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Seismic damages on fortified architectures: Lessons learned from three earthquakes (Emilia 2012, Central Italy 2016, Albania 2019)

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ABSTRACT: The recent earthquakes that hit the Mediterranean Europe area have highlighted the fragility of our historical built heritage. Paradoxically, even if they look as massive structures, designed to stand exceptional stresses, the fortified architectures were among the most damaged. The paper focuses on a comparative analysis of the main building features of these peculiar buildings, damaged by the strongest earthquakes in Europe in the last ten years – Emilia 2012, Central Italy 2016 and Albania 2019 – with the aim of recognizing the typical vulnerabilities, which favour the recurrence of specific damages. The experience acquired through the observation of these damage mechanisms allowed to assess the frequency of their occurrence, thus identifying the priorities of the interventions in relation to the seismicity of the analysed areas. Indeed the observation and classification of the real damage is seen as the first step for a focused preventive restoration approach.

Keywords: Fortified architecture, Castles, Damage mechanism, Earthquake, Empirical approach

1 INTRODUCTION

The recent earthquakes that hit the Mediterranean Europe area have highlighted the fragility of our historical built heritage. Paradoxically, even if they look as massive structures, designed to stand exceptional stresses, the fortified architectures were among the most damaged. In particular, the 2012 earthquake that hit the Emilia region in Northern Italy was the first important occasion to analyse on a large scale the vulnerabilities connected to the specific building typology of castles and other fortified architectures (Cattari et al., 2014), in a similar way to the one adopted after the Friuli earthquake for churches (Doglioni et al., 1994). This first study concentrated on a quite homogeneous group of 13 castles built in a plane, mainly in brick masonry: 10 recurring damage mechanisms were identified for that typology. Later, this study was widened and validated by Coïsson et al. (2017), through the analysis of more than 70 Italian castles damaged by earthquakes in the last 40 years. The research carried out on data from structures in different geographic areas, built with different materials and constructive features, allowed to define a chart of 19 recurring damage mechanisms.

The present paper aims at continuing this comparative analysis, widening the observation and catalogue of damages in areas outside the Italian peninsula. In particular, the research focuses on the analysis of the building features and of the materials characteristics of the fortified architectures of the analyzed areas and on the related vulnerabilities shown in the occasion of the recent severe seismic events: Emilia in May 2012 (Zanazzi, 2022), Central Italy in August and October 2016 (Coïsson, Ferretti and Lenticchia,

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2017) and Albania in November 2019 (Freddi et. al, 2021) (Figure 1). Despite these areas are not close one another and have different building histories and traditions, it was possible to identify similarities in the constructive features, due to the fact that all the buildings were built with the same purpose, and comparable macroelements could be defined, which tend to suffer damages following recurring mechanisms. This approach can be defined as phenomenological (Lenticchia and Coïsson, 2017), as it models the relations between two phenomena (the seismic action and the suffered damage) in a way which is consistent with the theory of structural engineering but is derived from the observation of the frequency of each damage type rather than directly from theoretical, numerical analyses. The awareness that the different masonry building typologies are characterized by specific, recurring vulnerabilities allowed to develop a prevention strategy at a territorial scale, thanks also to the adoption of a Geographic Information Systems (GIS). Indeed the observation and classification of the real damage is seen as the first step for a focused preventive restoration approach.

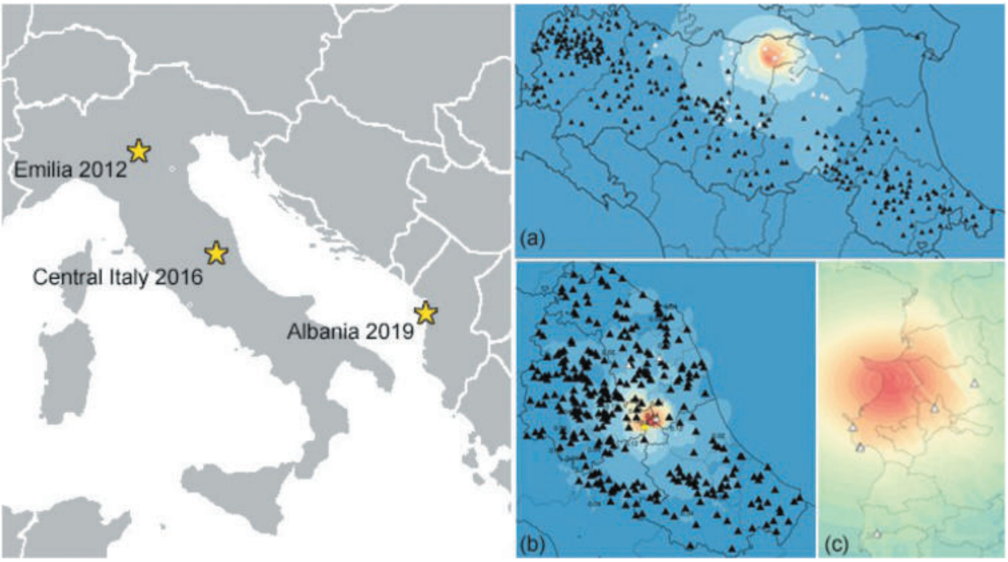

Figure 1. Location of the epicenters of the three analysed earthquakes (on the left) and of the damaged castles (on the right): (a) Emilia 2012; (b) Central Italy 2016; (c) Albania 2019.

2 MACRO-ELEMENTS AND BUILDING FEATURES

The term "fortified architectures" includes very disparate building types: fortresses, strongholds, castles, fortified walls and citadels, towers. From a structural point of view, the meaningful aspect is the presence of building parts, like towers, walls and palaces, characterized by typical macro-elements, with a characteristic response to seismic actions: merlons, battlements, pepperpot turrets and other protruding elements, together with more common macro-elements (vaults, stairs, floor and roof structures…).

These typical macro-elements, strictly connected to the warfare techniques, which evolved during centuries, are widely present in European fortified constructions, with variations based on the geographical areas, on the materials available, on the period of construction (or modification), on the strategic importance of the complex.

Looking at the three analysed areas, the adopted material, typological and morphological solutions will be identified in connection with the related vulnerabilities, which have favoured, in the occasion of the recent seismic events, the activation of typical damage mechanisms.

2.1 *Typical morphology and macro-elements*

The morphological aspect of Albanian castles is quite different from the Italian ones. Indeed, in general, Italian castles, even if they start with towers and walls surrounding an inner court, tend to fill in this court in time with palace-type buildings. This evolution follows an evolution in the use of these buildings, that were often transformed into residences after the 16th century, when the introduction of artillery made them unfit to stand military assaults. On the contrary, Albanian castles are still composed, in most cases, by wall enclosures and protruding towers and are usually devoid of palaces (Figure 2). For the Italian castles, the presence of these palaces, often added without an effective connection with the pre-existing walls, are a typical element of seismic vulnerability.

Figure 2. Three castles instantiating the general features of the three analysed regions. From the left: Rocca di Cento (Emilia), Castello di Capodacqua (Central Italy), Bashtove Castle (Albania).

Another difference that was observed is the absence, in the Albanian castles, of protruding parapets with corbels and machicolations. Indeed these structures were originally made in timber and were temporarily installed only in case of danger. In Italy, starting from the 9th-10th centuries, they started to be built in a permanent way, "translating" the timber framework in brick or stone masonry structures (Cassi Ramelli, 1964). In Albania this transition didn't take place and these elements continued to be built in timber, only when necessary. For this reason, at present only the traces of the slots than once hosted the beams can be seen (Karaiskaj, 1981).

2.2 *Materials and building techniques*

The materials traditionally used for construction in the three analysed geographical areas are not homogeneous, but they vary depending on the orographic conditions in which the single artifacts were built. In general, the buildings in alluvial planes, in Emilia but also in certain parts of Central Italy and of Albania, are usually built in clay bricks masonry, while the ones on the hills and mountains are generally in stone, with various shapes, dimensions and textures. In Emilia the masonry is often thick but composed of three leaves: the two external ones of good quality, but often not well connected, and the internal part made of a mixture of poor mortar, bricks and cobblestones (Figure 3).

The building techniques adopted in the construction also changed during time. If this is not a great issue for the analysed Italian castles, whose periods of construction were all comprised between the 10th and the 15th centuries, it is more meaningful for Albanian fortified architectures. The ones damaged by the 2019 earthquake and considered in this research belong to very different periods: the fortified walls of the city of Durres date back to the Roman period and were then modified in the Ottoman period, while the castles outside of town were built in the Middle Ages. The first ones are characterized by a high quality masonry, mostly in bricks, and in particular by a mortar with hydraulic properties and high strength. The latter are instead mostly in stone (also Bashtove, which is in a plane), with a more disordered texture and with a poor mortar, with a low quantity of binder.

Figure 3. Instantiating cross sections of walls. From the left: Rocca di San Felice sul Panaro (Emilia); Norcia curtain wall (Central Italy); Bashtove Castle (Albania).

In the Italian fortified constructions, the building features of the protruding parapets can be divided in two typologies: stone corbels ("gattoni"), observed mostly in Central Italy, composed by three or four stone elements cantilevered one over the other, and brick masonry structures, widely spread in the plane areas, composed of about 20 layers of bricks, slightly jutting out one over the other, usually strengthened by a hidden timber element on the top. In both cases, over these supporting structures, small arches were built, defining the space for the machicolations and the base for the crenellated parapet.

The timber element on top of the brick masonry elements was certainly introduced to carry the tensile actions connected to the strut and tie mechanism that develops due to the presence of the concentrated eccentric load of the parapet. Also other hypotheses have been made for secondary purposes of these elements: sustaining the structure during the setting of the mortar and transferring part of the load directly on the wall behind, relieving the corbelled masonry elements (Facchi, Grimoldi, Landi and Zamperini, 2020). Nevertheless, with the passage of time these timber elements became a source of vulnerability, as they were not well protected by weathering and it was impossible to make maintenance or monitor their conservation state. Most of these elements are now rotten, they are not able to stand the actions they were designed for and represent a discontinuity within the masonry.

Another focus should be made on the recent interventions made in the last 50 years on the analysed buildings, often with little care to the compatibility of the adopted materials. In all the three areas investigated, some cases could be observed where the introduction of reinforced concrete elements in floor and roof structures caused sever local collapses, due to the difference in stiffness between the strengthening element and the masonry. Very representative cases, from this point of view, are the Rocca di San Felice sul Panaro (Emilia), Rocca di Arquata del Tronto (Centro Italia) and the Castle of Kruja (Albania).

3 TYPOLOGY-RELATED VULNERABILITIES AND DAMAGES CHART

Recent studies (Cattari et. al, 2014; Coïsson, Ferretti and Lenticchia, 2017; Zanazzi, 2022) allowed to identify and schematize the main macro-elements that compose the examined building typology and a first interpretation of the related recurring damage mechanisms, based upon the observation of the real damage, comparing different case studies in Emilia and in Central Italy. In the present paper, this comparative analysis has been widened also to the Albanian castles damaged by the 2019 earthquake, spotting many similarities. Among the main common vulnerabilities we can highlight the inadequate connection between parts built in different periods – very common in fortified architectures which were adapted during time to the different defensive needs – which can favour hammering effects among the different parts. The most significant damage mechanisms regarding the single building parts are instead summarized as follows.

3.1 *Torsional damage mechanism of the tower*

The damage mechanism activates with in plane deformations due to the shear stresses in the masonry. In many cases, the presence of eccentric constraints like defensive walls can trigger a torsional response of the tower to horizontal actions, usually uneven along the height. The typical crack pattern is represented by inclined cracks, single or X shaped, which often pass through windows or other openings (Figure 4). An effective connection between the different structures and the presence of evenly distributed tie-rods can limit the development of this mechanism. On the contrary, the natural irregularity of the fortresses, both in plan and in elevation, with different height and slenderness of walls and towers, can induce a different dynamical response, which contributes to the activation of the mechanism. The mechanism is similar to the one proposed in the damage chart for churches for the bell towers (Modello A-DC, in D.P.C.M., 2006).

Figure 4. Torsional damage mechanism in the tower. From the left: Reggiolo Castle (Emilia); Pallotta Castle (Centro Italia); Bashtove Castle (Albania).

3.2 *Overturning of the merlons*

The damage mechanism activates with the out of plane rotation and/or the slipping of the merlon or part of it. The crack pattern is characterized by a horizontal crack indicating the creation of a sliding plane, generally at the base of the merlon itself (Ferretti et. al 2018; Lenticchia et al. 2018) (Figure 5). The cases in which a roof structure was added over the merlons were less subjected to this damage mechanism, as in some way the roof structure became a constraint and applied a vertical, stabilizing force, while the merlons which were free at the top were more vulnerable. In some cases, metal bars were inserted in the past between the merlons and the underlying masonry: this usually limits the risk of overturning or sliding, but it can induce stress concentrations at the interface, causing local damages in the masonry (e.g. in San Felice sul Panaro main tower). In general, the more the merlons are slender and placed in a high position, the more the activation of this mechanism is probable: e.g. merlons in

Albanian castles were in most cases quite squat and only in one case (Preza Castle) were subjected to overturning, while Italian merlons from the gothic revival period (end of the 19th century) often collapsed due to their high slenderness and limited connections, as they were built only as decorative elements.

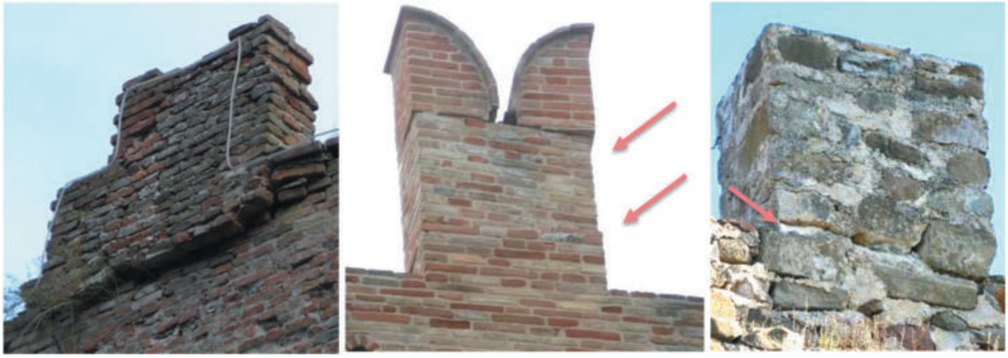

Figure 5. Overturning of the merlons. From the left: Reggiolo Castle (Emilia); Rancia Castle (Central Italy); Preza Castle (Albania).

3.3 *Shear collapse of the roof structures*

This damage mechanism activates for in plane shear deformations, due to a horizontal sliding. The consequent crack pattern is composed by horizontal cracks along the mortar joints, with the sliding of the roof structure over the underlying masonry. Good quality lintels over the windows and good connections between masonry and roof elements contribute to improve the behaviour. On the other hand, the presence of heavy and stiff roof structures, like reinforced concrete beams, can trigger and favour the development of this mechanism.

Figure 6. Shear collapse of the roof structures in San Felice sul Panaro Castle (Emilia); Tower of Norcia curtain wall (Central Italy); Kruja Castle (Albania).

Unfortunately these incongruous elements were often inserted during the 20th century, with the idea of limiting the decay phenomena with respect to the timber elements, but nowadays it is clear that their negative effects in terms of seismic vulnerability are often higher than the possible positive ones. It is therefore very important to spot these elements through a thorough survey and historical analysis in order to identify in advance this potential problem.

The decomposition in macro-elements is conventional, but it is aimed at the comprehension of the structural behaviour of these complex buildings. Even if simplified, the definition of these recurring mechanisms can be useful in the damage survey during the emergency phase, as already done for churches and palaces. As for all damage mechanisms regarding macroelements, it is also clear that they can activate only if the masonry is good enough to behave as a solid, otherwise it could crumble, especially in the case of rounded stone masonry, or delaminate, when the masonry is composed by several layers with lacking connections.

With the aim to improve the management of the emergency phase and to try to prevent the future seismic damage, the analysis of these data, related to recurring mechanisms, is fundamental and can take a great advantage from the adoption of GIS (Geographic Information System). Indeed, these systems, if designed with a proactive approach and combined with the seismic maps, can improve the knowledge and awareness of the seismic risk affecting the various cultural heritage assets. This is the base for the planning of future inspections and interventions, also allowing to identify the priorities from a structural point of view. This method has already been tested for the fortified architectures in the Emilia area (Zanazzi, 2022) and for Central Italy (Coïsson, Ferretti and Lenticchia, 2016) and is currently being developed also for the Albanian case, testifying the wide validity of the approach, which always starts from a deep knowledge phase on site.

4 CONCLUSIONS

The empirical observation of the damage and the experiences acquired during the three different analysed earthquakes allowed to carry out a comparative analysis of the damage mechanisms activated in the fortified architecture building typology. It was possible to notice that these mechanisms are recurring even considering different geographic areas, even if some changes in the materials and building techniques can be noticed. Indeed, at least in the European context, the fortified architectures have similar building techniques, connected to the warfare methods, thus defining similar macro-elements. A deep understanding of the building typology, with its common features and different specificities, allows to define its main vulnerabilities, thus becoming a first step for a correct and aware action on these cultural heritage assets, defining compatible structural interventions both during the emergency phase and in a preventive view, before the earthquake strikes. Focusing the interventions on the most endangered elements allows to define priorities, optimizing resources and limiting the loss of architectural elements of high cultural and social value.

AUTHORS CONTRIBUTION

Conceptualization, E.C. and E.Z.; methodology, E.C. and E.Z.; investigation, E.Z.; resources, E.C.; writing— original draft preparation, E.Z.; writing-review and editing, E.C.; supervision, E.C.; funding acquisition, E.C. All authors have read and agreed to the published version of the manuscript.

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