Seismic Damage Assessment of a Virtual Large Scale City Model

Seismic damage assessment of a virtual large-scale city model

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ABSTRACT: Recent social developments and economic transformation have changed the engineering design approach from building design level towards community design level (city, region, country). The latter approach involves modeling of interconnections between different systems (buildings, transportation, water network, etc.) rather than designing the buildings individually. Thus, new analysis tools are expected to be developed to simulate the complex response of a community subsequently to disasters. The need of such rational tools is the object of this research work. Two different numerical approaches to simulate the response of a large-scale built environment after a seismic scenario are explored by developing multipurpose numerical codes. A district of a virtual city is considered as a case study and the level of damage for built environment is estimated. This work could be the first step for further urban loss analysis, e.g. through agent-based models that could be updated online with the proposed simulation.

1 INTRODUCTION

Disaster events devastate the nature and human beings of a community. When a catastrophic event such as an earthquake occurs in a built environment, the consequential structural damage may cause high losses (casualties, repair costs, and repair time). The main goal of the paper is the seismic damage evaluation on the built environment through dynamic analysis. For seismic damage assessment of an urban area, computer-based simulation has become the most feasible and efficient methodology for scientific research and engineering application (Lu & Guan 2017). Given large-scale and complicated structural system, a computational model with balanced accuracy and efficiency is critical for earthquake disaster simulation. In this study two methodologies, based on the tri-linear and bi-linear backbone curve, are compared to evaluate in detail the seismic performance of the regular buildings.

Many studies claimed that the tri-linear backbone curve model can accurately represent the building's response in terms of inter-story (Vamvatsikos & Cornell 2005, Shi 2014). The first proposed approach is based on a nonlinear multi degrees of freedom system (MDOF) developed by Marasco et al. (2017). Nonlinear MDOF shear models are recognized able to satisfactorily capture the nonlinear properties of multi-story buildings, predict the Engineering Demand Parameters (EDPs), and assess a reasonable level of damage (Lu et al. 2014, Xu et al. 2014). The second methodology, developed by Cimellaro et al. (2017), is based on a simplified approach to obtain an equivalent single degree of freedom system (SDOF) through linear hypothesis.

The proposed methods have the ability to output the displacement contours for different time steps, thus making it possible to generate an animation of the building seismic responses. According to the Hazus (2012), the seismic damage is classified into five levels: slight, moderate, extensive, and complete damages. The same district of a virtual city model, called Ideal City, freely inspired to the city of Turin in Italy, is developed for evaluating the seismic effects at increasing intensities through proposed methodologies. It will be the starting step for further urban loss analyses, e.g. through agent-based models, which will be updated with respect to performance losses.

2 METHODOLOGY

2.1 *High fidelity model (HFM)*

The proposed methodology is discussed by Marasco et al. (2017). In this approach, the inter-story behavior of a regular building is simulated through a tri-linear backbone curve (Figure 1). The three main points of the curve are evaluated using a nonlinear static approach for a MDOF system. To achieve this goal, a MATLAB algorithm has been developed considering the uncertainties on the geometric and mechanical parameters used in the analyses. Variation of the parameters within an acceptable range is considered through a Monte Carlo Simulation (MCS) obtaining a set of tri-linear backbone curves for each building.

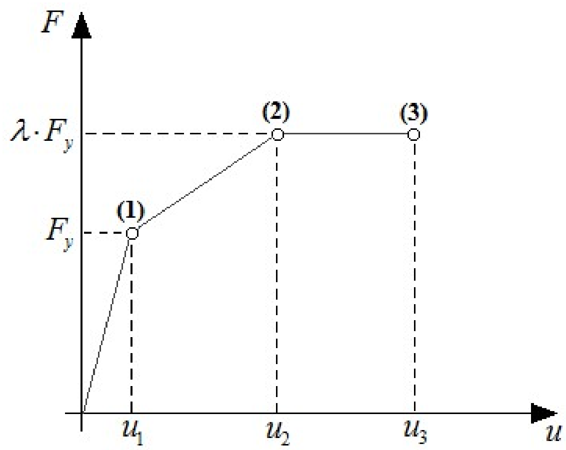

Figure 1. Tri-linear backbone curve.

The ranges of the main building's parameters are selected according to the knowledge level of the building. In addition, the deterioration of the mechanical properties (such as strength and elastic modulus of concrete) is taken into account through the aging equation proposed by Eurocode 2 (EC2 2004) according to the year of construction. Once the Matlab algorithm evaluates the tri-linear backbone curve at each step of MCS, the SAP2000 API is used to apply to all the buildings the data set obtained by the algorithm. This automated procedure is capable of reducing the computational time and analyze the dynamic responses dispersion caused by the data uncertainty. Therefore, the mean response and associated dispersion for each building within the virtual city can be estimated.

This approach is suitable to allow a decision-maker the ability to explore how their community responds to a disruptive event and quantify the mean performance of buildings and their uncertainty in the dynamic response after a hazard. Assimilating the dynamic nonlinear response of a structural system to a unique backbone curve leads to analyze the building as a nonlinear equivalent Single Degree Of Freedom (SDOF) model. The SDOF system simplification allows for a reduction in the computational efforts needed to assess the response of a large number of structures.

Finally, the hysteresis is considered according to the Takeda model (Takeda et al. 1970), as implemented inSAP2000. Figure 2 shows in detail the software data flow used in the simulations.

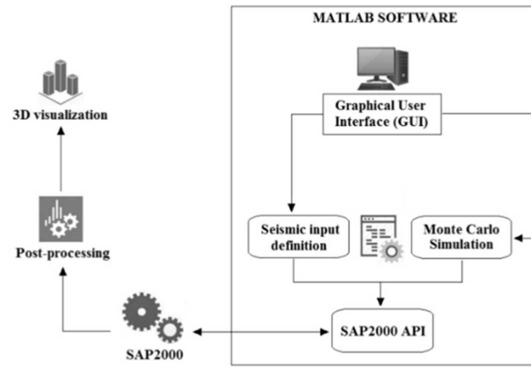

Figure 2. Software data flow.

According to the maximum drift, the structural damage is assessed for each building and the associated level of damage is evaluated (slight, moderate, extensive, complete). A 3D visualization tool is also provided, which shows the dynamic response of the building within the virtual.

2.2 *Simplified approach model (SAM)*

The proposed methodology is presented in Cimellaro et al. (2017). The building behavior is reproduced through a single degree of freedom (SDOF) model within a multipurpose FE software (Figure 3). A SOLID185 Element (eight nodes) represents the structure in ANSYS. It is fixed to the ground and has the same section of the real building's footprint. The mass is concentrated on the top of the building's model.

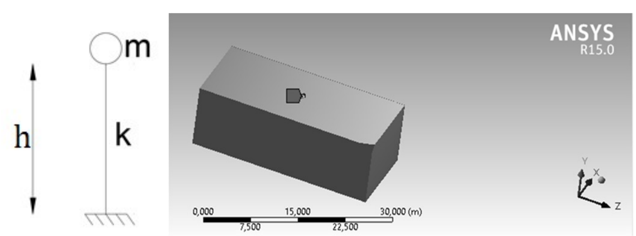

Figure 3. SDOF model and 3D visualization.

A self-weight for floor of 11 KN/m^2 is adopted accordingly with a widely accepted range of 10-12 KN/m^2. The period of structure (T) and equivalent SDOF stiffness of the building (k) are calculated by following:

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

$$K = \left(\frac{2\pi}{T}\right)^2 m_{tot} \tag{2}$$

$$K = \frac{GA_s + 3EI}{H + H^3} \rightarrow E \tag{3}$$

where C is computed by Eurocode 8 (1998), H is the building's height in meter, m_{tot} is the mass in Kg, T is the period of the first vibration mode in seconds, K is the stiffness of building, G is the shear modulus, and E is the elasticity modulus. The total mass is given by:

$$m^* = \sum m_i . \varphi_i \quad (4)$$

where m_i is the mass for floor and it can be assumed equal to 11 KN/m^2 and φ_i is the eigenvector of the building at floor i. Importing a 3D-GIS file into the FE code, the geometrical model of the regular buildings in a single step can be defined. Figure 4 exemplifies the general procedure for performing the solid FE mesh of the ideal city.

Figure 4. Method to import the geometrical model in a FE software.

The discretization of all buildings through this approach results very useful for both the polygonal visualization of the virtual city and, at the same time, for limiting the computational costs (low number of degrees of freedom). The seismic damage is classified as slight, moderate, extensive/complete. To assess the seismic damages of buildings through a linear approach, the force-based damage criterion in Xiong et al. (2016) is exclusively adopted. Thus, the bi-linear backbone curve consists in two key points (Figure 5).

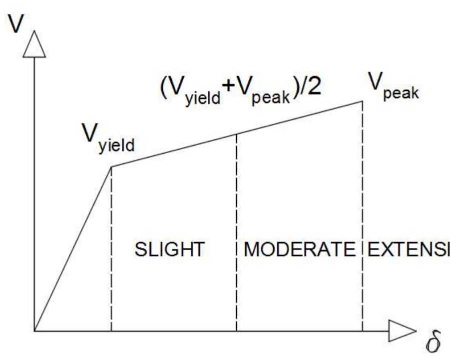

Figure 5. Bi-linear backbone curve.

The first one corresponds to yielding that is the turning point between the linear and the nonlinear behavior. According to Xiong et al. (2016), it is calculated such as:

$$V_{yield} = \Omega_1 V_{design} \quad (5)$$

where Ω_1 is the yield overstrength ratio of RC frames. As reported by HAZUS, a value of Ω_1 equal to 1,1 is adopted. The second point is the peak one corresponding to the peak strength.

$$V_{peak} = \Omega_2 V_{design} \quad (6)$$

To determine Ω_2, the statistical analysis is performed by Xiong et al. (2016) on RC frames designed following the Chinese seismic design code. For base shear forces that exceed the V_{peak} in Figure 5, the resulting damage is assumed in the range extensive/complete. Because, through a linear analysis, the displacement associated to highly nonlinear structural response can not be reasonably evaluated. The resultant base shear strength is calculated for each building and compared with the limit values in Figure 5.

3 DISTRICT SEISMIC RESPONSE SIMULATION

3.1 *Case study description*

A medium-size district of a virtual city model, called Ideal City, freely inspired to the city of Turin in Italy, has been considered to firstly assess the overall procedure and the structural behavior during an earthquake. The district is situated in Turin and contains nine regular buildings (Figure 6 and Table 1). Structures with "L" shape in reality are parts of buildings with a rectangular shape divided by a seismic joint.

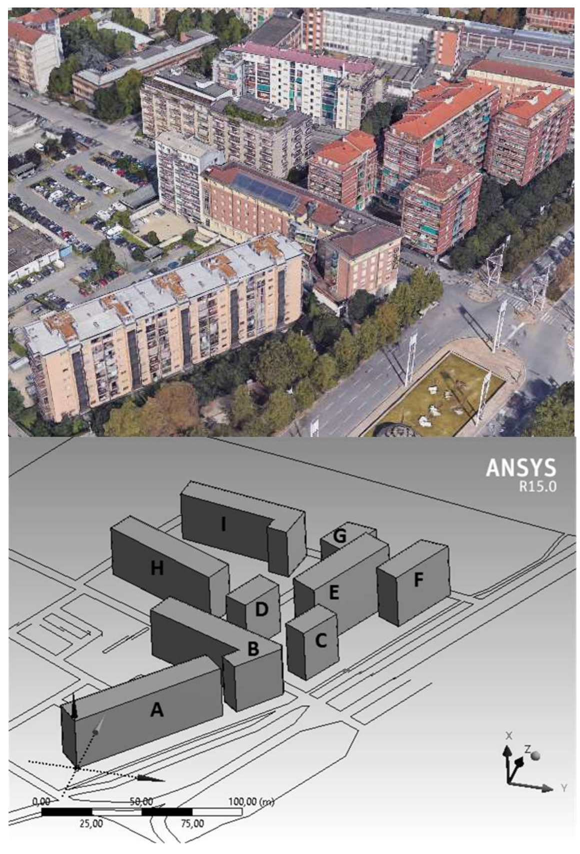

Figure 6. Case study buildings.

SIMQKE_GR software is used for generating the seismic acceleration input (Figure 7) as function of the geographical coordinates of the city, the soil type, the topography of the area, the total duration of the ground motion. The seismic input is applied to the virtual city at increasing intensities as shown in Table 2.

Table 1. Geometric building parameters.

Building	Height	Area
	m	m^2
A	28.9	1258
B	27.4	1242
C	29	293
D	29	319
E	36	810
F	28.4	475
G	28.4	323
H	28	951
I	28.4	862

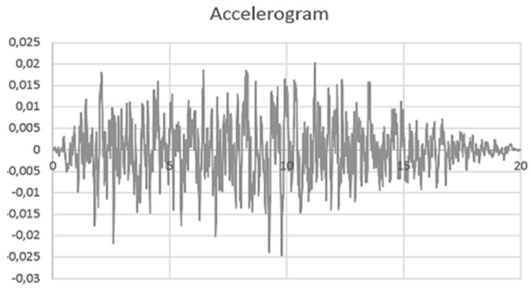

Figure 7. Generated accelerogram.

Table 2. Peak ground acceleration (PGA) for a constant duration Dr=20s.

Input Motion	PGA
	m/s2s^2
1	0.02
2	0.06
3	0.1
4	0.2
5	0.28
6	0.38
7	0.46

3.2 *Damage assessment by HFM*

Figure 8 shows the HFM results for different input motions corresponding to each building. On the horizontal and vertical axes respectively, the number of input motion and the maximum displacements on the top of the building values for the seven input motions are reported. The damage levels of the buildings for the different input motions are reported (S: slight, M: moderate, E: extensive, C: complete) in Table 3.

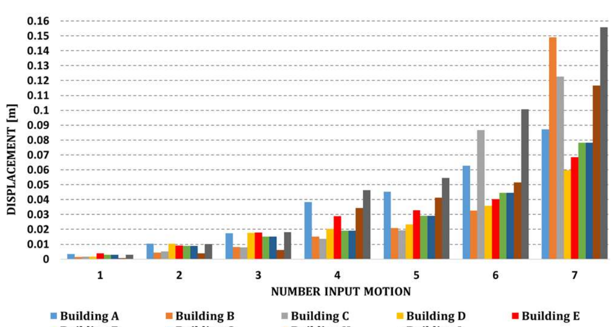

Figure 8. Maximum displacements evaluated by HFM.

Table 3. Damage state through HFM: S=slight, M=moderate, E=extensive, C=complete.

Building	Input motion number						
	1	2	3	4	5	6	7
A	<S	<S	<S	<S	<S	S-M	M-E
B	<S	<S	<S	<S	<S	S-M	M-E
C	<S	<S	<S	<S	<S	M-E	M-E
D	<S	<S	<S	<S	<S	S-M	M-E
E	<S	<S	<S	<S	<S	S-M	M-E
F	<S	<S	<S	S-M	S-M	S-M	M-E
G	<S	<S	<S	<S	S-M	M-E	M-E
H	<S	<S	<S	S-M	M-E	M-E	E-C
I	<S	<S	<S	S-M	S-M	M-E	M-E

3.3 *Damage assessment by SAM*

The results obtained by SAM for different input motions for each building are reported in Figure 9 in terms of maximum displacements. Obviously, being computed through linear analyses, they are halved with respect to those of HFM in Figure 8. Again, on the vertical axis, the maximum displacements on the top of each building are reported, while on the horizontal axis the number of input motion.
Table 4 reports the damage level for different input motions corresponding to each building of the district. Figure 10 illustrates an example of building visualization provided by SAM.

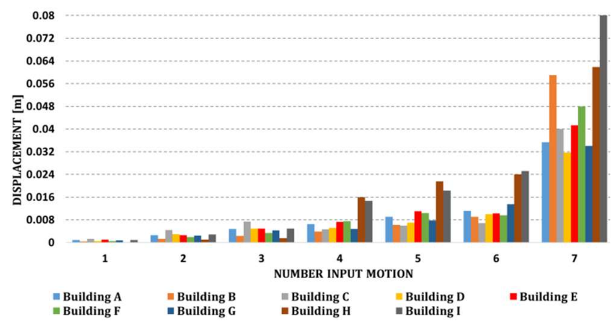

Figure 9. Maximum displacements evaluated by SAM.

Table 4. Damage state through SAM: S=slight, M=moderate, E=extensive, C=complete.

Building	Input motion number						
	1	2	3	4	5	6	7
A	<S	<S	<S	<S	<S	S	S-M
B	<S	<S	<S	<S	<S	S	M
C	<S	<S	<S	<S	<S	S-M	M
D	<S	<S	<S	<S	<S	S	S-M
E	<S	<S	<S	S	S	S	S-M
F	<S	<S	<S	S	S	M	M
G	<S	<S	<S	S	S	S-M	M
H	<S	<S	<S	S	S	S-M	S-M
I	<S	<S	<S	S	S	M	M

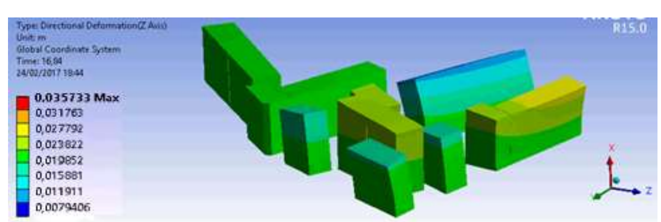

Figure 10. Example of visualization provided with SAM.

3.4 *Comparison between methodologies*

From the comparison between the outcomes of the two methodologies, similar responses can be found at the lowest input levels that are mainly characterized by linear behavior. For higher input motions, the linear response method by Cimellaro et al. (2017) obviously underestimates the displacements as shown in Figure 11 to Figure 19. Dynamic equilibrium equations are solved using direct integration method.

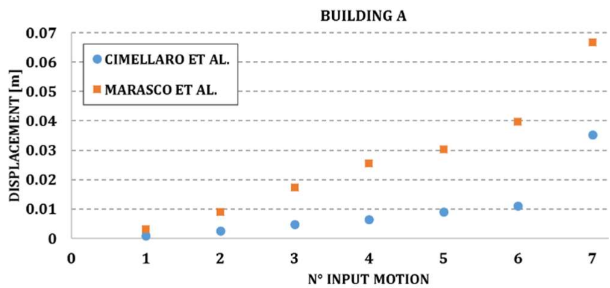

Figure 11. Comparison between two methods (Building A).

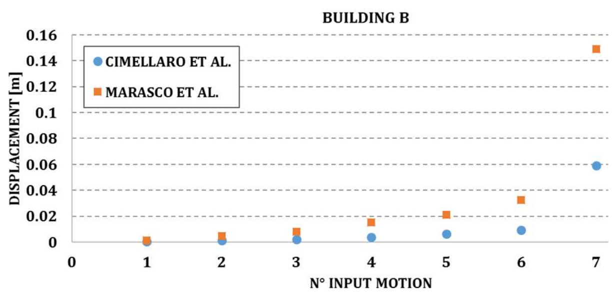

Figure 12. Comparison between two methods (Building B).

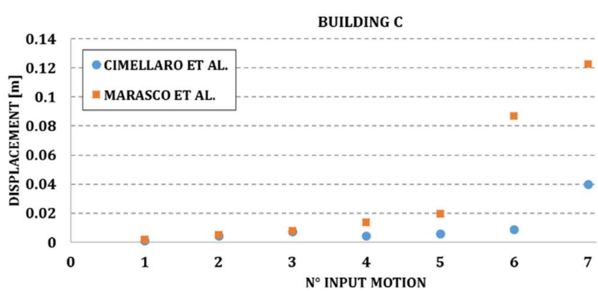

Figure 13. Comparison between two methods (Building C).

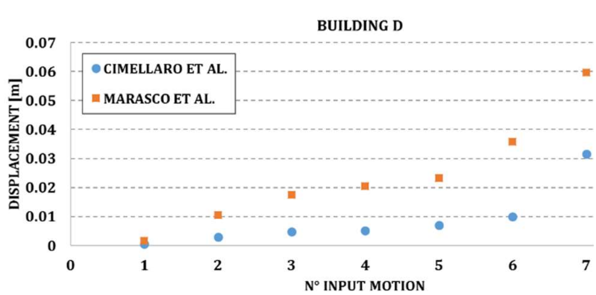

Figure 14. Comparison between two methods (Building D).

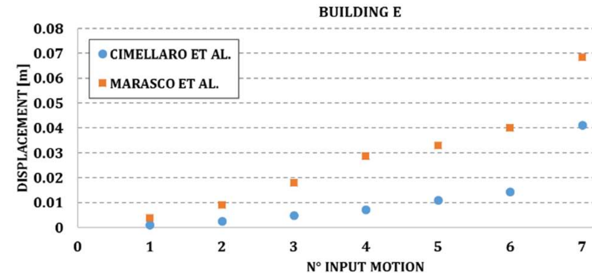

Figure 15. Comparison between two methods (Building E).

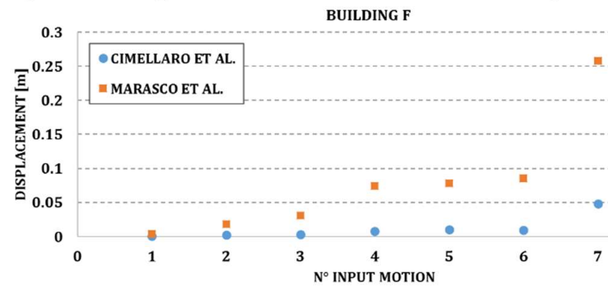

Figure 16. Comparison between two methods (Building F).

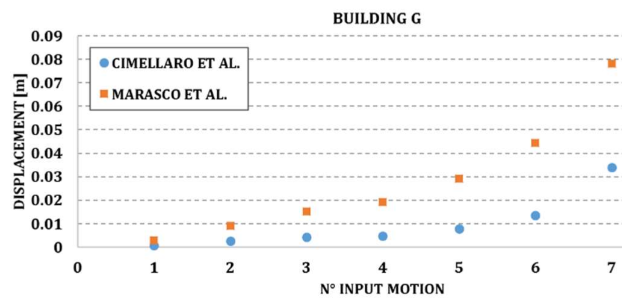

Figure 17. Comparison between two methods (Building G).

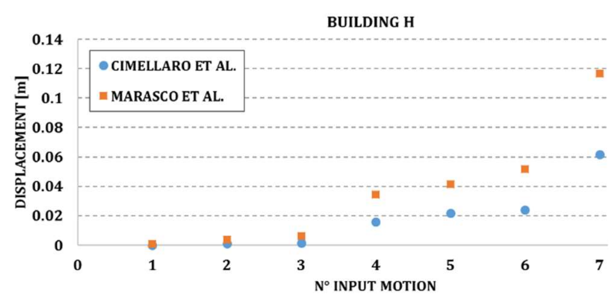

Figure 18. Comparison between two methods (Building H).

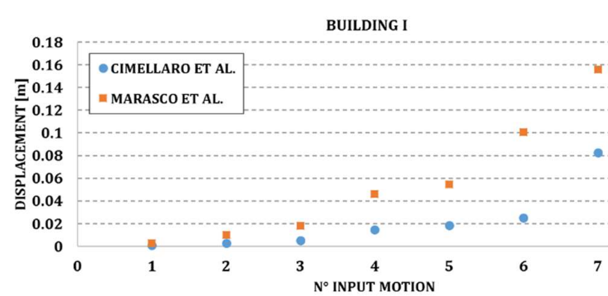

Figure 19. Comparison between two methods (Building I).

The natual vibrating periods of the equivalent SDOF models of both the methodologies are shown in Table 5. The SAM periods are lower than those obtained by HFM method, consistently with the adopted different methodologies. Indeed, in HFM the parameters of the equivalent SDOF are computed through 3D nonlinear dynamic analysis of the buildings.

HFM estimates the base shear (F_{yield}) and top displacement (u_{yield}) values corresponding to the formation of the first plastic hinge. Thus, the secant stiffness of the equivalent SDOF is given by:

$$K = \frac{F_{yield}}{u_{yield}} \tag{7}$$

Differently, SAM evaluates the equivalent SDOF stiffness (k) according to Eurocode 8 (see Equation 1 and Equation 2).

Table 5. Period equivalent SDOF

Building	T-High fidelity model	T-Simplified approach
	Sec	Sec
A	0.86	0.68
B	0.77	0.57
C	0.80	0.68
D	0.81	0.66
E	0.87	0.76
F	0.83	0.60
G	0.90	0.64
H	0.84	0.62
I	0.74	0.66

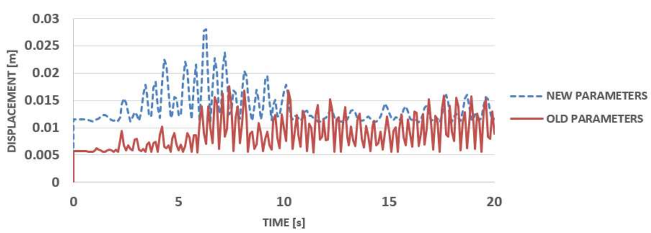

Figure 20. Displacements Building H – SAM

In order to deepen the comparison between the two methodologies, the building H is implemented in the linear SAM approach using the mechanical parameters computed by HFM. Figure 20 depicts the new displacements compared with those previous obtained through SAM employing input motion 4. The maximum displacement computed with new parameters, tends to solution computed with HFM.

Increasing the intensity of the input motion in HFM, the buildings' displacements belong to the nonlinear domain. As shown by previous results on damage state in HFM (Table 3), for PGA greater than 0.1g, buildings F, H, and I highlight elastic-plastic response and slight-to-moderate damage levels. Consistently, SAM also highlight modifications in the damage level with respect to lower input intensity levels but limited to slight damages.

Figure 21 depicts the linear and nonlinear response characteristics of SAM and HFM respectively. Accordingly to the linear approach, the displacements increase proportionally to the magnitude of seismic actions. Keeping constant a generic force (F) in plastic field, the displacement (u_2) of a nonlinear model is larger than the displacement (u_1) of a linear model.

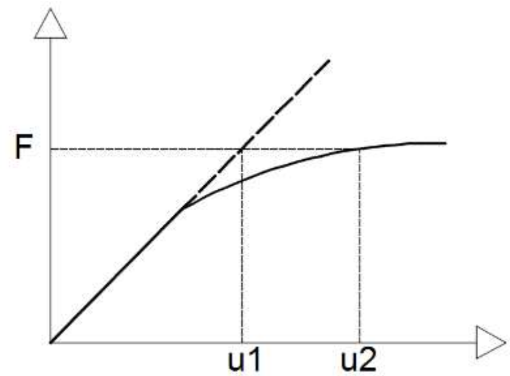

Figure 21. Linear model vs. nonlinear model

A further comparison is done in order to clarify the deviation between the two methodologies during the input motion 7. Table 6 summarizes the drift ratios obtained where HFM highlights larger responses consistently with the adopted nonlinear approach.

Table 6. Drift ratios for input motion n°7.

Building	HFM	SAM
	-	-
A	0.54	0.12
B	0.55	0.22
C	0.54	0.14
D	0.40	0.10
E	0.19	0.11
F	0.70	0.18
G	0.43	0.12
H	0.53	0.21
I	0.56	0.28

The study by Xiong et al. (2016) has been originally developed for predicting damage conditions through nonlinear time-history analysis. This hypothesis justifies the limited damaged levels in Table 4 with respect to Table 3.

Furthermore, the damage assessment method in SAM adopts a force criterion only. This assumption is reasonable at the earlier stage of seismic damage, when the stiffness of the structure is high and a small variation in deformation will lead to a significant change in the internal forces. For structural conditions beyond the peak shear force V_{peak} , the damage is assumed in the range "extensive/complete".

A further development of the present study will be focused on the modification of the trilinear curve by Xiong et al. (2016), for adapting the original methodology to the adoption of linear structural analyses.

The HFM method evaluates each building individually through nonlinear analysis. Tri-linear backbone curves are accordingly defined. Despite the different approaches to simulate the buildings response, both methods evaluate compatible levels of damages for the considered case study.

4 CONCLUSION

Two different approaches to implement dynamic time history analyses for damage assessment in a built environment of a virtual city are proposed. The simplified linear approach model (SAM) reduces the computational time but underestimates the damage states with respect to the high-fidelity model (HFM). This last is based on a nonlinear approach with higher computational costs with respect to SAM.

Both the methodologies are reasonable simplified approaches in order to calculate the damage state in built environment as long as the buildings are perfectly regulars. Therefore, they can give a significant contribution to disaster resilience analysis and prevention in urban areas through numerical implementation in the virtual city models. Furthermore, they are capable to significantly reduce the computational time in large dimension models reducing the total number of degrees of freedom.

The proposed methodologies can support decision-makers to explore how their communities respond to a disaster event, quantify the performance of buildings, and to plan the better resilience-building strategies to minimize losses and the recovery time.

5 ACKNOWLEDGEMENTS

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