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A NEW TOOL TO ASSESS THE RESILIENCE OF AN URBAN ENVIRONMENT UNDER AN EARTHQUAKE SCENARIO

G.P. Cimellaro[1], S. Marasco[2], A. Zamani Noori[2], O. Kammouh[2], S. Mahin[3]

ABSTRACT

This paper presents a new methodology to predict the potential damage and physical impacts of an earthquake on the built environment. A new methodology to the urbanized systems and large-scale simulations within a seismic scenario are explored, by evaluating multipurpose codes for numerical simulation. A 3-D building shape of a standard virtual city is developed for evaluating the seismic effects at increasing intensities. Once the buildings are integrated into the city, parallel simulations are applied to compute the global behavior of buildings after a disruptive scenario. Monte Carlo Simulations (MCS) are applied to take into account the epistemic uncertainties associated with geometry and mechanical properties within the range of observations. For each set of buildings' data, the nonlinear dynamic analysis is performed through SAP2000 Application Programming Interface (API) in order to assess the dynamic response of the buildings in an organized and automatic fashion. Accordingly, the city is mapped into different zones representative to the possibility of having different levels of damage (complete, extensive, moderate, and slight). This tool supports decision-makers to explore how their community will respond to a disruptive event, to develop different strategies for monitoring and control the emergency in urbanized areas.

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A NEW TOOL TO ASSESS THE RESILIENCE OF AN URBAN ENVIRONMENT UNDER AN EARTHQUAKE SCENARIO

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This paper presents a new methodology to predict the potential damage and physical impacts of an earthquake on the built environment. A new methodology to the urbanized systems and large-scale simulations within a seismic scenario are explored, by evaluating multipurpose codes for numerical simulation. A 3-D building shape of a standard virtual city is developed for evaluating the seismic effects at increasing intensities. Once the buildings are integrated into the city, parallel simulations are applied to compute the global behavior of buildings after a disruptive scenario. Monte Carlo Simulations (MCS) are applied to take into account the epistemic uncertainties associated with geometry and mechanical properties within the range of observations. For each set of buildings' data, the nonlinear dynamic analysis is performed through SAP2000 Application Programming Interface (API) in order to assess the dynamic response of the buildings in an organized and automatic fashion. Accordingly, the city is mapped into different zones representative to the possibility of having different levels of damage (complete, extensive, moderate, and slight). This tool supports decision-makers to explore how their community will respond to a disruptive event, to develop different strategies for monitoring and control the emergency in urbanized areas.

Introduction

Rising of global population and the massive economic development in areas prone to disasters have increased the chance of catastrophic incidents. Over the years, community resilience has attracted tremendous attention due to the increasing number of natural and man-made disasters. The absence of a concise and methodical approach makes it extremely difficult to evaluate resilience. Given the large number of buildings in a city, the seismic simulation of the buildings cannot be easily implemented without huge computational effort. Thus, several numerical models have been proposed to simulate the seismic damage to buildings in the recent years. Basically, the simulation models are classified into a data-driven method and a physics-driven method. The first is based on statistical data obtained from previous earthquakes. The main limitation is due to the inadequacy and leakage of statistical data for any world areas. To overcome these intrinsic limitations, the physics-driven methods have been progressing in recent

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years. The building seismic damage is based on the structural analysis of an individual building subjected to a given seismic input. Given limited attribute data of each building and the large number of buildings in an urban area, the seismic response prediction model of buildings must be relatively simple to reduce the computational time requested by the analyses. In this paper, a simplified and efficient physical approach is presented to estimate the physical damage caused from an earthquake scenario in a large scale urban city.

Buildings Database

The virtual city has been designed based on the buildings stock for the city of Turin, Italy. The virtual city has the area of 120.1 km^2 with the total population of 850,000. Four building sectors that provide essential functions to a community, including housing (residential building, hotel, shelter, etc.), education (school, university, library, etc.), business (shopping center, retail store, heavy industry, etc.), and public services (hospital, police station, church, airport, etc.) are considered. Table 1 lists in detail the building sectors supporting the physical, economical, and social dimensions of the virtual city. In total, the virtual city has 30,122 buildings. The plan dimensions of each building have been gathered through CADMAPPER file for the entire city of Turin. In addition, the numbers of story have been obtained by the shape-file of "*Carta Tecnica Comunale (CTC)*" of the city of Turin, available at the website http://www.comune.torino.it/geoportale/. The building inventory of the city is based on the building typology concept already used in many European countries at national and regional levels. However, the lack of information about some buildings makes it difficult to have perfect knowledge of any individual building. For this reason, some building's attributes (e.g. year of construction, type of deck) have been assigned based on known data for the entire city.

Six different categories of construction year have been utilized according to the main changing from standard Italian codes (Table 2). The numbers of buildings for each year of construction category have been assigned according to Cities on Power (CoP) European program research for the city of Turin [1]. According to Corrado et al. [2], typical Italian building construction elements depending on the year of construction are provided. Classification of building construction elements (e.g. deck,wall, etc.) plays a key role in the assessment of mass. Seven different typical deck and three typical external walls have been selected and distributed based on their year of construction (Fig. 1). All the buildings have been divided into groups based on material: concrete, masonry, and steel. Considering limited information in the building attribute data, an accurate determination of the nonlinear structural parameters is rather challenging. The major objectives of this work are to provide a simplified and accurate method for assessing the dynamic response of residential buildings in a generic built environment. For this purpose, the geometric characteristics of the structural elements (e.g. columns and beam sizes) have been defined in order to respect all the technical standards for a given year of construction and for a given seismic hazard scenario (medium or high level).

Table 1. Number of buildings stock and map of the city.

Physical Infrastructure	Building	Residential	23420
		Mobile Home	62
	Hospital		17
	Fire Station		3
	Police Station	Carabinieri	18
		Polizia Municipale	11
		Questura	31
	Educational	Elementary School	157
		Middle School	105
		High School	97
		University	70
Social Infrastructure	Hotel		31
	Historical Building		951
	Castel and Palace		18
	Church		176
	Sport		265
	Cinema		48
	Museum		156
	Theater		38
	Library		15
Economic Infrast.	Industrial Build.	Light	321
		Heavy	108
	Commercial	Retail store	25
		Malls	12

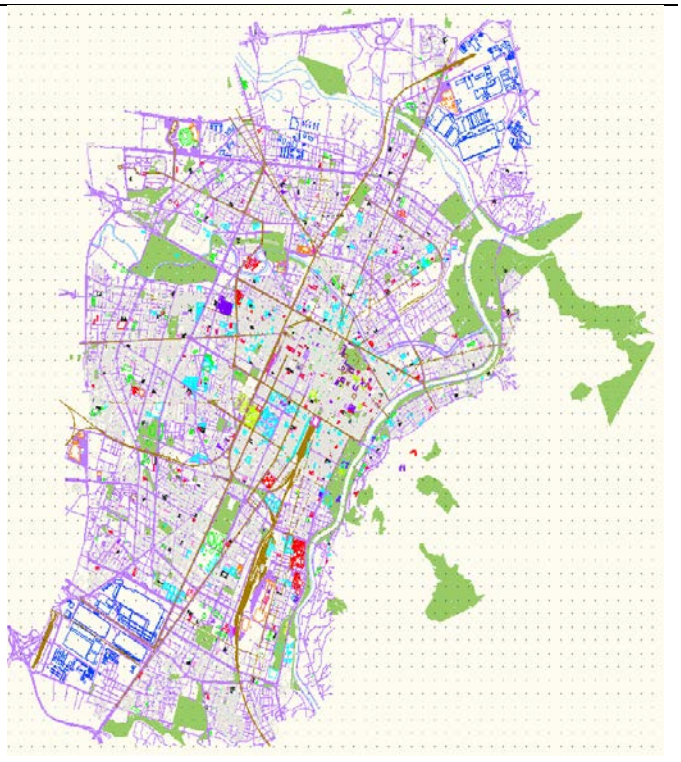
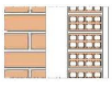


Table 2. Number of buildings stock and map of the city.

I	II	III	IV	V	VI
< 1916	1916-1937	1938-1974	1975-1996	1996-2008	> 2008

DESCRIPTION		YEAR
	Vault ceiling with solid bricks	< 1900
	Ceiling with wood beams and hollow bricks	< 1900
	Ceiling with reinforced concrete	1900 - 1930
	Vault ceiling with bricks and steel beams	< 1930
	Vault ceiling with hollow bricks and steel beams	1910 - 1940
	Ceiling with reinforced brick-concrete slab	> 1930
	Ceiling with reinforced brick-concrete slab, low insulation	> 1976

(a)

DESCRIPTION		YEAR
	Solid brick masonry (25 cm)	1900 - 1950
	Hollow wall brick masonry (30 cm)	> 1930
	Hollow wall brick masonry with solid and hollow bricks (40 cm)	1930 - 1975

(b)

Figure 1. Typical Italian building's decks (a) and walls (b) used for residential occupancy in different years (Corrado et al., 2012).

Nonlinear Model

A large component to an urban environment is residential buildings. 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). Thus, a concise and methodical approach is needed to estimate the fragility of the building framework. Nonlinear MDOF shear model is able to satisfactorily capture the nonlinear properties of multi-story buildings, predict the Engineering Demand Parameters (EDPs), and assess a reasonable level of damage [3-6]. In the proposed approach, the inter-story behavior of a regular building is simulated through a trilinear backbone curve (Fig. 2). Many studies claimed that the trilinear backbone curve model can accurately represent the building's response in terms of inter-story [7, 8].

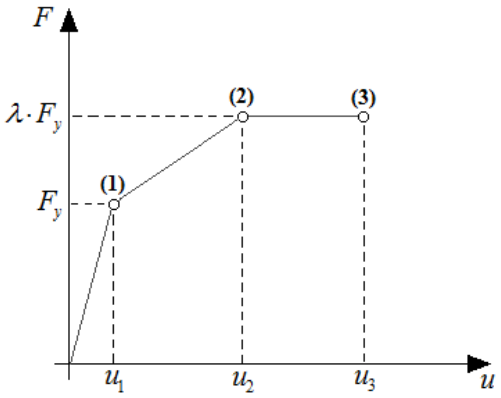


Figure 2. Trilinear backbone curve.

The first point of the trilinear backbone curve (1) indicates the yield point ($\lambda \cdot F_y - u_1$) corresponding to the formation of the first plastic hinge in the weakest base column. After the yield point, the stiffness is significantly reduced until the next point (2), for which the maximum shear base capacity ($\lambda \cdot F_y$) is reached. The ultimate point (3) corresponds to the collapse of the building (complete damage). The evaluation of the shear base and top displacement parameters for each point is discussed in the following subsections.

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 an MCS obtaining a set of trilinear backbone curves for each building. 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 [9] according to the year of construction. Once the Matlab algorithm evaluates the trilinear 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. Considering an SDOF system allows for a reduction in the computational effort needed to assess the response of a large number of structures. Finally, due to limited amount of detailed building information about its dynamic behavior, the hysteresis is considered according to the Takeda model [10] implemented in SAP2000.

Elastic Parameters

Generally, the geometry of a residential building is mostly regular in plan and elevation, therefore the mass and stiffness can be assumed to be mostly uniformly distributed. In these cases, the evaluation of the response of MDOF system with a nonlinear static procedure is close to the real response of the structure. Thus, a nonlinear static analysis is performed to assess the base shear and top displacement values corresponding to the formation of the first plastic hinge at the base level (yield point). In order to consider all Degrees Of Freedom (DOFs), the stiffness matrix of the structure is evaluated considering the building as a bending type system. Since the load patterns are applied on two main directions of the buildings [11], the modal characteristics are derived by considering the stiffness matrix in the two directions for a 2D system. Thereafter, the static condensation procedures are performed to reduce the number of DOFs to the translational DOFs. Moreover, the model assumes that the mass of each story is concentrated in the center of the mass on its elevation and represented by a mass point (Fig. 3).

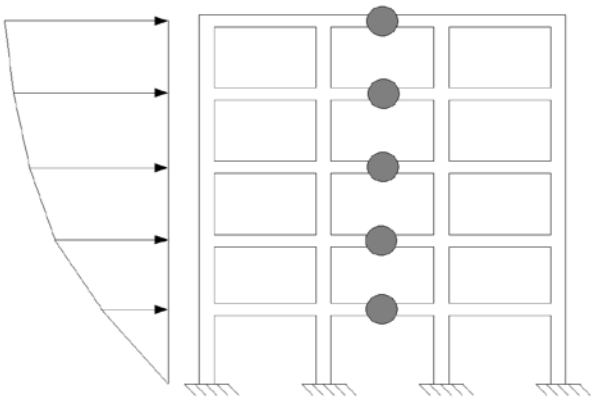


Figure 3. Concept of nonlinear MDOF system.

The yielding base shear force is assessed by applying a monotonic load pattern on the building proportional to a given modal shape. A multi-modal approach is carried out to consider all the modal shape contributions, especially for buildings that have geometric irregularities (Eq. 1).

$$\Phi_{tot} = \sum_{i=1}^{dof} \{\Phi_i\} \cdot g_i \tag{1}$$

where Φ_{tot} is the modal shape considering all modal contributions (Φ_i). The modal participation factors are represented by the term g_i.

Post- Elastic Parameters

Once the structure reaches the yield point, the stiffness is significantly reduced until point (2) for which the maximum shear base capacity is reached. Thus the top shear base remains constant and the top displacement increases (perfectly plastic behavior) until the ultimate value. The maximum shear base capacity is estimated through the kinematic approach of the limit analysis (Greenberg-Prager theorem). The general global collapse mechanism of a frame subjected to a distribution of horizontal forces (proportional to a given modal shape) is considered (Fig. 4).

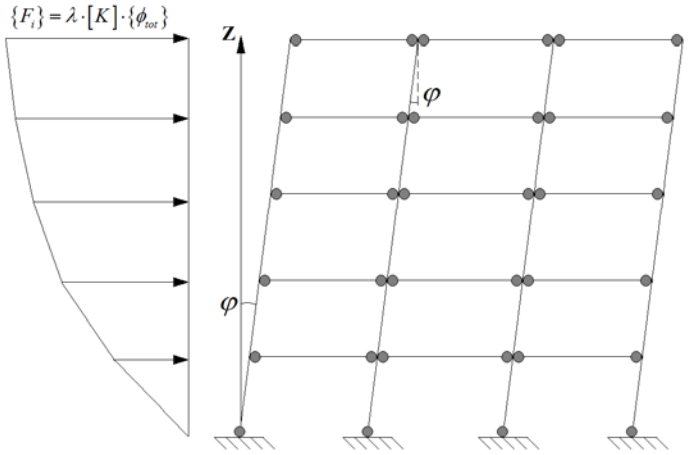


Figure 4. Global collapse mechanism.

This approach leads to take into account the strength contribution of all the structural elements (beams and columns). According to the kinematic theorem of the limit analysis, the global over-strength factor (λ) is assessed by the ratio between the internal and external work of the structural system with equal columns and beams dimensions (Eq. 2).

$$\lambda = \frac{n_c \cdot M_{y,c} + 2 \cdot n_{span} \cdot dof \cdot M_{y,b}}{\sum_{i=1}^{dof} \{F_i\} \cdot \{z_i\}} \tag{2}$$

where $M_{y,c}$ and $M_{y,b}$ are the yielding bending moment for the columns and beams, respectively. The parameters n_c represents the number of columns, n_{span} indicates the number of spans in the considered direction, and *dof* is the number of master DOFs which corresponds to the story number of the building. The external work is given by the denominator expression and it is due to the horizontal load patterns $\{F_i\}$ multiplied by the distance between the considered story and the base at each elevation level $\{z_i\}$.

One of the limitations of this procedure consists of the load pattern's shape. In fact, the monotonic horizontal force distribution does not change its shape due to the progressive formation of the plastic hinges in the columns (non-adaptive approach). In addition, a global mechanism has been considered as representative of the collapse mechanism. This hypothesis is reasonable for regular buildings designed according to the seismic standard codes. When a building is not well designed or seismically retrofitted (such as an old building), the collapse can be caused by a local mechanism for which the over-strength factor assumes lower values. In

these cases, the possible local mechanisms have to be identified and the over-strength factor will be assumed as the minimum values among all the defined factors.

Once the shear base capacity is determined, the top displacements corresponding to points (2) and (3) of the trilinear backbone curve (u_2 and u_3 in Fig. 2) have to be assessed. Since the shear base capacity is previously evaluated, the definition of reduction factor (R_μ) can be used to calculate the displacement u_2. The reduction factor accounts for ductility, over-strength, redundancy, and damping of a structural system (Eq. 3).

$$R_\mu(T,\mu,\xi) = \frac{F_{EL}(T,\xi)}{\lambda \cdot F_y(T,\mu,\xi)} \tag{3}$$

where $\lambda \cdot F_y$ is the maximum shear capacity and F_{EL} represents the equivalent elastic shear force. As mentioned previously, the reduction factors depend on ductility (μ), over-strength (λ), damping (ξ) and elastic building characteristics (such as period, T). Several mathematical formulations have been proposed for evaluating the reduction factor. One of the most used expressions is based on the equal energy rule (short period systems, $T<0.5$ s) or equal displacement rule (long period systems, $T>0.5$ s) (Eq. 4).

$$\begin{cases} R_\mu = \sqrt{2\cdot\mu - 1} & (T < 0.5s) \\ R_\mu = \mu & (T > 0.5s) \end{cases} \tag{4}$$

The ductility parameters are expressed as a ratio between the ultimate displacement and the displacement for which the maximum shear capacity occurs. According to the proposed trilinear backbone curve, the ductility is given by the ratio between displacements u_2 and u_3. Furthermore, the ultimate top displacement is evaluated based on the equal energy theorem (Fig. 5).

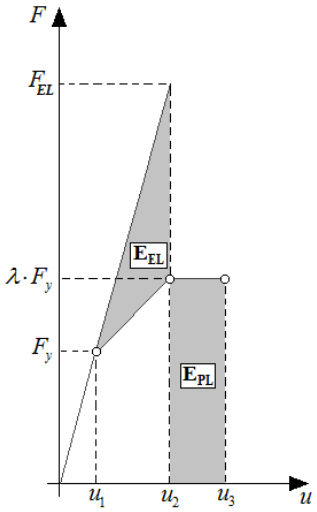


Figure 5. Equivalent elastic energy (E_{EL}) and elasto-plastic energy (E_{PL}) of the system.

According to the Fig. 5, the energy balance between the equivalent elastic energy (E_{EL}) and elasto-plastic energy (E_{PL}) is reported in Eq. 5.

$$(u_2 - u_1) \cdot \frac{(R_\mu - 1)}{2} = (u_3 - u_2) \tag{5}$$

In the proposed approach, the two unknown displacement values are evaluated through an iterative procedure. The reduction factor value is fixed and then the displacement u_2 is assessed (Eq. 6).

$$u_2 = \frac{R_{\mu,\,fixed} \cdot \lambda \cdot F_y}{k} \tag{6}$$

where k is the stiffness of the system. According to Eq. 5, the ultimate top displacement u_3 is evaluated and then the reduction factor is calculated by using Eq. 4. Performing this iterative procedure the final reduction factor is calculated.

Analysis Implementation and Simulation

The proposed approach is capable of applying nonlinear time history analyses to a large number of buildings. The dynamic response of the structural system in a built environment takes into account a considerable amount of parameters. The building inventory, containing all the information (such as material, geometry and mechanical properties) has been developed and allocated on an external server. All this data are accessible by a MATLAB code organized in several functions that manage the seismic input definition, MCS for evaluation of the nonlinear parameters, and SAP2000 API actions. Due to the large number of variables and the time requested for processing, parallel algorithms running on multiple processors are developed with MATLAB. The global behavior of each building has been modeled by using multi-linear plastic link element available in SAP2000. The mechanical characteristics have been defined automatically according to the obtained backbone curves from MCS. The equivalent damping coefficient has been assessed according to the Rayleigh formulation considering the first and second building's period as control periods.

Software Architecture

The analysis flow is controlled through an interactive graphical user interface (GUI) that allows for selection of an earthquake scenario in the virtual city (magnitude and epicenter location). Furthermore, the acceleration time history can be selected and processed in both North-South (NS) and East-West (EW) directions. In order to take into account the de-amplification of the seismic excitation with the epicenter distance, the shear wave velocity in the upper most 30 m (V_{S30}) for the city of Turin is included in the data. The V_{S30} map has been obtained via USGS website [12] at the link http://earthquake.usgs.gov/hazards/apps/vs30/. The Boore-Atkinson [13] attenuation law is used to estimate the attenuation of the time history's peaks. A Matlab function is provided for calculating distances between the selected epicenter and the center of the mass of each building. Moreover, the equivalent shear wave velocity is assessed according to the V_{S30} map, and considered in the attenuation model. The main Matlab function controls the building's data flow, then the MCSs are carried out to evaluate the backbone curves for each building, considering the epistemic uncertainties in the input model parameters.

SAP2000 API

The SAP2000 Application Programming Interface (API) is a programming tool that offers efficient access to the analysis and design technology of the SAP2000 structural analysis software. A direct interaction with third-party applications is allowed during run-time analysis. Both pre- and post-processing procedures are managed by a Matlab language code which mainly provides the two-way data exchange. This procedure is capable of significantly reducing the time needed for data exchange, especially for large data models. Once the Matlab functions assess the nonlinear parameters (trilinear backbone curve) and the processed seismic input, they are transferred to SAP2000 through API tool. Due to the limited amount of detailed building information, the hysteresis is considered according to the Takeda model. Thus, the nonlinear time history analyses are performed in the SAP2000 environment and the derived output is remotely controlled by Matlab.

Case Study

The proposed methodology has been applied to the virtual city and the results, in terms of displacements, are shown for a part of the city in Fig. 6. The maximum drift is assessed for each building and the associated level of damage is evaluated (slight, moderate, extensive, complete). A time history recorded during the Central Italy earthquake (Norcia station, PGA=0.42 g) [14], in both horizontal directions, has been used as earthquake scenario for the simulation. The predicted real time response of buildings can help decision makers to monitor and manage the resources during emergency situations.

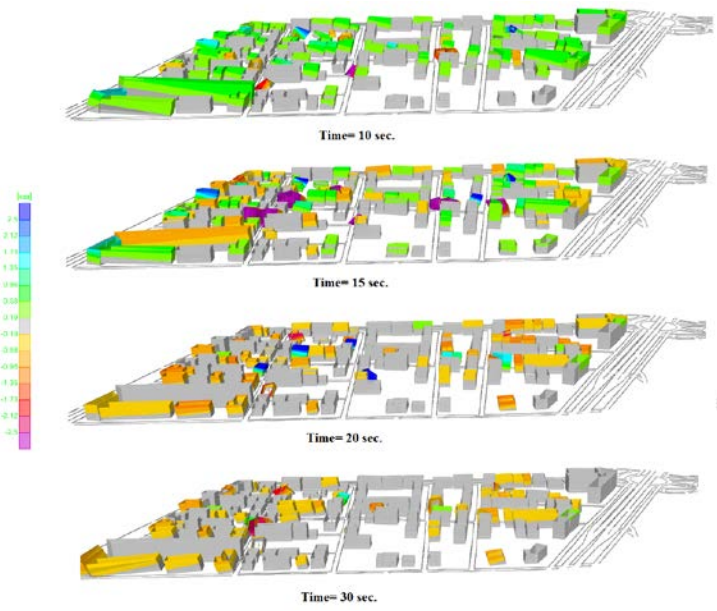


Figure 6. Displacement contours at four different time steps.

Conclusions

This paper deals with the development of different strategies for monitoring and control the emergency in urbanized areas. A new approach to implement dynamic time history analyses in a

built environment of a virtual city is proposed. The virtual city has been designed based on the buildings stock for the city of Turin, Italy. All the characteristics of each residential building have been collected and organized in a complete database. The global dynamic structural response has been simulated through multipurpose numerical codes. The uncertainties on the building geometric and mechanical parameters have been taken into account through a MCS. This procedure is capable to significantly reduce the time needed for data exchange especially for large data models. This methodology supports decision-maker to explore how their community responds to a disruptive event, quantify the performance of buildings following a hazard, and to plan the better resilience-building strategies to minimize the losses and recovery time.

Acknowledgements

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