2 m_{tot}}{\sum m_i \varphi_i}} \tag{11}$$

The ratio $\frac{m_{tot}}{m^*}$ is a kind of inverse of the participation coefficient for the first mode of vibration. Finally, the fundamental period for the equivalent SDOF is:

$$T^* = \frac{2\pi}{\omega^*} \tag{12}$$

From the response spectrum of the city of Turin, with a behaviour factor equal to one, the spectral acceleration and the spectral displacement for $T^*$ is calculated.

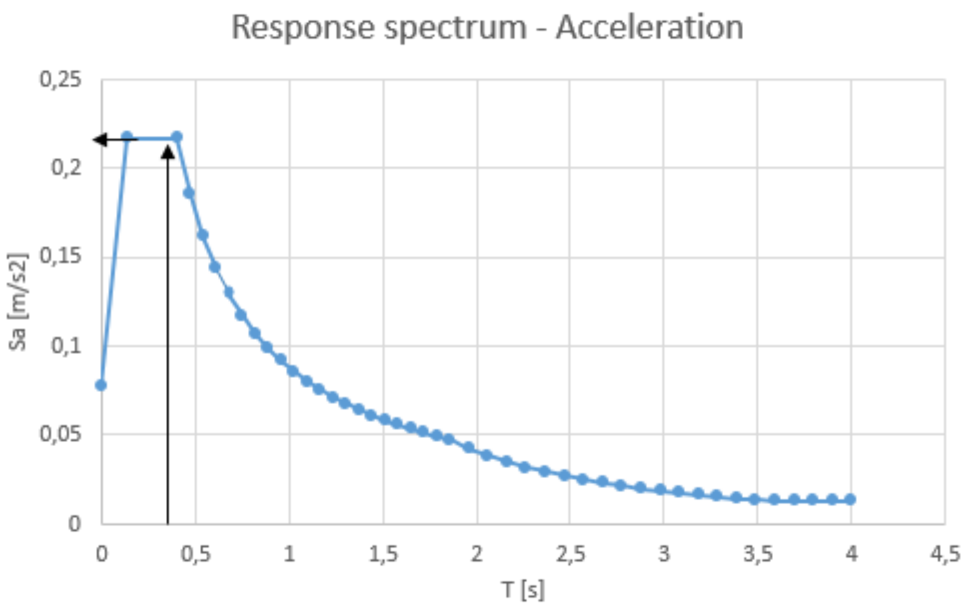



Figure 5: Response spectrum- Acceleration

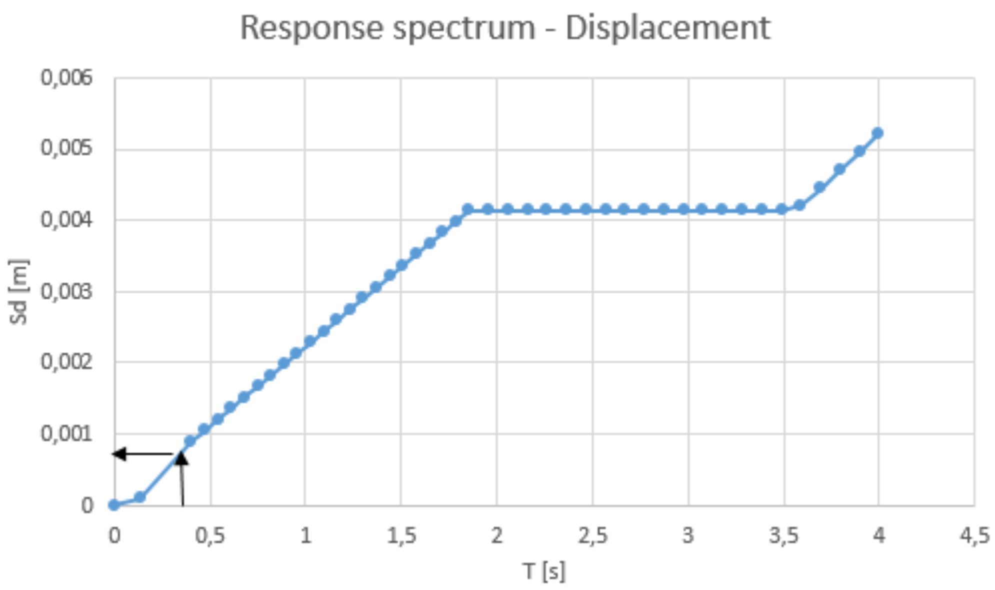



Figure 6: Response spectrum- Displacement

Appling to SDOF model on FE code a force $F = m^* S_a^*$ the resulting displacement response at the top $\delta_{S_a}$ is computed and compared with the spectral displacement $S_d^*$. Table 2 reports the spectral values. The displacement $\delta_{S_a}$ consists in 0.000708g meters, in good agreement with the spectral one.

| $S_a^*$ | $S_d^*$ | $T^*$ | $F$ |
|---|---|---|---|
| 0.217 g | 0.000747g m | 0.36 sec | 1874.9 kN |

Table 2: Spectral values.

### 2.3 MDOF FE model of the regular ideal building

A refined FE analyses of the regular building is performed in SAP2000 (Figure 7) [9] for reproducing the whole MDOF system behaviour. The weight of every floor is summarized in Table 3 accordingly with the first mode eigenvector. The corresponding masses are concentrated in the centre of mass at every floor. In this case of regular ideal building the centres of mass and stiffness are roughly in the same position.

| Floor | $W$ [kN] |
|---|---|
| 1 | 11 |
| 2 | 10.8 |
| 3 | 9.7 |

Table 3: Floors' weights.

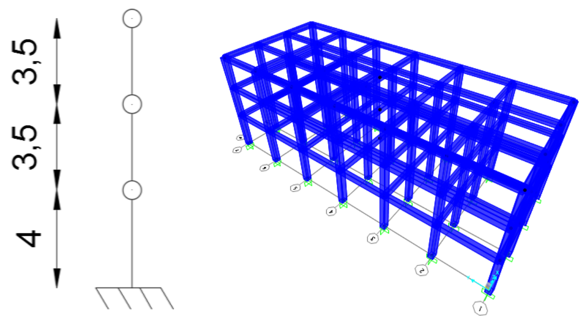



Figure 7: MDOF model on SAP2000

The fundamental period of the structure is computed through modal analysis. Then the response spectrum analysis is implemented in order to get the displacement at the top of the building. Satisfactorily comparison is reported in table 4. Figure 8 depicts the top displacement from the static spectrum analysis on the MDOF model.

| T [MDOF] | T [SDOF] | $\delta$ [MDOF] | $\delta$ [SDOF] |
|---|---|---|---|
| 0.38 sec | 0.36 sec | 0.0007g m | 0.0007g m |

Table 4: Period and displacement

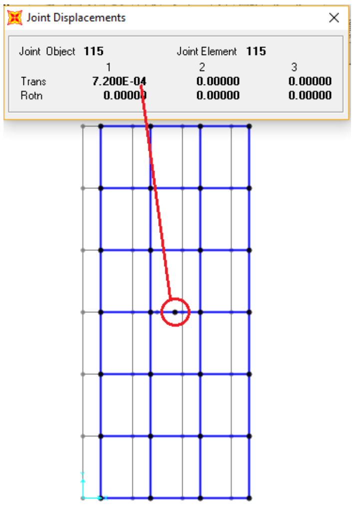



Figure 8: joint displacement at the centroid (top view).

The second mode of vibration (T2) also is translational but in the orthogonal direction to the first and the period of vibration is 0.33 seconds (Table 5). The second mode of vibration of the SDOF model is translational and the period is 0.29 seconds. Comparing these results, the SDOF model approximates satisfactorily the dynamic behavior of the structure in both directions.

| T2 [MDOF] | T2 [SDOF] |
|---|---|
| 0.33 sec | 0.29 sec |

Table 5: Period of the second mode of vibration.

## 2.4 SDOF FE model of the regular ideal building: solid element approach

The reference building is now represented through a solid element within the same multi-purpose FE software [6] employed for the beam element implementation of the previous section. The reason to use this finite element has a practical aspect: importing the 3D geometry of the buildings of the virtual city from CAD framework to Ansys, all volumes reproducing the buildings can be easily converted solid Fes. The advantage is to get and discretize all buildings of the city in Ansys in a single step, reducing essentially complications and time.
The calibration steps for the solid FE model are the same as the model with beam elements previously described. Thus, a general constant force F is applied at the top of the elastic model of the regular buildings in Ansys, reading the resulting top displacement ($\delta$). The modulus of elasticity is then modified, within a tuning procedure, until $\delta$ results equal to $\delta^*$. Table 6 summarizes the tuning values.

| Applied force | K | $\delta^*$ | E | $\delta$ |
|---|---|---|---|---|
| 100 kN | 259270.85 kN/m | 3.85E-4 m | 43.6 MPa | 3.85E-4 m |

Table 6: Tuning values.

Then the same spectral procedure through Figures 5 and 6 as for the SDOF FE model with beam element implementation is repeated with equivalent outcomes as in in Table 2. Figure 9 reports the top displacement resulting from the response spectrum equivalent static force; it results 0.000722g m as $S_d^*$ in Table 2. Therefore, the SDOF FE model of the regular ideal building with solid element is equivalent to that one with beam element approach.

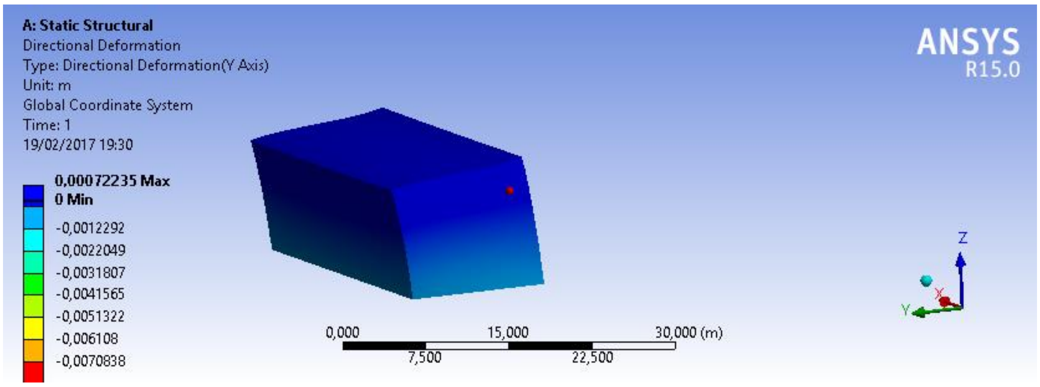



Figure 9: displacement of the solid model

## 2.5 Case of a finite number of buildings

By using the approach with solid element (section 2.3), the geometrical parameters are not necessary to calculate. The mechanical parameters (stiffness and mass) only are needed for the analyses computation. The method can be extended to all buildings of the ideal city. Figure 10 summarizes the procedure for an equivalent single degree of freedom model.

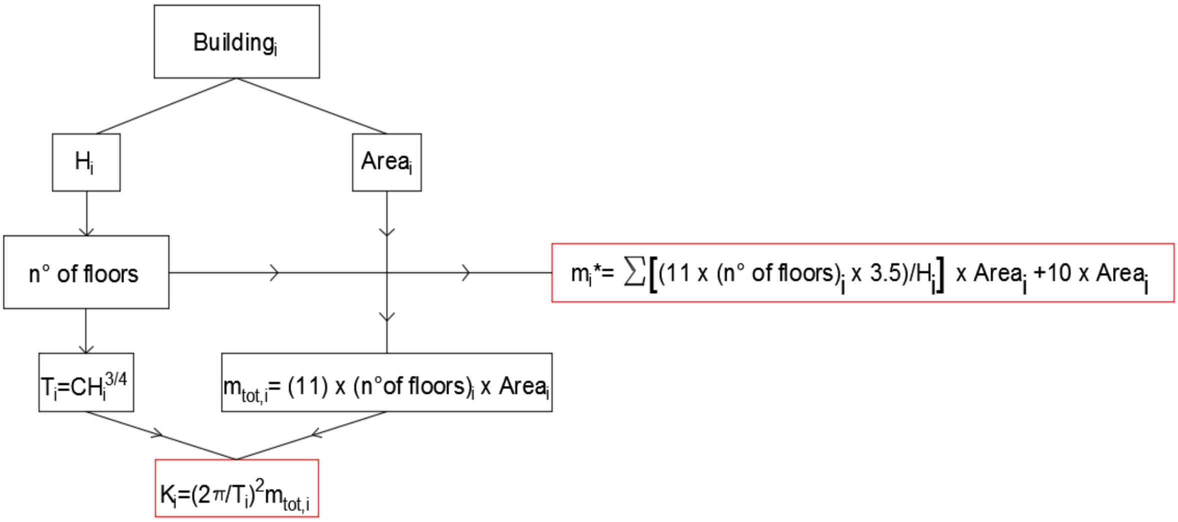



Figure 10: Method for stiffness and the mass identification for regular buildings.

Importing a 3D GIS in the FE code, the geometrical model of the regular buildings in a single step can be defined. However, before importing the geometry, a regular volume of the building (free of defects and negligible peculiarities) is necessary through the CAD software. Figure 11 exemplifies the general procedure for performing the solid FE mesh of the ideal city.


Figure 11: method to import the geometrical model in a FE software.

## 3 DISTRICT SEISMIC RESPONSE SIMULATION

A medium-sized district has been considered to firstly assess the overall procedure and the structural behaviour during an earthquake. The district is situated in Turin and contains nine regular buildings. Structures with “L” shape in reality are parts of buildings with a rectangular shape divided by a seismic joint. In figure 12 a top view of the district is reported.

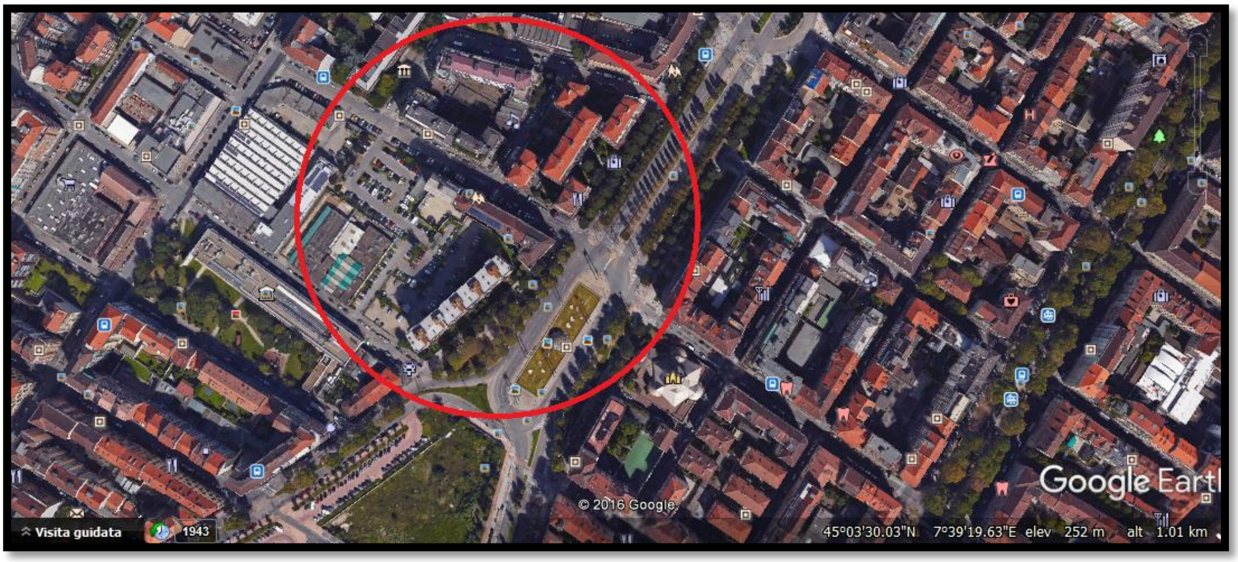
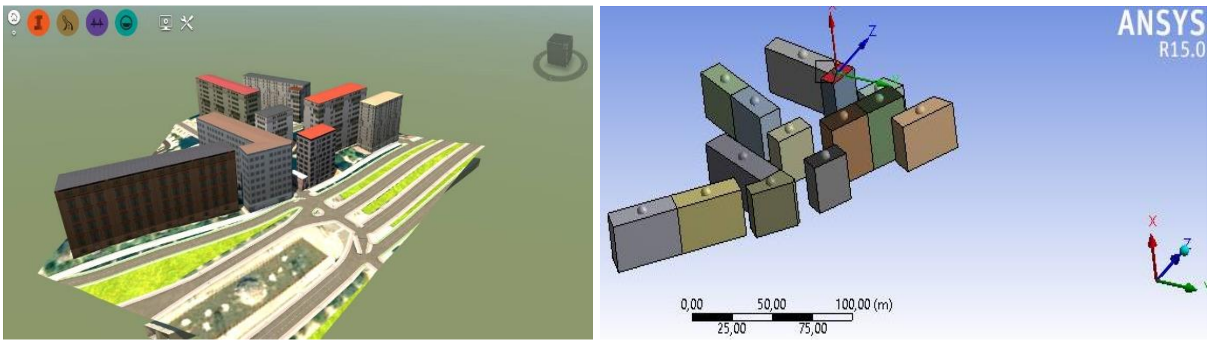


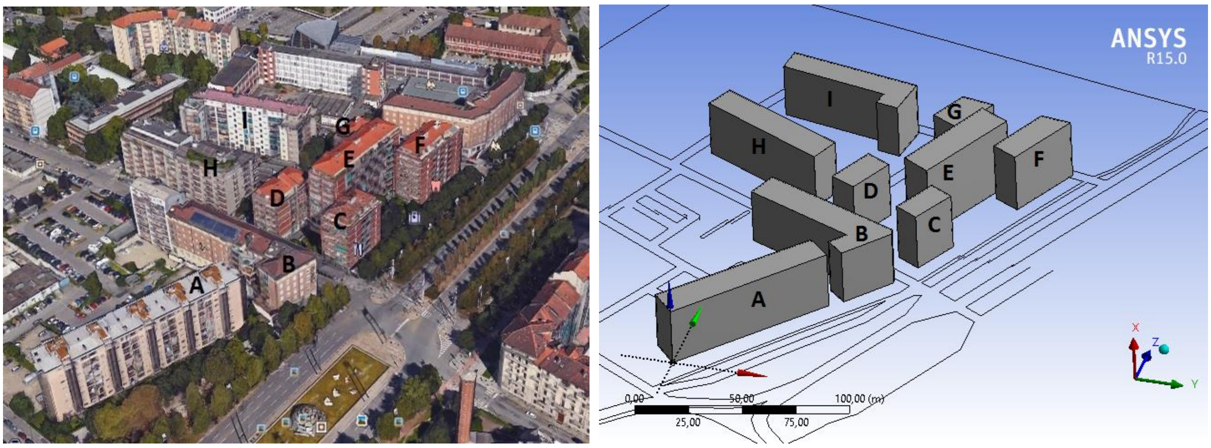

Figure 12: Study area

The 3D model of the buildings is defined through the design software “Infraworks 360” [10] and imported in Ansys. Figure 13 depicts the visualization of 3D model in Infraworks 360 and the model in Ansys. Figure 14 reports the comparison between the visualization of Google Earth and the FE software.




(a) (b)

Figure 13: the Infraworks visualization (a) and the Ansys one (b).




(a) (b)

Figure 14: The Google Earth visualization (a) and the Ansys one (b).

The stiffness and the mass for each building are computed as explained in Section 2 with the values in Table 7.

| Buildings | m* [Kg] | E [MPa] |
|---|---|---|
| A | 3825850 | 231.3024 |
| B | 6690600 | 233.4302 |
| C | 1952500 | 371.9756 |
| D | 1952500 | 337.2031 |
| H | 4892690 | 259.8985 |
| E | 5640000 | 406.9188 |
| F | 2461972 | 302.0051 |
| G | 1674141 | 247.6341 |
| I | 4467831 | 386.0803 |

Table 7: Mass and modulus of elasticity values.

The fundamental periods of the regular buildings in the district are computed through modal analysis. In Table 8 the frequencies associated to the first mode of vibration for every building are reported.

| Buildings | Frequency [Hz] |
|---|---|
| A | 1.3766 |
| B | 1.7686 |
| C | 1.4807 |
| D | 1.5161 |
| H | 1.6096 |
| E | 1.3259 |
| F | 1.6589 |
| G | 1.5616 |
| I | 1.7944 |

Table 8: Frequency of the first mode of vibration.

SIMQKE_GR software [11] is used for generating an accelerogram in function of the coordinates of the city, type of soil, topography of the area, total duration of the earthquake (Dr). It applied to the virtual city at increasing intensities.

| PGA [g] | Dr [s] |
|---|---|
| 0.002 | 20 |

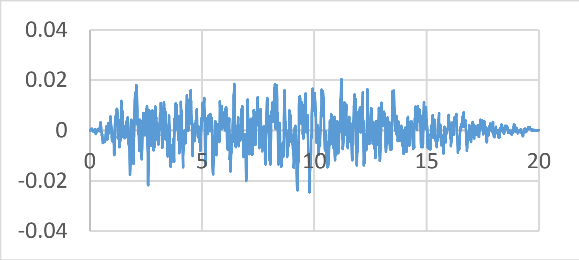



Table 9: peak ground acceleration (PGA) and total duration values

| PGA [g] | Dr [s] |
|---|---|
| 0.006 | 20 |

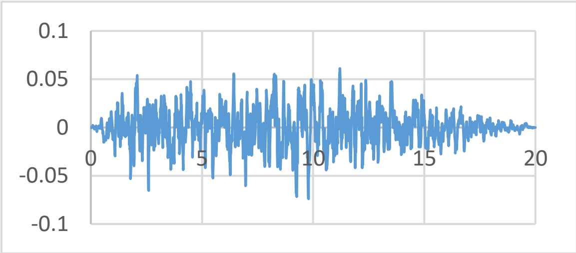



Table 10: peak ground acceleration (PGA) and total duration values

| PGA [g] | Dr [s] |
|---|---|
| 0.01 | 20 |

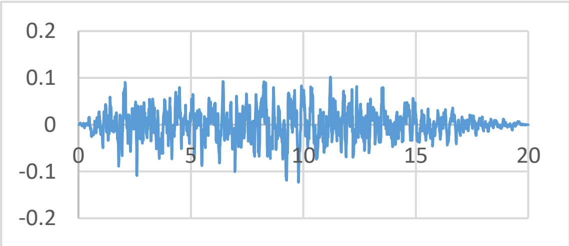



Table 11: peak ground acceleration (PGA) and total duration values

| PGA [g] | Dr [s] |
|---|---|
| 0.02 | 20 |

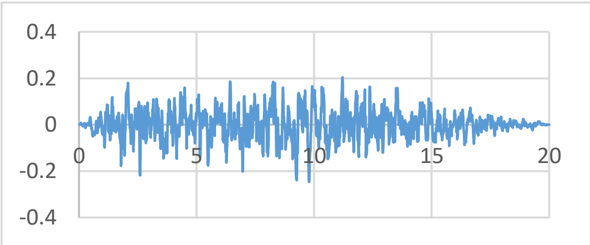



Table 12: peak ground acceleration (PGA) and total duration values

| PGA [g] | Dr [s] |
|---|---|
| 0.028 | 20 |

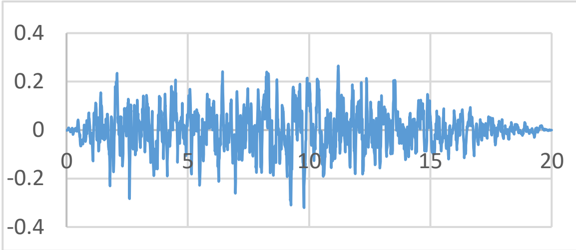



Table 13: peak ground acceleration (PGA) and total duration values

| PGA [g] | Dr [s] |
|---|---|
| 0.038 | 20 |

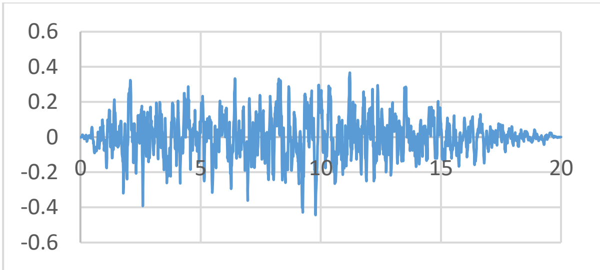



Table 14: peak ground acceleration (PGA) and total duration values

| PGA [g] | Dr [s] |
|---|---|
| 0.046 | 20 |

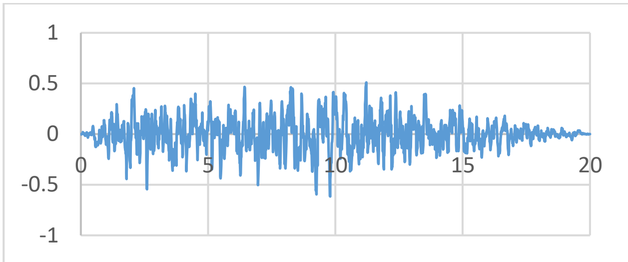



Table 15: peak ground acceleration (PGA) and total duration values

The following Figures 16 and 17 depict respectively the output displacements in direction *z* and *y* axes of the district stresses. With *x* the vertical axis, *y* and *z* the horizontal ones. Axis *y* is oriented with respect to North of 56°. The district seismic output is evaluated through linear analysis with direct integration of equation of motion. Damping is fixed to 0.05. In Turin the design peak ground acceleration 0.036g. In the figure 16 and figure 17 are represented the displacements along the two directions x,y concerning to the earthquake with a PGA equal to 0.046g

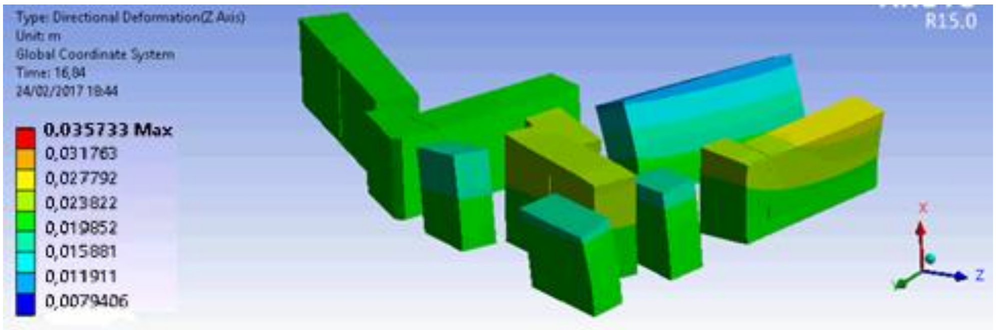



Figure 16: displacements along y axes

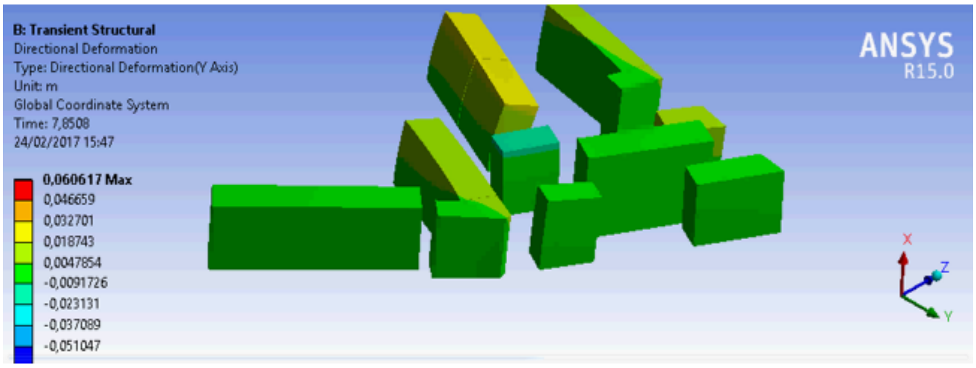



Figure 17: displacements along z axes

## 4 DAMAGE ASSESSMENT AT THE URBAN SCALE FOR LINEAR ELASTIC BUILDINGS MODELS

HAZUS [7] is software to estimate damage and losses caused by natural disasters. This methodology is developed by the Federal Emergency Management Agency (FEMA) to estimate the potential damage caused by natural disasters like earthquake. According to the Hazus report [7], the seismic damage is classified into five levels: none, slight, moderate, extensive, and complete damages. To assess the seismic damages of buildings, two sets of criteria are in existing literatures: the force-based damage criteria and the deformation-based criteria. The force-based damage criteria are used for the “slight” and “moderate” damage states, whereas the deformation-based criteria are used for the “extensive” and “complete” damage states. the RC frames reach the “slight damage” and “moderate damage” states when the internal force exceeds $V_{yield,i}$ and $\frac{V_{yield,i}+V_{peak,i}}{2}$, respectively, as shown in Fig.18 and reported in Table 8. The tri-linear backbone curve features three key points: the yield point, which is the turning point between the linear behaviour and the nonlinear behaviour and after which the stiffness is significantly reduced; the peak point, which is the point where the peak strength is reached; and the ultimate point, after which the story is deemed collapsed or completely damaged. The determination of strength and deformation parameters of each key point were discussed in the paper [1].

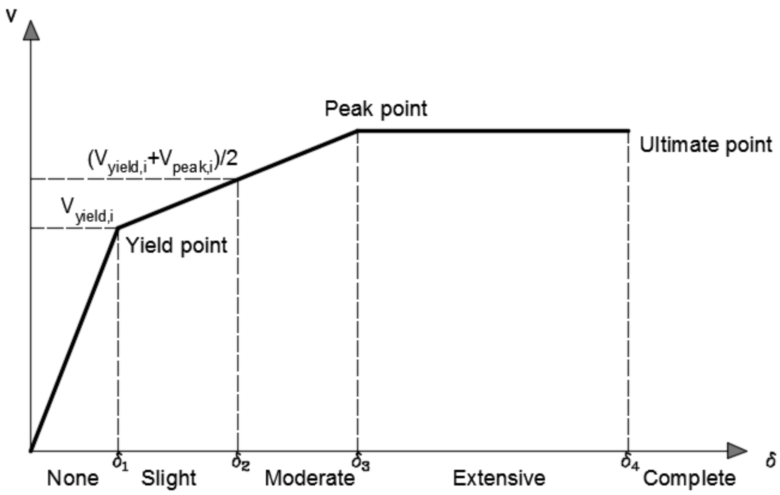



Figure 18: V-$\delta$ for Reinforce concrete frame

| | Slight | Moderate | Extensive | Complete |
|---|---|---|---|---|
| Reinforce concrete frame | $V_{yield,i}$ | $\frac{V_{yield,i}+V_{peak,i}}{2}$ | $\delta_{extensive}$ | $\delta_{complete}$ |

Table 10: Damage criteria

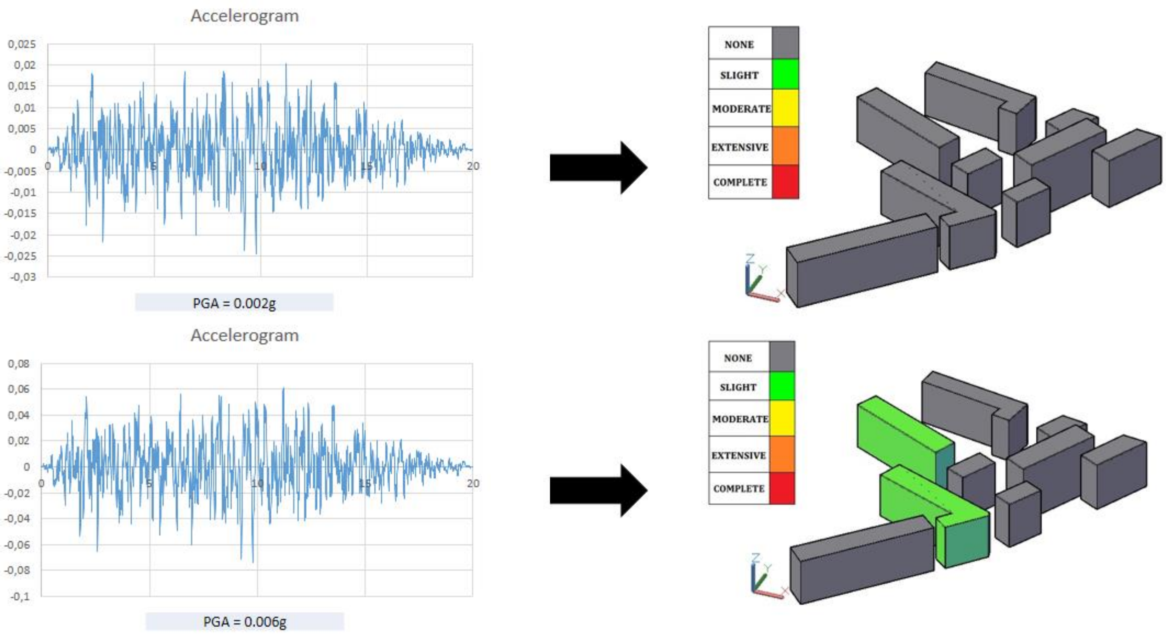



Figure 19: Damage state with PGA 0.002g and PGA 0.006g

Figures 19,20,21,22 depict through different colours the grade of damage of the buildings due to the seismic input discussed in section 3. The procedure identifies five different level of damage, accordingly with the implemented conditions.

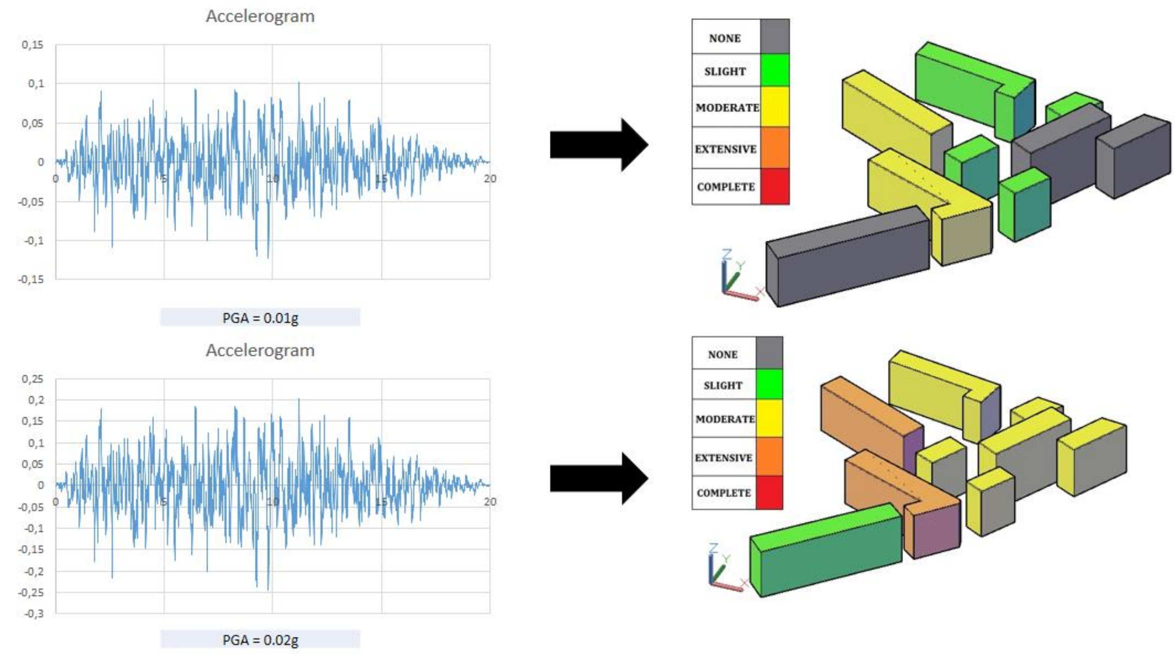



Figure 20: Damage state with PGA 0.01g and PGA 0.02g

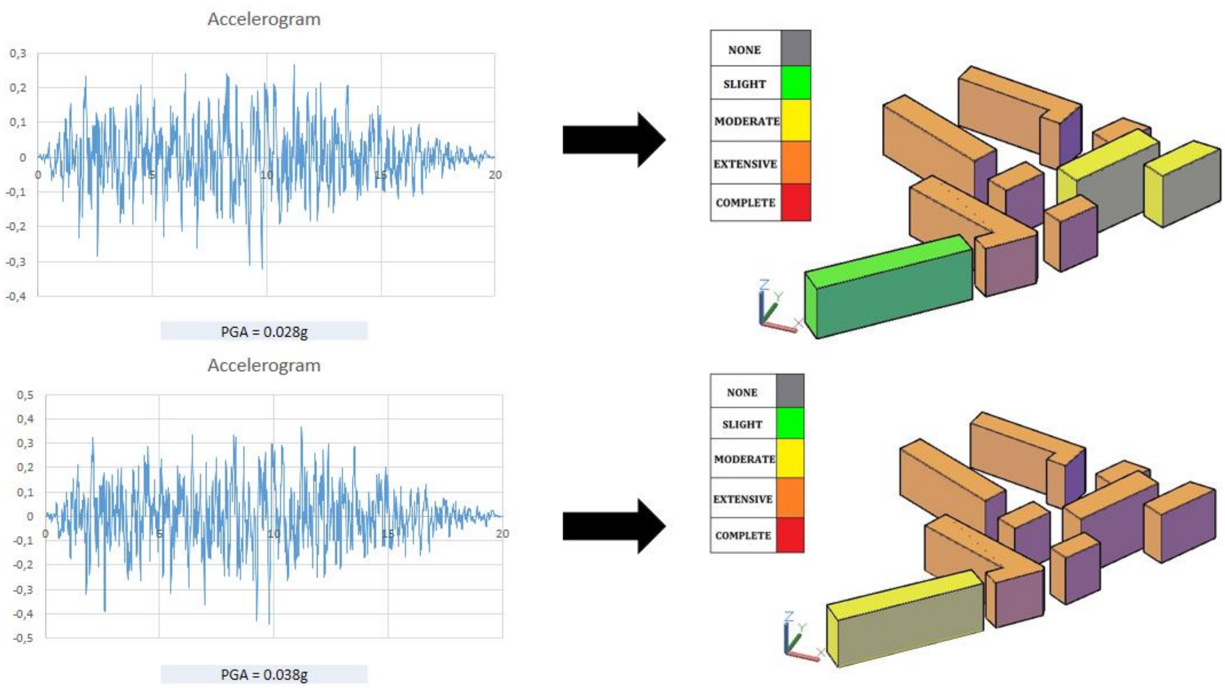



Figure 21: Damage state with PGA 0.028g and PGA 0.038g

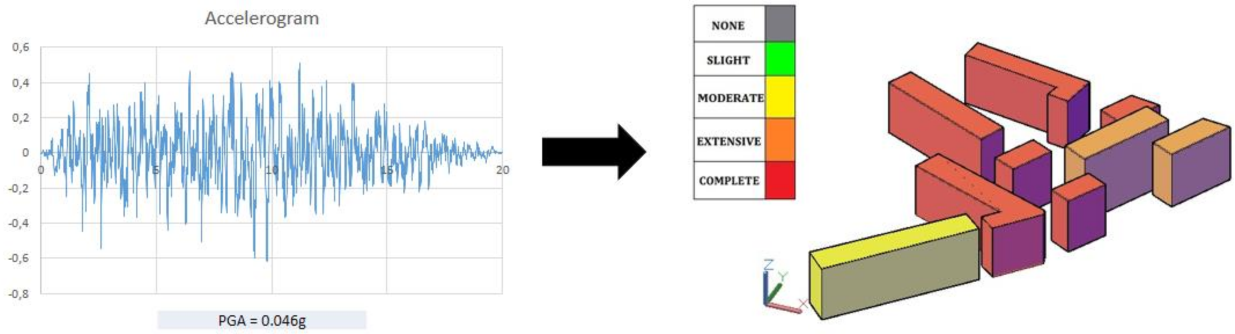



Figure 22: Damage state with PGA 0.046g

As shown in the Figure 19, the first damaged buildings are B and H. The fundamental natural vibration frequencies for these buildings are respectively about 1.71 for the building B and 1.61 Hz for the building H. The input periodogram PSD, Figure 23, shows that the maximum periodogram PSD value is at about 1.69 Hz. The fundamental natural vibration frequencies of the remaining buildings are larger than 2 Hz. Furthermore, building A is never seriously damaged because the direction of the building is essentially parallel to the direction of the earthquake and then the structure reacts to this force with the side with the high inertia. In Figure 22 almost all the buildings are seriously damaged due to PGA is fixed to 0.046g and the buildings were designed for 0.036g PGA.

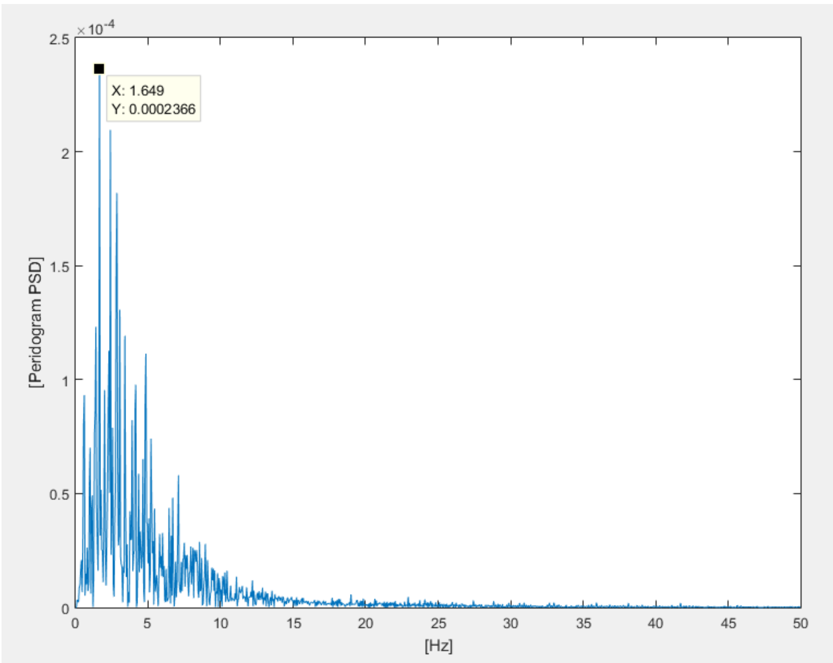



Figure 23: Periodogram PSD of the input

## 5 CONCLUSIONS

A simple SDOF model of a standard regular building with natural period equivalent to that one deduced from a MDOF model is obtained. It is also in agreement with the guideline prescriptions. Seismic displacements of the SDOF model are also equivalent to those corresponding to displacement response spectra.

This simplified approach can be extended and implemented into a more general procedure on a virtual city model. The preliminary tests on a small district result promising for extensive application to large number of regular building that usually characterize for large parts of urban areas.

Finally, a seismic damage prediction approach is also proposed within the same urban district through a widely accepted protocol at increasing input. Such simple application demonstrates that it can be also implemented at a larger scale as the virtual city one. The proposed loss prediction approach results of a reasonable accuracy and can give a significant contribution to disaster resilience analysis and prevention in urban areas.

## ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEAL RESCUE_637842 of the project IDEAL RESCUE-Integrated Design and Control of Sustainable Communities during Emergencies.

## REFERENCES

[1] C. Xiong, X. Lu, X. Lin, Z. Xu, L. Ye, Parameter Determination and Damage Assessment for THA-Based Regional Seismic Damage Prediction of Multi-Story Buildings. *Journal of Earthquake Engineering*, **00**, 1–25, 2016.
[2] X. Lu, B. Han, M. Hori, C. Xiong, Z. Xu, A coarse-grained parallel approach for seismic damage simulations of urban areas based on refined models and GPU/CPU cooperative computing. *Advances in Engineering Software*, **70**, 90–103, 2014.
[3] C. Xiong, X. Lu, M. Hori, H. Guan, Z. Xu, Building seismic response and visualization using 3D urban polygonal modelling. *Automation in Construction,* **55**, 25-34, 2015.
[4] T. Yamashita, H. Muneo, K. Kajiwara, Petascale computation for earthquake engineering. Computing in Science and Engineering, 13(4), 44-49, 2011.
[5] Eurocode 8: UNI ENV 1998, Design of structures for earthquake resistance, 1998.
[6] Ansys Inc., Canonsburg, PA, United States, 2015.
[7] HAZUS, *FEMA - Multi-hazard loss estimation methodology*. Washington, DC, 2012.
[8] Z.Q. Yin, Z. Zhao, S.W. Yang, Relation between vulnerability of buildings and earthquake acceleration spectra (1), *Journal of Earthquake Engineering and Engineering Vibration*, **23**(4), 195-200, 2003.
[9] SAP 2000, Computer and Structures Inc., Berkeley, California, 2015.
[10] Infraworks 360, Autodesk Inc., 2017.
[11] SIMQKE_GR, Piero Gelfi, University of Brescia, Italy.