



Fast evaluation of seismic vulnerability of RC building: a proposal of micro-zoning procedure for safety assessment

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Abstract

Effective risk management and mitigation of losses due to natural hazards require comprehensive knowledge of the vulnerability of structures and their capacity for immediate response to sudden, unpredictable events. While the precise timing and location of such events remain uncertain, their occurrence is an anticipated reality. Enhancing resilience and the capacity to assess and manage disaster effects necessitates equipping territorial management with detailed assessments of structural vulnerabilities and efficient tools for rapid safety interventions. Structural safety is a critical aspect of this process. Developing fast and reliable strategies and procedures is essential for establishing a coherent framework to guide risk mitigation activities. This study proposes a systematic approach to classifying and mapping risks associated with natural disasters, particularly earthquakes, landslides, and debris flows. The methodology involves categorizing structures based on their geometric and mechanical properties, grouping them into morpho-types with similar macro-characteristics. Localized maps are developed to identify uniform zones with comparable structural morphologies, delineating areas of similar vulnerability at micro and macro scales. The analysis employs a simplified pushover technique using a robust dislocation-based finite element method. Data obtained from these analyses are processed to define capacity curves for each morpho-type, serving as the basis for the classification system. The results are visualized through user-friendly tools, including abacuses, Geographic Information System (GIS) representations, and thematic risk maps, providing practical resources for risk assessment and territorial management.

Keywords Seismic vulnerability · Reinforced concrete buildings · Micro-zoning procedure · Structural safety assessment · Earthquake resilience · Simplified pushover

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1 Introduction

The assessment of the seismic vulnerability of buildings is a critical issue, especially in historic urban areas, for the preservation of cultural heritage. The importance of defining an effective and rapid method for estimating the vulnerability parameters of buildings also focuses on buildings of social importance, such as hospitals and schools and inhabited settlements in general. A wide range of approaches has been developed to address this issue, varying considerably in terms of the level of detail of the analyses and the volume of work required to collect the information. In this context, studies have been grouped according to the methodologies used and the building types analyzed. Among the techniques based on seismic vulnerability assessment, several approaches are based on post-seismic data studies and field surveys. Studies that rely on post-earthquake damage surveys and statistical analyses of observed damage provide an important empirical basis for seismic vulnerability assessment. Vicente et al. (2014) proposed a procedure calibrated on the Azores earthquake event of 1998, highlighting the structural characteristics that influence the behavior of masonry buildings during an earthquake. Ferreira et al. (2014) applied a similar strategy to assess the seismic vulnerability of masonry building façades in the historic center of Coimbra, Portugal, including the evaluation of more than 600 façades. Neves et al. (2012) conducted a detailed assessment of the building stock on the island of Faial, collecting significant data on damage mechanisms and seismic vulnerability of buildings. Some forms of uncertainty are non-random and, therefore, do not lend themselves to be treated or modeled by probabilistic theory. Therefore, a Fuzzy-Random approach is proposed to assess the different dispersion that affects building damage distributions, depending on the amount of cognitive uncertainty that characterizes the vulnerability assessment (Giovinazzi and Lagomarsino 2005; Oleng et al. 2024). A case study for seismic risk evaluation in Indonesia is presented in Hadi et al. (2024). Domaneschi et al. (2021) developed a methodology for estimating the seismic vulnerability of schools in Turkey, using an expeditious approach for identifying structural criticalities. In addition, Lagomarsino and Giovinazzi (2006) introduced two models in the RISK-UE project: a macro seismic model based on intensity maps and a mechanical model based on ground accelerations and spectral values. More expeditious approaches include the use of scoring methods and empirical models, which allow rapid vulnerability assessment. A vulnerability assessment for the urban roadway by using interval valued fermatean fuzzy analytical hierarchy process is presented in Yildirim et al. (2024). In Bal et al. (2008) the P25 Scoring Method for a rapid preliminary assessment of reinforced concrete (RC) structures calibrated on 323 RC buildings in Turkey is developed. Subsequently, Bal et al. (2006) tested the method on 126 damaged buildings and made modifications to improve the algorithm. A rapid screening for RC buildings at medium to high seismic risk in Turkey was proposed by Boduroglu et al. (2004). In parallel, Hom and Poland (2004) developed the national standard ASCE 31-03 for the seismic assessment of existing buildings in the United States. Probabilistic and stochastic approaches combined with mechanical methods are used for a more detailed assessment. Calvi (1999) presented an innovative approach for assessing the vulnerability of classes of buildings, using displacement capacity and energy dissipation to estimate the probability of damage. In Ferreira et al. (2013) the authors applied a simplified methodology to assess the seismic vulnerability of masonry buildings in the historic center of Seixal. Dolce et al. (2006) compared Italian and Greek procedures to assess loss and damage scenarios for the built heritage of the city

of Potenza. Fajfar (2000) presented the N2 method for the non-linear seismic analysis of buildings, used to estimate the seismic performance of reinforced concrete buildings. Lagomarsino et al. (2020) developed a method for assessing the seismic vulnerability of historic buildings. The described procedure follows a component-based approach to be implemented within modern probabilistic seismic risk analyses. It includes both in-plane and out-of-plane damage modes that can be activated in a URM structure. It has been applied to a three-story building, examined by varying some configurations of structural details, with the aim of simulating two different in-plane collapse mechanisms (with damage concentrated mainly on the columns or also in the spandrels) or to allow, in one case, also the activation of local out-of-plane mechanisms. Cosenza et al. (2018) provide guidelines that allow professionals to address the sophisticated concepts underlying modern seismic design, such as expected annual losses (EAL) and repair costs (expressed as a fraction of the Reconstruction Cost: %RC). Seismic risk classes of buildings and class improvements due to strengthening interventions can be assessed using the principles included in the guidelines. Su et al. (2015) presents the development of an integrated method combining remote sensing data and local knowledge to solve this problem. This method comprises two key interdependent steps. (1) Extract the heights and footprint areas of a large number of buildings accurately and quickly from individual high-resolution remote sensing optical images; (2) Estimate floor areas, identify structural types, develop damage probability matrices, and determine economic parameters to calculate monetary losses due to seismic damage. The work of Maio et al. (2015) addresses the construction characterization and morphology of an ancient urban center in the city of Faro, stimulating further reflection on the assessment of vulnerability and risk to the occurrence of natural and artificial disasters, such as earthquakes, tsunamis, floods or urban fires. In Manfredi et al. (2023), an approach based on the fragility curves (CF) of reinforced concrete (RC) buildings with a moment-resistant frame structure, representative of the existing Italian building stock, is derived through an analytical approach. Some structural morphotypes, such as megastructure, monoliths, isolated columns, slender shear walls are subjected to concomitant phenomena (Gennaro et al. 2023) proposed the evaluation of the damage of structures subject to horizontal forces focusing on rocking phenomena. In Faiella et al. (2022); Argenziano et al. (2023); Mele et al. (2021) nonlinear dynamic approaches are presented, taking into account viscoelastic parameters and its applications to megastructures. The work deals with non-linear dynamic analyses that include all the necessary steps to obtain reliable and realistic fragility results. The objective of the previous works is to furnish an instrument to evaluate the limit condition of structures under prescribed loads. The priority objective of urban planning (Losco et al. 2012) is the programming of territorial transformations, prioritizing the superior public interest. Reducing territorial risks, a key concern for communities aligns with this public interest. Urban planning actions should focus on mitigating risks by reducing exposure and vulnerability. In this context, traditional plan drafting techniques—often based on purely quantitative criteria, such as residential sizing—must evolve to incorporate performance-driven approaches. These approaches allow for risk mitigation actions to effectively influence territorial transformations. This perspective is particularly relevant when considering seismic risk. The Seismic Risk Class, applied to the built environment, can be used in the pre-dimensioning of residential areas within municipal plans, fostering eco-sustainable urban regeneration. This variety of approaches underlines the importance of an accurate and contextualized seismic vulnerability assessment to improve the resilience of historic and modern urban

areas against seismic hazards. The development of a series of procedures for damage assessment, from the building scale to the urban scale (Fabietti 2001), born for the recognition of damage after an earthquake has occurred, has opened up possible applications in the analysis and design phase of the urban plan, for the reduction of the vulnerability of the built heritage, although there are still limited experiences of plans at the municipal scale oriented to the implementation of strategies for the prevention/mitigation of the impacts of the earthquake. The need, emerging from the demand of the newly settled community, to improve/increase the safety of the territory entails the introduction of quality in urban planning, which, in the specific case of residential building heritage, translates into a building analysis that is not only quantitative but also performance-based. The attribution of the SRC to existing buildings represents a useful tool for this purpose that allows the municipal plan to pursue the objective of seismic risk mitigation through the reduction of the vulnerability of the built heritage. Similar considerations could also be extended to energy performance and other complex indicators of environmental, social, and economic sustainability that determine the habitability/usability of the building stock; all these qualities should enter the planning process through an updating of urban planning techniques from exclusively quantitative to performance-based. In this paper, a rapid seismic vulnerability assessment procedure for reinforced concrete buildings is described. The proposed method proposes a procedure that, through the principles of limit analysis, provides a classification of the built environment, allowing the vulnerability of buildings to be assessed quickly and effectively according to the morpho-type to which they belong. The computational procedure is briefly described, some examples of 'standard' morphotypes are illustrated, and the results are shown, which, as a natural development, will see the construction of vulnerability tables built according to the geometric and macroscopic characteristics.

This paper builds upon these methodologies to propose a micro-zoning procedure specifically tailored for the rapid evaluation of RC buildings subjected to seismic events and also for continuous seismic events over time, as in the case of the Phlegraean Fields at Pozzuoli. The paper is organized as follows :

- Section 2, a focus on the vulnerability and seismic risk associated with the human interaction with both the natural and manmade environment;
- Section 3, definition of the strategy of substructuring the problem using structural morpho-types;
- Section 4, simplified methodology analysis implemented using finite element method associated with limit analysis. For sake of completeness a benchmark is furnished;
- Section 5, results obtained and risk map proposal.

2 Territorial peril: vulnerability and seismic risk.

Any activity carried out by man involves interaction with both the natural and man-made environment and can give rise to unforeseen events, accidents, and, therefore, damage. An initial classification of territorial hazards could envisage dividing them into two macro-categories: natural and man-made, which, in turn, could be subdivided into seismic, volcanic, and hydro-geological, the first and technological, the second. Technological hazards could be further distinguished and classified into ecological (atmospheric, water, soil, acoustic pol-

lution), fire (forest, urban, and/or industrial area), chemical-industrial (production, storage, and transport), nuclear (production and storage), manufactured goods (structure collapse), and health hazards. Referring to the risk equation in the form $\text{Risk} = \text{Probability} \times \text{Vulnerability} \times \text{Exposure}$ or even $\text{Risk} = \text{Probability} \times \text{Danger}$ (with $D=V \times E$) and starting from the assumption that a null risk (like absolute safety) is a pure abstraction, it can be stated that natural hazard is related to the specific characteristics of a given territory. At the same time, vulnerability is consequent to the intrinsic characteristics of an object and/or a system of objects, completely independent of territorial hazard. Seismic risk assessment requires a multidisciplinary study that can be carried out using different procedures, approaches, and criteria with the aim of identifying, assessing, and quantifying all the possible effects of an earthquake on a given human context. Absolute risk assessment has some drawbacks: most of the data referred to are not definite values but are the result of probabilistic or statistical calculations, often obtained with high levels of approximation. It was precisely to solve this drawback that the relative risk assessment methodology was introduced. In this case, risk is assessed by comparison between the various areas into which the survey territory is divided. Indicative risk levels are defined (high, medium, low), which are then attributed to the multiple regions according to their hazard, exposure, and vulnerability. Crucial for effective urban planning is the concept of acceptable risk (as low as reasonably acceptable) since it is evident that a cancellation of seismic risk in a given area is to be considered absolutely unfeasible both for technical and practical reasons and for economic reasons. The effects of a seismic event may refer to a single element (e.g., the collapse of a building or a bridge) or to a functional system or part of it (e.g., the failure of the transport or water supply network) (Mascolo et al. 2018) and Mariano et al. (2020).

3 Structural morpho-types

The objective of this paper is the set up a procedure for the risk evaluation of the existing structures and infrastructures coming from natural disasters such as earthquakes, landslides, and debris flows, and the definition of novel approaches to classify the vulnerability of concrete structures. This paper is focused on the seismic vulnerability estimation. The procedure is helpful in every urban settlement through a systematic action of structural prevention and through a detailed classification of existing buildings, especially reinforced concrete, which is denoted by the frequency with which disaster events occur, even of minor entities. An example of events of minor magnitude but with considerable impacts on structural safety is a low magnitude but continuous seismic event that occurred during the bradyseism crisis that began in 2005 in Italy at Pozzuoli in the Phlegraean Fields. The objectives consist of identifying the risk for decision-making purposes, i.e., identifying the parameters that characterize it for risk assessment and mitigation. Disaster risk is expressed through the consequences that possible future earthquakes can produce, both economic and social. The seismic risk classification of individual buildings, which helps define the consequences that earthquakes may cause in the future, is closely tied to the earthquake resistance characteristics of the structure, determined by its geometry and mechanical properties. The aim is to define qualitative standards from site inspections and surveys by building typology, date of construction, and regulatory references of the construction time from which to derive quantitative data about the mechanical properties to be included in the simplified analyses.

The data and results of the surveys carried out have the purpose of building typical numerical models to be subjected to fast and reliable analyses of resistance and vulnerability. The characterizing of the organism at the building scale is obtained through the typification of the settlements through analyses aimed at identifying homogeneous areas by

- Geometry
- Date of construction (age of the structure and construction protocol)
- Regulatory references of the time of construction from which to derive information at the scale of the building sector,
- The neighborhood and the establishment of the predictable vulnerability

This information contributes to creating a numerical twin for each morphotype and identifying homogeneous areas from the point of view of risk parameters. Seismic micro-zoning, based on structural vulnerability, becomes feasible in this way. By establishing a micro-zoning on micro-seismic scales, we can evaluate the effects of an earthquake using a qualitative-topological classification of building vulnerability. This takes into account the level of damage that has been or could be caused. The goal is to develop simplified analysis and evaluation strategies based on indirect observations, leading to the interpretation of the building's structural performance level through the definition of quantitative parameters derived from observations and simplified measurements of the building complex. Due to several analyses on type structures, one can set up a database of the existing buildings, classified by their morphological aspects as

- Number of floors,
- Number of pillars in the two-plane direction,
- Dimensions of sections and distance from pillars.
- Cross-section type (reinforcements)
- Material

The idea behind the work is to use the limit analysis methods of the static approach to determine the capacity curves of the structures in a simplified way, starting from the essential parameters that describe the structures and their materials. These parameters must be collected from direct and indirect qualitative and quantitative survey campaigns on the territory, which constitute the database to draw the set of input parameters for the simplified modeling and obtain a protocol of easy access and consultation for decision-makers. The genetic makeup of the structures, consisting of their geometric, mechanical, and constructional characteristics, identifies their structural morphotypes. The synthesis of numerical analyses describes a SafeScore that represents the ductility required by the structure to withstand a seismic event. The SafeScore obtained from the structure categorizes it within a safety band, thus becoming a tool to support decision-making in safeguarding against natural disasters. The study is a comprehensive exploration that spans from the building to the city scale. The crucial task of recognizing the characteristics of the infrastructures under study includes understanding the state of conservation, morphology, and topology of the structures. By identifying typical structures and their characterizing qualitative aspects, one can equip decision-makers with the knowledge they need to make impactful choices.

4 Simplified push over approach (SPA)

The simplified analysis methodology is based on the static approach of limit analysis implemented through the writing of finite element procedures, which provide the basis of the spaces of the self-equilibrated stresses (Zona et al. 2021) of the structures within which to search for the optimal solution using linear optimization algorithms proposed by the authors (the FELA, Finite Element Limit Analysis, procedure) (Zona and Minutolo 2024). The basis of the self-equilibrated stress is defined starting from the Volterra dislocations modeled through shape functions isoperimetric to those of the displacements whose nodal values represent a discontinuous displacement field. The optimization procedure that seeks the limit multiplier as optimal among all the statically admissible ones returns the Melan residual as element dislocations through nodal parameters. In detail, the stress–strain relationship is expressed in terms of the strain representation obtained through the shape functions derivative according to the strain displacement model adopted (different structural models can be modeled using different elements in complete generality). Analogously, the same representation is introduced to map the internal dislocation as a function of displacement-like nodal parameters. The F.E.M. formulation that results from such a nodal mapping of stress and dislocation allows calculating the linear operator that links the internal self-equilibrated stress in terms of nodal parameters. Those nodal parameters play the role of design variables in the constrained maximum program that furnishes the limit load under a ramped or randomly variable load pattern. The resulting F.E.M. procedure allows calculating the limit loads directly (1), avoiding detailed step-by-step analysis that suffers both the requirement of detailed input of structural geometry and materials and, which is more critical, the precise knowledge of the load path history. The load path knowledge is the main criticism about any calculation one can perform on structures subjected to aleatoric loads such as that arising from catastrophic unpredictable events. Indeed, the limit analysis made through Melan’s approach does not depend on the load history but on the load pattern and its intensity limit domain. The formulation employed in the present work, stated in Zona and Minutolo (2024), introduces the eigenstress representation in terms of a set of the nodal parameters δ that map the eigenstrain as a dislocation distribution in the elements.

$$s_\alpha = \sup_\delta k | (k\sigma^* + \mathcal{V}\delta) \in D_e, \alpha = \begin{cases} sd & \text{shakedown} \\ c & \text{collapse} \end{cases} \tag{1}$$

The load limit multiplier results as the ‘sup’ of the load multipliers in the constrained optimization program (1), where:

$$\sigma^0 = \mathcal{V}\delta \tag{2}$$

The Eq. (2) defines eigenstress. The matrix \mathcal{V} is singular and has the dimensions of the element stress vector times the dimensions of δ . The rank of \mathcal{V} is equal to the multiplicity of the equilibrium equation solutions and coincides with the structure redundancies. By employing a comprehensive procedure, it is possible to estimate the safety level of the structure from both load and displacement. This procedure, a parametric analysis of a significant number of numerical experiments on several types of structures, is designed to define the abacuses. It encompasses the modeling of structures with various morphological

and topological aspects, and the structural response is thoroughly investigated, defining for each structure morpho-type the capacity curve through its main parameters. By analyzing the results of the experimental campaign, the structures are cataloged in typological classes, sharing the main parameters under consideration. Subsequently, depending on the parameters that have been recognized to play a relevant role for each morpho-type, such as span number in both base structure’s layout main directions, height, and ratios of the pillars and beams strength, each morpho-type safety factor is precisely defined. The safety factor, the ultimate displacement associated with collapsing, and the residual displacements related to residual stresses are the parameters describing the capacity curve of the structure, and this result can be compared among the morpho-type to investigate the analogies among the different structures to define the vulnerability level of groups of structures.

4.1 Methodology description

To perform a linear static analysis on frames, the FELA routine has been applied. The whole procedure can be summarized as follows. The frame model is built in FEM software, used only as a CAD interpreter. This strategy is an advantage in defining the nodal connections, the element type, and the boundary condition. To the scope, an automated routine has been set up to build several types of frames to be analyzed and inserted in a result table, constituting the base for vulnerability assessments (1). The FELA routine calculates the value of the elastic limit load multiplier, the collapse limit load multiplier, and the maximum elastic displacements and collects this result in a tensor, containing this result for each morpho-frame type. The procedure can be summarized in the following scheme:

A CAD compiler has been used to set up an automated routine to perform the analyses on the different structural morphologies. In more detail, a set of structures has been modeled with different numbers of floors, pillars, and distances between pillars. Each frame has different morphological properties, and the output filename contains information about the geometry:

$$\text{VirtualTWIN}_{i-j-h-k-l-m} \tag{3}$$

$i \rightarrow$ number of pillars in the x direction $\rightarrow i=\{4,6\}$

Evaluation of Vulnerability brief scheme

Morpho-type definition

- Geometry (base, height, horizontal simmetry, vertical simmetry)
- Construction age (legislation in force at the time of construction)
- Material (different concrete type)

DataBase Construction

- VirtualTWIN random generation
- VFEM approach to define ductility requirement : Simplified Pushover Analysis
- Results Collection and Normalization

SafeScore

- SafeScore definition through weighted parameters
- Risk Vulnerability Class Attribution

Fig. 1 Procedure scheme

$j \rightarrow$ number of pillars in the z direction $\rightarrow j=\{4,6\}$

$h \rightarrow$ number of floors in the y direction $\rightarrow h=\{1,7\}$

$k = 3 \rightarrow$ distance between each floor

$l \rightarrow$ distance between pillars in x direction $\rightarrow l=\{4,6\}$

$m \rightarrow$ distance between pillars in z direction $\rightarrow m=\{4,6\}$

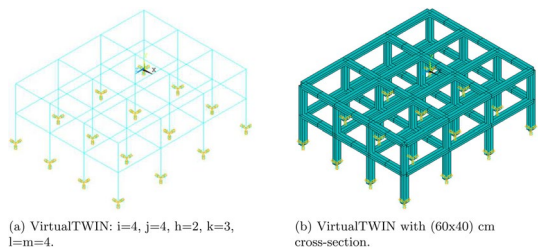
Another parameter taken into account in the virtual twin modeling is the cross-section of the horizontal and vertical beams. In this paper, the results obtained considering a cross-section of reinforced concrete measuring 60×40 cm are reported (2).

The results in terms of collapse multiplier are obtained, taking into account the specialized limit domain. For the calculation of the collapse multiplier, the optimization routine based on linear programming is used, which provides the solution to a constrained optimum problem with a linear objective function and linear constraints. In the case under examination, the constraints of the problem are represented by the boundary of the limit domain, and the objective function is the collapse multiplier. For the use of linear programming, the plastic compatibility domain of the generic section of the beams, written in the case of biaxial flexure having three stress components, is linearized by adopting a flat pitch schematization. Eight layers corresponding to each of the faces of the non-regular octahedron secant to the curved domain have been adopted. It is possible to assume a description with several flat layers that envelop the domain without losing the prerogatives of the algorithm, although it introduces some computational complications. Therefore, it was considered that the boundary polyhedron flaps are identified by six distinct values of the boundary stresses, $M_{y_{tu}}, M_{y_{cu}}, M_{z_{tu}}, M_{z_{cu}}, N_{tu}, N_{cu}$. In the subscripts of the stresses, the direction of the acting moments, y or z , and the traction or compression character of the stress as a positive or negative intercept with the corresponding axis (t / c) is highlighted. In this way, the pitches of the octahedron can be described by means of the relations:

$$\frac{M_y}{M_{y\beta u}} + \frac{M_z}{M_{z\beta u}} + \frac{N}{N_{\beta u}} = 1 \tag{4}$$

where $\beta = t$ or c and, where the quantities in the denominator can assume the values reported above and the terms in the numerator are the stresses resulting from the structural analysis. The generic stress can be expressed as a combination of the corresponding parts of V and the amplified elastic rate of an arbitrary multiplier k .

Fig. 2 Comparison of VirtualTWIN models



(a) VirtualTWIN: $i=4, j=4, h=2, k=3, l=m=4$.

(b) VirtualTWIN with (60×40) cm cross-section.

$$M_y = V_{M_y} \delta + kM_y, \quad M_z = V_{M_z} \delta + kM_z, \quad N = V_N \delta + kN \tag{5}$$

The positions listed above, substituted in the Eq. (4), provide the representation in terms of stress parameters. The belonging to the internal limit domain of the solicitation is equivalent to that this satisfies the inequalities of the linearized domain expressed by the following eight matrix inequalities in terms of δ and k (3).

The optimization program corresponding to the static theorem (in Melan’s form), consists in the search for the maximum k under the following constraints:

$$\begin{aligned} & \left(\frac{V_{M_y} \delta + kM_y}{M_{ytu}} + \frac{V_{M_z} \delta + kM_z}{M_{ztu}} + \frac{V_N \delta + kN}{N_{tu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ycu}} + \frac{V_{M_z} \delta + kM_z}{M_{ztu}} + \frac{V_N \delta + kN}{N_{tu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ytu}} + \frac{V_{M_z} \delta + kM_z}{M_{zcu}} + \frac{V_N \delta + kN}{N_{tu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ycu}} + \frac{V_{M_z} \delta + kM_z}{M_{ztu}} + \frac{V_N \delta + kN}{N_{cu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ytu}} + \frac{V_{M_z} \delta + kM_z}{M_{zcu}} + \frac{V_N \delta + kN}{N_{cu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ycu}} + \frac{V_{M_z} \delta + kM_z}{M_{ztu}} + \frac{V_N \delta + kN}{N_{cu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ycu}} + \frac{V_{M_z} \delta + kM_z}{M_{zcu}} + \frac{V_N \delta + kN}{N_{cu}} \right) < 1 \\ & \left(\frac{V_{M_y} \delta + kM_y}{M_{ycu}} + \frac{V_{M_z} \delta + kM_z}{M_{zcu}} + \frac{V_N \delta + kN}{N_{cu}} \right) < 1 \end{aligned} \tag{6}$$

The procedure has been validated for different structural types, also not concerning the civil engineering landscape (Zona and Minutolo 2024). Here, the example of a clamped simply supported beam is reported, Fig. 4, with the ratio between its length and height equal to 0.1. Mechanical constraints are one fixed end and another simply supported. The beam is loaded by a uniform vertical force per unit length P . The material has been assumed to be iso-resistant at the limit, hence $\sigma^+ = -\sigma^- = \sigma_0$. The structure has been calculated using \mathcal{VFEM} , where the FEM structure discretization used four-node quadrilateral elements and Lagrange shape functions. The material constituting the structure was linearly elastic and perfectly plastic; the elastic modulus, $E = 2.1 \cdot 10^5$ MPa, and Poisson ratio, $\nu = 0.3$. The limit domain is described in the stress space by the Eq. (5) with the position (6) that assumes

Fig. 3 Generic limit domain

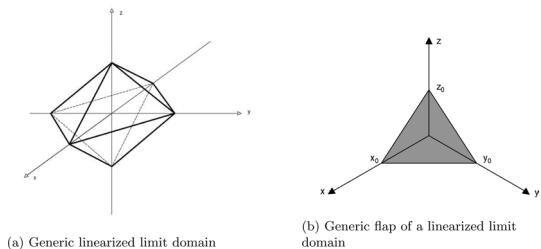


Fig. 4 Clamped-simply-supported beam with a distributed load

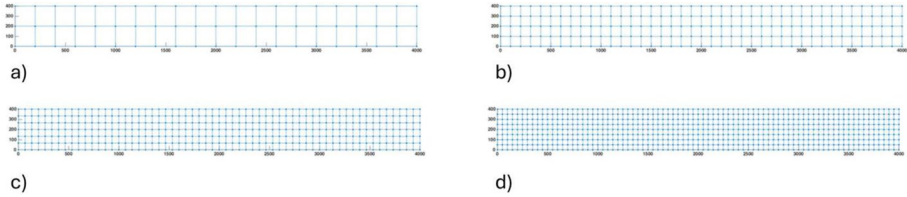
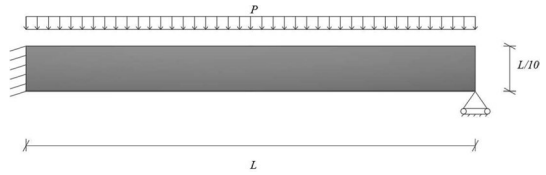


Fig. 5 Analyzed mesh: **a** 2x20 elements, **b** 4x40 elements, **c** 6 x 60 elements, **d** 8 x 80 elements

Table 1 Clamped-simply-supported beam collapse multiplier versus mesh refinement, the convergent results are in bold

	$\mathcal{V}FEMs_c \cdot 10^{-2}$			
Elements number	40	160	360	640
No penalty	2.22	2.22	2.22	2.66
Penalty	2.59	3.18	3.16	3.24

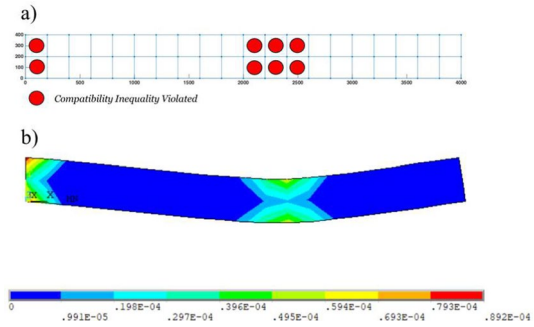
a linearized limit domain, see Fig.???. The calculation of the collapse load P_{lim} has been performed either by applying the penalty factor to account for the nonlinearity of the domain or by not applying it. Table 1 reports the collapse multiplier $s_c = P_{lim}/\sigma_0$ calculated with several element mesh numbers through the proposed formulation. A step-by-step calculation of the collapse load using a FEM commercial code, and a mesh of 640 elements, has been considered for comparison, which represents a reference solution whose resulting collapse multiplier is

$$s_c^a = \frac{P_{lim}^a}{\sigma_0} = 3.11 \cdot 10^{-2}. \tag{7}$$

The mesh refinements see in Fig. ref LastraTable that produce the calculation of the stress at new nodes produce a slight rotation of the stress vector at the element level that has influenced the constraints of the optimization program (5).

The inequalities satisfaction map has been reported in Fig. 6 and compared with a standard FEM plastic strain plot. By the reported map, it can be seen that the Lagrange multipliers do respect the expected plastic hinge positions that result from classical plasticity analysis on one-dimensional models of beams. In particular, the one-dimensional positioning of the plastic hinges of the supported cantilever subjected to uniform load is at 0.58578 of the span length, corresponding to 2360 mm of the beam. It can be seen that the location of the elements violating the constitutive constraints respects the expected analytical position of the plastic hinge, arising (Massonnet and Save 1961).

Fig. 6 Plastic Hinge at collapse :a Violation of compatibility inequalities map; b standard FEM plastic strain contour plot by step-by-step calculation



5 Results

A limit state is a situation beyond which the structure or a part of it ceases to perform the functions for which it was designed. Limit states are divided into two categories: a) ultimate limit states, corresponding to the extreme value of the load-bearing capacity; that is, the structure (or a part of it) is not able to support a further increase in load; b) Serviceability limit states, linked to normal use and duration requirements, correspond to the loss of functionality of the structure. Action is defined as any cause or set of causes (permanent loads, variable loads, impressed deformations, chemical-physical agents) capable of inducing limit states in a structure. In general, the term stress refers to any effect or set of effects (normal stress, shear, bending moment, deformations, displacements, crack openings, etc.) induced by actions on the structure. The achievement of an ultimate limit state (localized failure, loss of equilibrium, etc.) or of an operating limit state (excessive deformations, excessive displacements, etc.) can be caused by the concomitant intervention of various random factors deriving from uncertainties that may concern: the resistance of the materials used; the intensity of the actions; the geometry of the construction; the divergence between the effects actually induced by the loads and those calculated. Uncertainties must be quantitatively assessed in terms of probability based on available statistical data, as well as various considerations. The objective of safety checks is to maintain the probability of reaching the considered limit state within a pre-established value in relation to the type of construction under consideration, its influence on the safety of people, damage to property and its expected service life. The procedure has been applied to a dataset consisting of 252 different structural morphotypes. The results are reported in terms of SafeScore (SS) obtained as shown in Eq. (8):

$$SS = \alpha \cdot \beta \cdot \gamma \cdot \delta \cdot \eta \cdot \zeta \cdot S_{cFELA} \tag{8}$$

Where the coefficients of the S_{cFELA} represents respectively:

- $\alpha =$ base regularity
- $\beta =$ height regularity
- $\gamma =$ base – height ratio
- $\delta =$ age of construction
- $\eta =$ cross – section
- $\zeta =$ material

Table 2 Influence of the parameter on the SafeScore

Parameter	Min	Max	Function of
α	0.1	1	Number of pillars in the x and z direction
β	0.1	1	Number of pillars for each store
γ	0.5	1	Dimensions of the base and height of the structure
δ	0.1	1	Pillars and beams cross-section reinforcement
η	0.3	1	Cross-section dimensions
ζ	0.8	1	Resistance of concrete

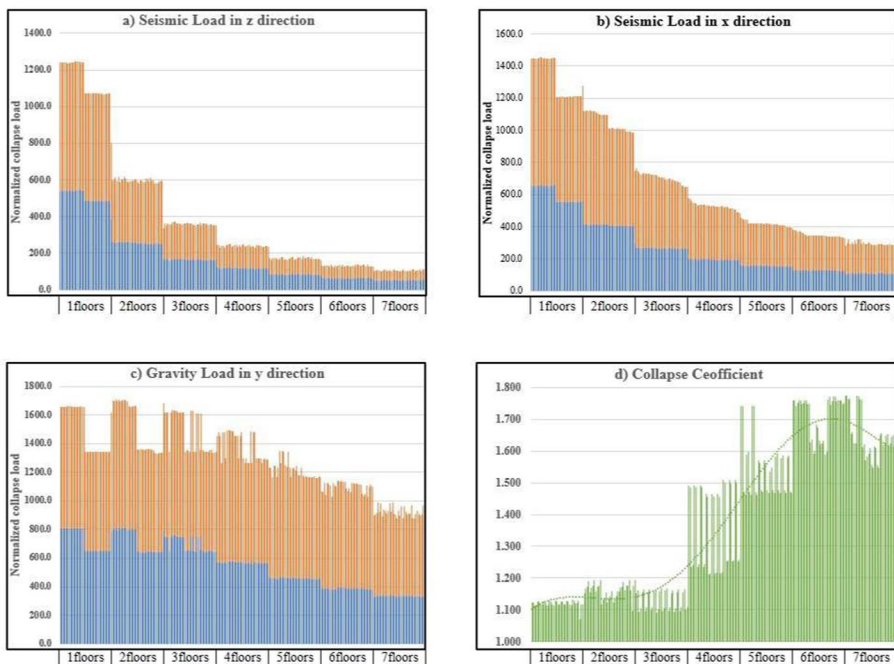


Fig. 7 Results diagram: **a** Seismic load in x direction; Difference diagram between limit load (SC2) and elastic limit (SE2) in x direction; **c** Seismic Load in z direction; Difference diagram between limit load (SC2) and elastic limit (SE2) in z direction

The influence of the parameters on the SafeScore are reported in Table 2

The first set of results are expressed in terms of elastic limit load, SE_i , collapse limit load, SC_i , and Ratio between SE and SC, R_i , where the subscript $i = \{1, 2, 3\}$ with :

$$\begin{cases} i = 1 & \text{gravity load} \\ i = 2 & \text{seismic load in x direction} \\ i = 3 & \text{seismic load in z direction} \end{cases}$$

It has to be highlighted the comparison for the whole frame family between the elastic limit and the collapse limit. Their difference is the ductility of the structure Fig.7.

Table 3 Description of classes

Class	Description	SafeScore
1	Safe structure	0.8–1
2	Soft intervention	0.6–0.8
3	Hard intervention	0.2–0.4
4	Demolition	0.01–0.2

It has to be noted that the elastic limit load is represented in blue, and the collapse load is depicted in orange. This comprehensive analysis results in the meticulous definition of a seismic class risk based on a vast number of structure morpho-type analyses (3). The particularization of structures by key geometric and morphological elements makes it possible to find common traits in the buildings that make immediate classification of the level of risk to which the case under consideration is subject. From this, 4 classes of risk are defined:

The results show, as expected, a strong dependence of the structure on the size of the section in the direction of the earthquake. The analyzed structures are calculated with a section of an equivalent material. Therefore, for the generation of a response abacus, it is necessary to relate the resistance domain described in the calculation of the procedure to the resistance domain of a reinforced concrete structure. This can be accomplished by considering the ultimate moment of the section and normalizing it with respect to the load multiplier. With such a procedure, the assessment of seismic risk can be done by visual inspection, giving the technician the possibility of making a rough, rapid, and constant evaluation (particularly in cases of inspections by the competent authorities for safety assessments, as well as in the design and verification phase). In this paper a city-level microzoning has been performed 8 and 9. The figures below present an example of seismic micro-zoning performed with the proposed simplified pushover analysis, highlighting the practical benefits of this new approach.

6 Conclusion

The system of structures and infrastructures is representative of a network of functioning processes that are also entirely seemingly disconnected from the building system in that within urban settlements are concentrated governmental, strategic, care, and relief functions that need to be appropriately designed, monitored, or adjusted. Appropriate knowledge of the system and its vulnerability allows planning for its progressive strengthening and adaptation by intervening in its components for the reduction or management of criticality through a precise program of intervention that highlights priorities so as to increase the resilience and efficiency of the entire manufactured system against natural disasters. The introduction of a Mitigation, Intervention, and Management Protocol makes it possible to analyze and classify the urban built environment and the historic and monumental building stock vis-à-vis its vulnerability to natural disasters, thus helping to increase the structural performance of the built environment. This makes it possible to apply its vulnerability class to each building through simplified analysis and rapid consultation of schedules. The use of such a classification would result in quantitative performance sizing. The proposed Protocol is becoming a guideline for future regulations. The emergency resulting from the occurrence of natural disasters is, in this way, countered by prevention. The work proposed proposes the definition of a Protocol for mitigation and prevention against disasters with a

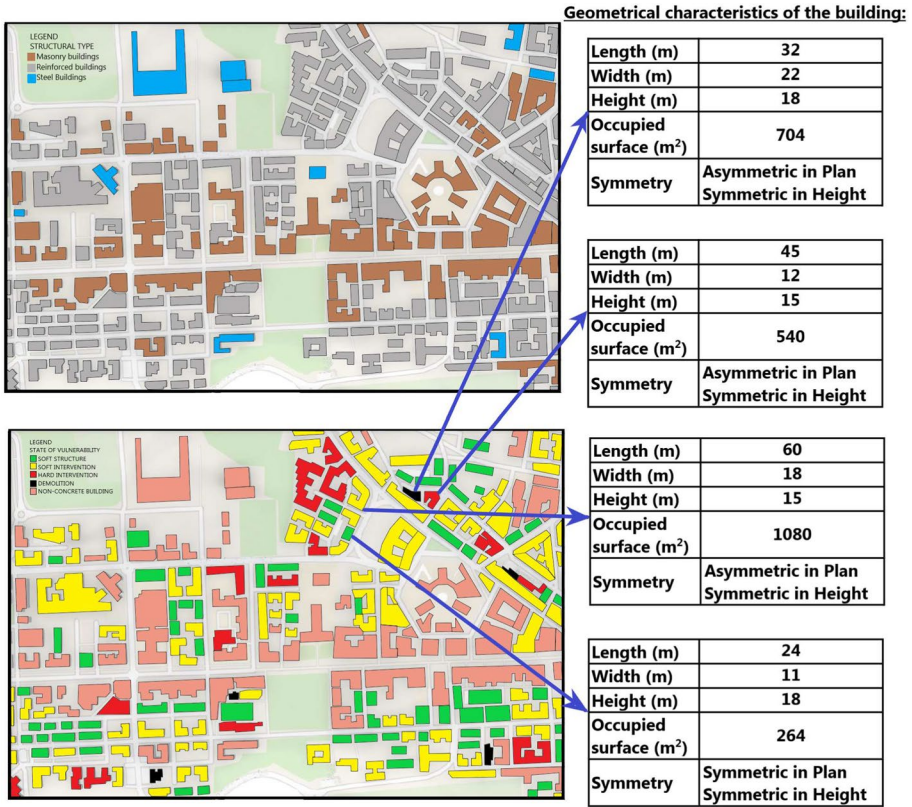
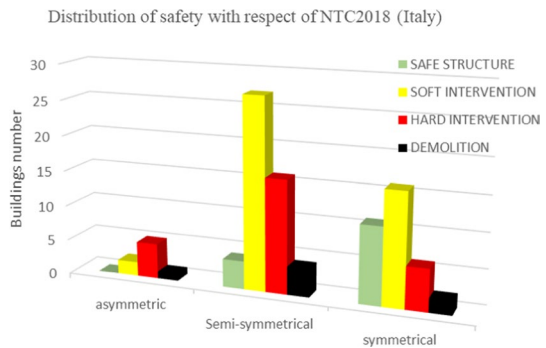


Fig. 8 Micro-zoning of a sector of the Italian town of Avellino

Fig. 9 Distribution of buildings symmetry and suggested intervention type



numerical approach on an analytical basis for determining structural capacity curves with a simplified analysis. The first significant innovation in structural capacity curve assessment lies in the type of analysis performed. Based on a discontinuous finite element algorithm that has already been extensively validated for multiple case studies, the analysis procedure provides direct and generalizable results as a function of structural morphology. Canonical methods based on a mechanical approach, that is, direct assessment of the seismic capacity

of the individual building or groups of buildings, while reliable, require in-depth knowledge of the building and a high computational cost to carry out the corresponding assessment. Therefore, apart from the inherent difficulties associated with carrying out a proper seismic analysis of existing buildings, they are not readily applicable to urban-scale assessments either from a technical, time, or economic perspective. To date, developments in the methodologies for identifying risk classes and seismic vulnerability have allowed an expeditious approach through which it is possible to directly establish the prediction of damage on buildings, thus the effects of seismic events, and indeed, the possible interventions to limit them. In this project, the two models are merged, using data obtained from monitoring to obtain dispatchable data and mechanical models for quantitative and qualitative data. The mechanical approach proposed for the definition of the Mitigation and Prevention Protocol against disasters overcomes the limitation of the computational cost of the procedures currently in use. One of the principal drawbacks of the limit analysis concerns the requirement of unlimited ductility of the structure for the procedure to hold. In the proposed procedure, the design variables, which are displacement parameters, are linked directly to the dissipated energy at the incoming collapse, and the dissipation at a load level lower than the collapse one can assume for the threshold of human life safety level or prescribed admissible damage level. In this manner, it is possible to estimate the safety level of the structure from both load and displacement through consultation of abacuses that provide the actual capacity curve of the building. The implication is an increase in the level of knowledge of the built environment through the implementation of a synthetic procedure to define from the typological characteristics, construction techniques, and locations in the territory of artifacts, subdivisions, and settlements the degree of risk and the level of alert even in real-time, providing the tools and procedures to implement an S.H.M. Structural Health Monitoring system.

The work is aimed at defining the nonlinear behavior of a random population of buildings through a simplified pushover procedure based on limit analysis procedures. A simplified pushover analysis can originate from applying the limit analysis of the structures through an approach based on the lower-bound approach. The advantage of this approach lies in the possibility of freeing oneself from the need to carry out step-by-step analyses that are computationally expensive and dependent on detailed knowledge of the actions acting on the structure. Furthermore, the static analysis does not require the prediction of specific collapse mechanisms, which are often not wholly describable through a well-defined configuration basis and, therefore, overestimate the actual value of the collapse limit. Ultimately, the independence from the a priori definitions of the family of collapse mechanisms allows the static analysis to be applied directly to structural typologies that are considerably different in terms of geometric and mechanical characteristics.

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