An expeditious methodology for the seismic vulnerability assessment of building aggregates

Riccardo Gulli, Giovanni Mochi*, Giorgia Predari

Highlights

An in-depth knowledge of the historical buildings allows us to predict the damage mechanisms that can be generated by an earthquake on a built fabric, thanks to the study of historical documents and to surveys carried out on site.

An expeditious assessment procedure based on indicators related to the masonry behaviour of building aggregates has been developed.

The method has a preventive purpose, as it allows to classify the building aggregates of a historical center before a seismic event occurs.

Abstract

The objective of this research is the development of a protocol for the expeditious evaluation of seismic vulnerability of building aggregates in Italian historical centres, which is based on the determination of synthetic indicators to provide a preliminary assessment of their potential damage under the earthquake. The 2012 earthquake in Emilia-Romagna allowed to test the effectiveness of this method. Its application to the building aggregates of the historic center of Mirandola (MO) allowed to verify how it would have been possible to identify in advance the damage scenario recorded after the earthquakes.

Keywords

Building aggregates, Seismic vulnerability, Historical centres, 2012 Earthquake

1. INTRODUCTION

The concept of seismic vulnerability referred to building aggregates has a different meaning when compared to the same words in the case of isolated buildings. For the latter, this concept can be expressed in the capacity of the building to absorb the seismic acceleration without producing negative effects on its usability, on the protection of users or on the loss of the asset.

For historical building aggregates, which derive from multiple phases of transformation and which are characterized by constructive solutions linked to local traditions, the most appropriate meaning of seismic vulnerability is the evaluation of their behaviour under an earthquake not in absolute terms,
but relatively to urban heritage.
Moreover, in the study of the seismic vulnerability of building aggregates, one of the objectives is the need to provide a valid aid to the technicians who must express a judgment on the behaviour of individual property units belonging to a building complex, to propose the best intervention solutions. Often, they don’t have the possibility to reach an effective knowledge because they don’t know the phases of construction and transformation of the building complex in its entirety [1]. In this concept, the concept of vulnerability of a building aggregate includes the possibility of obtaining useful information to reach a greater awareness in building interventions.

A research -mainly focusing on the historical centres of the area affected by the 2012 Emilia earthquake- was begun to define significant and effective levels of vulnerability and to validate hypotheses and proposals on the definition of a methodology to identify in advance the situations of greater fragility and the potential damage to parts of the buildings. The post-event scenario provided an important database to understand how the proposed methodology can be efficient for the described objectives through its application to the building aggregates of the historical centre of Mirandola. The ancient centre of this city is an excellent sample, as it is representative of the historical architecture in Emilia-Romagna both for the formation and transformation processes of the town, and for what concerns the construction characteristics deriving from local building traditions.

The studies of Antonino Giuffrè, and in particular the case of Ortigia, are the starting point of this research [2]. From that moment on, the focus has been shifted from the single building to the building aggregate as the minimal unit of the historical urban fabric [3], [4].

As Giuffrè had already pointed out, “the earthquake does not disintegrate houses, but it selects the structural parts and the weakest technological solutions, causing damage and collapse through mechanisms that can be defined in advance”. In fact, recent Italian earthquakes have highlighted how the primary seismic vulnerabilities of historical buildings can be found in the connection systems between the construction elements and in the stratifications and transformations experienced over time. In these terms, the vulnerability of building aggregates can be identified as the propensity to damage that is generated due to the constructive lacks of the building [5].

The original proposal on the possibility of measuring the vulnerability of the building aggregates in terms of damage propensity and constructive criticality is based on historical and archival research, which allows to identify the phases of construction and transformation of the built-up area. This plays a role of
primary importance together with the careful reading of the construction data both for what concerns the materials and for what concerns the realization techniques [6].

2. DESCRIPTION OF THE METHODOLOGY

The method requires different phases of study, first on the historical fabric, then on the building aggregates. The seismic vulnerability assessment derives from the calculation of indicators which are defined through the analysis of the typical evolutionary processes that have affected the aggregates, both in plan and in elevation and through the investigation of techniques and historical building solutions used in the local area. In fact, these factors are directly related to the methods of damage [7]. The final result of the evaluation is an overall index, which is basically the sum of partial indices, each multiplied by its own weight, which was initially determined on an experiential basis and subsequently refined on a statistical basis.

First of all, the methodology is based on the observation that the seismic damage of the historical building derives from the loss of stability of individual components, which are seen as rigid blocks moving due to the ground acceleration. Then, from the insufficient shear strength of the walls [8].

This second problem originates from issues related to the building materials; on the other hand, the first derives essentially from the processes of formation and modification of building fabrics, so that the comprehension of the transformation phases becomes the key-point for the behaviour prevision [9].

Understanding the first phase of the fabric construction is the starting point of this process; different phases of plan expansions, elevations, re-fusions, unifications, occupations of previous empty areas, demolitions and reconstructions lead to the current situation. This initial phase can only be hypothesized when there is no specific, historical or archaeological documentation, although some indirect sources may constitute an interesting reference base [10].

The study of the vulnerability of building aggregates followed the collection of data. The vulnerability has been defined through indicators which are considered significant due to their causal relationship with the damage: out-of-plane collapse of the façades and of the tympanums, cracks due to the rafters, hammering due to constructive irregularities (as the presence of concrete buildings in the aggregate), weak shear strength due to insufficient width of the masonry walls.

In addition to these, there is another essential indicator to include the global in Italia hanno messo in luce come primarie vulnerabilità sismiche dell’edilizia storica stiano da ricercarsi nei sistemi di connessione fra gli elementi costruttivi e nelle stratificazioni e trasformazioni subite nel tempo. In questi termini, la vulnerabilità degli aggregati edilizi può essere intesa come propensione al danneggiamento che si genera a causa delle carenze costruttive dell’edificato [5].

A ciò si è aggiunta un’originale proposta circa la possibilità di misurare la vulnerabilità degli aggregati edilizi in termini di propensione al danno e di carenze costruttive in cui la ricerca storica e archivistica, mirata alla individuazione delle fasi di impianto e indicie parziali multipliciti ci aviano un ruolo di primaria importanza insieme all’attenta lettura dei dati costruttivi sia per ciò che concerne i materiali utilizzati, sia per quanto attiene alle tecniche realizzative [6].

2. DESCRIZIONE DELLA METODOLOGIA

Il metodo prevede quindi diverse fasi di studio sul tessuto storico, prima, e sui singoli aggregati, poi. La valutazione della vulnerabilità sismica deriva dal calcolo di indicatori che sono definiti attraverso l’analisi dei processi evolutivi tipici che hanno interessato gli aggregati sia in pianta, sia in alzato e mediante l’indagine sulle tecniche e sulle soluzioni costruttive stagionali utilizzate in ambito locale poiché tali fattori sono direttamente correlati alle modalità di danneggiamento [7]. Il risultato finale delle valutazioni è un indice complessivo che costituisce sostanzialmente la somma degli indicatori parziali moltiplicati ciascuno per un proprio peso, determinato inizialmente su base esperienziale e successivamente perfezionato su base statistica. La metodologia si fonda innanzitutto sulla constatazione che il danneggiamento sismico dell’edificio storico deriva, in primo luogo, dalla perdita di stabilità di singole componenti intese come corpi rigidi posti in oscillazione dall’accelerazione del terreno e, solo in seconda battuta, dall’insufficiente resistenza a taglio delle murature [8]. Se il secondo problema è originato da questioni legate ai materiali impiegati, il primo deriva essenzialmente dai processi di formazione e modificazione dei tessuti edilizi per cui la ricostruzione delle fasi di trasformazione diviene la chiave fondamentale per la previsione del comportamento [9].

Il riconoscimento della prima fase di costruzione delle abitazioni costituisce il punto iniziale di questo processo che; passando per le diverse fasi caratterizzate da ampliamenti in pianta, sopraelevazioni, rifusioni, accorciamenti, intasamenti di precedenti aree vuote, demolizioni e ricostruzioni porta fino alla situazione attuale. Questa fase iniziale può essere solo ipotizzata, quando non esiste una documentazione specifica, storica o archeologica, sebbene alcune fonti indirette possano costituire un’interessante base di riferimento [10]. Dalla raccolta dei dati si è passati poi allo studio delle
aggregate behaviour; this refers to the entire construction, not only to the façades. This indicator, the wall disconnection index, allows to understand the possible damage to the internal parts of the serial building. The wall disconnection index is also essential since it allows to define the portions of façades that can be subjected to out-of-plane collapse, and the width of the fronts to be considered effective for the shear mechanism.

Figure 1. Example of graphical representation of the façades transformation phases.

3. THE HISTORICAL CENTER OF MIRANDOLA

Through the collection of information on the above issues, it was possible to define seismic damage scenarios that were compared with the real manifestations of what the 2012 earthquake produced on the building aggregates of the historical center. The surveys and bibliographic research have been carried out since September 2012; this allowed to establish the database to start the experimentation.

Initially, 31 blocks of the historic center were identified, which were then subdivided into further building aggregates characterized by compactness and continuity of the wall fabrics.
The blocks involved in the study are those mainly for residential use, excluding portions having a specialized use and those with a predominant presence of isolated buildings or belonging to individual phases of construction (ie areas characterized by religious institutions or complexes coinciding with single-use destinations).

The historical research has initially allowed to identify the phases of evolution of the centre. The construction of the fabric began with a first nucleus identifiable with an early medieval curtis, followed by a series of extensions that proceeded through successive construction phases until it reached the domain of the castrum by the Pico family in the fourteenth century. The fortunes of the family were linked to the progress of the city. Mirandola came to the modern period with a fortification of bastions and an extension of the town that made it one of the major cities between Modena and Ferrara.

At this point, the consultation of archival documents was combined with historical research, reaching the most precise definition of the transformations undergone by the different building aggregates. These documents referred to the post-unitary cadastral plans and estimated appraisals between the eighteenth and nineteenth centuries, where the buildings were also described through schematic graphical representations.

The survey activity allowed to understand the constructive characterization of the building aggregates, and this was then represented in specific drawings.

Together with the definition of the building component, the survey allowed to identify the damages suffered by the buildings along the public streets. This provided the framework for carrying out the evaluations on the expected efficiency of the methodology.

The conformation of the first construction of Mirandola was based on a hypothesis now generally shared; this consisted in the adoption of rectangular blocks and rectangular-shaped lots on which the houses were built, with the smaller side along the main roads, coinciding with the long sides of the blocks. This layout of the buildings -defined as “gothic lot”- is confirmed by the historical iconography, which shows a subdivision of the center into blocks with the described characteristics.

The buildings were concentrated along the streets and they left wide open spaces inside; over the centuries, these spaces have been affected by enlargements with a constant increase in building density. This density was further increased with the raising of buildings, from the original two levels to the height of four floors. In addition to the transformation processes already mentioned, these modifications were characterized by constructive solutions not designed to guarantee safety during seismic events.
For the transformations in the last two or three centuries, the archival research has allowed to record the processes of modification of the historical building with great reliability, thanks to the reports of the appraisers. These documents provide information of great interest on the previous building phases, as well as that of the first construction, such as the precise cataloging of some of the typical transformations described by the building typology texts [11].

Figure 2. Expansion phases of the historical center of Mirandola.

4. RESULTS

For each of the identified building aggregates, a damage scenario was obtained thanks to the methodology based on the described indicators. The reconstruction of this scenario on the façades allowed to do a comparison with the damage which was detected after the 2012 earthquake and to do some considerations.

The effectiveness of the methodological path is evidenced by the lack of unexpected damages. These are mainly referred to shear mechanism; therefore, it is necessary to clarify the hypothesis of evaluation of such damage indicator, as it is based on an empirical datum. In fact, it is estimated by a ratio between the sum of the width of the bearing masonries and the width of the whole façade between two masonry discontinuities.

The façade was defined as weak for shear stresses when this ratio was less than 45%. The presence of shear cracks in some façades where this ratio was...
high enough highlighted the need for greater attention in defining a different relationship. Perhaps the limit of 45% can be raised or special situations can be considered when the prevision has not received the evidence of the experience.

Regarding the prevision of out-of-plane mechanisms, the methodology proved to be very effective, managing to predict all such behaviour. The comparison between the prevision and the damage survey shows how the protocol indicates a potential damage higher than the real one. This can be interpreted as a margin of safety regarding the real situation, and we believe that this cautionary prevision should be related to an implicit characteristic of the method.

In fact, the protocol does not consider the actual energy generated by the earthquake; it cannot be related to the peak ground acceleration during the seismic sequence as it is linked to the construction processes, the structural deficiencies and the building features.

Accelerations could be considered later, with statistical data to record how the energy generated by the earthquake systematically damages an asset in a specific area, which is characterized by the use of typical materials and construction techniques.

Figure 3. Survey of the real damage on the façades.
The application of the protocol on the 31 aggregates of the historical center of Mirandola allowed to identify three classes of aggregate vulnerabilities; we highlight how the most vulnerable are some of the oldest building aggregates and others that have undergone more extensive transformational processes.

At the end of the evaluation, the damage map of the «reconstruction plan» was found. It was designed by the city administration on the basis of the Aedes cards which have been compiled by private technicians for each building. We remember how these cards are prepared for each housing unit by different technicians, each of them with his own objectivity, and how the classes identified are in a greater number than those under evaluation. But if we standardize the classes of the cards to our vulnerability classes, by compacting usable, partially uninhabitable and unusable buildings, we notice a good correspondence between the prevision and the survey of the damage.

Figure 4. Comparison between the results of the protocol and the survey of the “reconstruction plan”.

5. FURTHER DEVELOPMENT OF THE RESEARCH

The first result was the verification of the consistency and effectiveness of the analysis procedure for the vulnerability of building aggregates.

For the studies that have been carried out so far, the protocol shows a stability
of the results, due to the analysis of a context that is characterized by a wide historical and technical-constructive homogeneity. Therefore, if the procedure appears to be effective, it is still necessary to clarify which variations can make it more precise with regard to the prevision of certain damages. The underestimation obtained in some aggregates provided cues for further adjustments of the methodology, with a revision of the calculating method of partial indicators. A further partial indicator was introduced too, to estimate the presence and extension of false walls, which increase internal vulnerability.

In the meantime, the research has produced further outcomes regarding the definition of the protocol. Further analyzes are carried out for building aggregates in contexts similar to the historical center of Mirandola, such as Castelfranco Emilia, whose historical center has similar characteristics. The study is about to be completed on the aggregates of San Giovanni in Persiceto where the original circular urban layout offers interesting reasoning for morphological analyzes.

As in Mirandola, the analyzes concern the whole building aggregates of each historical center also in Castelfranco and San Giovanni in Persiceto, which are in a similar material context. In the meantime, single building aggregates have been analyzed in other historical centers, with the aim of understanding the role of local building traditions. Carpi, Fermo, Lanciano and Lucera are linked to the three mentioned centers because they are entirely built with brick walls, but the different geographical contexts could clarify the role of the peculiarities of traditional constructions. These comparisons can be made only through the introduction of a corrective parameter to allow an effective comparability of the results. This can be an index of the masonry quality, which considers the great importance of the nature and shape of the bricks as well as their meshing and connection in the transversal direction.

5. REFERENCES

contesti di provenienza potrebbero permettere di chiarire il ruolo giocato dalle peculiarità della costruzione delle architetture tradizionali. Tali confronti possono essere operati solo a partire dalla presenza di un parametro correttivo che permetta una effettiva confrontabilità dei risultati ottenuti e tale, crediamo, possa essere un indice della qualità muraria che tenga conto della grande importanza rivestita dalla natura e dalla forma dei conci costituenti oltre che dal loro ingranamento e connessione in direzione trasversale.