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A MECHANIC BASED MODEL FOR DEFINITION OF SEISMIC RISK AND REAL TIME DAMAGE SCENARIO OF BUILDINGS

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Abstract. *SP-BELA (Simplified Pushover Based Earthquake Loss Assessment) is a mechanic based fragility methodology adopted in large scale vulnerability assessment for the definition of seismic risk and damage scenario. The method has been developed for RC cast in place [1], RC pre cast [2] and low vulnerability masonry buildings [3]. SP-BELA identifies numerically the damage limit states by checking deformation and stress limit conditions on the structural elements of buildings. The capability of SP-BELA methodology to represent the seismic performance of Italian buildings has been improved through a calibration process recently completed. By using data collected from observed damage in the earthquakes occurred in Italy from 1976 (earthquake of Friuli) to 2009 (L'Aquila earthquake), calibration coefficients have been computed. They have been adopted in order to define fragility curves for five damage levels (those of EMS98 scale, [4]) and for five vulnerability classes. SP-BELA has been adopted to define seismic risk and damage scenario of Italian residential and school buildings. In order to provide a user friendly tool to support decision makers during emergency management, a platform with GIS functionality has been developed. When an earthquake occurs, the WebGIS platform can evaluate real time damage scenario and seismic risk maps. The platform allows to input data of an occurred earthquake. The tool allows to define ground shaking scenario in terms of magnitude, epicentre position, depth, fault mechanism and attenuation relationship. The fault can be defined by starting from an Italian database, the DISS database (Database of Individual Seismogenic Sources [5]) of INGV (National Institute of Geophysics and Volcanology). Alternatively, a new user digitalized fault can be input. The platform allows also the evaluation of real-time damage scenarios with ShakeMap. Finally, it enables to visualize in tables and maps the seismic risk calculated for different return period and time windows. This paper describes the adoption of SP-BELA methodology for the definition of seismic risk and real time damage scenario of Italian residential and school buildings.*

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1 INTRODUCTION

In the first hours after the occurrence of a seismic event is particularly helpful to have a tool that, using only the hypocenter parameters provided in real time by INGV, returns a first evaluation of the expected damages and losses in order to trigger an early response to support and manage the rescue activities. To this end, WebGIS (Geographical Interface System) platforms can be developed as a tool to allow decision makers to check seismic risk maps and run real time damage scenarios. Seismic vulnerability is a measure of how prone a building is to damage for a given severity of the ground shaking. One of the vulnerability methodology able to be implemented in a WebGIS platform is SP-BELA (Simplified Pushover-Based Earthquake Loss Assessment). SP-BELA is a mechanical method that allows to define the damage probability through a comparison between the displacement capacity and the displacement demand required by seismic shaking. Recently, the SP-BELA methodology was calibrated through the comparison of numerically calculated damage scenarios and data on observed damage collected during earthquakes occurred in Italy starting from the 1976 Friuli earthquake up to the 2009 L'Aquila earthquake. Observed damage data are convenient to overcome the difficulties to model some collapse mechanisms, when few data on the phenomena are available. Moreover, the observed damage data are useful to define the building vulnerability in terms of damage level, instead of limit conditions numerically identified, according to the EMS98 (European Macroseismic Scale) scale [4] usually adopted by decision makers to plan the emergency phase.

The WebGIS platforms described in this paper include the application of the method to Italian residential and school buildings. In the first case, the minimal unit definition of the damage scenario and seismic risk is the municipality and the exposure database has been provided by ISTAT. In the second case, the exposure database is the survey of all school buildings ("Anagrafe Edilizia Scolastica"), carried out by the Ministry of Education ("MIUR") to identify various safety-related parameters.

2 EXPOSURE, VULNERABILITY AND HAZARD DEFINITION

To determine seismic risk and damage scenarios, assessment must be defined by the exposure, vulnerability and hazard of the interested area. The exposure is the distribution of the population and of the manufactured, while the vulnerability is the buildings susceptibility to be damaged due to seismic events. Both are territory man-made features. The hazard, instead, is the probability that, an earthquake with intensity higher than a certain threshold occurs in a given time window and in a specific area. The hazard is a territory physical characteristic.

2.1 Exposure databases used

In Italy, the exposure database for residential buildings is the ISTAT database. Every 10 years a survey takes place and, among other information, data on material of construction, number of storeys and age of construction of buildings are collected and shared. Starting from these data, within each municipality, the building stock was classified in five category where the vulnerability class is connected with the age of construction according to [6] and the date of seismic classification of the municipality for masonry and reinforced concrete (RC) buildings. By comparing the seismic zone to which the municipality was assigned to the period of construction, it was possible to identify if residential buildings were designed or not according to the seismic design provisions. The building typologies and the related vulnerability classes identified are shown in Figure 1.

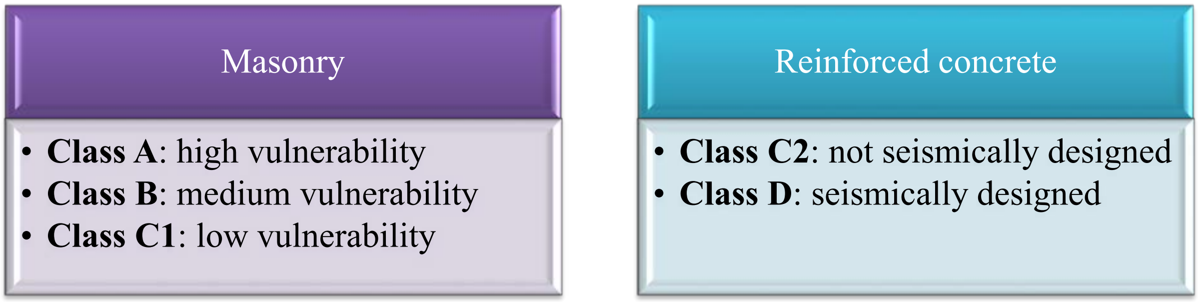

Figure 1: Vulnerability classes.

The same methodology was employed for the school buildings. Initially, school buildings of the “Anagrafe Edilizia Scolastica” database were sorted in 37 classes. However, 17328 buildings of this database lack of data on their structural typology or number of storeys; therefore, they could not be included in one of the classes above mentioned. Hence, some assumptions were done to automatically assign the needed information for classifying these school buildings. Furthermore, additional hypotheses were required for assigning one of the two main considered structural typology (masonry and reinforced concrete) to those buildings with a mixed typology. The “reinforced concrete and masonry” or “masonry and other typology” structures were analysed as masonry buildings, whereas the “reinforced concrete and other typology” structures were classified as “reinforced concrete” buildings. With these assumptions, it was possible to include 7211 buildings of those 17328 without clear specifications. Therefore, 10117 school buildings of the “Anagrafe Edilizia Scolastica” database could not be analysed, since lack of information for assigning a structural typology or because their assigned structural typology is “other”. By starting from the available 49503 school buildings of the “Anagrafe Edilizia Scolastica” database, the analysed buildings are 39386, subdivided into the five vulnerability classes described above.

2.2 Vulnerability evaluation

The seismic vulnerability of buildings were evaluated by using SP-BELA method. SP-BELA combines the definition of a pushover curve with a displacement-based framework similar to the one in DBELA (Displacement-Based Earthquake Loss Assessment) [7]. In this way, the fragility of building classes at different limit states can be obtained. The main component of the methodology involves the definition of the capacity of a buildings population based on a prototype structure selected to be representative of the vulnerability class. A simplified pushover analysis was carried out to obtain the base shear capacity. The pushover curve is elastic perfectly plastic with the exception of RC buildings in which the contribution of infill panels plays a role for low levels of damage [8]. It was assumed that infill panels collapse at heavy damage levels since the deformation of RC frames exceeds the deformation capacity of infill panels themselves. The definition of the displacement capacity on the capacity curve which relates to different limit states were defined trough rotation capacity of plastic hinges, as suggested in the technical literature and drift capacity given by experimental test for RC and masonry buildings, respectively in [1] and in [3]. For masonry buildings the use of pushover curves corresponds to the assumption of low vulnerability (class C1), since the pushover curve is representative of in-plane failure mechanism of masonry panels. In order to calculate the base shear capacity, the relationship proposed by [9] and the correction proposed by [10] have been taken into account.

Once the capacity is known, each point on the capacity curve that corresponds to damage limit states can be used to define the properties of an equivalent SDOF (Single Degree Of Freedom) system, which is equivalent to the original system in terms of equivalent period of vibration, displacement capacity and amount of dissipated energy. The dissipation of energy is taken into account through a coefficient η that can be related to the ductility and the damage as documented in [1]. The coefficient η, which is lower than 1, can be used to multiply the spectral ordinate or to divide the displacement capacity. The demand in SP-BELA is modelled by using displacement spectral ordinate. The procedure to calculate the probability of exceedance of each limit states is the following. For each building of the sample, the pushover curve is calculated. Once the equivalent period of vibration, the displacement capacity and the coefficient η are known, for each limit state a point on the plane of the spectrum can be plotted. If the point is above the spectral curve, the capacity is higher than the demand and hence the corresponding building satisfy the limit condition. When the point is below the spectrum, demand is higher than capacity and the building does not satisfy the limit condition thus evolving in the higher damage condition (Figure 2). By repeating the procedure for all the buildings of the sample, the number of points below the spectral curve divided by the population dimension gives the exceedance probability.

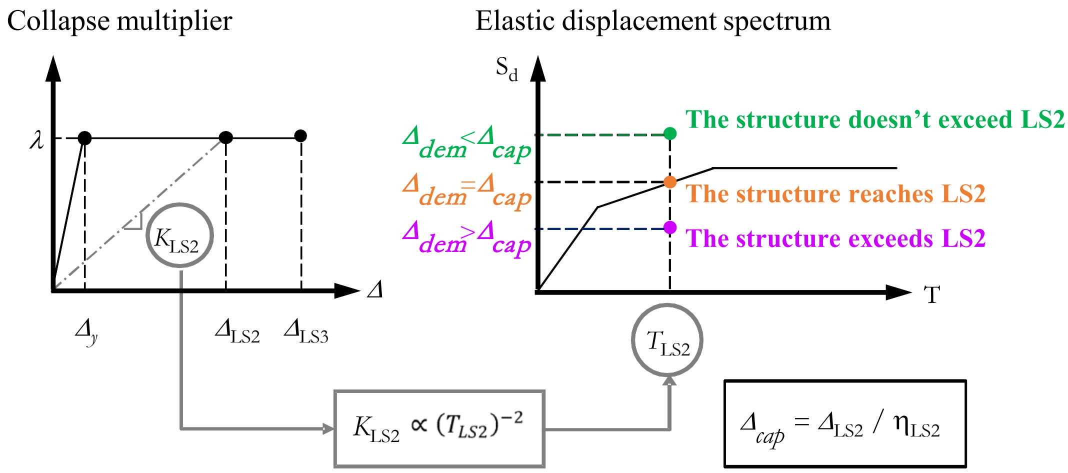

Figure 2: Procedure to calculate the probability of exceedance the limit conditions.

2.3 Calibration of SP-BELA methodology

The calibration of the SP-BELA method was a demanding task since it has drawn upon the results of various studies and the observed damage data. As known, the building vulnerability can be expressed by fragility curves (the lognormal cumulative distribution function is the most widely used to give a mathematical representation to fragility curves). The assumption underlying the calibration is that the vulnerability of a structural typology affects only the average value of the distribution of the fragility curve, but it doesn't change the uncertainty in terms of behavior of the building class. Hence, coefficients that relate the average of fragility curves for different vulnerability classes have been calculated, while the coefficients of variation have not been modified.

The calibration has overcome the SP-BELA methodology shortcomings due to the lack of information that allow to model all the mechanisms that can arise in a structure. The first aspect that it was decided to solve was the one related to the possibility to assess only the fragility of a well designed masonry building, which doesn't trigger to any out of plane failure mechanisms (Class C1). The introduction of calibration coefficients allowed to evaluate also the fragility of masonry buildings with medium (class B) and high (class A) vulnerability. The coefficients that correlate the capacity of these three classes of masonry buildings have been obtained by the

DPMs (Damage Probability Matrix) processed by [11]. These DPMs have been used also to find a relationship between limit states (LS1-low damage, LS2-sever damage and LS3-collapse) for which the capacity curves are calculated and damage levels (from D0 - absence of damage to D5 - collapse) of the EMS scale [4]. The assumptions were: (i) severe damage limit state (LS2) corresponds to damage level D3 and (ii) collapse limit state (LS3) corresponds to damage level D4. The curves for the other damage levels were then calculated by applying coefficients that modify the average of the curves for levels of damage D3 and D4. Hence, the curves for damage D1 and D2 were obtained from the curve for damage level D3, while the curve for damage level D5 was obtained from the curve of damage level D4. The variability of the curves was considered constant.

A correction of the aforementioned coefficients was applied accounting for the observed damage data of the most recent Italian earthquakes (Table 1).

Where	When	Mw
Friuli	1976	6.46
Irpinia	1980	6.89
Abruzzo	1984	5.89
Umbria-Marche	1997	6.01
Pollino	1998	5.64
Molise	2002	5.74
L'Aquila	2009	6.3

Table 1: Earthquake of which the observed damage data are available.

The calibration was performed by producing with SP-BELA the damage scenarios corresponding to the real earthquakes listed in Table 1, for which the forms with the observed damage data are available. These forms report the damage level, from D1 (light damage) to D5 (collapse) as in the EMS98 scale [4], assigned by the surveyor to the building. It is worth highlighting that, in the collection forms related with the Irpinia 1980 earthquake, there are 8 damage levels that do not precisely corresponds to D1, D2, D3, D4 and D5. Hence, some assumptions of obtained damage levels have to be undertaken by starting from data coming from survey forms, i.e.:

- D1 and D2 from the Irpinia survey form correspond with the absence of damage;
- D3 from the Irpinia survey form corresponds with D1;
- D4 from the Irpinia survey form corresponds with D2;
- D5 from the Irpinia survey form corresponds with D3;
- D6 from the Irpinia survey form corresponds with D4;
- D7 and D8 from the Irpinia survey form correspond with D5.

The calibration, made by different phases, led to the identification of a set of coefficients which allow a good agreement between the analytically calculated scenarios and the real ones, as shown in Figure 3 for the case of the Pollino 1998 earthquake selected between the case studies.

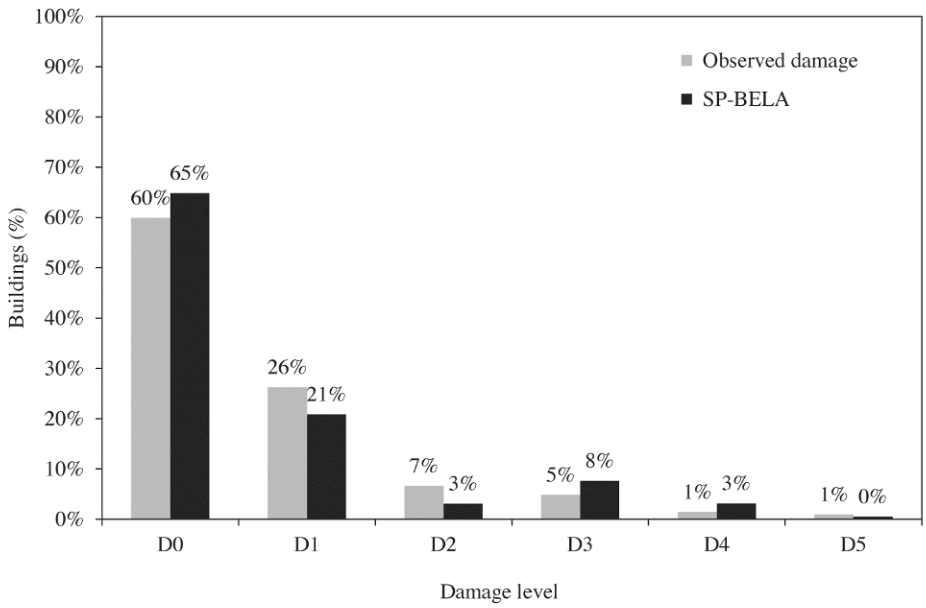

Figure 3: Percentage of buildings that reach a certain level of damage for the Pollino 1998 earthquake: comparison between observed data and SP-BELA calculations.

2.4 Seismic hazard

The seismic risk assessment requires hazard curves derived from the probabilistic hazard study performed by DPC-INGV project [12], for a grid of points used for the whole country. The hazard curve of the place where the building is located, gives the recurrence probability of a seismic event with a given level of severity in a specific exposure time t_d. Severity can be expressed in terms of the Annual Frequency of Exceedance (AFE), which is the reciprocal of the return period T_r. The hazard curve represents the relationship between AFE and a ground motion parameter, for example PGA (Peak Ground Acceleration). The logarithm of the PGA and the logarithm of the corresponding AFE ($=1/T_r$) can be assumed to be linearly-related, at least for return periods of engineering interest. The gradient of the log-log hazard curve is named –k, according to the definition in Part 1 of the Eurocode 8 [13]. The hazard curve can be built by points corresponding, for the Italian territory, with the PGA for the 9 return periods reported in the INGV-DPC project [12]. The hazard curves were used for the seismic risk calculation, as described in the next chapter.

Furthermore, for the definition of the damage scenario the hazard can be represented by:

- epicentre coordinates and magnitude;
- activated fault and fault mechanism;
- ShakeMap.

In the first case, the user has to define the epicentre coordinates, the magnitude and the focal depth. In the second case, the user can indicate the fault that has been activated, by using a list of the DISS (Database of Individual Seismogenic Sources) database [5] or a fault mapped by himself. Finally, the user can use as seismic input one of the ShakeMap already loaded into the system or a new ShakeMap taken from the INGV website. In the first two cases, the user must also select the GMPE (Ground Motion Prediction Equation) that he wants to use to calculate the ground shaking scenario from this list: Boore and Atkinson 2008[14], Akkar and Bommer 2010[15], Bindi et al. 2011[16], Cauzzi and Faccioli 2008[17]. Figure 4 shows the acceleration spectra obtained for the L'Aquila 2009 earthquake at a distance of 10 km from the epicentre with the four attenuation relationships considered.

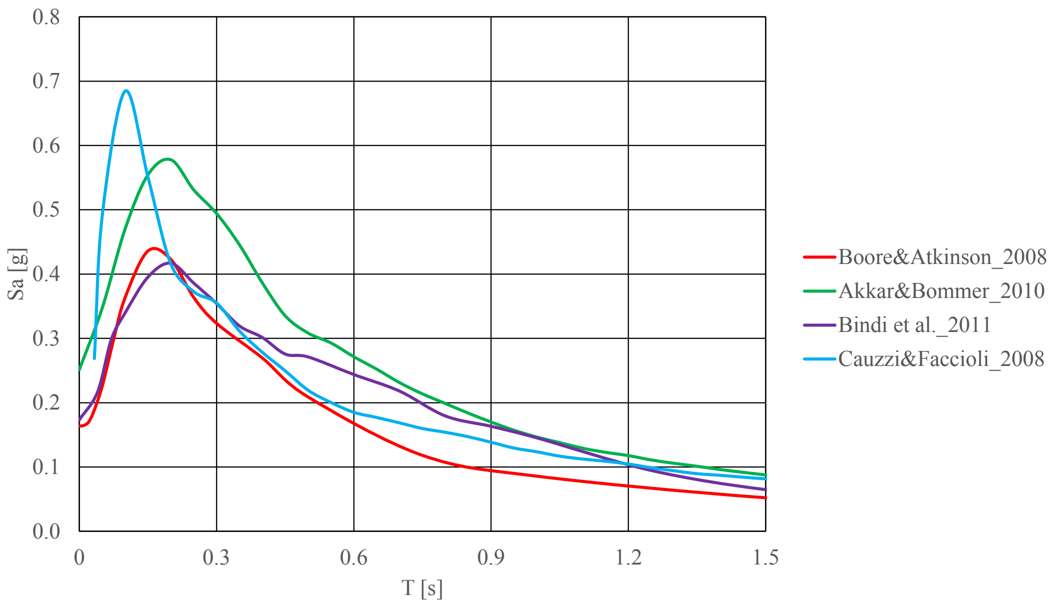

Figure 4: Acceleration spectra for the L'Aquila 2009 earthquake at 10 km of distance from the epicentre.

3 SEISMIC RISK AND DAMAGE SCENARIO

The combination of exposure, vulnerability and hazard allows to evaluate the seismic risk and the damage scenario.

If the unit definition is the individual building, in this case the school building, the structural behavior and the hazard are assigned to each structure. The seismic risk or damage scenario are calculated in terms of probability that the selected school building reaches a certain damage level.

However, in case of residential buildings in a municipality, to each building is assigned the same hazard related to the centroid of the municipality. The buildings in the municipality are classified into five vulnerability classes identified based on the ISTAT, and to each vulnerability class corresponds its own structural properties for the different limit states. The seismic risk or the damage scenario associated to the municipality are expressed in terms of number or percentage of buildings that reach a certain damage level. It is also possible to calculate the seismic risk or the damage scenario in terms of "impact". With the expression "impact" we refer to the combination of the damage levels that defines the buildings useable, damaged and unusable. In Table 2 the adopted combination is shown.

Impact	Correlation with damage levels
Useable	D0+0.6•D1
Damaged	0.4•D1+0.2•(D2+D3)
Unusable	0.8•(D2+D3)+(D4+D5)

Table 2: Correlation between "impact" and damage levels.

The correlation reported in Table 2 comes from the damage and usability database of the L'Aquila 2009 earthquake. The database required a pre-processing, made by the CNR-ITC of L'Aquila, where the damage of structural components was combined to have a single usability evaluation.

3.1 Seismic risk

The seismic risk is the unconditional probability of failure of the damage level, since the condition on the occurrence of the seismic event is removed by considering the probability that the event happens in the selected exposure time.

By starting from the hazard curve described in §2.4 and assuming that the occurrence of the events follow the Poisson process, that is a memoryless distribution that each event occurs independently of one another, it is possible to calculate the hazard curve in probabilistic terms. Three observation times t_d are taken into account in this study: 1 year, 10 years and 50 years. Therefore, since two curves are available – the hazard curve and the fragility curve – both expressed by the same input parameter, the exceedance curve (see Figure 5) of a given damage level in the exposure time t_d can be constructed as a discrete function.

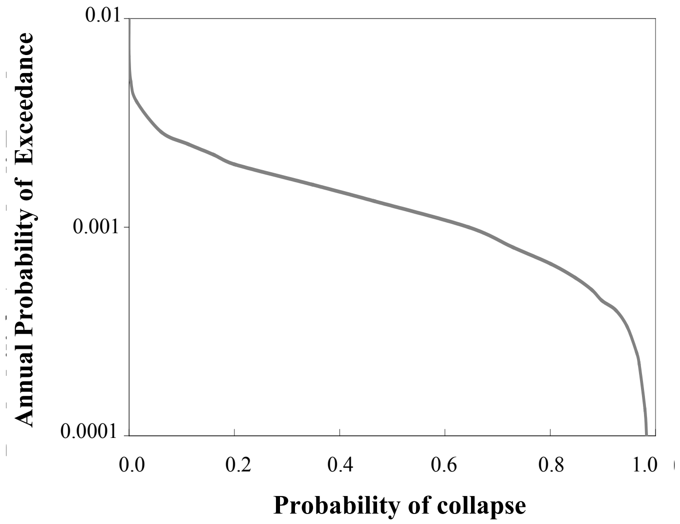

Figure 5: Exceedance curve of the collapse limit state in an exposure time of 1 year, for a given class of buildings.

The area under the curve of Figure 5 represents the risk of reaching the damage level D5 (collapse) in the time window t_d of one year. By integrating the exceedance curves, seismic risks can be calculated for five damage levels and the three selected time windows

3.2 Damage scenario

In addition to the calculation of the seismic risk, it is also possible to calculate damage scenarios in real time. The seismic input can be obtained from different GMPE as a function of the given magnitude and distance, or directly from a ShakeMap. The four GMPE selected, reported in §2.4 [14, 15, 16, 17], are among the most recent published. Important requirements that drove the choice were:

1) a simple functional form, which allows to generate a scenario also in the immediate post-earthquake with essential information of the event location but in the absence, for example, of the fault structure;
2) estimation of spectral ordinates in terms of displacement or acceleration valid for both high and low frequency;
3) good performance in terms of comparison with the spectra resulting from the recordings of different Italian earthquakes.

When the magnitude and the distance between the epicentre is available as well as the fault and the point in which the school building is located, or the centroid of the municipality, by using one of the GMPE, it is possible to calculate the ground shaking intensity at that point. This represents the hazard, which is then combined with the building vulnerability. Similarly, if a ShakeMap is used, the ground shaking is directly taken by the ShakeMap. In Figure 6 the ShakeMap for the L'Aquila 2009 earthquake in terms of PGA used for the production of damage scenarios is shown.

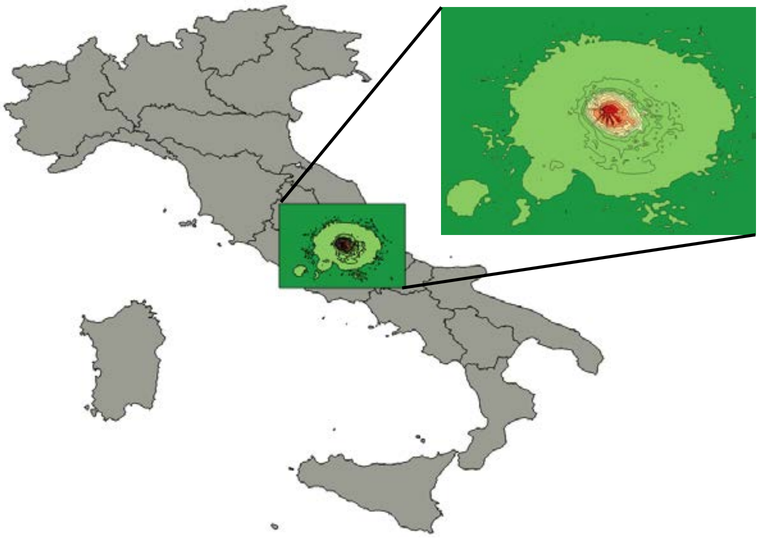

Figure 6: Shakemap for L'Aquila 2009 earthquake in PGA.

4 WEBGIS PLATFORM

In order to view on maps and tables the input and output data of the risk and scenario analysis, two WebGIS platforms were developed: one is related to residential buildings and the other one to school buildings. The central window of the WebGIS shows the map of Italy. By selecting a municipality or a school building on the map, specific information for the selected element are displayed such as those described in Table 3.

	Residential buildings	School buildings
exposure data	number of buildings in each vulnerability class	structural typology and number of stories of the building and original data on the collection form
seismic hazard	elastic constant probability response spectrum for different return periods related to the centroid of the municipality	elastic constant probability response spectrum for different return periods related to the building position
fragility curve	curves for all the vulnerability classes and number of stories present in the municipality	curves for the vulnerability class and number of stories assigned to the building
seismic risk	number or % of buildings that reach a damage level in a time window or in a return period	probability that the building reaching a damage level in a time window or in a return period

Table 3: Information in the WebGIS platforms.

Figure 7 shows the residential buildings WebGIS Home Page, while Figure 8 shows the same related to the WebGIS for school buildings. The information mentioned in Table 3 are shown simply by selecting the interested item and then opening the tab located at the top of the window.

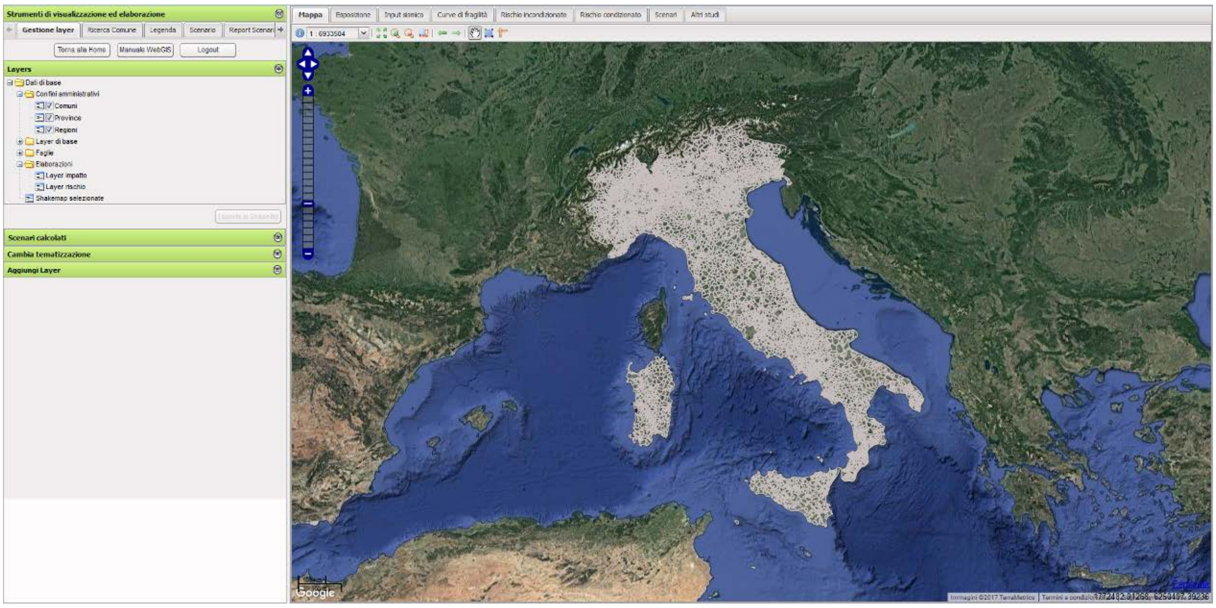

Figure 7: WebGIS for residential buildings Home Page.

Figure 8: WebGIS for school buildings Home Page.

Figure 9 reports an acceleration spectrum for a return period of 475 years available on the WebGIS platform after selecting, in this case, a municipality. Figure 10 and Figure 11 show the fragility curves respectively for residential and school buildings. In the first case, the fragility curves are plotted for all the vulnerability classes representative of the selected municipality. In the second case, only the fragility curves for the selected school building are shown.

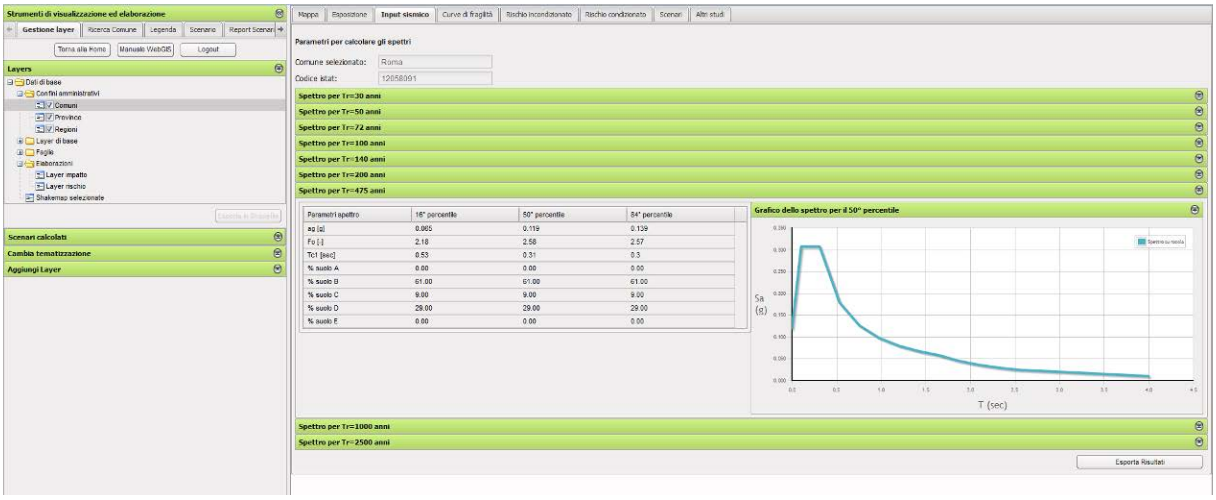

Figure 9: Acceleration spectrum for the selected municipality.

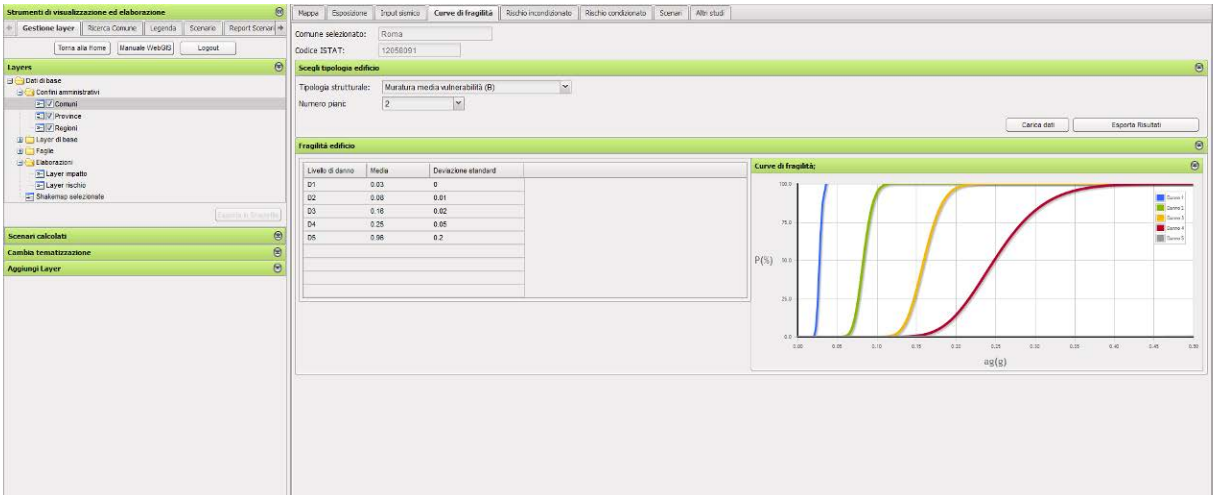

Figure 10: Fragility curves for residential buildings.

Figure 11: Fragility curves for school buildings.

The WebGIS platforms allow to perform risk and damage scenario analysis, as described above. Figure 12 shows an example of a map that represents, for residential buildings, the seismic risk in a time window of 50 years in terms of percentage of unusable buildings.

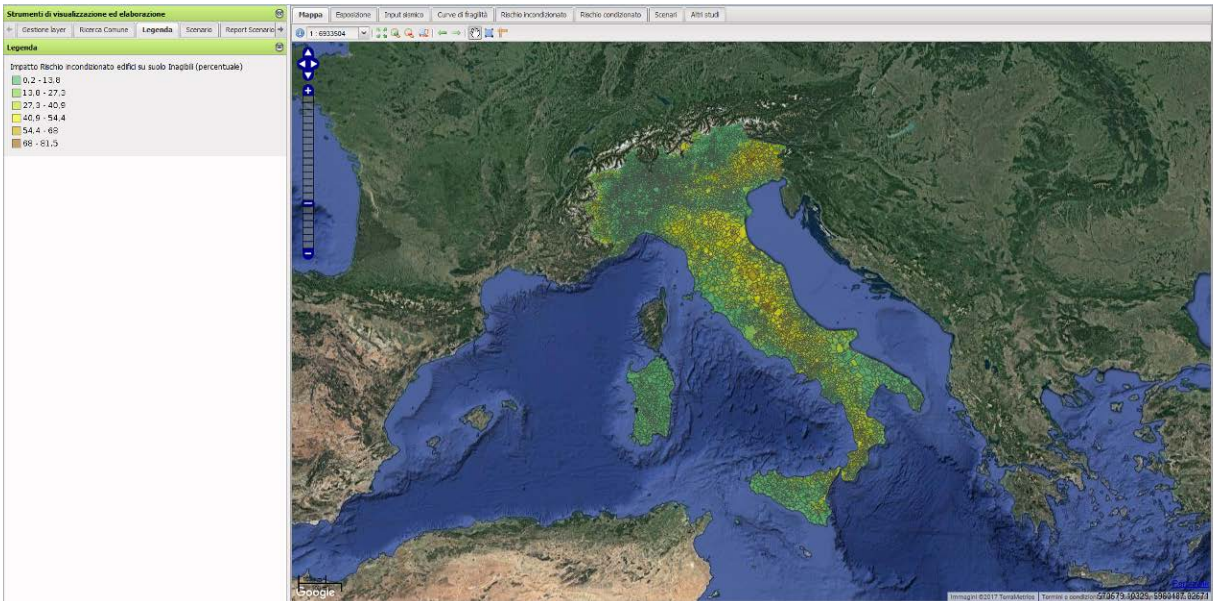

Figure 12: Seismic risk in a time window of 50 years in terms of % of unusable residential buildings.

The most important feature of the platforms is the possibility to run the real time damage scenario. The user can choose to enter the input parameters of the earthquake in terms of: (i) coordinates of the epicentre, magnitude and focal depth, (ii) fault that has been activated, from a list of the DISS database [5] (Figure 13) or a fault input by the user, and at last (iii) a shakemap. Figure 14 shows an example of a real time damage scenario calculated for residential buildings. The star indicates the earthquake epicentre location. The assigned colors to the municipality area indicate, in this case, the percentage of buildings that has reached the damage level D2.

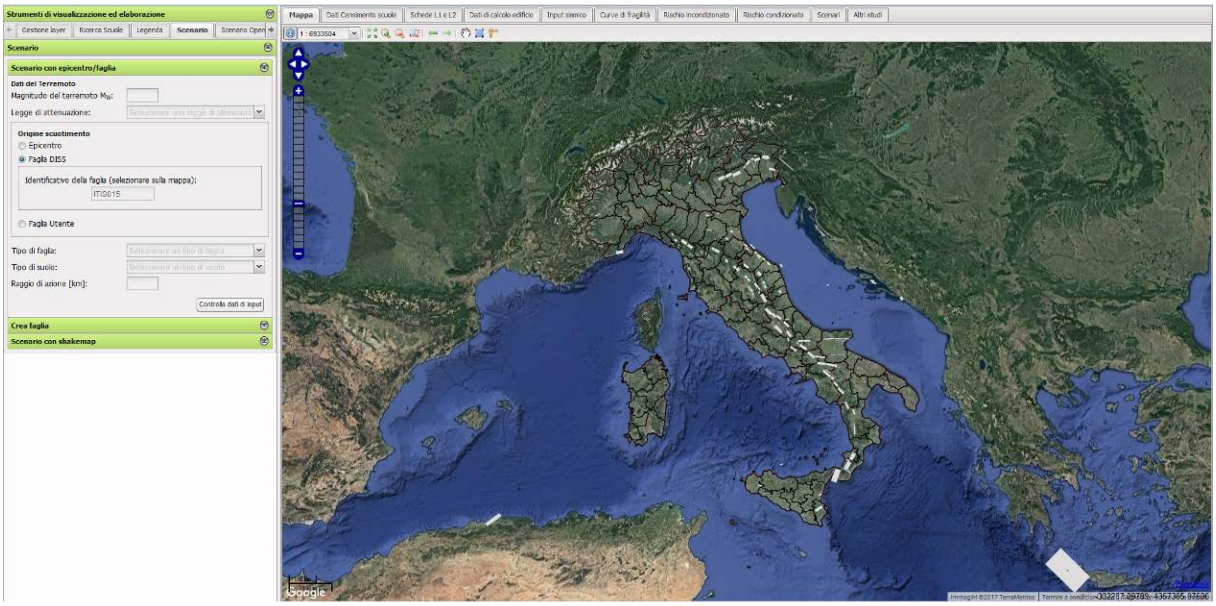

Figure 13: Faults from DISS database.

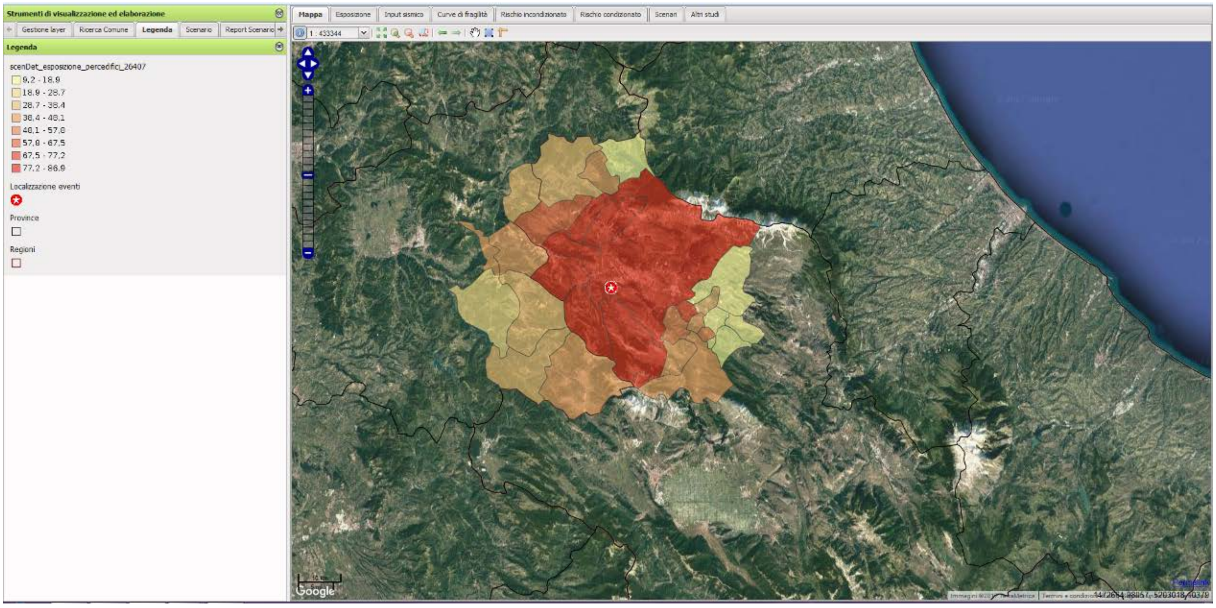

Figure 14: Example of real time damage scenario for residential buildings.

5 CLOSURE

In the aftermath of a catastrophic event, the difficulties that may be encountered in emergency management are manifold. To this end, it is very useful to have a tool that produces damage scenarios in real time and that gives a realistic framework, in terms of impact of the earthquake (i.e. buildings damages). This paper, deals with the implemented methodology to develop seismic risk maps and damage scenario analysis for residential and school buildings in the Italian territory. The vulnerability of the buildings has been calculated by the mechanic method SP-BELA calibrated on the observed damage data of the most recent Italian earthquakes. The tool is constantly evolving and expected to improve as follows:

- taking into account the vulnerability assessment of the damage accumulation effects as a result of aftershocks and or other events occurred nearby;
- assessing the site amplification effects through the use of seismic microzonation maps;
- using, in the analysis for residential buildings, as a minimum definition unit the census area instead of the municipality in order to have a spatial distribution of the damage within the municipality territory.

In conclusion, mechanic methods have the benefit to be adjusted although they are limited by the lack of data on the building environment. Thus, the quality of the results can be improved when more detailed data become available in terms of exposure and / or ground shaking records.

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