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HISTORIC MILITARY ARCHITECTURES IN THE PROVINCE OF MANTUA: THE EFFECTS OF THE 2012 EARTHQUAKES

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Abstract. *The research concerns the evaluation of the structural performance of the defence heritage in the Mantua area after the seismic sequence of May 20 and 29, 2012. The earthquake highlighted the high vulnerability of this heritage in the neighbouring Emilia-Romagna region where several brittle collapses of towers and fortification walls occurred. Over the centuries, the area was military strategic due to the complex hydrologic configuration between the rivers Po, Mincio, Secchia and several artificial canals and ditches, so that since Middle Ages, the fixed courses were fortified by an imposing net of defensive structures. Nevertheless, the changes of the political equilibrium and configuration of Italy over time, led to the progressive loss of importance of those defensive structures till their almost complete dismantling during the Austrian dominion. Most of the building materials were reused in new hydraulic structures. The survived structures, mostly donjons, were transformed over time in civic towers or in public buildings, such as town halls or museums. Despite collapses did not occur, several recursive damages were documented after the 2012 earthquakes: especially cracks located in the supported top structures as well as in the upper part and in the main body of the towers, due to in plane and out plane seismic actions. The masonry discontinuities due to the building evolution and the lack of structural connection between the load bearing walls increased the vulnerability. At present, progressive interventions are planned according to the preservation of historic architecture; the design has to be based on the deep knowledge of the building, including features, materials properties, structural layout, building technique, damages. In this context, the Municipality of Mantua planned interesting activities of control of the main towers. The paper explores the recursive damages, the present situation and future intervention strategies for an important architectural heritage.*

1 INTRODUCTION

The seismic sequence started in the spring of 2012 highlighted the extreme vulnerability of an important historical and architectural heritage in regions concerned, for a long time, not at risk and only recently included in the maps of seismic zoning (2003). Although in the past numerous earthquakes struck the area between Emilia-Romagna and Lombardy regions - North Italy - [1], the memory of seismic hazard has diminished given the remoteness in time of destructive events, surpassed by emergencies that occur with frequency almost annual and linked to the flood of many important rivers.

As pointed out by C. Togliani in a recent lecture [2], the Mantua area suffered the effects of earthquakes with epicenters in neighbouring areas damaging tall structures such as towers. Nevertheless, some local events were documented such as the earthquake occurred in Goito in 1683: the earthquake caused several damages, particularly to the bell tower of the parish church and the collapses of the fortress walls.

Despite significant damage occurred in Mantua as the disastrous collapse of the lantern of the Church of Santa Barbara, the area most affected by the earthquake was next to the epicentre, corresponding to the so called Oltrepò Mantovano (Fig. 1). In this area, damages were documented in many churches, bell towers and historic buildings, including fortified buildings.

The Spring 2012 earthquake highlighted the high vulnerability of the defence architectures in the neighbouring Emilia-Romagna region where several brittle collapses of towers and fortification walls occurred, despite the supposed low seismic risk of the area [3].

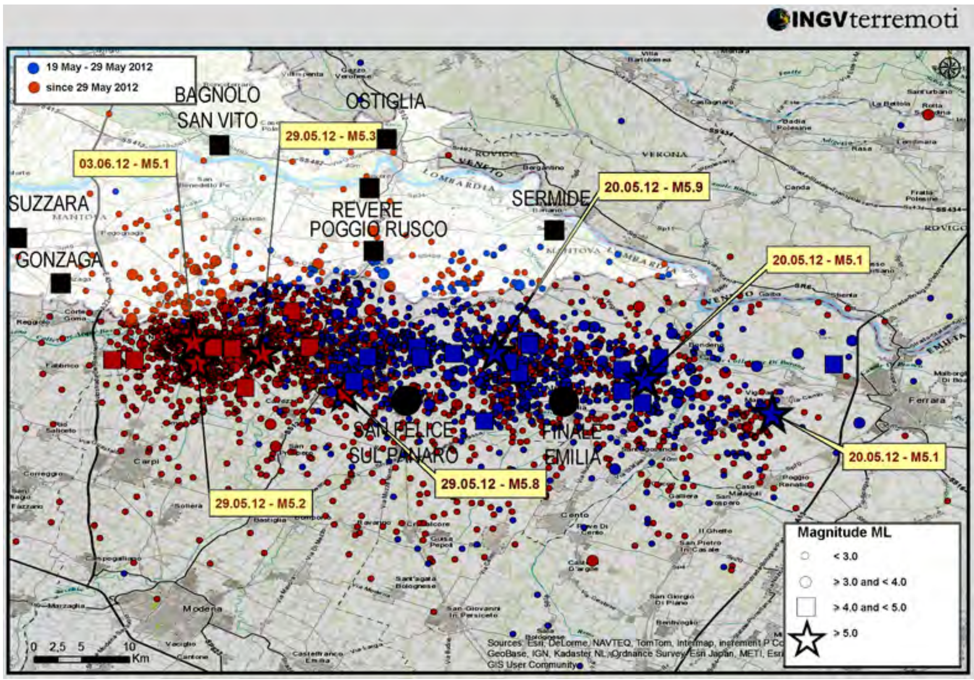


Figure 1: Seismic sequence and epicentres. Elaboration from the original data of DPC-INGV (Department of Italian Civil Protection - Institute of Geophysics and Volcanology). The province of Mantua is indicated in white.

The interpretation of the surveyed damages in the defensive heritage of the Mantua's southern province beyond the river Po showed recursive behaviour. Over the centuries, the area was militarily strategic due to the complex hydrologic configuration between the rivers Po, Mincio, Secchia and several artificial canals and ditches; then, since Middle Ages, the fixed courses to cross the territory were fortified by an imposing net of defensive structures

[4]. Nevertheless, the changes of the political equilibrium and configuration of Italy over time, led to the progressive loss of importance of these defensive structures till their almost complete dismantling during the Austrian dominion. Most of the building materials were reused in new hydraulic structures or embankments in order to prevent the frequent floods.

The survived structures, mostly donjons, were transformed over time in civic towers or in public buildings, such as town halls or museums. Despite collapses did not occur, several damages were documented after the 2012 earthquakes. At present, progressive interventions are planned according to the preservation of historic architecture replacing the emergency prompt interventions; the design has to be based on the deep knowledge of the building, including features, materials properties, structural layout, building technique, damages. The paper explores the recursive damages, the present situation and future preservation strategies for an important architectural heritage.

2 THE BUILT HERITAGE

The territory of Mantua, in various historical periods, was a strategic area from the military point of view both for its geographical position, being a border land, both for the natural hydrological conditions of the area between the rivers Po, Mincio, Secchia and numerous canals or ditches.

The cartographic representation of the territory since the fifteenth century documented the presence of a widespread system of fortifications and defensive structures designed to control the territory, evenly distributed in the province but now mostly destroyed (Fig. 2) [4]. The memory of these presences survives in place names or in the organization of the urban plan. However, it is important to note the almost total disappearance of these structure volumes, disused and neglected since the beginning of the eighteenth century, and gradually demolished to reuse the building materials in the construction of new structures, mainly hydraulic infrastructures.

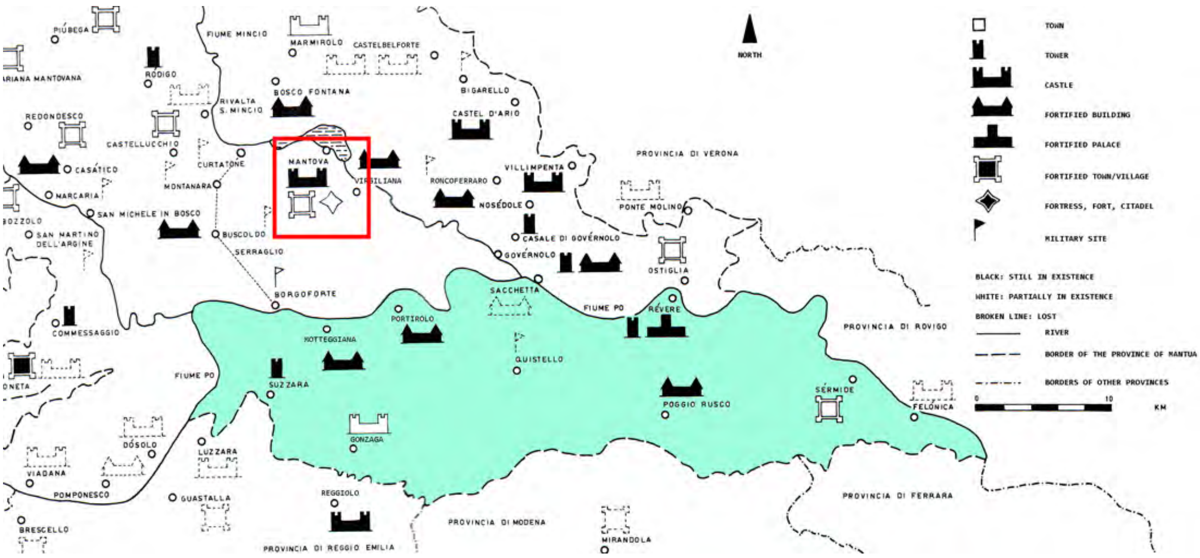


Figure 2: Map of the fortification in the south part of the province of Mantua. Light green indicates the Oltrepò Mantovano, the area damaged by the earthquakes of Spring 2012. Elaboration from [4].

The complex of fortifications was organised in different defensive systems, developed from the Roman castrum, as Castel d'Ario or Pegognaga, built in strategic position for the defence in a borderland between the natural water barrier of the rivers and the territory of Mantua and Verona.

The Oltrepò territory was area of conflict for the commercial traffic hegemony over the Po river between Mantua and neighbouring populations. For instance, the Scaliger Castle of Ostiglia was built to cope the onslaughts of Mantua and then it was absorbed into the Gonzaga Duchy; today, only three towers embedded in the historic centre are the only remains of this imposing fortress. At the beginning of the twelfth century, at Revere on the opposite bank of the Po of Ostiglia, Modena built a fortified system with seven towers. Even this complex defensive system became part of the Gonzaga Duchy. Today three towers survive, two of them incorporated in the Ducal Palace, built by Luca Fancelli for Ludovico II Gonzaga.

During the government of Matilde di Canossa, the Benedictine monks of the San Benedetto Po complex, began an extensive reclamation of the Oltrepò with important works. Several fortified architectures belong to this period like the tower of Bagnolo San Vito (close to Governolo), that was part of a structure with six towers according to the research of local historians.

The most important step for the fortified architecture is certainly the Gonzaga period, characterized by significant and substantial adaptation and upgrading of the defensive structures for the attacks with modern artillery. These works were entrusted with important military engineers and architects, such as firstly Bartolino da Novara who designed and built for Francesco Gonzaga the castle of San Giorgio in addition to the Ducal Palace in Mantua. Luca Fancelli, the Beccaguto, Bernardino Facciotto were other famous architects of defensive works for the Gonzaga family. The deposition of the last duke in 1707, Ferdinando Carlo Gonzaga-Nevers, and the transfer of the State Administration of Mantua to the Austrian led to the gradual neglect of numerous works of fortifications; furthermore, the new administration allowed the progressive demolition of such structures, the removal and reuse of the building materials for other works, mainly hydraulic infrastructures.

The remain structures are clearly recognizable in the urban texture; they are an important heritage of considerable functional and architectural variety, including towers or donjons, now isolated for the demolition of the accompanying defensive structures (such as the Civic Towers of Suzzara, Gonzaga or Revere), or incorporated into the historical urban texture (many towers of Mantua or Ostiglia), and defensive structures converted into noble palaces and, therefore, in public buildings, in general town halls or museums (Palazzo Ducale at Revere or the Castle of San Giorgio). Furthermore, the state of preservation at the time of the earthquake was much variable, ranging from buildings with a low level of maintenance to buildings still in use, or even just repaired.

3 THE DAMAGE

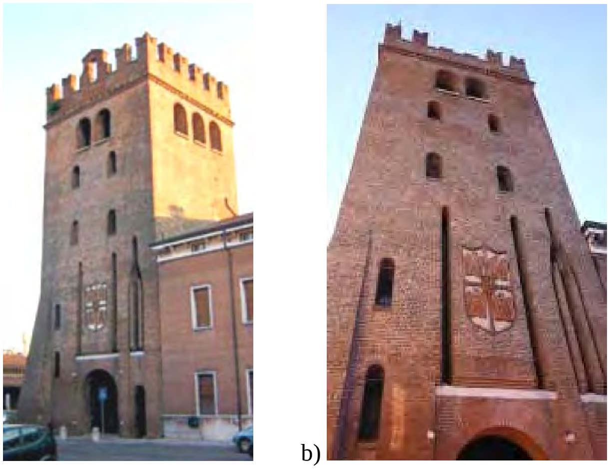
In general, the structural behaviour of a historic building in masonry, as well as the applicability of the techniques of intervention, are closely related to the morphology and characteristics of the masonry itself, the general organization of the structure derived from the evolution over time of the building and the properties of the constraints between the various structural elements [5]. The seismic response, therefore, is difficult to generalize and to qualify for the wide variety of architectonic typologies, methods and construction techniques, as well as the transformation occurred over time and the decay issues affecting each building.

However, the knowledge widened in the various activities of post-seismic damage survey starting from the earthquake in Friuli [6], allowed the developing of interpretation criterion on the specific vulnerability of some building typologies; these research led to the extension of specific assessment forms [7], [8] act to the prompt damage survey through simplified scheme of the recursive crack pattern occurred to churches (and bell-towers) and palaces after the past earthquakes [9]. As known, the first post-seismic action is the drafting of lists concerning the buildings damaged by the earthquakes and the following organisation of the inspections [10].

The on site inspection phase has the dual purpose of assessing the extent of damage and the need to design interventions for safety, through the filling in the damage survey forms developed by the National Civil Protection Agency and by the Ministry for Cultural heritage and Activities (Working Group on Cultural Heritage - GLABEC), respectively, for the churches (model A -DC) and the palaces (model B-DP) [11].

Although this is a valuable and essential method to assess the state of damage of a structure, the safety evaluation, and thus the priority of intervention measures, it was developed specifically for churches and palaces, and only partly applicable to fortification or defence architecture. In particular, similar damage mechanisms occur to several fortification towers and to bell towers, mechanism reported in the churches forms; similarly the damage mechanism form of palaces is used to analyze the crack pattern of castles, despite not satisfying in full the properties and the type of damage [3], [12]. Remain partially excluded from these methodology of damage survey some fortification architectures, the defensive walls and terreplains, ramparts or bulwarks that may present special design features directed to the damping of the artillery shots, rather than strength.

Although the examined defensive architectures were near the epicentres of the earthquakes, ruinous collapse, as in the case of the fortresses of Emilia [3], did not occurred despite showing significant damage and cracks. The reported damage to towers are often concentrated in the upper part, with the partial collapse or damage to the battlements and of any superposed structure, usually belfry, as happens to bell-towers subjected to seismic actions (Fig. 3). The collapse of the lantern of the Church of Santa Barbara, the chapel of the Palazzo Ducale in Mantua, as an example, was probably the most evident damage in Mantua; it is a clearly recognizable gap in the urban skyline near the Castle of San Giorgio, when accessing to the city from the bridge with the same name.



a) b)

Figure 3: Civic Tower of Sermide before (a) and after the earthquake (b). The reported damages included the partial collapse or damage to the battlements.

Damage to the belfry is also present in the Civic Tower of Suzzara, the only remain of the castle, dating back to the thirteenth century; the damage mechanism seems caused by the rotation of the corner pillars and by the following corner expulsion; this damage is easy readable through the crack observation on the front north and west (Fig. 4).

In the analyzed architectures, being now mainly isolated buildings or not well connected to other existing buildings, the documented damage are frequently caused by bending effects with the formation of vertical cracks or sub-horizontal cracks with the following discretization of the walls and outward rotation of the corner elements. The collapse of one of the symbolic buildings of the 2012 earthquake, the Clock Tower of Finale Emilia, was determined by the progression of this damage mechanism. The cracks visible on both the north front, both on the south front of the Civic Tower of Suzzara at the clock level, in a position very similar to that of the Tower of Finale Emilia, document a similar structural behaviour, as well (Fig. 5).

Figure 4: Civic Tower of Suzzara (a). The damage mechanism seems caused by the rotation of the corner pillars and by the following corner expulsion (b-d)

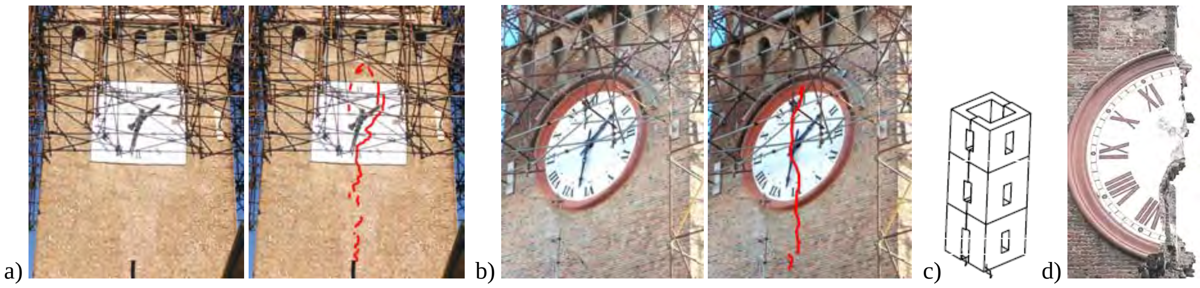


Figure 5: Civic Tower of Suzzara: the tower has vertical cracks in the central part respectively of the fronts south (a) and north (b). The damage is present in the forms of the Civil Protection for bell-towers (c) and is very similar to the one of the collapsed Clock Tower of Finale Emilia (d), symbol of the Emilia earthquake.

A frequent intervention to defence buildings was the opening enlargement to fit new needs and requirements, being originally of small size. The alignment of the openings, especially if placed close to the corner, as in the Tower Falconiera at Poggio Rusco (Fig. 6), and the shear behaviour of the walls and the typical St. Andrew-cross cracks below the windows (Fig. 6b), have triggered subsequent kinematic rotation of the corner (Fig. 6c,d).

Similar damage affects in a more accentuated way the Tower of Prisons at Gonzaga (Fig. 7), where the formation of a deep vertical crack on the south side caused the overturning mechanism of the south-west corner (Fig. 7b,c); the clear out-of-plumb justifies the massive prompt intervention for the safety of the tower (Fig. 7d).

The addition of structures by simple building of new volumes without effective links frequently occurred in the past; in case of earthquake this can cause a shifting movement between the different volumes, and the resulting separation of the interface boundaries or even local damage due to hammering (Fig. 8).

The closing and opening of new holes in the wall is usually carried out by simple addition to the masonry of new frames without connections. Opening infillings (windows, doors, chimneys, fireplaces, niches, etc.), or wide discontinuities due to the historic construction phases, effectively link or not, during the earthquake tend to behave independently or even to detach, not collaborating effectively with the adjoining side panels (Fig. 9). Furthermore, at the interfaces cracks progressively spread, as well wall portions could start the overturning. In the case of buildings evolved and transformed over time, damage and cracks could be caused by the several structural discontinuity even not linked due to the use both of different materials, both the different construction techniques. This is the case of the Palazzo Ducale in Revere; a former fortification was modified on the base of a plan by Luca Fancelli. Apparently it was little damaged on the external fronts, apart from the collapse of one of the heavy Venetians chimneys (Fig. 10), and some cracks on the north front where an intervention is already in progress. Nevertheless, it shows widespread damage indoor due to the heterogeneity of the walls because of the several construction phases, often not effectively linked between them.

In a minor way, also in the Palazzo del Podestà, in the Palazzo Ducale in Mantua and especially in the Castle of San Giorgio, the earthquake caused slight damage related to the lack of effective connection between the historic building phases or to former damage. Despite this damage did not cause evident structural problems, the seismic actions and the movement of the existing cracks damaged important decorative elements, also creating serious concerns for the frescoes by Mantegna in the Camera Picta, located in the Castle of San Giorgio and still not fully accessible.

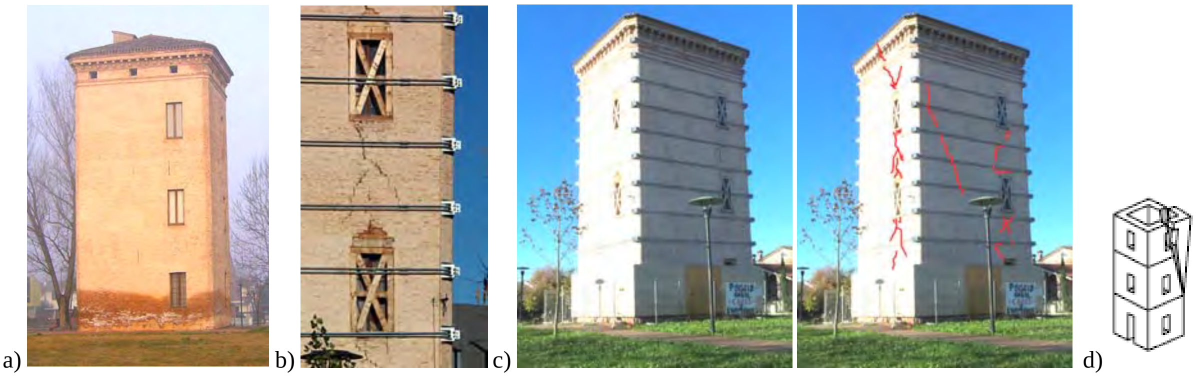


Figure 6: Torre Falconiera at Poggio Rusco before the earthquake (a); details of the shear cracks under the openings (b). The damaged platbands required a reinforcement of the openings with a wooden structure. The crack pattern (c) shows a shear behaviour of the walls that triggers a corner movement (d).

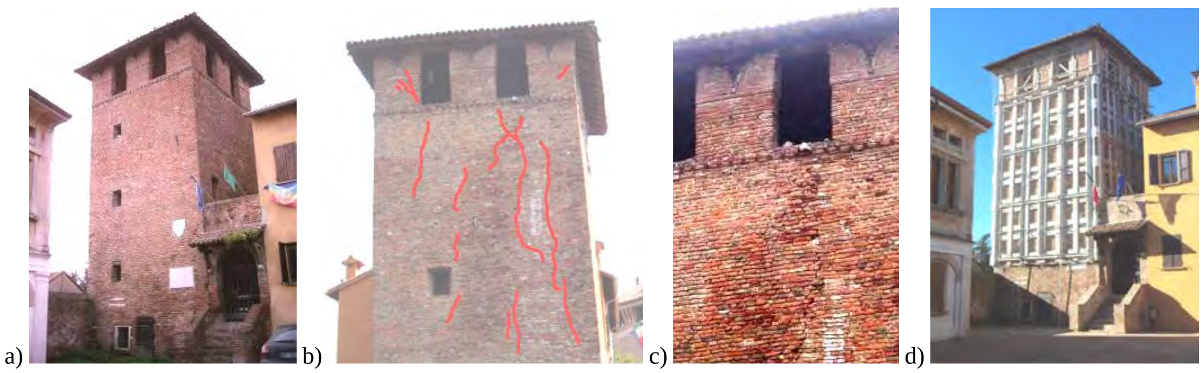


Figure 7: Tower of Prisons at Gonzaga before the earthquake (a); the formation of deep vertical cracks (b) in the south side was caused by the overturning mechanism of the south-west corner (c), and highlighted by an apparent out of plumb which justified the massive emergency intervention for the safety of the tower itself (d).

Deformations or movements of the walls, even if limited, can damage arches or separate vaults, as happened in the vault at the base of the Civic Tower of Gonzaga apparently not damaged in the outside walls (Fig. 12).

It is worth to remind the masonry typology frequently observed in damaged tall buildings -

bell-towers and towers - or in thick masonry panels, built by multiple leaves brick masonry, with an outer leaf connected with regular courses of headers to the internal irregular masonry.

a) b) c)

Figure 8: Torre Matildica at Bagnolo San Vito (a). The interface between the two volume is damaged by the possible hammering or sliding during the seismic action (b,c).

a) b) c)

Figure 9: Torre Matildica a Bagnolo San Vito (a). The presence of several discontinuities in the upper area (b) of all the fronts was due to the constructive phases not effectively linked is evident from the cracks at the interface, and reinforced by both local supporting wooden frames both tie-rods elements to tie the top of the tower (c).

a) b) c)

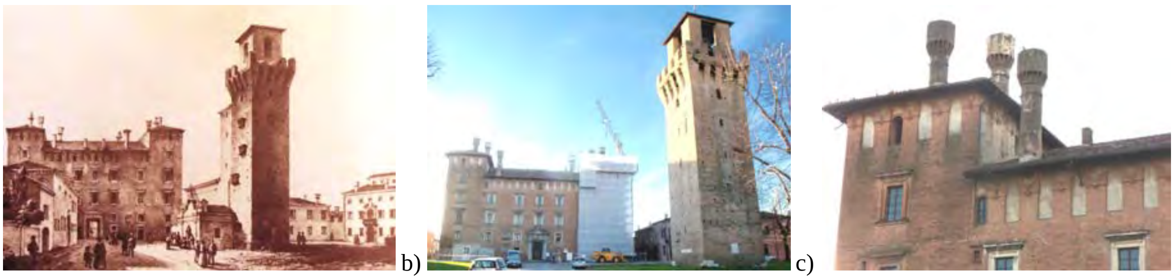


Figure 10: Palazzo Ducale of Revere before the intervention of 19th century (a). Apparently it was little damaged on the external fronts, apart from the collapse of one of the heavy Venetians chimneys (b,c), and some cracks on the north front.

4 THE INTERVENTION FOR SAFETY

The last phase of the post-seismic emergency in general concerns the emergency safety intervention, according to procedures and criterion closely related to the damage index and the safety evaluation resulting after the filling in the damage assessment form for cultural heritage.

The experiences of past seismic events allowed to develop strategies and practices of intervention widely tested, identifying local and global strengthening [13], [14], [15]. In particular, localized seismic improvement interventions are aimed to restrain those mechanisms activated by the seismic event. The global interventions, instead, involves all the required actions to improve the seismic response of the whole structure.

Emergency safety intervention are preferably local and aimed at the preventing the evolution of kinematic mechanisms already activated by the earthquake; this intervention should be carried out possibly with lightweight systems and avoiding procedures that can modify the structural scheme of the building in an unpredictable way; furthermore, the intervention musts guarantee the accessibility of roads and squares and, therefore, the management of the emergency and the subsequent phases of reconstruction.

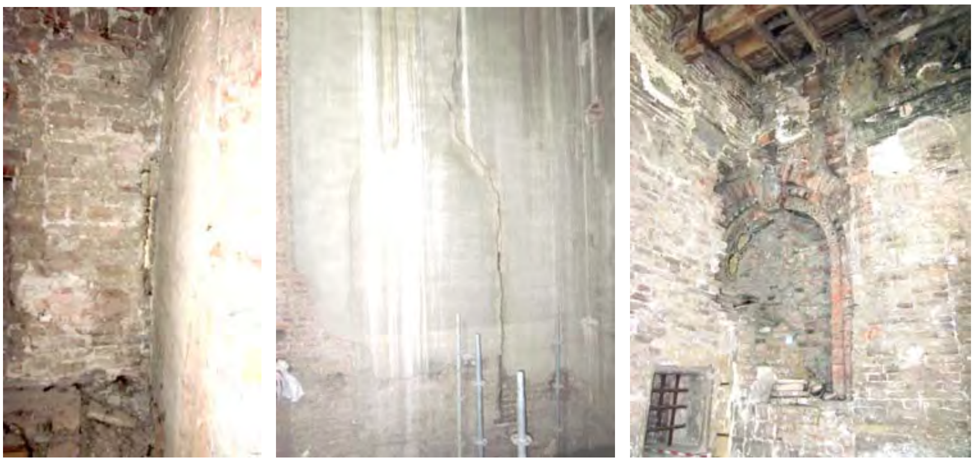
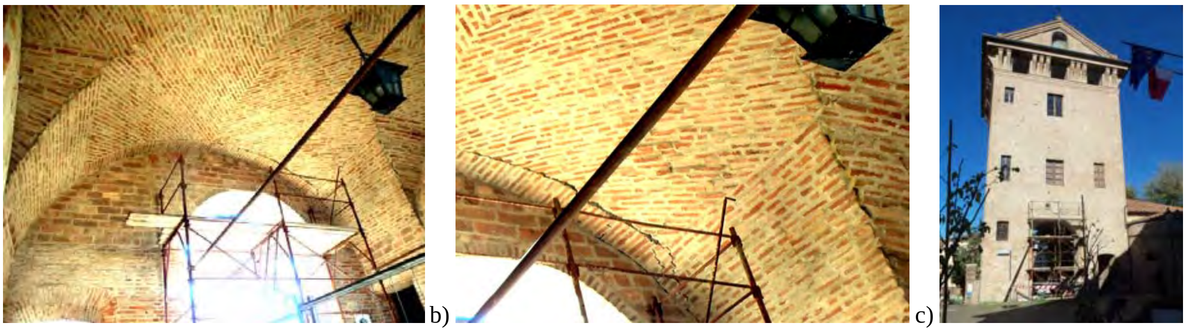


Figure 12: Palazzo del Podestà in Mantua. Examples of damage related to the lack of effective connection between the historic building phases.



a) b) c)

Figure 12: Civic Tower of Gonzaga. Details of the vault damage (a,b). Deformations or movements of the walls, even if limited, can damage arches or separate vaults from the perimeter walls, as happened in the vault at the base of the Civic Tower of Gonzaga apparently not damaged in the outside walls (c).

The documented damage in the analysed defence architectures required local interventions such as wooden frames supporting the cracked lintels in the openings and the tie ringing both of the upper part of the structures, or of the belfry elements such as the Civic Tower of Suzzara, both of the whole structure as in the Tower of Prisons at Gonzaga or in the Tower of Falconiera at Poggio Rusco. Of course, the characteristic and the extension of the interventions were strictly related to the damage type and diffusion. The interventions were mainly carried out by steel cables, beams and steel plates, beams and planks of wood and other suitable systems for the distribution of the stresses on the walls.

5 THE PRESENT SITUATION

After about two years, all the defence architectures here considered are in safe condition in most case because of the emergency intervention and showing globally less catastrophic damage on comparison to religious architecture in the same area. However, this is mainly a temporary situation, waiting for the fund availability or the conclusion of the competition to start the structural repair. For some buildings the preliminary procedures for the preparation of definitive repair or strengthening projects have been already concluded, or even in some cases, such as the Civic Tower of Sermide or the Castle of Revere, interventions are already on going.

The experiences of the last decades in the preservation, strengthening and repair of historic buildings in seismic areas and resumed in the latest versions of the Italian seismic code, have established the need for a preliminary in-depth knowledge of the building as a support for subsequent choices and intervention strategies [5], [16]. It is an important step, which also requires an appropriate timing in order to steer the possible options for the building preservation and/or repair, considering the state of damage of the structure, as well as its possibilities and potential vulnerabilities; the collection of this information may lead to projects that have as priority the structural safety in full compatibility with the characteristics of the building, through interventions directly on the structure, or by considering monitoring programs of the status quo to support maintenance programs.

The choice of the repair technique, therefore, will take into account with awareness the building properties and characteristics, opting for materials and techniques appropriately formulated on the basis of suitable tests, and whose effectiveness is demonstrated for the solution of the specific problem affecting the building. Of course, these projects have not the timing of a safety intervention on the structure in emergency conditions, but they must guarantee the requirements for the preservation of a historic building.

Without damage clearly due to the earthquake or anyway in unclear situation due to the complexity of the structures, the position of the Municipality of Mantua seems very mature and aware of the contemporary requirements of safety and preservation of historical heritage; the strategy is directed towards the control of the present state of the structure with diagnostic inspection and permanent continuous monitoring [17], [18].

For example, on the Gabbia Tower, an extensive investigation was carried out since the end of July 2012 including a permanent dynamic monitoring of the structure still active (Saisi 2014). The assessment of the structural integrity and of the load-bearing capacity of the building required firstly careful inspection and on-site investigation and the following modelling and numerical analysis; this information was articulated within a synergistic process where information and methodologies flow from several disciplines and related to the reconstruction of the building evolution, the materials and construction techniques and the possible state of decay.

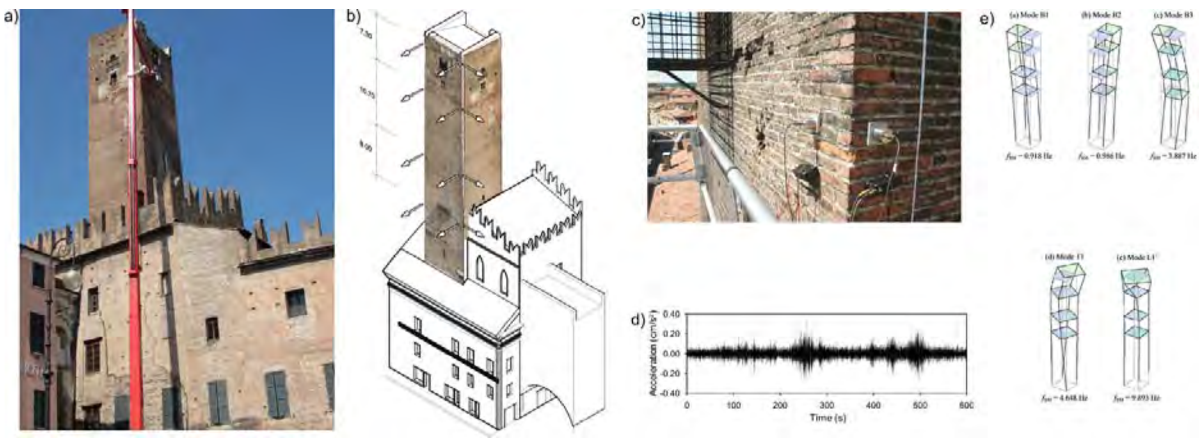


Figure 11: Gabbia Tower in Mantua. An extensive investigation was carried out since the end of July 2012 including dynamic testing and a permanent dynamic monitoring of the structure, still active [17].

6 CONCLUSIONS

The research presents a general view of the damage detected on the defence architectural heritage in the province of Mantua, hits from the seismic sequence of spring 2012. These structures, once very numerous, were decimated by the known historical events of progressive neglecting and subsequent demolition and reuse of materials in other works. However, a complex built heritage, mainly transformed into civic towers or public buildings, remains with a strong visual and symbolic impact in the urban areas.

Despite this military architecture had significant cracks, they did not show the catastrophic damage highlighted by other construction typologies, such as the historical religious buildings, or the ruinous collapses documented in the very close Emilia Romagna area.

In the extreme difficulties of the moment and of the post- seismic situation, with intervention priorities focused mainly to repair residential, productive or public buildings, it is important to highlight the interest in these structures, often considered the symbol of the city with intervention respectful of the building preservation.

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