Sandro Parrinello Raffaella De Marco
editors

Digital Strategies for Endangered Cultural Heritage

FORTHCOMING INTERSPECIES

Handbook of Research on Strategies and Creative Interdisciplinarity
for the Digitization and Safeguard of Endangered Heritage

Pavia University Press

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The event, organized by the international network INTERSPECIES and by experimental laboratory of research and didactics DAda-LAB of DICAr - Department of Civil Engineering and Architecture of University of Pavia, aims to introduce a Cross-fertilisation of Competencies among institutions and partners within the scientific fields and disciplines involved. It wants to address the necessary background for advanced strategies on safeguard policies for Cultural Heritage, thorugh the topics of digital survey, numerical computing, structural evaluation, technological intervention, restoration design, visual communication, and service marketing-
The event has provided the contribution of international experts and lecturers, from the scientific and professional sectors in the field of Cultural Heritage. The scientific coordinator of INTERSPECIES Network is Prof. Sandro Parrinello, and the scientific responsible for the organization of the Summer School is Dr. PhD. Raffaella De Marco.

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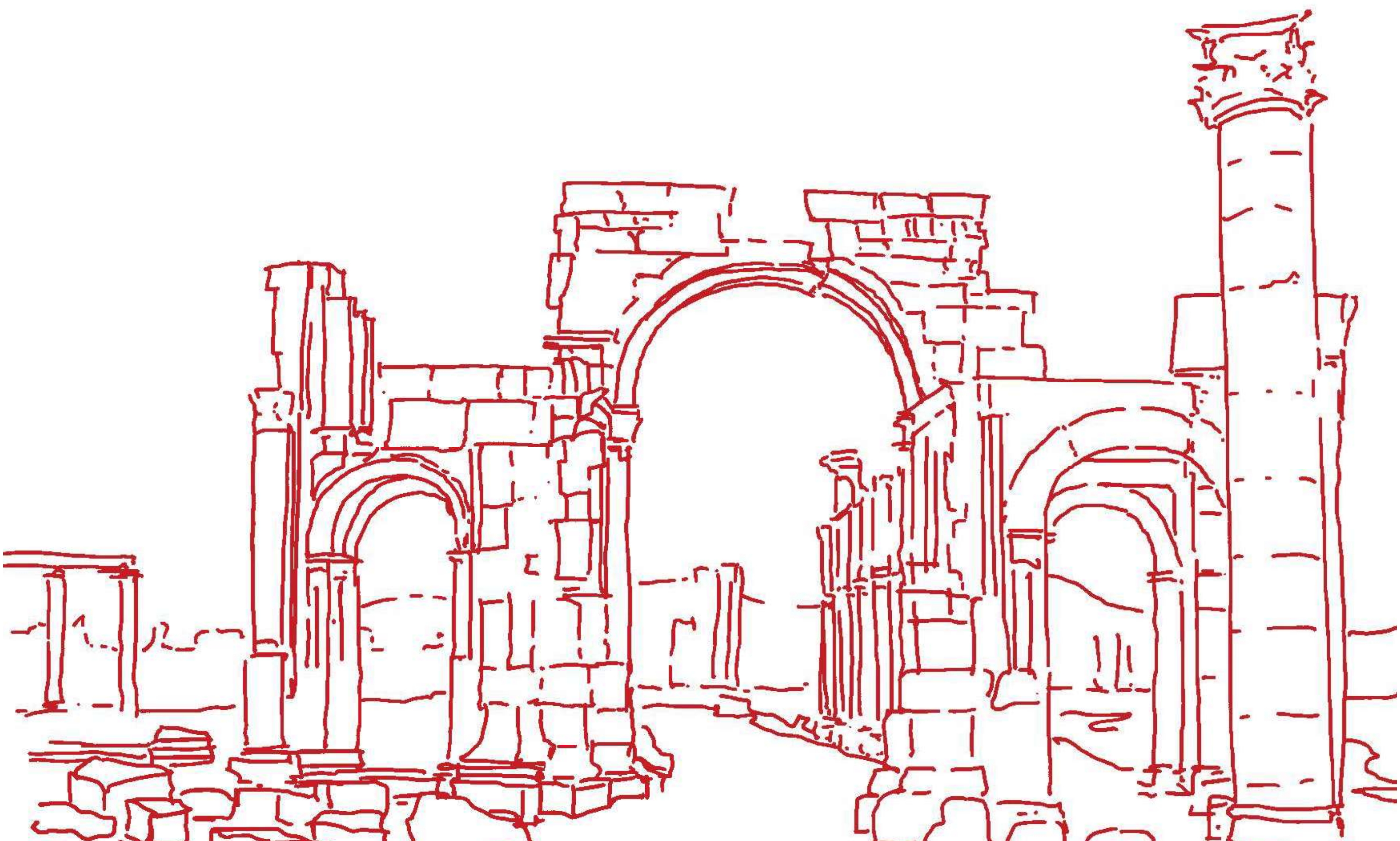

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Abstract

The highly heterogeneous morphology of urban realities, derived from the development of buildings through different historical periods, characterizes the territory of the Italian countryside. The seismic risk widely exposes the Italian orographic context, so mitigation and reduction of the effects on buildings is a crucial topic. Vital support for the analysis of structural vulnerability is the representation models for underlaying the main vulnerability phenomena. This research aims to define an integrated multilevel tool capable of managing, analyzing, and representing the data's multiplicity, heterogeneity, and complexity necessary to evaluate the seismic vulnerability of masonry buildings in the historical centers. The information acquired through a process of knowledge and elaborated through parametric modeling systems (BIM) can determine the most likely collapse kinematics, therefore, to evaluate each structural unit's levels of seismic vulnerability. This paper shows the methodology tested on the case study of San Rocco Village in Sora (FR) and describes the results in detail.

Keywords

Historical centers, BIM, Masonry, Seismic vulnerability.

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Multilevel BIM Analysis for the Assessment of Seismic Vulnerability of Masonry Buildings

Introduction

The debate on safeguarding historic centers has reopened in Italy with vigor. In particular, after the last seismic events that affected the municipalities of Central Italy: the L'Aquila earthquake (2009), the Emilia Romagna earthquake (2012), and the Central Italy earthquake (2016). These historical centers are considered environmental monuments to be protected and preserved due to the originality of their urban layout. They were born for the most part in the Middle Ages and Renaissance. The *nuclei* models such as spindle, enveloping, and multi-directional depend on the orography of the place of settlement and its height (Fig. 1).
These recurring models occur throughout the national territory: commonly, layouts can be found in all the Italy regions. From a structural and architectural point of view, the historical centers are almost totally characterized by masonry buildings made with materials readily available on the construction site. Over time, buildings have been subject to changes, extensions, modifications, and interventions. This aspect generates heterogeneous systems of construction interconnected between them in aggregate solutions. The heterogeneity of the construction techniques used for the construction of the buildings causes significant vulnerabilities from a structural point of view due to the numerous types and materials for the single parts of the buildings. From a social and cultural point of view, these historic centers represent the cultural identity, and unfortunately, they are subject to numerous degradation phenomena that make them highly vulnerable. They are vulnerable from an environmental point of view and a social point of view, for instance the depopulation of historic centers.
After these considerations, the safeguarding of these centers starts with a knowledge project highlighting the main factors contributing to seismic risk assessment. A map has been prepared to show the location of minor historical centers (less than 5,000 inhabitants) to understand the seismic risk exposure. It is visible that they form the backbone of Italy. It emerged that they make up 70% of the Italian municipalities. These analyzes required the design of a Geographical Information System called HT_GIS, an acronym for Historical Town_Geographical Information System, using an open-source software Q-GIS. The system, based on the data relating to the most recent update of the ISTAT census, integrated with data obtainable from the websites of Regions, Provinces, and Municipalities, can display in overlay the information from the associated database and graphically returns the location and size for n° of inhabitants of minor historical centers. With the overlaying of the INGV map of the seismic hazard with the distribution map of the minor historical centers, it emerges that the minor historical centers are in the Apennine areas in which the most recent seismic classification has attributed the zone 1 and 2 with the maximum macroseismic intensity. The result is evident, thinking that these centers were born in medieval times, and they are on the slopes or top of hills for strategic

reasons. Reducing the seismic risk of these centers means necessary intervention in the reduction and assessment of vulnerability and the identification of the principal vulnerabilities in the preventive phase (Fig. 2).
With this awareness, this contribution aims to define an integrated multilevel tool capable of managing, analyzing, and representing the multiplicity, heterogeneity, and complexity necessary for defining the seismic vulnerability of masonry buildings constituting the historical centers. To achieve this aim, it has been developed two types of approach: a 'qualitative' based on a simplified survey and a qualitative analysis capable of defining the most probable local collapse mechanism for masonry buildings; and a 'quantitative' approach based on an advanced survey for the knowledge of the detail of buildings and quantitative analysis for the determination of the spectral acceleration of activation of the collapse mechanism. The integrated tool was structured through BIM to create complex models capable of simulating the risk scenarios to which historical centers are subject (Fig. 3).

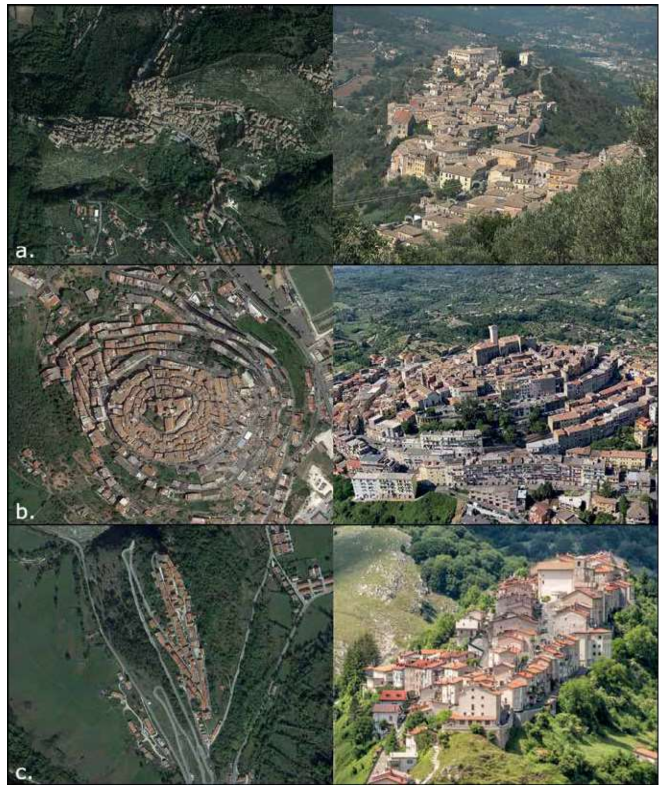

Fig. 1 Urban layout: a) Arpino – multidirectional; b) Palombara Sabina – Eveloping; c) Opi - Spindle.

Methodology: 3D multilevel approach

The construction heterogeneity of these agglomerations, as already mentioned, makes the analysis complex based on a close interrelation between the survey and the structural analysis. For these reasons, state of the art is fundamental for the definition and development of the approaches. Tools, techniques, and technologies used for the traditional direct survey have led to the knowledge of the most recent advanced survey techniques, which, thanks to the digitization of processes, have allowed the development of digital photogrammetry, which is widely used in following applications. At the same time, the background of the methods and empirical approaches for the analysis of existing move toward survey methods and simplified analyzes such as the AEDES methodology developed by the National Group of Defense of the Territory (GNDT) and the CARTIS project recently proposed by the department of civil protection and by ReLUIS for the assessment of the vulnerability of ordinary buildings. The proposed methodology highlights the strong correlation between the levels provided for analyzing the seismic vulnerability towards local collapse mechanisms and the related traditional and advanced survey techniques. The visualization of the results in a static way for the first qualitative level and dynamic/informative for the second level constitutes an immediate and easily interpretable tool for the design of interventions in order to reduce the vulnerability of buildings (Fig. 4).
The first level, the 'qualitative approach', is based on a quick/simplified survey in situ and a characterization of the materials that constitute the input elements for an algorithm developed in Boolean Algebra language (true/

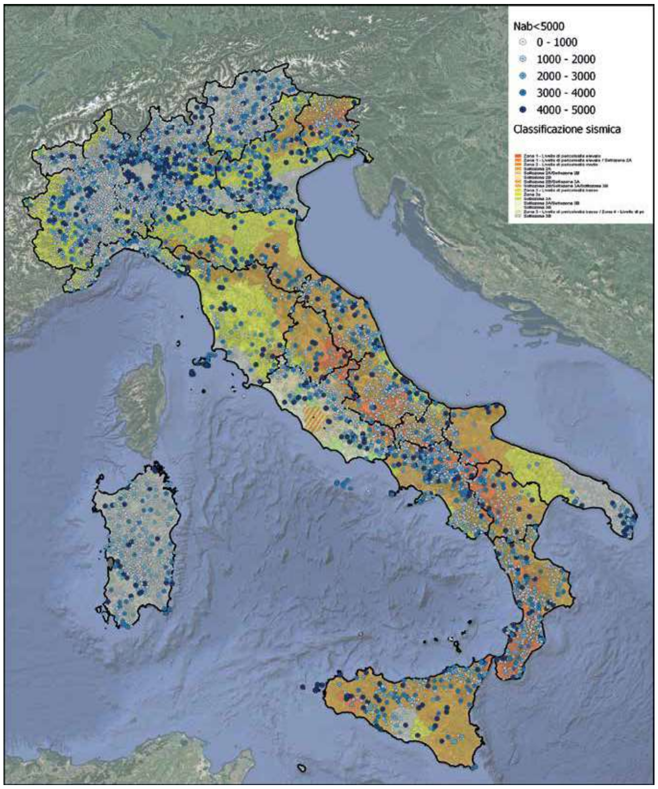

Fig. 2 HT_GIS: overlay of the minor historical centers on the seismic hazard map.

false) for the identification of the most probable local mechanism of the collapse of the facades of masonry buildings. These mechanisms are widely described in the literature as global overturning, partial overturning or along the openings, and vertical and horizontal bending. The methodology allows a 3D graphic model to bring together the information obtained from the survey and the results view of the analysis. Thanks to the algorithm that compares the dataset of the information acquired in the survey phase with the structural peculiarities that characterize the collapse kinematics of masonry buildings, the collapse mechanism with the highest probability of occurrence can be identified. The algorithm's structure is a set of typological, structural, and constructive deficiencies responsible for activating a probable mechanism together with the basic geometric and dimensional information. Therefore, it is possible to determine the probable mechanism that can be activated by comparing the presence or absence of detected structural characteristics and such structural peculiarities that characterize particular collapse kinematics. The algorithm is structured in 3 phases: the first is a data input phase, in which a survey form is compiled with general information on the building and the geometric and structural characteristics derived from the simplified surveys carried out in situ. Attention should be paid to the identification of constructive and structural details that characterize the mechanism's activation and to some characteristics of the geometric composition of the facade, such as the alignment of doors and windows, or the presence of the tympanum in the facade. The second phase consists in processing the data collected with assessing critical issues. The algorithm identifies whether or not the presence of the slenderness of the facade, joints of the slab, curb at the top, joints of the wall orthogonal with the facade, chains and tie rods, alignment of the openings in the façade, discontinuity of wall sections, considerable distance between the walls perpendicular to the facade, presence of the tympanum on the facade. The results obtained from the qualitative approach's analyses can be represented in graphic form by associating the collapse mechanism identified by the algorithm with a 3D graphic model created after the simplified survey (Fig. 5). After processing the data based on their combination (true if present, false if absent), it can process the comparison with the critical conditions that activate a specific mechanism. And at the end, the output phase with the identification of the most probable collapse kinematics.

The 'quantitative approach' is defined based on detailed and advanced instrumental surveys aimed at deepening the knowledge of the buildings and performing a quantitative evaluation of the vulnerability of the building. At this level, the procedure's objective is to evaluate the spectral acceleration a_0 activating the potential out-of-plane

local mechanisms detected in the previous qualitative level analysis by using more refined structural models.
To apply the quantitative analysis, therefore, it is necessary:
- to have information on the geometry of the individual elements;
- to know the construction details accurately;
- to characterize the masonry mechanically.

It is necessary to use laser scanners or digital, aerial, and terrestrial photogrammetry to gather structural details to obtain a consistent set of geometric information. The most economical and fastest tool is undoubtedly the digital photogrammetry which allows obtaining 3D models, returned as point clouds, to get the mesh used in the structural analysis software. On the other hand, the mechanical characterization of the masonry can be carried out through non-destructive on-site tests and/or laboratory tests or to refer to the characteristics collected by guidelines (table C8.5.I of the Circular no. 7 of 2019). Alternatively, Masonry Quality Index (MQI) can be used. This method evaluates the MQI to correlate it with the average values of compressive strength, shear strength, and the average modulus of elasticity provided in table C8.5.I of Circular no. 7 of 2019.
The data collected from these phases are employed in the proposed procedure to perform a linear kinematic analysis according to the Italian code for evaluating the spectral acceleration activating the identified potential out-of-plane mechanisms and then quantitatively assessing the corresponding level of seismic vulnerability (Fig. 6).

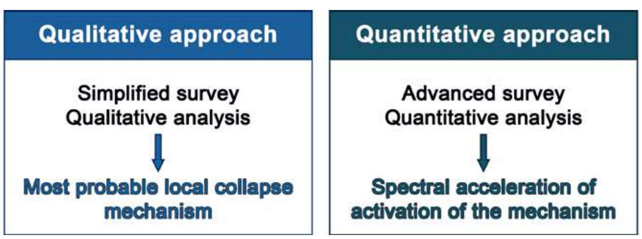

Fig. 3 Qualitative and quantitative approaches.

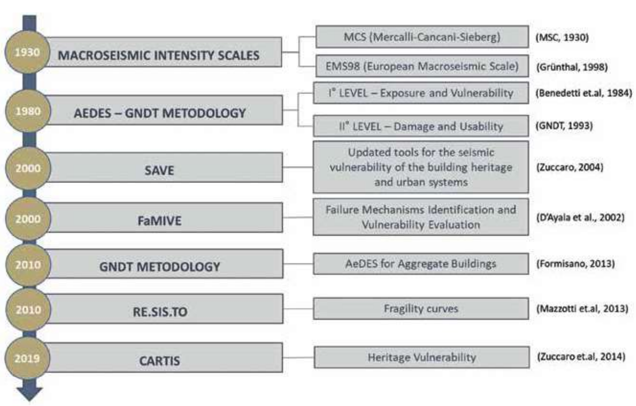

Fig. 4 Simplified and empirical methodology for the assessment of the vulnerability of ordinary buildings.

Case study

The methodology is tested and applied to a real case study: Borgo San Rocco in Sora in the province of Frosinone in Italy. It is a small village in a minor historical center of Roman origin, then medieval, and for its location given the high hydrogeological vulnerability that distinguishes it. It is located near the Liri river and on the side of Monte San Casto. Furthermore, from a seismic point of view because Sora is located in an area with a high seismic hazard and over the years, it has been affected by numerous seismic events, including important ones such as the 1915 earthquake in Avezzano which almost completely razed the urban buildings of the city to the ground. The village consists of 2 building curtains similar to two interconnected structural aggregates. The area is characterized by Porta San Rocco, better known as the Arch of San Rocco. Starting from the first half of the nineteenth century, in addition to redefining the city limits, it essentially became the connecting element between the two opposing buildings (Fig. 7).
By applying the approach of level 1 - qualitative approach - it is necessary to carry out a rapid survey of the aggregate consulting the archive material: in particular, the documents held by the Municipal Technical Office relating to the post-earthquake surveys of 1984, consisting of floor plans, section, and elevations. This

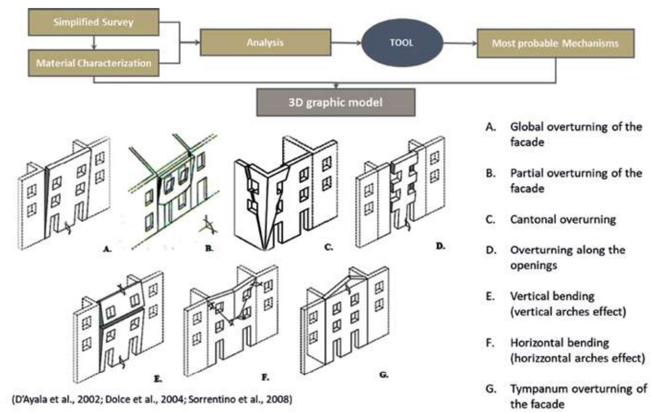

Fig. 5 Qualitative approach.

information makes it possible to identify and define the individual structural units that make up the two aggregates; for convenience, side A is the aggregate on the riverside, and Side B is the aggregate on the mountainside. It is noted that the entire village consists of 36 structural units, of which 20 belong to Side A and 16 to Side B. Each of them has been assigned a unique identifier. For each of them, the general characteristics of the facade have been evaluated, such as the length of facades, the height of buildings, an analysis of the level of horizontal elements, which are often misaligned between adjacent buildings in such configurations, and the alignment of openings, intended as doors and windows. A survey form has been compiled for each US to apply the algorithm developed to

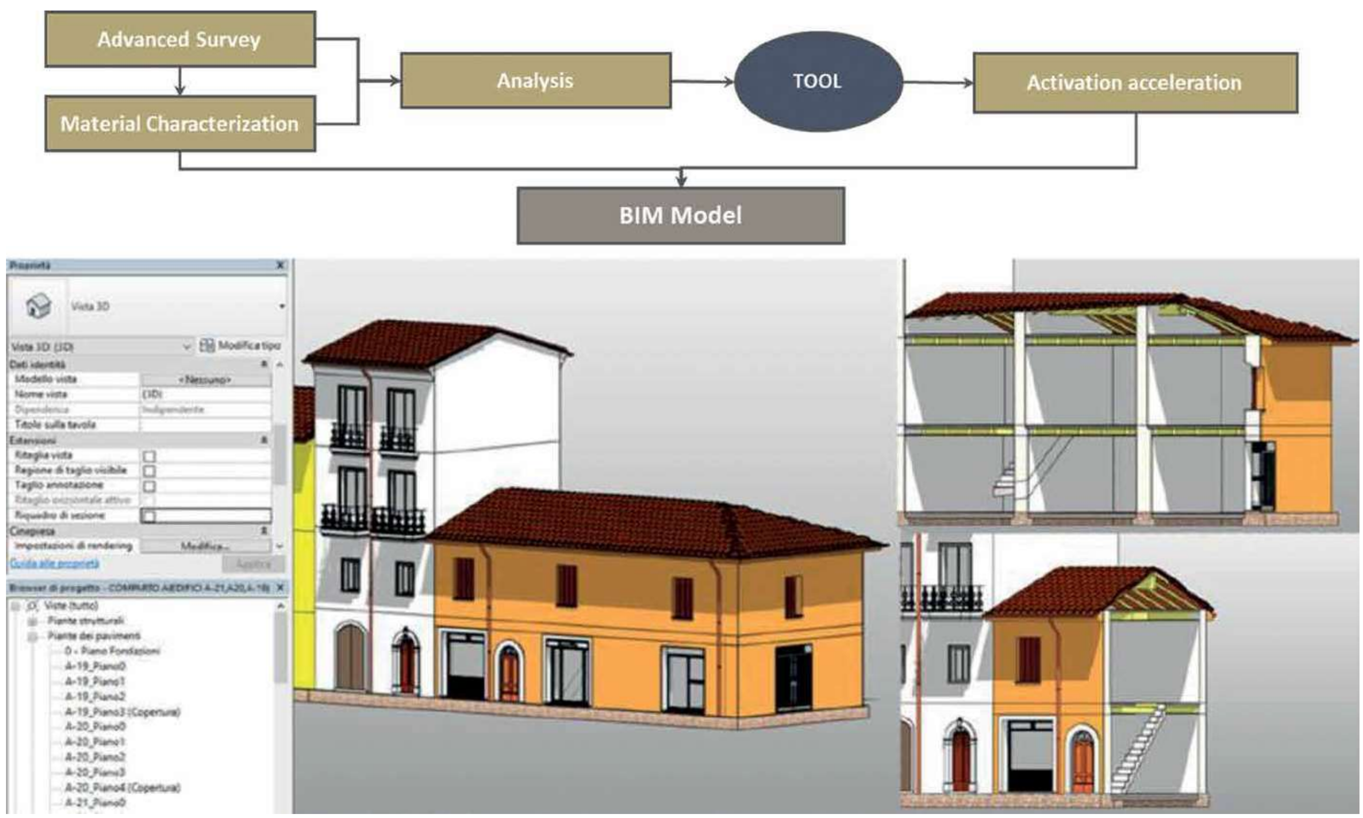

Fig. 6 Quantitative approach.

Fig. 7 Sora. Borgo San Rocco.

identify the collapse mechanism. At this stage, attention is paid to identifying those architectural and structural features that allow us to identify the possible local mechanism of the collapse of the facades. It is possible to visualize the types of collapse mechanisms affecting the aggregates by associating the results with an appropriately created 3D graphic model to have a clear qualitative indication of the vulnerability they are subject to. The results show that most buildings have a partial collapse of the facade and horizontal bending mechanism for Side A. At the same time, for Side B, US units have the Global overturning mechanism and the Partial overturning and horizontal bending mechanism (Fig. 8).

The second level of analysis is based on a more detailed survey. In particular, aerial digital photogrammetry has been used with drones, which starts from photographs taken by drones; it is possible to reconstruct a cloud of 3D points with a digital process. It has been necessary to design the flight plan in the ideal wind and lighting conditions for taking the images. It has been processed about 1300 photos of the village, which allowed the creation of an easily digital model for the knowledge of the geometric information of the buildings employing suitable photogrammetric processing software. Each cloud point obtained has spatial coordinates X Y Z, and it is easy to know the distance between 2 points. The point cloud, imported into BIM, constitutes fundamental support for creating the HT_BIM 3D model. It is possible to model from the general to the particular by integrating into a single model all the geometric, functional, material, and performance information of the elements according to the typical logic that characterizes BIM objects. Furthermore, as foreseen by the proposed methodology for this level of detail, it has been necessary to characterize the chemical and mechanical parameters of the materials through tests carried out in the Chemistry and Materials laboratory of the University of Cassino for the determination of the characteristics, as required by the most recent standards. Construction techniques Italian standards NTC18 (Fig. 9). All these data, considered input data, were the basis for the realization of structural models for the execution of the linear kinematic analysis that allows obtaining the activation multiplier of the collapse mechanism (α) and the spectral acceleration of activation of the collapse mechanism (a_z). In this way, it is also possible to perform the checks required by Italian standards by comparing the capacity with the demand, thus passing from a qualitative result, indicating the most probable mechanism, to a quantitative one. Since it also indicates whether the mechanism can be activated and, consequently, the level of seismic safety (or vulnerability) of buildings towards these mechanisms (Fig. 10).

The diagrams show the results obtained for each US shown on the abscissa the acceleration of activation of the mechanism. On the same graph, the value of the PGA, the peak acceleration expected at the site, is shown in red. It can be observed that most of the facades are subject to the possibility of activation of the identified mechanism. In particular, buildings with a mechanism activation acceleration value lower than the PGA value in red are subject to activation. In other words, it is observed that most of the US has a marked level of seismic vulnerability.

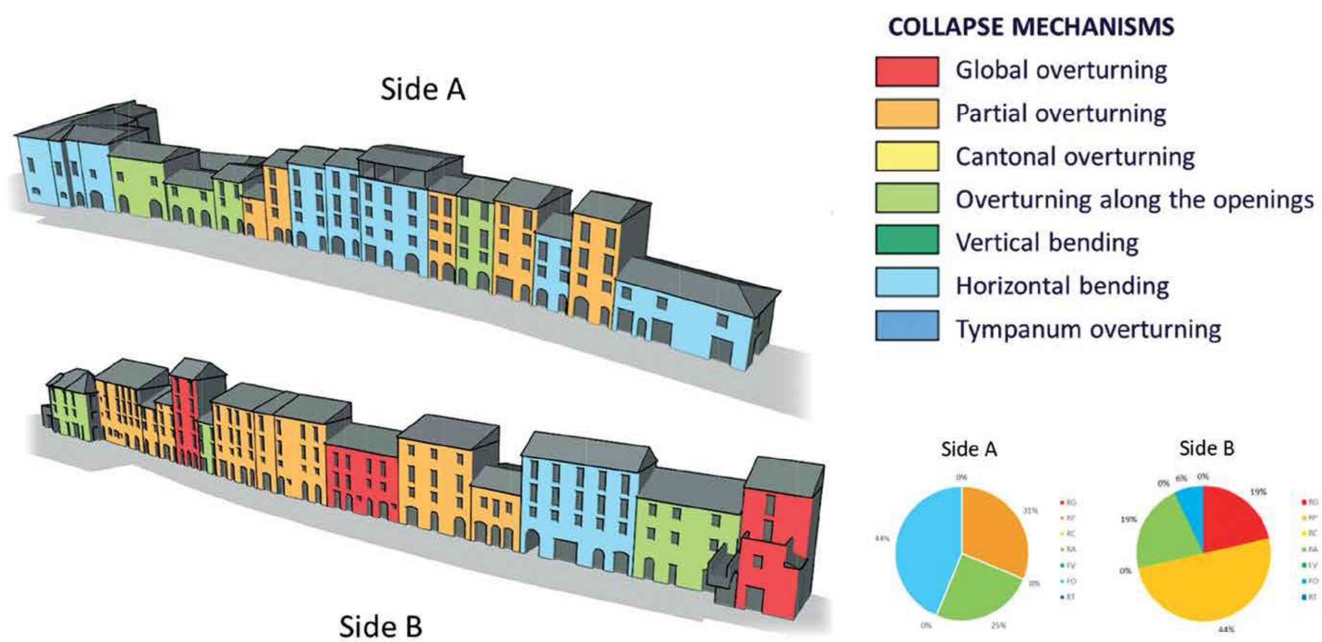

Fig. 8 Qualitative analysis results.

The same results can be viewed in the BIM model developed dynamically and automatically with the color maps based on the activation value of the mechanism. This type of visualization allows immediate recognition and visualization of vulnerable buildings (Fig. 11).
The information obtained from the two levels is crucial for the local administrations that govern the territory because it highlights which units prioritize intervention, which is more vulnerable to seismic actions. They, therefore, constitute a support system for technicians who have to intervene because it is identified as the most probable mechanism of collapse. Consequently, they can define interventions to reduce them. Lastly, an attempt was made to verify the possibility of using a national database on ordinary buildings as input data to apply the proposed multilevel analysis. Reference was made to the CARTIS database wanted by the Civil Protection in collaboration with ReLUIS (network of university seismic engineering laboratories) for ordinary buildings' typological/structural characterization. The CARTIS project aims to compile buildings by building and sectoral data sheets of the Italian urban buildings. This information is cataloged in a searchable national database that presents valuable information for the operation of approach 1 of the proposed system. The developed system is dynamic since it allows a national database for its operation, considering the info as input data, and this can allow a rapid assessment of the seismic vulnerability of many buildings.

Conclusions

The research studies the consistency of minor historical centers in Italy by developing the HT_GIS system, showing that they are where they should not be. For this reason, it is needed the development of an instrument based on an innovative multilevel procedure for analyzing masonry buildings by defining tools for surveying, archiving/displaying HT_BIM data, and structural analysis from simplified to complex models, according to a qualitative and quantitative approaches. The application of the tool

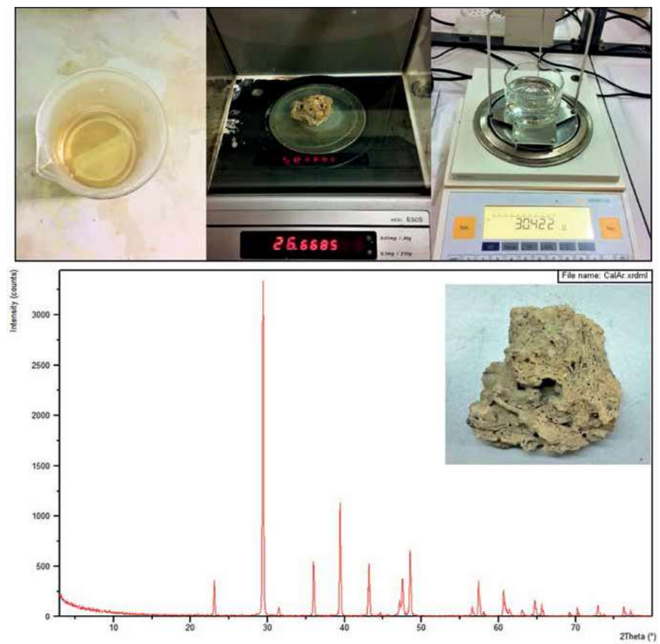

Fig. 9 Open porosity determination, acid attack and diffrattometric analysis (LABMAT – UNICAS).

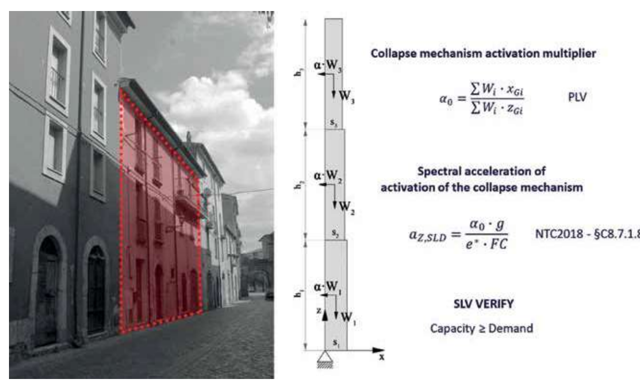

Fig. 10 Linear kinematic analysis on building 12A.

developed on the actual case study of Borgo San Rocco in Sora (FR) shows the vantage of this methodology, along with the verification of possible connection of the developed tool with the national databases on the existing

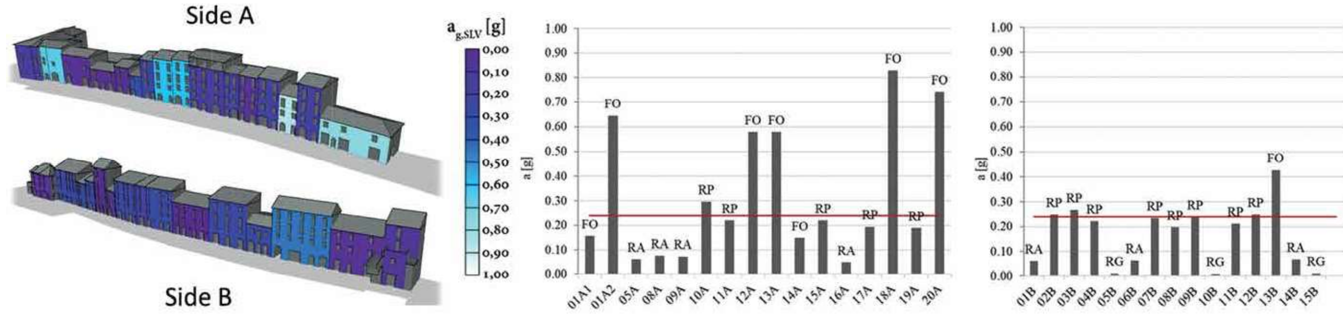

Fig. 11 Quantitative analysis results.

building (e.g., DB CARTIS). Therefore, the developed tool constitutes good support for local administrations (indication of intervention priorities) and technicians (indication of the type of intervention).

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