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Unreinforced masonry buildings in aggregate of urban settlements: Current approaches and critical issues for the seismic vulnerability assessment

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A B S T R A C T

The paper explores the architectural complexity of unreinforced masonry buildings in aggregate typical of urban historic centers, focusing on their seismic vulnerability. These buildings often stem from the gradual transformation of urban areas over centuries, also leading to significant variability in materials, geometries, construction techniques, maintenance status, and connections between adjacent Structural Units (SUs). The study outlines the key features and vulnerability factors of this structural typology, with a particular focus on the methodologies proposed in the literature for the seismic safety verification of a single SU, as well as for assessing the seismic vulnerability of buildings in aggregate at the urban scale. The paper highlights the peculiarities and shortcomings of each currently available methodology, emphasizing the unresolved issues and drawing possible solutions, with particular reference to the "aggregate" effect, i.e. the interaction between the SUs. This study underscores the complexity of assessing the seismic vulnerability of buildings in aggregate, emphasizing the importance of considering both in-plane (IP) and out-of-plane (OOP) mechanisms, as well as the pounding effect.

1. Introduction

The "buildings in aggregate configuration" is typical of a wide range of historical architectural assets such as fortresses, churches, abbeys, and convents as well as residential buildings typical of urban settlements. The paper focuses on this latter class. Buildings in aggregate consist of a set structural units (SUs) – often with heterogeneous characteristics - interconnected with varying degrees of effectiveness determined by their evolutionary history, which may interact under seismic or dynamic actions [1]. A significant number of existing Unreinforced Masonry (URM) buildings, especially those located within historical centers, are not isolated but rather aggregated into several adjacent SUs that interact with each other Fig. 1.

URM buildings in aggregate are often the result of the gradual transformation of urban settlements over centuries. That may potentially lead to significant variability in terms of materials, geometries, construction techniques, state of maintenance, and, especially, types of connections between adjacent SUs. This stratification has given rise to magnificent historic centers, rich in history and inestimable artistic-architectural value and therefore of great cultural interest, where each building is the result of its evolutionary process. Their peculiarities can be deciphered through numerous structural details that distinguish them.

The beauty of historic centers stems from their uniqueness and authenticity, which, from an engineering standpoint, presents a significant challenge due to the wide variability of not standardized structural features in each SU. In full awareness of proposing a drastic simplification, and precisely due to the complexity hardly reducible to standard classifications, the buildings in aggregate of urban settlements are broadly classified in this paper into two main macroclasses Fig. 2.

The first (Fig. 2*a*) includes aggregates, typical of large cities' portions, that have developed through a quite planned urbanization, where buildings align with streets according to specific rules and order; they are quite common in the 18th and 19th centuries. In these cases, it is often possible to identify individual SUs from the adjacent ones for which it is possible to recognize a quite autonomous system of vertical walls able to support ordinary and seismic actions, even if their response is potentially affected by interaction phenomena. The second macroclass encompasses aggregates typical of the oldest parts of cities and small settlements, which have evolved spontaneously over centuries without specific a-priori urban standards (Fig. 2*b*). In such aggregates, it is often impossible to consider a single SU as distinct from the rest of the aggregate.

In the first case, it is reasonable to consider modeling the individual SU by then incorporating in a more or less simplified way the constraints

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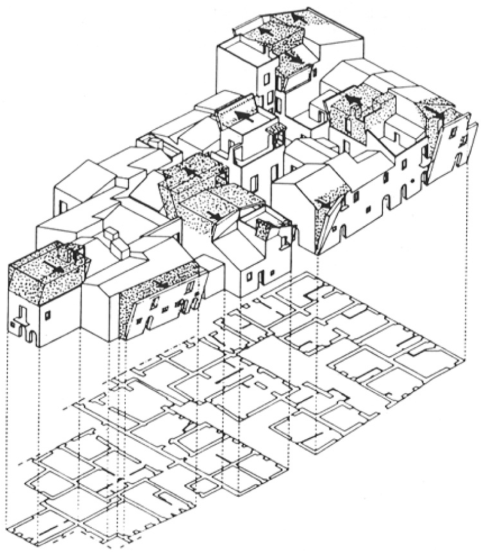

Fig. 1. Qualitative seismic damage forecast in an aggregate (Ortigia, Siracusa) [2].

provided by the adjacent units. Conversely, in the second case, it becomes highly challenging to isolate and model a single SU accounting for load transfer and the sharing of structural elements with other adjacent units, Fig. 3.

In such situations, it may be more appropriate to model the entire aggregate, even though it can be costly and computationally demanding. However, in such case, for not affecting the accuracy of the assessment, it is necessary to collect information on several SUs, which often belong to different owners, implying various technical difficulties. Therefore, for all these preliminary issues, it emerges how determining the appropriate scale of analysis for buildings in aggregate is a complex and non-trivial issue.

The seismic risk assessment of urban centers and the consequent plan of effective mitigation policies are a highly relevant matter, worldwide. This importance has been further emphasized by the devastating consequences witnessed in urban centers, especially historic ones, as a result of various seismic events [3–11].

Earthquakes not only result in a potential loss of human lives but also have a substantial impact on the economy, both in terms of direct costs, such as emergency management and reconstruction, and indirect costs, including a substantial reduction in Gross Domestic Product (GDP) due to declines in production activities often also associated to the tourism for these small historical centers [12,13].

While there are existing literature review articles that provide an overview of modeling approaches and analysis methods for masonry in general, considering masonry as a material or the response of isolated buildings [14–17], this article will specifically focus on the intricacies of buildings in aggregate, excluding aspects that are already covered about masonry modeling itself.

Despite the significant importance of historical centers, there is still considerable debate in the literature regarding the most effective analysis approaches for these structures in aggregate. Also the lack of regulations reflects the complexity surrounding URM buildings in aggregate.

Considerable efforts have been made in the literature to address the difficulties associated with assessing the seismic vulnerability of buildings. Various methods have been proposed, including mechanical methods (analytical and numerical) and typological-heuristic methods (score-based and empirical) [18]. However, at the scientific level, there is still no complete agreement on the treatment of this topic due to multiple concurrent factors that influence the response of the URM buildings when they are in aggregate configurations. As it will be discussed in Section 2, the literature does not provide definitive answers regarding the beneficial or negative effects of being part of an aggregate for SUs (except for the most obvious cases). Furthermore, there is no consensus on the most suitable tool for conducting vulnerability analyses of buildings in aggregate.

The mutual interaction between adjacent SUs, determining the extent of modeling required to capture the aggregate effect, as well as the combined analysis of local and global mechanisms, are among the relevant challenges to be considered in the seismic assessment of historic URM aggregates.

The strong interest in this issue and the need for the comparison and validation of calculation tools are evidenced by the presence of some experimental campaigns, such as the one inspired by the built environment in Basel, Switzerland, [19] and the more recent "Adjacent Interacting Masonry Structures" (AIMS) project, which is part of [20]. Within the AIMS project, shake-table tests have been carried out on a two-unit, double-leaf stone masonry aggregate. The system was subjected to two horizontal components and a blind prediction was organized to compare various modeling approaches and assumptions and, thus, understand the current level of uncertainty associated with modeling such masonry aggregates [21].

To date when a unit is part of an aggregate, the influence of adjacent units on the response has either been overlooked or accounted for in a simplified manner [21,22]. These experimental campaigns highlight the complexity of the subject and emphasize that the assessment of the seismic vulnerability of aggregated buildings remains a highly debated and open issue.

Indeed, the blind prediction results of the AIMS project indicated that several modeling parameters significantly influence the response of masonry buildings in aggregate, resulting in a very large coefficient of variation (CoV), especially in the displacement (160–268 %) estimates. This occurred despite the fact that the uncertainties at both the material and structural element levels were seemingly small (since hypotheses on that were addressed by detailed experimental tests at these smaller scales). It is concerning that the majority of the models underestimated the order of magnitude of displacements highlighting the need for further research [21].

Given the significant relevance of this timely and demanding issue, the objective of this paper is to conduct a comprehensive study of the state of the art concerning this matter.

The aim is to provide an overview of the existing tools in the literature by discussing their applicability, strengths, and limitations.

Accordingly, this paper is divided into two main sections.

The first one (Section 2.1) aims to provide an overview of buildings in aggregate by outlining their specific features This section explores how aggregates can be classified based on their geometric configuration and identifies the vulnerability factors (Section 2.2) and prevailing damage modes (Section 2.3) associated with them.

The second macro-section of the paper firstly examines some of specific recommendations available in technical regulations (Section 3) and then, classifies and illustrates the methods proposed in the literature thus far to address the seismic assessment (Section 4). Specific research questions are addressed analyzing the available applications of these assessment methods to real cases. Through the critical analyses of all of them, the section also highlights the characteristics and strengths of each method, as well as the critical points that still exist in the literature. All the examined results allowed in the conclusions (Section 5) to outline possible directions of future research. Fig. 4 illustrates the flow-chart of the structure paper and lists the research questions faced in Sections 3 and 4.

2. Buildings in aggregate: classification, key features, vulnerability factors, and damage mechanisms

The assessment of the structural safety of buildings in aggregate presents various conceptual and operational challenges. Firstly, there is

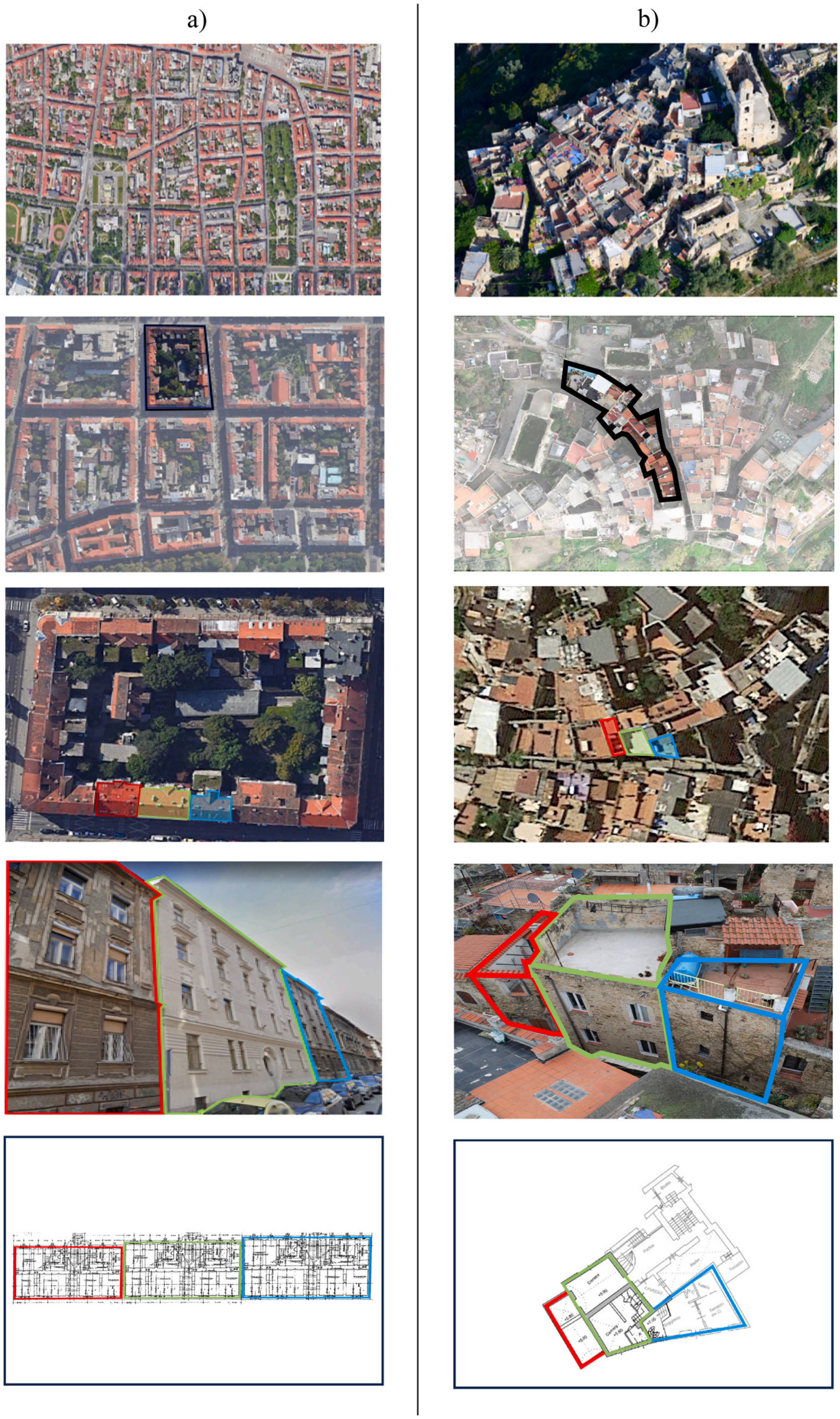

Fig. 2. a) Buildings in aggregate typical of the old town center of Zagreb. b) Buildings in aggregate of the small historic centre of Bussana Vecchia (IM).

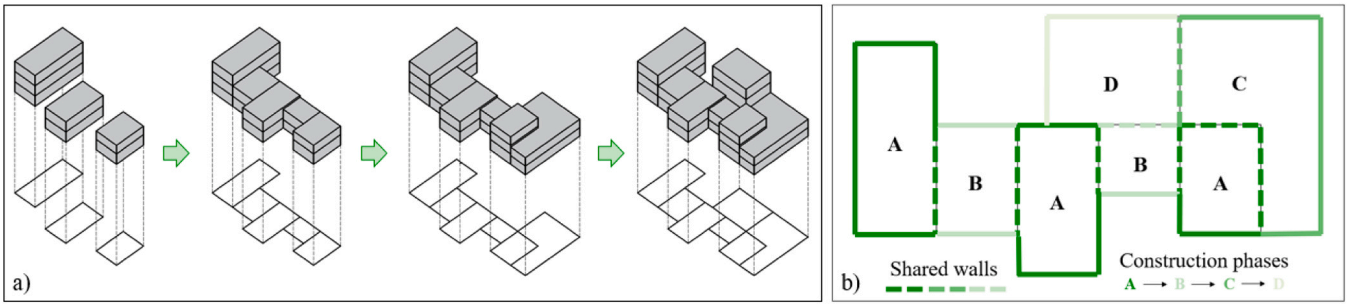

Fig. 3. a) Example of spontaneous evolution of individual SUs into buildings in aggregate; b) Example of a hypothetical sharing of neighboring internal walls.

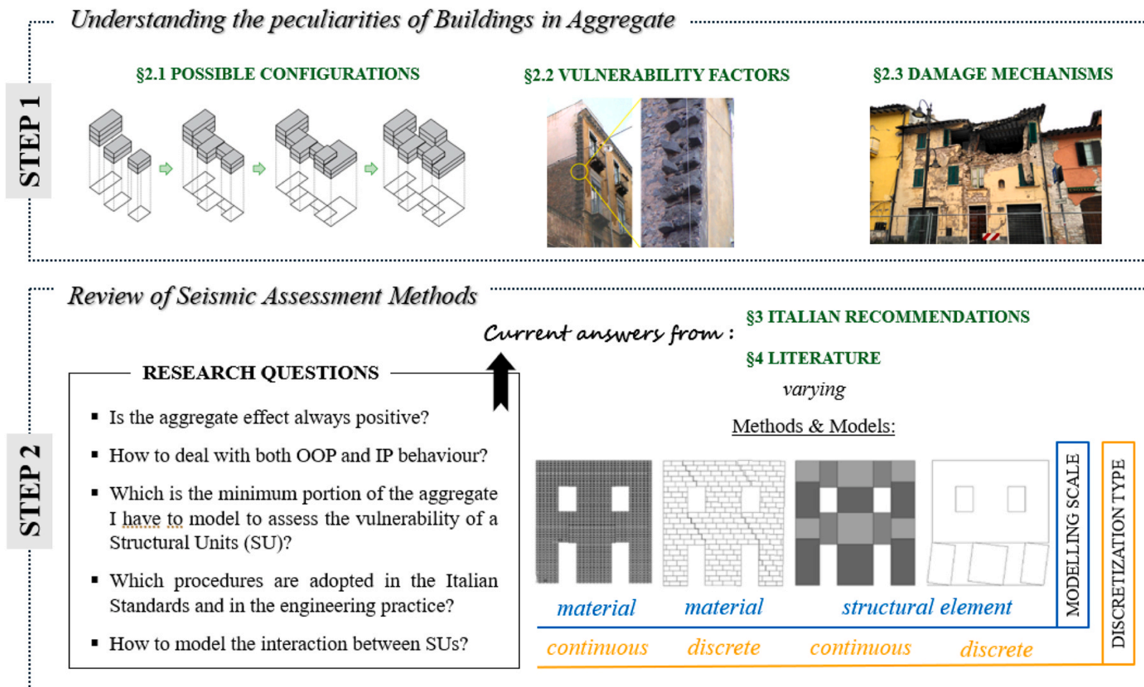

Fig. 4. Flowchart and research questions at the basis of the paper.

the complexity of determining which portions of the aggregate can be individually modeled, considering the intricate interrelationships among the SUs. Secondly, there is the challenge of devising analysis methods that strike a balance between accuracy and practicality, allowing for a widespread application even at a professional level [23].

Before analyzing the available methods for assessing buildings in aggregate, it is necessary to understand the huge variety of configurations which may characterize them, how they can be classified, what vulnerability factors characterize them, and what damage mechanisms they may exhibit.

2.1. Classification of building configurations in aggregate

Buildings in aggregate often are the result of an evolution over time: born as isolated buildings, they could have become row buildings or a complex one [24].

Examining the construction phases of a building, Fig. 3, is crucial to determine whether the wall structures that have been added over time form a closed set of wall boxes or if there are hidden intrinsic defects or variations within the building that are not visible from the outside.

In historical buildings, building practices and craftsmanship realized the concept of "box-like behavior", which refers to the combination of walls and horizontal elements that constrain each individual wall panel both vertically and horizontally. This configuration usually occurs in isolated buildings and ensures the structural integrity and stability of walls [25]. On the contrary, the progressive formation of building aggregates can create building units in which the façade wall in not well connected to the original adjacent ones. Conversely, specific provisions for promoting a good interlocking between adjacent buildings may be observed in high seismicity areas, thanks to the awareness of builders (see Fig. 5).

Therefore, understanding the genesis of a SU within a building in aggregate is a fundamental step for its classification.

SUs can be classified based on their position within the aggregate (end unit, corner unit, interlocking unit, projecting unit, and dual-facing unit) and they can be classified based on their elevation in relation to the rest of the building aggregate (towering unit, enclosed unit, and aligned unit), Fig. 6.

However, as explained above, in small historic centers, there is often a common and overlooked issue of being unable to identify a well-defined SU within the building aggregate. To address this challenge, it is possible to first classify the individual walls (fronts) based on both their location and their elevation. The scale of fronts can also be useful in cases where the SU is structurally independent of the rest of the aggregate but is characterized by flexible diaphragms or weak connections between walls. In these contexts, the scale of fronts can thus become the

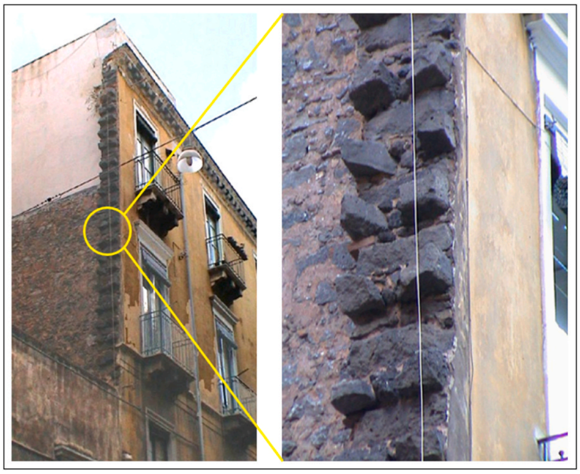

Fig. 5. Example of use of units already set to promote a good interlocking between adjacent buildings in the case of subsequent expansion.

scale of verification.

2.2. Vulnerability factors and damage modes characterizing buildings in aggregate

The assessment of the structural safety of buildings in aggregate within historic city centers is a matter of significant practical relevance due to the multitude of possible configurations involved. Vulnerability factors of URM buildings in aggregate certainly include those common to isolated buildings such as the quality of materials and of the execution, the state of maintenance, the in-plane and in elevation regularity, the quality of connections among walls that identify the SU, the opening's misalignments and the foundations' condition [26–28].

In addition, for buildings in aggregate, further factors affecting their vulnerability must be taken into account.

A vulnerability of the urban fabric may be associated with changes in construction techniques. Over the years, it has been observed that people have sometimes modified the construction technique within an aggregate or implemented structural interventions without considering the contiguous units and their corresponding wall boxes. This may introduce vulnerabilities that were not present before, affecting the overall structural integrity of the aggregate [29].

In the aggregates typical of small historical centres of peripheric areas, another issue is the relationship between the houses and the natural slope on which they are situated [24,30].

Fig. 7 illustrates some of this key characteristic of these configurations, such as the variation in height between downstream and upstream walls and the level of the inter-story floors and roof structures. In fact, often these settlements exhibit a dual slope configuration. The first and more pronounced slope is the transversal slope, while the second, gentler slope determines the incline of the main paths within the settlement. These variations in slope can have implications for the structural behavior of the buildings within the urban fabric and their arrangement within the aggregate.

Aggregates located on slopes are often subject to site amplification effects as well, [31]. However, this paper will only focus on aspects related to structural response.

Additional factors that need to be considered for buildings within aggregates are the position of the SU in the aggregate, the presence of adjacent buildings with different heights, the presence of staggered floors, the quality of connections and the opening's misalignments between adjacent buildings (Fig. 8). The importance of these factors on determining the seismic vulnerability of a building in aggregate has been discussed in the literature [29–35]. However, there is still uncertainty about the hierarchy of these factors, namely which ones have a greater influence on the assessment of seismic vulnerability.

Some of these factors, such as the plan position, irregularities in elevation, and the staggered floor levels of the SU compared to adjacent ones, had already considered in the development of a data collection form for a systematic study of the historic center of Casentino (AQ) following the earthquake of L'Aquila on April 6, 2009 coordinated by

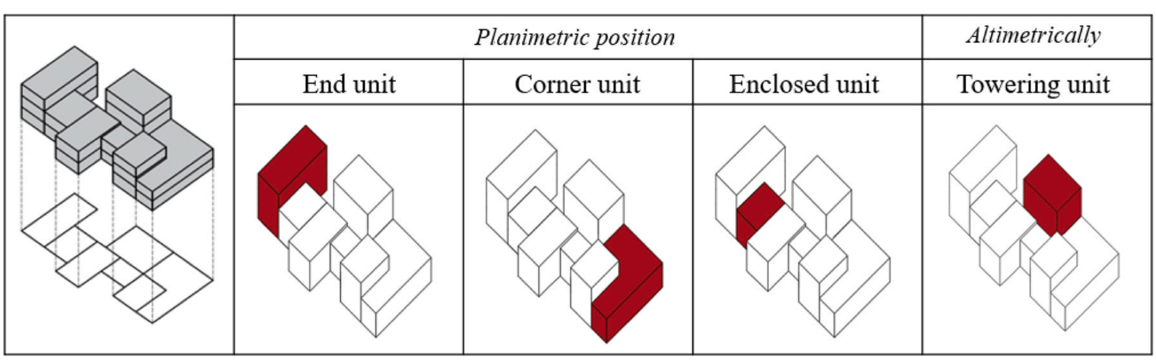

Fig. 6. Examples of planimetric and altimetric positions that SUs can occupy within the aggregate.

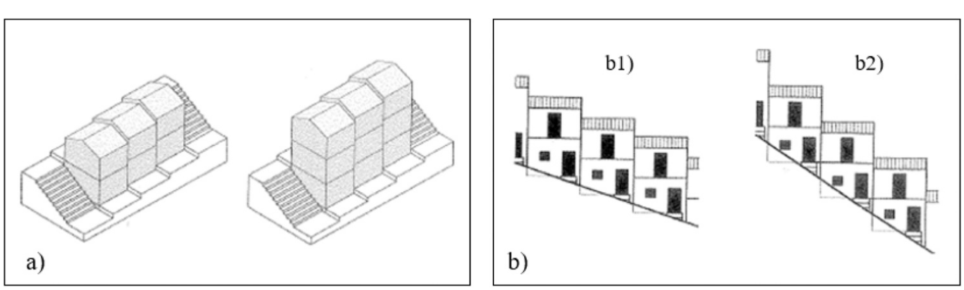

Fig. 7. Aggregate model on slope conditions, particularly transverse to the row of buildings (a). Misalignment between horizontal diaphragms due to longitudinal slope of the site (b): b1) medium slope; b2) steep slope. [25].

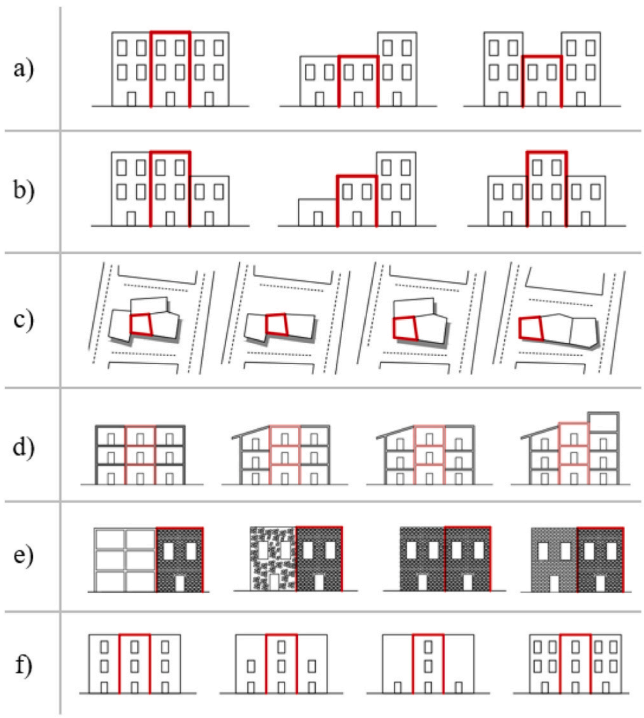

Fig. 8. Additional factors that need to be considered for buildings within aggregates [31]: a) in elevation interaction; b) plan interaction; c) staggered floor; d) structural heterogeneity; e) Percentage difference among opening areas of adjacent facades.

Prof. S. Lagomarsino (University of Genoa), Prof. S. Cattari (University of Genoa), Prof. C. Tocci (University of Rome 1) and Prof. C. Carocci (University of Catania) [3,36,37]. This form, depicted in Fig. 9, was specifically designed by research units from the University of Genoa, the University of Catania, and the ITC-CNR to consider the specific construction characteristics present in the settlement of Casentino. So this form, in addition to including vulnerability factors already universally recognized for isolated buildings [38] (in blue), also takes into account those factors that characterize buildings in aggregate (in red). A machine-learning vulnerability model has been recently developed in [39], by using the above mentioned empirical data, highlighting in particular the relevance of state on maintenance as a vulnerability factor.

The seismic vulnerability of buildings in aggregate has been highlighted through post-earthquake surveys following recent earthquakes, both in Italy and worldwide. Referring to the previously introduced scale of fronts, a front can be subjected to actions in-plane (IP) – when the horizontal action acts on the main plane of the wall, out-of-plane (OOP) – when the horizontal action acts orthogonally on the main plane of the wall and buildings in aggregate can also be subject to interaction mechanisms between adjacent SUs, Fig. 10.

To identify the recurring damage mechanisms, reference was made to a damage mechanism chart that was developed during the damage survey in the historic center of Casentino (AQ).

The primary type of damage observed in masonry buildings' aggregates within historical centers is often associated with out-of-plane (OOP) local collapse mechanisms. These mechanisms involve the overturning of wall and summit portions, as shown in Fig. 11. The lack of appropriate connections between floors and walls, as well as between perpendicular walls, fosters these types of failures [29].

Local OOP mechanisms are also facilitated by the frequent presence of construction irregularities, such as walls of the last building, built to obstruct empty spaces, which often were not properly interlocked to the previous built units. Geometric irregularities, such as varying heights between adjacent buildings, can also contribute to the vulnerability of the aggregates. These factors collectively contribute to the increased susceptibility of building aggregates to OOP collapse mechanisms during seismic events [29]. Therefore, what increases the vulnerability of the SUs to OOP damage mechanisms is not being part of the aggregate, but rather the architectural and geometric configuration resulting from the formation of the aggregate, such as the lack of interlocking between adjacent SUs walls, height irregularities, etc.

In addition to the OOP collapse mechanisms discussed earlier, irregularities in the plan and/or elevation of masonry aggregates can also lead to damage mechanisms associated with the IP response of masonry walls, Fig. 11. Indeed, from the perspective of IP mechanisms, a SU within an aggregate may be even less vulnerable compared to when it is isolated [39], as also further discussed in Section 4. However, this concept is not always valid when the SU is located at the edge or corner of the aggregate, especially when the aggregate has a highly irregular plan configuration, as this can result in torsional effects that may

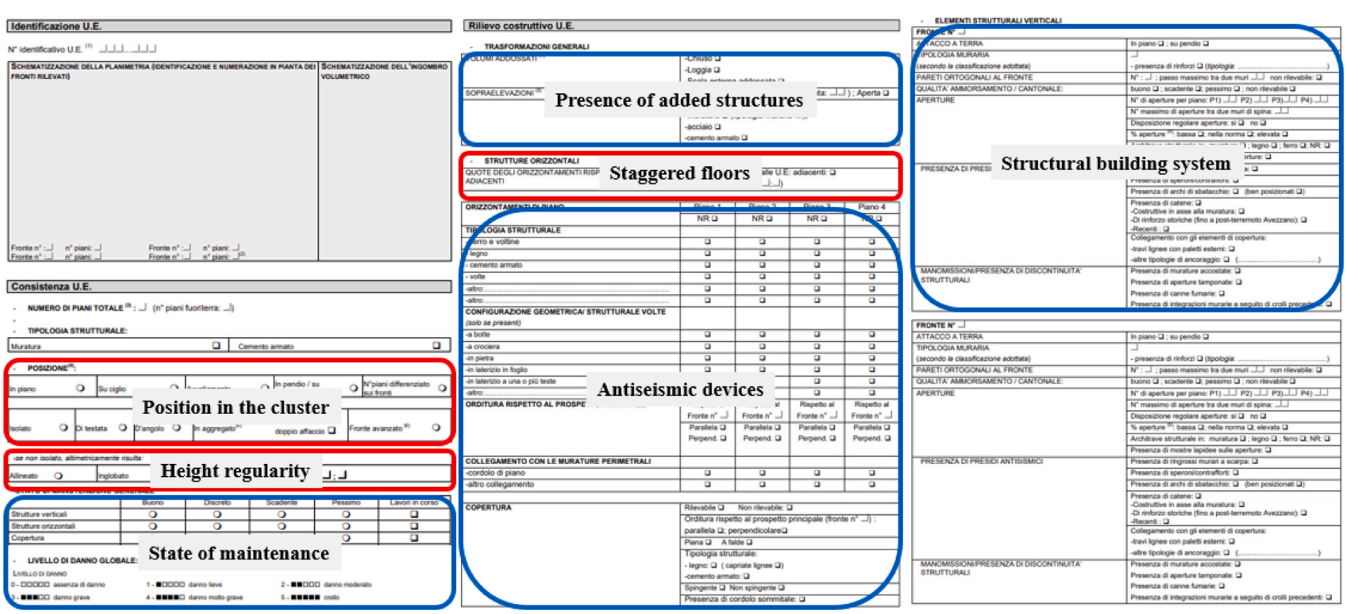

Fig. 9. Form prepared for the systematic collection of data on the historic center of Casentino (AQ) following the earthquake of L'Aquila on April 6, 2009 [36].

Fig. 10. Examples of damage mechanisms observed after the Central Italy sequence of 2016–2017: IP (a), OOP (b), pounding (c).

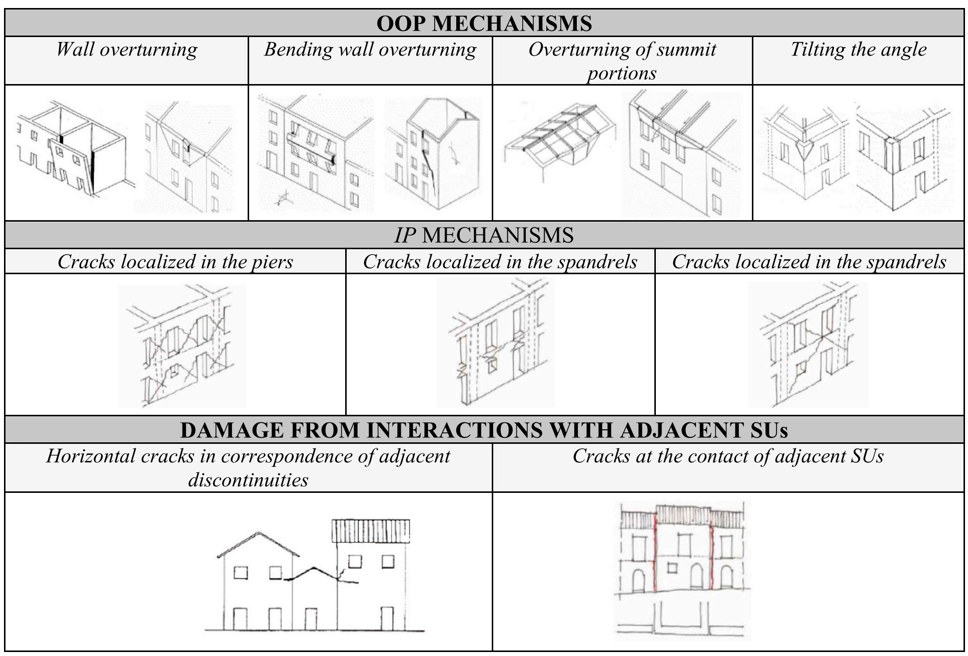

Fig. 11. Classification of damage mechanisms adopted in the surveys made in Casentino. Adapted from [36].

increase the vulnerability of the SU.

Of course, also mechanisms which involve both IP and OOP responses may also occur as a result of irregularities and interactions within the structural system [40].

While the damage types presented above are also typical of standalone masonry buildings, among the additional common damages caused by the interaction between SUs within building aggregates, there are the horizontal cracks in correspondence with adjacent discontinuities and vertical cracks at the contact of adjacent SUs, Fig. 11. These cracks are typically induced by non-synchronous motion between the adjacent structures, especially when characterized by different stiffness properties, and can be exacerbated by factors such as the presence of misaligned floors or damage concentration at the emerging portion of the higher building. Pounding damage was observed in many cases following significant earthquakes, even if it is not such relevant from the statistical point of view and capable of producing the collapse of SUs. In the 1985 Mexico City (Mexico) earthquake (Mw = 8.0), pounding damage was detected in over 40 % of 330 collapsed or severely damaged buildings surveyed and in 15 % of all cases it was identified as the main cause of collapse [41]. In the 1971 San Fernando (California, USA) earthquake (Mw = 6.9), a series of pounding-induced failures were observed, of which most of the damages were localized in buildings in aggregate [41]. Additionally, photographic surveys after the 2010 Christchurch (New Zealand) earthquake (Mw =6.3) portrayed the severe damage present in URM aggregates due to pounding [41–43]. Such type of damage was observed as well as after various Italian earthquakes, as testified for example in [9].

3. Overview of the recommendations provided by the Italian Standards

Despite the widespread presence of buildings in aggregate, there is a lack of standardized procedures to assess their seismic vulnerability; this is strictly linked to the difficulty of standardizing the multiple configurations of buildings in aggregate. Currently the country that provides the most targeted tools is Italy, where almost 50 percent of existing buildings are contiguous on at least one side (a percentage even higher in the case of historic centers) and where specific tools were also developed to face the urgent needs posed by severe seismic events that hit Italy in the last twenty years. The Italian technical Standard NTC2018 [9] specifically refers to this topic only in §8.7.1 where it states that in the presence of buildings in an aggregate, in contact or interconnected with adjacent buildings, the verification methods generally used for new constructions may be inadequate. It is emphasized that when analyzing a building that is part of an aggregate, possible interactions resulting from structural contiguity with adjacent buildings must be considered [44]. To address this, the SU under study must be identified, highlighting the actions that may arise from adjacent SUs. The standard defines that the SU must have continuity from the sky to ground in terms of the flow of vertical loads and, as a general rule, must be delimited by either open spaces, structural joints, or buildings that are structurally contiguous but, at least typologically, different.

In addition to the requirements normally applied to buildings not arranged in the aggregate, the Code highlights that specific considerations need to be made for the effects of unbalanced forces on walls shared with adjacent SUs. These forces can result from height differences between floors, misalignments in both vertical and horizontal directions, and adjacent SUs of different heights. When conducting a global analysis of a single SU, simplified methodologies than ordinary and modern structures are allowed be used. For example, for buildings with rigid floors within their plane, the verification can be performed using non-linear static analysis (NSA) but each inter-story of the building should be analyzed and verified separately while neglecting the variation of axial forces in the piers due to seismic action. Torsional effects can be disregarded in the analysis, except for corner or end SUs, as well as parts of the building that are not constrained or not connected to other SUs on any side. It can be assumed that the floors can only translate in the direction of the considered seismic action. For corner or head SUs, simplified analyses are permitted, but it is necessary to consider possible torsional effects.

Conversely, if the floors of the building are not sufficiently rigid within their plane, the analysis can focus on individual walls or coplanar wall systems. Each wall should be subjected to the relevant vertical loads and corresponding earthquake actions parallel to the wall. Paragraph C8.7.1.3.2 of the NTC2018 Circular explains the process of investigating building aggregates, which should be developed by taking up the concepts reported in [45].

A bit more detailed and specific guidelines for dealing with buildings in aggregate are provided in [1]. These Guidelines were developed in response to the seismic event that occurred in the Abruzzo Region in 2008, which underscored the urgent need for interventions to recover, strengthen, and improve the seismic performance of buildings in aggregate. The main objective of these Guidelines was to provide a systematic framework for the methodology and operational tools to be used in surveying, diagnosing, selecting interventions, and preparing final intervention projects for buildings in aggregate. They offer the necessary tools to assess the mechanical behavior of the aggregate by understanding its construction system, interpreting the causes of damage, identifying anomalies and structural vulnerabilities, and formulating appropriate intervention methods.

Regarding the adoption of simplified models and methods, Appendix B of these Guidelines describes a mechanical model that allows for simplified verification using the linear static analysis approach. The verification process is simplified because it involves calculating the collapse acceleration of the structure, which is then compared with the design seismic action to evaluate a safety index. The mechanical model described in the Guidelines assumes the perfect coupling of the piers for calculating the resistance and displacement capacity. A more detailed description of such a method is in Section 4.5 where other mechanical-analytical approaches are reviewed.

A recent and highly interesting document regarding aggregates located in historic centers is [46]. This document focuses on the reconstruction, specifically the repair with seismic improvement, of damaged buildings located in historic centers affected by the 2009 Abruzzo earthquake thus indeed is not strictly focused on methods for the seismic vulnerability assessment. The procedure adopted for determining the financial support provided by the State for the reconstruction of building aggregates in historic city centers is primarily parametric. The contribution is defined in advance based on the level of damage and vulnerability of the buildings affected by the earthquake. Regarding the financing model, the document provides an analysis of the built environment in historic centers, highlighting the definitions of Building Aggregate (AE), Minimum Intervention Unit (UMI), SU, and Building (ED), and subsequently delving into a more detailed examination of their characteristics. Table 1 provides an overview of the definitions introduced in these documents for defining the concepts of SU or AE.

4. Review of seismic assessment methods

4.1. Classification of possible approaches and scales of analysis

The following sections aim to review and analyze the methodologies proposed in the literature for assessing the seismic vulnerability of buildings in aggregate. These methodologies serve different purposes and are based on different approaches. Some methods are drawn for the safety verification of individual buildings within an aggregate, while others are intended for the large-scale vulnerability assessment (Fig. 14). Consequently, the output of these methods can be either a safety index or a fragility curve. Some analyses focus on studying archetypes to develop fragility or vulnerability curves for a specific class of buildings, enabling damage scenario assessments. Other studies concentrate on analyzing a particular building to assess its damage and derive a safety index specific to that structure. In recent years, various methods have been adopted and proposed to address the challenges associated with assessing the seismic vulnerability of buildings.

Within this general framework, although the issue of interacting buildings affects a significant portion of the built environment in many countries, only a few have conducted specific studies on the subject. Fig. 12 shows where the buildings in aggregate studied in the literature to date are geographically located compared with the seismicity of the area.

The methods for seismic assessment proposed in the literature can be categorized into mechanical methods, including numerical and analytical approaches, as well as typological-heuristic methods such as score-based methods and empirical approaches (Fig. 13).

The paper seeks to provide an overview of these methodologies, their strengths, limitations, and applications to contribute to the understanding and advancement of seismic vulnerability assessment for buildings in aggregate.

Typological/heuristic methods (empirical and score-based methods) classify buildings into classes depending on materials, structural features, and other factors influencing building response.

Mechanical methods predict the seismic effect on the structure through the use of an appropriate mechanical model, which can vary in complexity, of the whole building or of an individual structural element. These methods can be classified into different groups based on the type of model used to represent the structure: analytical methods utilizing simple models and those numerical relying on more detailed analysis. Methods based on simplified mechanical models are well-suited for analyzing a large number of buildings and require only a few input parameters. The second group, including the more sophisticated methods, is generally used for evaluating single structures at a higher level of detail and is based on more refined modeling techniques. Analytical procedures associated with these methods may involve linear static, nonlinear static, linear dynamic, and nonlinear dynamic analyses.

Detailed analyses are often conducted for verification or damage analysis of specific structures, focusing on capturing the behavior and response of the building under seismic loads. These analyses aim to provide a comprehensive understanding of the structural performance and potential vulnerabilities.

On the other hand, analyses of archetypes are usually carried out to develop fragility curves, which are probabilistic representations of the likelihood and severity of damage for a specific class of buildings. These curves enable damage scenario assessments and can be useful for risk assessment and mitigation planning at a larger scale. Additionally, some analyses serve as a means of calibration or validation of other methods.

Table 1
Definition of SU and Aggregate Building (AE) in Standards [1,44-47].

DOCUMENT	DEFINITION	
	Structural Unit (SU)	**Building Aggregate (AE)**
[44]		*A building aggregate is a set of at least three structurally interconnected buildings with even partially effective connections, including those resulting from progressive building additions, which may interact under seismic action. The aggregates may form part of a building block.*
[45]	*The SU must have continuity from top to bottom, as far as the flow of vertical loads is concerned, and will normally be bounded either by open spaces, by structural joints, or by buildings that are structurally contiguous but, at least, typologically different.*	
[47]	*The SU is a portion of an aggregate comprising cells linked together in elevation and plan by a common construction process and considers all the elements involved in the transmission of vertical loads to the ground.*	*It is the result of an articulated and often non-uniform genesis, due to multiple factors (construction sequence, use of different materials, etc.)*
[1]	*The SU is a sub-unit of the aggregate. It must have continuity from top to bottom, so as to contain within the flow of stresses due to vertical loads, and, as a rule, it will be delimited either by open spaces, by structural joints, or by contiguous buildings constructed with different types of construction and structure. The unity of the structural behavior with respect to dynamic actions as well as static ones must also be taken into consideration.*	*It is the non-homogeneous ensemble of buildings (SU), interconnected by a more or less structurally effective connection determined by their evolutionary history, which may interact under seismic or dynamic action in general.*
[46]	*In accordance with what is described in §2.4 of the manual [48]: "Within the buildings in aggregates, buildings are identified, defined as homogeneous unis and generally distinguishable from adjacent buildings by type of construction, difference in height, age of construction, staggering of floors, etc. Buildings therefore constitute unique static organisms and can be distinguished and identified on the basis of the following criteria – buildings constructed at different times; - buildings constructed with floors at different heights."*	*According to what is indicated in the Guidelines for the survey, analysis and design of seismic repair and consolidation interventions of masonry buildings in aggregate, 2010 and in [Carpi et al. 2013], a building in aggregate "can be understood as a set of buildings (SUs) not necessarily homogeneous, interconnected with a more or less structurally effective connection determined by their evolutionary history that may interact under seismic or dynamic action in general. (…).*

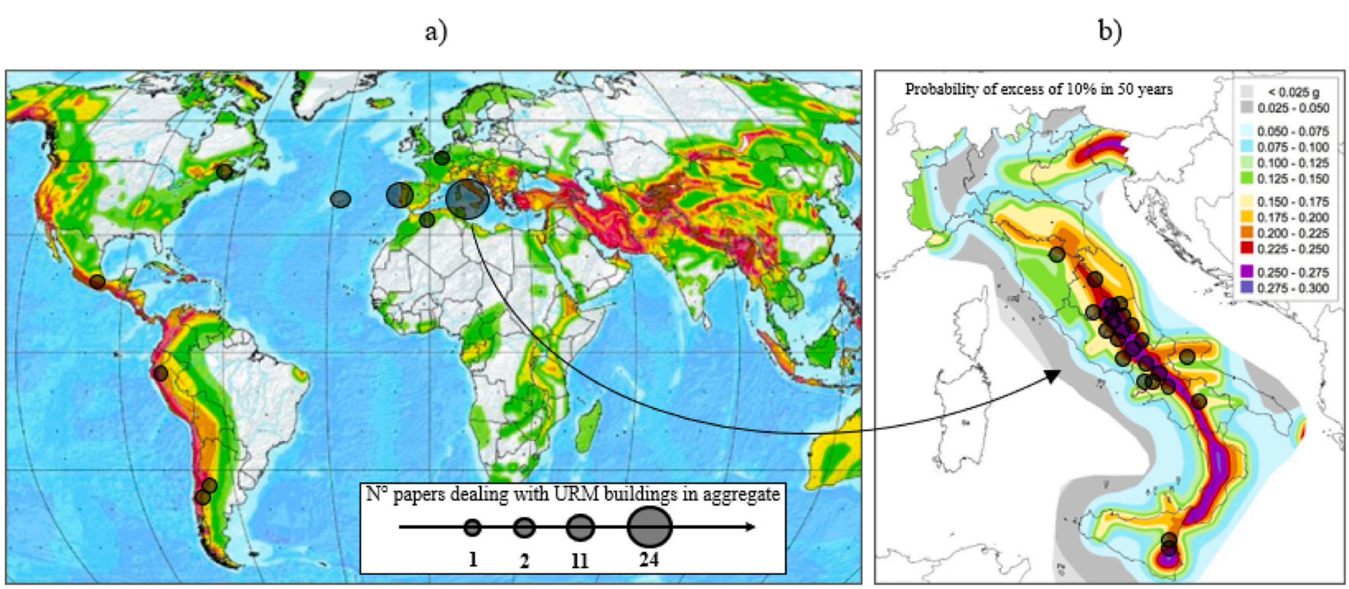

Fig. 12. Geographical location of case studies of aggregates analyzed in the state of the art. a) Global seismic hazard map generated by the Global Seismic Hazard Assessment Program (GSHAP, https://www.gfz-potsdam.de/gshap); b) Seismic hazard map of Italy generated by the National Institute of Geophysics and Volcanology (INGV, http://zonesismiche.mi.ingv.it/).

These studies focus on comparing and benchmarking different approaches or models to assess their accuracy and reliability in predicting the seismic vulnerability of buildings.

4.2. Score-based methods

The section analyzes the Vulnerability Index Method (VIM) proposed in the literature by Formisano [31,49–53] Vicente [32,33,54,55], Brando [56,57], and Stefanini [58]. These methods share a common denominator, namely, to calculate the vulnerability index of buildings in aggregate.

The methods of Formisano, Vicente, and Stefanini propose calculating the vulnerability index (VI) using a formula with the same structure: the vulnerability index is calculated as the sum of the product of each vulnerability factor (p_i) by its respective weight (c_i), Eq. (1.1). In (1.1) N is the number of vulnerability factors (Table 2): N=14 in

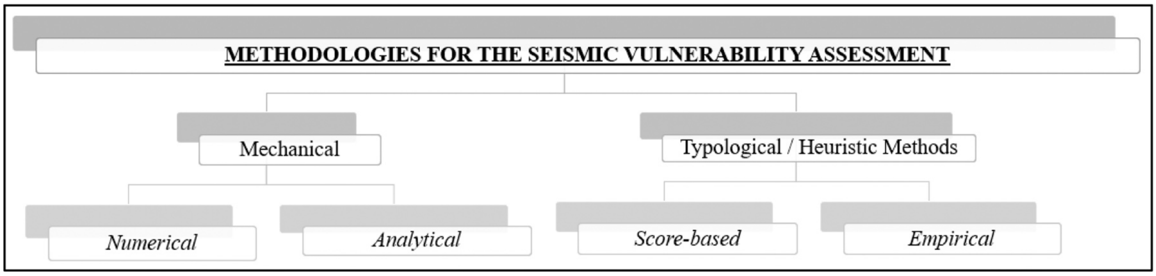

Fig. 13. Classification of methodologies for the seismic vulnerability assessment.

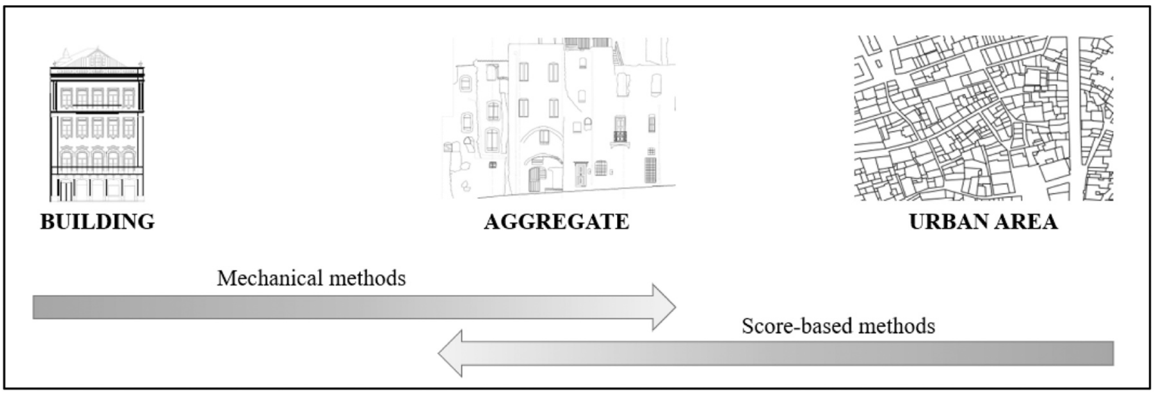

Fig. 14. Scale of application of seismic vulnerability assessment methods.

Vicente, N=15 in Formisano; N=20 in Stefanini.

$$I_V = \sum_{i=1}^{N} c_i \cdot p_i \tag{1.1}$$

These methods share the same structure as the GNDT (i.e. the Italian National Group Against Earthquakes) method, which is the first scoring method developed in the literature. However, this method was originally created for isolated structures and therefore does not include specific factors for buildings in aggregate. The GNDT procedure involves assigning one of four scoring classes (A - B - C – D; A = the best, D = the worst) to ten parameters that represent the geometric and mechanical characteristics of the building. These classes are defined in increasing order of hazard. While this methodology is suitable for assessing the vulnerability of isolated buildings, it is not appropriate for buildings in aggregate since the survey sheet on which it is based does not consider the structural interaction between adjacent buildings. To address this limitation, Formisano in [60] proposed a modified evaluation sheet that includes five additional evaluation parameters specifically designed to account for the aggregate condition Fig. 15.

These parameters can increase or decrease the vulnerability of a SU within a block of buildings, depending on the specific case. These factors, which were partly derived from previous studies found in the literature [61], include:

1. Interaction in height with adjacent buildings.
2. Planimetric position of the building within the aggregate.
3. Presence of staggered floors between the building under investigation and adjacent buildings.
4. Presence of typological or structural heterogeneity between adjacent buildings.
5. Difference in the percentage of façade openings between adjacent buildings.

These factors have been identified as important considerations for assessing the vulnerability of buildings as a whole and their impact on the overall vulnerability of a SU within a block of buildings.

The procedure proposed by Formisano was initially set up by conducting parametric analyses on a masonry SU representative of the municipality of Sessa Auronca. Subsequently, a masonry building block was selected within an investigation area of the historical center of Torre del Greco, a town in the district of Naples, and then subjected to numerical analysis for validation purposes. Finally, the proposed methodology was applied to the entire surveyed area of Torre del Greco, which also allowed the creation of a damage map of the built-up area in relation to a given ground shaking level [31,49,50]. This methodology was also applied to conduct a large-scale seismic vulnerability assessment of a historical masonry compound in San Pio delle Camere (L'Aquila, Italy) [51], as well as to assess the vulnerability of aggregates in the historical center of Arsita (L'Aquila) [52,53], to the case study of Castelpoto, a municipality of Benevento (Italy) [62], to obtain fragility curves for the areas of Scarperia (Tuscany, Italy) [63] and Latronico (Basilicata, Italy) [64], Figs. 16 and 17.

Vicente also proposed a formulation of the VI primarily based on the GNDT II level approach [59] for assessing the vulnerability of residential masonry buildings. This methodology relies on post-seismic damage observations and survey data collected across a wide area, with a focus on the key parameters that have a significant impact on building damage, requiring individual surveys. The overall vulnerability is calculated by considering the weighted sum of 14 parameters. This method was applied to the historical center of Coimbra (Portugal) [32,33], for the characterization of the buildings on Faial Island (Azores) [54], for the seismic vulnerability assessment of masonry buildings of the old city center of Seixal in Portugal [66], of the historical city center of Faro (Portugal) [65], of the historic center of Horta (Azores) [55] and finally to make a seismic vulnerability assessment of a limited urban area of the Historic Downtown of Mexico City by obtaining vulnerability maps and damage scenarios for different earthquake intensities [67].

In [58] Stefanini et al. adapted the GNDT procedure for masonry patio buildings in aggregate. The adaptation involved the inclusion of new parameters that take into account the particular construction characteristics of the patio house typical of Marocco and the interaction between buildings. These new parameters include slenderness,

Table 2
Comparison of vulnerability parameters considered in the score-based method of GNDT [59], Formisano [49], Vicente [32], Brando [56] and Stefanini [58].

	MANUALE GNDT		FORMISANO ET AL.		VICENTE ET AL.		BRANDO ET AL.		STEFANINI ET AL.	
STRUCTURAL BUILDING SYSTEM	P1	Type and organization of the resistant system	P1	Organization of vertical structures	P1	Type of resisting system	P3 P4	1st mode mechanism 2nd mode mechanism	P1.1	Type of resisting system
	P2	Quality of resistant system	P2	Nature of vertical structures	P2	Quality of the resisting system	/		P1.2	Quality of the resisting system
	P8	Distribution of resistant elements in plan	P4	Distribution of plan resisting elements	P3	Conventional strength	/		/	
	/		/		P4	Maximum distance between walls	/		P1.5	Maximum distance between walls
	/		/		/		P5	Arches	P3.4	Portico surfaces
	/		/		/		P6	Vaults	/	
	/		/		/		/		P1.4	Maximum slenderness
FLOOR SLABS AND ROOFS	/		/		P5	Numbers of floors	P2	Number of stories	P1.3	Numbers of floors
	P5	Horizontal structures	P7	Type of floor	P11	Horizontal diaphragms	P7	Slabs	P2.1	Horizontal diaphragms
	P9	Roofing	P8	Roofing	P12	Roofing system	P8	Thrusting forces	P2.2	Roofing system
OPENINGS	/		P15	Percentage difference of opening areas among adjacent facade	/		/		/	
	/		/		P10	Wall facade openings and alignments	/		P3.5	Area of openings and alignments
IRREGULARITIES	P6	Plan regularity	P5	Plan regularity	P8	Plan configuration	P11	Irregularities	P3.3	Plan configuration
	P7	Elevation regularity	P6	Height regularity	P9	Regularity in height			P3.7	Turrets
INTERACTION	/		P12	Position of the building in the aggregate	P7	Aggregate position and interaction	P1	Position in the cluster	P16	Planimetric interaction
	/		P14	Effect of either structural or typological heterogeneity among adjacent structural unit	/		/		P4.3	Typological and structural discontinuity
	/		P11	Presence of adjacent buildings with different height	/		/		P4.1	Altimetric interaction
	/		P13	Presence and number of staggered floors	/		/		P3.6	Presence of staggered floors
	/		/		/		P14	Non seicmic external hazard		
LOCATION	P4	Location of the building and type of foundations	P3	Location of the building and type of foundation	P6	Location and soil conditions	P13	Site effects	P3.1	Building location and foundations
MAINTENANCE STATUS	P11	Current status	P10	Physical conditions	P13	Fragilities and conservation state	/		P5.3	General state of conservation
	P3	Conventional resistance	/		P3	Conventional strength	/		/	
	/		/		/		/		P5.2	Interventions and changes to the original system
NON STRUCTURAL ELEMENTS	P10	Non-structural elements	P9	Details	P14	Non-structural elements	P12 P10	Non-structural elements Stairs	P5.1	Non-structural elements
	/		/		/		P9	Presence of added structures	P3.2	Foreparts

wall-to-wall distance, plan configuration, presence of turrets, interventions or modifications to the original system, overall state of conservation, and planimetric interaction. In [56], Brando et al. proposed a scoring method similar to the one proposed in the Guidelines for the Seismic Risk Assessment of Churches [68]. The procedure defines a VI for each SU, which is determined by "fragility indicators" associated with structural characteristics that contribute to increased vulnerability, and "protection indicators" associated with anti-seismic devices that, if present, can mitigate vulnerability for the corresponding vulnerability parameter (Pk). The vulnerability parameters (P_k) encompass 14 factors and are defined based on the building's typology and observations of past earthquakes' effects on similar buildings. The values of the ρk coefficients have been selected through engineering judgment, considering observed causes of collapse after the 2009 earthquake, as well as damage reconnaissance activities conducted by other authors in the past. For example, post-seismic inspections carried out after past earthquakes (among others [51,54,69]) have shown that a building located at the corner of an aggregate is more likely to sustain severe damage (up to D5)

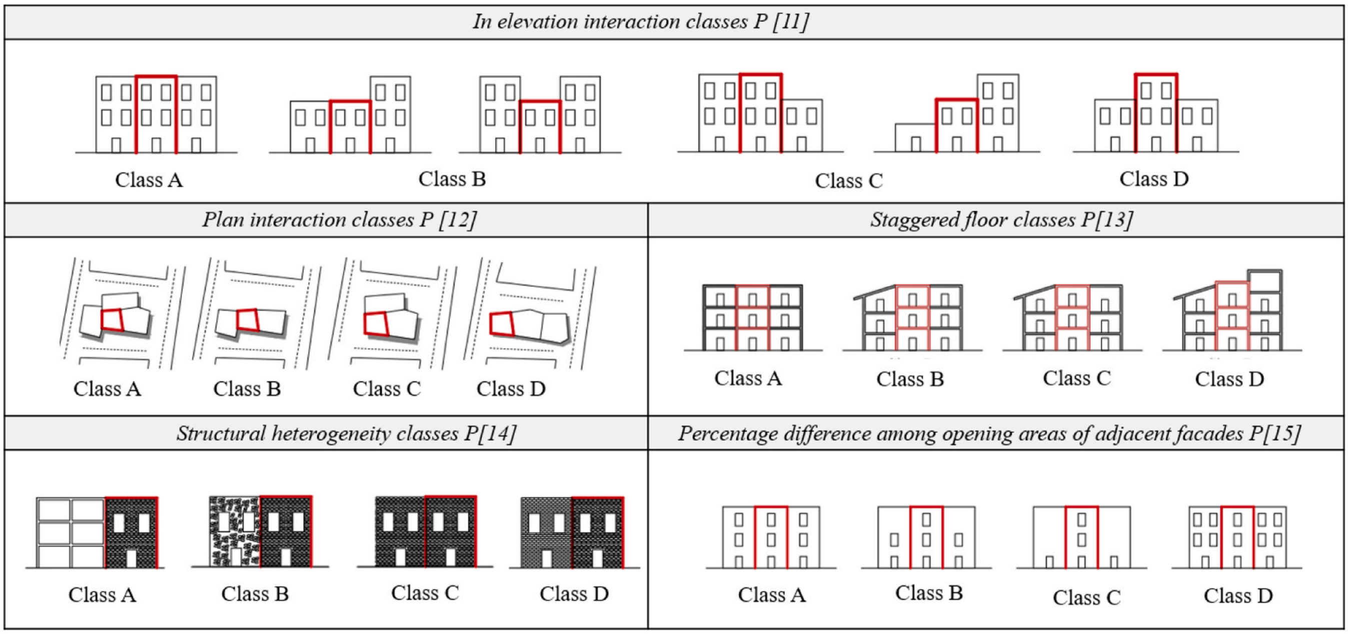

Fig. 15. Five additional evaluation parameters specifically designed to account for the aggregate condition [31].

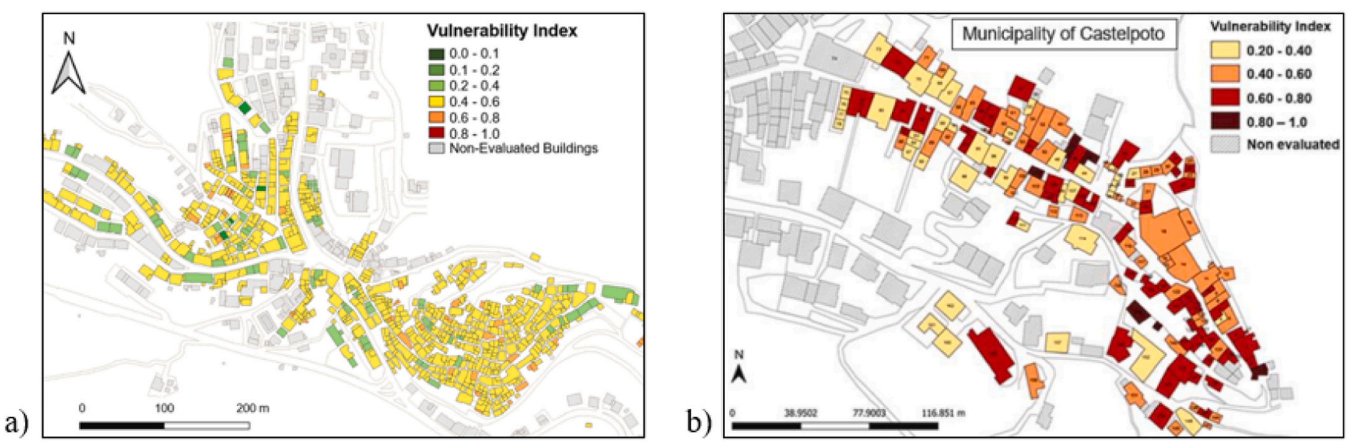

Fig. 16. Distribution of the vulnerability of buildings in the municipality of Latronico (a) [64] and Castelpoto (b) [62].

compared to a building with similar characteristic located at the center of an aggregate block [56]. This method was used to assess the seismic vulnerability of small historic centers of Goriano Sicoli and Poggio Picenze in Abruzzo, Italy, which were affected by the L'Aquila earthquake in 2009, of the historic center of Scanno, in Abruzzi, Italy [70] and the historic center of Campotosto, in Italy, which was affected by the Central Italy earthquake in 2016 [57].

Table 2 presents a comparison between the parameters considered by the GNDT method and those proposed by Vicente [32], Formisano [31] and Brando [56]. These parameters are divided into eight macro-categories, namely Structural Building System, Floor Slabs and Roofs, Openings, Irregularities, Interaction, Location, Conservation Status, and Non-Structural Elements. The attributes which specifically characterize the response of the building when in aggregate are marked in blue. Upon examining the comparison, it becomes apparent that the majority of methods allocate only a limited number of parameters to address the specific characteristics of the aggregate.

As shown in Table 2, while in the methods of Formisano and Stefanini there are many parameters specific to buildings in aggregate, in the methods of Brando and Vicente, the "*aggregate effect*" (referring through with the same configuration of a SU considered as isolated or interacting with other adjacent buildings) is taken into account only by the parameter considering the position of the SU within the aggregate. This suggests that this parameter carries greater weight compared to the weight assigned to the same parameter in the previous two methods.

Moreover, the multiplicative coefficient that considers the weight of each vulnerability factor has been calibrated in two different ways: through numerical modeling [31,50] or through expert opinion [71].

The vulnerability index can be used to create a ranking to classify the buildings and identify what is more or less vulnerable. It can also be used to develop vulnerability curves for which the formula developed by Lagomarsino & Giovinazzi [61] is used in most of afore mentioned proposals to derive them to estimate the level of damage given a certain level of intensity [63].

Finally, Romis in [35] shows the comparison between real and theoretical damage for Campi Alto di Norcia using the different vulnerability methods previously presented. Formisano method [50] provides less conservative vulnerability values, with underestimating of the real damage; the average value of the real damage lies in the middle between the GNDT [72] and the Vicente [32] methods, showing how the latter can better catch the influence of the aggregate effect for the presented case study, Fig. 18.

Fig. 17. Distribution of the vulnerability of buildings in the municipality of Coimbra (a) [32] and of Faro (b) [65].

Romis, based on these results, recalibrated the weights proposed in [32] by Vicente to achieve a good agreement between the observed and theoretical damage scenario for Campi Alto Norcia. Results revealed the main limitations of these methods, and, as a whole, of statistical methods, i.e., their high dependence on the building characteristics and on the seismic scenario originally used to calibrate and validate them. Moreover, none of these methods explicitly differentiate the impact of being in aggregate on the IP or OOP mechanisms.

4.3. Empirical methods

Empirical approaches rely on the statistical analysis of damage data collected during post-earthquake field surveys [73–79]. Interpreting empirical damage data can be challenging due to various sources of uncertainty, particularly related to data acquisition, which must be carefully considered. However, since empirical damage data is derived from direct observations of actual seismic performance, it serves as a valuable source of information. Moreover, due to their statistical nature, empirical approaches are effective tools for describing vulnerability in large-scale applications [80,81]. In [82], the impact of building position on the empirical seismic vulnerability of URM buildings is investigated by statistically analyzing post-earthquake damage data from the L'Aquila earthquake (2009), which is available from the Da.D.O. platform [18].

Fig. 19 shows the fragility curves in terms of five damage levels (defined to be consistent with the definitions of the European Macroseismic Scale, [83]) resulting from this study; the damage refers to the overall response without explicitly distinguishing between IP and OOP

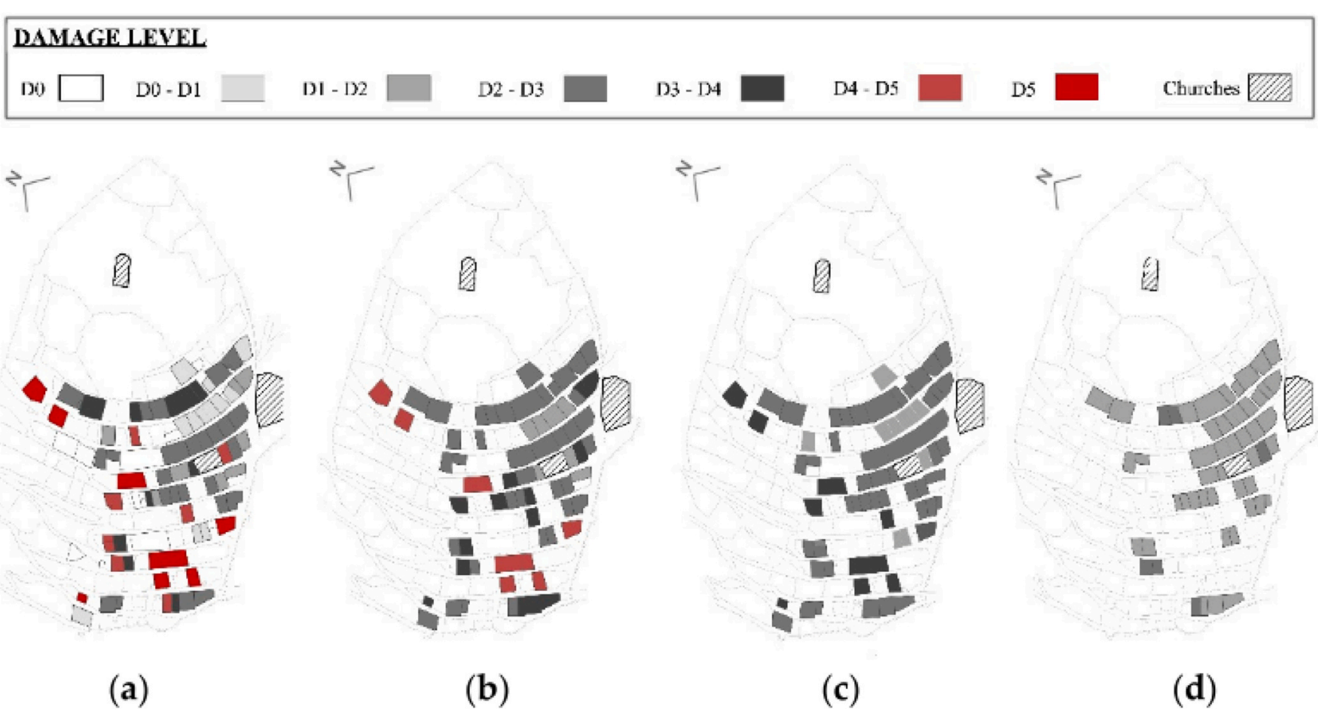

Fig. 18. Comparison between the real damage detected in the case study (a) and the theoretical damage scenarios evaluated through (b) the GNDT, (c) the Vicente and (d) the Formisano method for each SU [35].

mechanisms since this distinction is not available in the AEDES form used to collect post-earthquake damage data. Results show that SUs of buildings in aggregate are more vulnerable than isolated buildings, even if it is relevant to specify that the two stocks cannot be considered completely homogeneous on all the other structural features; in other words, this comparison cannot be completely conclusive on determining the impact of the so-called "*aggregate effect*". The impact on results is more evident in case of regular layout and good-quality masonry rather than in irregular layout and poor-quality masonry. The statistical analysis of post-earthquake damage data suggests that structural irregularity, a characteristic of masonry aggregates compared to isolated buildings, has a more significant influence on vulnerability than building position [82]. In cases of highly regular and homogeneous aggregates, higher vulnerability of external SUs is observed. Conversely, in more common scenarios where aggregates consist of SUs of varying height and characteristics, with dry connections, damage concentration tends to occur at the interfaces between SUs exhibiting different dynamic behaviours [82].

Another interesting study conducted by Valluzzi et al. [29] over a wide area affected by the 2016 Central Italy Earthquake confirmed that the vulnerability associated with poor masonry materials and wooden horizontal diaphragms carries greater weight compared to that associated with other factors generally considered crucial (e.g., number of floors and position in the aggregate). However, this study reveals that the position of the cell in an aggregate has a modest influence on the activation of mechanisms: the internal portions showed a 15 % exceedance of IP mechanisms compared to the extreme and isolated SUs, and 8 % more than ones located at corners. The OOP mechanisms are activated prevalently at the extreme and corner cells and in isolated buildings, as they do not benefit from the confinements of other cells.

4.4. Numerical methods

In the literature, there are various ways to classify numerical modeling approaches [16,17,84,85]. In the following analysis, the classification proposed in [16] has been adopted. Accordingly, mechanical numerical models are categorized based on two criteria: the scale of modeling (wall material or structural elements) and the type of discretization (continuous or discrete) [86].

The classification includes the following types of models:

- CCLM (Continuous Constitutive Law Models): These models utilize finite element modeling with phenomenological or micromechanical homogenized constitutive laws. They provide a continuous representation of the structure and its behavior.

- SEM (Structural Elements Models): These models typically employ equivalent frame (EF) modeling, discretizing the structure into piers, spandrels, and rigid nodes.

- DIM (Discrete Interface Models): These models use discrete modeling, representing the structure as blocks and interfaces. They focus on the interaction between different discrete components.

- MBM (Macro-Blocks Models): These models apply the upper bound theorem of limit analysis to predefined collapse mechanisms consisting of rigid blocks. They make assumptions compatible with the behavior of masonry structures and provide an overall understanding of the structure's response.

By considering the scale of modeling and the type of discretization, these mechanical models offer different approaches to analyze and understand the behavior of structures.

A comprehensive review of existing modeling strategies for masonry structures can be found in the literature, such as in references [14,87].

The numerical models provide a more detailed representation of the structural behavior than approaches described in Sections 4.2 and 4.3 and can capture complex interactions and failure mechanisms, aiding in understanding the response of the building under seismic forces.

The most debated topics concerning the study of buildings in aggregate are: i) how to model the interaction between SUs, therefore evaluating the pounding effect; ii) how to consider both IP and OOP mechanisms, given that the former are involved in the global behaviour

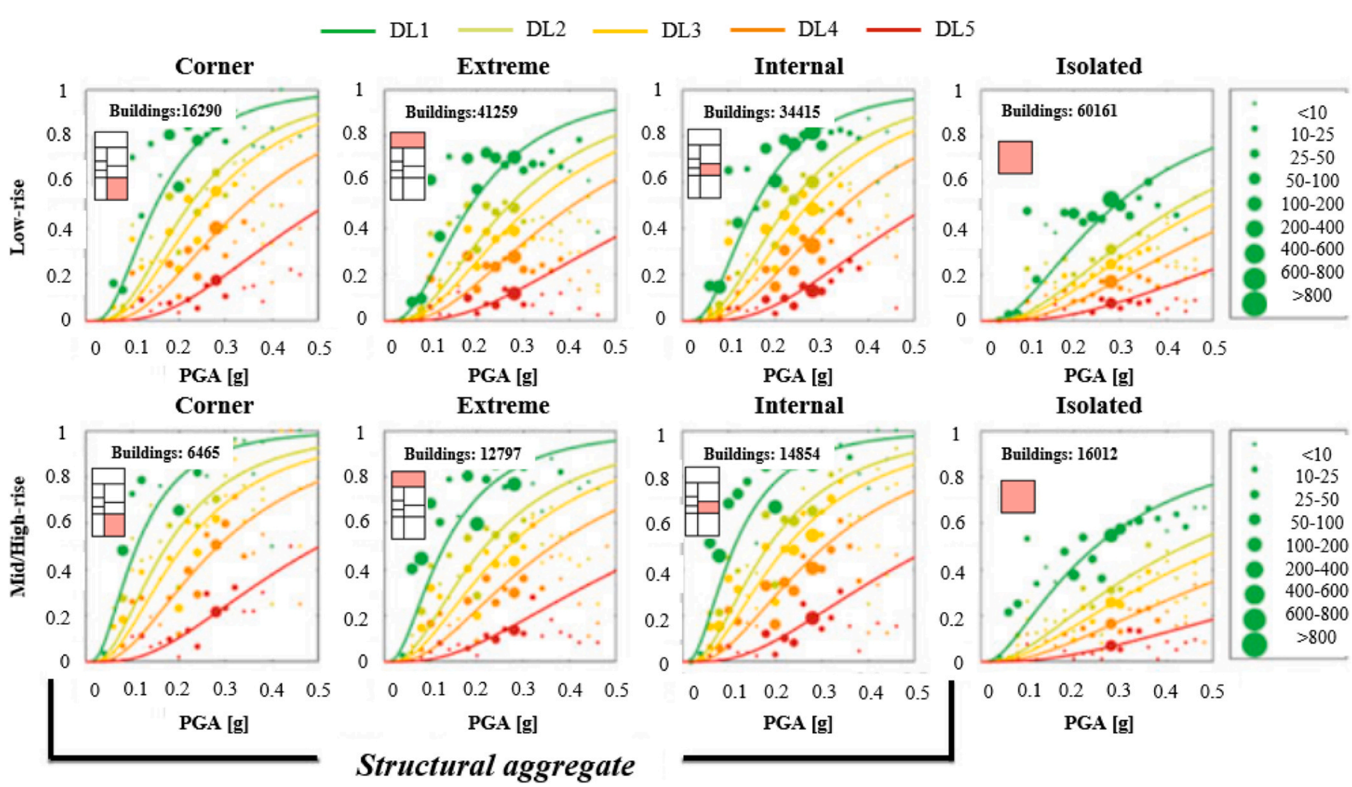

Fig. 19. Empirically derived fragility curves in terms of physical damage levels for URM buildings, according to the building position: corner, extreme, internal, and isolated buildings [82].

while the latter occur at a local scale; and iii) understanding whether the *aggregate effect* (position within the aggregate) has a positive or negative impact on the SU Fig. 20.

Analyzing in more detail the numerical modeling approaches applied in the literature to buildings in aggregate, it follows that the SEM approach is the most widely used so far in literature. It idealizes the structure into panel-scale structural components with a phenomenological or mechanical-based response [52,69,71,88–106]. Typically, masonry walls are considered a combination of piers (vertical elements) and spandrels (horizontal elements) connected by rigid areas (nodes). These approaches primarily focus on analyzing the global seismic response of masonry buildings.

The global seismic response is closely related to the IP capacity of the walls or the load transfer due to the presence of diaphragms. Global

Fig. 20. Numerical modeling strategies for masonry structures in aggregate.

analyses (static and/or dynamic incremental and iterative) are typically performed on 3D models to account for load transfer between load-bearing walls caused by horizontal actions [14]. Tremuri is among the most commonly used software for modeling using the EF method [107–110].

In the SEM framework, pounding damage is typically modeled through zero-length interface elements, characterized by linear compression and nonlinear tension softening laws inferred from axial stress-strain and flexural tests on masonry samples [111]. In [100] the connection between different units was established using steel ties that were uniformly distributed at a rate of two ties per square meter over the area of the load-bearing walls in the transverse building direction. Another approach, as presented in [88,99] explicitly accounted for the interaction effect between adjacent units by modeling the units separately from each other. This was achieved by introducing a finite-length gap representing the semi-length of the shared wall and connecting the units using elastic truss elements (with no tensile behavior) and orthotropic membranes. These elements were utilized to simulate potential transversal sliding between the SUs (Fig. 21). Additionally, struts were employed to model the ability of SUs to spread apart while preventing the interpenetration of elements. This approach allows to account for different scenario: the case where the adjacent SUs are structurally independent and have independent walls, even if in contact; and the case where one of the SUs is an infill unit that relies on the walls of the adjacent SUs, thus lacking proper interlocking between walls. In fact, these two cases may be treated differently, i.e. adopting in the second case only the strut element without the orthotropic membrane.

EF methods typically assume that any activation of the local (OOP) failure mode is prevented.

An interesting approach proposed by [88] combines the use of an EF model for the IP response of the aggregate with a rigid-block assumption for the OOP response, employing a newly developed three-linear analytical constitutive model Fig. 22. Although the OOP response is evaluated separately, it is based on time histories derived from NLDAs (Non Linear Dynamic Analyses) performed on the 3D global model, thereby implicitly considering the filtering effect provided by the dynamic response of the structure at the upper level and also implicitly accounting for the interaction between SUs and the pounding effect.

In [103], the setback of fragility curves considering OOP mechanisms is negligible, Fig. 23. The same approach has also been applied in [88] and [113], cases where the OOP mechanisms lead to a significant setback of fragility curves, Fig. 24.

These studies show how results depend on the relationship between IP and OOP behavior and on the fact that IP damage can increase the dissipative capacities of the main structure and thus, through the filtering effect, lead to a reduction in seismic action at elevation, which influences OOP mechanisms.

In [114] is proposed a formulation of a three-dimensional macro-element for modeling the dynamic IP and OOP behavior of masonry panels, which extends the approach of a previously developed macro-element to simulate the IP response. The proposed three-node, three-dimensional macroelement is implemented in the software OpenSees and describes the main features of IP and OOP behavior of a masonry wall, including second-order geometrical effects and a coupled shear/flexural response [114]. In [111], it is demonstrated how the OOP failure of elements is influenced by the modeling assumptions concerning the connection to floors in buildings with deformable diaphragms and the precise modeling of boundary connections in buildings with stiff floors.

A smaller number of structures are modelled using CCLM (Fig. 27 *(a)*). In continuous approaches, masonry is modeled as a continuous deformable body [39,115–122]. Due to the mechanical complexity of masonry, defining appropriate homogeneous constitutive laws is a challenging task. This can be pursued through direct approaches, such as constitutive laws calibrated based on experimental evidence, or through homogenization procedures and multiscale approaches, where the constitutive law of the material (considered homogeneous in the structural scale model) is derived from a homogenization process that relates the structural scale model to a material scale model representing the main heterogeneities of masonry. The homogenization process typically relies on refined modeling strategies (e.g., block-based models) of a representative volume element of the structure. As shown in [21], in these models, the unit-to-unit interface modeling is either modeled only in compression, by inserting a 3 mm gap between the SUs, or by modeling the connection between SUs as a nonlinear 2D surface accounting for mode I and mode II failure at the interface (compression-shear). These approaches usually implicitly account for OOP mechanism failure, albeit often requiring a significant computational effort, the definition of several experimental and non-physical input parameters, and/or advanced user expertise to interpret and post-process the results obtained [123].

DIMs approaches take into account the heterogeneity of masonry,

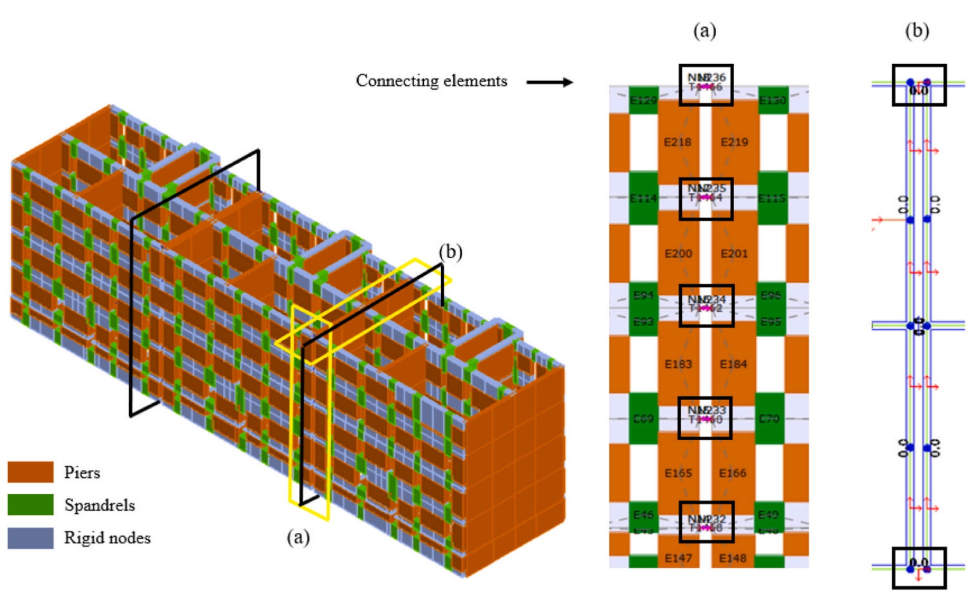

Fig. 21. (a) Tremuri model of an aggregate. (b) Detail of the model elevation at the connection between two adjacent SUs and detail of the elastic truss elements with null tensile behavior and of the fictitious floor connecting two adjacent units [112].

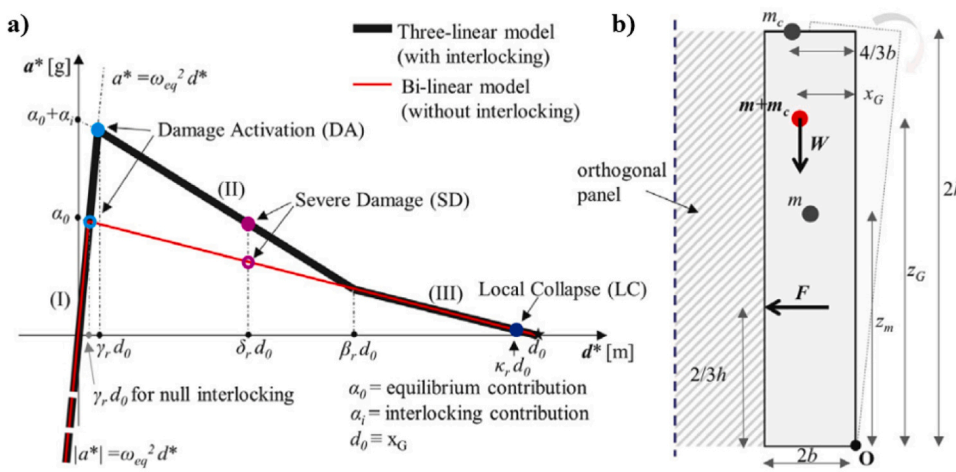

Fig. 22. (a) Constitutive model for the OOP mechanisms with an indication of the attainment of the limit states; (b) Simplified scheme assumed for the walls [88].

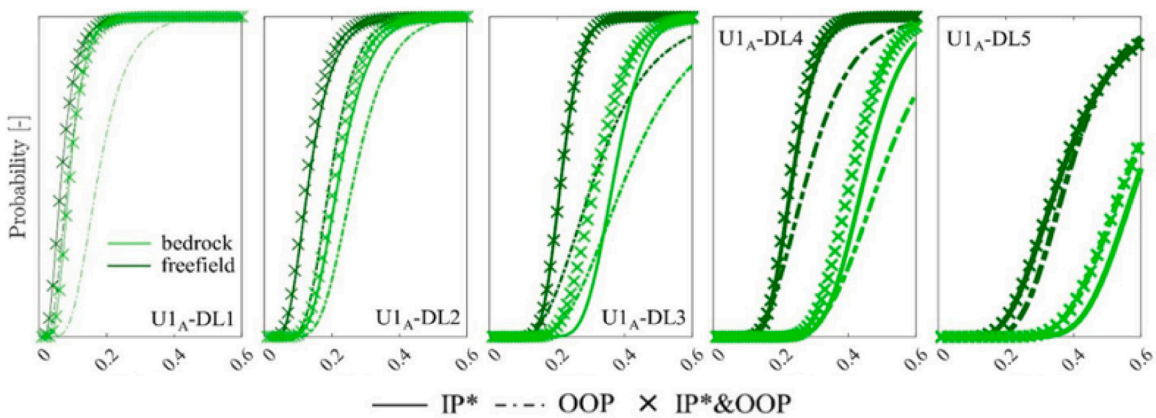

Fig. 23. Fragility curves related to IP and OOP mechanisms as well as the combined ones for each damage level [103] - the setback of fragility curves considering OOP mechanisms is negligible.

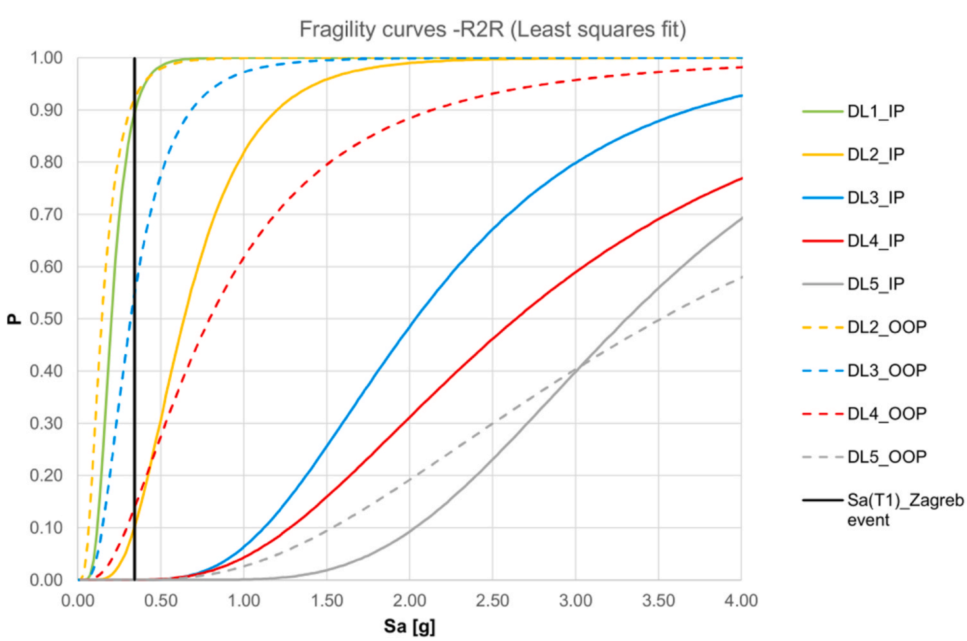

Fig. 24. Fragility curves considering IP and OOP response [113]- the setback of fragility curves considering OOP mechanisms is significant.

characterized by blocks assembled by mortar (or dry) joints, which governs the main aspects of its mechanical and failure response. These models therefore take into account the actual masonry texture, which substantially controls the anisotropy and failure pattern of the material. These models accurately represent the masonry texture, controlling the anisotropy and failure pattern of the material. This modeling strategy allows for the representation of the actual masonry bond, the inclusion of various structural details (e.g., corner toothing between orthogonal walls), and the consideration of simultaneous IP and OOP responses of masonry walls and their interactions using 3D solid models. However, the main issue of these models resides in their huge computational demand together with the calibration of many parameters they require. Indeed, a few examples of application to full-scale masonry structures can be found in the literature, particularly for buildings in aggregate [124–127]. Furthermore, the actual bonding of existing masonry structures is often not fully known, which may require approximations in the block-by-block discretization approach. In [41] to reduce the otherwise prohibitive computational expense typically entailed by DIM and consider building-scale models, a new macro-modelling strategy is devised that idealizes masonry as an assembly of solid rigid blocks connected by nonlinear interface springs. Using this technique a comprehensive parametric study is conducted to investigate the pounding between adjacent URM facades. The results suggest that the severity of damage due to SU interaction is particularly dependent on the different structural material, number of stories and the difference in height of the adjacent units.

While numerical models have been extensively used for detailed analyses and assessing the aggregate effect, their application for archetype studies and fragility curve development is relatively less frequent, Fig. 25. Fragility curves are typically derived from empirical or analytical approaches, which may utilize simplified assumptions and scoring systems to assess the vulnerability of different building types. The numerical approach can serve as a valuable tool for calibration and validation purposes. By comparing the results of numerical models with those obtained from simplified methods or empirical data, the accuracy and reliability of the simplified approaches can be assessed. This helps in improving and refining the simplified methods and enhancing their applicability for practical seismic vulnerability assessments. The literature predominantly showcases their application in analyzing specific structures in detail for safety verification or damage analysis purposes.

Considering the main open issues regarding the study of aggregate buildings, such as the modeling of interaction between structural units, the pounding effect, the interaction between IP and OOP mechanisms, and the aggregate effect, there is still a great deal of confusion on how to address these topics. The complexity of these phenomena has also been highlighted by recent experimental campaigns, such as the SERA AIMS project [21]. As anticipated in the introduction, the AIMS project conducted shake-table tests on a two-unit, double-leaf stone masonry aggregate. The tests subjected the aggregate to two horizontal components of dynamic and a blind prediction exercise was organized to evaluate modeling approaches and assumptions and understand the level of uncertainty associated with modeling such masonry aggregates. The participants were provided with the full set of material and geometrical data, construction details and original seismic input and asked to predict prior to the test the expected seismic response in terms of damage mechanisms, base-shear force, displacements and interface openings in both directions [21]. The modeling approaches featuring the DIM method led to the best predictions in terms of displacements [123], while a submission using rigid block limit [128] analysis led to the best prediction in terms of damage mechanisms. Blind prediction studies on masonry aggregates had not yet been conducted before this project, therefore, it is very interesting to understand what emerged from the results regarding the opening of the interface between the two SUs due to structural interaction. In some cases, the unit-to-unit connection was modeled with zero cohesion and tensile strength (compression-shear), in other cases, the participants modeled the interaction only in compression, while in two cases, the connection between SUs was not modeled. CoV values computed for all submissions together were large with a CoV of 160–268 % for displacement quantities. The largest CoV values were obtained for the interface openings, highlighting that the interaction between the units of an aggregate is very difficult to predict.

Despite numerous numerical analyses aimed at investigating the aggregate effect, conclusive results have not yet been reached. Moreover, in some cases they are also contradictory with respect to the results provided by the empirical approach, as testified for example in Fig. 26 where the results of fragility curves derived from NLDAs carried out on SEM models highlight a beneficial impact of the "aggregate effect" on the IP response of SUs. In particular, this is evident for the enclosed unit (US3 – 4 stories), while for the end units it depends on the specific aggregate features (e.g., planimetric configuration, adjacent unit structural features). This study considered also the effects of soil-structure interaction (FB fixed-base and CB compliant-base; A stiff soil, C soft

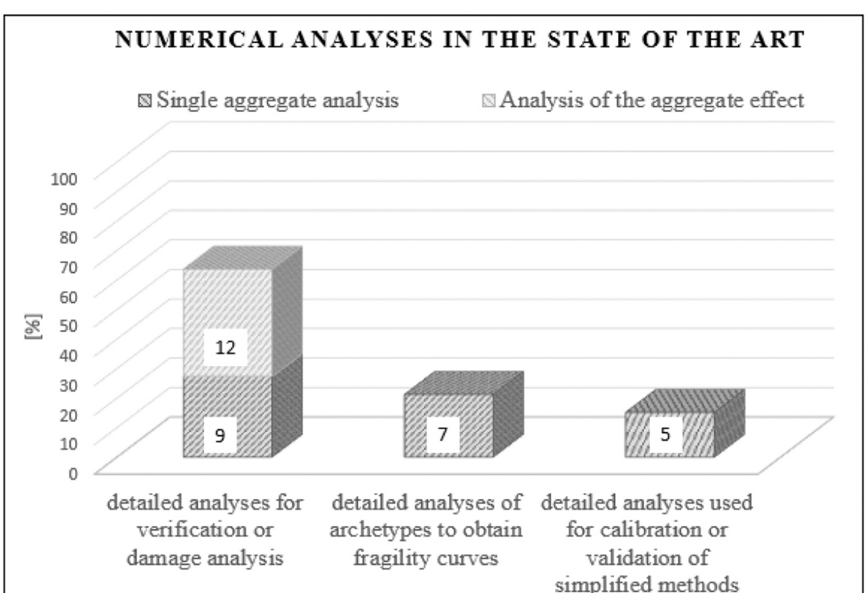

Fig. 25. Objectives of aggregate numerical analyses of the literature sample analyzed.

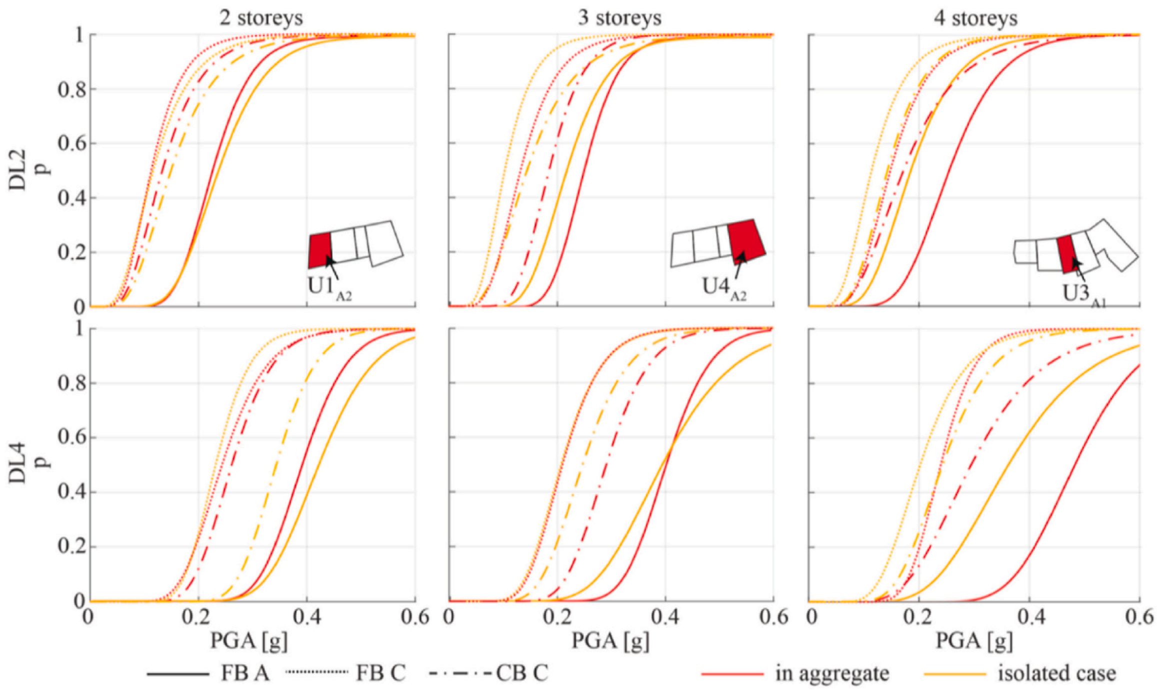

Fig. 26. Effect on the derivation of fragility curves of the aggregate effect [129]. The study focuses only to the impact on the IP response.

soil), which indeed result not relevant on the aggregate effect.

In [53], the comparison of results derived from numerical modeling, considering a macro-element approach that neglects OOP mechanisms, showed that buildings considered isolated structures have lower strength and stiffness than those of the same structures grouped in aggregates. Moreover, from the comparison in terms of vulnerability indices, it was found that the cluster condition reduces the seismic vulnerability of both structural units. The beneficial aggregate effect on the seismic behavior of structural units (SUs) has also been demonstrated in [69], analysis conducted using a macro-element approach neglecting OOP mechanisms: when inserted into aggregates, SUs can sustain seismic displacement demands greater than those resisted by isolated buildings. This effect is more pronounced for the leading SU than the intermediate one, with the former being able to attain, at the collapse limit state, an ultimate displacement about three times greater than that of the isolated SU, whereas the latter shows an ultimate displacement 1.30 times greater than the isolated SU. Therefore, [69], the SUs belonging to the examined building compound suffer less seismic damage than they could undergo when considered as single structures. In [100], the single SU appears to be more vulnerable than a terraced house for all derived fragilities. The results show that a row of terraced units requires more intense ground shaking to reach a specific damage limit when compared with the end-unit tested in the lab. The results also confirm the intuitive feel for the beneficial effect that the aggregate configuration of terraced buildings may have on the seismic response of the units when they are linked along their weak plan direction. This difference is particularly evident for minor damage states (i.e., DL1 and DL2). Another aggregate study is presented in [71], in which an increment in the values of the collapse PGA was found when aggregating identical SUs and considering the seismic action in the direction of the aggregate development. However, in the direction perpendicular to that of the aggregate development, the different geometrical properties of the resisting walls lead to an increase in vulnerability motivated by the installation of some torsional effects, particularly in the external SUs, for which lower values of PGA were obtained. In contrast, in [101], it emerged that the seismic behavior of isolated buildings does not significantly improve in the direction of aggregate development; rather, the aggregate seems to inherit the deficiencies of the seismic resistance of the individual buildings it comprises. In the direction perpendicular to that of the aggregate development, the expected damage of the aggregate is similar to the value obtained for individual buildings. This may be due to the fact that in the aggregate, the buildings behave like isolated ones but with some confinements that may produce a small improvement in their individual behavior. In [122], the findings indicate that the overall arrangement of the SUs significantly influenced their performance, depending on their location and the direction of external forces. When considered together, neighboring units exhibited a group effect that enhanced their resistance, which could not be observed when analyzing each unit as isolated. This beneficial effect is still apparent even with a flexible floor configuration, although to a lesser extent compared to the rigid floor case. The beneficial effect of the aggregate compared to the isolated configuration has also been demonstrated in [129]. In [29], it is demonstrated that the position of the cell in a cluster has a modest influence on the activation of mechanisms: the internal portions showed a 15 % exceedance of IP mechanisms compared to the extreme and detached cells, and 8 % more than ones located at corners. OOP mechanisms are activated prevalently at the extreme and corner cells and in detached buildings, as they do not benefit from the confinements of other cells. In [82], it is stated that structural irregularity, characterizing masonry aggregates with respect to isolated buildings, has a stronger effect on vulnerability than building position. A higher vulnerability of external SUs was observed in the case of extremely regular and homogeneous aggregates, whereas in the much more frequent case of aggregates with SUs of different heights and characteristics and with dry connections, damage concentration would occur at the interface between SUs with different dynamic behaviour Fig. 27.

As shown in Fig. 27 *(b),* despite the most widely used modeling approach in the literature is the SEM approach, the type of modeling that has most taken into account the interaction between IP and OOP mechanisms so far is that through DIM and CCLM. Instead, the pounding effect has been predominantly considered by the DIM approach. Most SEM models assume that any activation of local failure modes, primarily associated with the OOP response of masonry walls, is prevented [130];

The contribution of OOP behavior to the global strength and stiffness of the walls is generally considered negligible compared to the overall

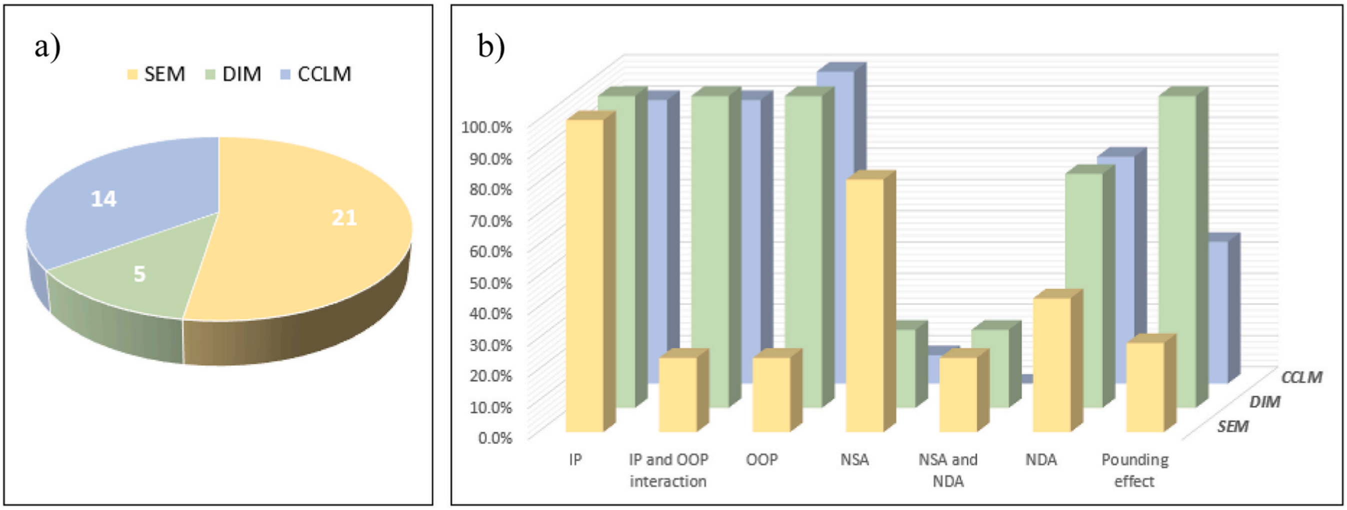

Fig. 27. (a) Number of literature use of modeling strategies considering a total of 40 papers on numerical models analyzed. (b) Statistical analysis of the types of analysis performed (NSA, NDA, both), the type of mechanism analyzed (IP, OOP, both) and the pounding effect between adjacent SUs was considered in the sample of models analyzed divided according to modeling approaches.

building response, which is mainly governed by IP damage[131]. Although simultaneous IP and OOP responses may occur [132,133], it is generally accepted that they can be adequately analyzed separately without considering their interaction [134].

However, neglecting the OOP contribution may lead to an overall underestimation of the initial stiffness and peak strength. Specifically, in cases where the OOP contribution is significant (e.g., for massive structures), the SEM approach may underestimate the capacity curve (in terms of global stiffness and peak strength) compared to more accurate CCLM models, as demonstrated in some comparative studies [134]. The integration of IP and OOP mechanisms is a very complex issue that concerns not only buildings in aggregate but all masonry structures, [135–137].

4.5. *Analytical methods*

Mechanical-analytical models, although necessarily based on simplified and conventional assumptions, provide an analytical description of the structural response by explicitly considering a limited number of mechanical and geometric parameters.

By firstly focusing on methods that consider on the IP behavior, in most cases, these models rely on simplified assumptions, including the uniform distribution of compressive stress on the resisting walls based on static loads, infinite stiffness of floors, and perfect coupling of wall elements. The strength calculation typically focuses on shear mechanisms, considering only approximate modes of collapse due to bending.

Several proposals have been made in the literature regarding these methods [138–141]. One such proposal is the mechanical model for first-level evaluations presented in the document "Guidelines for the evaluation and reduction of seismic risk of cultural heritage" [142], and the revision of the model of [141] in [143,144].

A simplified mechanical model specifically designed for buildings in aggregate is presented in [1] and applied in [145]. This model enables a quantitative assessment of the collapse acceleration, denoted as a_{SLV} (corresponding to the Life Safety Limit State) or damage a_{SLD} (corresponding to the Damage Limit State), depending on the specific limit state being examined. The model assumes that the collapse of the Analysis Unit (AU) is primarily due to the failure of the vertical resistant elements (piers). The collapse acceleration a_{SLV} is then compared to the maximum acceleration at the site, denoted as a_g, in order to determine the corresponding safety index. The proposed verification procedure is inspired by the principles of linear static analysis. However, it simplifies the process by not requiring a verification of each individual structural element. Instead, it focuses on calculating the collapse acceleration and comparing it to the design acceleration, thus providing an assessment of the safety index. The shear strength $F_{SLU,x,k}$ of the k-the floor of the SU in the X direction is provided by Eq. (1.2).

$$F_{SLU,x,k} = \frac{\theta \cdot \alpha_k \cdot \mu_{x,k} \cdot \sum_{i=1}^{M_{x,k}} A_{k,i} \cdot \tau_{r,k,i}}{\beta_{x,k}} \tag{1.2}$$

This expression takes into account the aggregate condition through the coefficients θ, α_ke $\beta_{k,x}$. The coefficient θ considers that the analyzed unit (AU) is placed within the context of the aggregate. It aims to consider, for example, the torsional effects induced in the AU due to the planimetric irregularity of the aggregate. These effects need to be calibrated based on the position of the AU within the aggregate. The coefficient $\alpha_k$accounts for the adopted force distribution; in the case of aggregates, force distribution that considers the interaction effects between the AU and adjacent SUs is permitted. Finally the $\beta_{k,x}$ coefficient represents a plan irregularity coefficient. In the case of AU adjacent to walls of adjacent SUs, it can be assumed to be equal to one, thus assuming that the torsional effects associated with this plan irregularity coefficient are inhibited by including the AU in the aggregate.

If the horizontal structures of the AU are flexible, the analysis should focus on the individual walls, or at most, effectively connected coplanar wall systems. Each wall is analyzed as an independent structure, considering the relevant vertical loads and the earthquake action in the direction parallel to the wall. On the other hand, if the floors are sufficiently rigid, an overall analysis of the AU is performed, considering the simultaneous contribution of the different resistant walls in the direction of the examined earthquake action.

However, some critical points have emerged from the application of this method. These include the determination of the fundamental period of the structure, taking into account the effect of the aggregate in the direction it develops; the shape of the eigenvector and the most suitable distribution of forces to consider; the consideration of only IP failure mechanisms; and finally, the validity of the assumptions on which this method is based, such as the infinite stiffness of the floors and the perfectly coupled response of the piers.

Referring to methods that take into account both IP and OOP mechanisms, the Vulnus method, developed by the University of Padua, stands out [146]. It consists of an automatic procedure for analyzing the seismic vulnerability of isolated or aggregated masonry buildings for a preliminary global assessment of structural capacity. Particularly interesting is the application of this method to the Umbrian historical centers of Campi Alto di Norcia and Castelluccio di Norcia, situated in the seismic area and characterized by various building typologies and different levels of aggregation. What emerges from the method is that historical masonry buildings tend to be more vulnerable to OOP mechanisms rather than IP mechanisms. Additionally, the SUs situated within the aggregates appear to fare better compared to those located at the end or corner of the aggregate [147].

Another method that takes into account both IP and OOP mechanisms is the FaMIVE method (Failure Mechanism Identification and Vulnerability Evaluation) developed by D'Ayala e Speranza [148] for studies on the vulnerability of masonry buildings in historic centers at a territorial scale. This methodology utilizes a mechanical approach that, through the survey of significant geometric data of building facades, leads to the modeling of collapse mechanisms resulting from an equivalent static lateral action simulating earthquake action. This method has been applied to the historic center of Arsita, from which it emerged that the walls of the buildings in this historic center are more affected by IP collapse mechanisms rather than OOP ones [149].

Referring instead to analytical methods exclusively aimed at OOP, there are numerous well-established methods in the literature that define analytical expressions for calculating the collapse multiplier regarding the activation of OOP mechanisms [150–152]. A complete state of the art on the available approaches for the assessment of local mechanisms is out of the scope of this paper, since the issue regarding OOP mechanisms in the case of buildings in aggregate is to appropriately define the boundary condition assumption, specifically the degree of constraint provided by the walls of adjacent SUs. More specifically, it is understood that, although OOP mechanisms are relevant for minor historical masonry buildings, this is not strictly related to the "aggregate effect" but mainly to the local structural features. In fact, the potential increase in OOP vulnerability does not stem from the "aggregate effect", but rather from the geometric configurations and structural features coming out from the formation of the aggregate, such as the lack of interlocking between walls, protruding elements, etc, i.e. the local structural features.

5. Conclusions and future research lines

In Italy and the rest of the world, most historic centers consist of masonry buildings in aggregate. Unfortunately, despite their widespread presence, standardized procedures for assessing their seismic vulnerability do not exist. The difficulty in standardization arises from the fact that SUs can exhibit multiple features, leading to significant structural variability that makes the a-priori identification of the most relevant ones (i.e. the ones most affecting the seismic response) varying the cases very complex. Understanding which are the most important parameters, those that influence whether one damage mechanism is activated rather than another, is not so straightforward in buildings in aggregate. In recent years, substantial efforts and advancements have been made in the literature regarding this issue (also including the use of modern machine learning techniques in [153]), and several methodologies have been proposed for assessing the seismic vulnerability of buildings in aggregates. This paper presents the methodologies that have been employed thus far in addressing the topic of aggregates, along with the real case studies where these methodologies have been applied.

These vulnerability assessment methods have been developed for different purposes: some are designed for individual building assessments, including verification purposes, while others are intended for large-scale assessments. The resulting output of these different methods can be either a fragility curve or a safety index. Current research trends and the latest applications in the field of seismic risk mainly focus on mechanical models, which allow the utilization of sophisticated hazard analyses (seismic input in spectral form) and the explicit consideration of various parameters that define the structural dynamic response. Methods based on simplified mechanical models are more suitable for analyzing a large number of buildings, as they require fewer parameters and are computationally less demanding compared to detailed mechanical models. Numerical methods, on the other hand, are sophisticated techniques typically used to evaluate individual structures at a higher level of detail, employing more refined modeling techniques. The main challenges in the field of aggregates include determining the most appropriate method to use and addressing the existing deficiencies in describing all the factors upon which the response of aggregates depends.

Despite significant efforts in research studies, some shortcomings remain evident from the analysis of various methods and approaches in the literature. Particularly, the aggregate effect and the explicit consideration of the interaction between local mechanisms (such as OOP or pounding mechanisms) and the inter-unit behavior are lacking in most studies. The integration of IP and OOP mechanisms is a very complex issue that concerns not only buildings in aggregate but all masonry structures. From the state-of-the-art it emerges that the integration of these two mechanisms is often overlooked, with a focus either solely on the IP response (using equivalent frame-type macro-models) or the OOP response (using macro-blocks). Discrete or continuous modeling approaches implicitly consider both IP and OOP responses, but in this way a distinct classification is missing, and this makes it challenging to conduct safety verifications. Therefore, this topic remains very complex and difficult to address, despite the various modeling options. There are experimental campaigns that aim to understand how much the OOP response degrades after IP damage occurred, but these tests mostly refer to infills of reinforced concrete buildings.

Empirical methods often treat unit location as an additional vulnerability source, making it challenging to investigate in-depth whether the interaction among SUs is detrimental or beneficial based on the characteristics of SUs. Furthermore, several analytical methods only account for the inter-unit or OOP response separately, without considering their interaction.

From the perspective of IP mechanisms, a SU inside an aggregate is less vulnerable compared to the condition it is isolated. However, this concept is not always valid when the SU is located at the edge or corner of the aggregate, especially when the aggregate has a highly irregular plan configuration, as this can result in torsional effects that may increase the vulnerability of the SU. Regarding OOP mechanisms, being part of an aggregate does not affect the OOP response of the SUs. The potential increase in OOP vulnerability does not stem from the aggregate effect, but rather from the geometric configurations and structural features coming out from the formation of the aggregate, such as the lack of interlocking between walls, protruding elements, etc.

While numerical analyses are too demanding, especially in the engineering practice, to analyze entire aggregates, the large-scale approaches developed thus far tend to oversimplify the complexity of aggregates by disregarding their specific characteristics. From wide analysis of observed damage in masonry building in historical centres, after the recent earthquakes in Italy, the phenomenon of pounding is not the statistically most significant, and it does not result as the most dominant in producing the collapse mechanisms of the SUs. However, the proper modeling of boundary conditions is necessary, as these can influence the structural response and the modal behavior of the structure.

Simplified methods, from the perspective of their potential use in professional settings, appear to be the most suitable approach for assessing and identifying the most vulnerable SUs within aggregates that require intervention. However, as currently conceived, these simplified methods still have several limitations that hinder their effectiveness and reliability.

The significant social and economic impact of earthquakes necessitates proactive seismic adaptation measures for the built heritage and the promotion of a safety culture. The standardization of seismic risk assessment methodologies for aggregate structures, similar to those available for isolated buildings, would be a remarkable achievement in safeguarding the historical centers, which hold immense historical value. Future research developments could focus on refining the simplified models and their parameters, given the complexity of the topic, potentially incorporating machine learning techniques. Additionally, when considering mechanical methods, it is essential to analyze the interaction between SUs in order to capture the actual damage mechanisms of the structure and perform safety verifications. The main strategy is to model the entire aggregate, or at least some adjacent SUs, to accurately simulate the boundary conditions. A possible hybrid approach could involve modeling the SU as an isolated building and applying appropriate constraints (links and concentrated actions—forces or masses) to replicate the interaction with adjacent buildings. However, the complexity of calibrating these parameters has so far discouraged the adoption of this approach, which explains why we did not find specific literature on the subject.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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