WP 1 – BE and SUOD: State of the Art (SoA), risks and human behavior

T1.2 - SoA-based definition and characterization of BE as network of buildings, infrastructures, connecting space in reference to SUOD occurrence and users' typologies

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Abstract

In this deliverable 1.2.2. it exposes a synthesis of the state of the art of the scientific literature concerning the preventive evaluation of the seismic damage of masonry buildings built with traditional techniques (unreinforced masonry buildings). This theme has an indirect origin in the definition of macroseismic scales starting from the damage observed by buildings in the event of an earthquake. From these studies, methods have been developed that use different approaches dedicated to the evaluation of the building heritage present in a certain part of the urbanized territory (macro-seismic expeditious approaches §2.1) or focused on the behavior of individual buildings, with more complex analytical approaches (mechanical approach §2.2 and kinematic §2.3).
Furthermore, a topic of interest for the development of research in BE S2ECURE is the evaluation of how seismic damage to buildings can cause the fall of debris, creating an obstacle to circulation in the streets and squares of historic centers. The study of the scientific literature on this topic proposes significant contributions regarding analytical and experimental approaches (§ 3.1) and expeditious approaches (§ 3.2), the latter more useful for studying large areas such as an entire historical center.
Finally, in §4, the considerations for defining the application of the methods illustrated in this deliverable for the purposes of the BE S2ECURE research are set out.

Keywords

Assessment seismic damage; seismic modifications of BE; assessment seismic debris.

Approvals

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Summary

1. Introduction

The BE aeral spaces during a SUOD vent (like an earthquake) may undergo modifications that influence their normal and emergency use. This is due to various factors related to damage to the surrounding buildings, to the system of underground utilities, to power lines and road pavements.
The purpose of this deliverable is to highlight which studies are present in the literature on the identification of these damages, the possibility of their preventive evaluation and the proposal of solutions that can allow to mitigate the risk of loss of functionality. Indeed, these open spaces (aeral spaces) perform a fundamental function in the event of an earthquake to allow the population to safely evacuate to the collection and shelter points.
In accordance with the general approach of the BE S2ECURE project, the area of interest of this study can be identified in the historical centers of Italian cities subject to high or significant seismic risk and which are simultaneously important venues of cultural heritage.
In general we can say that the relationship between seismic risk and cultural heritage is a theme that has aroused a lot of interest in the last two decades, starting with the agencies that protect this heritage. Among the first contributions in this sense was that of the UNESCO World Heritage Committee in 2008 (UNESCO, 2008) and, subsequently, the provisions of the Ministry of Heritage and cultural activities and tourism of the Italian government (OPCM_Italian Government, 2011). In 2016 the EU published an action plan dedicated to the Sendai Framework for Disaster Risk Reduction in which, for the first time, cultural heritage is considered as an operational target, following the same line taken the year before from the UN General Assembly (United Nations, 2015).
The inclusion of all historic centers in the concept of cultural heritage to be protected is now consolidated in Italian legislation. The fundamental reference is constituted by the legislative decree n. 42/2004 (Italian Government, 2004), but the concept of widespread cultural heritage to be associated with historic centers has been a strong point of Italian urban planning culture since at least the second post-war period.
Therefore, a seismic risk reduction strategy for this heritage must considering a very large set of buildings which for the most part was built before 1900 using bearing masonry structures that have only partially received a functional and structural requalification. Moreover, these historical centers still remain absolutely important in social and economic life since they host administrative functions, courts, banks, schools, commercial activities and residences as well as constituting the highest real estate value area.
The seismic risk in these highly used and populated areas therefore derives not only from the vulnerability of a building and urban scale, but also from the high exposure. For this reason, it is very important to define risk reduction strategies that include both actions to improve the safety levels of buildings and actions that make it possible to rescue and evacuate the inhabitants.
The BE typical of Italian historic centers (see D111 and D112 in this regard) has a high density of buildings, streets of limited width, squares and parks whose characteristics influence the safety conditions in the event of a seismic event. The focus of this deliverable is precisely to identify, through the study of scientific literature, the methods for assessing how the earthquake modifies the elements of the built environment, with particular reference to the buildings facing the streets and squares of the historic centers.

2. Seismic damage of traditional masonry buildings

2.1 The study of buildings damage as the basis of macroseismic scales.

The first studies on masonry building damage in the event of an earthquake were aimed at indirect measurement of the intensity of the shaking in order to classify earthquakes.
The study of the effects caused by an earthquake on the environment to determine the intensity of the shaking has first application in the scale published in 1883 by the Italian seismologist Michele Stefano De Rossi and the Swiss seismologist François-Alphonse Forel. Their scale was divided into 10 degrees with increasing intensity and in which effects on instruments, on people's sensations, on objects, on construction and on the environment were reported. In 1902 Giuseppe Mercalli proposed a new version of the De Rossi - Forel scale, redefining the effects gradualness focusing on the better definition of the higher intensities (Gaudiosi et al., 2014). In his proposal, the relationship between intensity and effect on the buildings is more emphasized, diversifying the damage according to a different construction quality, while considering only one typology, that is masonry buildings. On this scale, mention is made of the presence of human victims in increasing quantities in the last three degrees; as regards the ninth grade, Mercalli believes that the seismic intensity connected to this level leads to losses of human lives not numerous, but scattered in different points of the inhabited areas. It is believed that the clarification derives from the real knowledge of the conformation of the inhabited centers, in which areas of greatest vulnerability existed Figure 1and Figure 2). This minds the competence of the Italian seismologist in understanding buildings and urban centers features.

Figure 1 Mercalli's drawing on the seismic damage of buildings after the 1887 Liguria earthquake (from Archivio storico Reale Osservatorio Vesuviano)

Figure 2 Photograph taken by G.Mercalli in Diano Marina (IM) in 1887 (from Archivio storico Reale Osservatorio Vesuviano).

Mercalli proved to be very careful in buildings damage study, from the earthquake in Liguria in 1887 in which he carried out surveys and took photographs that testify to the level of injury, partial or total collapse of many buildings. From this activity he deduced that there were not only different levels of construction quality, but that the types of damage were recurrent according to the different building categories. Following the publication of his modification of the De Rossi - Forel scale, it was possible to trace the maps of isosismicity through which to identify the levels of the effects of the single earthquake on large territories and, therefore, of its perceived intensity (Figure 3).

Figure 3 Map of the isoseismal lines of the Calabrian earthquake of 23 October 1907

Simultaneously with Mercalli's work, the geophysicist Adolfo Cancani worked on defining his own scale based on the accelerations measured in some Asian earthquakes (Japan 1891 and India 1897). He proposed a 12-degree scale at the International Seismological Conference in Strasbourg in 1903, with the introduction of grade XI (catastrophe) and XII (huge catastrophe) which formed the basis for the work of seismologist August Sieberg.

After the Messina earthquake of 1908, Mercalli also introduced a modification of its scale published in 1902, bringing grades from 10 to 12, thus aligning with Cancani's proposals and finally in 1912 Sieberg unified the Mercalli and Cancani scales. a first publication of the unified scale was in 1923 and subsequently, in 1930, there was the definitive publication of the Mercalli Cancani Sieberg scale, known as the MCS-1930 scale.

So, if Mercalli was the creator of an updated observational mode, Cancani was the architect of the expansion of the original 10 degrees into 12 while Sieberg developed a more widespread and complete description of the effects on people, the environment and buildings for each single degree. In MCS-1930 the characterization of buildings is expanded according to the different construction systems. The framed buildings and also the wooden houses are inserted for the first time, to witness an opening towards European contexts where these solutions are more used than in Italy. In addition, the quantity of heavily damaged buildings for the attribution of the degree of intensity is included in the MCS-1930, demonstrating a greater awareness of the complexity of the scenarios to be analyzed.

In 1931 the MCS-1930 scale was adapted to the North American context by Wood and Neumann and published as a modified Mercalli Scale (MM-1931). On this scale, the set of buildings to be considered expands compared to the MCS-1930; indeed, poorly constructed buildings, improperly designed buildings, ancient constructions, buildings with good construction techniques and buildings with high design and construction standards, as well as tall buildings are considered. In addition to the injuries of different sizes, some partial collapses are also described, such as off-lead walls or overturned to the ground both in masonry buildings and in framed buildings. But both in MCS-1930 and in MM-1931 there is no systematic definition of the vulnerabilities related to the different ways of building so that these scales do not rationally take into account the influence of building vulnerability. In fact, it is not possible to define a level of damage as a function of a specific number of damaged buildings of one type rather than another even if the progression of the damage, between one degree and another, can be considered from the descriptions given.

Medvedev made a move towards greater objectivity of observational analysis in 1953 with the GEOFIAN scale of the Earth Physics Institute of USSR Academy of Science in which for the first time the subdivision by homogeneous construction typologies appears to implicitly define a different vulnerability to the earthquake (Barosh P.J., 1969):

Group A: Single story buildings with walls of unfinished stone, brick, adobe, etc.
Group B: Brick and stone houses
Group C: Frame houses.

In addition, 4 damage levels are determined (Light damage, Considerable damage, Destruction and Collapse) and 4 classes of number of damaged buildings (Majority, Many, Individual). There are scales defined for the effects on Buildings and Structures, on the environment and a final cumulative scale in which human victims are also taken into consideration: all these different scales are made up of XII degrees.

In 1964 the MSK-64 (Medvedev-Sponheuer-Karnik) scale (Barosh P.J., 1969) was published in which the descriptions of the 3 types of buildings, the 3 definitions of quantity of damaged buildings (integrated with numerical data) and the 4 damage degrees were improved. A proposal is made to associate the accelerations of the terrain with the intensity classes; also compare a first matrix in which it is possible to define the intensity of the earthquake from the different percentages of damaged buildings belonging to the 3 construction typologies.
In 1956 a further version from the MCS scale was proposed by Richter and was called the modified Mercalli scale (MM-56) widely used in southern Europe. Compared to previous versions of the MM scale, this introduces 4 defined building classes, and therefore indirectly introduces 4 vulnerability degrees. These 4 classes are constituted according to the quality of the materials used, the construction techniques and the presence or absence of a project suitable for resisting horizontal forces.
A revision of the available scales became necessary in the last part of the twentieth century to consider better the presence of buildings made with earthquake-resistant solutions and to be able to expand the panorama of vulnerability classes and improve the completeness of the macroseismic analyzes. therefore a revision of the MSK-64 was promoted by the European Seismological Commission, which produced the first EMS (European Macroseismic Scale) in 1992; this was used experimentally and was officially adopted in 1998 (EMS-98) (Grünthal, 1998).
The updated vulnerability table provides 4 types of buildings: masonry (with 7 subtypes), reinforced concrete (with 6 subtypes), steel and wood; for each of these, there are 6 vulnerability classes with the highlighting of a more probable class and a range of greater or lesser probability (Figure 4).
The damage modality is extended and characterized in a greater way with 5 degrees for masonry structures and 5 degrees for reinforced concrete structures (Figure 5 and Figure 6).

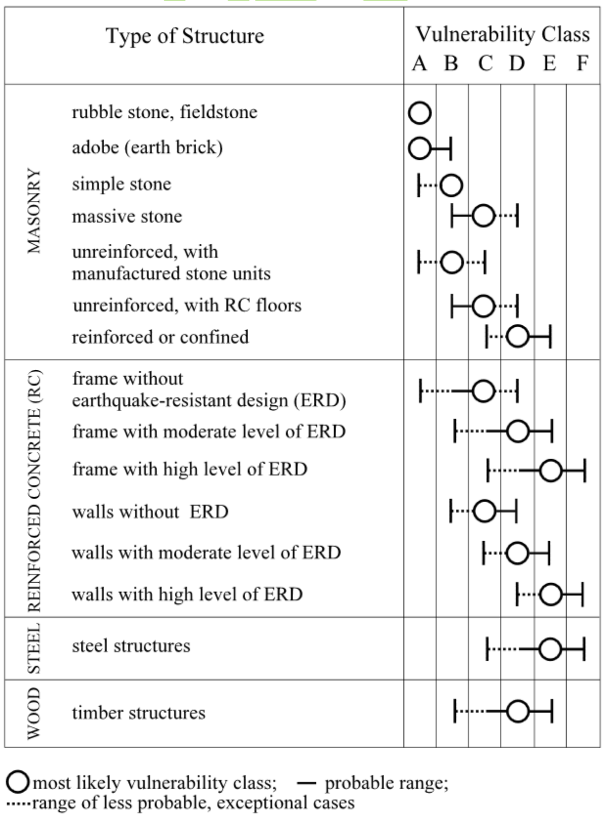


Figure 4 The EMS-98 Vulnerability Table

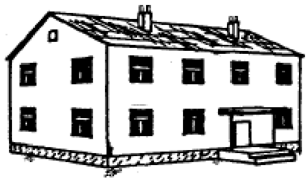
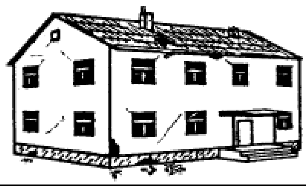
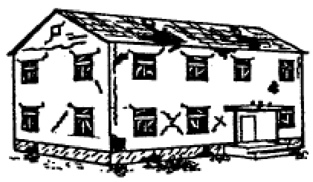
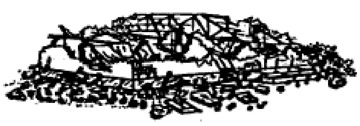
Classification of damage to masonry buildings	
	**Grade 1: Negligible to slight damage** **(no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage** **(slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	**Grade 4: Very heavy damage** **(heavy structural damage, very heavy non-structural damage)** Serious failure of walls; partial structural failure of roofs and floors.
	**Grade 5: Destruction** **(very heavy structural damage)** Total or near total collapse.

Figure 5 Damage degrees to masonry buildings

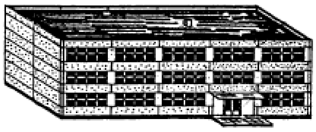
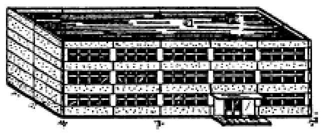
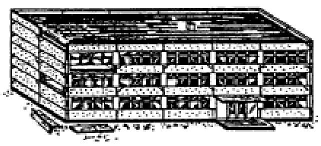
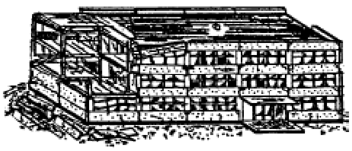
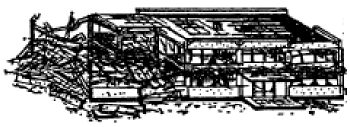
Classification of damage to buildings of reinforced concrete	
	**Grade 1: Negligible to slight damage** **(no structural damage,** **slight non-structural damage)** Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.
	**Grade 2: Moderate damage** **(slight structural damage,** **moderate non-structural damage)** Cracks in columns and beams of frames and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.
	**Grade 3: Substantial to heavy damage** **(moderate structural damage,** **heavy non-structural damage)** Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of conrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.
	**Grade 4: Very heavy damage** **(heavy structural damage,** **very heavy non-structural damage)** Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.
	**Grade 5: Destruction** **(very heavy structural damage)** Collapse of ground floor or parts (e. g. wings) of buildings.

Figure 6 Damage degree to reinforced concrete buildings

Even the quantities of damaged buildings are carefully defined, associating the three dimensional classes (few, many and most) with the percentage quantities that are not rigidly distinct (Figure 7).

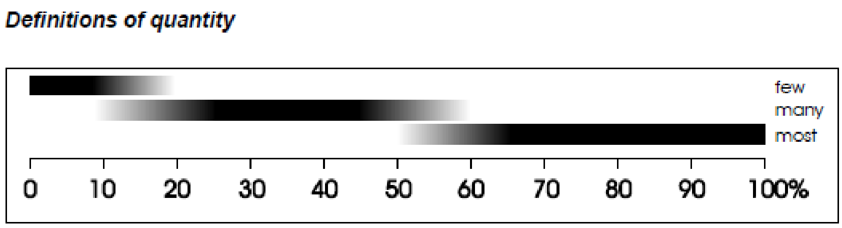


Figure 7 The EMS-98 definitions of quantity of damaged buildings

The typical subdivision into 12 degrees of macroseismic intensity remains, but now the attribution of intensities is less tied to subjective interpretations, since the variables are accurately described.
The different types of seismic design used in different periods are also analyzed in the document in order to adequately consider the effects on more recent constructions.
The presentation of the evolution of the macroseismic scales highlights how for greater precision in defining the intensity of an earthquake (I) it was necessary to include other factors in the first formulations (MCS) and, above all, the vulnerability (V), in addition to a better description of the damage suffered by the buildings (D). So it can be said that if originally the relationship was:

$$I = f(D) \tag{1}$$

while starting from the GEOFIAN scale and up to the EMS-98, passing through MSK-64, the problem is now posed as:

$$I = f(V, D) \tag{2}$$

This relationship can be expressed in matrix form as in the Table 1, referring only to the vulnerability classes of masonry buildings (A. Bernardini et al., 2007):

Table 1 Relationship between Intensity I, Vulnerability, quantity of damaged buildings and Damage Dk

Dk/I	0	1	2	3	4	5
V		Few A or B				
VI		Many A or B, Few C	Few A or B			
VII			Many B, Few C	Many A, Few B	Few A	
VIII			Many C, Few D	Many B, Few C	Many A, Few B	Few A
IX			Many D, Few E	Many C, Few D	Many B, Few C	Many A, Few B
X			Many E, Few F	Many D, Few E	Many C, Few D	Most A, Many B, Few C
XI			Many F	Many E, Few F	Most C Many D, Few E	Most B, Many C, Few D
XII						All A or B, Nearly All C, Most D or E or F

It is clear that a different approach to the problem, specific for the engineering field, can derive from this result; it is therefore possible to estimate the vulnerability or expected damage as inverse functions, that is:

$$V = f'(I, D) \qquad (3)$$

or

$$D = f''(I, V) \qquad (4)$$

These approaches have characterized a wide range of studies that have deepened the implicit relationships related to the use of EMS-98. In fact, if (2) is considered valid, further results may derive in terms of what is reported in (3) and (4) through a mathematical approach that associates the concept of probability that V and D can be obtained starting from the other data.
This research path had its beginning before the adoption of EMS-98 and then starting from MKS-64 with the studies carried out on the damage detected after the 1980 Irpinia earthquake (Braga et al., 1982). From these studies, the concept of Damage Probability Matrix (DPM) emerged with which it is possible to determine the probability of occurrence of different degrees of damage having as input the macroseismic intensity I and the vulnerability class of a given building. In (Giovinazzi & Lagomarsino, 2004) and in (A. Bernardini et al., 2007) this first hypothesis of use of DPM was developed starting from the new data defined by EMS-98 and using fuzzy logic (Zadeh, 1965) to translate mathematically correct evaluations such as “few" and "most" found in EMS-98.
The result of this update is shown in Figure 8 in which the term "White" reported by the authors (A. Bernardini et al., 2007) indicates the expected average value of the vulnerability class and μ_D the expected damage value calculated according to the formula following:

$$\mu_D = 2.5 + 3\tanh\left(\frac{I + 6.25V - 12.7}{3}\right) \quad \Big| \quad 0 \le \mu_D \le 5 \qquad (5)$$

It is valid for masonry buildings, where I and V respectively indicate the macroseismic intensity and the vulnerability defined always starting from EMS-98 through a fuzzy set associated with each vulnerability class (A. Bernardini et al., 2007).

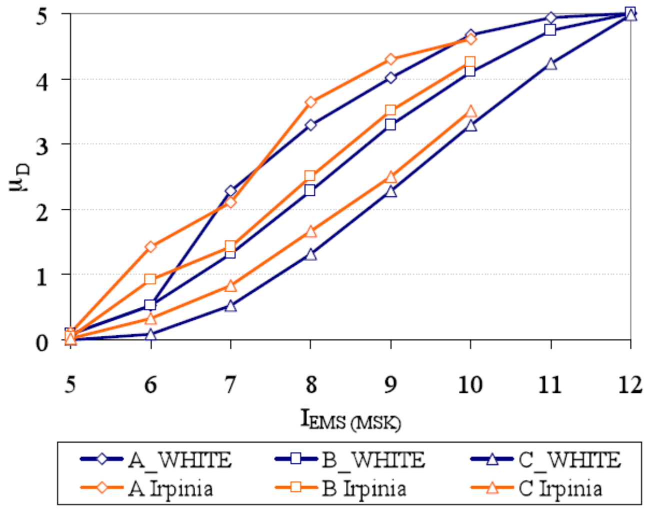


Figure 8 Comparison between (Braga et al., 1982) and (Bernardini et al., 2007) approach

The macroseismic approach proposed above can be considered effective to estimate the level of damage on a territorial scale. However, this approach cannot provide reliable answers when the number of buildings to be examined is limited in a well-defined BE, as required for the purposes of the BE S2ECURE project.
As an example, see the comparison made between the damage detected in San Giuliano di Puglia in 2002 and the damage estimated according to a macroseismic approach (Vona et al., 2009); in this study it emerges that in different areas of the studied area the macroseismic approach tends to underestimate the real damage. This can derive from various factors, such as not considering the effects due to the characteristics of the soils (amplifications or damping), but also from the fact that the incidence of local construction characteristics has a decisive weight (Figure 9).

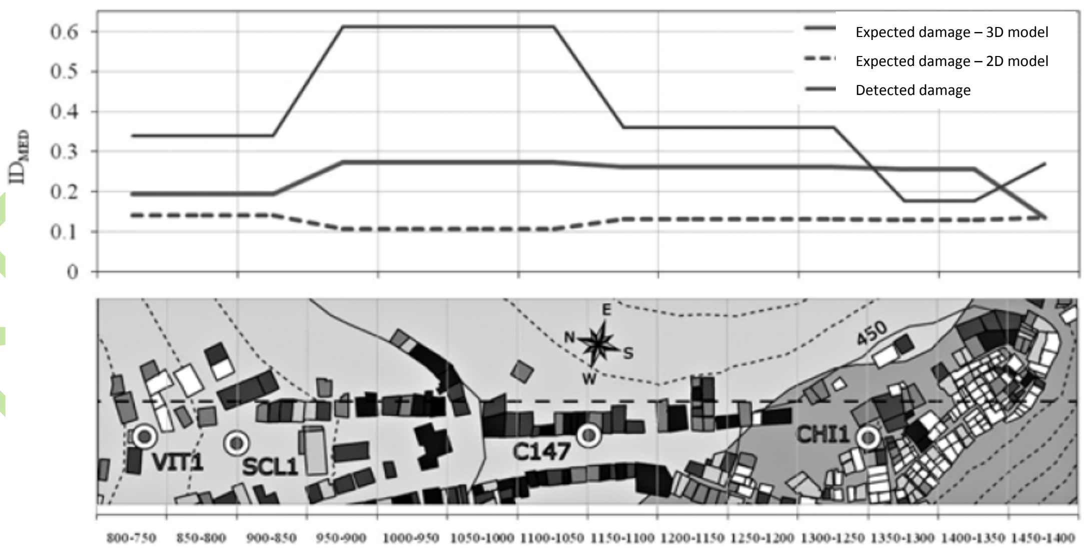


Figure 9 Comparison between expected damage and real seismic damage along an buildings alignment, called "microsection" by authors (Vona et al., 2009)

2.2 Damage assessment through the mechanical approach

So-called "mechanical" methods of analysis use non-linear calculation procedures to define the damage conditions of existing buildings. With these methods it is possible to evaluate the achievement of certain limit states and then determine the safety levels of buildings as the ratio between the building's ability to resist specific accelerations (Capacity) and the expected intensity with a defined probability of exceeding a specific return period (Request). These methods, when applied to individual buildings, require a careful analysis of all the mechanical and construction features and a large calculation burden. For this reason it is not possible to apply the large number of buildings while maintaining the same reliability of the results. Using only some characteristics of the existing buildings, it is possible to arrive at approximate evaluations also on a substantial number of buildings (analysis on a territorial scale). This is achieved by using a grouping by types of buildings that have homogeneous features.
In this way, it is possible to develop fragility curves that allow to obtain the probabilities that for a given seismic intensity, a certain class of buildings reaches a particular limit state. Within the Syner-G research project, funded by the European Union with the 7th Framework Program, WP3 has specifically dealt with the identification of a large number of fragility curves. These are divided by type of structure, specific calculation methodology, geographical reference context, specific lognormal distributions and type of input (displacement spectra or PGA) (SYNER-G, 2009).
The fact that these curves are based on types of buildings makes this analysis usable only in those contexts where these types are considered actually present with defined characteristics (Figure 10 and Figure 11). This makes it clear that the influence of local data is particularly relevant.

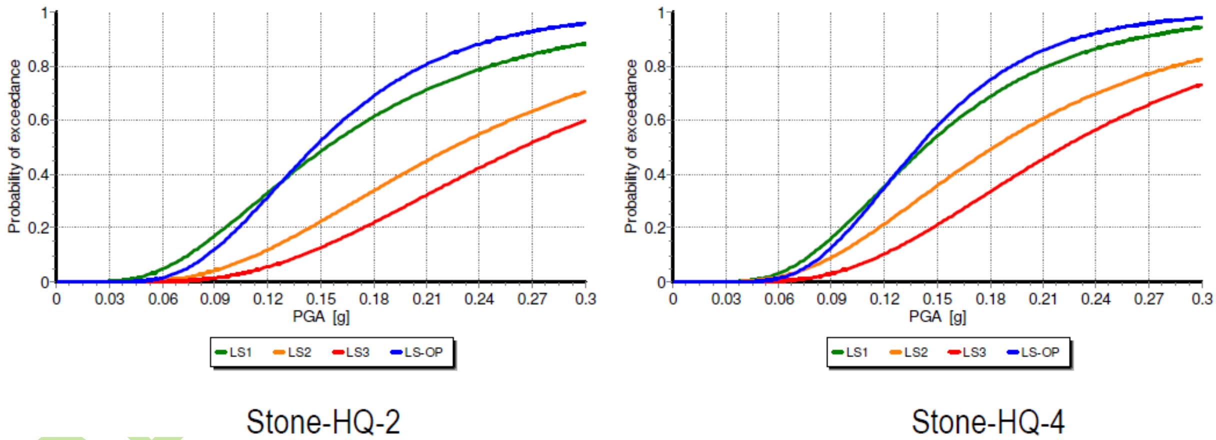


Figure 10 Fragility curves with applicability in Italy for 4 SL (No damage, LS1, LS2 and LS3). Building tipology: high quality stone masonry with 2 and 4 storeys (SYNER-G, 2009). In-Plane failure mechanism and Out-of-Plane mechanism.

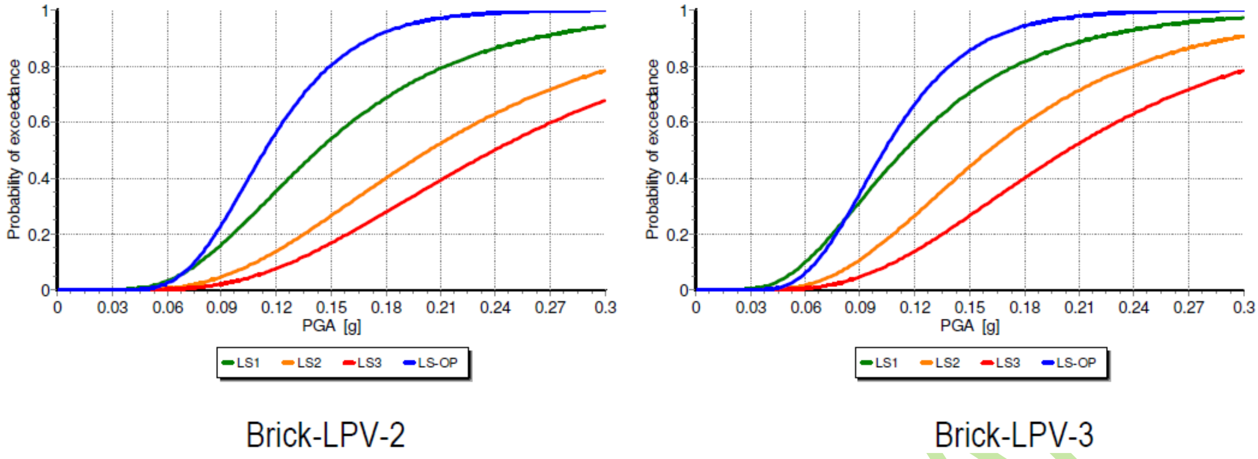


Figure 11 Fragility curves with applicability in Italy for 4 SL (No damage, LS1, LS2 and LS3). Building tipology: brick masonry and low percentages of void with 2 and 3 storeys. (SYNER-G, 2009). In-Plane failure mechanism and Out-of-Plane mechanism.

It is clear that these data, useful for the purpose of assessing seismic risk on a territorial scale, do not provide specific information for understanding the damage to individual buildings or aggregates, the level of simplification adopted being too high. The masonry quality is considered in an inaccurate way as well as the differences existing between the different Italian regions are not adequately considered (Mochi & Predari, 2016).
Instead, specific fragility curves could be constructed, obtained with different methods, and therefore also related to specific typological classes of buildings from defined contexts. Further curves could be defined not only for damage in the plane and damage out of the plane, but also for specific mechanisms deriving from the poor masonry quality which in many cases leads to very serious damage levels. That is, there can be very serious damage simply through the complete breakdown of the walls due to poor masonry quality.
A summary of the fragility curves for territorial analysis, obtained with different approaches, is reported in Table 1 deriving from (SYNER-G, 2009) to which reference is made for references:

Table 2 List of different methods can be used to estimate a fragility function

Method	Reference
Empirical	• Colombi et al. (2008) • Lagomarsino and Giovinazzi (2006) • Nuti et al. (1998) • Rota et al. (2008)
Expert opinion-based	• Kostov et al. (2004)
Analytical – Nonlinear Static	• Ahmad et al. (2011) • Borzi et al. (2008b) • Cattari et al. (2004) • D'Ayala et al. (1997) • Lang (2002) • LESSLOSS (2005) – Istanbul Case Study • LESSLOSS (2005) – Lisbon Case Study • Oropeza et al. (2010) • Pagnini et al. (2008) • RISK-UE (2003) (CIMNE approach) • Karantoni et al.(2011)
Analytical – Nonlinear Dynamic	• RISK-UE (2003) (UNIGE approach) • Rota el al. (2010)
Analytical – Nonlinear Static and Dynamic	• Erberik (2008)

The knowledge of the probability of exceeding a given Limit State is fundamental for the evaluation of the vulnerability conditions of the building heritage and ultimately for the assessment of the hazard of this heritage with respect to seismic actions. However, when knowledge of the type of crisis that will affect a building during an earthquake is required, in order to evaluate how this crisis affects the areal spaces of a BE, the data obtainable with the fragility curves cannot be used. In fact, most of the methods that are used to obtain these fragility curves favor the mechanisms in the plane rather than those out of plane. This derives from the fact that the buildings that have well-ancored walls and floors well connected to the load-bearing walls develop a box-like behavior, defined as Global Mechanism, which can be analyzed in numerical terms as a framed pseudo-structure.
Buildings that do not have this behavior due to their characteristics and due to the transformations they have received over time, develop other crisis modes in which the loss of the balance of portions of the structure is found rather than the overcoming of mechanical strength in the masonry (Local Mechanism).
For buildings that have behaviors of this second type, specific analysis methods must be developed which start from the a priori recognition of some possible damage in which portions of walls tend to come out of their own plane.
The experience accumulated over decades of observations and surveys on the damage caused by earthquakes on historic masonry buildings have shown that Local Mechanisms are the most frequent condition (Sorrentino et al., 2017).
An accurate structural analysis of the problem of local mechanisms in historic masonry buildings is found in (D’Ayala & Speranza, 2003). Starting from the method of collapse mechanisms, whose first application is found in (A. Bernardini et al., 1990), the authors have expanded this approach through extensive in situ observations and with the correlation of seismic collapse with PGA. The validation of this proposal took place with the case study of the historic center of Lisbon. Subsequently, the FaMIVE method was developed, which has 12 possible collapse mechanisms as its basis, mainly out of the plane, and through which it is possible to define defined vulnerability functions for single or aggregate buildings (Figure 12). In 2005 the method was perfected, allowing the definition of vulnerability and also the ability expressed in terms of the last displacements that cause the crisis out of the plan (D’Ayala, 2013).

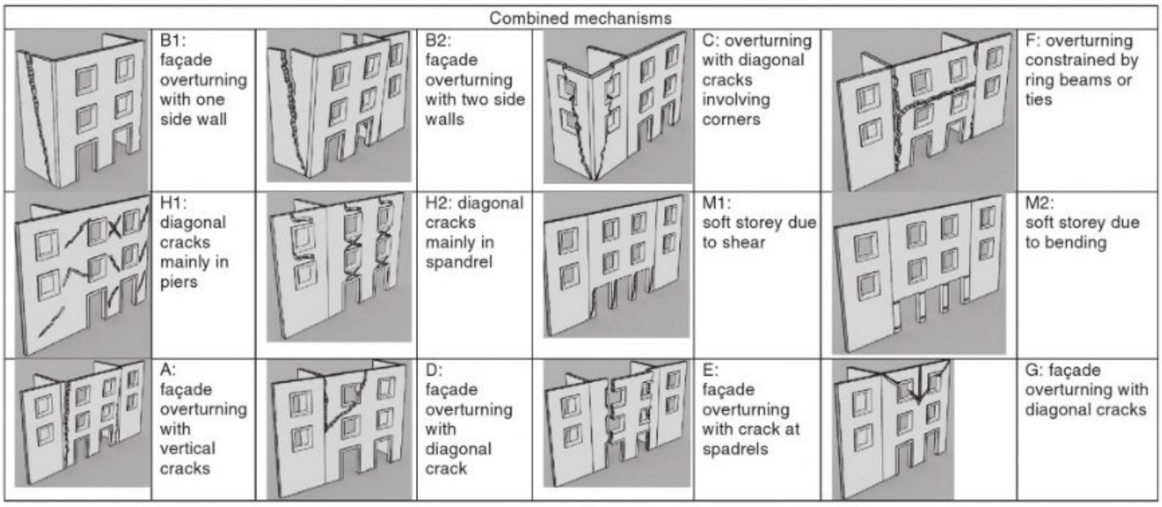


Figure 12 The twelve possible failure mechanism used in FaMIVE (D’Ayala, 2013)

The method has become a complete procedure through a spreadsheet and macro that allow to define, starting from the real data of the individual buildings to be analyzed, which is the mechanism that activates at the lower accelerations and therefore to define which is the most likely mechanism. If applied to a larger number of buildings, as was done for the validation processes, it can provide curves of capacity and fragility for an entire building heritage (Figure 13).

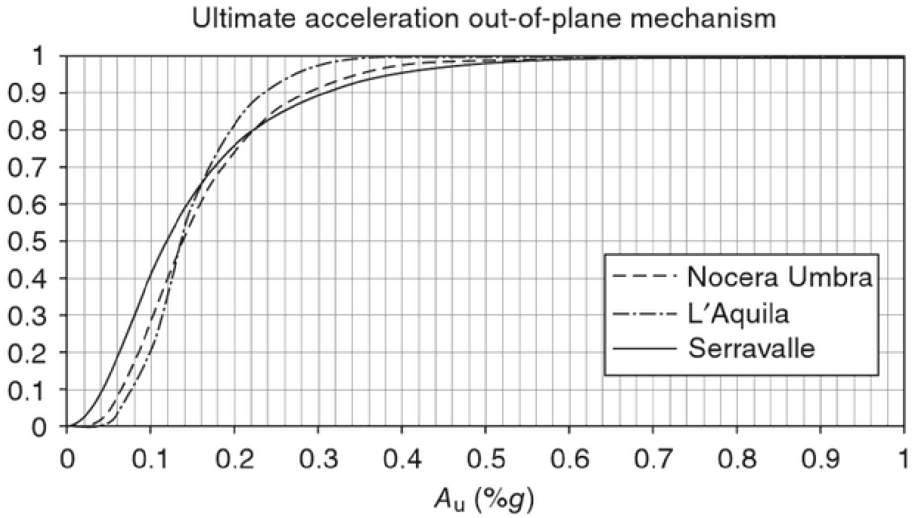


Figure 13 Fragility curve in term of ultimate acceleration and percentage of analyzed buildings for three cases-studies: Nocera Umbra and Serravalle (earthquake 1997) and l'Aquila (earthquake 2009) (D'Ayala, 2013).

2.3 The kinematic or macro-element approach

The FaMIVE procedure is based on local mechanisms and not on the global behavior of a historic masonry structure. By local mechanism we mean a behavior due to the conception of the masonry building as composed of sets of structural elements that have an autonomous behavior and that the earthquake sets in motion. Then the crisis comes by overcoming the equilibrium of each set of elements considered as a rigid body (Figure 14). This approach derives from direct observation of the seismic damage to historic buildings and built with traditional construction techniques. The first contributions are found in (Giuffè, 1991), (Giuffrè, 1992), but the first organic discussion is in (Giuffrè, 1993).

Figure 14 Observed damages and identification of failure mechanism (Sorrentino et al., 2017).

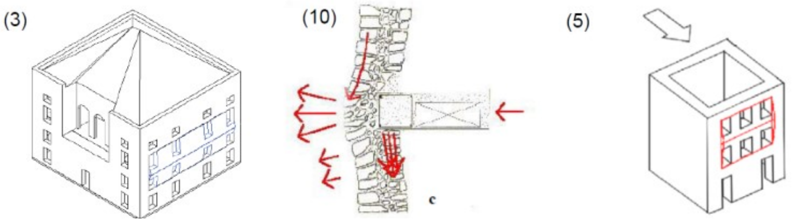
So the structural collapse is analyzed by applying the kinematic limit analysis of rigid blocks since the behavior of many ancient masonry buildings does not conform to the box-like behavior due to the lack of connections between horizontal and vertical structures and between the load-bearing walls.

Since historic masonry buildings present architectural and construction solutions that are typical of specific geographical contexts (Mochi & Predari, 2016), the failure modes are also typical of homogeneous classes of buildings. From this derives the possibility to study the different kinematic forms of damage, dividing them into categories of typical local mechanisms, and to perfect, for each of these, verification procedures based on the limit analysis of the kinematic type. Furthermore, since these forms have been found in numerous surveys of historic centers damaged by the earthquake, it is possible to evaluate in advance, after having carried out surveys on the buildings to be analyzed, what the mechanisms that can be triggered.

This procedure has been present in Italian legislation since 2003 (OPCM_Italian Government, 2003) and has also been investigated. The FaMIVE method undoubtedly constitutes an interesting improvement of this procedure and other studies have allowed the extension of the kinematic approach with advanced analytical methods, such as the Capacity Spectrum Method for the evaluation of the safety condition of existing constructions (Fajfar, 1999) (Lagomarsino & Giovinazzi, 2006); in (Sorrentino et al., 2017), in addition to a discussion of some recently developed methods dedicated to the evaluation of off-plan mechanisms (another name for the kinematic approach), an interesting energy approach is introduced.

The ability to draw up abacus of the various macro-elements (sets of structural elements to form rigid blocks) is one of the major strengths of the method. The limit kinematic analysis for each of these elements is made possible by the development of specific kinematic equations associated with each macroelement.

An extensive discussion of the various mechanisms summarized in damage abacus is found within the deliverables of the European NIKER project (Figure 15) (NIKER, 2010).



Scheme of the kinematic mechanism

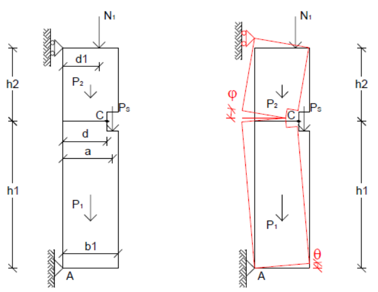


Table 6.5 Variables

Variables	
P_1	Self weight of the lower wall
h_1	Height of the lower wall
b_1	Average thickness of the wall
P_2	Self weight of the upper wall
h_2	Height of the upper wall
b_2	Average thickness of the wall ($b_2 = b_1$)
N_1	Load acting on the wall
d_1	Arm of the load ($d_1 = b_1/2$)
P_s	Load of the intermediate floor
a	Arm of the load P_s
d	Position of the C hinge

Principle of virtual work: $-P_1\delta_{P_{1y}} - P_S\delta_{P_{Sy}} - P_2\delta_{P_{2y}} - N_1\delta_{N_{1y}} + cP_1\delta_{P_{1x}} + cP_S\delta_{P_{Sx}} + cP_2\delta_{P_{2x}} + cN_1\delta_{N_{1x}} = 0$

$$c = \frac{P_1\frac{b_1}{2} + (P_2+N_1)d + P_S a + \frac{P_2+N_1}{h_2}\left(d-\frac{b_1}{2}\right)h_1}{\frac{(P_1+P_2+2P_S)h_1}{2}}$$

Figure 15 Vertical bending failure mechanism (NIKER, 2010).

Since these macroelements are found in a large number of buildings, it is possible to set an assessment of the safety conditions by recognizing which of these macrolements are present in a building and check which acceleration activates that specific mechanism.
In the Italian legislation on the evaluation of the safety of cultural heritage (OPCM_Italian Government, 2011) there is an interesting application of this method for churches, developed starting from studies started after the 1976 Friuli earthquake (Doglioni et al., 1994).
An interesting extension of the kinematic or macroelements method to the New Zealand context is found in (Gálvez et al., 2018) where the general approach forms the basis for the creation of macroelements typical of that historical architectural heritage (Figure 16).

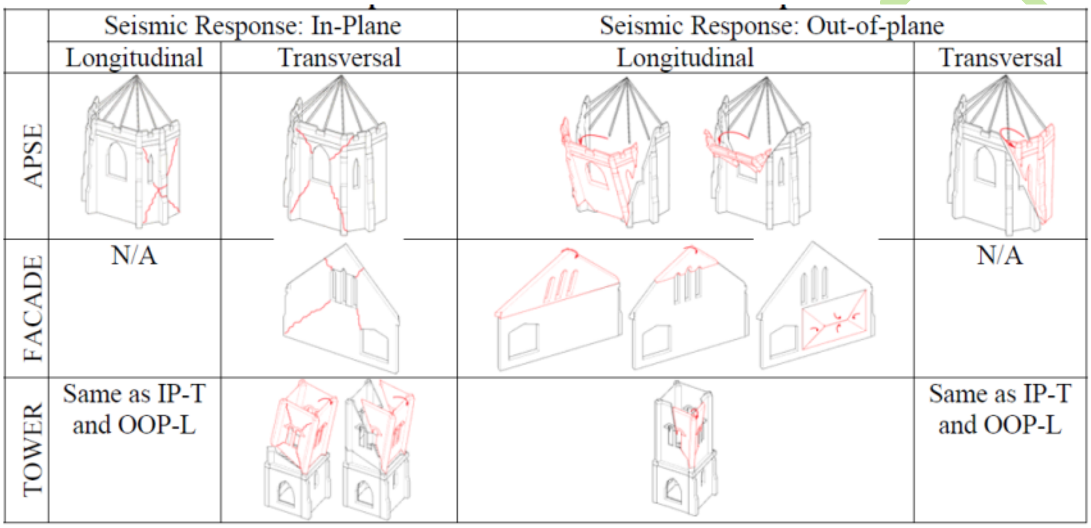


Figure 16 Macroelements analysis of a neozelandian churh (Gálvez et al., 2018).

3. The problem of quantifying debris

3.1 The analytical - experimental approach

In order to estimate the effect of an earthquake on the aeral spaces of a BE, the estimate of the debris of the buildings that can hinder the outflow operations and in general the safety of the inhabitants assumes fundamental importance.
The studies analyzed in the previous parts have as their main objective the evaluation of the safety of historic masonry buildings against seismic actions. It is therefore necessary to understand if they can also be useful in defining the amount of masonry that can collapse on the open spaces bordering the building.
Although the kinematic or macro-element method is based on the presence of a limited repertoire of breaking modes, no study has been found that also derives from this procedure an estimate of the amount of masonry that can collapse in case of activation of the single mechanism. The energy approach previously mentioned (Sorrentino et al., 2017) could constitute a valid starting point through the balance between energy produced by the seismic shaking and the energy necessary to overturn a certain volume of masonry.

Another possible way seems to be to create fragility curves for the different possible mechanisms in order to estimate, for a defined input acceleration (PGA for example), the probability of exceeding the limit equilibrium.

In this way, it would be possible to obtain realistic assessments of the quantity of debris associated with a particular type of building, with certain construction characteristics and quality of materials. The quality of the construction is decisive for the triggering of certain mechanisms. In the case of insufficient quality of the masonry, in fact, the damage mechanism for macroelement is not activated, but the disintegration of the masonry is recorded instead. The kinematic approach starts from the consideration that the wall can be defined as monolithic and this is achieved only when both the individual constituent elements and the presence of suitable mortar manage to confer this characteristic (NIKER_b, 2010).

For the estimation of debris from buildings damage in the event of an earthquake, more approximate methods have been proposed. The objective of studies of this type are, for example, the probabilistic evaluation in the event of an earthquake that closes roads due to damage to the surrounding buildings.

Some of these studies refer to an approach through the fragility curves of the buildings surrounding the road, eventually reaching to construct a fragility curve of the road itself to define its probability of blocking. In the first of these articles (Anelli et al., 2020) the authors elaborate a procedure to achieve fragility curves for each street of a built-up area. This procedure is part of identifying the vulnerability functions (fragility curves) of the buildings facing the stretch of road to be analyzed. These can be directly calculated or extracted from the catalogs available in the literature (SYNER-G, 2009) and in open platform Open Quake (OpenQuake.org, n.d.).

These curves are useful for adapting to the various possible cases an interesting proposal for calculating the maximum area occupied by a collapse of a masonry building developed in (Domaneschi et al., 2019). This research, based on the modeling of sample buildings and validated in the laboratory on live models, allows to estimate with great reliability the area occupied by the debris of a building that reaches the level of complete collapse (Figure 17and Figure 18).

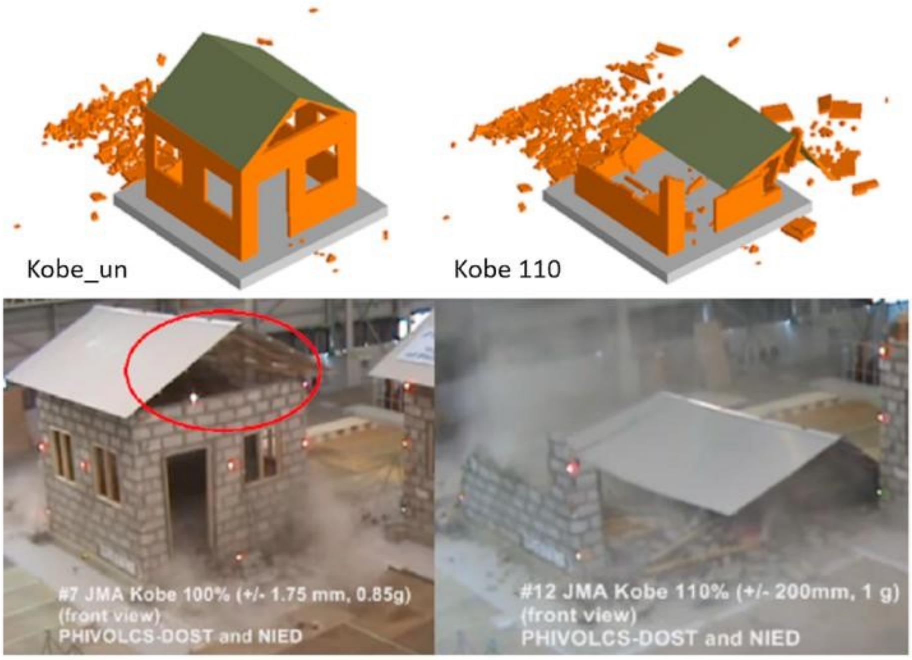


Figure 17 Comparison between AEM numerical model and experimental model (Domaneschi et al., 2019).

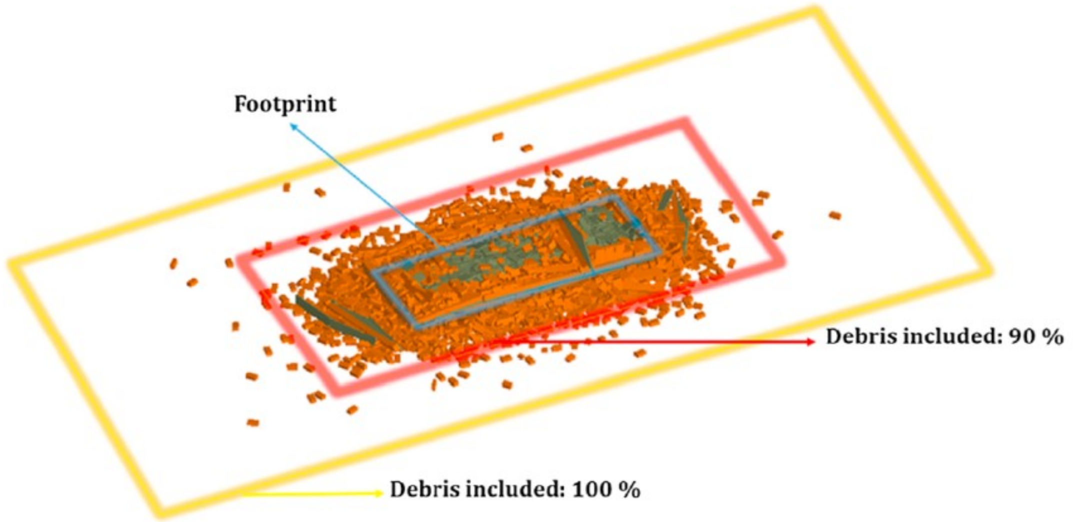


Figure 18 Footprint area of collapsed building and amplified debris area (Domaneschi et al., 2019).

According to this approach, the area containing the total amount of debris is amplified by a factor ε equal to:

$$A_{d,max} = A_f \cdot \varepsilon^2 \quad (6)$$

with:

$$\varepsilon = 1.228 + 0.07869 \cdot \left(\frac{a}{b}\right) + 0.05626 \cdot \left(\frac{A_f}{V_b} \cdot \frac{h_b^2}{a}\right) \quad (7)$$

where a and b are the minor and major sides of the analyzed building, A_f its area and V_b its volume with $V_b = A_f * h_b$

It is necessary to specify that these results are valid for a particular set of mechanical characteristics of the analyzed building, used in numerical analysis (Table 3):

Table 3 Set of mechanical characteristics used, representative of the traditional buildings in center of Italy.

f_m [N/cm²]	f_{vk} [N/cm²]	E [N/cm²]	G [N/cm²]
100	2.0	690	230

The influence of the mechanical characteristics is significant. Tests carried out by the authors using other values show how the area of debris decreases with increasing mechanical characteristics. Since the values used in the study are the lowest in Italian regulations and since, according to the authors, they are representative of the traditional construction of the areas affected by the 2016 earthquake, the authors consider that the area obtained is representative of the situation of the buildings of the center of Italy.

By superimposing the area thus obtained on the existing situation on an urban scale, the authors determine whether the existing roads around the buildings are affected by the presence of debris (Figure 19).

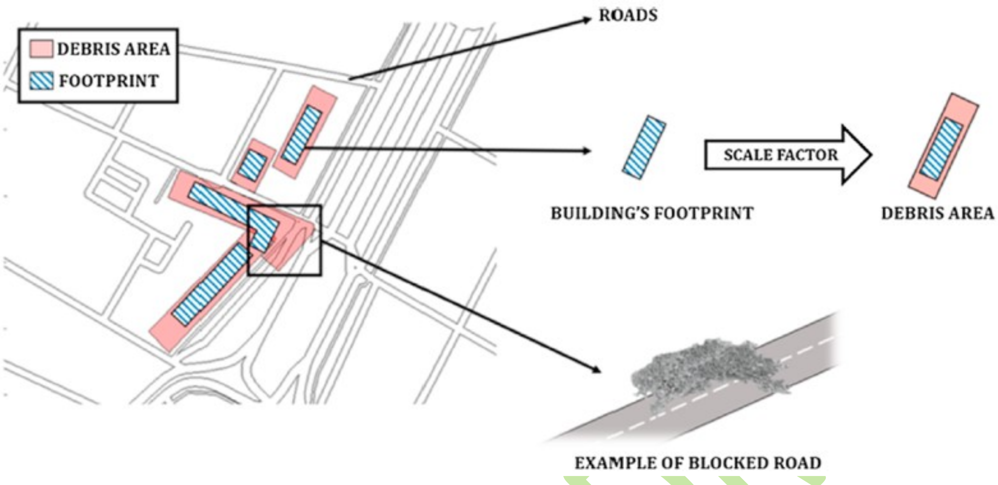


Figure 19 Debris and roads interaction [DOMANESCHI 2019].

In (Anelli et al., 2020) the applicability of the results obtained in (Domaneschi et al., 2019) is extended through the use of the fragility curves representative of the buildings along the roads to be analyzed (Figure 20). With this proposal, the limit of the definition of equation 7 is exceeded only for a certain set of mechanical characteristics and therefore for a single type of wall structure.

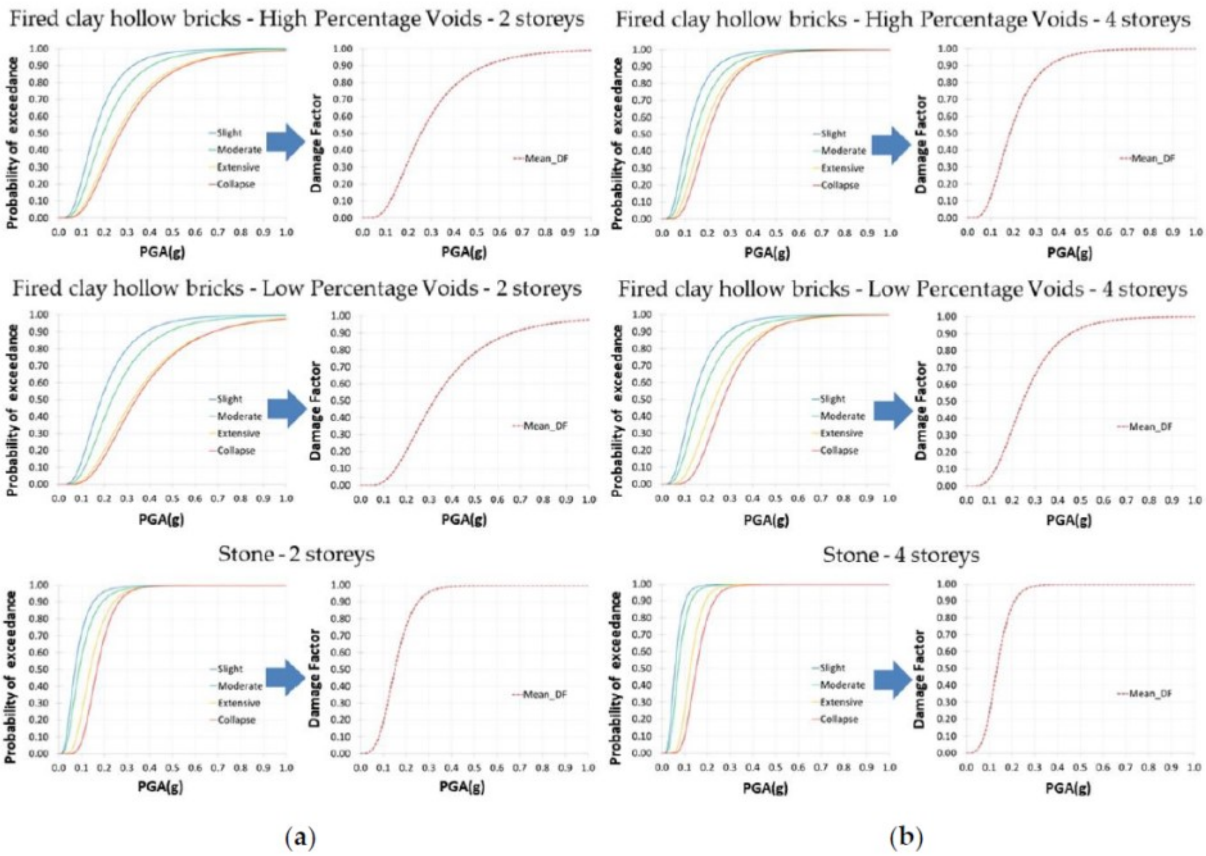


Figure 20 Analysis of road segments and structural aggregate in "Corso Umberto I" in Amatrice (Italy). Vulnerability functions for typical unreinforced masonry buildings of (a) two storeys and (B) four storeys (Anelli et al., 2020).

Furthermore, the possibility that the collapses all occur on one side or on two sides with respect to the plan development of the building is taken into consideration according to a probabilistic treatment present in (Argyroudis, 2010) and (Argyroudis et al., 2015). In this way the authors can draw up graphs for each type of building and according to the fragility curves, transformed into damage factor curves (DF), they obtain the volumes of the debris on the ground to be compared with the width of the roads (Figure 21).

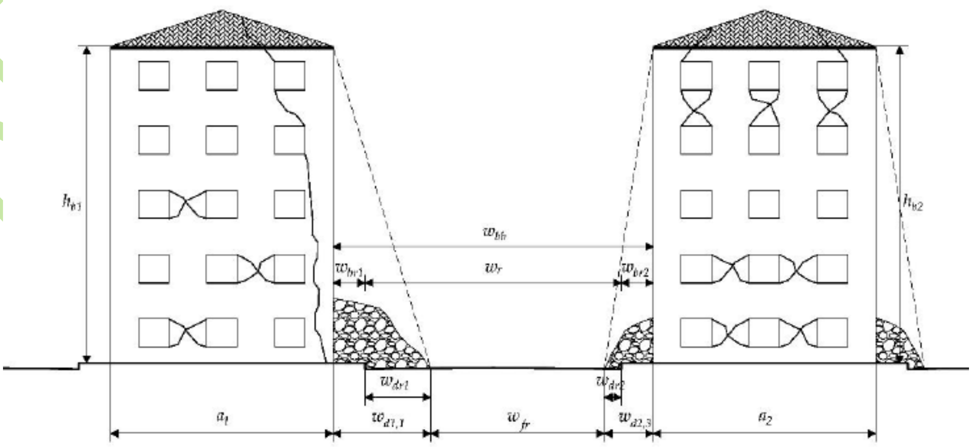


Figure 21 Geometric characteristics (Anelli et al., 2020)

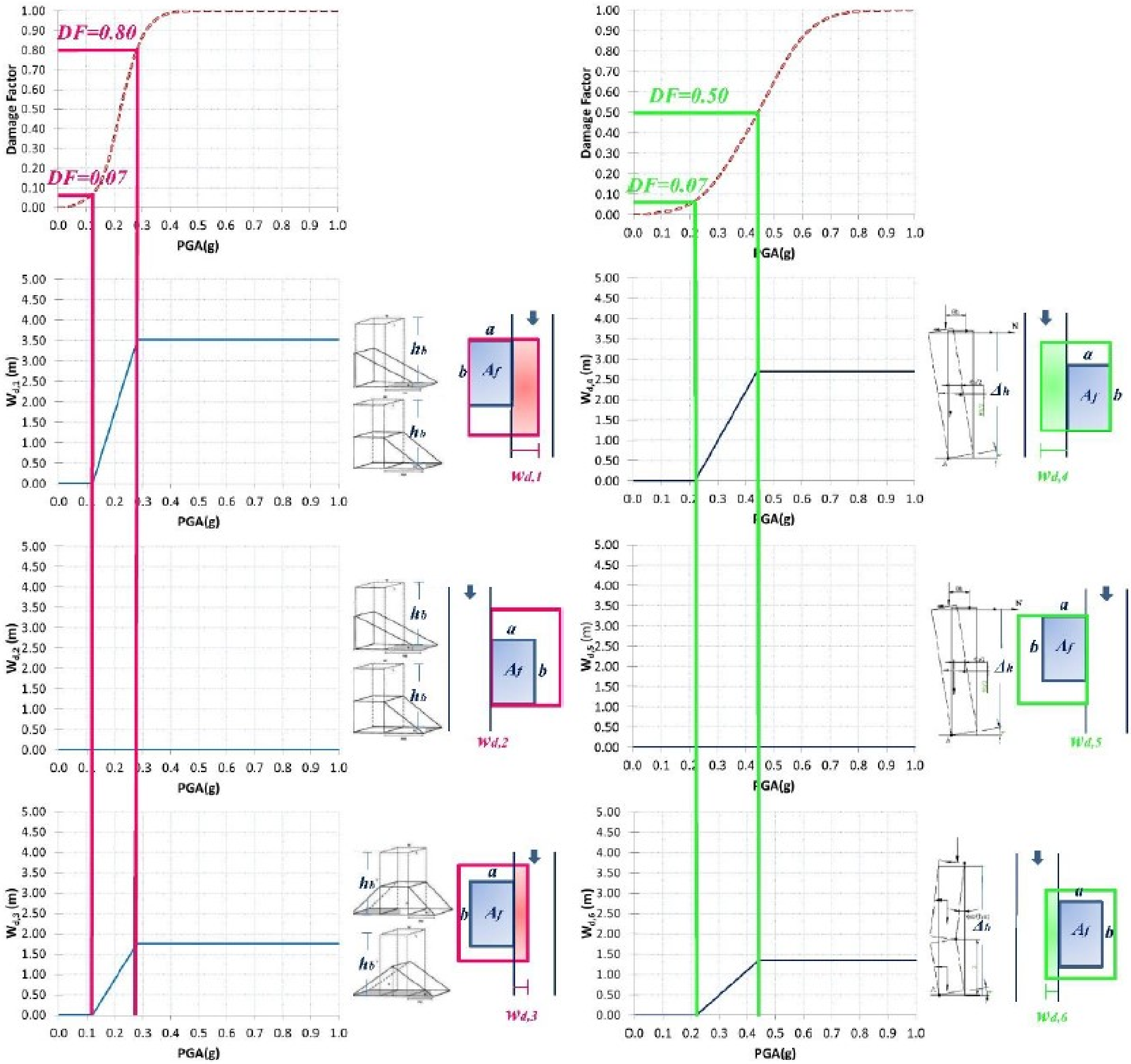
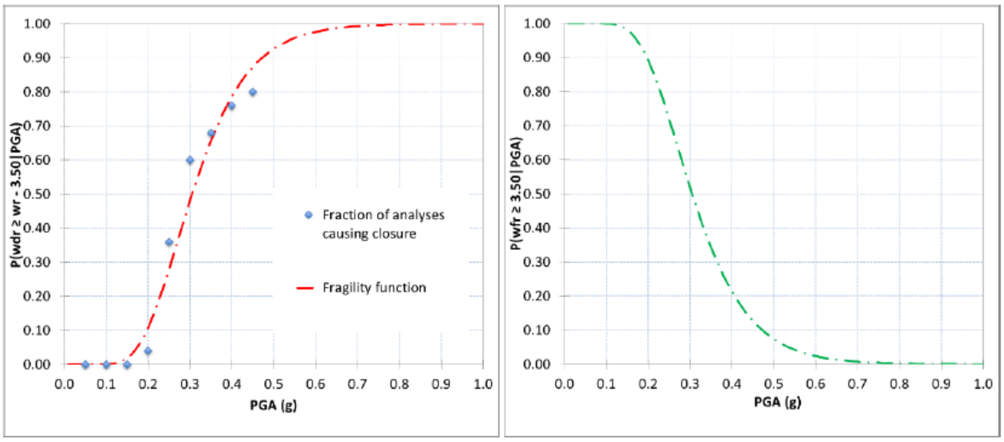


Figure 22 Construction of debris graphs for (a) masonry buildings and (b) reinforced concrete (RC)

Finally, from these data the authors elaborate the fragility curves of the analyzed roads in terms of PGA and probability of opening or closing (Figure 22and Figure 23).



(a) (b)

Figure 23 Fragility curve of a generic urban road segment in terms of (a) probability of closure and

3.2 The expeditious approaches

Other methods to assess the influence of debris caused by buildings damage on the usability of roads use more expeditious approaches. An interesting comparison and critical analysis can be found in (G. Bernardini et al., 2020) to which you are referred for a complete overview.
Some methods exclusively based on the relationship between the height of the buildings and the width of the facing road are cited: GM1 in (CLE, 2010) and GM2 in(Ferlito & Pizza, 2011). These methods in light of the damage caused by the last Italian earthquakes, have provided unsatisfactory forecasts, determining scenarios much more restrictive than real ones.
Other cited procedures correlate the amount of debris with the buildings vulnerability through approaches that use experimental formulas: EM1 in (E. Quagliarini et al., 2016) and EM2 in (Santarelli, Bernardini, & Quagliarini, 2018), (Santarelli, Bernardini, Quagliarini, et al., 2018).
Further other methods allow a predictive evaluation through an estimate of the level of damage associated with the intensity levels provided in EMS-98, The first, DS1, is cited in (Artese & Achilli, 2019) (Figure 24) and the second, DS2, is always cited in(Santarelli, Bernardini, & Quagliarini, 2018) and (Santarelli, Bernardini, Quagliarini, et al., 2018).
The conditions for which it is expected that the facing road will be blocked by the debris of the damaged building are shown below:

geometric methods

GM1 in (CLE, 2010): $h \geq W$

GM2 in (Ferlito & Pizza, 2011): $h/_2 \geq W$

where
h = height of each building facing the street;
W = street width facing the considered building;

experimental methods

EM1 in (Quagliarini et al., 2016): $d_{ruins} \geq W$

where $d_{ruins} = QX_1 \, W$

and

$$QX_1(\%) = \begin{cases} 0 \text{ if } V^*_1 \leq 0.17 \\ 295.28V^*_1 - 49.47 \text{ if } 0.17 < V^*_1 < 0.51 \\ 100 \text{ if } 0.51 \leq V^*_1 \end{cases}$$

and $V^*_1 = V_{FP} {}^* M_{ev} / M_{ev,max}$

where V_{FP} is the normalized building vulnerability evaluated by method in(Ferlito & Pizza, 2011), M_{ev} is the earthquake moment magnitude of the event normalized for the maximum moment magnitude expected $M_{ev,\,max}$(=9.5);

EM2 in(Santarelli, Bernardini, & Quagliarini, 2018) and (Santarelli, Bernardini, Quagliarini, et al., 2018):

$d_{ruins} \geq W$

where $d_{ruins} = QX_2 \, W$

and

$$QX_2(\%) = \begin{cases} 155.55V^* \text{if } 0 < V^*_2 < 0.87 \\ \\ 100 \text{ if } 0.87 \leq V^*_2 \end{cases}$$

and $V^*_2 = V_{GL} {}^* M_{ev} / M_{ev,max} {}^* h/W$

where V_{GL} is the normalized building vulnerability evaluated by method in(Giovinazzi & Lagomarsino, 2004), M_{ev} is the earthquake moment magnitude of the event normalized for the maximum moment magnitude expected $M_{ev,\,max}$(=9.5);

damage scenario methods

DS1 in(Artese & Achilli, 2019): $W < 1/3h$ for building affected by 4th EMS-98 damage grade;

$W < 2/3h$ for building affected by 5th EMS-98 damage grade;

where

h = height of each building facing the street;
W = street width facing the considered building;

DS2 in(Santarelli, Bernardini, & Quagliarini, 2018) and (Santarelli, Bernardini, Quagliarini, et al., 2018): $h/W \geq 1$^$k95 \geq$ *4th EMS-98 grade*

where
$k95$ = value of cumulative distribution function at 95th percentile of probabilistic approach in (Lagomarsino & Giovinazzi, 2006);
h = height of each building facing the street;
W = street width facing the considered building;

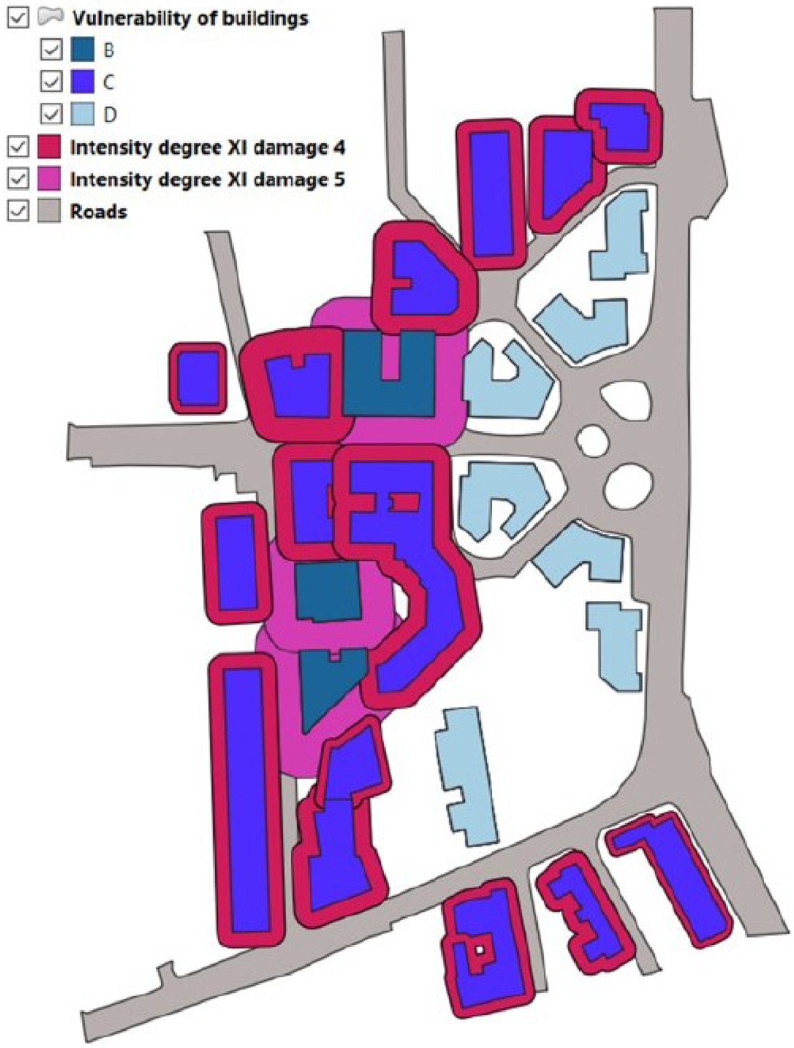


Figure 24 Scenario for intensity degree XII (damages below 4th are not considered) from (Artese & Achilli, 2019)

The different methods mentioned above have been the subject of an application on 50 case studies from some centers severely affected by the 2016 earthquake in central Italy. From this some critical points emerged in terms of reliability of the different methods. The two exclusively geometric based methods GM1 and GM2 have shown effective correspondence to forecasts in 64% and 52% of cases respectively; they rated 36% and 48% of the cases as closed roads while in reality they remained open.

The two methods based on the vulnerability of existing buildings EM1 and EM2 led to an effective correspondence in 50% and 60% of the processing respectively and an overestimation of 2% and 26% of the cases.

The two methods based on the estimated damage scenario DS1 and DS2 had a full correspondence in 46% and 64% of the cases, with an overestimation of 12% and 36% respectively.

An interesting correction of the results obtained was carried out with the two methods based on the expected damage scenario. By inserting in the assessments not the expected damage, but the damage detected, according to the EMS-98 classification, after the 2016 earthquake, a better reliability was achieved.

For the DS1 method there was full correspondence in 46% of cases and an overestimation in 2% of cases. The DS2 method is the one that has had the best performance showing a full correspondence in 96% of the situations and an overestimation in 4%.

Validation with real situations shows how some approaches are affected by incorrect assessments. The two methods based only on simple geometric observations do not provide completely incorrect evaluations for the cases studied. No road is considered open after the earthquake, but roads are considered closed which in the real scenario are open and passable (overestimate).

The two cases based on the vulnerability declare 48% (EM1) and 14% (ES2) of the roads open respectively, which are actually closed (Figure 25).

The DS1 method, based on the damage forecast, considers 22% of the roads open which are actually closed while the DS2 method does not incur any errors but only in the overestimate already mentioned.

Therefore it can be said that the more complex procedures than the merely geometric ones, except DS2, give worse results in terms of reliability than the simple criterion of GM1.

Probably the assessments in terms of vulnerability cannot be considered reliable for the purpose of the result sought. Damage estimates also have limited reliability if they fail to provide a better forecast than GM1.

These results allow several and further considerations. With reference to the methods of predicting vulnerability and those relating to damage scenario with a macroseismic approach, these are to be considered excessively approximate. Or they would require greater attention in the survey and analysis of real buildings to obtain better levels of reliability. An exclusively external survey can provide unsecured data for the assignment of a reliable forecast of the behavior in the event of an earthquake.

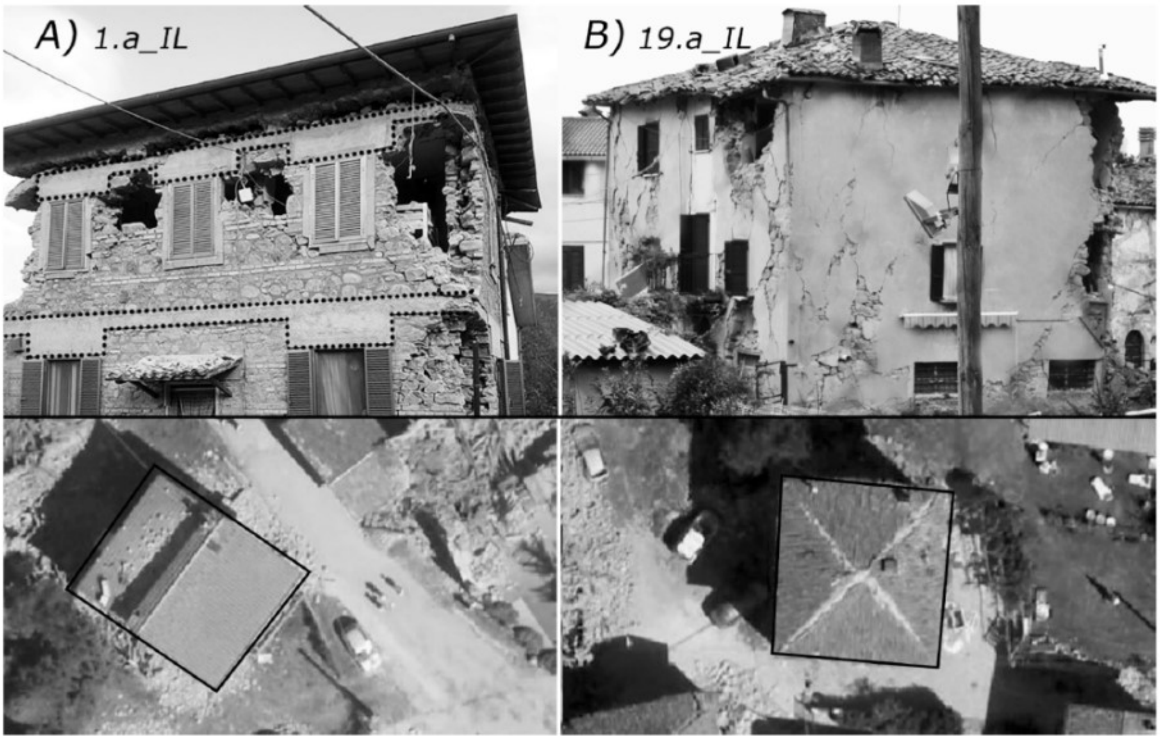


Figure 25 Structural units with differences between real-world and predicted path availability: two case study A) 1.a_IL on the left side and B) 19.b_IL in the right; according to(Santarelli, Bernardini, & Quagliarini, 2018) and (Santarelli, Bernardini, Quagliarini, et al., 2018) EMS-98 approach facing streets should have been blocked but from observations they result clear; the dotted black lines in A) highlight the presence of a particular retrofitting intervention (reinforced concrete rings) that could influence the failure mode..

There is therefore a noticeable difference in the level of representation of the different problems. As long as the purposes of the analyzes are intended to provide assessments or to make decisions on a territorial scale, the approximate methods can provide satisfactory indications. If more detail is sought, also to analyze a problem on the urban scale, the level of attention and the quality of the survey of the buildings features must considerably improve.

A specific contribution to understand this problem is found in(Enrico Quagliarini et al., 2019). This interesting assessment of the reliability of the expeditious methods for assessing the level of macroseismic damage compares the theoretical results with the real situations detected after the 2016 earthquake in central Italy.
To estimate the damage scenario, two methods are used in this contribution: the updating of the macroseismic method proposed in (Lagomarsino & Giovinazzi, 2006) and a similar method proposed by Ferreira(Ferreira et al., 2010). The analyzes carried out show how the first method achieves greater

reliability. The better approximation to the real data probably derives from a more effective assessment of the vulnerability within the method used in(Lagomarsino & Giovinazzi, 2006). This shows how greater attention to the definition of this important indicator can lead to better results in terms of forecasting seismic damage scenarios. The way to obtain a better estimate of the vulnerability lies in the use of expeditious assessment methods, but adequately based on the identification of the characteristics of the buildings and their shortcomings in terms of mechanical behavior.

The method reported in (Lagomarsino & Giovinazzi, 2006) defines, for each individual building, the level of macroseismic damage according to EMS-98, through:

$$\mu_{D\,L} = 2.5\left[1 + tanh\left(\frac{I + 6.5V_L - 13.1}{Q_L}\right)\right]$$

where:

μ_{DL} represents the expected damage according to the formulation in(Lagomarsino & Giovinazzi, 2006), I is the expected macroseismic intensity, V_L the vulnerability of the building always estimated according to the method of the same author (see D.1.2.1.) and Q_L an index of ductility equal to 2.3.

The expected percentage of exceedance for a class of buildings with the same level of damage is estimated through the Probability Mass Function (PMF):

PMF: $$p_k = \frac{5!}{k!\,(5-k)!}\left(\frac{\mu_D}{5}\right)^k\left(1 - \frac{\mu_D}{5}\right)^{5-k}, k = 0,1,2,3,4,5$$

The same contribution (Enrico Quagliarini et al., 2019) also presents the extension of this method to the assessment of damage to an entire aggregate, using a more expeditious formulation of the vulnerability defined in (Mazzotti, 2008)(. With this hypothesis, it is verified that the level of reliability of the results remains in any case sufficiently high so that operating with a method that allows greater expeditiousness can effectively contribute to estimating the expected damage in large areas of Italian historic centers.

4.Conclusion

This deliverable summarized the state of the art concerning studies on the assessment of damage to buildings and aggregates in the event of an earthquake. The macroseismic approaches were presented, which constitute the first level of the relationship between cause (levels of earthquake intensity) and effects on buildings (levels of damage), mediated by the concept of vulnerability and therefore of their building characteristics; subsequently analytical approaches based on the overall behavior of buildings were exposed. The kinematic approach was then presented, which comes closest to the real behavior of traditional buildings where there is no box-like behavior.

In addition, the contributions concerning the evaluation of the debris produced by the damage to buildings that can totally or partially obstruct the open spaces have been summarized. This assessment is very important since streets and squares perform an important function as elements to allow the saving of the inhabitants and the rescue of victims in the inhabited centers in case of natural disasters.

For the purposes of the BE S2ECURE research these topics are of particular interest. In fact, the state of the art presented must provide elements for the definition of the tools to be used in order to preventively evaluate the changes that the earthquake produces on the built environment.

Since the field of interest of the project concerns large areas of historic cities, methods based on detailed mechanical analyzes do not constitute a useful solution since, although more precise, they require high resources in order to time for the survey and for the elaborations of calculation. On the other hand, it has been seen that expeditious methods can have sufficient reliability in case you want to characterize the behavior of a large number of buildings, but tend to present reliability problems when the analysis focuses on some well-defined portions of the environment built.

In light of the above, it is proposed that for the purposes of defining the expected level of damage in the various built environments that will be analyzed within the BE S2ECURE project, the method in (Enrico Quagliarini et al., 2019) is used with the application of diversified vulnerability indices V , but always promptly assessed (see D.1.2.1) according to the level of detail required.

A further request for the current project is the evaluation of the amount of debris on the ground which, after an earthquake, can disturb the outflow of the inhabitants and their rescue. For this need, it is proposed to consider the method discussed in paragraph 3.2 of this deliverable, proposed in (Santarelli, Bernardini, & Quagliarini, 2018) and (Santarelli, Bernardini, Quagliarini, et al., 2018) in which the vulnerability index will be calculated both as in (Lagomarsino & Giovinazzi, 2006) and as in (Mochi & Predari, 2016) (see D.1.2.1).

In order to define a greater or lesser reliability of the two vulnerability indices, and ultimately the estimate of the debris on the ground, validations will be carried out in some cases through the analytical procedure shown in(Anelli et al., 2020).

Since this procedure requires the use of specific fragility curves, in those cases these curves will be obtained through analytical procedures such as the FaMIVE method (see above) or the Vulnus method (see D.1.2.1).

Through the application of these analytical methods, in some case studies, it will be possible to evaluate any corrections to be made to the expedition procedure as well as to define its reliability. In addition, the use of methods based on a mechanical approach may provide useful indications for the validation of the risk matrix presented in D.1.2.1.

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