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Seismic Vulnerability Assessment of Historic Centers with Two Fast Methods Based on CARTIS Survey Methodology and Fragility Curves

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Abstract: After an earthquake, legislation tends to permit the rapid demolition of damaged buildings, including the built heritage, for safety reasons, as was the case for many small historic centers after the 2016 earthquake in central Italy. A balance should, of course, be struck between safety and preservation. There must be a willingness to engage in continuous interaction with the various bodies involved in post-earthquake management, particularly in the preventive phase of the complex activities regarding the issues of the seismic vulnerability of historic built. The widespread historical built heritage in Italy requires fast and reliable assessment procedures that allow a large-scale evaluation of the vulnerability of historical buildings before a seismic event. To this end, a proposal is presented here for the inverse use of the protocol for the seismic vulnerability survey of historic centers by means of a system called CARTIS form, coordinated since 2015 by the Italian consortium of Seismic and Structural Engineering Laboratories (ReLUIS). This rapid assessment is compared with an equally fast method for constructing fragility curves, based only on the information available in the ReLUIS–CARTIS database, defining the relationship between the probability of reaching a level of loss of structural safety or a vulnerability index as a function of the seismic acceleration PGA and the ground orography. The methodology outlined could be considered to be progress in cultural heritage diagnostics on a large scale, considering cultural heritage to be the diffuse historical residential masonry buildings that form the historic centers.

Keywords: seismic vulnerability assessment; minor architectural heritage; historic built; fragility curves; safety factor; CARTIS form; residential buildings; masonry buildings

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1. Introduction

In countries with a high seismic risk, the issue of built-heritage management is rarely addressed before a catastrophic event. Political issues and owner resistance often lead to the postponement of safety and protective measures that could serve to reduce damage to the building in the event of a catastrophic event.

In the event of an earthquake, the delay with which preventive measures are taken would result in the loss of part of the built and historic fabric. In fact, after an earthquake, legislation (as the local ordinances signed by the extraordinary commissioner for reconstruction) tends to allow the unimpeded demolition of damaged buildings, as was the case in many Italian historic sites after the 2016 earthquake in central Italy.

While such drastic decisions are necessary for security reasons, they also highlight the need to strike a balance between security and preservation that does not allow places to lose their identity and important historical memory.

In order to achieve this goal, it is necessary to create a risk awareness in the community apt to promote preventive assessment of the vulnerability of widespread historic built and to program an action plan to improve and adapt the more vulnerable situations. Such measures will not guarantee an optimum response of the whole building to future earthquakes, but they will certainly reduce the probability of widespread collapse while safeguarding human life.

In Italy, the large number of small historic habitats, which are inextricably linked to the territory to which they belong, contribute to defining the country's historical and cultural identity. Unfortunately, their gradual abandonment is often due to the lack of adequate housing and structural safety standards, especially in seismic areas. Moreover, after a seismic event, historic areas may remain out of bounds for decades while awaiting reconstruction.

The preservation of this important diffuse identity requires preventive measures to reduce seismic vulnerability and strengthen the resilience of the territory, therefore stimulating economic and social improvements while taking into account the risks associated with the territory.

The vulnerability assessment of a widespread building was almost always addressed in the post-earthquake phase [1–5]. The approaches implemented by the Civil Protection Department, the regions, and the technicians in charge of inspections almost always involved the filling in of survey data sheets [6,7]. Various approaches to quantifying vulnerability were then formulated from the collection of these data [8,9].

The approaches developed often require very detailed knowledge of the building, which is not always possible in times of seismic calm for undamaged and privately owned buildings. For preventive vulnerability assessment, simpler approaches that can be easily applied by administrations are preferable. Such approaches may be less precise than those already mentioned, but they can provide a reliable overall picture from which to start targeted and more detailed safety checks, thus also reducing the economic impact.

The extensive historical heritage that is characteristic of many areas in Italy calls for a definition of rapid and reliable assessment procedures that allow the vulnerability of historical buildings to be evaluated on a large scale prior to a seismic event.

To this end, the research presented here addresses the formulation of a simplified approach enabling a rapid assessment of the vulnerability of a diffuse architectural heritage.

The approach presented here is a proposal for the reverse use of the protocol for the survey of historic heritage through a module called CARTIS, coordinated by the National Consortium of Seismic and Structural Engineering Laboratories (ReLUIS).

In other words, working on the field observations of residential buildings required by the map, grouped in homogeneous categories with percentages, we proceed to identify the area in the historic hub where the masonry buildings are located and listed and which belong to the widespread architectural heritage. In this example, positive and negative weights are assigned to selected points on the CARTIS card in order to quickly assess the seismic vulnerability as low, medium, or high. This information can be displayed on an available town map to pinpoint to the local authorities simply and clearly which buildings or groups of buildings require more attention and, therefore, closer inspection to confirm this assessment and, consequently, to inform the proprietor of the need to take preventive action.

This rapid assessment is compared with an equally rapid method of constructing fragility curves. Fragility curves are a widely used method to calculate the seismic response of buildings [10–14], but their design often requires significant modeling of the building response under horizontal loads, and they are not always easily and widely applicable.

The approach proposed here, on the other hand, is based on a deterministic approach already found in the literature [15–17], which, based on geometric and mechanical parameters, is able to estimate the local seismic response of a building in terms of the factor of safety SF. The geometric and mechanical parameters are taken from the CARTIS database, from ISTAT data (National Institute of Statistics), or data held by local authorities without any specific request made to the owners.

The deterministic approach is implemented with a probabilistic approach that assumes the safety factor, SF, as a random parameter and studies its evolution as the expected peak ground acceleration, PGA, changes. The construction of fragility curves describes the probability of reaching a certain level of safety loss as the PGA varies for different topographies and soil types.

The methodology presented here could be considered a step forward in cultural heritage diagnostics on a large scale, considering as cultural heritage the widespread historic residential masonry buildings that form the historic centers.

2. CARTIS Template for the Typological-Structural Characterization of Historic Centers

Within the framework of the Italian ReLUIS 2014/2018 project in the line entitled "Development of a systematic methodology for the assessment of exposure at a territorial scale on the basis of typological/structural characteristics of buildings", requested by the Italian Department of Civil Protection, a project was launched aimed at the knowledge of the existing diffuse residential heritage on the Italian territory. The experimental application of this protocol is based on a mapping of the territory by means of a survey template of the historic areas, called "CARTIS-Typological-structural characterization of urban districts" [18,19] and visible here https://www.protezionecivile.gov.it/static/09c8499fe4acaa014adf2f86539fc720/allegato-b-scheda-cartis-comparto.pdf (accessed on 16 September 2024). The objective is to take a census of the ordinary residential building types, spread throughout the different districts of a city, consisting of homogeneous portions of the urban fabric, according to the age of construction and/or structural construction technologies, initially dividing them into masonry and reinforced concrete buildings.

CARTIS only examines ordinary residential buildings, exclusively or with a part intended for service use, excluding all other buildings such as monumental heritage (religious buildings, historic palaces, towers, etc.), strategic buildings (hospitals, schools, barracks, prefectures, civil defense headquarters, etc.) and special structures (industrial warehouses, shopping malls, etc.). In fact, there are recently other CARTIS templates dedicated to other types of construction other than residential, such as CARTIS Churches and CARTIS Large-Span buildings, such as industrial warehouses.

The main purpose is to create an up-to-date tool that can be used throughout Italy in order to qualitatively investigate and detect widespread local building techniques and their intrinsic vulnerability. The data collection is very detailed. In fact, in order to fill in the form, it is necessary to observe building by building in the municipal territory, starting from the base cartography provided by the local technical office of municipalities, subsequently divided into compartments (municipal areas characterized by homogeneity of the building fabric in terms of age of first establishment and/or construction and structural techniques and often corresponding to a district). The subdivision of the local area is addressed using information derived from historical surveys, which will make it possible to define the various construction phases of the built-up area.

Punctual and different data will be used to report grouped data referring to types with common characteristics and reported on the template with percentage values (geometrically different buildings are counted, built in different eras, with different types of masonry and reinforced concrete structures, number of floors, geometric irregularities, different construction details, with deformable or non-deformable floors, thrusting or non-thrusting roofs, with different intrinsic or intervention-induced vulnerabilities over time, such as elevations or enlargement of ground-floor openings, etc.). Therefore, these data only relate to static/structural vulnerabilities, and since the objective is to statistically analyze the entire national territory, only the presence of recurrent and widespread cases over a territory with different seismic vulnerabilities is identified, while unique, special cases or types present with a minimum percentage (less than 5%) are not considered.

The template does not deal with the existence of the damage and its extent since the survey was carried out in "peacetime", away from seismic events. The general state of preservation of the recurring typological class is pointed out. An additional advantage is the registration of the records on a web platform: the database becomes a useful tool for extrapolating families of data to support specific scientific research in order to improve the definition of vulnerability models (classes and curves), to associate regionally prevalent building types with appropriate vulnerability classes, and, in conclusion, by providing a dataset on ordinary buildings and widespread historic construction that was not possible before.

A negative aspect is the final restitution of data, which results in the loss of the detailed analysis on each individual building since only data referring to the different main typologies are entered, reported with values in percentages, and which simplifies the set of specific information detected on the buildings. The location of the most vulnerable buildings within the municipality is also lost, despite timely onsite analysis, in order to identify them exclusively within an area as large as the compartment.

For this reason, a different use of these data is presented.

3. The Inverse Use of the CARTIS Protocol for the Seismic Vulnerability Survey of Historic Centers

It is intended here to propose a further use of the data collected through the CARTIS form to provide direct feedback to local authorities after the survey.

Once the site has been surveyed and the collected data saved in the dedicated CARTIS database, some results can be reported in the cartography provided by the municipality, providing the local government with a timely list of residential buildings or building aggregates that appear vulnerable to seismic risk. Those buildings can be marked with a simple colored graphic display (red, yellow, green), listing them in order of priority or urgency for thorough inspection to be made by a local technician or professional.

This is a simple qualitative method of reporting some observations made in the field. In detail, it is proposed to assess the degree of seismic vulnerability of buildings and building aggregates through the presence/absence of certain items flagged in the CARTIS sheet to which a numerical weight is attributed. In order to carry out this synthesis, it has been decided to take the individual data obtained from each building, used to compile the CARTIS sheet and create a new file in which only selected items are shown, including those that highlight certain problems from a seismic point of view. For example: (a) the presence of an added story, (b) an irregular distribution of openings, (c) a high percentage of openings on the ground floor, (d) staggered floors, (e) the presence of isolated pillars, (f) state of preservation, etc. Of course, positive entries can also be considered, such as the presence of pre-existing structural interventions, such as iron tie-rods and buttresses, a good state of conservation, etc. Positive entries can also be selected by selecting the negative ones chosen but with a positive connotation: regular distribution of openings, good state of preservation, etc. The method assigns a weight (+1 or −1) to all selected positive and negative items. The total score of each building is then compared with one of some selected buildings that can be judged, according to visual inspection and the flagged data in CARTIS form, as belonging to one of the three different categories: apparently low, medium, and high seismic vulnerability. In this way, it is possible to define a threshold value for the three classes that is calibrated to the characteristics of the building typology present in a town. The threshold values can be different for each historic area according to the different vulnerabilities observed. When the threshold value for selecting the three categories is selected, the color is assigned to the mapped buildings.

The above-mentioned items need not necessarily be the same for all historic centers. They can be reduced or increased depending on the local characteristics of the masonry building typology. It is, therefore, a subjective choice of the main items crossed out in the CARTIS form based on visual observation and experience gained from surveying all the buildings in the historic center by the person filling out the CARTIS form. This method can also be applied to building aggregates: once the major items had been selected, percentages were entered for the buildings that make up the entire aggregate or block. An example is reported in Figure 1. The town of Caravaggio (16,182 inhabitants), in the province of Bergamo, Lombardy region, despite having a lower seismic class of 3, shows medium to high seismic vulnerability from the analysis. This finding results from several factors, one of them being the massive presence of reinforced concrete buildings inserted in the blocks of the historic town center, adjacent to masonry buildings, and numerous elevations on historic buildings. The most interesting find, however, turns out to be the state of preservation of the buildings; in fact, for all the building aggregates, at least one building was found to be in a medium, poor, or very poor state of preservation, facing the street and adjacent to structures of public use or buildings of historical value, thus increasing the level of risk.

Figure 1. Historic center of Caravaggio (BG): example of expeditious seismic vulnerability assessment of masonry residential buildings, using data from the CARTIS sheet [20] modified by the author. The residential building aggregates are here all numbered.

A second example is carried out in Desio town (MB) (Figure 2), where the second rapid assessment method, based on fragility curves, is also used. The example presented here illustrates that the methodology was carried out in the historical center of the municipality of Desio (MB). The town of Desio, in the Lombardy region, is in an area considered by the Italian Design Code as a medium-low seismicity zone [21] (seismic zone 3), as for Caravaggio (Figure 1). The historic town center is characterized by a very simple structural typology in brick masonry: a two-story building with an average height of 3 m per floor. This typology represents around 63% of the building stock despite the size of the town (41,646 inhabitants) and its mainly industrial character. This building typology is widely found throughout the Lombardy region and, therefore, can be taken as an example that can also be extended to Lombard areas with higher seismicity, such as the areas of Brescia on Lake Garda (seismic zone 2). Compared to the case of Caravaggio, other data from CARTIS have been added here in the score attribution (Table 1): some negative (the high presence of openings on the ground floor and the presence of cornices and balconies on the street) and some positive (the non-presence of the items selected as negative, such as the low percentage of openings at ground-floor level and the absence of cornice and projecting balconies along passage roads).

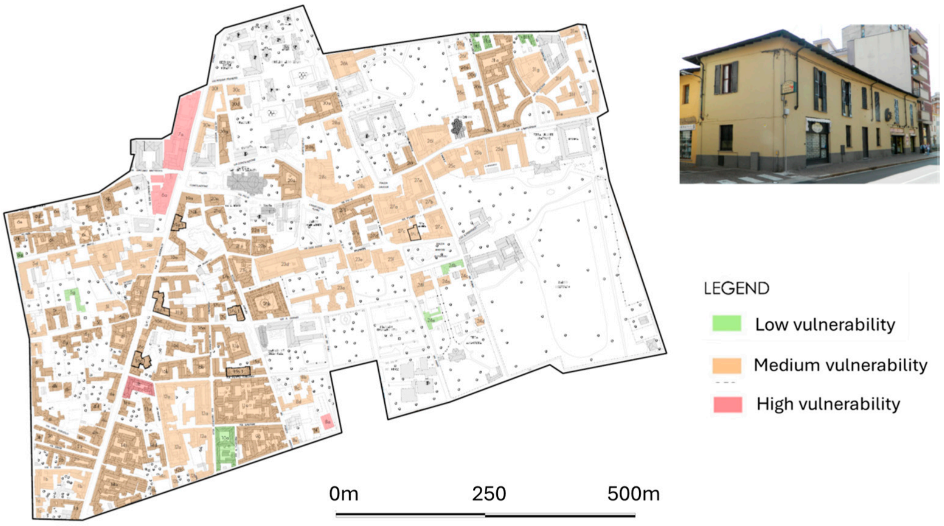


Figure 2. Historic town center of Desio (MB): example of expeditious seismic vulnerability assessment of masonry residential buildings in compartment n.1 using data from the CARTIS sheet.

Table 1. Example of selected data from CARTIS form used for the inverse methodology applied to Desio historic center.

Seismic Vulnerability Items	Numerical Weights
Building aggregate with the majority of buildings belonging to different types (non-homogeneous)	−1
Mixed structures with concrete elevation	−1
The presence of cornices and/or balconies on the street	−1
General state of preservation (poor)	−1
High presence of ground-floor openings (>30%)	−1
Irregularities of openings in perimeter walls	−1
Irregularities in height	−1
Regularity of openings in perimeter walls	+1
General state of preservation (good)	+1
Low percentage of ground-floor openings (<19%)	+1
Absence of cornices and/or balconies on the street	+1
Building aggregate with the majority of buildings belonging to the same types (homogeneous)	+1

Obviously, this classification turns out to be qualitative since it is based on surveys carried out on the exterior of the buildings, but it can be a first tool for identifying those more serious cases; this can be followed at a later stage by a request for further investigation that notes the state of preservation of the interior of the buildings, deficiencies, damage or erroneous interventions carried out over time.

4. Rapid Assessment of the Seismic Response of Masonry Buildings with Fragility Curves

Another method of assessing the seismic vulnerability of a historic town center can be the building-by-building analysis carried out to compile the CARTIS Building sheet of buildings representative of the recurring typologies in the historic center described in the previous paragraph. In fact, the CARTIS data can represent the basic data to allow the application of a simplified calculation procedure to evaluate the probability of loss of performance as the magnitude of the expected seismic stresses varies. This application is based on the combination of two different approaches: a deterministic approach, available in the literature and already applied in some Italian regions such as Marche, and a probabilistic approach, which implements the predictive aspect based on the data provided by the deterministic approach.

4.1. The Deterministic Approach

The deterministic method, developed by Borri and de Maria [15–17], describes the structural response of masonry buildings by calculating a safety factor SF, which depends on the geometric and mechanical characteristics of the selected building.

The geometric data required by the methodology concern the number of floors above ground, the average height of each floor above ground, the covered surface area of each floor, the length and thickness of the shear walls that can be recognized in the plan, both in the x and y directions.

These data are easily available from sheets such as CARTIS sheets or data held by the local administrations.

The mechanical data required for the application of the procedure cover the average shear strength of the masonry, the average compressive strength of the masonry, and the density of the masonry itself.

Initially, the mechanical parameters used can be the average parameters reported in the literature, reserving any further investigations if the results of the fast method show anomalies in the probability of loss of performance. For the proposed case, reference is made to the parameters in Table C8.5.1 of the Italian technical standards for construction NTC2018 [21].

The site parameters of interest for the definition of the safety factor are the characteristic parameters of the seismic zone in which the site is located and which characterize its elastic response spectrum. For each return period considered, these parameters of interest are as follows: the expected acceleration, a_g, and the spectral amplification factor F0. The parameters a_g and F0 values are evaluated for the whole Italian territory and can be found in Annex A and B to NTC 2008 [22].

Two other important parameters for the site characterization are the type of subsoil and the orography of the area.

Usually, these physical and geological parameters are easily available in the literature or from the local administrations.

When all this information is available, the procedure proposed by Borri and de Maria in [15,16] and modified in probabilistic terms by the authors in [23] can be applied to different seismic contexts.

The safety factor SF, considered to be the seismic response, is the lower of two safety factors derived from the building characteristics: the static safety factor SF_S and the global safety factor SF_G.

$$SF = min[SF_S;\ SF_G] \tag{1}$$

The SF_S factor is mainly concerned with the response of the building under vertical loads and depends on gravity loads and material characteristics. The SF_G factor describes the behavior of the building to horizontal forces and therefore considers not only the geometric characteristics of the building, such as plan organization and regularity in elevation, but also the seismic, topographical, and geological characteristics of the site and the horizontal forces generated by the peak acceleration.

A detailed description of the parameters now introduced and their use in the proposed approach can be found in [15,16,23]. In [23], the complete theoretical approach was developed with the explanation of the formulas needed for practical application.

The factor, SF, measures the loss of performance capacity in terms of residual percentage capacity.

To assess the safety factor, plans and sections of the building are required, as information on the quality of the masonry and data on the geology, topography, and seismicity of the area, which can only be found in databases such as CARTIS or the databases of the local authorities. To assess the seismicity of the site, it is possible to use the tools provided by the Department of Civil Protection and the National Institute of Geophysics and Volcanology [see https://rischi.protezionecivile.gov.it/it/sismico/ and https://esse1-gis.mi.ingv.it/mps04_eng.jsp, accessed on 16 September 2024].

4.2. The Implementation with a Probabilistic Approach

For a rapid assessment of the vulnerability of masonry structures subjected to different levels of PGA, the deterministic method found in the literature was implemented with a probabilistic approach based on the construction of fragility curves.

The aim of this work was to construct a simple method to quantify the probability of recording a performance loss greater than a certain value as the expected PGA value varies. The application of fragility curves requires the definition of a random variable; the variable we consider significant in this analysis is the loss of performance as measured by the SF parameter, which is easily quantifiable based on data collected from open databases (such as the CARTIS database) and without carrying out specific diagnostic investigations.

The procedure adopted was to identify a homogeneous sample of buildings located in the same seismogenetic zone, select a set of PGAs (a^*) characteristic of the seismogenetic zone, and then the corresponding spectral amplification factor F0. These parameters are applied to each of the selected buildings, and the seismic response is processed in terms of SF associated with a given acceleration, a*.

In the case of seismic response, the safety factor SF, which is always the smaller of the two parameters SF_S and SF_G, is the global safety factor SF_G.

Figure 3 schematizes the analysis process, building by building (blue frame) and for the whole group of buildings (yellow frame).

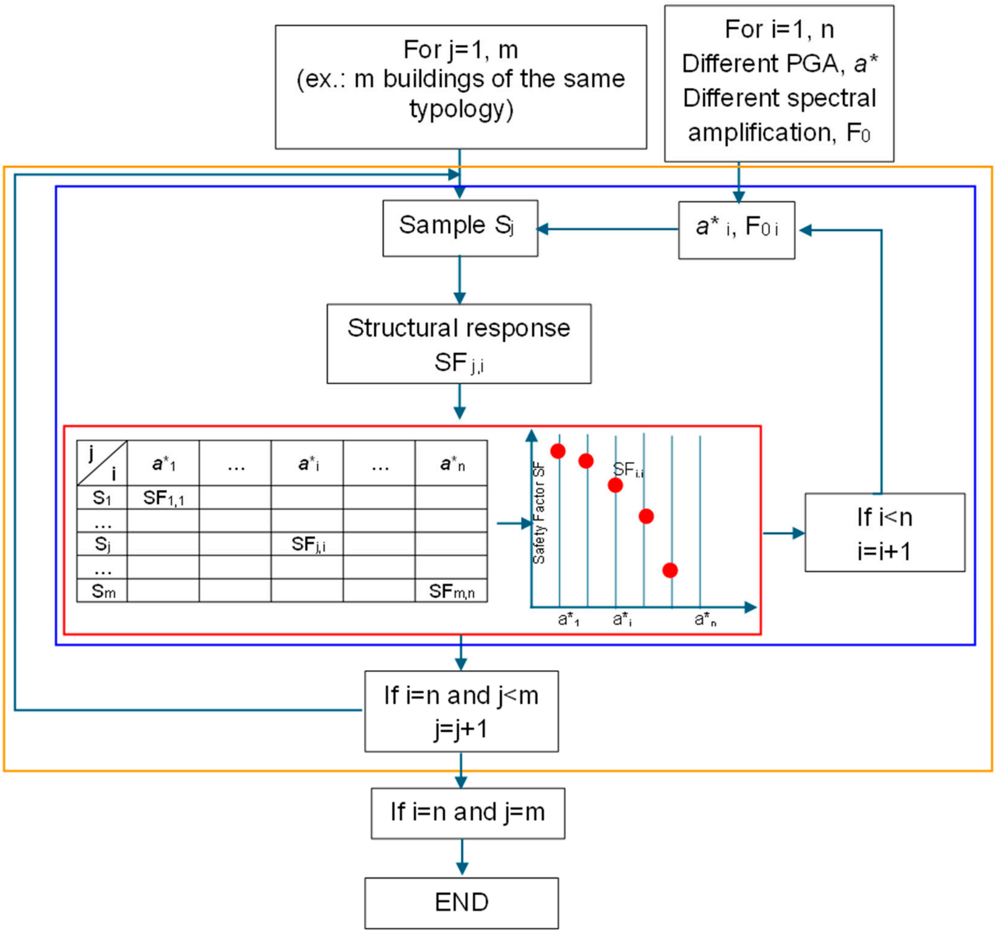
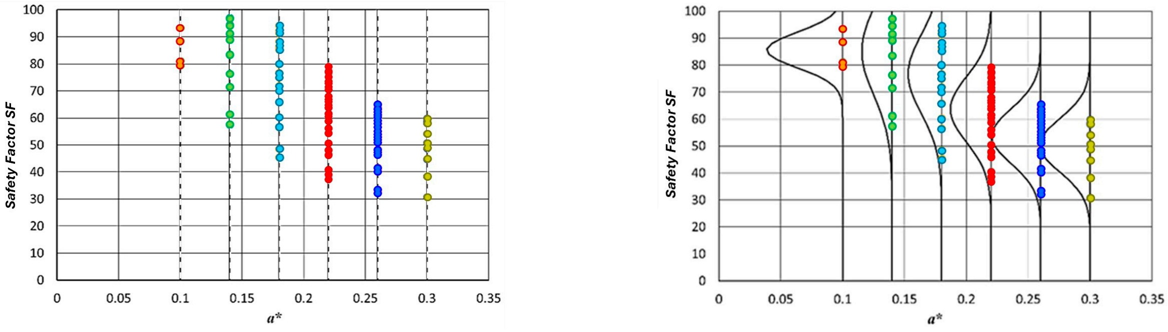


Figure 3. Diagram of the calculation process of the variation of the safety factor SF as the expected seismicity changes.

From the process described in the diagram in Figure 3, for each a* it is possible to collect in discrete form the SF values for all the buildings in the sample (Figure 4a). The dispersion that characterizes these values requires that we address the issue of predicting the behavior of the SF variable in probabilistic terms. Therefore, each set of discrete SF_S associated with a given a* was modeled with a probability density function (PDF), $f(SF, a^*)$, which describes the physical aspect of the problem well and can also account for rare events in the tails of the distributions (Figure 4b).



(**a**) (**b**)

Figure 4. Evolution of the safety factor SF as a* varies. (**a**) Discrete representation of the values obtained from the sample of buildings S; (**b**) Probabilistic modeling of each dataset for each value of a* with an appropriate PDF [23, modified by the author].

The modeling shown in Figure 4 allows the construction of fragility curves for different values of expected performance loss. Indeed, assuming threshold values $\overline{sf}$, the areas below and above the PDF describe the probability of 'failure' (in our case, the probability of the SF reaching the threshold, $\overline{sf}$) and the probability of 'survival' (in our case, the probability that the safety factor SF is above the threshold value of $\overline{sf}$).

In probabilistic terms, these areas are constructed as the integral of the area underlying the PDF $f(SF, a^*)$, in the interval $(-\infty; \overline{sf})$ and in the interval $(\overline{sf}; +\infty)$ and, respectively, represent the probability cumulative distribution function (CDF), $F(\overline{sf}, a^*)$ (Equation (2)), and the survival probability function (SDF) $\mathfrak{I}(\overline{sf}, a^*)$ (Equation (3)) (Figure 5):

$$F(\overline{sf}, a^*) = \int_{-\infty}^{\overline{sf}} f(SF, a^*) \tag{2}$$

$$\mathfrak{I}(\overline{sf}, a^*) = [1 - F(\overline{sf}, a^*)] = \int_{\overline{sf}}^{\infty} f(SF, a^*) \tag{3}$$

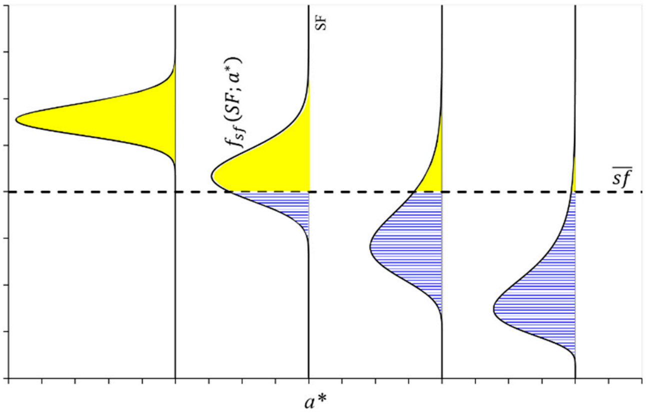
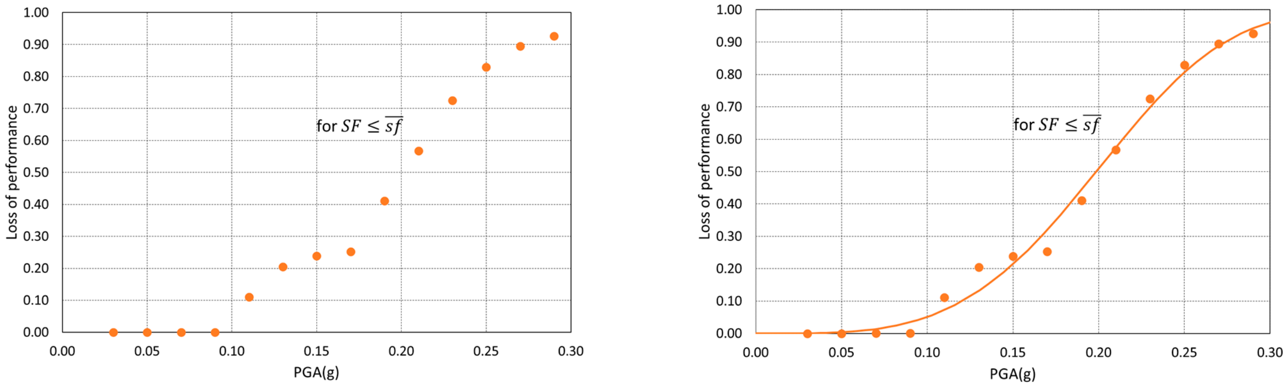


Figure 5. Qualitative representation of the probability that the SF value is less than or equal to the threshold value, defined by $F(\overline{sf}, a^*)$ (dashed area) and the probability that the SF value is greater than the threshold value, defined by $\mathfrak{I}(\overline{sf}, a^*)$ (colored area).

By graphing the calculated areas for a given threshold $\overline{sf}$, it is possible to describe an experimental fragility curve as that of Figure 6a. The experimental curve can then be modeled with an appropriate probability cumulative distribution (CDF) (Figure 6b).



(**a**) (**b**)

Figure 6. Probability of reaching a certain threshold $\overline{sf}$ ($SF \leq \overline{sf}$): (**a**) experimental fragility curve; (**b**) theoretical modeling of the experimental fragility curve.

The choice of probability distributions is the most difficult hurdle in this modeling.

In fact, to properly consider possible rare events, we cannot only rely on the reliability of statistical and parametric optimization tests but also need to know the physics of the phenomenon under study. In a range of possible distributions, the intuition of how the evolution of the phenomenon may occur in the immediate, coupled with the mathematical structure of the function of the immediate occurrence rate $\lambda(\overline{sf}, a^*)$ (also called the hazard rate) certainly supports the choice [24–27].

$$\lambda\left(\overline{sf}, a^*\right) = \frac{f\left(\overline{sf}, a^*\right)}{\Im\left(\overline{sf}, a^*\right)} \tag{4}$$

In the case studies presented, gamma distributions were chosen to model the PDFs for each value of a*, as gamma distributions have an increasing but tending asymptotic function λ, which interprets well the trend of the collected experimental SFs: SFs are variable but never exceed a certain threshold. Instead, for modeling the fragility curves, we have assumed a Weibull distribution with a function λ increasing to infinity.

A distribution with λ tending to infinity describes a phenomenon that, if it has not yet occurred, as the variable x considered increases, the probability that it will occur in the immediate interval (x + dx) increases rapidly, making its occurrence almost certain. Since what we are trying to predict is the loss of performance due to increasing stress caused by increasingly higher accelerations, if the predicted loss of performance has not yet occurred, as the acceleration, a*, increases, the probability that it will occur in the interval (a* + da*) becomes increasingly probable, therefore the choice of a Weibull distribution seems justified. The authors are, however, aware that this choice is not univocal and may open up interesting areas of discussion, but that is beyond the context of this work.

5. The Methodology Applied to a Case Study

The method presented in Section 4 shows good flexibility of use and can also be applied by referring to data collected in existing datasets such as CARTIS and/or municipal databases.

The case study presented here was designed with the intention of applying the method using only the available data, without any onsite survey or experimental testing at this stage.

The municipality chosen is again the town of Desio, in the province of Monza-Brianza (MB), in the Lombardy region, as presented in Section 3.

As mentioned in Section 3, the structural typology of the buildings in the municipality of Desio (MB) is characteristic of a large part of the Lombardy region, so it was decided to evaluate their seismic response not only for the acceleration values characteristic of the actual area of the town of Desio but also for the seismicity values characteristic of the Lake Garda area (Seismic zone 2, NTC2018 [21]) (see Table 2).

Table 2. Return period reference values for the Lombardy region (moderate seismicity according to NCT2018 zone 2) used in the study to define the action in the fragility curves.

Return Period (Years)	PGA(g)	F_0
30	0.042	2.551
50	0.057	2.483
475	0.158	2.483
975	0.206	2.485
2475	0.283	2.466

The parameters reported in Table 2 are provided by the Italian legislation in Annex A and B of the NTC 2008 [22].

The town of Desio has recently been degraded from seismic zone 4 to seismic zone 3. The subsoil is of category C: medium-density coarse-grained soils or medium-firm fine-grained soils, and topographic category T1: flat surface with slopes with an inclination of less than 15°. The geological and topographical parameters are SS = 1.5 and ST = 1.

For the municipality of Desio, ten buildings were studied, all homogeneous in terms of construction typology. The data necessary for the application of the proposed procedure were obtained from the CARTIS database and the drawings of the buildings.

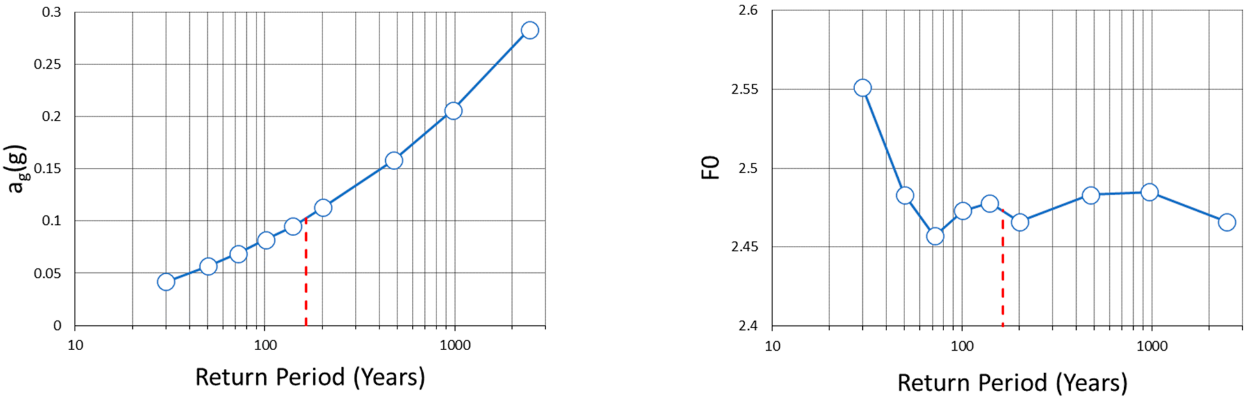
The damage parameter assumed to describe the loss of performance due to earthquakes of different severity is the safety factor, SF, as the minimum between two parameters defined as static safety factor SF_S and global safety factor SF_G (Equation (1)). These two factors are quantifiable based on the geometric data of the structure on the strength characteristics of the masonry, which can be quantified either empirically with a masonry quality analysis [23] or with non-invasive or moderately invasive instrumental tests [28] and then associated with the local seismicity. The static safety factor, SF_S, depends on the gravity loads, the mechanical characteristics of the materials, and the confidence factor, CF, introduced in the Italian code NTC2018 [21] to establish the degree of building knowledge then under consideration.

Therefore, for each of the 10 buildings, the safety factor SF (the lowest between the static factor SF_{Si} and global factor SF_{Gi} for each i building) was computed for all the acceleration values as well as the consequent loss of performance in the structural response.

From Table 2, it is clear that the range of possible accelerations (PGA) characteristic of the Lake Garda area for the different return periods goes from a value of about 0.04 g to a value of about 0.30 g. Based on this observation, the probabilities of performance loss for the 10 sample buildings were evaluated using acceleration values included in the range 0.04 g–0.30 g with an incremental step of 0.02 g.

For each acceleration value analyzed, a value of the spectral amplification factor, F0, must be associated. For return periods different from those in Table 2, it is possible to obtain the spectral parameters through linear interpolations of the code values. (Figure 7). Therefore, the value of the acceleration and F0 useful in this application can be obtained by reading their values at the same return period (Figure 7 red line).

The next step was the construction of the fragility curves describing the probability of exceeding selected thresholds of loss of the SF factor as the PGA, a*, varied. Figure 8 shows the fragility curve evaluated for the threshold $\overline{\text{sf}} \leq 20\%$, i.e., what is the probability that for a given PGA value, the building loses 20% of its performance measured in terms of SF.



(**a**) (**b**)

Figure 7. Graphical representation of the trend of the spectral parameters a_g (**a**) and F0 (**b**) for the Lake Garda area. The circles correspond to the values of the Italian code. For return periods different from those in Table 2, it is possible to obtain the spectral parameters through linear interpolations of the code values. The values of a_g and F0 associated with a return period of 164 years are shown in red as an example.

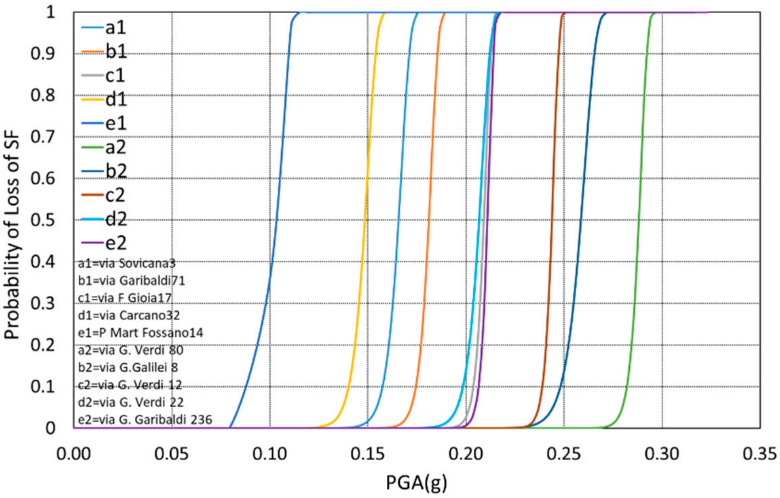


Figure 8. Fragility curves construction for each building of the full sample of 10 buildings in Desio town, calculated with a threshold $\overline{sf} \leq 20\%$.

The values of the safety factor, SF, computed for each interval permitted the construction of experimental fragility curves, and the following modeling of them this a theoretical probability distribution (Weibull-type probability distributions) [23,24].

In Table 3, for the 10 buildings chosen, the parameters of the Weibull distribution are reported.

Figure 8 shows a very similar trend of the fragility curves for all buildings, which means a good homogeneity in the mechanical characteristics of the buildings. However, the loss of performance occurs for different PGA values for the set of buildings analyzed; this variation in behavior is certainly due to the organization in the plan of the buildings, i.e., the presence or absence in the plan of bracing walls in the x and y directions.

The results obtained for the sample of 10 buildings were used to construct the fragility curves for the typology studied. (Figure 9).

Table 3. Weibull distribution parameters for the 10 buildings studied.

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}}$$

Building	α	β	Mean	Variance
a1	37.206	0.167	0.165	0.0271
b1	15.575	0.128	0.124	0.0153
c1	72.602	0.210	0.209	0.0430
d1	32.898	0.150	0.148	0.0218
e1	19.915	0.104	0.101	0.0103
a2	42.308	0.208	0.205	0.0420
b2	44.230	0.189	0.186	0.0348
c2	58.741	0.176	0.174	0.0304
d2	46.360	0.208	0.206	0.0424
e2	86.378	0.212	0.210	0.0443

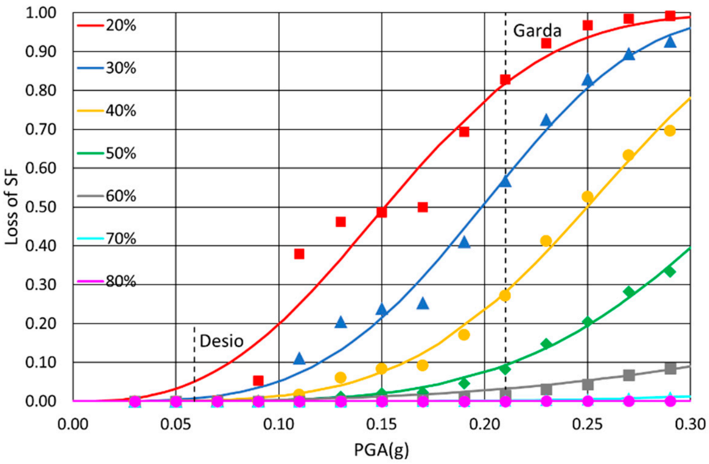


Figure 9. Fragility curves constructed for different performance loss thresholds and characteristics of the studied typology, located on a flat location with a medium-sized subsoil.

Figure 9 shows that the typology studied certainly proves to be adequate for the low seismicity characteristic of the municipality of Desio (MB). In fact, for a return period of 975 years (considered to be the service life of collapse period) for Desio, the higher expected PGA is 0.059 g (dashed line in Figure 9, marked with Desio).

However, this typology also seems to be a good one for areas in Lombardy with higher local seismicity, such as the Lake Garda area. In fact, for a PGA of 0.21 g with a return period of 975 years (Table 2 and dashed line in Figure 9 marched with Garda), it can be seen that the highest performance losses are 20% and 40%, with different probabilities of occurrence. Performance losses greater than 40% appear to have a lower probability of occurrence, which gives hope that even if earthquakes of significant magnitude were to occur in these areas, the seismic response of most buildings could be relatively good.

Thanks to its flexibility of application and the easily available basic data, the method predicts the seismic response of an individual building in terms of loss of performance as the expected acceleration changes under known geomorphological conditions. Considering a fairly homogeneous sample of buildings also makes it possible to predict the possible seismic response of a given building type under known geomorphological conditions.

The method has limitations in terms of the difficulty of extending it to an aggregate and the difficulty of accounting for certain vulnerabilities, such as irregularities in plan and elevation. A more extended analysis can be achieved by combining the method proposed here with a method of quantifying vulnerable aspects such as the one proposed in Section 3.

As far as the number of samples is concerned, a sample of 10 buildings turns out to be quite significant since the structural typology identified as representative of the historic center of the municipality of Desio (MB) turns out to be rather homogeneous. Certainly, a larger sample size would certainly lead to an improvement in the modeling.

A probabilistic approach requires a relatively large sample size in order to be considered reliable. It helps to reduce epistemic uncertainties, i.e., uncertainties that depend on controllable factors such as the number of samples, the correct choice of modeling approaches and probabilistic distributions, and the estimation of their parameters. As mentioned earlier, these latter aspects must be supported by a correct knowledge of the process to be modeled and an adequate knowledge of the mathematical form of the distributions and, in particular, of their hazard rate or exceedance probability function.

The choice of distributions used in modeling the proposed approach has been commented on here. Although the authors are aware that the issue is open and the choice is certainly not unambiguous, they consider it optimal for now.

A probabilistic approach then suffers from random uncertainties that are difficult to control. For example, in the proposed case study, it is difficult to account for errors or defects that may have occurred during construction, which cannot be detected by the plan geometry but may affect the response of the structural system.

Limitations that have been highlighted in the application of the proposed approach, especially at the individual building level, relate to the small sample size in predicting the exceedance of various performance loss thresholds. This problem is related to the choice of the amplitude of the survey intervals, which is always a delicate choice. Adequate knowledge of the local seismic history and seismic microzonation can certainly support such choices. In the proposed case, the interval amplitude is 0.02 g, which allows the threshold transitions to be captured quite well.

With the observations now made, the authors suggest that this methodology be approached critically but without underestimating the quality of the approach and its validity in a rapid vulnerability survey for an urban area.

6. Comparing the Two Methods

The two vulnerability analysis methods presented here are very different and are based on different initial data. The first method, which is very qualitative, has the advantage of enabling a visual examination of all the buildings in the historic town center and quickly identifying those buildings that are the most vulnerable and at risk, taking into account the entries on the CARTIS card. The second method, on the other hand, is quantitative and requires as starting data the correct plan geometry of each single building, as well as the seismic data of the area. The application of the probabilistic method, on the other hand, requires slightly more detailed knowledge of each individual building; in fact, its application starts from the study of the overall seismic response of the building to given stresses and therefore requires as starting data the correct plan geometry of each individual building, as well as the seismic data of the area. The parameter that measures the seismic response is the global safety factor SF_G proposed by A. Borri and A. De Maria in [17], here considered to be a random variable as the seismic stress varies. While the original method proposed in [17] evaluates the SF_G factor at a single moment in the seismic history, the proposed probabilistic approach allows the prediction of the evolution of the SF_G value in terms of the probability of percentage loss of this value as the expected acceleration varies. The constructed fragility curve then describes the probability of percentage loss of safety level for different percentage values. This makes it possible to plan safety interventions or more detailed inspections for buildings that show a tendency to lose the initial safety level at accelerations close to those predominantly recorded in the area.

It is, therefore, a less subjective method than the first method, but it is not feasible to apply it to all the buildings in a historic town center, as it requires more time to collect the surveys, process the data, and make a probabilistic assessment. We therefore suggest the application only to a sample of the most significant recurrent typologies.

Its application becomes effective when combined with the previous method. In fact, the probabilistic method applied to buildings that do not have a high degree of vulnerability could show deficiencies in behavior that could lead to changes in the classification and lead to different maintenance and control choices from those that would have been planned using only the analysis with the CARTIS sheets.

They are, therefore, two complementary methods. The methods are not alternative but complementary also because the second does not take into account certain vulnerabilities that are present on the CARTIS sheet and therefore usable for its 'reverse use' (such as the presence of curved floors, irregularities in plan and elevation, and the extension to a building aggregate).

What has been described is reflected in the results obtained by applying the two methods to the historic center of Desio: the results for the historic town center of Desio show very similar fragility curves as a trend for all the buildings in the sample the fragility curves obtained from the probabilistic analysis show a very similar trend for all buildings in the sample, but it seems that the triggering of the loss occurs for different values of expected acceleration for each building (Figure 8); while for the analysis obtained with the inverse CARTIS method the buildings are all classified in the medium vulnerability class. Combining the two pieces of information shows that for a probable 20% loss of performance, building e1 (Figure 8) requires attention and could be investigated first in order to direct seismic strengthening measures.

On the other hand, if one were to act only on the basis of results related to the structural type (Figure 9), it would be possible to assert that the two methods help to understand the level of vulnerability of the building type (inverse CARTIS) and the probability of loss of performance that can be expected for that building type as the expected acceleration changes.

It should again be noted that both methods must be applied prior to a possible seismic event in order to be able to have a picture of possible priorities for intervention to improve seismic effects. Therefore, it is not possible to consider the level of damage present in the different vulnerability classes, as the buildings have not yet been damaged by the earthquake. The possible presence of damage is only noted under the heading 'state of preservation' for the CARTIS inverse method and with the introduction of a reducing factor for the mechanical properties of the masonry for the calculation of the safety factor.

7. Conclusions

In Italy, the large number of small historic habitats located in areas of high seismic risk, which are inextricably linked to the territory to which they belong, contribute to defining the country's historical and cultural identity. Unfortunately, their gradual abandonment is often due to the lack of adequate housing and structural safety standards. However, if recovered, those could represent a great opportunity for the sustainability and revitalization of the often increasingly impoverished territory and the development of the local population, offering a good quality of life.

To achieve this objective, it is necessary to reduce safety and seismic vulnerability during periods of seismic calm by means of rapid surveys, which, in a short time and with limited resources, can identify the critical points in an extensive urban fabric that require further investigation; it is necessary to create a tool that helps administrations to put to good use the available resources towards increasingly conscious intervention choices.

It is within this framework of action that the proposed work is intended to fit.

To this end, a proposal was presented here for the inverse use of the protocol for the seismic vulnerability survey of historic centers through a form called CARTIS (ReLUIS). This fast assessment is compared with an equally fast method of constructing fragility curves, an important step forward in the ReLUIS–CARTIS database and defining the relationship between the probability of reaching a level of loss of structural safety or a vulnerability index as a function of the seismic acceleration PGA and the ground orography.

A method of study is presented that can create an opportunity for interaction with the various participants in the municipal administrations and to carry out preventive measures on the complex activities revolving around the issues of seismic vulnerability, not only of monumental assets but of entire historic town centers. The opportunity is provided by the active participation in the recent campaign to test the protocol for surveying historic centers through a form called CARTIS, coordinated by the university consortium ReLUIS, commissioned by the Department of Civil Protection, and aimed at surveying the different structural typologies of ordinary recurring residential buildings prevalent in the municipal area with their observed seismic vulnerability factors, if any.

The analyses carried out to fill in the CARTIS sheet can, therefore, provide a detailed picture of the village, a history on which the municipality can decide to work in the medium to long term, leaving it to their owners to make the appropriate changes to reduce the vulnerability of individual buildings/aggregates over time. The CARTIS sheet thus proves to be a valid tool, despite its many uncertainties, as a first approach to studying the state of the built heritage extending across the Italian municipalities, highlighting the most vulnerable and, at the same time, the most deserving of protection. With the translation of the ReLUIS–CARTIS form into foreign languages and the availability of the data collected building by building, it is possible to apply both the inverse use of CARTIS and the fast method of constructing fragility curves presented here in any seismic area.

An important future attempt will be to try and automate this output, which is currently still done manually, by extracting data from the CARTIS database that has already been georeferenced. Interactive maps would certainly be very useful. One possible development could be the creation of a database in which each aggregate or building could be assigned all the data that identifies it: geometric, mechanical, and state of preservation, with the possibility of updating when maintenance or adaptation work is carried out.

The methodology presented here, not alternative but complementary, could be considered to be progress in cultural heritage diagnostics on a large scale, considering as cultural heritage the multiplicity of historical residential masonry buildings forming the historic centers that characterize a country.

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