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SP-BELA: A STRUCTURAL SEISMIC VULNERABILITY ASSESSMENT METHODOLOGY BASED ON PUSHOVER CURVES

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Abstract

SP-BELA (Simplified Pushover-Based Earthquake Loss Assessment) is a method that allows to define the vulnerability of a building taxonomy by associating it with a portfolio of capacity curves. The main advantage of this method is that it keeps the capacity of the buildings separate from the demand imposed by the shaking at the site. This makes SP-BELA highly flexible and applicable to buildings of all structural types whose response to inertial actions can be described by a pushover curve. The method describes the seismic behaviour of a building taxonomy through the simplified mechanical model of a prototype building. The model includes the known data of the taxonomy (e.g., number of floors) and generates a population of buildings using random variables that represent the variability of the buildings belonging to the taxonomy. Therefore, the more data available, the more reliable and accurate the definition of seismic capacity will be because less unknown data will need to be generated.

This article outlines the application of the method to the reinforced concrete (RC) and masonry buildings since these structural types are the most representative of the built environment in Italy and Mediterranean countries. The article also defines the calibration process to which SP-BELA undergoes, testing its ability to numerically replicate the damage scenario of events that occurred in Italy in recent decades. Potential future developments of the methodology are also discussed. Lastly, we briefly document the implementation of SP-BELA in platforms that the Eucentre Foundation developed for the Italian Civil Protection Department (ICPD) to assess the seismic risk of the Italian building assets and calculate the damage scenario due to an earthquake.

Keywords: Seismic assessment, Nonlinear static analysis, Structural vulnerability, Reinforced concrete buildings, Masonry buildings.

1. Introduction

This article presents the SP-BELA (Simplified Pushover-Based Earthquake Loss Assessment) method for seismic vulnerability assessment. When it was first published [1], [2], SP-BELA had all the characteristics to belong to the family of mechanical methods. In fact, it combines the definition of structural capacity through a simplified pushover analysis similar to that proposed in [3], with a displacement-based structural verification method based on displacements according to Direct Displacement Based Assessment (DDBA).

The DDBA defines the nonlinear properties of the building by establishing an equivalent single-degree-of-freedom (SDOF) system that corresponds to the original structure in terms of vibration period, amount of energy dissipated due to nonlinearity, and displacement capacity. The first displacement-based method implemented in a vulnerability model was proposed by Calvi [4]. For reinforced concrete (RC) structures, the method proposed in [4] was further developed by Pinho et al. [5] and Crowley et al. [6], leading to the definition of the DBELA (Displacement-Based Earthquake Loss Assessment) method. In Europe, Tsionis and Fardis [7] developed fragility curves for RC buildings with nonlinear static analysis. The same approach was used by Karantoni et al. [8]for regular masonry buildings considering in-plane and out-of-plane failure mechanisms. For the seismic assessment of Italian buildings there are many approaches in the literature. These include Del Gaudio et al. [9], who

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developed fragility curves for RC buildings using the simplified mechanics-based method applied to an equivalent SDOF system. For masonry buildings, Lagomarsino and Cattari [10] suggest mechanics-based methods referring to non-linear static analyses to describe the building performance.

The fundamental components of SP-BELA are:

- Identification of a building prototype representing the taxonomy;
- Creation of a building dataset through Monte Carlo generation, starting from the building prototype;
- Simulated design of buildings of the aforementioned dataset according to code regulations;
- Definition of a simplified pushover curve for each building in the dataset. The pushover curve should identify displacements characterizing the attainment of specific damage conditions identified by limit states.

Most of the mechanic-based methods published in the technical literature result in the creation of fragility curves that compare the building capacity with the demand imposed by earthquakes for various levels of ground shaking severity. The primary distinctive feature of SP-BELA is the separation between demand and capacity. The capacity of the building taxonomy is compared with the earthquake demand at runtime. This approach makes the method very flexible. Some advantages are listed below:

- It allows for the consideration of the specific ground shaking characteristics during runtime analyses instead of representing the severity of the ground motion using a single parameter (e.g. Peak Ground Acceleration (PGA), Spectral acceleration (Sa), etc.). This makes the method suitable for accounting for different local site conditions and various types of ground shaking, such as crustal, volcanic, and subduction events;

- It allows for the consideration of various building codes, as the design process can be adapted to include different design options. This flexibility enables the description of taxonomies in relation to the specific design code adopted during the construction of the buildings;

- It can be applied to any structural typology, as long as its seismic performance can be represented by a pushover curve.

Although SP-BELA was initially a mechanics-based method, it evolved into a hybrid approach during further development. In fact, the method is calibrated through comparisons between numerically simulated damage scenarios and observed damage data. This innovation allows the method to address some of the limitations inherent in purely mechanics-based approaches, as will be explained in detail in the paper.

Overall, this paper provides a description of the SP-BELA method and its calibration process. Furthermore, the paper shows some practical applications of the method to different assets exposed to risk.

2. Definition pushover curves with SP-BELA

The structural capacity is defined through the pushover curve with a piecewise linear curve. To establish the aforementioned curve, we need the displacement capacities at the control points (i.e., Limit States) and the base shear strength. The latter is then transformed in dimensionless parameter by dividing it by the seismic weight of the building. The Limit States (LSs) under consideration have to be numerical thresholds whose exceedance can be mathematically identified. In SP-BELA, we consider:

- LS1: Slight damage/operational limit condition. After the earthquake, the building is still functional and does not need any structural interventions;
- LS2: Severe damage limit condition. The building cannot be used after the earthquake has occurred and requires structural interventions.

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- LS3: Collapse/life safeguard. Beyond this limit condition, the building is no longer safe because it doesn't withstand the gravity loads for which it was designed. The building will be demolished because structural interventions are either not feasible or cost effective.

In a probabilistic procedure for a large-scale seismic vulnerability assessment, the capacity curve can be derived from a reasonable estimation of the strength and displacement capacities. In simplified methods the capacity curve results from the repetition of the pushover analysis of buildings in a sample generated by varying random variables (i.e., building geometry, loads, and material parameters) according to probabilistic distribution laws. Once the capacity curve is determined, the properties of the SDOF system for each limit state are identified through: (i) the vibration period T, which is calculated based on the secant stiffness and the building mass, and (ii) the equivalent damping ξ, which is determined using relationships linking it to the ductility μ. In SP-BLA the equivalent damping ξ is calculated with the following formula proposed by Priestley et al. [11]:

$$\xi = 0.05 + 0.565\left(\frac{\mu - 1}{\pi\mu}\right) \tag{1}$$

The building taxonomies used to describe the "as built" in Italy are as follows:

- RC buildings, including the effects of infill walls which can be regularly or irregularly (pilotis) distributed along the height. These taxonomies are further divided based on whether the buildings were designed for gravitational or seismic loads. In the former case, only wind actions are considered as lateral loads in the simulated design. In the latter case, lateral forces also include inertial loads for which the building was designed according to the law in force at the time of its construction. Finally, a further subdivision is made into floor classes;
- Masonry buildings. Since SP-BELA relies on defining capacity through a pushover curve, it is capable of describing the behaviour of masonry buildings with global behaviour that triggers a collapse mechanism within the wall plane. This behaviour characterises masonry buildings with low vulnerability. To account for the behaviour of masonry with medium and high vulnerability, capacity correction coefficients have been calculated through a calibration as explained in Chapter 4. Masonry buildings are also divided into various floor classes.

Details on the implementation of SP-BELA for RC and masonry buildings are provided in the following sections.

2.1.RC Buildings

The pushover curves representative of the RC "as built" in Italy [12], [3], [13], in SP-BELA are calculated for the prototype building shown in Figure 1. If buildings are not seismically designed, their frames are generally oriented in only one direction. In the orthogonal direction, frame behaviour is, instead, ensured solely by the collaborating floor width.

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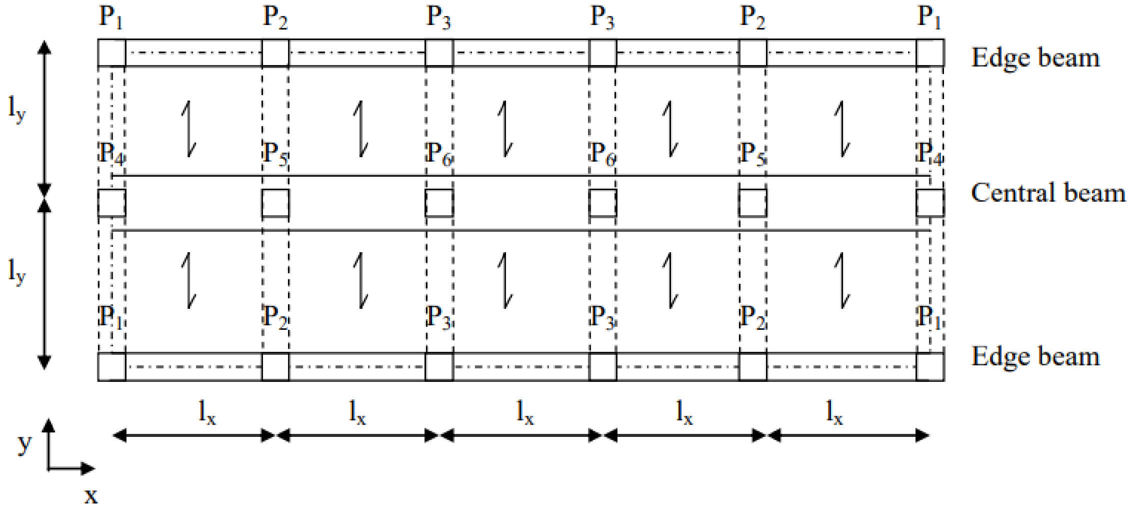

Figure 1. Layout of prototype building considered in SP-BELA as representative of RC buildings taxonomies (Borzi et al. 2008a).

To calculate the collapse multiplier λ, which corresponds to the dimensionless base shear resistance relative to the seismic weight, the distribution of bending moments and shears generated by the combination of gravity and horizontal actions must be defined. It is assumed that the seismic action corresponds to a triangular force distribution. Different distributions could be adopted in SP-BELA to account for higher modes of vibration beyond the first, which could be significant, such as in the case of multi-storey buildings.

The procedure for defining how bending moments and shears are distributed in the building elements is inspired by Priestley et al. [11]. For each column of the structure it calculates the shear resistance as the minimum value among the following:

- The shear strength of the column itself;
- The shear corresponding to the flexural capacity of the columns;
- The shear corresponding to the flexural capacity of the beams supported by the column.

Shear failure of beams collapse is not considered because beams tend to rarely fail in shear due to the shear reinforcement designed to withstand gravitational loads. Further details on the checks performed in SP-BELA for the definition of column shear resistance can be found in [1].

Once the shear resistance of columns is defined for each level, the collapse multiplier is calculated as follows:

$$\lambda_i = \frac{V_C^i}{W_T} \frac{\sum_{j=1}^{n} W_j z_j}{\sum_{k=i}^{n} W_k z_k} \tag{2}$$

where W_T is the total weight of the building, W_i is the weight associated with level i at elevation z_i, and V_{Ci} is the sum of shear resistances of the columns on level i. The collapse multiplier λ is the smallest value among all the λ_i values for each level.

The collapse mechanism is then defined as follows:

- If shear collapse occurs in any of the columns, the analysis stops. This choice is consistent with the fact that shear collapse mechanism is brittle and lacks the ability to dissipate energy.
- After the opening plastic hinges in all beams, if plastic hinges are activated at the base of all columns on a certain level, a global mechanism is considered (Figure 2a).

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- If the columns of a certain level fail in flexure, the activation of a storey mechanism is considered (Figure 2b).

Mixed situations may occur where only some columns are stronger than the beams and vice versa. In such cases, a clear collapse mechanism cannot be identified. Finite element analyses undertaken to validate the procedure implemented in SP-BELA [14] have shown that, in this case, the collapse mechanism is an average between the global mechanism and the storey mechanism.

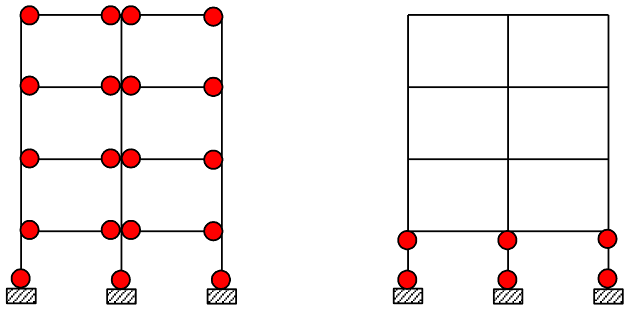

Figure 2. a) global and b) soft storey collapse mechanism (Borzi et al. 2008a).

Given the collapse deformation, the displacements of the equivalent SDOF system are defined at the centre of mass of the buildings based on the inter-story drift values corresponding to the selected limit states. Further details on the application of SP-BELA for reinforced concrete buildings are provided in [1].

2.2. Masonry Buildings

As previously mentioned, the taxonomy of masonry buildings for which the pushover curve is directly calculated includes only those with low vulnerability. These are buildings where masonry walls activate an in-plane failure mechanism and collaborate due to the redistribution of seismic actions associated with the stiff behaviour of the floors. For such buildings, given the presence of rigid diaphragms, a soft storey mechanism is assumed. Therefore, plasticity is concentrated within a storey, i.e. the storey for which the ratio between the resistance to seismic action and shear capacity is the lowest. In SP-BELA, the collapse multiplier at the storeys is calculated with the Equation 3 proposed by Benedetti and Petrini [15]:

$$\lambda_i = \frac{1}{W_T \frac{\sum_{k=i}^{n} h_i \; W_i}{\sum_{j=1}^{n} h_j \; W_j}} A_i \tau_{ki} \left[1 + \frac{\sum_{k=i}^{n} W_k}{1{,}5\tau_{ki} A_i (1+\gamma_{AB})} \right]^{1/2} \tag{3}$$

where W_T is the total weight of the building, W_i is the weight associated with the i-th level, τ_{ki} is the reference shear strength at level i for zero axial load, A_i is the area of all the masonry walls resisting at level i in the direction of applied load, n is the total number of storeys, γ_{AB} is the ratio between A_i and B_i, and B_i is the greater between the longitudinal and transverse wall areas. Once λ_i is calculated for each level, the collapse multiplier for the building corresponds to the minimum value assumed by the λ_i values.

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The equation reported in [15] only considers the shear-resistant mechanism and neglects possible three-dimensional effects, such as torsion due to potential eccentricity between the centre of mass and the centre of stiffness. Therefore, Restrepo-Vélez [16] suggested introducing the corrective factor of λ as in Equation 4.

$$\lambda = \Phi_c^{-1} min\{\lambda_i\} \tag{4}$$

The corrective coefficient Φ_c was evaluated by means of the results obtained from 3D finite element analyses conducted using the SAM code, specifically developed for defining capacity curves of masonry buildings. SAM stands for Simplified Analysis of Masonry and was developed at the University of Pavia starting from the late 1990s [17],[18]. Based on a linear regression of the results obtained from analyses conducted by Restrepo-Vélez [16], the following formulation for Φ_c was derived:

$$\Phi_c = 5.5 \frac{\tau_{ki}}{\frac{L_W}{L_T}} + 0.5 \tag{5}$$

where L_T is the length of walls oriented in the direction of load application while L_W is the total length of walls oriented in the direction of load application, excluding openings.

Similarly to RC buildings, once the collapse deformation shape and the inter-story drift values corresponding to the considered limit states are known, the displacements of the equivalent SDOF system can be calculated. Further details on the implementation of SP-BELA for masonry buildings are provided in [2].

3. Definition of Damage Probability with SP-BELA

As outlined in Chapter 2, the points on the pushover curve define the characteristics of an equivalent SDOF system. The assessment of capacity against the demand imposed by the earthquake in SP-BELA aligns with the principles of the DDBA. The probabilities of exceeding a selected limit state is graphically shown on the displacement spectrum (Sd) plotted as a function of the vibration period in Figure 3, where the points represent the SDOF to which the building is reduced. Thus, these points have coordinates of the equivalent vibration period and the equivalent displacement capacity, which is amplified by dividing by the code coefficient η (see Equation 6). The latter coefficient accounts for the equivalent damping ξ and, hence, the portion of energy dissipated due to material hysteresis:

$$\eta = \sqrt{\frac{10}{5 + \xi}} \tag{6}$$

The green points above the displacement spectrum curve represent the buildings in the sample that have a capacity exceeding the demand, satisfying the verification for the reference limit state. On the contrary, the points below the displacement spectrum curve (red points) do not satisfy the verification for the reference limit state since the demand is greater than capacity. Consequently, these buildings evolve into the subsequent damage limit condition. The number of such elements relative to the sample size corresponds to the probability of exceeding the seismic action to which the comparison refers.

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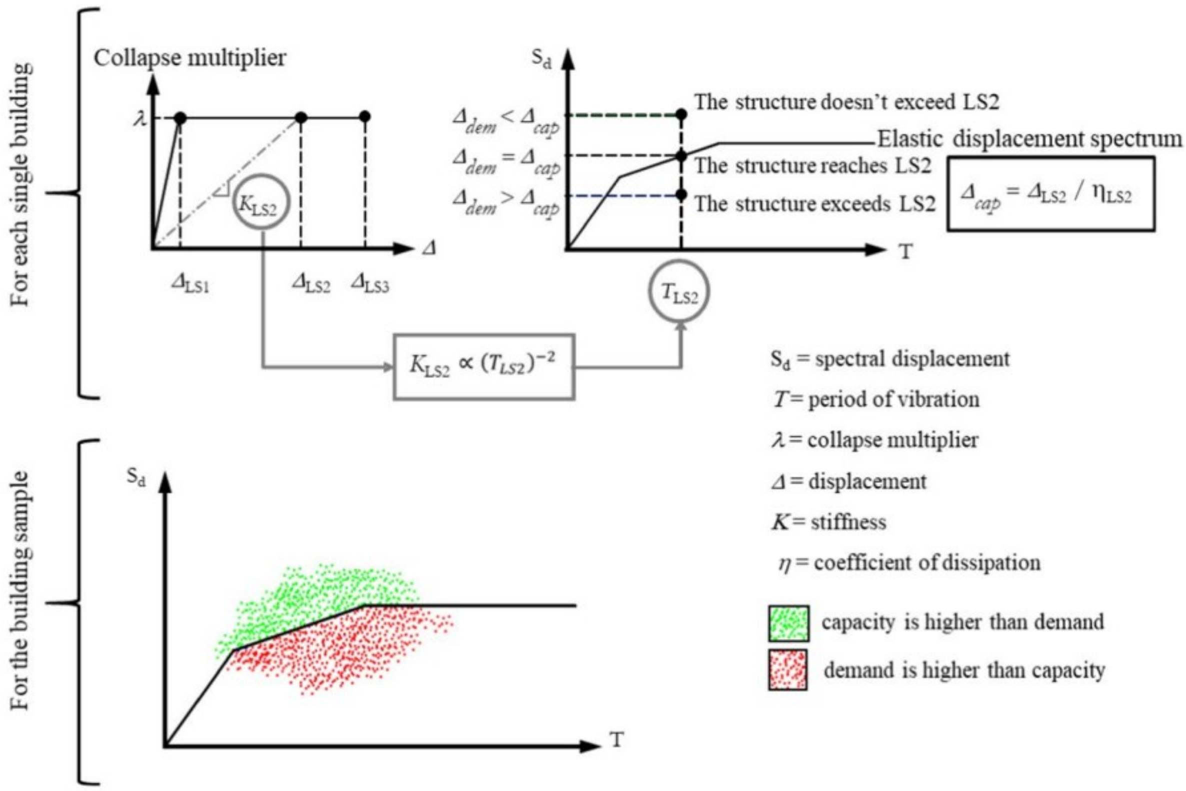

Figure 3. Scheme of the procedure to calculate the probability of exceedance of a selected damage limit state [19].

4. Calibration of SP-BELA

The capacity curves initially obtained from SP-BELA to assess the structural capacity of building classes refer to the three damage limit states (LSs) identified by the current Italian Building Code [20] and described in Chapter 2. Furthermore, as anticipated, masonry capacity curves can only be produced for buildings with low vulnerability. It is therefore necessary to calibrate the capacity resulting from SP-BELA with two different set of coefficients to obtain:

- the capacity of RC and masonry buildings in terms of five damage levels (from DL1 to DL5), the latter defined according to the European Macroseismic Scale 1998 (EMS-98, [21]), starting from LS2 and LS3;
- the capacity of masonry buildings with high and medium vulnerability from those with low vulnerability.

The calibration is based on comparing the actual damage as reported in survey forms due to the specific events happened after 1976 Friuli earthquake onwards with the corresponding damage scenarios calculated with SP-BELA. As Ground Motion Prediction Equation (GMPE), we have adopted the one proposed by Bindi et al. [22], since it performed well for the Italian territory.

The comparison between the actual damage and performed damage scenarios also accounts for the observed damage of non-structural elements, derived from the extent of the reported damage to the infill walls. Since non-structural elements are considered up to damage level DL3, only structural damage is considered for damage levels DL4 and DL5. The earthquakes considered for the calibration process are the mainshocks of: 1980 Irpinia, 1998 Pollino, 2002 Molise-Puglia, and 2009 L'Aquila. We did not consider the 1997 Marche-Umbria and 2012 Emilia sequences because for:

- 1997 Marche-Umbria event, we lacked information about the damage to non-structural elements, due to the lack of specific fields in the survey form used during the inspections;

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- 2012 Emilia event, even if damage to non-structural elements is reported in the survey form used during the inspections, it is likely that it was compromised by the aftershocks.

To convert the reported damage to the infill walls into EMS-98 damage levels [21], we used the approach of Del Gaudio et.al. [23] for the events 1998 Pollino, 2002 Molise-Puglia, and 2009 L'Aquila (Table 1). For the 1980 Irpinia earthquake, we have applied a metric developed in Eucentre and reported in Table 2

Table 2. Then, for each building, we compare the non-structural damage level with the structural damage level: the greater of the two is associated with the entire building.

Figure 4 and Figure 5 show the comparison between the observed and calculated damage scenarios for RC and masonry buildings related to the 1980 Irpinia, 1998 Pollino, 2002 Molise-Puglia, and 2009 L'Aquila earthquakes. Based on this comparison, we have derived the two set of calibration coefficients for SP-BELA. These coefficients are reported in [24], where a detailed description of the calibration procedure is also provided.

Table 1. Metric proposed by Del Gaudio et al. (2017) to convert the damage to infill walls reported in the AeDES survey form into the damage levels DLs according to the EMS-98 scale [21]

Damage according to EMS9-8	**Infill walls**	
	Damage levels in the AeDES form	**Damage extension**
DL1	D1	<1/3; 1/3-2/3; >2/3
DL2	D2-D3	<1/3; 1/3-2/3; >2/3
DL3	D4-D5	<1/3; 1/3-2/3; >2/3

Table 2. Metric proposed by EUCENTRE to convert the damage to the infill walls recorded in the 1980 Irpinia survey form into the damage levels DLs of the EMS-98 scale [21]

Damage according to EMS-98	**Infill walls**
	Damage levels in the 1980 Irpinia survey form
DL0 (absence of damage)	D1
DL1	D2 D3
DL2	D4
DL3	D5-D5-D6-D7-D8

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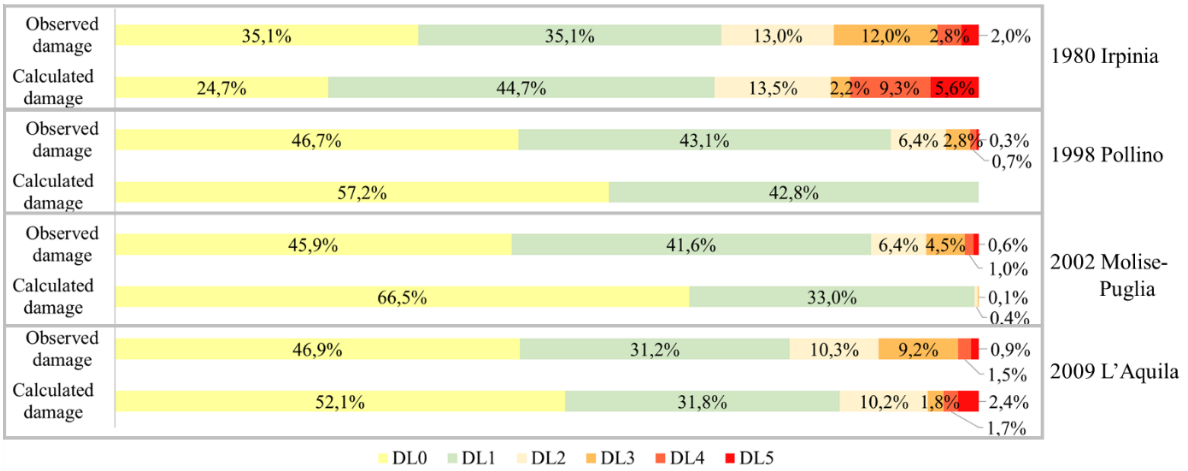

Figure 4. Comparison of real damage scenario (observed scenario) and scenario calculated using the SP-BELA method (calculated scenario) for RC buildings.

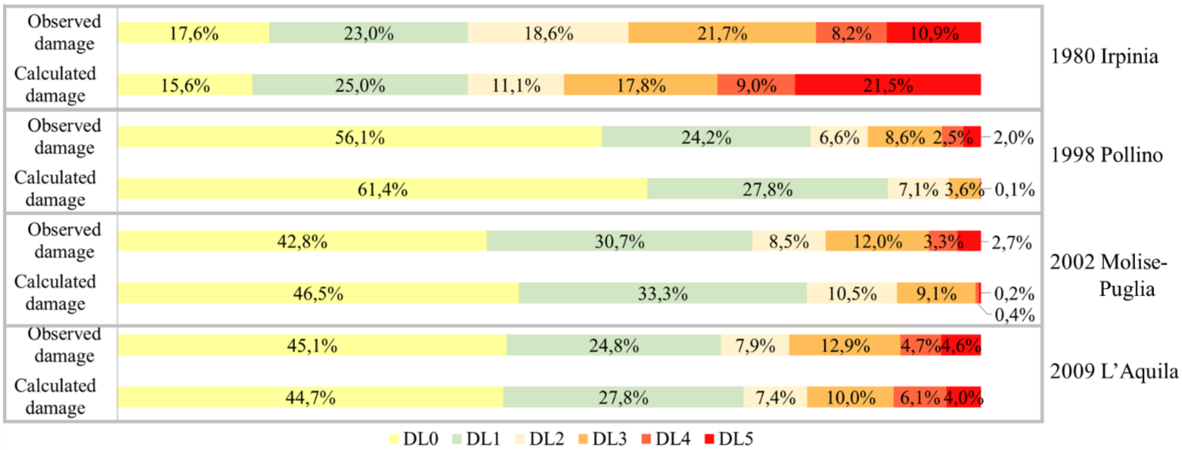

Figure 5. Comparison of real damage scenario (observed scenario) and scenario calculated using the SP-BELA method (calculated scenario) for masonry buildings.

5. Applications of SP-BELA

SP-BELA has been implemented in web-based GIS (WebGIS) tools developed for calculating seismic risk and real-time damage scenarios for buildings. These tools are available in the EUCLIDE (EUCentre for Loss Impact and Damage Evaluation) platform (see the home of EUCLIDE in Figure 6), which also includes tools to calculate seismic risk maps and real-time damage scenarios for infrastructures (e.g., tunnels, bridges, and infrastructures of harbours and airports). The Web-GIS tools for buildings consider:

- Residential buildings;
- Strategic buildings, such as hospitals and schools.

The key distinction between tools dedicated to residential and strategic buildings is that residential buildings are not identified one by one but by referring to the building stock of a given area (e.g., municipality or a sub-portion of a municipality) for which information is available. In contrast, strategic buildings are identified individually. However, even for strategic buildings we need to conduct large-scale vulnerability assessments due to the limited information we have on each of them. With the available information, in fact, we can only classify strategic buildings into taxonomies. Consequently, the results should be considered as averages and not as representative of specific individual buildings.

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Figure 7 provides an overview of the home of EUCLIDE: in the first line there are the three WebGIS tools for residential buildings, schools, and hospitals.

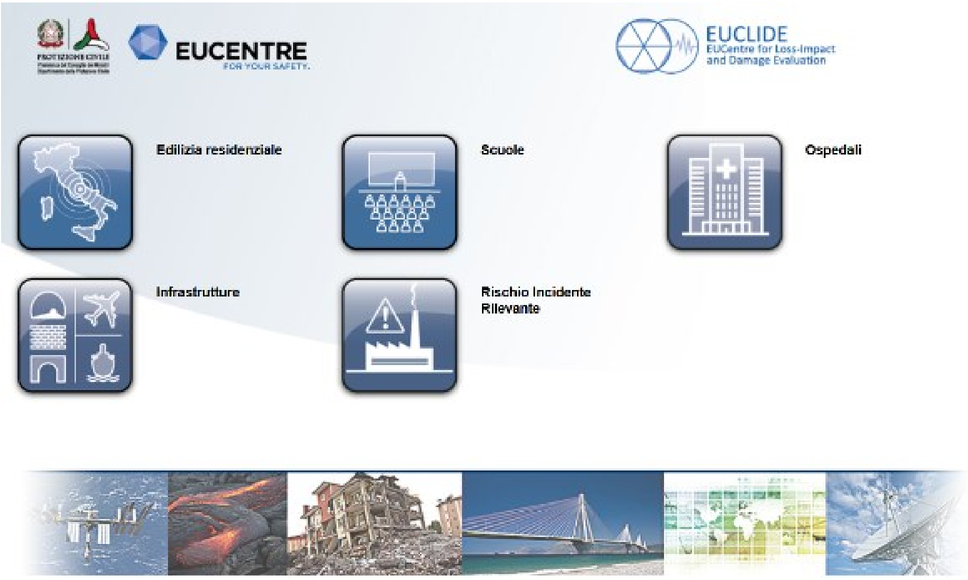

Figure 6. Homepage of EUCLIDE.

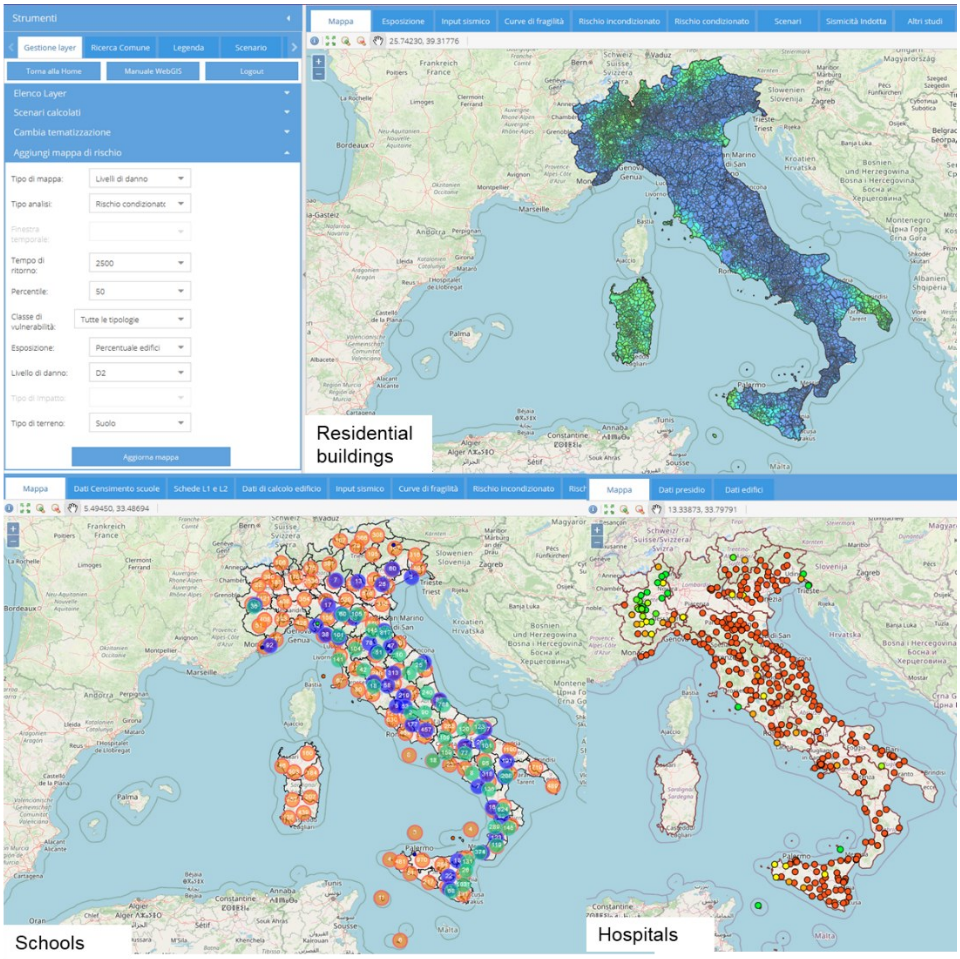

Figure 7. Homepage of the three webtool that have buildings as the exposed asset.

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6. Concluding Remarks

SP-BELA is a method for defining the seismic vulnerability of buildings on a large scale. The method is based on the definition of capacity curves. Originally developed as a mechanical method, it is classified as a hybrid method because damage data from events that have occurred in the Italy over the last 50 years have been used to:

- calibrate the results;
- compensate for the limitations of a purely numerical method, mainly related to situations that cannot be numerically reproduced.

In defining damage probabilities, whether in time-based and event-base analysis, capacity is compared to demand. The SP-BELA approach makes this comparison more straightforward to include effects that alter the frequency content of the earthquake, such as site effects and the different nature of the rupture that provoke the ground shaking.

On the other hand, the damage assessment using fragility curves allows to graph a parameter adopted as a representative measure of shaking severity on the x-axis. However, with a single parameter, it is not equally effective in accounting for all the factors that act and alter the nature of the seismic input.

We plan to further develop the method in the future in order to extend the range of buildings to which SP-BELA can be applied. The first activity in this direction is the integration of the effects of seismic mitigation measures (e.g., building retrofitting), implemented as part of seismic risk mitigation campaigns in earthquake-prone countries.

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