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Seismic risk mitigation of cultural heritage – The three case studies from phd research on the areas affected by the 2012 Emilia Earthquake: Fortified architectures, cemeteries, theaters

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ABSTRACT: This paper presents the three doctoral research, discussed in 2022 and funded by the Emilia-Romagna Region's program "Three-year High Skills Plan for Research, Technology Transfer and Entrepreneurship", thematic objective 10 of the ERDF ESF 2014/2020. The survey and analysis of seismic damage mechanisms, set up on three specific complex building type - castles, cemeteries and theatres - are the main theme of these research. Indeed, these three types under study, particularly vulnerable during the 2012 earthquake, were surveyed in the first post-earthquake operations using the conventional tools to date adopted by the Ministry of Cultural Heritage(MiC) through the 2006 D.P.C.M.: Model A-Churches and Model B-Stately Buildings. An initial analysis revealed that the extensive application of the two current MiC forms resulted in the loss of quantitative and qualitative information necessary for the knowledge and subsequent management of the reconstruction process. Therefore, a training proposal matured from the collaboration between the two Universities of Ferrara and Parma and the Regional Agency for Reconstruction - Earthquake 2012. Its main aim is the definition of specific methodologies for the survey and analysis of seismic damage to ensure mitigation and prevention of seismic risk. This approach led to the proposed implementation of the current damage survey systems, modulating specific forms for each of the three types. Then specific methods and digital tools – Lidar, GIS, BIM– were proposed by the authors. These tools were applied to optimise the damage survey phases and to query the data collected during the study phase for seismic damage prediction. The three research thus sought to make a concrete contribution with operational solutions to the needs that emerged in the post-earthquake emergency phases.

Keywords: Seismic damage forms, Survey procedures, Integrated digital tools, Proactive tools

1 INTRODUCTION

In May 2012, the Emilia-Romagna region, particularly the provinces of Reggio Emilia, Modena, Bologna and Ferrara, was hit by two main shocks. The first main shock of magnitude 5.9 on the Richter scale, which occurred on May 20, 2012, affected the Po Valley area of Modena between the municipalities of Mirandola and Finale Emilia. The second, on May 29, registered an ML 5.8 quake a few kilometres west of the previous epicentre. In total, the 2012 Emilia earthquake area included 33 municipalities and 57 localities.

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The damaged cultural heritage within the crater area amounted to about 80 per cent of the protected buildings. As prepared by the national regulatory framework, the first phase of damage reconnaissance on cultural heritage was entrusted to and coordinated by the MiBACT (today MIC, Ministry of Culture). From an operational point of view, the damage surveys on a regional scale was entrusted to the teams composed of MiC officials that organised damage survey activities.

During the first post-earthquake phases, the damaged cultural property was surveyed using two seismic damage forms provided by the MiC: the A-DC model for churches and the B-DP model for stately buildings (D.P.C.M., 2006). One of the main key point of these tools is to estimate the damage index based on the activated mechanisms, which provide a preliminary economic estimate for the the subsequent reconstruction phase

The adoption of MIC's two standard models, for analysing complex *architectural types*, such as castles, cemeteries and theatres (Figure 1), has revealed some critical issues. Indeed, the lack of specific forms for the *types* mentioned above resulted in the loss of valuable quantitative and qualitative data (Libro and Coïsson, 2021). Therefore, although the two tools allowed, in the emergency phase, a first expeditious survey through the identification of collapse mechanisms activated under seismic action, the result is an inaccurate damage survey, with an inconsistent estimate of the damage index.

Noting these critical issues that affected the exhaustive documentation of seismic damage of some *architectural type* and thus the planning of the first safety operations and subsequent restoration interventions, the Agency for Reconstruction initiated a scientific-operational collaboration with the Universities of Ferrara and Parma. Therefore three doctoral fellowships were funded in 2018 to analyse three specific *architectural type* - castles, cemeteries and theatres for which the application of current MiC procedures was critical to the process of damage documentation, preservation and reconstruction.

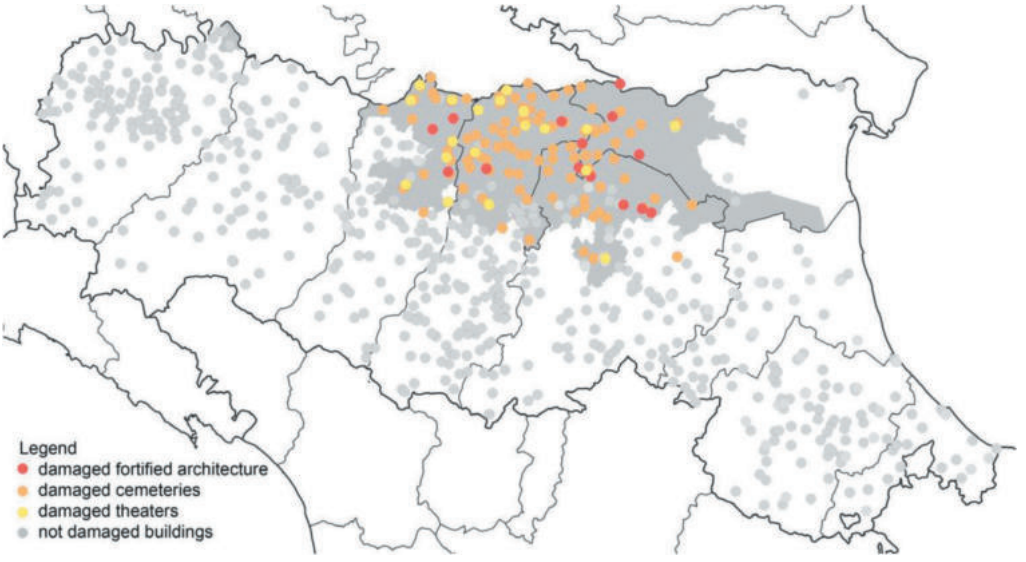


Figure 1. Geolocation of damaged assets, belonging to the three typologies examined.

2 FORTIFIED ARCHITECTURE

One of the above three researches focuses on the analysis of typical and recurrent seismic damage mechanisms of fortified architectures in the Emilia region. The thesis (Zanazzi, 2022) examined fortified structures built mainly between the 10th and 15th centuries, with similar morphological and constructive features, focusing on the 21 fortified architectures damaged by the 2012 Emilia earthquake.

2.1 *From the analysis of critical issues of the emergency phase*

These architectures usually consist of fortified residences, towers, curtain walls and various protruding elements (corbels, battlements, turrets, etc.). Each architectural element has a specific kinematic behaviour (Cattari et al., 2014; Coïsson, Ferretti and Lenticchia, 2017). Therefore, although fortified architectures have specific typological vulnerabilities, only existing forms could be used after the Emilia shocks. In particular, Sheet B for Stately Buildings was adopted to survey castle damage. As a result, several critical issues emerged. For example, numerous forms were often filled out for a castle, given the composite nature of this typology. Indeed, survey teams often used the "other" box to describe the typical damage mechanisms of the castle. These problems are closely related to the typological characteristics of fortified architecture.

2.2 *To design of tools for the emergency phase survey and the prevention of vulnerabilities*

Considering the difficulties that emerged from the application of the current inventory sheet (Stately Buildings Model B-DP), in order to facilitate the expeditious survey, two tools were therefore developed: an abacus of typical mechanisms (Figure 2), significantly expanded from those found in the literature, and a specific damage form for the typology examined, with an attached compilation manual. These tools were defined on the model of the existing sheets and based on the studies on typological vulnerabilities (Doglioni, Moretti and Pertini, 1994).

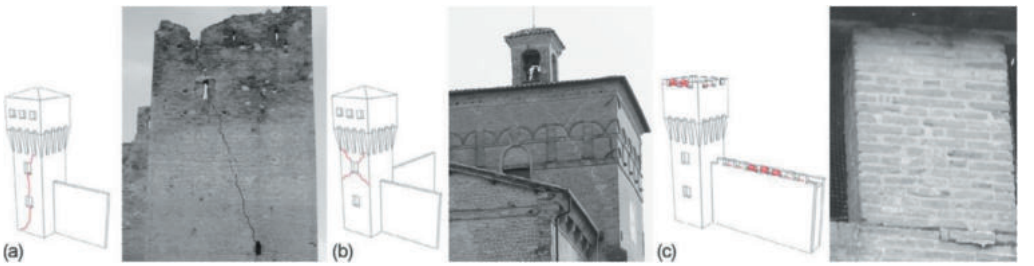


Figure 2. Three of the most frequent mechanisms of fortified architecture: (a) shear cracks in the main body of the tower (Reggiolo Castle); (b) shear crasks in the upper part of the tower (Soliera Castle); (c) overturn of the merlons (San Felice Castle). Editing by Elena Zanazzi.

The abacus includes thirty-seven kinematics, divided into three lists relating to the three different assets that make up the castle: fortified residences, towers and curtain walls. Regarding the damage assessment form, it is divided into three parts. The first collects the general data of the castle, which can be pre-filled before an earthquake occurs. The second is specific to each of the three assets of the castle and finally a summary form, in which to report the preliminary economic evaluation on the complex and the Damage Index.

The third tool is a GIS (Geographic Information System) database, designed with a proactive approach (Coïsson, Ferretti and Lenticchia, 2016; Lenticchia and Coïsson, 2017), for the prediction of the vulnerability of the fortified architectures on a territorial scale functional to the identification of the most urgent and priority interventions, to plan a maintenance program (Della Torre, 2010). In particular, statistical analysis revealed correlations between constructive characters and the onset of the damage mechanism. For example, it was noted that shear mechanisms of merlons are more frequent in the merlons supporting a roof, while freestanding merlons, without a roof and connected only at the base, are more damaged by overturning mechanisms. Obviously, with some exceptions, depending on the constructive features of the single element and, in this case, on the type of connection of the merlon with the elements in the roof.

Moreover, by uploading the shakemaps (Web-2) of INGV (Italian National Institute of Geophysics and Volcanology), on the GIS database, it was possible to compare the data related to the damage levels with the seismic action of the site and then define experimental

fragility curves for three of the most recurrent mechanisms: shear cracks in the main body of the tower with possible torsional effects; shear cracks in the upper part of the tower; overturning mechanism of the merlon.

In order to verify the predictive methodology adopted, these fragility curves have been applied to the territory of the Province of Parma, located outside the area affected by the 2012 earthquake. Once the Parmesan case studies were geo-localised, it was possible to associate them with the expected acceleration values, expressed in PGA, of the seismic hazard map of INGV (Web-3). Furthermore, from the analyses carried out, it was possible to identify the probability of activation of the three mechanisms mentioned above. For example, it was observed that the probability of the overturning of merlons is high (Figure 3). Indeed, for 10 out of 17 castles, the probability of this mechanism occuring in a moderate form (D2-D3) is around or over 50%, and over 30% in a severe form (D4-D5). However, as already illustrated, the overturning of a merlons well connected to the roof structured is rare. Therefore, on the base of the statistical data, the freestanding merlons, without a roof, should have higher priority in case of preventive interventions. However, it is not excluded that merlons with bad connections to the roof could also overturn. After all, every historic building constitutes a unique element and, for this reason, it must be protected.

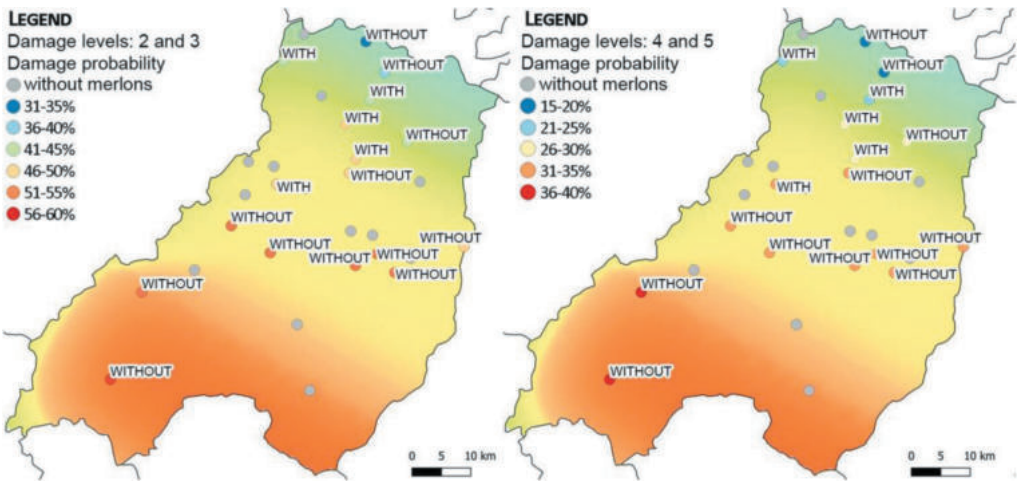


Figure 3. Probability of occurrence of the merlon overturing for medium (left) and severe (right) levels of damage in the Province of Parma. In this analysis the merlons, "whit" and "without" a roof, were considered. Editing by Elena Zanazzi.

This methodology has proven to be very useful in identifying vulnerabilities in the territory and acting in a preventive way, i.e. before the damage occurs. Therefore, this approach has the double advantage of optimising the management of economic resources, often limited, and allowing the material conservation of the architectural heritage, avoiding operating during the emergency phase, instead aiming to define strategies for the protection of the cultural heritage on a larger scale.

3 CEMETERIES

One of the most numerous samples among the *special types* damaged by the earthquake is the *cemetery type* with more than 100 buildings damaged, a percentage equal to 70% of the entire complex of historic cemeteries located within the crater area. For this *type of building*, the use of form A-DC and B-DP has highlighted the need to intervene with appropriate adjustments in order to reach a more sustainable economic assessment that was often underestimated.

Accordingly, the aim of this research is to analyse the damage suffered by this *type* so as to improve the damage assessment procedures, both in the emergency phase and in terms of seismic risk mitigation. The main purpose is to address the cultural heritage restoration policies towards more technically and economically sustainable actions.

Therefore, based on the data collected for the cemeteries damaged in the "Emilia 2012" earthquake, the *cemetery type* was investigated according to its several aspects: architectural and morpho-typological, economic, level of damage, and finally vulnerability. Each of these aspects provided the framework for the definition of a new first-level tool that could be both a damage survey tool and a proactive vulnerability assessment tool.

The research originated not only from historical analysis, but also from the morphotypological analysis of the Muratorian school (Muratori, 1960; Caniggia & Maffei, 1979, Maffei & Maffei, 2011, Dalla Negra, 2017). The relevance of typological analyses to the vulnerability of historic buildings was first introduced in the research carried out by Antonino Giuffrè's group (Giuffrè, 1988). Only through what is called a "phenomenological-structural reading" can we identify those "permanent and changing rules" (Dalla Negra & Zuppiroli, 2012) that enable us to interpret an organisms' composition. Indeed, historic buildings have basically, a poor box-like behaviour compared to modern ones. This is due both to the intertwining of constructive and seismic history and to the architectural evolution of each building, which has led to changes and alterations. Since their collapse is initially local and not global, it is important to identify the possible homogeneous areas within which such collapse can occur. For this reason, these rules provide the framework within which it is possible to carry out structural seismic assessment, and they were the key point through which it was possible to define the five macro-elements (Doglioni, Moretti and Pertini, 1994) comprising the cemetery organism: columbaria, enclosure, crossing elements, family tomb and funeral chapel.

Once these macro-elements were defined, the research focused on the analysis of the damage and vulnerability features through the data concerning the cemeteries damaged by the 2012 earthquake. Indeed, this building type has so far been investigated in its relationship with the habits and customs of different eras, in the relationship between cemeteries and cities and on the role the former has played in the development of the latter, or in the architectural characteristics of some examples of particular architectural value. Structural feature, or expected seismic behaviour are not usually analysed. From the point of view of seismic damage, however, it is no longer possible to postpone damage studies on this *building type*, for which seismic damage is compounded by health and functional problems that cannot be resolved with the tools normally available for other cultural heritage. In order to achieve this aim, a critical survey of the crack framework, which emerged after the 2012 earthquake and was collected in the photographic documentation attached to the two existing forms, was carried out. The cracks, the natural expression of the collapse mechanisms, were then analysed to understand which kinematic mechanisms were activated accordingly to the macro-elements' definition. Once an extensive analysis on all the damage cemeteries had been carried out, it was selected only those mechanisms whose recurrence suggested a typical behaviour of cemetery structures during the earthquake.

The constructive features were also analysed with the aim of identifying those aspects, easily detectable through a visual building's inspection, useful for defining a vulnerability index. On the basis of methodological approaches already widespread and shared by the scientific community (Ortega et alii, 2019), a study was carried out to analyse seismic vulnerability for this *type* as well, combining the score-based approach (Benedetti & Petrini, 1984) with the macroseismic one (Lagomarsino & Podestà, 2005). The results provided a further element for the preparation of a scheduling tool aimed not only at the survey of the damage but also providing useful support in decision-making processes for seismic risk mitigation. Indeed, it is in land governance that vulnerability analyses of first level have their greatest potential. A more conscious understanding of vulnerability at a large scale is among the most important tools to address seismic risk mitigation policies, which are now the basis of almost every intervention on existing buildings.

The results of all the analyses carried out were transferred to a new damage survey tool specifically tailored on *cemetery type* (Figure 4).

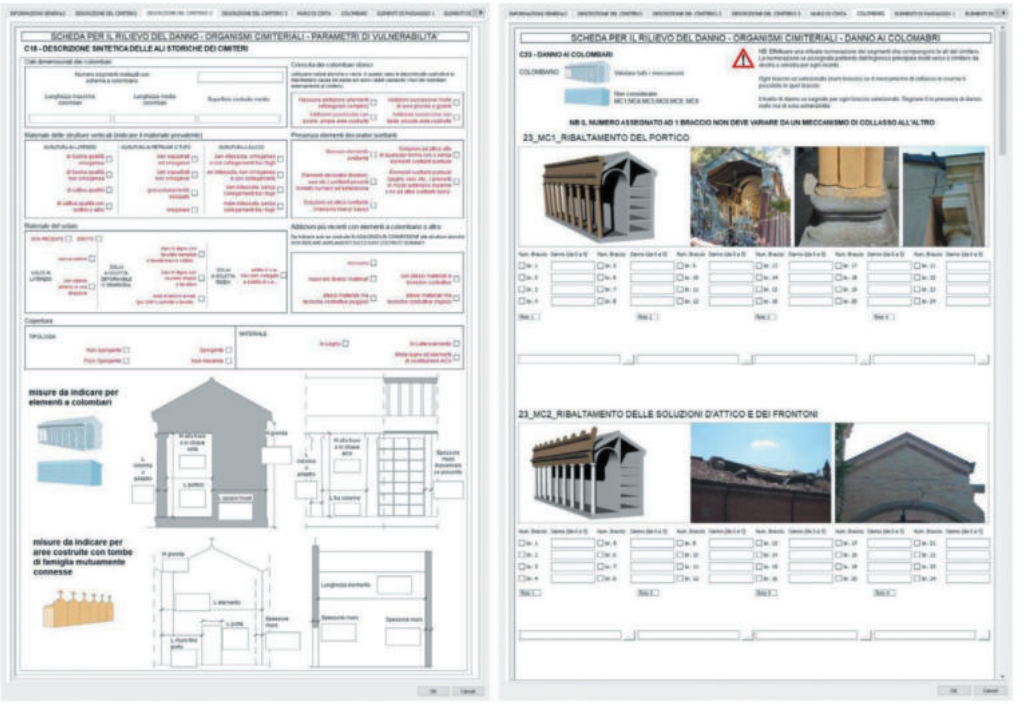


Figure 4. Pages from the damage form for cemeteries. On the left an example of the vulnerability parameters to be acquired for proactive analysis, on the right an example of the damage survey sections. Editing by Veronica Vona.

This form was designed to maintain those features of synthesis, immediacy of use, and quickness (Lagomarsino et alii, 1997) that should be inherent in existing damage survey tools. For this reason the form drafted has been tested to verify its correspondence to the previuos requirements. Therefore, several professionals were recruited from the construction and heritage field and requested to attempt the compilation of the forms (Figure 5). Following these tests, a new version of the cemetery damage survey form was redefined and it was also developed to be used as a support for territorial decision-making processes.

Indeed, the complete compilation of the tool provides an estimate of the damage index and the related repair cost. The partial compilation, on the contrary, allows for the definition of a vulnerability index correlated with a vulnerability curve for cemeteries. In the first case it is possible to use the tool in the immediate and urgent phases of the emergency to determine the material and economic impact of the earthquake on the assets. In the second case, instead, it is possible to address the policies of seismic risk mitigation through vulnerability analyses at a territorial scale. Finally, its status of land-management tool has resulted in its development on a GIS-based digital format for its integration within the regional technical cartography and to fully benefit from the potentials derived from GIS applications for wearable devices.

4 THEATRES

The research used the 'holistic approach of integrated survey methodology to document, survey, and represent the specific significances (historical, artistic, architectural, technological-structural, and socio-anthropological) of historic Emilia-Romagna theatres hit by the 2012 earthquake.

A multi-level, multi-criteria methodological path was developed using integrated survey methods and digital technologies to document the specific historic theatres' significance. Their application made it possible to survey, classify, and decode [Maietti, 2019] the complexity of

Figure 5. Photo of the experimental phase: a professionals during his attempt to the compilation of the form. Ph.Veronica Vona.

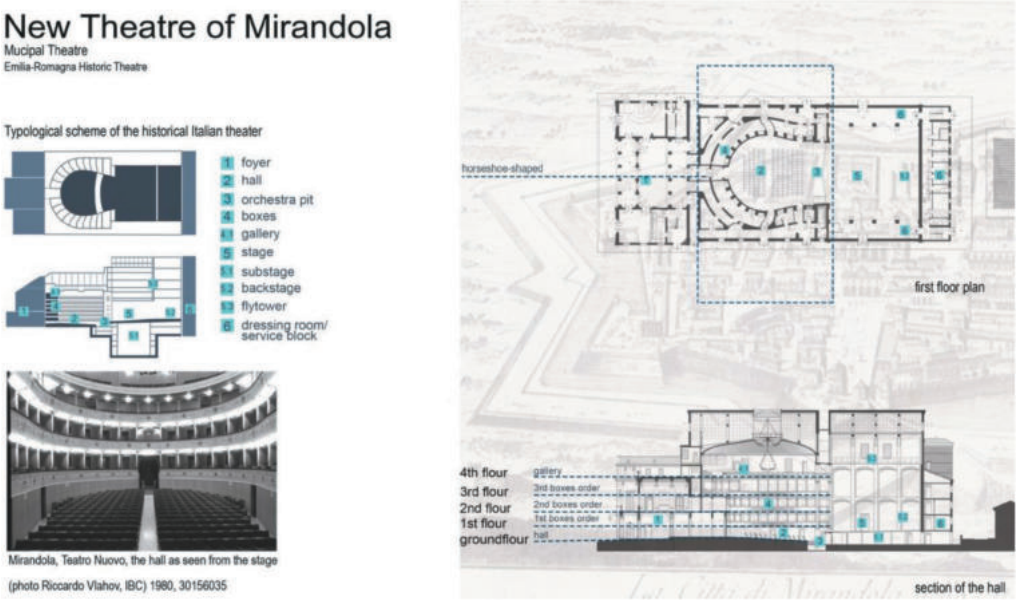


Figure 6. Nuovo Theater - Mirandola (MO) characterised by a horseshoe plan with boxes. Editing by Martina Suppa.

theatres and provide appropriate survey procedures for managing and preserving the assets under study.

Based on this premise, the research, developed a procedural workflow for the integrated documentation of cultural heritage aimed at seismic damage survey for the specific architectural typology: the Historic Theaters of the Emilia-Romagna Region.

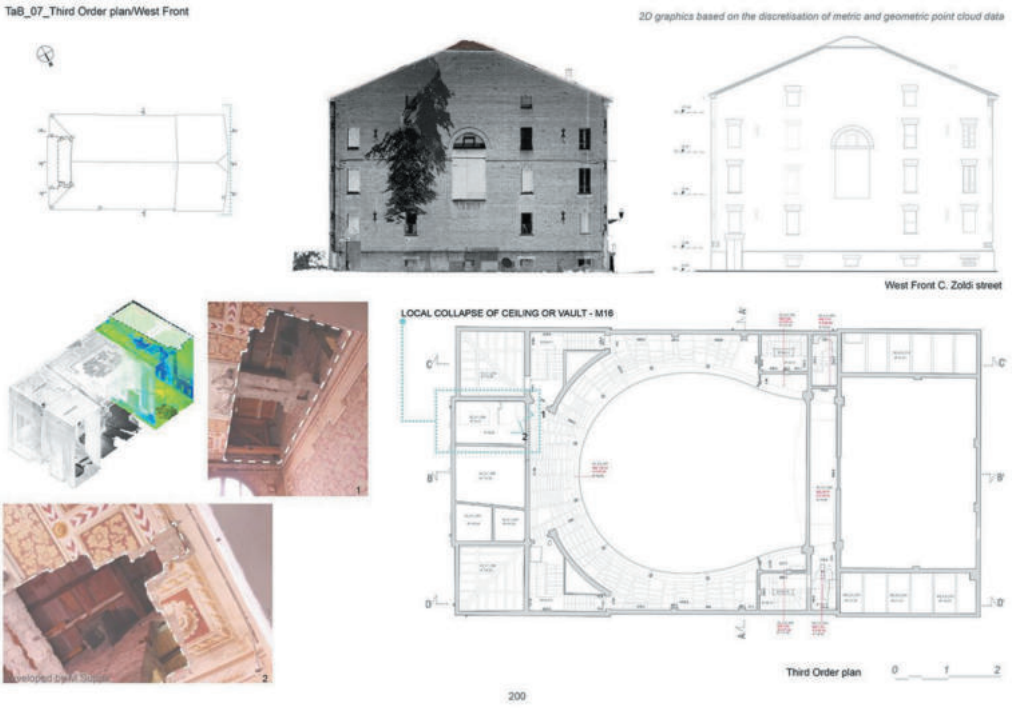
The reasons connected to the architectural-cultural meanings and socio-economic significance of historic theatres over time in the regional area, together with the reasons closely related to the critical issues encountered in the survey and assessment of seismic damage in the emergency phase, led the 2012 Reconstruction Agency-SISMA to select historic theatres as the object of investigation. The study proposed knowledge, analytical, and application sampling to calibrate the integrated method on the direct experience of damage survey for regional historic theatres, which can be summarised in 4 WPs:

- *(WP 1) State of the Art* - preliminary analysis: the legislative framework on an international, national and regional scale; existing risk management databases at an international, national, and regional scale; the survey procedures applied during the emergency phase for the damage assessment of historic theatres (A-DC and B-DP MIC forms); the existing integrated survey procedures involved to the documentation of cultural heritage; the typological characters of historic theatres, and existing standards and protocols of integrated documentation on an international and national scale to elaborate a meta-sheet, which, although set on the specific case study, had a matrix of standardised categories and information levels applicable to other types of cultural heritage.

– *(WP 2) The definition of the extensive integrated methodology for establishing a workflow ofintegrated procedures aimed at damage survey.* Through the double level of analysis, historical morphological and comparative critical MIC damage records archived by ARRER were studied. The comparative-critical analysis on the macro sample of 25 damaged Historic Theaters highlighted the criticalities of the theatres' B-DP filing model used for the damage survey. In addition, a comparative analysis was done on an application sample of 11 damaged theatres for which the respective RUP (Single Project Manager for public administration) provided information. This in-depth study made it possible to identify starting from the level of damage, the use of metric, geometric and diagnostic surveying methods and techniques, and the types of representations implicated. Finally, based on the sampling analysis and the typological knowledge of the asset, ad hoc criteria were identified for the survey of seismic damage in theatres.

– *(WP3) the Workflow Development of Integrated Procedures.* The workflow consists of 3 levels:
– *L1 (Screening Level)* represents the digitised implementation of the MIC damage survey models used in 2012A-DC and B-PD forms -sectioned on the analysed architectural typology. The digital tool is named SD T (Seismic Damage-Theaters) and represents the matrix of a single digital database related to the 106 historic theatres surveyed on a regional scale. The SD T is structured 13 main categories and has been structured based on the ICCD sheets and implementing the models mentioned above. All known information and data related to each theatre are collected and digitised. The purpose of the DS T is to provide a digital registry of each theatre to optimise the data retrieval and damage status survey phases during emergency operations. The methodological path for this level involved extending the analysis to a regional and international scale. The theatres examined belong to geographic areas of high seismic risk: on a regional scale - the Romagna area with Teatro A. Masini of Faenza; on an international scale - the Croazi with the National Theater of Split.
– *L2 (Survey Level).* It uses integrated surveying tools - laser scanner and digital

photogrammetry. It provides a survey protocol for acquiring data aimed at surveying seismic damage to obtain 3D morphometric models intended as a data database that can be consulted and implemented over time. Within the second level of the workflow, guidance is provided for coding, interpretation and representation of the acquired data by the 2011 directive, applying Inception's DAP for data acquisition through an integrated survey system (Data



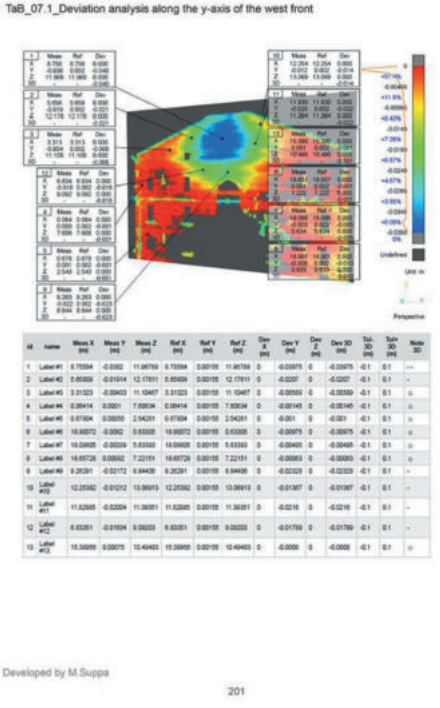


Figure 7. Seismic damage survey on the pilot case of the Theater of Novi di modena, use of the scan data for the representation of the metro-geometric aspects and the analysis of the deformation framework. Portion analysed: west elevation. Editing by Martina Suppa.

acquisition: 3D laser scanner, digital photogrammetry) set to the specificities of the damage survey. Application of L2 was tested on the pilot case of Novi di Modena (Figure7);

– *L3 (HBIM PLUS Level)* is the first and second levels collector. Specifically, the information

collected from the SD T and the data acquired and processed in L2 are used to build parametric HBIM models, which are then linked to the HBIM semantic platform of the INCEPTION project. At this workflow level, attention was paid to the information layer (LOI) that the parametric BIM models can include by developing a dedicated set of rules on seismic damage. The decision to have HBIM models is intended to overcome the form tools' limitations and trace the damage survey directly and punctually to the shape datum of the cultural asset.

– *(WP4) The Identification of the HBIM platform* - INCEPTION as a management and monitoring tool on the theatre's reconstruction process actions. The HBIM environment is configured as a valuable database for documentation, classification and storage of essential information for the knowledge of theatres, updated metric and geometric surveys, predictive analysis on damage and state of preservation. In addition, it represents a support for conservation planning action for professionals and control over the management and maintenance of the property throughout its life cycle, part of the institutional bodies operating in the field of protection and conservation.

The research identifies in the used methodology of Building Information Modeling for culture Heritage (HBIM) the opportunity to directly relate the digital model of the historic building with the information and morphometric database to optimise within the collaborative environment the monitoring and management of theatres and the steps of the decision path.

5 CONCLUSION

The "2012 Emilia" earthquake has enabled us to identify both the strengths and the weaknesses in the procedures of emergency management, which was very useful for the reconstruction, as well as for the documentation of the damaged heritage.

For this reason, the analysis of some special building type damaged by "2012 Emilia" earthquake represented a great opportunity to implement the existent instruments and procedure for both the emergency phase and the normal life-cycle of these buildings. New damage survey forms, new predictive GIS-system for the vulnerability analysis, a 3-level workflow for the management of restoration process, these are the main outcome of the research that may affect both future disaster scenarios and the prevention of their effects.

These results should nevertheless be understood as an initial, although advanced, step in the development of tools for damage survey or seismic risk mitigation. Many limitations to the analyses have in fact emerged, such as that concerning the constructive features of the geographica area examined (castles), the size sample (cemeteries) or the criticality in the use of semantic platform (theatres).

These limitations have often been accepted and integrated within the proposed outcomes from the perspective of future development together with open issues such as the complete digitisation of all tools or their interoperability with the current cartographic systems. Indeed, only further investigation and real use of this tools will reveal additional directions for progressive improvement.

AUTHORS CONTRIBUTION

Paragraph "Fortified architecture" is edited by Elena Zanazzi, paragraph "Cemeteries" by Veronica Vona and paragraph "Teatres" by Martina Suppa.

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